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New Small Mobile Ozone Lidar instrument with extended capability for stratospheric ozone monitoring (SMOL-X)

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Abstract: In 2022-2023, the JPL Table Mountain Atmospheric Lidar Team developed several affordable, compact and automated mobile tropospheric ozone lidars (Small Mobile Ozone Lidar, or SMOL) that can be quickly deployed on the field for air quality studies and satellite validation (see companion abstract by Chouza et al.). Leveraging on technical and field deployment experience acquired with the SMOL instruments, a new system with extended capability was developed with the objective of measuring ozone throughout the lower and mid-stratosphere (up to 37 km) with a precision better than 10% for a time resolution of a few hours. The concept is similar to the SMOL systems, i.e., automated, compact, and affordable enough to deploy multiple units in a highly strategic and synergistic way. The performance of this new SMOL-X instrument will be presented, and several deployment configurations will be proposed in the context of the anticipated reduced spaceborne stratospheric ozone monitoring capability.

1. Introduction

Over the past several years, the Jet Propulsion Laboratory (JPL) Atmospheric Lidar Team put significant efforts into improving the long-term sustainability of their lidar instruments fleet contributing to the Network for the Detection of Atmospheric Composition Change (NDACC).

The first step consisted of developing automation and remote operation capability [1], which resulted in a spectacular increase of the sampling frequency, from about 100 measurement nights per year before automation to nearly 200 measurement nights per year after automation.

The second step was the development of more compact, more affordable ozone lidar instruments. Leveraging from 30+ years of experience of designing lidars, the JPL Lidar Team built and deployed on the field a new class of tropospheric ozone differential absorption lidar (DIAL), the Small Mobile Ozone Lidar (SMOL, see companion abstract by Chouza et al.). This very compact lidar can be transported in the back of the pickup truck for a rapid and versatile deployment on the field for air quality studies. Most importantly, the cost of a SMOL instrument is just under $100k (parts only), which is 5 to 10 times cheaper than most existing tropospheric ozone lidars.

The third and most recent step was the development a new version of SMOL with an extended range optimized for the measurement of stratospheric ozone, SMOL-X. This new lower- and mid-stratospheric ozone DIAL was built and tested successfully, for a tag-price of $120k (parts only). SMOL-X can measure vertical profiles of ozone between 4 km and 36 km altitude above ground with a precision better than 10% for a 3-hour averaging time. Because of its affordability and ease of deployment, this new class of stratospheric ozone DIAL provides new opportunities for NDACC deployment in remote areas, and is poised to fill critical measurement gaps, especially as we enter an era of anticipated shortfall of satellite measurements.

Hereafter, the SMOL-X system will be briefly described. Early validation results will be presented and discussed in the context of future deployment for NDACC.

2. Brief system description

The SMOL-X system design is tightly inspired from that of the original SMOL system built to measure tropospheric ozone [Chouza et al., companion abstract]. Many concepts such as compactness, simplicity, availability and affordability of its components, are replicated from the SMOL model (see Fig. 1). Therefore, only the main differences with the SMOL design will be reviewed here.

Figure 1: Photo of SMOL-X (right) together with SMOL1 and SMOL2 (left and middle)

The SMOL-X emitter consists of a combination of doubled (532 nm) and quadrupled (266 nm) Nd:YAG laser of approximately 100 mJ per pulse at 10 Hz at 266 nm. The 532 nm emitted wavelength is used for polarization measurements, with the main target to be polar stratospheric clouds (PSCs). The polarization receiver is still ongoing development, and the rest of this abstract will therefore focus on ozone. The 266 nm wavelength is sent through two Raman cells filled with H2 and D2, allowing a shift to 299 nm (first Stokes), 316 nm, and 341 nm (second Stokes). These wavelengths are used to cover the measurement of ozone through an altitude range of 4 km to 38 km above ground.

The SMOL-X receiver consists of two fiber-coupled telescopes, one telescope for high altitude ozone and aerosol polarization measurements, and one telescope to accommodate low altitude ozone measurements . A 10-inch diameter parabolic f/4 mirror coupled into a 1 mm fiber is used for the high-intensity (H) ozone DIAL pair at 316 nm and 341 nm to cover altitudes between 20 km and 38 km, and for a high-intensity pair at 299/316 nm to cover altitudes between 10 km and 23 km. The 299H, 316H and 341H nm wavelengths are separated sequentially by ways of long-pass dichroic mirrors. The low altitude ozone receiver (299L/316L nm) is built with 3-inch diameter lenses focused into 0.2 mm fiber to cover the altitudes 5-15 km.

The PMTs, multi-channel scalers (MCS), data acquisition software and format used in SMOL-X are identical to those of the SMOL systems (see companion abstract by Chouza et al.).

3. First results

The SMOL-X 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 was developed to retrieve stratospheric ozone, temperature, aerosol, tropospheric ozone, and water vapor for all JPL lidars contributing to NDACC, as well as other lidar instruments contributing to the NDACC, TOLNet (Tropospheric Ozone Lidar Network) and GRUAN (GCOS reference Upper Air Network) networks.

