

The Small Mobile Ozone lidar (SMOL) - Development and validation

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Abstract: Ozone profile measurements at high temporal and vertical resolution are needed to better understand physical processes driving tropospheric ozone variability and to validate the tropospheric ozone measurements from spaceborne missions such as TEMPO (Tropospheric Emissions: Monitoring Pollution). As part of the Tropospheric Ozone Lidar Network (TOLNet) efforts allocated to provide such measurements, and leveraging on the experience of more than 20 years of ozone lidar measurements at Table Mountain Facility, the JPL lidar group developed the SMOL (Small Mobile Ozone Lidar), an affordable differential absorption lidar (DIAL) system covering all altitudes from 150 m to 10 km a.g.l. In this abstract, we will review the main characteristics of SMOL, the preliminary results of its first field deployment during the Synergistic TEMPO Air Quality Science (STAQS) and Atmospheric Emissions and Reactions Observed from Megacities to Marine Areas (AEROMMA) campaigns in summer 2023, as well as discuss upcoming deployments and collaborations.

1. Introduction

Over the last decade substantial progress has been made towards commercially viable and robust lidar systems, with the largest progress concentrated in ceilometers, wind, and water vapor lidars.

While some of that progress can be attributed to the leveraging on the development of infrared laser sources by the telecommunications industry, substantial progress can also be credited to system automation techniques and a conscious effort made to make them more robust and less costly.

The SMOL system is intended to contribute to this effort, providing TOLNet with a more cost-effective ozone lidar for air quality monitoring, satellite, and model validation as well as to investigate the potential of assimilation for air quality forecasts. While developing the SMOL concept, a few design criteria and requirements were followed:

(a) Lidars are typically associated with a large upfront cost. In the case of

SMOL, the marginal hardware cost was capped to 100k USD to make it competitive with alternative measurement techniques.

(b) Another issue normally associated with lidars is the high operational cost due to the need of qualified lidar personnel for its operation. A fully autonomous system with limited and simple maintenance requirements was an additional requirement to reduce the cost per acquired profile. By having a network of identical systems, we also expect to reduce the processing and data archiving burden by simplifying the processing chain.

(c) Finally, the performance of the SMOL system had to be comparable to that of the already existing TOLNet systems, covering the low and mid troposphere with a temporal resolution of under 30

minutes, a random uncertainty of under 10%, and a vertical resolution in the 0.1-1 km range.

2. System description

The SMOL system (Fig. 1) is built around a two-door aluminum enclosure on wheels. The two-door setup allows easy access to all lidar subsystems and facilitates any field maintenance required on the unit, while having the unit on wheels allows the relocation of the unit over short distances and the loading and unloading from pickup trucks without the need for additional equipment like forklifts. The overall dimensions of the unit are 1 m x 1.5 m x 2 m (width x depth x height), including a protective barrier added at the top of the enclosure to prevent accidental exposure to the outgoing laser beams. The weight of the unit is approximately 400 kg.



Figure 1. The SMOL system at JPL Table Mountain Facility.

The SMOL transmitter is based on a flashlamp-pumped Nd:YAG laser followed by doubling and quadrupling crystals. The laser unit outputs 266 nm pulses with an energy of 50 mJ at 20 Hz. The output of the laser is then divided by a 50/50 beam splitter and redirected by piezo actuated mirrors into two Raman conversion cells filled with hydrogen and deuterium at 5.5

bar and 12.4 bar, respectively. The piezo actuated mirrors allows the operator to steer the beams and align them to the receivers. The Raman cells have plano-convex lenses with a 250 mm focal length at their input to improve the Raman conversion efficiency. The output of the cells is then recollimated and transmitted through anti-reflection coated fused silica windows into the atmosphere. The output of the system is approximately 5 mJ at 289 nm, 5 mJ at 299 nm, and 1 mJ at 266 nm, which corresponds to a conversion efficiency of approximately 20% to the first Stokes line. The output diameter of both beams is 15 mm, with a divergence of 0.25 mrad. With this configuration, the unit has a NOHD (0.25 sec) of ~120 m, which allows operations without restrictions of air-traffic control.

The receiver of the SMOL units consists of three fiber-coupled telescopes to accommodate the dynamic range of the atmospheric return. The high and medium range receivers look at the 289/299 nm wavelength pair, while the low range channel looks at the 266/289 nm pair coming out from the deuterium-filled Raman conversion cell. The 266/289 nm wavelength pair is not only less sensitive to aerosol contamination typically found in the boundary layer, but also corresponds to the output of only one of the cells, which reduces the sensitivity to transmitter/receiver misalignment in the lower part of the receiver range.

