First application of VIIRS Day-Night band for nighttime particulate matter air quality studies

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Elvidge et al., 1997

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DMSP OLS

The U.S. AF(DMSP) Operational Linescan System: Unique capability to collect low-light imagery (PMT)
- Polar orbiting satellite- 3000 km swath
- Spatial Resolution: 2.7 km @ nadir
- Spectral band: 0.5-0.9 um.
- Nocturnal global coverage
- Flown since 1972
- Equator crossing time: 17:31 & 5:31
- 1992 DoD and NOAA establish digital archive for DMSP at NOAA NGDC
- No onboard calibration; 6-bit quantization

Suomi NPP VIIRS Day-Night-Band (DNB)

- The Suomi National Polar-orbiting Partnership (NPP) satellite was successfully launched on 28 October 2011.
- Visible/Infrared Imager/Radiometer Suite (VIIRS) - one of five instruments onboard NPP.
- Spectral band: 0.5-0.9 um
- Has a 3000 km swath width and nearly constant resolution (0.75 km) from nadir to limb.
- 14 orbits per day, 16-day repeat cycle; Nocturnal global coverage
- Equator crossing time: 13:30 & 1:30
- Onboard calibration; amplification for 3-level of gains (low, medium & high) respectively with 13-, 13-, & 14-bit quantization
- One of 22 bands on VIIRS
DNB spectral response function

![Graph showing spectral response function with different temperatures (T=5500K, T=3500K, T=2700K, T=1000K, T=500K) and normalizing full moon max.](image)

- $E(\lambda)$ (Wm$^{-2}$sr$^{-1}$µm$^{-1}$)
- Wavelength ($\mu$m)
- Spectral Response Function

Key temperatures and spectral maxima:
- $T=5500K$
- $T=3500K$
- $T=2700K$
- $T=1000K$
- $T=500K$

Full moon max. is indicated by the orange horizontal line.
### National Ambient Air Quality Standards

**NAAQS as of Oct. 2011**

<table>
<thead>
<tr>
<th>Pollutant [final rule cite]</th>
<th>Primary/Secondary</th>
<th>Averaging Time</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Carbon Monoxide</strong> [76 FR 54294, Aug 31, 2011]</td>
<td>primary</td>
<td>8-hour</td>
<td>9 ppm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1-hour</td>
<td>35 ppm</td>
</tr>
<tr>
<td><strong>Lead</strong> [73 FR 66964, Nov 12, 2008]</td>
<td>primary and secondary</td>
<td>Rolling 3 month average</td>
<td>0.15 μg/m³ (1)</td>
</tr>
<tr>
<td><strong>Nitrogen Dioxide</strong> [75 FR 6474, Feb 9, 2010] [61 FR 52852, Oct 8, 1996]</td>
<td>primary</td>
<td>1-hour</td>
<td>100 ppb</td>
</tr>
<tr>
<td></td>
<td>primary and secondary</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Ozone</strong> [73 FR 16436, Mar 27, 2008]</td>
<td>primary and secondary</td>
<td>8-hour</td>
<td>0.075 ppm (3)</td>
</tr>
<tr>
<td><strong>Particle Pollution</strong> [71 FR 61144, Oct 17, 2006]</td>
<td>PM&lt;sub&gt;2.5&lt;/sub&gt;</td>
<td>primary and secondary</td>
<td>Annual</td>
</tr>
<tr>
<td></td>
<td>PM&lt;sub&gt;10&lt;/sub&gt;</td>
<td></td>
<td>24-hour</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sulfur Dioxide</strong> [75 FR 35520, Jun 22, 2010] [38 FR 25678, Sept 14, 1973]</td>
<td>primary</td>
<td>1-hour</td>
<td>75 ppb (4)</td>
</tr>
<tr>
<td></td>
<td>secondary</td>
<td>3-hour</td>
<td>0.5 ppm</td>
</tr>
</tbody>
</table>

