Data Mining Support for Aerosol Retrieval and Analysis: Our Approach and Preliminary Results

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joint work with

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Outline

• Understanding Properties of Aerosol Retrievals by Analysis of Integrated Satellite and Ground Based Observations
  (Han, B., Vucetic, S. and Obradovic, Z., In preparation)

• Discovering the Major Sources of Correctable Retrieval Error of Deterministic Retrieval Models

• Improving Aerosol Retrieval Accuracy by Integrating Multisource MODIS and MISR Data
  (Xu Q., Obradovic, Z., Han, B., Li, Y., Braverman, A., Vucetic, S. Proc. 8th Int’l Conf. Information Fusion, 2005)

• Integration of Deterministic and Statistical Retrieval Algorithms
  (Han, B., Vucetic, S., Braverman, A. and Obradovic, Z., Engineering Applications of Artificial Intelligence journal, in press)

• Facilitating Efficient Retrievals from Arbitrarily Large Datasets
  (Peng, K., Obradovic, Z. and Vucetic, S. Proc. 16th European Conf. Artificial Intelligence, 2004;
AOT Retrieval Problem

• Aerosol
  – small particles produced from natural and man-made sources
  – multiple types (soil dust, carbonaceous, sulfate, sea salt aerosols)

• Problem
  – predict (retrieve) aerosol optical thickness (AOT) and aerosol type
  – characterize and quantify the effect of aerosols on Earth’s radiation budget

Haze over East USA
(see more at http://alg.umbc.edu/usaq/)
Satellite-Based Data: MISR and MODIS

• **Given:**
  – radiance attributes, spatial-temporal information
  – satellites (NASA Earth Observing System)
    Terra: Dec. 1999
    Aqua: May 2002
    Aura: July 2004

• **Instruments:**
  – MISR: Terra, 9 camera (7 minutes to see a scene by all 9), 4 bands per camera, *global coverage 9 days*, repeating cycle 16 days, AOT retrieval resolution 17.6km
  – MODIS: Terra and Aqua, 1 camera, 36 wavelengths, *global coverage 1–2 days*, repeating cycle 16 days, AOT retrieval resolution 10km

• **Goal:**
  – long-term global observation and analysis of the land surface, biosphere, solid Earth, atmosphere, and oceans
Patterns of MISR AOT Retrieval

<table>
<thead>
<tr>
<th>Year</th>
<th>Dec - Feb</th>
<th>Mar - May</th>
<th>Jun - Aug</th>
<th>Sep - Nov</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>MISR observations began 24 February</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2001</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td></td>
<td></td>
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<tr>
<td>2003</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2004</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

MISR aerosol optical depth

- 0.0
- 0.1
- 0.2
- 0.3
- 0.4
- 0.5
- 0.6
- 0.7
- 0.8
- 0.9
- 1.0
AERONET (Aerosol Robotic NETwork): a federated international network of sun/sky radiometers at 311 sites, around 40 over U.S. Collects AOT data every 5-15 mins in 10 spectral bands.
AOT Retrieval Properties

• Satellite-based
  ♦ global coverage
  ♦ high spatial resolution
  ♦ low temporal resolution
  ♦ moderately accurate retrieval
  ♦ retrieved by computationally expensive forward simulation algorithm

• Ground-based
  ♦ limited spatial coverage
  ♦ high temporal resolution
  ♦ more accurate retrieval
Deterministic retrieval algorithms

- constructed as inverse operators of high-dimensional nonlinear functions based on lookup tables representing the most common conditions
- derived from forward-simulation models according to the domain knowledge of aerosol physical properties
- allow straightforward estimation of retrieval uncertainty

Drawbacks of deterministic retrieval algorithms

- high computational cost due to inversion of nonlinear forward models
- slow development due to manual construction of the postulated physical models
- inadequate accuracy due to limited size of constructed look-up table and partial understanding of the complex processes
- often compromise of accuracy, speed and prior knowledge

