NIGHT-TIME REMOTE SENSING OF FINE PARTICULATE MATTER IN THE NEAR GROUND ATMOSPHERE BY GROUND-BASED HYPERSPECTRAL IMAGING

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ABSTRACT:

Spatiotemporal variations in attributes of particulate matter (PM) in ambient air are important estimates of environmental pollution and public health risks. In particularly, the exposure to fine PM, with count mean diameters of less than 4µm, has been associated with undesirable health effects. Therefore, methodologies that analyze the size profiles of fine PM in ambient air segments at ground-level are entailed.
Indeed, remote sensing in the visible-NIR range has already been engaged in measuring the multi-spectral signatures of PM, providing estimated size distributions of fine PM in atmospheric columns. However, the solar-based measurements require daylight and provide PM profiles in vertical atmospheric columns that do not correlate well with the ground-level PM attributes in an urban-scale resolution, which is the most relevant to public health.
A ground hyperspectral camera was used for imaging illuminating targets through horizontal, urban-scale, open paths in order to detect effects of fine PM in spatial segments stretched between the camera and chosen targets. Spectra were acquired in the range of 400-1100nm which corresponds to fine PM in between 0.5-2µm. The aim of this study was to design an imaging procedure and apply a proper target selection, in order to detect changes in the size resolved PM concentrations. A night-time imaging was implemented as a new source for information using remote street lights emission, instead of commonly used reflectance. Change detection was demonstrated for haze event with comparison to emission spectra acquired through clear ambient air.

1. INTRODUCTION

Air pollution, including particulate matter is a complex and dynamic phenomenon with time and space variation that span over multiple scales. Particulate Matter (PM) in ambient air usually has a bi- or tri-lognormal size distribution, comprised of an ultra-fine mode having count median diameter (CMD) of less than 0.1µm, a fine accumulated mode with CMD in between 0.1-2.5µm, and a coarse mode with CMD in between 2.5-10µm. Ambient aerosols evolve by different mechanisms from different natural and anthropogenic emission sources. Therefore PM from different emission sources have a characteristic particle size distribution (PSD) as well as a characteristic chemical composition. Spatiotemporal variations in size

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attributes of ambient aerosols, in particular PM with CMD<4μm, are regarded as important estimates for public health risk assessment (Vedal, 1997). Methodologies that analyze and quantify the size profiles of fine PM in ground-level, urban scale, open paths are seek out, as they are the most relevant to public health.
Both satellite and ground remote sensing (RS) are applied for characterizing atmospheric aerosols by analyzing the aerosol interactions with electromagnetic radiation in different visible-NIR wavelengths or multiple angles. Relying on solar radiation, these methods are limited by sun elevation angle and cloud cover, and also by revisit periods of satellite-borne sensors. Current RS procedures can provide estimates of bi-modal size distributions in vertical atmospheric columns (Wang et al., 1996). However, correlation between vertical aerosol profiles and ground-level ambient PM specific distribution at urban-scale resolution is highly influenced by geo-site specific seasonality and corresponding mixing layer height (Schäfer et al., 2008). Standard ground-level stations that monitor particulate matter (PM) provide only integrated concentrations in discrete and sparse locations. Consequently, their data is susceptible to sporadic readings. Our research focused on implementing night-time hyperspectral imaging using remote street lights as targets. An oblique imaging procedure was developed in order to acquire emission signatures, instead of the commonly used reflectance. Spectral variations, related to measured variations in PM size resolved concentrations, were demonstrated during extreme events of ambient PM loadings.

2. DATA AND INSTRUMENTS

2.1. Instruments

Image spectroscopy was applied by VDS Vosskühler Cool-1300Q, a camera which was originally developed for biomedical applications and has been adapted for ground environmental monitoring purposes. The camera consists of Peltier-cooled (-20^{o}C) progressive scan CCD sensor (SONY Exview HAD technology) that fits the exposure range of 10ms – 1000s. Its sensor, which is sensitive to radiation in between 300-1100nm, produces spectral cubes of 1280x1024pixels with 12bit radiometric resolution. The acquisition which is based on interferometer optics and FFT (fast Fourier transform) generates signals with spectral resolution of 1-9nm FWHM. Currently the camera is equipped with Nikon's NIKKOR 105mm telephoto lens with 23°20' field of view (FOV).
An aerosol mini spectrometer (GRIMM 1.108) was simultaneously measuring near the camera, providing real-time local sampling of particle number concentrations at 15 size channels between 0.3-20μm. Data from the faculty meteorological station was also collected, including temperature, relative humidity, wind speed, and wind direction. Both the aerosol spectrometer and the meteorological station record one minute average readings.
It should be noted that a spectroradiometer (Spectral Vista Co. GER 2600) was also used in a consecutive study to measure the emission sources and to calibrate the digitized signal of the camera to radiance units. It also provides complimentary optical data in the NIR range during laboratory scale measurements. Radiance spectra were measured in between 350-1050nm (1.2nm FWHM, 512 Channels) and in between 1050-2500nm (8-12nm FWHM, 128 Channels).