*12 μg/m³, FR, 15 Jan. 2013*
# Proposed change for 24-hour PM$_{2.5}$ NAAQS

<table>
<thead>
<tr>
<th>AQI Category</th>
<th>Index Values</th>
<th>Existing Breakpoints (1999 AQI) ($\mu$g/m$^3$, 24-hour average)</th>
<th>Proposed Breakpoints (µg/m$^3$, 24-hour average)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>0 - 50</td>
<td>0.0 - 15.0</td>
<td>0.0 – (12.0 - 13.0)</td>
</tr>
<tr>
<td>Moderate</td>
<td>51 - 100</td>
<td>&gt;15.0 - 40</td>
<td>(12-1 - 13.1) – 35.4</td>
</tr>
<tr>
<td>Unhealthy for Sensitive Groups</td>
<td>101 – 150</td>
<td>&gt;40 – 65</td>
<td>35.5 – 55.4</td>
</tr>
<tr>
<td>Unhealthy</td>
<td>151 – 200</td>
<td>&gt; 65 – 150</td>
<td>55.5 – 150.4</td>
</tr>
<tr>
<td>Very Unhealthy</td>
<td>201 – 300</td>
<td>&gt; 150 – 250</td>
<td>150.5 – 250.4</td>
</tr>
<tr>
<td>Hazardous</td>
<td>301 – 400</td>
<td>&gt; 250 – 350</td>
<td>250.5 – 350.4</td>
</tr>
<tr>
<td></td>
<td>401 – 500</td>
<td>&gt; 350 – 500</td>
<td>350.5 – 500</td>
</tr>
</tbody>
</table>

*Note: Parentheses indicate a range*
NAAQS uses **daily and annual averages of PM$_{2.5}$**

**Can we use DNB to estimate surface PM$_{2.5}$ at night?**

- At night, aerosols are often mixed in a shallow nocturnal boundary layer.
- Retrieval of AOD from DNB is still in its infancy; preliminary work include Zhang et al. (2008) and Johnson et al. (2013).
- We like to make a first attempt to apply DNB for night time PM$_{2.5}$ air quality.
- Aug – Oct 2012. Focus area: Atlanta

**PM$_{2.5}$: 5 ug/m$^3$**  
**VIIRS DNB, 7 Sep. 2012**

**PM$_{2.5}$: 13 ug/m$^3$**  
**VIIRS DNB, 8 Sep. 2012**
Observed diurnal variation of PM2.5

VIIRS overpass time at night: representative of 24-hr mean PM2.5

Graphs showing diurnal variation of PM2.5 concentrations with error bars and a trend line. The x-axis represents hours of the day (EST) and the y-axis represents PM2.5 concentration in µg/m³.
Case Analysis

Moon Nights

Low PM$_{2.5}$
Large VZA $\rightarrow$

Moonless Nights

Nadir view $\rightarrow$

High PM$_{2.5}$
City lights enhance the signal for detecting PM$_{2.5}$ changes.

Using moonlight alone to detect PM2.5 appears very challenging.
Keep it simple:

- Assume that upward visible radiance at the surface is isotropic, constant, and can be estimated with maximum composite method.
- Focus on moonless, cloudless, and no-rain nights.
- Neglect multiple scattering, and estimate AOD with Beer-Lambert law.
- Assume that PM$_{2.5}$ are well mixed in a constant height $H$, and has constant mass extinction efficiency ($Q_{mext}$).

\[
\ln\left(\frac{I}{I_0}\right) = \frac{-\tau}{\cos(VZA)} = -PM_{2.5}Q_{mext}H \cos(VZA)
\]

[Graphs showing linear relationships with equations and correlation coefficients for Site, A (suburb), Site, E (Urban Center), and City center light Vs. Regional PM.]
Tackle the first assumption: parameterize $Q_{mext}$ as a function RH

Based upon the visibility and RH measured by NWS and IMPROVE (Malm et al., 1994) parameterization. Visibility $\rightarrow$ extinction follows Koschmieder equation.

