A compact mobile ozone Lidar for atmospheric ozone and aerosol profiling

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ABSTRACT

A compact mobile differential absorption lidar (DIAL) system has been developed at NASA Langley Research Center to provide ozone, aerosol and cloud atmospheric measurements in a mobile trailer for ground-based atmospheric ozone air quality campaigns. This lidar is integrated into the Tropospheric Ozone Lidar Network (TOLNet) currently made up of four other ozone lidars across the country. The lidar system consists of a UV and green laser transmitter, a telescope and an optical signal receiver with associated Licel photon counting and analog channels. The laser transmitter consist of a Q-switched Nd:YLF inter-cavity doubled laser pumping a Ce:LiCAF tunable UV laser with all the associated power and lidar control support units on a single system rack. The system has been configured to enable mobile operation from a trailer and was deployed to Denver, CO July 15-August 15, 2014 supporting the DISCOVER-AQ campaign. Ozone curtain plots and the resulting science are presented.

Keywords: ozone, lidar, air quality, boundary layer

1. INTRODUCTION

Tropospheric ozone, is not emitted directly into the air, but is created by chemical reactions between oxides of nitrogen (NOx) and volatile organic compounds (VOC) and reaches unhealthy levels on hot sunny days in urban environments. Ozone can also be transported long distances by winds. The US Environmental Protection Agency currently has an 8-hour ozone standard of 75 ppb but will probably lower the standard to between 60 to 70 ppb in the future. The new standard will make it more difficult for US urban areas to remain in attainment without new ozone reduction regulations. Questions will arise such as "Is the ozone concentration generated by local emission or being transported for distant urban areas?"; "What is the role of stratospheric intrusions?'; "Is the ozone the result of forest fires?" and "What is the magnitude of natural and human generated ozone?". These questions are not easily answered by ground ozone monitor stations since they cannot determine the vertical distribution of ozone. Ozone lidars have the ability of not only determining the ground ozone level but also the altitude of ozone distributions, which can add insight on transport of ozone from distant regions.

This paper will describe an ozone lidar called the Langley Mobile Ozone Lidar (L-MOL) which was deployed for the first time in the NASA "Deriving Information on Surface Conditions from Column and Vertically Resolved Observations Relevant to Air Quality" (DISCOVER-AQ) campaign which used aircraft, balloons, in situ instruments and ozone lidars to measure and understand the air quality of the urban area surrounding Denver CO, USA during July and August of 2014. Figure 1 shows the terrain where L-MOL was deployed on Table Mountain, (1842-m ASL) Golden, CO 15-km west of Denver, CO (1609-m ASL). Mountains to the west block pollution from Denver from ventilating and the area around Denver is generally a high flat plane. Near-surface pollution is one of the most challenging problems for Earth observations from space. However, with an improved ability to monitor pollution from DISCOVER-AQ, will result in better air quality forecasts, more accurate source determination of pollutants in the air and more closely determined fluctuations in emissions levels. Measurements were taken in concert with ground observations in order to shed light on how satellites could be used to make similar, consistent measurements over time, with the ultimate goal of putting better air quality data in the hands of policymakers.