Objective of Our Study

- Support aerosol retrieval and analysis by complementing deterministic algorithms through development of data mining methodology that utilizes
  - multi-sensor satellite data of varying quality and
  - ground-truth information
Specific Aims of Our Study

Determine

1. If analysis of accurate statistical AOT retrievals using integrated satellite and ground observations can improve *understanding* properties of deterministic AOT retrievals;

2. If data mining can help *discovering* the major sources of *correctable* retrieval errors of deterministic retrievals; and

3. If data mining can facilitate development of *joint-sensor* retrieval algorithms that take advantage of aerosol observation from multiple instruments.
Our Approach and Preliminary Results

• **Analysis of AOT retrievals**
  – by learning relationships between satellite based attributes and ground based AOT observations using:
    • global neural network models;
    • local neural networks and local spatial interpolation models;
    • hybrid statistical models

• **Understanding correctable AOT retrieval errors**
  – by learning decision trees to characterize conditions when statistical retrievals are more accurate than model-driven deterministic retrievals

• **Developing joint-sensor retrievals**
  – by using attributes derived from MISR and MODIS and a target representing AOT retrieval by AERONET
• Understanding Properties of Aerosol Retrievals by Analysis of Integrated Satellite and Ground Based Observations
  (Han, B., Vucetic, S. and Obradovic, Z., In preparation)

• Discovering the Major Sources of Correctable Retrieval Error of Deterministic Retrieval Models

• Improving Aerosol Retrieval Accuracy by Integrating Multisource MODIS and MISR Data
  (Xu Q., Obradovic, Z., Han, B., Li, Y., Braverman, A., Vucetic, S. Proc. 8th Int’l Conf. Information Fusion, 2005)

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• Facilitating Efficient Retrievals from Arbitrarily Large Datasets
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Integration of MISR and AERONET Data

**MISR:** AOT at resolution 17.6km, radiance at resolution 1.1km. Average cloud-free and high quality (valid) voxels in +/-0.15° spatial region

**AERONET:** average AOT observations in a time windows

A Collocated Point = Average of MISR attributes in space + Average of AERONET AOT in time
Integration of MODIS and AERONET Data

**MODIS**: AOT at resolution 10km, radiance at resolution 5km. Average cloud-free and high quality (valid) voxels in $\pm 0.15^\circ$ spatial region

**AERONET**: average AOT observations in a time windows

A Collocated Point = Average of MODIS attributes in space + Average of AERONET AOT in time
Leave-one-AERONET-site-out cross validation experiments were performed on these datasets to:

- Identify influence of relevant attributes to AOT retrieval quality
- Understand effects of various spatial and temporal aggregation intervals
- Compare deterministic vs. statistical AOT retrieval properties in time, season, by surface type and other patterns

Temporal and spatially collocated satellite + ground data over continental US:

- MISR+AERONET: period 2002-2003
- MODIS+AERONET: period 2002-2004
- MISR+MODIS+AERONET: period 2002-2003
## Attributes for Learning of AOT Retrieval

- Trained feedforward networks on data grouped by AERONET sites
- Evaluated by leave-one-AERONET site-out cross validation

### Attributes for Training

<table>
<thead>
<tr>
<th>MISR Attributes input into ANN training</th>
<th>MODIS Attributes input into ANN training</th>
</tr>
</thead>
<tbody>
<tr>
<td>151/147</td>
<td>34/28</td>
</tr>
<tr>
<td>36 mean values of radiance</td>
<td>7 mean values of radiance</td>
</tr>
<tr>
<td>36 std values of radiance</td>
<td>7 std values of radiance</td>
</tr>
<tr>
<td>36 minimum radiance</td>
<td>7 minimum radiance</td>
</tr>
<tr>
<td>37 geometric attributes</td>
<td>5 geometric attributes</td>
</tr>
<tr>
<td>Number of cloud-free points</td>
<td>Number of cloud-free points</td>
</tr>
<tr>
<td>Surface feature type</td>
<td>Surface feature type</td>
</tr>
<tr>
<td>MISR AOT retrievals at 4 wavelengths</td>
<td>MODIS AOT retrievals at 3 wavelengths</td>
</tr>
</tbody>
</table>

Large number of attributes – curse of dimensionality problem is addressed by sensitivity analysis and PCA
**Objective:** Analyze influence of attributes to AOT retrieval accuracy based on change in neural network output given small perturbations in each attribute.

