Open Path Optical Sensing of Particulate Matter

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Ravi M. Varma, Ram A. Hashmonay, Michael A. Bolch

ARCADIS, P. O. Box 13109, Research Triangle Park, NC 27709

D. Bruce Harris

NRML (D343-04), US EPA, Research Triangle Park, NC 27711

Byung J. Kim

US Army Engineer Research and Development Center-Construction Engineering Research Laboratory (ERDC-CERL), 2902 Farber Drive, Champaign, IL 61822

ABSTRACT

Airborne fugitive and fine particulate matter (PM) from various sources contribute to exceedances of state and federal PM and visibility standards. Recent studies have shown that an optical remote sensing (ORS) approach can be used for characterizing airborne PM by measuring multi-spectral light extinction. The optical open path remote sensing instrument used in this study is a monostatic Open Path Fourier Transform Infrared (OP-FTIR) instrument collecting light extinction data through a controlled cloud of PM. Preliminary optical depth measurements and the unique absorption features for the PM as seen by the OP-FTIR for different sample releases are presented. The extinction spectra from OP-FTIR measurements were used to retrieve size distribution information and comparisons were made with aerodynamic particle sizer (APS) measurements. This paper discusses the concepts behind these recent developments and results from the experiments.

INTRODUCTION

The theory for gas absorption spectroscopy is well known and has been used for the past several decades to develop technology for aerosol detection[2,3]. The following equation describes the IR light extinction by a particle/gas mixture as a function of wavelength, λ:

$$A(\lambda)=\sigma_e(\lambda)\cdot L+\sigma_g(\lambda)\cdot CL \qquad (1)$$

where σ_g is the absorption coefficient of the gas, L is the optical path length of the IR beam and C is the concentration . The wavelength-dependent extinction coefficient for the particle, σ_e, is given by:

$$\sigma_e(\lambda)=\frac{\pi}{4}\sum_j Q_e(\lambda)_j\cdot N_j\cdot d_j^2 \qquad (2)$$

where j denotes the particle size index, $Q_e(\lambda)$ is the complex refractive index dependent extinction efficiency, N is the particle number density, and d is the particle diameter. At each wavelength, the contributions of all particle sizes add to produce the total extinction due to particles. Absorption by aerosol material (liquid or solid), as expressed by the imaginary part of the complex refractive index, will occur in a particular wavelength for a particular aerosol material, typically in the fingerprint region where IR spectra are more complex (The complexity of infrared spectra in the 1450 to 600 cm^{-1} region makes it difficult to assign all the absorption bands, and because of the unique patterns found there, it is often called the fingerprint region. Absorption bands in the 4000 to 1450 cm^{-1} region are usually due to stretching vibrations of diatomic units, and this is sometimes called the group frequency region.). In the extinction spectrum for a suspended aerosol cloud this absorption will usually be represented by a derivative-like shear of the spectrum baseline (See Figure 1 below) if size dependent scattering occurs in the region. If the particles are very small or several absorption lines are adjacent to each other, the absorption feature in the extinction spectrum may look similar to typical gas absorption features (Lorentzian). Whatever the shape of the absorption feature may be, the magnitude of the feature must correlate perfectly with the scattering baseline offset (of the absorbance spectrum from zero) as they represent the aerosol cloud.