The L-MOL is part of a NASA sponsored ozone lidar network called Tropospheric Ozone Lidar Network (TOLNet) and consist of five ozone lidars (3 mobile and 2 stationary) that span the continental US. This network will help evaluate the future role of satellites in measuring tropospheric ozone profiles.
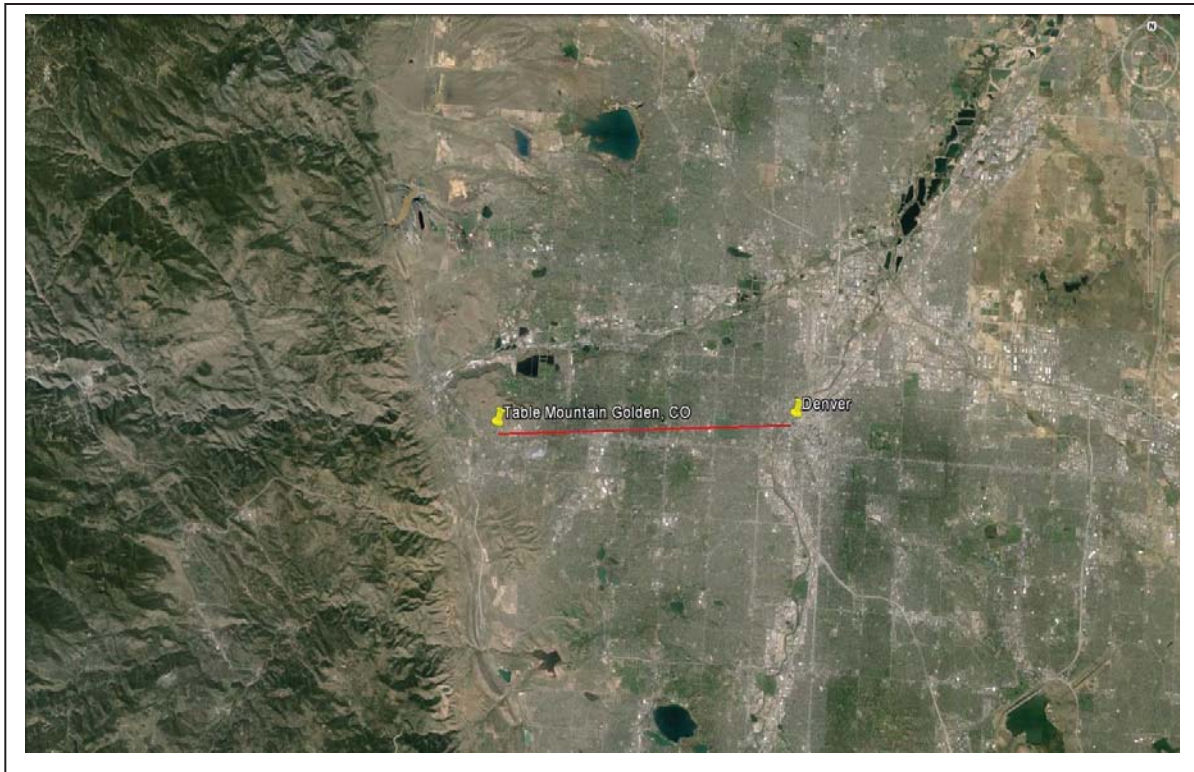
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Fig. 1. View of terrain during the DISCOVER-AQ Denver, CO campaign. The lidar was located at Table Mountain, Golden, CO 1- km west of Denver.

2. LIDAR SYSTEM DESCRIPTION

The lidar system consists of a UV and green laser transmitter, a telescope and an optical signal receiver box with associated (Licel) photon counting and analog channels as show in Fig. 2. The laser transmitter consist of a Coherent Evolution 30 TEM00 1-kHz diode pumped Q-switched Nd:YLF inter-cavity doubled laser pumping a Ce:LiCAF tunable UV laser with all the associated power and lidar control support units on a single system rack[1]. A custom-designed Ce:LiCAF tunable UV laser has a wavelength range of 280 to 295-nm that is selectable between two or more wavelengths as shown in Fig. 3. The current wavelengths are online 286.4 nm and offline 293.1 nm. The 527-nm visible beam is transmitted into the atmosphere for aerosol measurements. The CLBO fourth harmonic 262 nm pump beam is split by a beamsplitter into two pump beams that pump each face of the Ce:LiCAF crystal. A short laser cavity consisting of a 60% reflective (1m radius of curvature) output mirror, a dispersive prism and a flat HR mirror is used to produce the UV wavelengths. In order to produce different wavelengths, the high-reflectivity flat rear mirror is mounted on a servo controlled galvanometer motor to allow rapid tuning between the on and offline ozone wavelengths. Typical laser results are 6.8-W at 527-nm, 800-mW at 262-nm and 70-mW at the UV transmitted wavelengths [2]. The lidar receiver system consists of a receiver telescope with a 40-cm diameter parabolic mirror. A fiber optic cable transmits the received signal from the telescope to the receiver box, which houses the PMT detectors. A separate telescope with PMT and filter is used to sample the very near field to allow ozone profiles from 100-m above ground.

