Multi-angle Multi-wavelength Light Scattering of Smokes and Cooking Aerosols

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Outline

• Background
• Experimental Apparatus
• Measurement and Automation
• Light Scattering Model
• Planned Experiments
• Summary
Background

• The purpose of multiple measurement angles or light sources is to provide some discrimination of the aerosol to distinguish smokes from other non-fire aerosol sources.

• In principle, it is possible to theoretically design a multi-wavelength, multi-angle detector. Unfortunately, many of the properties of smoke and nuisance aerosols including refractive index, size distribution, and particle morphology are unknown and change over the time interval of interest.

• One way to collect the information needed to design new smoke detectors is to make direct measurements of real smokes and nuisance sources as they evolve.
• Weinert [1] showed it was possible to distinguish soot from nuisance and smouldering smokes by computing the polarization ratio (the ratio of horizontally polarized scattered light from horizontally polarized beam to vertically polarized scattered light from a vertically polarized beam), and from an asymmetry ratio (the ratio of intensities at 45° and 135° of vertically polarized scattered light from a vertically polarized beam).

• Wang, et al. [2] describe a test apparatus to measure scattered light intensity from three angles (30°, 90° and 150°) at a single wavelength, 635 nm. They showed discrimination of sources using ratios of 30°/90° and 150°/90° scattering angle intensities.

1Weinert D., [2003] Light Scattering by Smoke and Nuisance Aerosols, Ph.D., Victoria University of Technology, Australia.

Electron Micrographs of Smokes

Cotton Wick Smolder Smoke

Soot Agglomerates

NASA
Polarized Light Scattering

Polarized Scattering Coordinates

V

P
## Background

Weinert’s Polarized Light Scattering Measurements
Wavelength 633 nm

<table>
<thead>
<tr>
<th></th>
<th>Forward Scattering Ratio ($\sigma_{vv}5^\circ/\sigma_{vv}20^\circ$)</th>
<th>Asymmetry Ratio ($\sigma_{vv}45^\circ/\sigma_{vv}135^\circ$)</th>
<th>Polarization Ratio ($\sigma_{HH}90^\circ/\sigma_{vv}90^\circ$)</th>
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<tbody>
<tr>
<td><strong>Black Soots</strong></td>
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<tr>
<td>Propylene</td>
<td>6.3</td>
<td>4.9</td>
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<td>Heptane</td>
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<td>Acetylene</td>
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<tr>
<td>Ethylene</td>
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<td>4.5</td>
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<td><strong>Smolder Smokes</strong></td>
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<tr>
<td>Beech Wood</td>
<td>2.0</td>
<td>15.5</td>
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<td>Cotton Wick</td>
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<td>0.48</td>
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<td>PU foam</td>
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<td><strong>Nuisance Aerosols</strong></td>
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<tr>
<td>Toast</td>
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<td>Cooking Oil</td>
<td>3.4</td>
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<tr>
<td>Dust</td>
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<td>11.3</td>
<td>0.51</td>
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NIST has constructed a combination nephelometer/polarimeter to measure light scattering characteristics of fire smokes and nuisance source aerosols.

The apparatus consists of four stacked nephelometer devices, each with different laser wavelengths and similar to the single wavelength apparatus described by Wang, et al. [2], followed by a polarimeter section based on the design of Weinert [1].
Design Elements

• A configurable multi-angle, multi-wavelength nephelometer was designed to measure scattered light at fixed angles of 15°, 22.5°, 45°, 67.5°, 90°, 112.5°, and 135° with laser diode light sources of wavelengths 405 nm (violet), 638 nm (red), 785nm, (near infrared) and 980 nm (near infrared).

• A polarimeter that can measure scattered light from ~5° to 150° was designed. Optical elements for three separate wavelengths are available: 405 nm, 635 nm, and 850 nm.
Experimental Apparatus
Smoke Nephelometer / Aerosol Polarimeter (SNAP)
Experimental Apparatus
Experimental Apparatus

Cross section of nephelometer stage
Experimental Apparatus
Experimental Apparatus

Top down view of polarimeter section
The device is able to record scattered light intensities from up to 16 photodetectors placed at desired angular positions for each of the various wavelengths.

Data is collected at a rate of nominally one Hz.

The nephelometer can be configured to mimic existing or proposed multi-angle, multi-wavelength detectors.