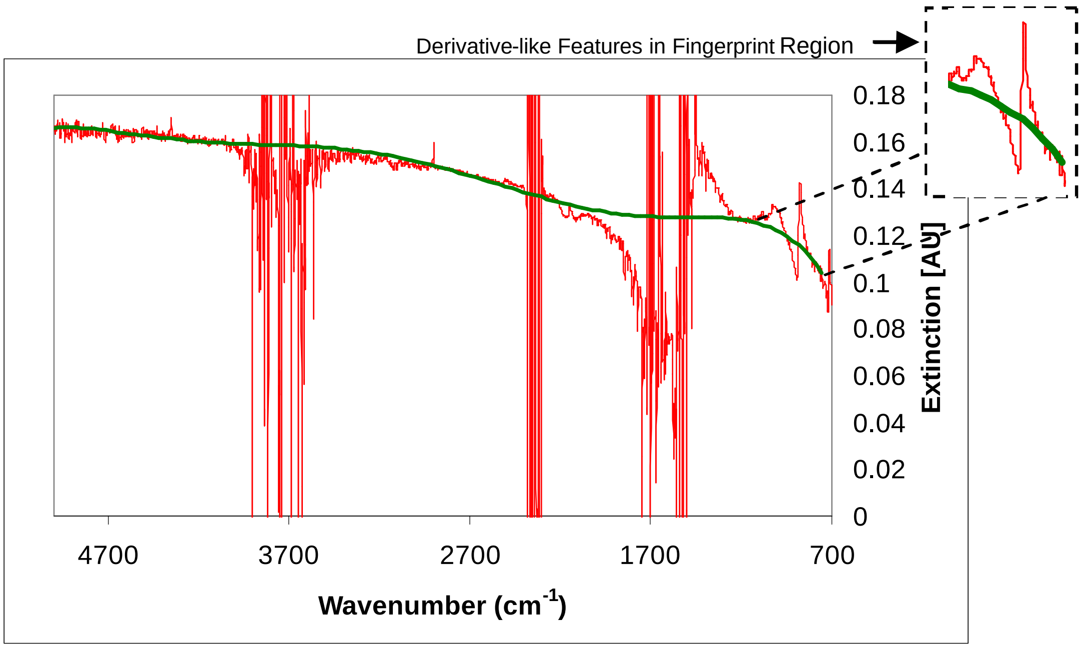
OP-FTIR absorbance spectra acquired during changing aerosol conditions reveal related changes in very broad features of the baseline. Previous research found that these wavelength-dependent baseline features can be quantitatively related to changes in the aerosol size distribution and type[2, 3]. These studies applied the Mie theory to fit the measured extinction spectrum obtained for condensed water aerosol collected in a controlled shower chamber and for dirt road dust, to size distributions of the target particles. An iterative inversion algorithm originally proposed for radiative transfer problems is used.[3] The kernel matrix for the inversion procedure includes the extinction efficiency values for all ranges of wavelength and size. To solve for the size distribution one has to invert the kernel matrix. This inversion procedure is described in detail in Hashmonay and Harris (2001).[2].

RESULTS

IR Extinction Spectra for Dust

The aerosol detection technology, mentioned in the previous section, has been used by researchers in ARCADIS during the past several years to study particulate matter (PM). Initially used for the detection of water droplets,[1] this technology was extended to ongoing dust monitoring and jet engine exhaust studies supported by the Strategic Environmental Research and Developmental Program (SERDP), diesel engine emission studies supported by the EPA and a US ARMY supported ongoing PM monitoring study for military generated obscurants such as fog oil, graphite and dust. Using an active open-path FTIR, it has been possible to detect and identify, each type of plumes released. Figure 1 shows a typical dust plume absorbance spectra from an active OP-FTIR measurement over a 70 meter optical path length. The specific derivative-like features (e.g., one near 900 cm^{-1}) are unique features for the kind of dust used for this experiment. The smoothed baseline of the absorbance spectrum (shown in green) contains the information on the mass distribution of the aerosol plume encountered by the optical beam.