To obtain an ozone atmospheric measurement, the transmitter sends a laser pulse into the atmosphere at alternating on-line and off-line wavelengths (500Hz each line) [2]. The 527-nm green laser output is always transmitted giving a return from atmospheric aerosols. The system has been configured to enable mobile operation from a trailer, shown in Figure 4, which is environmentally controlled, and is towed with a truck to sites that are equipped with power. The objective is to make the system mobile such that it can be setup at remote sites to support major air quality field campaigns.
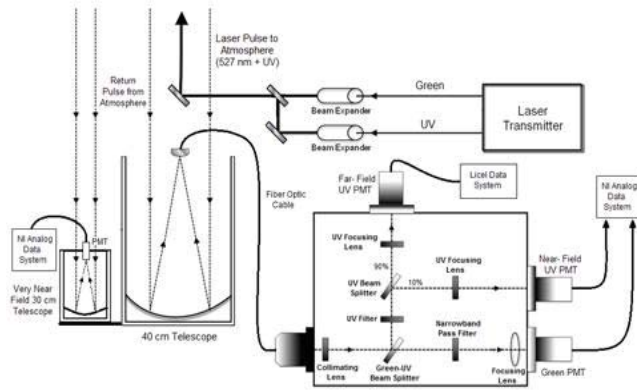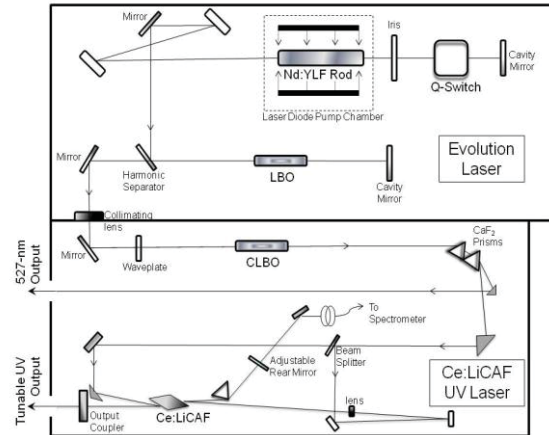
Fig. 2 Overall ozone lidar schematic.

Fig. 3 Laser transmitter schematic.

Fig. 4 Ozone lidar trailer at Table Mountain, Golden, CO.

3. DATA ANALYSIS DESCRIPTION

3.1 Data aquisition and control components

The data aquisition and control components for the lidar include the Licel [3] digitizer, the National Instruments chassis, and custom data processing software as shown in Fig. 5. The Licel unit provides 2 channels for the incming lidar signal: 1) far field analog, and 2) far field photon counting.