For the ozone retrieval, GLASS uses the classic DIAL technique with the NDACC-standardized definitions of vertical resolution and uncertainty described in [2,3]. The uncertainty sources considered include measurement noise (Poisson statistics), absorption cross-sections and their temperature dependence, molecular extinction, saturation (dead-time) correction, and background noise extraction. An optional cloud and/or aerosol correction is also applied, wherever needed. By default, the effective vertical resolution scheme used is constrained by random uncertainty. This approach consists of applying a specific amount of smoothing such that the STNR after smoothing remains constant. In the case of SMOL-X, random uncertainty is forced to 7% and 4%, but with a smoothing window not exceeding 2 km or 4 km maximum, for the low-intensity and high-intensity ranges respectively. After ozone is retrieved for each intensity range (low, high), a single merged profile is obtained by selecting the best combination of each range, the merging typically occurring around 20 km above ground.

Three validation periods were undergone in summer 2023, fall 2023 and spring 2024, during which the JPL-TMF stratospheric ozone (TMSOL), tropospheric ozone (TMTOL) and

SMOL-X lidars were operated simultaneously for several hours at a time. The results from the first validation campaign (June-Aug 2023) are summarized in Figure 2. Here, the results are focused on altitudes above 10 km as SMOL-X did not have yet a low-intensity range installed until the spring 2024 validation campaign. Figure 2 shows excellent agreement - well within 10% - between TMSOL (a high capability stratospheric ozone DIAL providing reference measurements to NDACC) and SMOL-X.

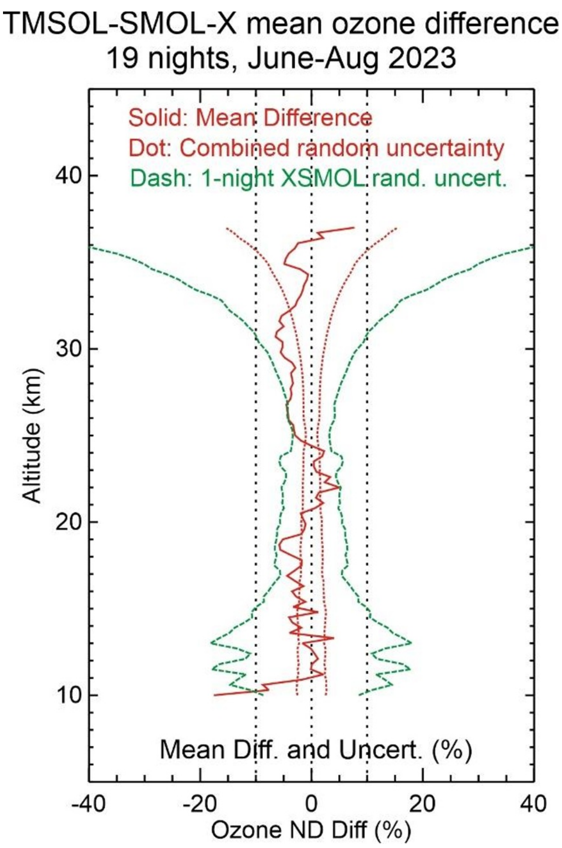

Figure 2: Solid red curve: Mean difference (%) between TMSOL and SMOL-X and SMOL-X during the summer 2023 validation period (19 profiles); Dash red curves: TMSOL-SMOL-X combined relative random uncertainty (%); Dash green curves: SMOL-X ozone relative uncertainty (%) computed for one night (green)

The third validation campaign (spring 2024) is still ongoing. Final results from this period will be shown at the ILRC Conference next summer. During this latest validation period, a low-intensity pair (299L/316L) was added to cover the altitudes 5-15 km, more selective interference filters at 316 nm and 341 nm were installed, and a mechanical chopper was added on the high-intensity channels to block the intense returns from the lowest altitudes, thus reducing the magnitude of signal-induced noise. These upgrades allowed to improve slightly signal-to-noise ratio at the top, cut-off the profiles slightly higher than previously, and ensure to remain below 10% ozone random uncertainty at 35 km for a 3-hour-long measurement.

4. Proposed future deployment strategy

Based on the promising results of the 2023-2024 validation campaigns, successful deployment of SMOL-X on the field can be foreseen as early as fall 2024. Considering the approaching end of the Aura Microwave Limb Sounder (Aura-MLS) life expected for 2026, a deficit of spaceborne observations dedicated to the monitoring of the stratospheric ozone layer is anticipated. The study of nighttime, polar ozone processes will be particularly impacted. The upcoming gap in observing capability can be partially filled by the reinforcement of ground-based capability. The deployment of several SMOL-X instruments in key remote areas could contribute favorably to filling the gap. As a first step, it is planned to deploy SMOL-X to the New Zealand Antarctic station of Arrival Heights to monitor the seasonal development of PSCs and polar ozone depletion.

Assuming that more SMOL-X units could be built in the near future, the Arctic is another region where the deployment of a SMOL-X instrument would be highly desirable (e.g., Alaska, Canada, Greenland, Spitzbergen). Regions of the globe where observations are lacking, such as tropical and southern hemisphere sites are also of high priority. Finally, specific regions of the globe such as northeastern Pacific, northwestern America, and the Indian monsoon region are particularly interesting for the study of troposphere-stratosphere exchanges (STE).

Because of its affordability and ease of deployment, this new class of stratospheric ozone DIAL provides several new opportunities for NDACC deployment in remote areas, and can promisingly contribute to reduce the critical stratospheric ozone measurement capability gap that is anticipated for the next decade.

5. Acknowledgements

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6. References

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