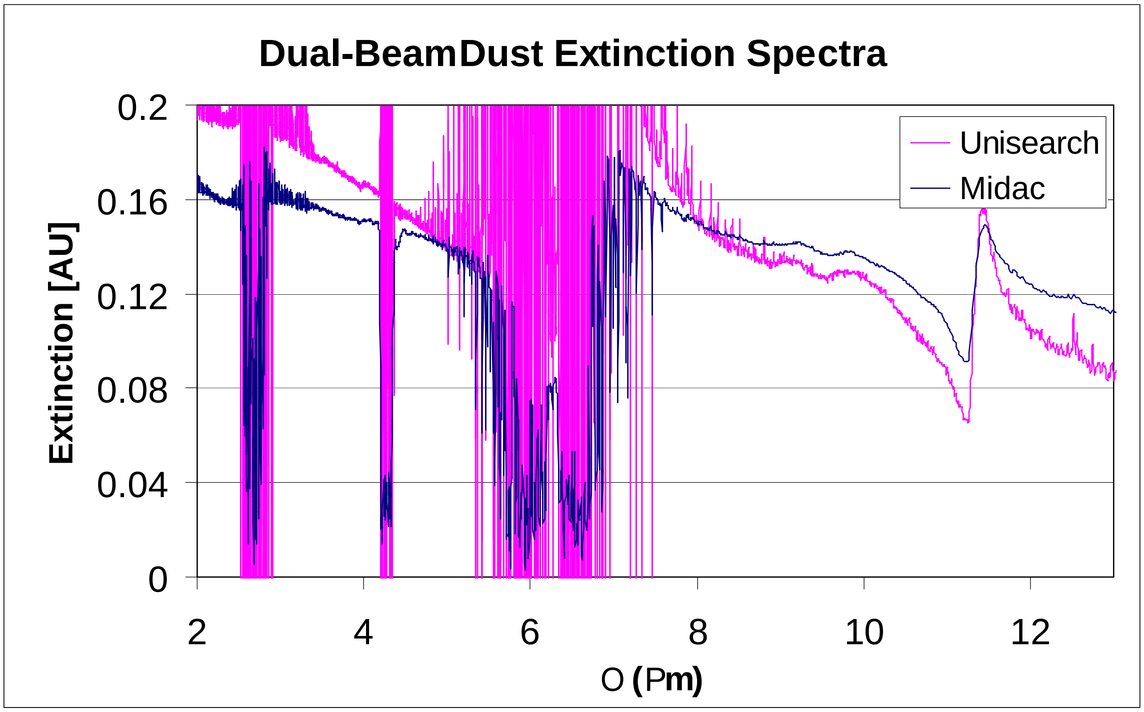
Figure 1. Dust Plume Features Measured by a Monostatic OP-FTIR System



PM Mass Distribution Retrieval from OP-FTIR Instruments

Light extinction spectra measured by the two OP-FTIR instruments with an optical pathlength of 70 meters are provided in Figure 2. This data was collected during October 9-14, 2002. A Unisearch OP-FTIR was looking up towards a mirror 5 meters above the ground, through the upper portion of a dust plume released. The spectra from the Unisearch OP-FTIR show larger light extinction (optical depth) at shorter wavelengths when compared to spectra from a Midac OP-FTIR that was looking at a mirror on the ground, through the lower portion of the same dust plume. This is demonstrated by the extinction values and slope of the baseline in the extinction spectra by the Unisearch OP-FTIR at the shorter wavelength region.

Figure 2: Light Extinction Spectra Measured by Two OP-FTIR instruments



At the longer wavelength region the Midac OP-FTIR has larger extinction values, meaning that the extinction is primarily due to larger particles. The strong absorption feature for this dust plume at around 11.5 μm on both spectra confirms that the same dust was detected by both of the OP-FTIR instruments. Mie theory for light scattering can be used to obtain the size and mass distribution of the plume given the optical parameters, such as complex refractive index of the dust for a range of wavelengths. Figure 3 provides the baseline of spectral data (to avoid water and other absorption features) and corresponding fit for both OP-FTIR measurements from Mie theory calculations. Sharp absorption feature is reproduced by higher values of imaginary refractive indices for the corresponding wavelengths. The slope of spectral extinction baseline is used in an inverse Mie theory algorithm to retrieve mass distribution information.

Figure 3: Comparison of Extinction from Two OP-FTIRs (The x-axis is the wavelength in µm)

