Mobile Tropospheric Ozone Differential Absorption Lidar (DIAL) and Ozone Profiling in New York during Summer 2023

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Abstract: A mobile tropospheric Ozone (O_3) Differential Absorption Lidar (DIAL) system was recently developed at the City College of New York (CCNY) as part of the Tropospheric Ozone Lidar Network (TOLNET). The CCNY Trailer O_3-DIAL was validated against the CCNY laboratory O_3-DIAL, and the results show that it can retrieve O_3 from around 0.5 - 4.5 km. In August of 2023, the mobile O_3 lidar was deployed to Columbia University Lamont-Doherty Earth Observatory (LDEO) - Columbia University (CU) in Palisades, New York (41.0˚N, 73.91˚W). In this study we present lidar time-height ozone mixing ratio observations from various high O_3 episodes in NYC and LDEO together with surface O_3 analyzer measurements and TROPOMI satellite measurements of the O_3 precursor nitrogen dioxide (NO_2) to gain insight into emission and transport processes.

1. Introduction

Ozone is one of the primary pollutants in the New York City Area and during high ozone episodes can exceed the 70 ppb National Ambient Air Quality Standards (NAAQS) for surface ozone [1]. Emissions from transportation and industrial activities generate abundant ozone precursors such as nitrogen dioxide (NO_2) and volatile organic compounds (VOCs) [2]. It is critical to observe the vertical distribution of ozone and other pollutants over time to understand the processes that lead to poor air quality, but there is a lack of such ongoing observation of vertical ozone distribution in NYC.

At the CCNY Optical Remote Sensing Lab, we developed the mobile O_3-DIAL system based on the laboratory O_3-DIAL that was built in 2022. The entire lidar system is housed in a vibration-absorbing mechanical frame inside of a 20 ft long trailer. In July of 2023, the mobile DIAL system was completed and validated against the laboratory DIAL system. The mobile DIAL system was then transported to Lamont Doherty Earth Observatory alongside a Vaisala CL31 Ceilometer and 2B Technologies Ozone Analyzer where it remained from August to September of 2023.

Figure 1 shows images of the lidar system in the trailer. The frame is organized into three layers, each handling a major aspect of the lidar system. The top layer contains the transmitter, the middle layer handles reception of the return signal, and the bottom layer contains the data acquisition unit.

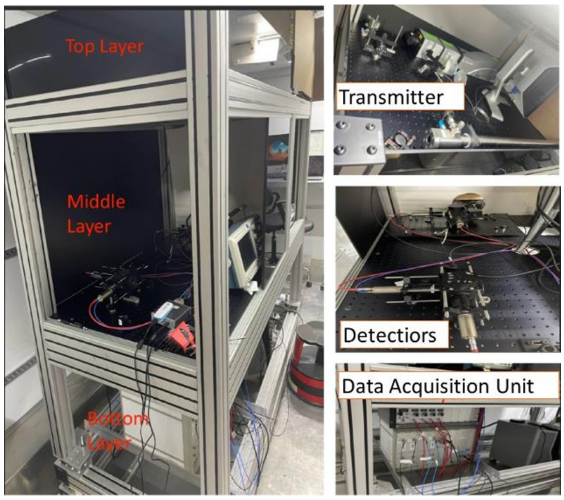

Figure 1. The main components of the CCNY Trailer O_3 -DIAL system

2. Methodology

Differential Absorption Lidar is a lidar remote sensing technique that is used to retrieve vertical profiles of trace gas concentrations in the atmosphere. Ozone DIAL utilizes two close by wavelengths in the ozone Hartley band (200 – 310 nm) with different amounts of ozone absorption. The wavelength with stronger ozone absorption is referred to as λ_{on}, and the less absorbed wavelength is λ_{off} . By comparing the returned signal power from each wavelength, the range-resolved ozone number density, N_{O_3} can be determined [3].

The CCNY Trailer O_3-DIAL system uses a Nd:YAG laser which has been frequency quadrupled to 266 nm to pump a 1 meter long CO_2 Raman cell to generate the "on" and "off" wavelengths at 287.2 nm and 299.1 nm by the Stimulated Raman Scattering (SRS) effect. The laser fires at a repetition rate of 20 Hz with about 50 mJ per pulse. The raman cell pressure was varied to optimize the output power at the desired on and off wavelengths, and the optimal pressure was found to be 160 psi. At this pressure the output power is 8.48 mJ and 3.78 mJ for the on and off wavelengths, respectively.

The transmitted laser light is sent vertically into the atmosphere from a hatch in the trailer roof, and backscattered light is collected by a 2-inch refractive telescope and a 20-inch Cassegrain telescope for near-range and far-range signal detection, respectively. Photomultiplier tubes (PMTs) convert the optical energy into analog electrical signals, which are then digitized and sent to a computer for analysis by a Licel Data Acquisition unit. A schematic of the major components of the mobile DIAL system and how they interact with each other is shown in Figure 2.

