Use of Optical Remote Sensing Techniques to Monitor Fugitive Dust Emissions from Tracked and Wheeled Vehicles Moving in Desert Areas

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Outline

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  – Particulate Matter (PM) emissions from traveling vehicles
  – Methods for monitoring PM fugitive emissions
  – Optical Remote Sensing (ORS) method

• Method Development
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    • Data calibration and inversion
    • Integration method for quantifying PM emissions and characterizing PM physical properties
  – Field implementation
    • Tracked vehicles
    • Wheeled vehicles
• Results and Discussion
  – Characterization of dust plumes generated from wheeled and tracked vehicles
  – 2-D mass concentration profiles of PM plumes
  – PM emission factors for vehicle movement

• Summary and Conclusions
Particulate Matter (PM) emissions from military vehicle
Methods for Measuring PM Mass Emissions for Fugitive Sources

• **Point Methods**
  – Flux tower method (Gillies et al, 2005)
  – Tracer gas method (Kantamaneni et al, 1996)

  Accuracy and resolution are limited to the height of towers and number of point sensors

• **ORS Methods**
  – Path-Integrated (PI) ORS method (Varma et al, 2007)
  – Range-resolved ORS method (Method under Development)
    • Ability to capture large plumes,
    • higher spatial and temporal resolution
Advantages of ORS
ORS Devices

Working Mechanism of LIDAR*

* LIDAR: Light Detection And Ranging
Field setup

- Tower containing dust tracks
- Reflective target of MPL
- LT
- Fugitive dust plume
- Military vehicle
Methodology

- **Step 1 Quantify 1-D mass concentration profile**
  - MPL data calibration $\rightarrow$ normalized relative backscatter (NRB) signal
  - Lidar inversion $\rightarrow$ extinction profile

- **Step 2 Construct 2-D mass concentration profile**
  - Mie calculation $\rightarrow$ PM mass/extinction profile
  - Multiple 1-D PM profiles plus interpolation $\rightarrow$ 2 D PM profiles

- **Step 3 Integrate 2-D PM concentration profile with wind data** $\rightarrow$ PM-10 and PM-2.5 emission factors
Methodology

MPL data correction and range normalization → Raw MPL data

Normalized relative backscattering (NRB) → Plume transmittance

Extinction profile, $\sigma (x,y,t)$ → Lidar equation inversion method

$PM_{2.5}$ and $PM_{10}$ mass conc. $C_m = \sigma K^*$

Inverse of mass extinction efficiency, $K^* = C_m / \sigma$

Point $C_m$ from DustTrak

Path-averaged $\sigma$ from OP-LT

$PM_{2.5}$ and $PM_{10}$ emission factor: $g/vkt$ for vehicle

2-D $PM_{2.5}$ and $PM_{10}$ concentration profile, $g/m^3$

Wind speed and direction from anemometers
MPL Data Calibration

Step 1

- Raw MPL signal
- Deadtime correction
- Subtract Dark count, \( p_{dc}(r) \)
- Subtract Afterpulse, \( p_{ap}(r) \)
- Subtract background, \( p_{bg} \)
- Range correction
- Overlap correction
- Energy normalization

\[ NRB = \frac{\{p(r) \times D[p(r)] - p_{dk}(r) - p_{ap}(r) - p_{bg}(r)\} \times r^2}{O_e(r) \times E} \]
Step 1

**Lidar Inversion**

\[
\text{NRB}(r) = \left( \frac{C}{S} \right) \left( \sigma(r) \right) \left( \exp \left( -2 \int_0^r \sigma(r') dr' \right) \right)
\]

(lidar equation)

\[
\sigma(n) = \frac{\text{NRB}(n)}{\frac{C}{S} - 2 \sum_{1}^{n} \left[ \text{NRB}(n) \times 15 \right]}
\]

\[
T_p = \sqrt{\frac{\text{NRB}_p}{\text{NRB}_0}} = \exp \left( - \sum_{i=1}^{N} (\sigma_i \times 15m) \right)
\]

\[
S = \frac{\sigma}{\beta}
\]