The functionality of the National Instruments (NI) unit is implemented using a Field Programmable Gate Array (FPGA) and includes the data aquisition from 3 additional channels: 3) Very near field lidar telescope channel, 4) Near field (3% of far field) channel, and the 5) 527-nm aerosol channel. Additional functionality of the NI unit, includes generation of the laser and gate pulses for the UV laser and PMT in addition to the synchronous generation of the sine wave responsible for the Ce:LiCAF selection of the operating online and offile UV wavelengths. The FPGA functionality also includes several additional auxiliary channels for laser power monitoring, temeprature, pressure, and humidity sensors.
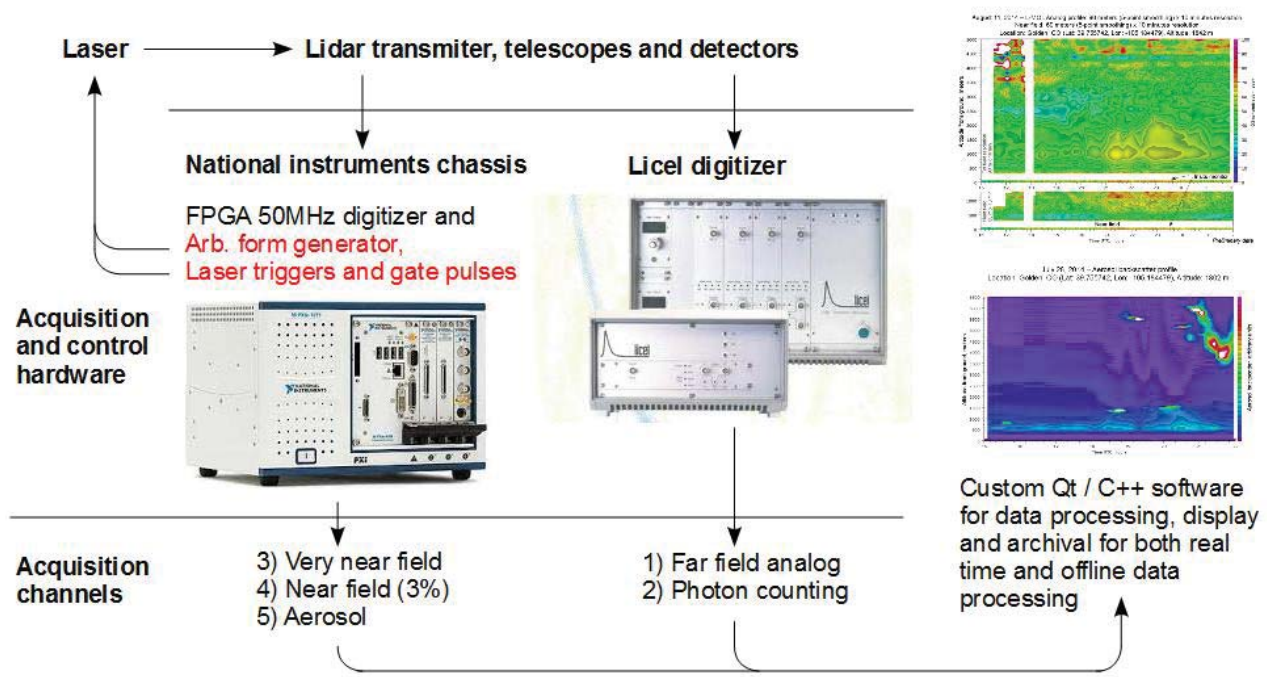
Fig. 5. Illustration of the main hardware and software components and their purpose.

The data processing and merging of individual data channels is illustrated in Fig 6, as can be seen 5 lidar channels previously described are fed into the lidar data processing software. The 4 UV lidar channels with the esception of the aerosol channel are processed using the same algorithm depicted in Fig 5. As can be seen, standard lidar processing proceduures performed include background subtraction and range squared correction, time and altitude averaging of the signals, and the post-processing smoothing of the retrieved ozone mixing ratio profile. The application of the DIAL equation [4] relies on the cross-section data from the HITRAN database extracted for the corresponding wavelengths and temperatures used. The additional aerosol lidar profile is used for aerosol corrections. The aerosol profile correction currently involves Rayleigh correction with Mie correction being implemented.
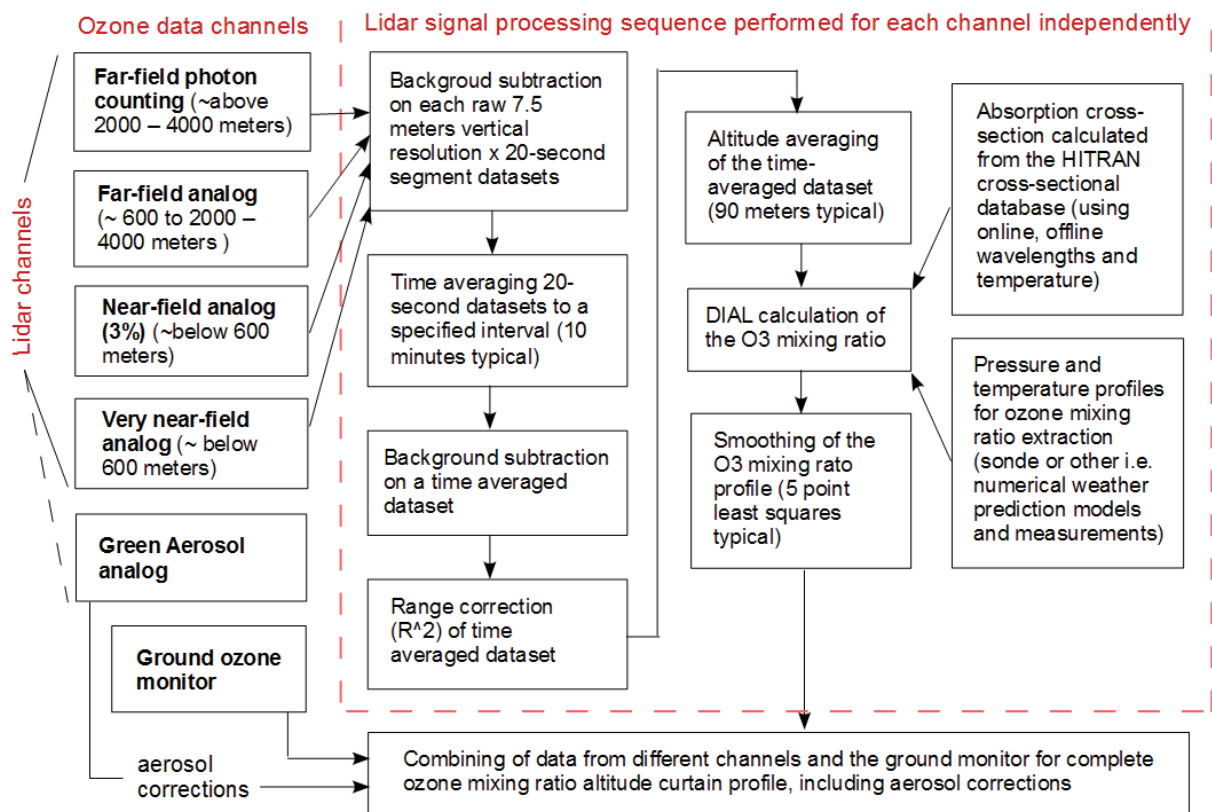
Ozone data channels | Lidar signal processing sequence performed for each channel independently