2.2. Imaging setup and procedure

The camera was set on the roof of the Civil Engineering building in the Technion, Haifa, and was pointed in one of the following directions: a southern direction (192°) that captures a scene of street lamps at Nesher road, 1km open path uphill, and street lamps at the foot of the arts center building of Haifa University, 1.8km open path uphill; and a north eastern direction (65°) that captures the refinery facilities area in Haifa-bay, 4.2km open path downhill.

Comment [TJ1]: Aspect?

Since artificial light emissions served as the image objectives, exposure conditions were opted to minimize sensor saturation on one hand, while eliminating modulations by the electricity network frequency (50Hz) on the other hand. Hence, exposure time and speed of lens aperture were fixed during the entire imaging sessions to 50ms per interferometer step and 1/16 respectively. The ensuing overall acquisition time per image including file construction was 45s.

2.3. Selection of emission pixels for analysis

The apparent beam cross-section may cover more than 60 pixels (Figure 1), but emission of artificial street light, as imaged from one km distance, is neither homogeneous nor isotropic: the emission is extremely high at center of the beam and usually "blinds" the sensor, then steeply decays towards the edges. Therefore an accurate imaging geometry and pixel resampling is required. All images were referenced image-to-image in order to sample the same physical position of the light source and the same segment of the beam. The error of the procedure was 1 pixel. Overlapping images of daylight and dark scene were used to select the region of interest (ROI). The element of the lamp in the daylight image was used to set a center for the ROI, while ROI statistics in the night-time image were used to define the common pixels of high signal amplitude. An area of 21 pixels that roughly represents a 2m beam radius was chosen for a street lamp at Nesher road. This area was used to demonstrate change detection as described in the following section.

3. RESULTS AND DISCUSSION

Mt. Carmel slope, where Nesher Road and Haifa University are situated, is a partially rural dark scene, with sparse light sources. In contrast, the downhill refineries scene represents a crowded urban-industrial scene with a dense distribution of light sources, which is also less accessible than Nesher road. Therefore, street lights on Nesher road were chosen for the basic development of the imaging procedure including acquisition and pixel sampling.

The ROI for a street lamp in Nesher Road (Figure 1) was used to retrieve changes in emission during two extreme events of ambient PM loadings. The first one was Yom Kipur, a holiday when all transportation and industrial activity in Israel seize and the ambient air is usually dry and clear. Accordingly, night imaging was pursued at the end of Yom Kipur, on 9/10/08. The second was a haze event on 19/2/09. A series of images was acquired during the decay of this event.

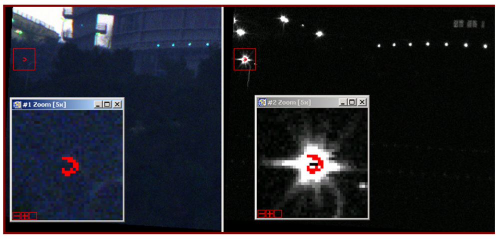

Figure 1. Pixel selection for street light analysis based on overlapping day and night images of Mt. Carmel scene.

The relative humidity, temperature and wind speed also differed greatly between the two events influencing the water vapor/droplets content in the open path (Figure 2).

Considering the aerosol-informative spectral bands which are reported in the literature (Kusmanoski et al., 2007), including 406nm, 449nm, 520nm, 599-601nm, 676nm, 749-755nm, and 857-869nm, emission of the chosen street light covers at least partially the optical range which is required for retrieval of PM size distributions and concentrations in the open path (Figure 3).