C: System constant
\[T_p\]: Plume transmittance
\[\beta\]: Backscattering coefficient, \(m^{-1}sr^{-1}\)
\[\sigma\]: Extinction coefficient, \(m^{-1}\)
\[r\]: Distance
\[S\]: Extinction-to-backscattering ratio
Methodology

Step 2

1. Raw MPL data
2. MPL data correction and range normalization
3. Normalized relative backscattering (NRB)
4. Extinction profile, $\sigma(x,y,t)$
5. Lidar equation inversion method
   - PM$_{2.5}$ and PM$_{10}$ mass conc. $C_m = \sigma K^*$
   - 2-D PM$_{2.5}$ and PM$_{10}$ concentration profile, g/m$^3$
   - Wind speed and direction from anemometers
6. Plume transmittance
7. Inverse of mass extinction efficiency, $K^*$
   - $K^* = C_m / \sigma$
8. Point $C_m$ from DustTrak
9. Path-averaged $\sigma$ from OP-LT
10. PM$_{2.5}$ and PM$_{10}$ emission factor: g/vkt for vehicle
PM Concentration From Extinction Profile

Mass concentration, $C_m$, is determined by:

$$C_m = \sigma \times K^*$$

where

$$K^* = \frac{2}{3} \frac{\int_{D_p\min}^{D_p\max} \rho p^3 N(D_p) dD_p}{\int_{D_p\min}^{D_p\max} Q(\alpha, m) p^2 N(D_p) dD_p}$$

$K^*$ is a function of physical and optical properties of the PM plume (i.e., particle size distribution, refractive index), which is assumed to be constant during an event.

Calibration of $K^*$:

$$K^* = \frac{C_m}{\sigma}$$

DustTack $\rightarrow$ OP-LT
Methodology

MPL data correction and range normalization

Normalized relative backscattering (NRB)

Extinction profile, $\sigma (x,y,t)$

PM$_{2.5}$ and PM$_{10}$ mass conc. $C_m = \sigma K^*$

2-D PM$_{2.5}$ and PM$_{10}$ concentration profile, g/m$^3$

Wind speed and direction from anemometers

Inverse of mass extinction efficiency, $K^*$

$K^* = C_m / \sigma$

Point $C_m$ from DustTrak

Path-averaged $\sigma$ from OP-LT

PM$_{2.5}$ and PM$_{10}$ emission factor: g/vkt for vehicle

Step 3
PM Emission Factor Equation

Equation to determine the mass emission factor for traveling vehicle:

\[
EF = \frac{1000}{Y} \times \sum_{t=0}^{T} \left[ \sum_{y=0}^{Y} \sum_{z=0}^{Z} C_m(y, z, t) \Delta y \Delta z \right] u \cos \theta \Delta t \quad \text{(g-PM/vkt)}
\]

EF: emission factor; \( C_m \): mass concentration; \( y \): horizontal dimension; \( z \): vertical dimension; \( t \): temporal dimension; \( \theta \): angle between measurement plane and wind direction; vkt: “vehicle kilometer traveled”
Field Setup

Top view of the field setup

- Tracked vehicle movement
- Wind
- Unimproved road
- Dust plume
- MPL path
- 275 m
- 89 m
- LT path
- Reflective target
- DT aerosol monitors
- Retroreflector
- Scanning MPL

Note: map not to scale
Dust Plume Generated by a Tracked Vehicle
Tracked vehicle (M88) moving at 24 km/hr


- Height above ground (m)
- Distance from MPL (m)

Mass Concentration (g/m³)
Tracked vehicle (M88) moving at 24 km/hr
Tracked vehicle (M88) moving at 24 km/hr
Tracked vehicle (M88) moving at 24 km/hr
Wheeled vehicle (M270) moving at 24 km/hr


Height above ground (m)

Distance from MPL (m)

Mass Concentration (g/m³)
Wheeled vehicle (M270) moving at 24 km/hr
Wheeled vehicle (M270) moving at 24 km/hr
Wheeled vehicle (M270) moving at 24 km/hr
Measured Emission Factors at Different Speeds

