The Dark Target aerosol retrieval algorithm: From MODIS to VIIRS (and beyond)

Robert C. Levy (NASA-GSFC) and the ”Dark-Target” retrieval team

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 and Falguni Patadia (USRA)

Outside of #33:
- Folks at University of Atmos-SIPS (Wisconsin)
- Folks at MODAPS (GSFC)
For Aerosol Optical Depth (AOD):

<table>
<thead>
<tr>
<th>Target metric</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal Resolution</td>
<td>5-10 km, globally</td>
</tr>
<tr>
<td>Accuracy</td>
<td>MAX(0.03 or 10%)</td>
</tr>
<tr>
<td>Stability / bias</td>
<td>&lt;0.01 / decade</td>
</tr>
<tr>
<td>Time Length</td>
<td>30+ years</td>
</tr>
<tr>
<td>Temporal Resolution</td>
<td>4 h</td>
</tr>
</tbody>
</table>

These are requirements for “climate” monitoring. Maybe different requirements for other applications (air quality, ocean fertilization, weather forecasting...).
Dark-Target: A “Single View” aerosol algorithm

What a sensor observes

Attributed to aerosol (AOD)

“Established 1997” by Kaufman, Tanré, Remer, etc) for MODIS

Separate logic over land and ocean
Retrieve: AOD at 0.55 μm, spectral AOD, etc
Can run in near-real-time (NRT; takes 2 minutes)
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: ±(0.15τ + 0.05)
  - Ocean: ±(0.10τ + 0.04)
- getting close to CDR accuracy requirements!
MODIS-Terra vs MODIS-Aqua

The two MODIS instruments are TWINS!
Do they observe the world in the same way?

C6: Terra-Aqua (DT) had global offset of 0.015 (13%)
C6: And the offset drifted...

- Terra-Aqua global offset of $\Delta \tau \approx 0.01-0.02$
- $\Delta \Delta \tau$ is unphysical
- Seasonal pattern/differences were larger in later years (post 2011).
Using “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!
Urban Retrievals in MODIS 6.1

Surface reflectance correction as a function of urban %

➔ Significant reduction in AOD bias

Implemented in C6.1

Is local, will not affect Terra-Aqua difference

(DISCOVER-AQ, Summer 2011 in Maryland, USA)

Gupta et al., 2016, AMT
What about Future MODIS?
(“Maintenance Mode”)

• Our MODIS work is now under Senior Review since late 2017.

• We are funded for “maintenance”. 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).
**Aerosol Optical Depth (AOD) from MODIS 6.1:**

<table>
<thead>
<tr>
<th>Target metric</th>
<th>Target</th>
<th>Current with MODIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal Resolution</td>
<td>5-10 km, globally</td>
<td>10 km over ice-free and cloud-free scenes <em>(No desert for DT)</em></td>
</tr>
</tbody>
</table>
| 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 mission lifetimes.
• With luck, they will last until early 2020s.
• But for climate, we need to continue the MODIS record over 30+ years

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

• The NOAA operational products are “too different” from MODIS for climate research.
• Both DT and DB algorithms are ported
To develop “continuity” we port algorithms! (Example: DT from MODIS → VIIRS)

- Deal with differences in wavelengths (gas corrections/Rayleigh, etc)
- Deal with differences in resolution, etc.
- Retrieve on VIIRS (compared with retrieval on MODIS):

Levy et al., 2015
NASA VIIRS Dark Target Products (2015)
MODIS-Terra vs MODIS-Aqua vs SNPP-VIIRS

Terra (10:30, Descending)

Aqua (13:30, Ascending)

VIIRS (13:30, Ascending)
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)
Calibration is hard: “Match files”

Example: 0.86 µm channel over “clear” sky

Transmission

VIIRS M7 MODIS B2

Figure 2. Example MODIS/VIIRS match up for two near-coincident granules (beginning one minute apart). The S-NPP VIIRS granule is outlined in red, and MODIS Aqua in blue. Suitable matched pixels are shown in green.

Cloud Optical Properties: 0.86 µm Channel Radiometry

Sayer et al., AMT 2016

Meyer et al., this morning

VIIRS 865 should be multiplied by:

Sayer et al., AMT 2016

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

See Poster by Virginia Sawyer
Towards consistent global aerosol using DT

VIIRS on SNPP (and beyond) should include all updates (e.g. 6.1) for MODIS.
Compared to GCOS requirements
For Aerosol Optical Depth