Lidar channels

Far-field photon counting (~above 2000 – 4000 meters)

Far-field analog (~ 600 to 2000 – 4000 meters)

Near-field analog (3%) (~below 600 meters)

Very near-field analog (~ below 600 meters)

Green Aerosol analog

Ground ozone monitor

Backgroud subtraction on each raw 7.5 meters vertical resolution x 20-second segment datasets

Time averaging 20-second datasets to a specified interval (10 minutes typical)

Background subtraction on a time averaged dataset

Range correction (R^2) of time averaged dataset

Altitude averaging of the time-averaged dataset (90 meters typical)

DIAL calculation of the O3 mixing ratio

Smoothing of the O3 mixing rato profile (5 point least squares typical)

Absorption cross-section calculated from the HITRAN cross-sectional database (using online, offline wavelengths and temperature)

Pressure and temperature profiles for ozone mixing ratio extraction (sonde or other i.e. numerical weather prediction models and measurements)

aerosol corrections

Combining of data from different channels and the ground monitor for complete ozone mixing ratio altitude curtain profile, including aerosol corrections

Fig 6. Processing sequence and merging of data from different lidar channels

3.2 Embedded supplementary in-situ ozone monitoring

An ozone in-situ (5.5-m height) monitor is used and controlled by a Raspberry PI computer [5] and the Qt C++ based framework [6]. This enables uninterrupted 24/7 monitoring of in-situ ozone concentrations and suplements the lidar retrievals at with ground level ozone. This implementation is depicted in Fig 7 and is based on the usage of the 2B Technologies ozone monitor Model 205 [7]. One of the advantages of such implementation is very low power consumption and easy expansion of hardware capabilities through addition of