**Results:** The most sensitive attributes for MIST-AERONET and MODIS-AERONET

<table>
<thead>
<tr>
<th>MISR - AERONET</th>
<th>MODIS - AERONET</th>
</tr>
</thead>
<tbody>
<tr>
<td>MISR_AOT446nm</td>
<td>Corrected_MODIS_AOT470nm</td>
</tr>
<tr>
<td>MISR_AOT558nm</td>
<td>Continental_MODIS_AOT470nm</td>
</tr>
<tr>
<td>ScatteringAngle of Camera BF</td>
<td>Optical_Depth_Land_And_Ocean</td>
</tr>
<tr>
<td>ViewZenAngle of Camera DA</td>
<td>Average MODIS Radiance 470nm</td>
</tr>
<tr>
<td>Average Radiance 446nm of Camera AF</td>
<td>Minimum MODIS Radiance 470nm</td>
</tr>
<tr>
<td>Average Radiance 446nm of Camera AA</td>
<td>Minimum MODIS Radiance 2130nm</td>
</tr>
<tr>
<td>Radiance Std at 672nm of Camera AF</td>
<td>Minimum MODIS Radiance 555nm</td>
</tr>
<tr>
<td>Average Radiance 558nm of Camera AA</td>
<td>Average MODIS Angleset: Solar_Zenith</td>
</tr>
<tr>
<td>Radiance Std at 672nm of Camera AN</td>
<td>Continental_MODIS_AOT 660nm</td>
</tr>
<tr>
<td>Minimum Radiance 558nm of Camera AA</td>
<td>Minimum MODIS Radiance 659nm</td>
</tr>
</tbody>
</table>
Correlation to AERONET AOT

MISR Average Radiance AN – 447nm  MODIS Average Radiance at 470nm

Non-Linear Relationship with AERONET AOT
Correlation to AERONET AOT

Linear Relationship with AERONET AOT
Results: Accuracy Comparison
MISR/MODIS AOT vs. Neural Network Based Retrievals

Correlation and prediction error vs. AERONET AOT for different time windows of data fusion (MISR/MODIS AOT not used at ANN)

<table>
<thead>
<tr>
<th>Time window for averaging AERONET AOTs</th>
<th>MISR AOT</th>
<th>ANN Prediction based on MISR attributes</th>
<th>MODIS AOT</th>
<th>ANN Prediction based on MODIS attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>± 30 mins</td>
<td>Corr=0.87 RMSE=0.08</td>
<td>Corr=0.89 RMSE=0.08</td>
<td>Corr=0.75 RMSE=0.21</td>
<td>Corr=0.81 RMSE=0.10</td>
</tr>
<tr>
<td>± 60 mins</td>
<td>Corr=0.85 RMSE=0.08</td>
<td>Corr=0.88 RMSE=0.08</td>
<td>Corr=0.75 RMSE=0.21</td>
<td>Corr=0.80 RMSE=0.10</td>
</tr>
<tr>
<td>± 120 mins</td>
<td>Corr=0.84 RMSE=0.11</td>
<td>Corr=0.86 RMSE=0.10</td>
<td>Corr=0.70 RMSE=0.23</td>
<td>Corr=0.76 RMSE=0.11</td>
</tr>
<tr>
<td>Whole day</td>
<td>Corr=0.79 RMSE=0.13</td>
<td>Corr=0.83 RMSE=0.11</td>
<td>Corr=0.68 RMSE=0.24</td>
<td>Corr=0.73 RMSE=0.13</td>
</tr>
</tbody>
</table>

We didn’t count the collocated points with MODIS AOTs out of [0, 4].

