Remote sensing of airborne particulate matter using multiangle spectroradiometry and spectropolarimetry

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Particulate matter (PM) impacts on human health

Airborne PM is a well-known cause of cardiovascular and respiratory diseases.

- **Coarse** particles (PM\textsubscript{10} - PM\textsubscript{2.5}) irritate our respiratory systems.
- **Fine** particles (PM\textsubscript{2.5}) penetrate deep into our lungs. Toxins can migrate to other organs.
  - Heart attacks
  - Stroke
  - Lung disease, lung cancer
  - Aggravated asthma
  - Low birth weight and preterm delivery
Importance of particle type

- Although PM is implicated in many adverse health impacts, the relative toxicity of specific **PM types** is not well understood.

- PM “type” refers to the fractional proportions of PM$_{10}$, PM$_{2.5}$, and PM$_{2.5}$ components (sulfate, nitrate, organic carbon, black carbon, dust).

- According to the US EPA (2013):
  - [T]he evidence is not yet sufficient to allow differentiation of those constituents or sources that may be more closely related to specific health outcomes.
  - The use of central fixed-site monitors to represent population exposure is a key factor limiting our knowledge as to which PM types pose the greatest health risks.
Multi-angle Imaging SpectroRadiometer (MISR)

- 9 view angles between ±70°
- 275 m sampling
- Four spectral bands:
  446, 558, 672, 866 nm

Terra launch, Dec. 1999
Oblique-angle sensitivity to aerosols over many surface types

van Donkelaar et al. (2010, 2015)

PM$_{2.5}$ maps derived from MODIS and MISR are used in many health studies, e.g.,

- Global Burden of Disease (Brauer et al., 2012)
- Relative risk of death from circulatory system diseases (Jerrett et al., 2017)
- Associations between PM$_{2.5}$ and low birth weights (Fleischer et al., 2014)
- Increased breast cancer mortality risk from PM$_{2.5}$ exposure (Tagliabue et al., 2016)
Relating AOD to PM concentration

\[ [\text{PM}] \approx \left[ \frac{4\rho r_{\text{eff}}}{3Q_{\text{ext}} H} \right] \text{AOD} \]

- \( \rho \) = particle density
- \( r_{\text{eff}} \) = effective particle radius (ratio of 3\textsuperscript{rd} to 2\textsuperscript{nd} moment of size distribution)
- \( Q_{\text{ext}} \) = extinction efficiency (ratio of optical to geometric cross section of the particles) under ambient conditions
- \( H \) = height of the aerosol layer

Gupta and Christopher (2009)

- These factors are highly variable
- Difficult to obtain reliable accuracies from first principles

For more information, refer to Gupta and Christopher (2009).
Mapping of PM$_{2.5}$ over India with MISR

Empirical regressions work better, e.g., PM$_{2.5} = A \times \eta \times \text{AOD} + B$

$\eta$ is calculated from GOES-Chem and is a function of aerosol size, type, diurnal variation, vertical distribution, and relative humidity.

A, B = correction factors are derived from surface PM$_{2.5}$ measurements.

Dey et al. (2012)
Liu et al. (2004, 2007)
van Donkelaar et al. (2006, 2010)
Multiangular sensitivity to particle size and shape

Scattering phase function

- Large spherical aerosols
- Large irregularly shaped (dust) aerosols

Scattering angle (degrees)

- Air molecules (very tiny)
- Small spherical aerosols
- Large spherical aerosols

July 2007

Kahn and Gaitley (2015)

0.2 < AOD < 0.5

8 component particle types

Volume Weighted Particle Diameter (μm)

Mass Fraction

Spherical, non-absorbing

Non-spherical

Spherical, absorbing

Mixture Group
New MISR global 4.4 km resolution AOD product to be released Fall 2017

- High-resolution aerosol data is important for urban-scale air-quality and health impact assessments.
- Compared to the current MISR V22 aerosol product, the new V23 product will:
  - improve the spatial resolution from 17.6 km to 4.4 km
  - increase spatial coverage and enhance the ability to resolve aerosol spatial gradients
  - increase accuracy at high and low AODs compared to AERONET sunphotometer data

Garay et al. (2017)
Use of MISR fractional 4.4-km AODs for speciated PM$_{2.5}$ retrieval in California

PM$_{2.5}$ speciation = $\sum_{i=1}^{8} f_i(MISR \text{ fractional AOD}_i) + f_k(\text{predictor}_k) + f_{x,y}(x,y) + f_t(t)$

- $f_i(MISR \text{ fractional AOD}_i)$ is smooth term of MISR fractional AOD$_i$
- $f_k(\text{predictor}_k)$ is the smooth term of predictor variables $k$, including elevation, PBLH, NDVI and road length
- $f_{x,y}(x,y)$ is a 2-D smooth spatial function of sites’ coordinates
- $f_t(t)$ is a nonlinear term of DOY or the YEAR varying smoothly in time