optional components and sensors with software modifications. In particular, the TOLNet ground measurememnt archival format requires information about the pressure, temperature, humidity, wind speed and direction at the measurment site in addition to the ozone mixing ratio. These additional parameters may be conveniently recorded by inexpensive and small footprint sensors which can be easily interfaced with the embedded computers such as Raspberry PI.
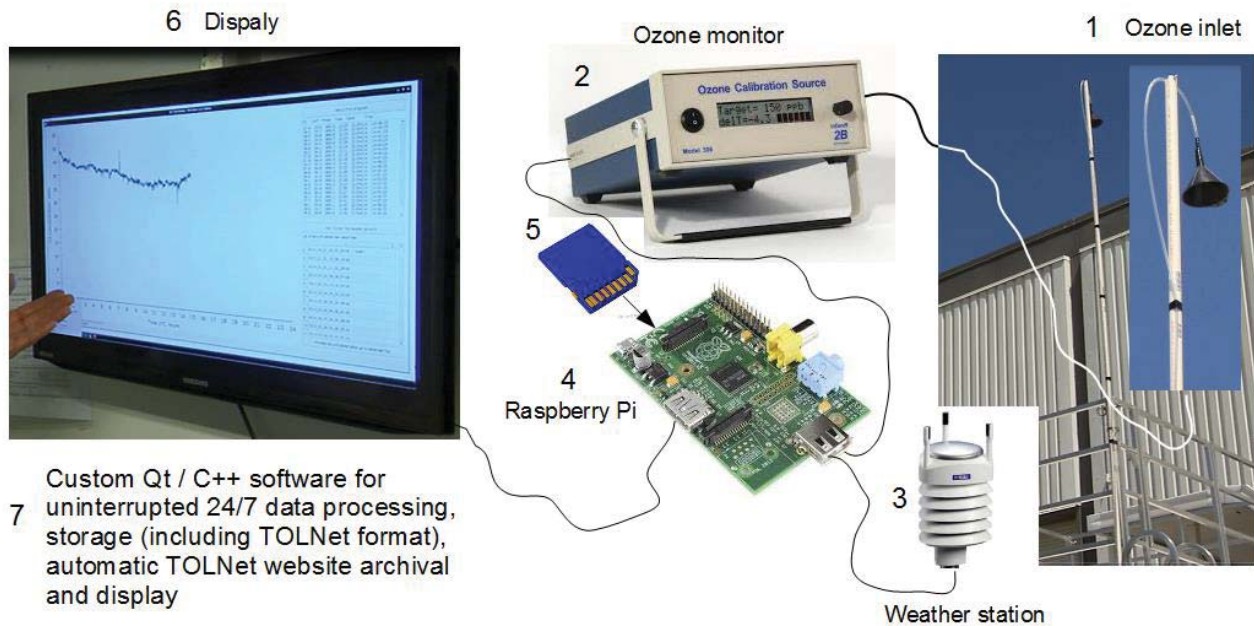
Fig 7. Embedded in-situ ozone monitoring. The ambient air is being transported from the inlet (1) to the 2B Tech Model 205 ozone monitor (2) which sends the digitized data to the embedded computer (4) carrying out data processing, storage (5) and visualization (6) using custom software (7). Addition of a weather station (3) is being implemented.

4. DISCOVER-AQ OZONE LIDAR RESULTS

The lidar was for the first time deployed at the Boulder Atmospheric Laboratory in Erie, CO on July 16, 2014 where a collocated ozonesonde was launched. The comparison of the ozonesomde and lidar curtain plot is show in Fig. 8. The curtain shows a typical Denver ozone profile with low ozone the morning and ozone generated in the midday. Severe weather terminated the profile at 19 UTC. The good correspondence of the curtain with the ozonesonde and in-situ measurements gave confidence that the lidar was profiling ozone adequately. The lidar was then moved to Table Mountain, Golden, CO where the measurement campaign was completed.
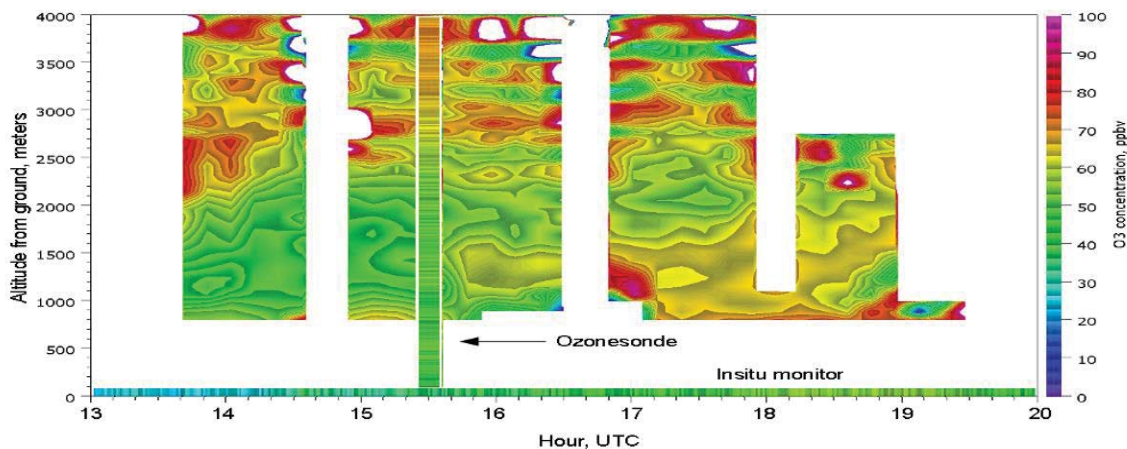
Fig. 8 Collocated ozonesonde launched at the Boulder Atmospheric Observatory in Erie, CO July 16, 2014 and L-MOL ozone curtain profile. Weather terminated the measurements at 19 UTC. 90-m vertical resolution with 5-point smoothing and 10-min. horizontal resolution.