- MODIS retrieval has a **systematic positive bias**
- For AERONET AOT averaging time window of ± 30 mins or ± 60 mins, retrievals were the most accurate (both deterministic and statistical)
The prediction errors were larger in summer, at coast sites and at regions with larger variance of elevation.

Monthly average of prediction errors (|ANN pred – AERONET AOT| over AERONET site

Notation:
Elevation std around a site
- <= 70m
- > 70m
AOT Error
- AOT Err > 0.12
- 0.12 >=AOT Err> 0.09
- 0.09 >=AOT Err> 0.06
- 0.06 >=AOT Err> 0.03
- AOT Err<=0.03
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Decision Tree Analysis
For Understanding Retrieval Errors

**Objective:** Use decision tree to analyze the conditions where MISR or MODIS AOT retrievals could be improved by neural network predictions

**Method:**
1. Define a classification problem

<table>
<thead>
<tr>
<th>Positives:</th>
</tr>
</thead>
</table>

\[ |\text{MISR/ MODIS AOT} - \text{AERONET AOT}| \geq \sigma \text{ and } \frac{|\text{MISR/ MODIS AOT} - \text{AERONET AOT}|}{|\text{ANN Prediction} - \text{AERONET AOT}|} \geq \theta \]

<table>
<thead>
<tr>
<th>Negatives:</th>
</tr>
</thead>
</table>

Otherwise.

\( \sigma, \Theta \) are selected by considering the discrimination of two AOT retrieval models as well as class balance. For MISR, \( \sigma=0.02, \Theta=2 \); For MODIS, \( \sigma=0.05, \Theta=3 \)

2. Learn decision tree to identify retrieval error rules
Results: MISR AOT Correctable Error
Discovered by Decision Tree Analysis

Decision Rules of MISR-AERONET fusion results

- # of Cloud_free Pixels in the region <= 265
- MISR CameraBF_Radiance_672nm_Avg >= 49.05
- MISR CameraAN_Radiance_672nm_Minimum < 161.59
- MISR CameraAN_ViewZenith_Angle < 6.99
  - MISR CameraAF_Radiance_866nm_Std < 132.70 (26%)
  - MISR CameraAF_Radiance_866nm_Std>=132.70
- MISR CameraAA_RelViewAzimuth_Angle < 65.26 (72%)
  - MISR CameraAA_RelViewAzimuth_Angle >= 65.26 (25%)

Discovered rule:
When cloud dominates a region, and MISR radiance and geometric parameters satisfy some conditions, neural network predictions outperform MISR AOT retrievals at 72% of locations.
Results: MODIS AOT Correctable Error
Discovered by Decision Tree Analysis

Decision Rules of MODIS-AERONET fusion results

-- MODIS Minimum Radiance at 470nm < 6.22 (24%)
   -- MODIS Minimum Radiance at 470nm >= 6.22
      -- Sensor Zenith Angle < 47.52
         -- Percentage of Region in Desert < 65% (55%)
         -- Percentage of Region in Desert >= 65% (80%)
      -- Sensor Zenith Angle >= 47.52 (36%)

Discovered rule:
When MODIS minimum radiance at 470nm, sensor zenith angle satisfy some condition, and the region is in desert area, neural network predictions can improve MODIS retrieval at 80% of locations
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• Facilitating Efficient Retrievals from Arbitrarily Large Datasets  
Results: AOT Retrieval by Integration of Multi-Source Data

<table>
<thead>
<tr>
<th>MISR AOT</th>
<th>MISR Attr</th>
<th>MODIS AOT</th>
<th>MODIS Attr</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.5935</td>
</tr>
<tr>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>0.632±0.065</td>
</tr>
<tr>
<td>-</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>0.651±0.056</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>0.3901</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>0.545±0.076</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>0.312±0.061</td>
</tr>
<tr>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>0.552±0.046</td>
</tr>
<tr>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>0.700±0.065</td>
</tr>
<tr>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>0.684±0.047</td>
</tr>
</tbody>
</table>