<table>
<thead>
<tr>
<th>Target metric</th>
<th>Target</th>
<th>Current with MODIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal Resolution</td>
<td>5-10 km, globally</td>
<td>≤10 km over ice-free and cloud-free scenes <em>(No desert for DT)</em></td>
</tr>
<tr>
<td>Accuracy</td>
<td>MAX(0.03 or 10%)</td>
<td>±(0.04+10%): Ocean</td>
</tr>
<tr>
<td></td>
<td></td>
<td>±(0.05+15%): Land</td>
</tr>
<tr>
<td>Stability / bias</td>
<td>&lt;0.01 / decade</td>
<td>Nearly stable trends, but offsets still</td>
</tr>
<tr>
<td>Time Length</td>
<td>30+ years</td>
<td>Can do with MODIS + VIIRS</td>
</tr>
<tr>
<td>Temporal Resolution</td>
<td>4 h</td>
<td>2+ / day <em>(Terra + Aqua/VIIRS)</em></td>
</tr>
</tbody>
</table>

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

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)
Port DT algorithm to GEO!

Spectral/Spatial: AHI / ABI ≈ MODIS / VIIRS

<table>
<thead>
<tr>
<th></th>
<th>MODIS</th>
<th>VIIRS</th>
<th>AHI</th>
<th>ABI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue</td>
<td>0.47/0.5</td>
<td>0.49/0.75</td>
<td>0.47/1.0</td>
<td>0.47/1.0</td>
</tr>
<tr>
<td>Green</td>
<td>0.55/0.5</td>
<td>0.55/0.75</td>
<td>0.51/1.0</td>
<td></td>
</tr>
<tr>
<td>Red</td>
<td>0.66/0.25</td>
<td>0.67/0.75</td>
<td>0.64/0.5</td>
<td>0.64/0.5</td>
</tr>
<tr>
<td>NIR</td>
<td>0.86/0.25</td>
<td>0.86/0.75</td>
<td>0.86/1.0</td>
<td>0.86/1.0</td>
</tr>
<tr>
<td>NIR</td>
<td>1.24/0.5</td>
<td>1.24/0.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cirrus</td>
<td>1.38/0.5</td>
<td>1.38/0.75</td>
<td></td>
<td>1.38/2.0</td>
</tr>
<tr>
<td>SWIR</td>
<td>1.61/0.5</td>
<td>1.61/0.75</td>
<td>1.61/2.0</td>
<td>1.61/1.0</td>
</tr>
<tr>
<td>SWIR</td>
<td>2.11/0.5</td>
<td>2.25/0.75</td>
<td>2.25/2.0</td>
<td>2.25/2.0</td>
</tr>
</tbody>
</table>

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!!

KORUS_Taehwa

XiangHe

KORUS_Olympic_Park

AERONET

AHI

Pawan Gupta
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,...)
Towards synergy of aerosol observations

Suborbital High-Spatial Resolution


MAS/eMAS (aboard ER2 aircraft)
MODIS-Terra (10:30)
MODIS-Aqua (13:30)
VIIRS (SNPP 13:30)
VIIRS on JPSS-1, -2, -3, -4

GEO
AHI
ABI (GEOS-R/16), Additional GEO

EPIC (DSCOVR at L1)

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

<table>
<thead>
<tr>
<th>Target metric</th>
<th>Target</th>
<th>with LEO + GEO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal Resolution</td>
<td>5-10 km, globally</td>
<td>≤10 km over ice-free and cloud-free scenes</td>
</tr>
<tr>
<td>Accuracy</td>
<td>MAX(0.03 or 10%)</td>
<td>±(0.04+10%): Ocean</td>
</tr>
<tr>
<td></td>
<td></td>
<td>±(0.05+15%): Land</td>
</tr>
<tr>
<td>Time Length</td>
<td>30+ years</td>
<td>30+ years (MODIS + VIIRS on JPSSx)</td>
</tr>
<tr>
<td>Stability / bias</td>
<td>&lt;0.01 / decade</td>
<td>Not there yet, but possible?</td>
</tr>
<tr>
<td>Temporal Resolution</td>
<td>4 h</td>
<td>20+/day (daylight only) where GEo</td>
</tr>
</tbody>
</table>

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.
Etcetera

Improvements to DT algorithm/products

• Improved coverage for heavy aerosol events (Indonesian fires, Beijing smoke, etc) = Yingxi Shi
• Improved dust detection and dust optical properties to reduce bias for dust climatology = Yaping Zhou
• Improved retrievals (and coverage) over coastal environments = Yi Wang/Jun Wang (U-Iowa)
• Alternatives for aerosol retrieval over brighter surfaces?
• Retrievals on higher resolution data (eMAS, Landsat, Sentinel) = Shana Mattoo

Use of DT products by Science Team

• Synergy with UV radiances (e.g. OMPS/VIIRS) = Santiago Gásso
• Correcting for 3D effects in aerosol near clouds = Tamás Varnai
• Using DT and other products to look at fires in India = Pawan Gupta
• Using DT and other products to look at dust and radiation = Hongbin Yu
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