The high-altitude receiver is implemented with a 6-inch diameter parabolic f/5 mirror coupled into a 1 mm fiber, while the medium and low altitude receivers are built with 1-inch diameter lenses focused into 1 mm and 0.2 mm fibers, respectively. In all cases the fibers have a numerical aperture of 0.22. The fiber outputs of the receiving telescopes are redirected into a spectrometric detection unit, where the output of the fibers is recollimated. After recollimation, the atmospheric backscatter is sent through a first set of filters for solar background reduction. In the case of the high and medium range channels, the filter has a center wavelength of 292 nm and a 32 nm full-width at half maximum (FWHM) transmission window, while for the low range receiver, a short pass filter with a cutoff wavelength of 300 nm is used.

After background reduction, the atmospheric backscatter of the high and medium range

channels is split into two beams with 50:50 beam splitters. The 289 nm detection arm uses an interference filter with a 285 nm center wavelength and 10 nm FWHM bandpass window, while the 299 nm detection arm uses a 299.1 nm center wavelength with a 1.2 nm FWHM transmission window. In the case of the low altitude receiver, a dichroic beam splitter is used to separate the 289 and 266 nm returns. The 289 nm receiver arm uses the same filter as in the other two receiver pairs, while the 266 nm receiver arm uses an interference filter with the center wavelength of 266 nm and a FWHM transmission window of 5 nm.

Finally, all the interference filters are followed by plano-convex lenses that focus the atmospheric return into the photomultiplier tube (PMT) photocathode. All the PMTs used in SMOL are of the photon-counting type (Hamamatsu H12386-110). The output of these detectors is sent into a multi-channel scaler (MCS) implemented on a Xilinx Zynq-7010 system-on-chip (SoC), where the signals are digitized and stored in Hierarchical Data Format version 5 (HDF5) together with a set of system parameter needed for the data retrieval.

3. Data retrieval

The SMOL raw lidar data acquired in HDF-5 format are processed using the Global Lidar Analysis Software Suite (GLASS) data processor developed in-house at JPL-TMF. The GLASS program is a state-of-the-art lidar processing software written in Interactive Data Language (IDL) and initially developed to retrieve stratospheric ozone, temperature, aerosol, tropospheric ozone, and water vapor for the four JPL lidars contributing to NDACC, namely MLSOL at the Mauna Loa Observatory, and TMSOL, TMTOL, and TMWAL at the JPL-Table Mountain Facility. GLASS was later expanded to process the raw data of a dozen other lidar instruments contributing to the NDACC, TOLNet and GRUAN (GCOS reference Upper Air Network) networks.

GLASS uses the Differential Absorption Lidar (DIAL) technique and a standardized definition of vertical resolution and uncertainty [1,2].

The uncertainty sources considered include measurement noise (Poisson statistics), absorption cross-sections and their temperature dependence, molecular extinction, saturation correction, background noise, and aerosol

correction (if applicable) [2]. The effective vertical resolution schemes used in GLASS can either be constrained by altitude or by random uncertainty. An altitude-constrained vertical resolution scheme consists of fixing vertical resolution as a function of altitude, independently of the lidar STNR. On the other hand, a noise-constrained vertical resolution scheme consists of applying a specific amount of smoothing such that the STNR after smoothing remains constant. For the SMOL instruments, a noise-constrained vertical resolution scheme is applied, specifically forcing to a constant 7% random uncertainty throughout the profile, but not exceeding 500-m, 1 km and 1.5 km vertical resolution for the low-intensity, medium-intensity and high-intensity ranges respectively. After ozone is retrieved for each intensity range (low, medium, high), a single merged profile is obtained by selecting the best combination of each range.

The SMOL data processing by GLASS is typically done automatically for a given time interval. The results undergo thorough QA/QC before they are uploaded to the TOLNet data server (<https://tolnet.larc.nasa.gov/>). The default high-temporal resolution product (referred to as “HIRES” product at TOLNet) consists of one profile every 30-minutes. Other products with different temporal or vertical resolutions can be produced, depending on the application needs (e.g., “CLIM”, “CALVAL”).