Meng et al. (2017)
Daily speciated PM$_{2.5}$, 2010-2015

Meng et al. (2017)

Measurement = -0.03 + 1.03 x prediction
Adjusted $R^2 = 0.66$

Measurement = -0.07 + 1.04 x prediction
Adjusted $R^2 = 0.60$

Measurement = -0.05 + 1.04 x prediction
Adjusted $R^2 = 0.54$

Measurement = -0.01 + 1.03 x prediction
Adjusted $R^2 = 0.58$
Averaged annual means of predicted sulfate and nitrate PM$_{2.5}$ concentrations

Meng et al. (2017)
JPL Airborne Multiangle SpectroPolarimetric Imager (AirMSPI)

• Gimbaled camera with selectable view angles between ±67°
• Uses electro-optical measurement approach to provide accurate polarimetric imaging without moving parts
• 10 m sampling
• 355, 380, 445, 470*, 555, 660*, 865*, 935 nm (*polarized)

Flying since 2010 on the NASA ER-2 aircraft (20 km flight altitude)
PODEX, SEAC4RS, CalWater-2, RADEX, ImPACT-PM, ORACLES
Inclusion of polarization reduces retrieval scatter and bias

Without polarization

\[ y = ax + b \]
\[ a: 0.855 \]
\[ b: -0.025 \]

MAD: 0.049
\[ R^2: 0.922 \]

9 angles w/o pol.

With polarization

\[ y = ax + b \]
\[ a: 1.000 \]
\[ b: 0.007 \]

MAD: 0.023
\[ R^2: 0.946 \]

9 angles with pol.

MAD = mean absolute difference

Xu et al. (2017)
AirMSPI sensitivity to aerosol particle properties

Xu et al. (2017)
Fresno, CA 6 Jan 2012, 20:23 UTC

Limited sensitivity to coarse mode with UV/VNIR observations only

Data: https://eosweb.larc.nasa.gov/project/airsmspi/preliminary-airmspi-datasets
MISR stereoscopic sensitivity to aerosol plume height

Kahn et al. (2008), Val Martin et al. (2010)

Miller et al. (2011)
Stereoscopic and time-lapse sensitivity to plume-tracked winds

- Middle East and African dust storms have significant environmental and societal impacts.
- Northwesterly Shamal winds are responsible for major dust events.
- MISR’s near-surface wind and aerosol nonspherical fraction data products enable development of a Shamal climatology and seasonal dust prediction capability.

Yu et al. (2015, 2016)
Multi-Angle Imager for Aerosols (MAIA)

- MAIA was selected in March 2016 as part of NASA’s Earth Venture Instrument program
- The satellite instrument will target major urban areas to assess the impacts of different types of airborne PM on human health
- TBD satellite and launch into sun-synchronous orbit, 600-850 km altitude, ~2021

| birth outcomes (restricted intrauterine growth, preterm delivery, low birth weight) |
| acutale illness events (e.g., asthma flare-ups), premature deaths |
| chronic cardiovascular and respiratory disease |

- Candidate Primary Target Areas
- Other target areas to be observed for air quality and climate science

Liu and Diner (2017)
MAIA instrument

- Contains a pair of spectroradiometric/polarimetric cameras on a 2-axis gimbal to image the selected target areas

Along-track multi-angle viewing to ±67°

Cross-track axis enables viewing targets off the sub-S/C track

Target dimensions ≥ 300 km cross-track x 150 km along-track

Nadir footprint ~200 m

PM data products to be generated in ground processing at 1 km resolution

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<th>Band (nm)</th>
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<th>385</th>
<th>415</th>
<th>445</th>
<th>550</th>
<th>645</th>
<th>749</th>
<th>762.5</th>
<th>867</th>
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- polarimetric

  absorbing particles  fine particles  coarse particles

(MISR, MODIS, TOMS, POLDER + airborne heritage)
Concluding remarks

- Benefits of multiangle imaging:
  - Oblique views enhance the aerosol signal relative to many types of surface background, including urban areas and deserts
  - Sampling of the particle phase functions provides sensitivity to particle size and shape—enhanced by inclusion of polarimetry
  - Stereoscopy maps aerosol plume injection heights
  - Time-lapse between views allows tracking atmospheric winds

- MISR and AirMSPI data illustrate these capabilities

- Regression of satellite AOD with surface PM and other environmental variables is effective for mapping airborne particulate concentrations

- MAIA will integrate UV/VNIR/SWIR and polarimetric observations to map PM types in major cities around the world
  - Epidemiologists on the MAIA science team will use the resulting data products to conduct health impact investigations
Thank you
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