Accuracy comparison (R²) on 5 16-day cycles:

MISR Attr (MODIS Attr) denotes neural network learned on all MisrAeronet (ModisAeronet) attributes excluding the MISR AOT (MODIS AOT)

Result: Improved accuracy by integrating MISR and MODIS data

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• Facilitating Efficient Retrievals from Arbitrarily Large Datasets
Integration of Deterministic and Statistical Retrieval

- **Approach:**
  - Use deterministic algorithms over a fraction of locations
  - Use these annotations to learn statistical models elsewhere

- **Statistical retrieval algorithms explored**
  - Global Neural Network (GANN),
  - Inverse Distance Spatial Interpolation (IDSI),
  - Region-Specific Neural Networks (RSNN),
  - Error Correction Model by IDSI applied to GANN error (ECM),
  - Weighted Averaging Model with global and local components (WAM)

\[
F_j(x_i, \beta) = \alpha_j f_G(x_i, \beta_G) + (1 - \alpha_j) f_j(x_i, \beta_j)
\]

(Han, B., Vucetic, S., Braverman, A., Obradovic, Z. *Engineering Application of Artificial Intelligence*, in press.)
Results: Integration of Deterministic and Statistical MIST AOT Retrievals

• When learning from low fraction of deterministic AOT retrievals accuracy of integrated retrieval was increasing nearly linear

• Accuracy with 10% of deterministic AOT retrievals: WAM the best choice

<table>
<thead>
<tr>
<th>Model Name</th>
<th>GANN</th>
<th>LDSI</th>
<th>RSNN</th>
<th>ECM</th>
<th>$WAM_{GANN+LDSI}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R^2$ (7.1 - 7.16)</td>
<td>0.839</td>
<td>0.837</td>
<td>0.841</td>
<td>0.864</td>
<td>0.864</td>
</tr>
<tr>
<td>$R^2$ (7.17 - 8.1)</td>
<td>0.648</td>
<td>0.582</td>
<td>0.465</td>
<td>0.700</td>
<td>0.728</td>
</tr>
<tr>
<td>$R^2$ (10.1 - 10.16)</td>
<td>0.359</td>
<td>0.684</td>
<td>0.638</td>
<td>0.575</td>
<td>0.745</td>
</tr>
<tr>
<td>$R^2$ (10.17 - 11.1)</td>
<td>0.446</td>
<td>0.439</td>
<td>0.465</td>
<td>0.472</td>
<td>0.661</td>
</tr>
</tbody>
</table>

• Using deterministic retrieval over only 2% of locations the $RMSE_{stat}$ was about
  • 1.3 times larger than $RMSE_{det}$ in summer and
  • 1.15 times larger than $RMSE_{det}$ in fall cycles
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Large Scale AOT Retrievals

- **Objective:**
  - Learning *efficiently* statistical retrievals from arbitrarily *large* data

- **Challenges:**
  - Huge and heterogeneous data vs. limited computational resources

- **Approach:**
  - Build ensembles and simultaneously adjust sample size and model complexity based on current learning performance

**Results:**

- Efficient Learning of Neural Network Ensembles from Arbitrarily Large Datasets
  

- Efficient Learning from Massive Spatial-Temporal Data through Selective Support Vector Propagation
  
  (Qin, Y. and Obradovic, Z. Proc. 17th European Conf. Artificial Intelligence, in press)
Summary

• Statistical models based on integrating satellite and ground observations can provide more accurate retrieval than MISR/MODIS AOT retrievals alone
• Data mining analysis can reveal the conditions when deterministic retrieval can be significantly enhanced
• Accuracy of AOT retrieval can be improved by integrating data from multiple sources
• Integration of local and global statistical retrievals is beneficial when combined with deterministic retrievals
• Efficient statistical retrieval by learning from large stream data is possible
Thank You!

More information:
http://www.ist.temple.edu

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