4. Instrument validation

Several field campaigns focusing on air quality in heavily populated areas of the US took place between end of June and the beginning of August 2023. As part of the TOLNet contribution to these efforts, the JPL TMF lidar group deployed two SMOL units to the Los Angeles (LA) basin region and operated them in conjunction with the fixed TMTOL [3] system at TMF (34.38N, 117.67W). The SMOL-1 unit was deployed at the JPL main campus in Pasadena (34.20N, 118.17W), while the SMOL-2 unit was deployed at the campus of the California State University (34.19N, 117.33W) in San Bernardino.

The measurements during these campaigns were mainly grouped into two intensive observation periods (IOPs) of approximately 5 days each, with some measurement in-between. During the first IOP (focus of this work, Fig. 2),

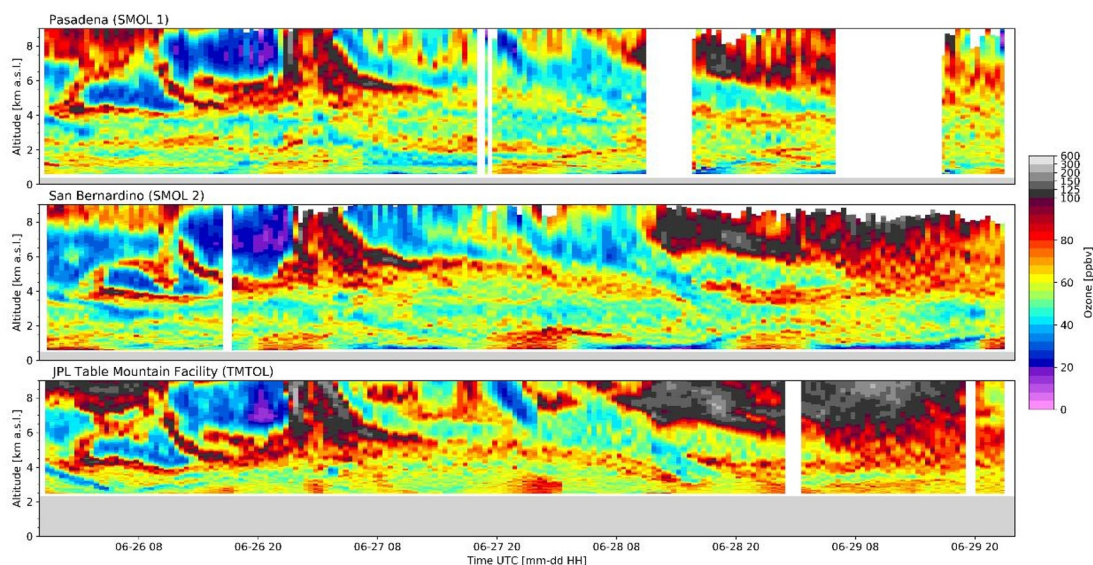


Figure 2. Overview of SMOL-1, SMOL-2 and TMTOL ozone measurements during the first IOP.

the NASA DC-8 hosted a large set of in-situ measurements, including the NNO_x [4] and CL instruments, while the NASA G-V carried the NASA Langley HSRL aTnd ozone DIAL [5].

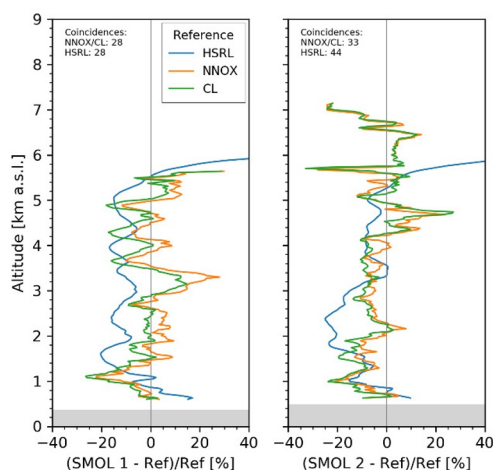


Figure 3. Summary of the comparison between the SMOL lidars and the DC-8 in-situ and G-V HSRL measurements.

All these simultaneous measurements provided a unique opportunity to validate the performance of the SMOL lidars. As a coincidence condition, we selected a 25 km radius, which represents a compromise between the number of coincidences and representativity error. The results of this comparison are summarized in Fig. 3.

The results show a generally good agreement through the troposphere, with the difference between all techniques generally under 20 %.

5. References

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6. Acknowledgements

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