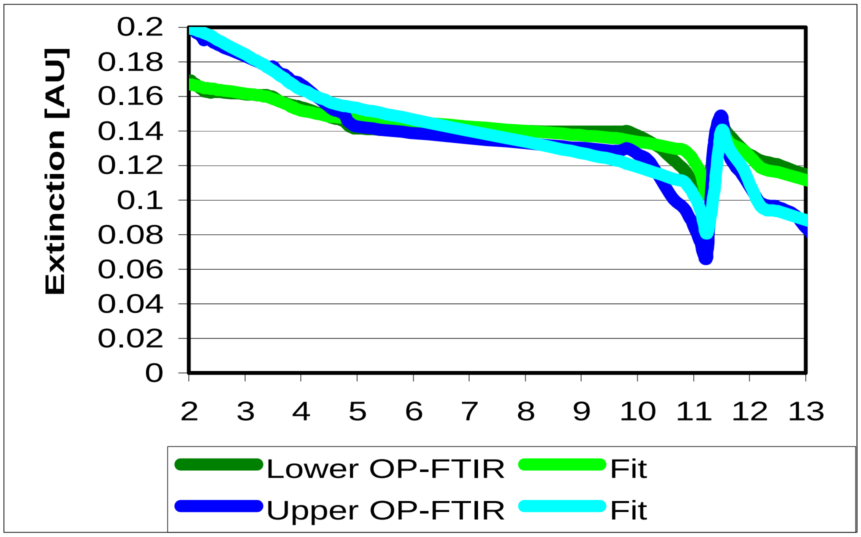
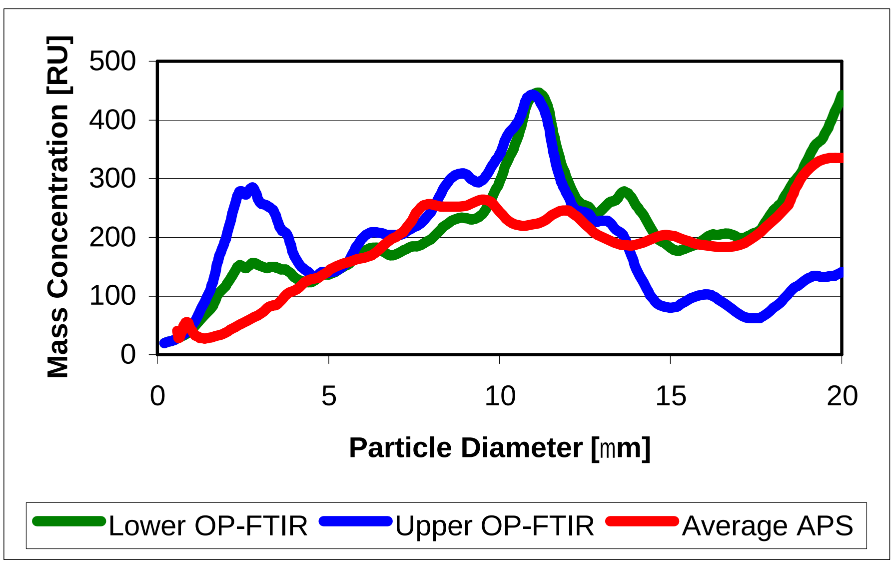


Figure 4 shows the mass distribution obtained from extinction measurements from both OP-FTIRs with that of a two-minute averaged measurement by an Aerodynamic Particle Sizer (APS, TSI, Inc.) instrument. Even though the APS point monitor was placed a few meters away from the plane of OP-FTIR measurements, the size distribution retrieval using the Mie-theory agrees well with the average distribution from the APS.

Figure 4: Comparison of Mass Concentrations from the Two OP-FTIRs and the APS



CONCLUSIONS

Recent studies have shown that a multi-spectral optical remote sensing approach can be used for characterizing airborne PM. These studies show a relationship between plume PM size and plume light extinction. Each plume type under study showed unique features in specific regions of the OP-FTIR extinction spectra. These kinds of features can generally be used to identify the plume material. The OP-FTIR extinction measurements for a dust plume combined with an inverse Mie algorithm were used to retrieve the average mass distribution. These calculated mass distribution values were then successfully correlated with the corresponding average APS measured mass distribution, as shown in Figure 4. While particles of a few to several microns (1-20 μm) in diameter will have major impacts on IR extinction spectra, smaller PM will significantly affect the visible (VIS) or ultraviolet (UV) wavelength region. These smaller PM are suspended for a much longer time (and travel longer distances) in the atmosphere, posing serious health concerns and becoming a major contributing factor for poor visibility. It is therefore recommended that both OP-FTIR and OP-UV/VIS spectrometers be utilized when characterizing fine dust emissions.

REFERENCES

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KEY WORDS

Open Path, Optical Remote Sensing, FTIR, Particulate Matter, Mie Theory