\[ Q_{mext} = \frac{3.92PM_{2.5}}{Visibility} \]
Improved results after treating RH effect

Site, A
suburb

\[ Y = -0.008 \times + 0.564 \]
\[ R = -0.78 \]
\[ N = 15 \]

Site, E
Urban Center

\[ Y = -0.013 \times + 1.245 \]
\[ R = -0.71 \]
\[ N = 15 \]

City center light
Vs.
Regional PM

\[ Y = -0.018 \times + 2.916 \]
\[ R = -0.73 \]
\[ N = 15 \]
Summary

• Advantages of using VIIRS DNB to derive PM$_{2.5}$
  – Avoid day-time boundary layer cloud contamination.
  – Nocturnal boundary layer often is stable (& sometimes associated with inversion), easier to characterize.
  – Fine resolution 750 m, all the time.
  – Daily global coverage, better than MODIS.
  – Appear representative of daily-mean PM$_{2.5}$.
  – Provide unique constraint for AQ models.

• Challenges
  – City light spectra at surface: highly variable, not well studied.
  – City light BRDF at surface: not well studied.
  – RTM modeling (moonlight + city light).
  – Currently, DNB georeference is not terrain corrected.

Overall, an exciting field with more discoveries and applications to come!
VIIRS also offers unique capability for monitoring PM2.5 at daytime
<table>
<thead>
<tr>
<th>Band number/gain</th>
<th>VIIRS wavelength (µm)</th>
<th>Lee et al., 2006.</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1, dual</td>
<td>0.412</td>
<td>0.742 × 0.259</td>
</tr>
<tr>
<td>M2, dual</td>
<td>0.445</td>
<td>0.742 × 0.259</td>
</tr>
<tr>
<td>M3, dual</td>
<td>0.488</td>
<td>0.742 × 0.259</td>
</tr>
<tr>
<td>M4, dual</td>
<td>0.555</td>
<td>0.742 × 0.259</td>
</tr>
<tr>
<td>I1, single</td>
<td>0.640</td>
<td>0.371 × 0.387</td>
</tr>
<tr>
<td>M5, dual</td>
<td>0.672</td>
<td>0.742 × 0.259</td>
</tr>
<tr>
<td>M6, single</td>
<td>0.746</td>
<td>0.742 × 0.776</td>
</tr>
<tr>
<td>I2, single</td>
<td>0.865</td>
<td>0.371 × 0.387</td>
</tr>
<tr>
<td>M7, dual</td>
<td>0.865</td>
<td>0.742 × 0.259</td>
</tr>
<tr>
<td>DNB, multiple</td>
<td>0.7</td>
<td>0.742 × 0.742</td>
</tr>
<tr>
<td>M8, single</td>
<td>1.24</td>
<td>0.742 × 0.776</td>
</tr>
<tr>
<td>M9, single</td>
<td>1.38</td>
<td>0.742 × 0.776</td>
</tr>
<tr>
<td>M10, single</td>
<td>1.61</td>
<td>0.742 × 0.776</td>
</tr>
<tr>
<td>I3, single</td>
<td>1.61</td>
<td>0.371 × 0.387</td>
</tr>
<tr>
<td>M11, single</td>
<td>2.25</td>
<td>0.742 × 0.776</td>
</tr>
<tr>
<td>M12, single</td>
<td>3.70</td>
<td>0.742 × 0.776</td>
</tr>
<tr>
<td>I4, single</td>
<td>3.74</td>
<td>0.371 × 0.387</td>
</tr>
<tr>
<td>M13, dual</td>
<td>4.05</td>
<td>0.742 × 0.259</td>
</tr>
</tbody>
</table>
Surface PM$_{2.5}$ Estimate

Use of VIIRS reflectance:
- reduces the model bias from -5.6 μg/m$^3$ to 3 μg/m$^3$
- increase $R^2$ from 0.69 to 0.87.
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