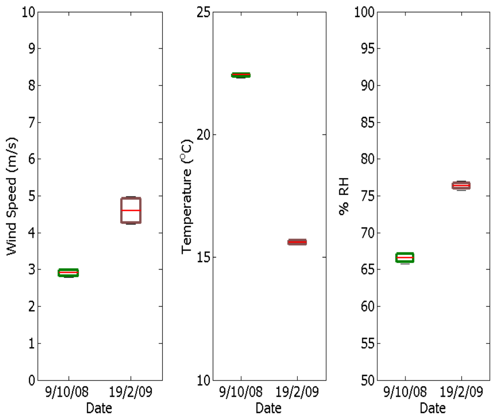

Figure 2. Meteorological parameters (left to right): wind speed, temperature and relative humidity. 9/10/08 vs. 19/2/09.

Yom Kipur on 9/10/08 happened to occur right after a rain event and was characterized by a dry and quiescent ambient air (Figure 2). Therefore the signals imaged on this evening may be regarded as baseline or reference signal. As such, one would expect attenuation with respect to reference signal during the haze event on 19/2/09. There are evidently changes in the signal, which correspond to changes in fine PM number concentrations of fine particles as measured by an aerosol spectrometer (Figure 3). The gradient of signal attenuation around 800nm seems well inline with the increase of fine PM concentration, in particular PM having diameters in between

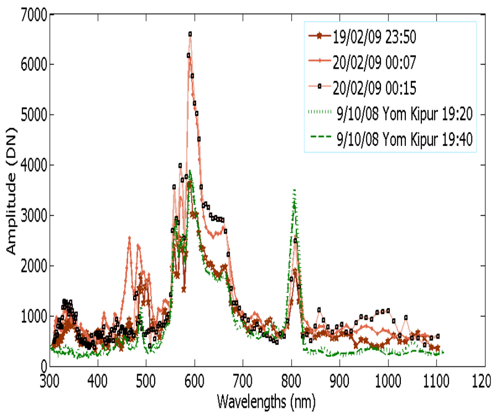

Figure 3. Emission spectra of a street light at Nesher road, averaged over the selected ROI.

0.3-0.65µm. However, it is evident that the signal amplitude actually increases much beyond reference signal in between 500-800nm as fine PM concentrations decrease. Taking into consideration that haze may be in liquid phase and in view of measured temperature and relative humidity during haze event, the increasing amplitude may result from forward scattering by water droplets in the open path. As forward scattering by water droplets is dominant for diameter size of equal or higher size than radiation wavelength (Petty, 2006), droplets diameters in between 0.4-0.7µm may have generate the depicted increase in spectrum during the haze event.

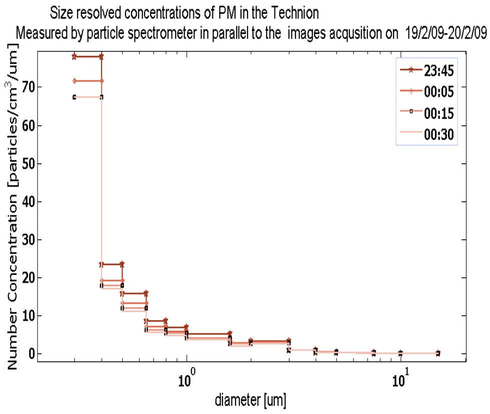

Figure 4. Size resolved concentrations of fine PM measured in the Technion by aerosol spectrometer on 19/2/09

4. CONCLUSIONS

An urban scale procedure was adjusted for nighttime imaging spectroscopy, providing spectral signatures which correspond to measured changes in PM concentrations, for particle diameters in the range of 0.3-1.6µm.

Careful registration of the night scene and pixel resampling were called upon in order to reduce sampling errors due to the steep decay of the emission intensity towards the beam circumference. Current registration procedure results in an error of one pixel. This is still a considerable error in view of the efficient area

Comment [TJ2]: Night scenes ???

for analysis, which is roughly 20 pixels (1 pixel~$1m^2$) when the image is acquired at 1km away from the light source. Further accurate registration should pursue.

Evident change in spectral signatures was demonstrated for haze event. It should be followed by comparison to spectral signatures of dry PM loadings (dust-like), considering differences of size attributes and contribution of relative humidity to the spectrum. Present results are of qualitative nature; it remains to examine whether quantitative information regarding particle size and concentration in the open path can be further extracted.

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