Figure 9 shows a curtain profile from July 29, 2014 with the very near field telescope data displayed. The morning was clear with the boundary layer at 500-m (AGL) at 16 UTC and increasing to 1000-m starting at 19 UTC. The curtain shows the consistency between the far field, very near field and in-situ measurements. Higher ozone from the morning residual layer at 1500-m is mixed by a growing convective boundary layer at mid-day (19UTC – 6 hours).
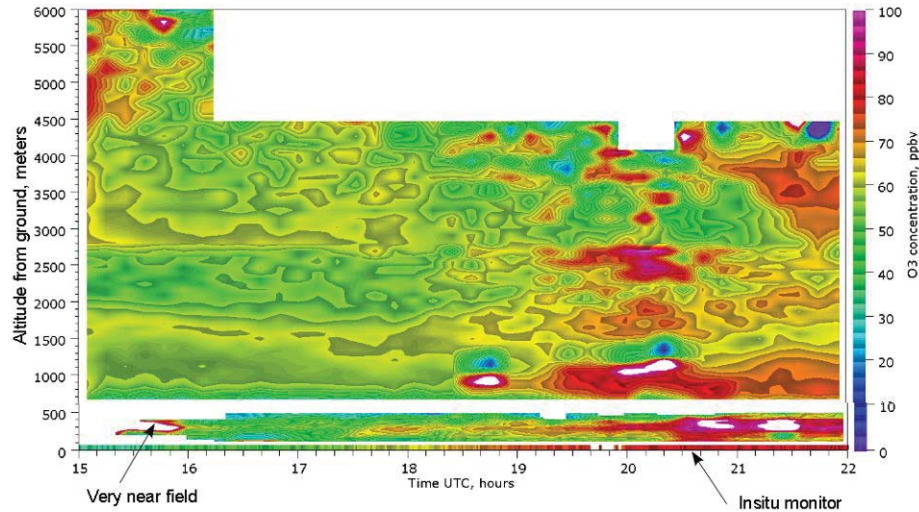