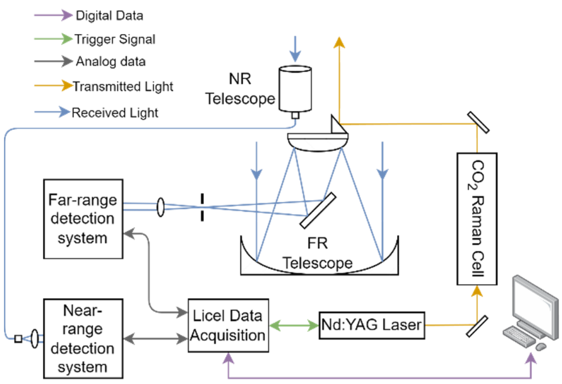

Figure 2. Schematic of the CCNY Trailer O_3 -DIAL system

The ozone number density, N_{O_3} can be calculated from [3]:

$$N_{O_3}(r) = \frac{1}{2\Delta\sigma_{O_3}\Delta r}\left[\ln\left(\frac{P_{off}(r+\Delta r)}{P_{off}(r)}\frac{P_{on}(r)}{P_{on}(r+\Delta r)}\right) - \ln\left(\frac{\beta_{off}(r+\Delta r)}{\beta_{off}(r)}\frac{\beta_{on}(r)}{\beta_{on}(r+\Delta r)}\right)\right] - \frac{\Delta\alpha_{mol}}{\Delta\sigma_{O_3}} - \frac{\Delta\alpha_{aer}}{\Delta\sigma_{O_3}} \quad (1)$$

Where $\Delta\sigma_{O_3}$ is the differential ozone absorption cross section of the on and off wavelengths. $P_{on,\ off}$ and $\beta_{on,off}$ are the returned lidar power and backscatter coefficient for either the on or off wavelength. $\Delta\alpha_{mol}$ and $\Delta\alpha_{aer}$ are the differences in absorption by molecules and aerosols of the "on" and "off" wavelengths.

3. Results

The CCNY trailer O_3-DIAL was first deployed near the existing CCNY laboratory O_3-DIAL (within 50 meters of each other). The two lidars made quasi-simultaneous observations. Figure 3 shows the time-height distribution of ozone mixing ratios retrieved from the two ozone-DIAL systems on July 12, 2023. Both retrievals are made with 10-min average. It can be seen that they generally agree well at 1-4 km altitude for the 7.5-hour long measurement. In the PBL (<2 km) both retrievals indicate high ozone formations. Both observation results indicate aloft ozone at 2.5-4 km altitude, but there are slight differences on the fine structures of aloft ozone, which might be attributed to different signal-to-noise ratios and signal smoothing. In addition, both lidar observations show consistent broken clouds at 2 km altitude at 16:00-18:00 UTC.

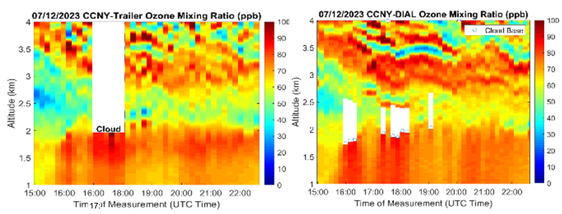

Figure 3. Comparison of ozone measurements between Trailer O_3-DIAL lidar and Lab O_3-DIAL on July 12, 2023

We can observe production of ozone in the boundary layer on July 12, as indicated by the aerosol lidar in the afternoon hours, shown in Figure 4. The boundary layer was stable during that period at a height of about 2 km.

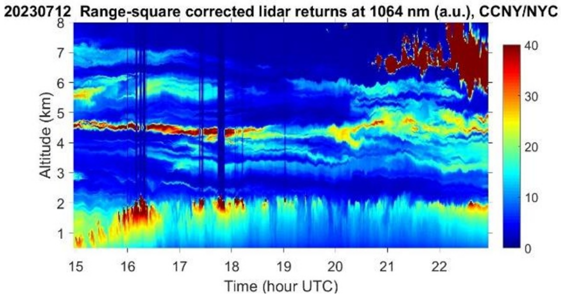

Figure 4. Range-corrected signal of CCNY aerosol lidar at 1064 nm on July 12th, 2023

From Figure 5 we can see that the observations from the two lidars are consistent with the surface ozone as measured by an on-site ozone analyzer.

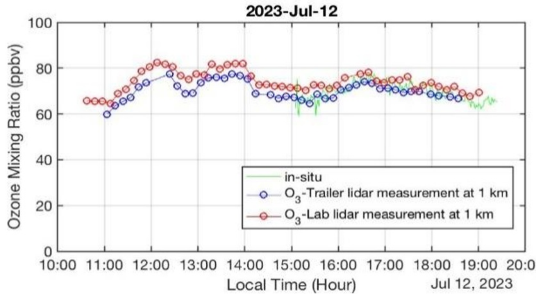

Figure 5. Comparison of the ozone mixing ratio measurements of in-situ ozone sampler and CCNY Lab and Trailer O_3-DIAL at 1 km.