(A) M270

Median Vehicle Speed (km/h)

Mean PM Emission Factor (g-PM/vkt)

PM$_{10}$

PM$_{2.5}$
Measured Emission Factors at Different Speeds

(C) M88

Mean PM Emission Factor (g-PM/vkt)

Median Vehicle Speed (km/h)

PM\textsubscript{10}

PM\textsubscript{2.5}
Measured Emission Factors at Different Speeds

(A) HEMTT

Mean PM Emission Factor (g-PM/vkt)

Median Vehicle Speed (km/h)

PM$_{10}$

PM$_{2.5}$
Emission Factors vs. Vehicle Momentum

\[ y = 0.798x \]
\[ R^2 = 0.74 \]

\[ y = 2.012x \]
\[ R^2 = 0.66 \]
<table>
<thead>
<tr>
<th><strong>YTC field campaign</strong></th>
<th><strong>Mass Emission Factor of PM$_{2.5}$</strong></th>
<th><strong>Mass Emission Factor of PM$_{10}$</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vehicle</strong></td>
<td><strong>Weight (kg)</strong></td>
<td><strong>Weight (ton)</strong></td>
</tr>
<tr>
<td>Bradley (TV)</td>
<td>29,937</td>
<td>33</td>
</tr>
<tr>
<td>M113 (TV)</td>
<td>12,349</td>
<td>14</td>
</tr>
<tr>
<td>M1A1 (TV)</td>
<td>60,909</td>
<td>67</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Fort Carson field campaign</strong></th>
<th><strong>Mass Emission Factor of PM$_{2.5}$</strong></th>
<th><strong>Mass Emission Factor of PM$_{10}$</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vehicle</strong></td>
<td><strong>Weight (kg)</strong></td>
<td><strong>Weight (ton)</strong></td>
</tr>
<tr>
<td>M88 (TV)</td>
<td>63,504</td>
<td>70</td>
</tr>
<tr>
<td>M270 (TV)</td>
<td>24,948</td>
<td>28</td>
</tr>
<tr>
<td>M113 (TV)</td>
<td>12,338</td>
<td>14</td>
</tr>
<tr>
<td>HEMTT (WV)</td>
<td>19,958</td>
<td>22</td>
</tr>
</tbody>
</table>

**Modeled EF = 281.9k(S/12)$^{0.9}$(W/3)$^{0.45}$**

where $k = 1.5$ (for PM10) or 0.15 (for PM2.5); $S$ is silt content (4%-56%), $W$ is vehicle weight in tons.
Summary and Conclusions

- This study demonstrates the capability of Micropulse LIDAR to characterize/quantify dust plumes that were generated from tracked and wheeled vehicles:
  - the horizontal and vertical dimension
  - temporal variability
  - extinction profile

- An optical remote sensing (ORS) method was successfully developed to measure PM2.5 and PM10 fugitive dust emissions

- Wheeled vehicle (HEMTT) generate more dust than the tracked vehicles

- Fugitive dust emissions is related to the product of vehicle mass and speed (0.66 < R2 < 0.74)
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• Desert Research Institute (DRI)
Thank you!
Plume passing through lidar path

Top view of a dust plume passing the MPL’s optical path
A lidar profile

Date: 2005/10/27, Time: 16:54:9, profile No.: 3250

Bin#

Original signal, Mc/s

0 1 2 3 4 5 6 7 8

20 30 40 50 60 70 80

Dust plume position
Reflective target
Schematic of the hybrid dust measurement configuration. The DM pairs consist of one PM10 and one PM2.5 monitor.
OP-LT Calibration Measurements Made at Yuma Proving Grounds - The six dust events with high dust correlations (R > 0.9)
Plot of the OP-LT and DM-PM10 Calibration Measurements. a) The full 1,840-point data set, b) The six high-correlation events (508 points) data set
Comparison of PIMC determined with the new method to the PIMC determined from the grid of DT monitors for 20 events at Fort Carson. Top: 4 DT monitors in new method, second and third from top: 3 DT monitors in new method (1, 2, and 4 and 1, 3, and 4), bottom: 2 DT pairs in new method.