After leaving the device, the aerosol is directed to the polarimeter section then it can be directed to measurement instruments to record size distribution and concentration.
Measurement and Automation

Polarimeter

- Data collection is automated with the stage rotation progressing by prescribed angular steps and polarization states changed automatically by flipping and rotating optical mounts.
- A software-implemented lock-in amplifier is used to make low noise measurements of the relatively weak scattering signals.
- The detector is a silicon avalanche photodetector.
  - Advantage - no high voltage like with a PMT, small form factor, not subject to damage by ambient light.
  - Disadvantage - reduced sensitivity compared to a photomultiplier tube PMT detector.
- After leaving the device, the aerosol can be directed to measurement instruments to record size distribution and concentration.
Mie Light Scattering Model
Mie Light Scattering Model

Original Mie scattering demo program, August 2005, by Martin Fierz (martin@fierz.ch)
Modified by TC to include amplitude plots for monodisperse, polydisperse, and polydisperse with acceptance angle integration.

This VI demonstrates the usage of mie2.dll, a dynamic-link-library which you can call in your LabView program. The demo lets you select the refractive index of a sphere, and the size parameter and computes total scattering, total extinction and angular distribution of the scattered light for p-, s-, and unpolarized light. Mie2.dll uses the Bohren-Huffman Mie code.

Polar Plot

unpolarized
p-polarized
s-polarized
Mie Light Scattering Model
Scattering Calculations

- Linearly polarized and un-polarized laser light
- Mean particle sizes from 0.1 μm to 2.0 μm
- Log-normal size distribution with fixed geometric standard deviation of 1.7
- Particle refractive index fixed at 1.5 + 0i
- Computed Results
  - Forward Scattering Ratio - $I_{vv15^\circ}/I_{vv22.5^\circ}$
  - Asymmetry Ratio - $I_{vv45^\circ}/I_{vv135^\circ}$
  - Polarization Ratio – $I_{HH90^\circ}/I_{vv90^\circ}$
  - Un-polarized Asymmetry Ratio - $I_{45^\circ}/I_{135^\circ}$
Scattering Calculations

405 nm Laser Wavelength

- Forward Scattering Ratio
- Asymmetry Ratio
- Polarization Ratio
- Un-polarized Asymmetry Ratio

638 nm Laser Wavelength

- Forward Scattering Ratio
- Asymmetry Ratio
- Polarization Ratio
- Un-polarized Asymmetry Ratio

785 nm Laser Wavelength

- Forward Scattering Ratio
- Asymmetry Ratio
- Polarization Ratio
- Un-polarized Asymmetry Ratio

980 nm Laser Wavelength

- Forward Scattering Ratio
- Asymmetry Ratio
- Polarization Ratio
- Un-polarized Asymmetry Ratio
Experimental Plan

• Instrument calibration with a condensation monodisperse aerosol generator. Spherical particles from \( \sim 0.1 \, \mu m \) to 5 \( \mu m \) with narrow size distributions

• Full-scale UL 217 room experiments
  – Flaming soot
  – Smoldering smokes
  – Cooking aerosols
Experimental Plan

• Use the top nephelometer section with the following setup:
  – Two beams, 638 nm and 980 nm, with horizontal and vertical polarizations split between two stages each
  – Horizontally polarized beams at 638 nm and 980 nm and detectors with horizontal polarizers at 45°, 90° and 135°
  – Vertically polarized beams at 638 nm and 980 nm and detectors with vertical polarizers at 15°, 22.5°, 45°, 90° and 135°
Experimental Plan

• Compute ratios as a function of time:
  – Forward Scattering Ratio - $I_{vv}^{15^\circ}/I_{vv}^{22.5^\circ}$
  – Asymmetry Ratio - $I_{vv}^{45^\circ}/I_{vv}^{135^\circ}$
  – Polarization Ratio – $I_{HH}^{90^\circ}/I_{vv}^{90^\circ}$
  – Un-polarized Asymmetry Ratio - $I_{45^\circ}/I_{135^\circ}$

• Verify soot discrimination

• Look for any other source discrimination
Summary

- A robust, portable nephelometer/polarimeter was developed to measure light scattering characteristics of fire smokes and nuisance source aerosols.
- The nephelometer section is a configurable multi-angle, multi-wavelength device able to mimic current light-scattering detector configurations.
- Nephelometer section will be used to examine light scattering discrimination of fire smokes and nuisance sources at two wavelengths.