Fig. 9 Analog and photon ozone profiles spliced together with 90-m analog and 112.5-m photon counting vertical resolution and 10-min. horizontal resolution on July 28, 2014. The very near field telescope data has 60-m resolution.
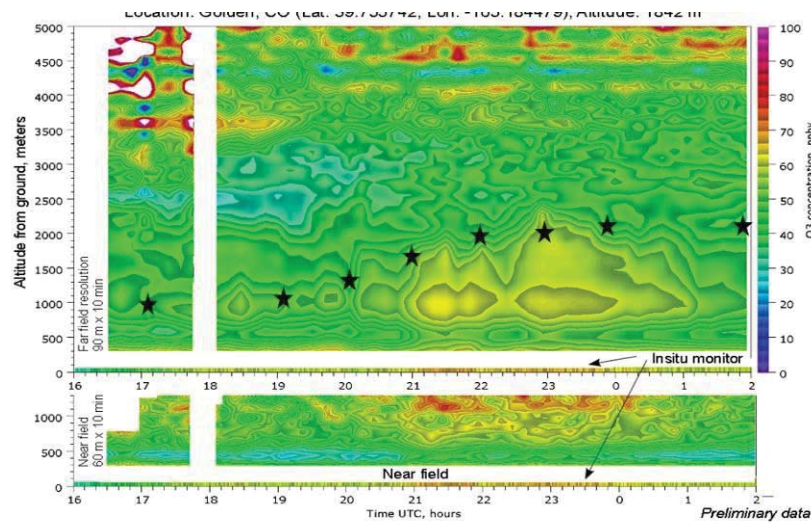
Fig. 10 Analog curtain profile for August 11, 2014 with 90-m vertical resolution and 10-min. horizontal resolution. Stars show approximate boundary layer height. Near field resolution was at higher 60-m resolution.
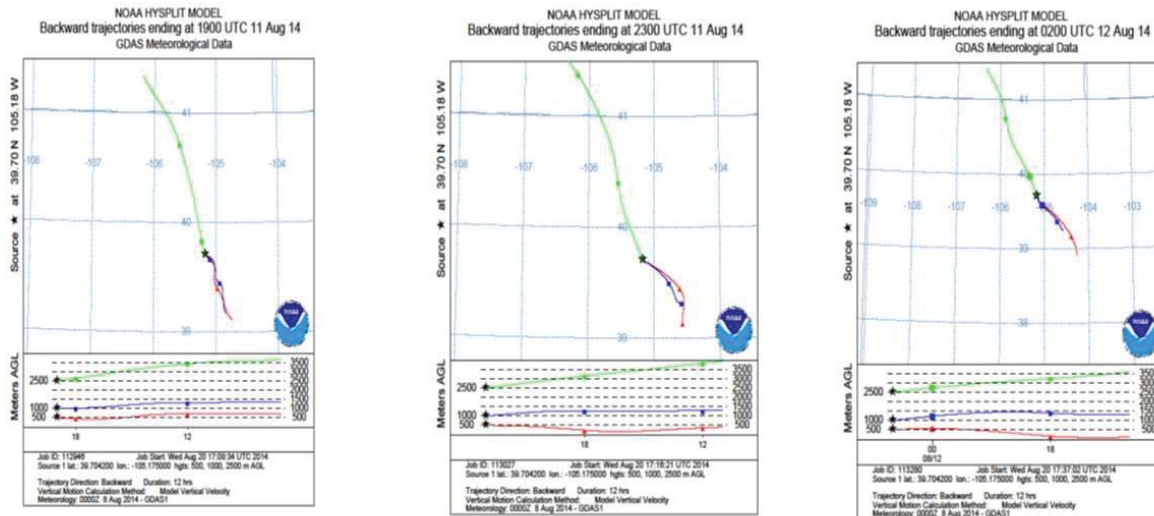

Fig. 11 Air mass back trajectory plots for altitudes 500, 1000 and 2500m for times of 19, 23 and 2 UTC.

Figure 10 shows the ozone curtain for August 11, 2014 with the analog resolution of 90-m vertical and 10-min. horizontal resolution. The boundary layer is approximated by the stars on the curtain. The lower curtain is the near field return with 60-m resolution, which better resolves the ozone maximum of the far field curtain. The figure shows altitude regions of different ozone concentrations. Between 500-1000-m high ozone is shown from 21-0 UTC (3-6 PM MST) and at 2500-m a band of low ozone is observed. By using HYSPLIT air mass back trajectory analysis the 12 hour air mass at 500, 1000 and 2500-m is shown in Figure 11. As shown in the figure the air mass at 500 and 1000-m comes from regions south of Denver where ozone precursors are high, but at 2500-m the air mass is coming from the northwestern mountain region with much less ozone precursors. After 23 UTC the insolation is decreasing and the generation of ozone in the boundary layer decreases.

5. CONCLUSIONS

The Langley Mobile Ozone Lidar was deployed in the DISCOVER-AQ campaign in the Denver, CO area in support of the air quality science investigation by providing daily ozone atmospheric profiles from Table Mountain, Golden, CO. The lidar operated for 23 days between July15 and August 12, 2014 and produced ozone curtain plots that will allow a better understanding of the area air quality for future satellite missions. No stratospheric intrusions were noted, but transport of ozone and precursors was noted coming from the Denver urban region. Air mass back trajectories were able to identify the source regions of low and high ozone. Ozone layers above the morning boundary layer were found to mix with the increased height boundary layer of the late afternoon. This first campaign of the L-MOL system gives confidence for deployment in future tropospheric air quality campaigns.

Acknowledgements

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