In August 2023, the mobile O_3-DIAL was deployed for the field measurements LDEO which is in the northern suburb of New York city (~ 20.5 km from CCNY site). The trailer lidar was operated for a month-long period under favorable weather conditions. The lidar system generally collected data from mid-morning to late afternoon due to the commuter schedule limitation of the operators. High ozone formation and transport from the NYC urban area were observed in the PBL. Some aloft ozone associated with the wildfire smoke plume were also observed. As an example, Figure 6 shows the time-height distribution of ozone on August 14th, 2023, at LDEO and NYC. The temporal build-up process of ozone in the PBL (<1.5 km) was indicated, which is consistent with the ground in-situ measurement, shown in Figure 7. The ozone mixing ratios were larger than 60 ppb after 18:00 UTC and over 70 ppb after 19:00 UTC. The surface ozone mixing ratios in NYC were lower than at LDEO, but elevated ozone displayed similar buildup after 18:00 UTC.

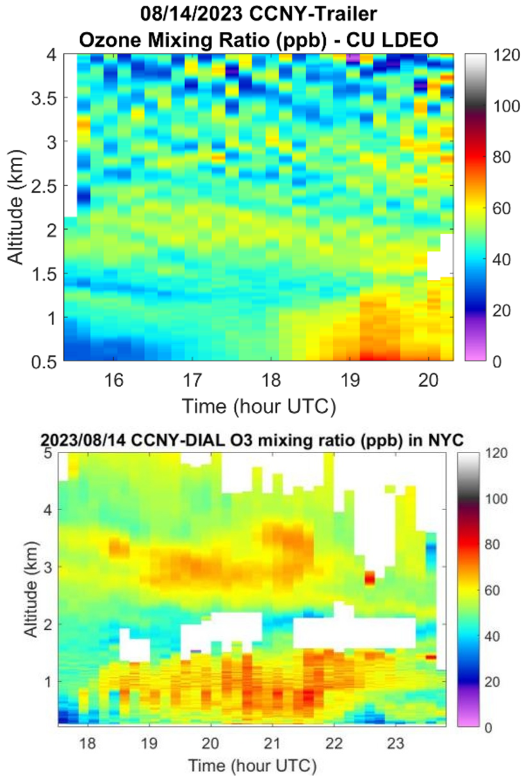

Figure 6. Comparison of ozone measurements between Trailer O_3-DIAL lidar and Lab O_3-DIAL on August 14, 2023

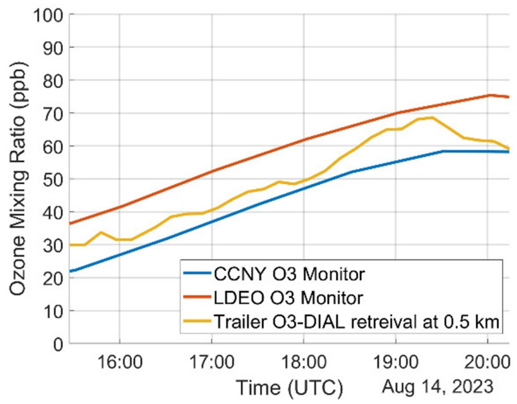

Figure 7. Comparison of the O3 mixing ratio measurements on August 14th, 2023

In Figure 8, the tropospheric NO_2 column measured by the TROPOMI satellite on August 14th, 2023, at 17:46 UTC [4]. White asterisks indicate the locations of CCNY and LDEO on the map. The satellite image shows a high NO_2 plume concentrated around Manhattan, which appears to be transporting northeast towards the Long Island sound and Connecticut, and not towards the LDEO site. This indicates that precursor NO_2 plume from NYC was not a big contributor to ozone observed at the LDEO area, and the ozone production at LDEO was due to local sources.

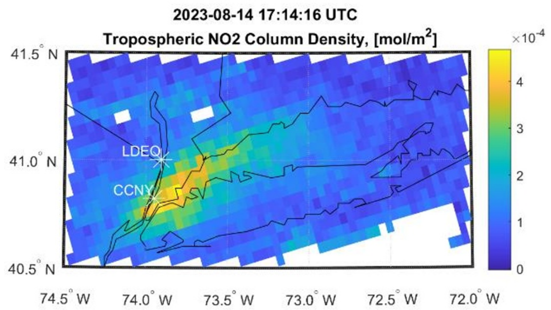

Figure 8. Tropospheric NO_2 column measured by TROPMI on August 14th, 2023 [4]

The trailer lidar observations over the summer also indicated other episodes of ozone exceedance of NAAQS at LDEO (not shown here), which was associated with urban pollution transport, depending on prevailing wind direction.

4. Conclusion

The CCNY Trailer O3-DIAL was validated against the CCNY Lab O_3-DIAL and in the range of 1 to 4 km, the O_3 retrievals between the systems agree well with each other. Further optimization of the far-range receiver system could result in a better signal to noise ratio, which will allow us to retrieve O_3 at altitudes higher than 4 km more consistently. By deploying the Trailer O3-DIAL system at sites of interest, especially areas in the proximity to NYC, we can gain increased insight into the processes behind pollution emission and transport, enhancing our understanding of the conditions that lead to poor air quality episodes in NYC and vicinity. Data from satellite and in-situ measurements also help us to understand the role that O_3 precursors such as NO_2 play in these episodes.

5. Acknowledgement

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6. References

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