DEVELOPMENT AND APPLICATION OF AN AIRBORNE DIFFERENTIAL ABSORPTION LIDAR FOR THE SIMULTANEOUS MEASUREMENT OF OZONE AND WATER VAPOR IN THE TROPOPAUSE REGION

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ABSTRACT

A new, combined, lidar system has been developed that is able to simultaneously measure profiles of ozone and water vapor onboard of a comparatively small aircraft. The concurrent measurement of these complementary trace species in the upper troposphere and lower stratosphere allows inferring exchange processes in the tropopause region.

Whereas an advanced H_2O differential absorption lidar at 935 nm has successfully been developed and extensively tested at DLR in the past, we concentrate here on amending this lidar by addition of a UV channel to measure ozone.

The transmitter of the ozone DIAL is based on a near-IR optical parametric oscillator that is frequency-converted into the UV spectral range by intracavity sum frequency mixing. Hereby, a continuous UV tuning range of ~ 302-316 nm has been achieved. The average output power in this range is higher than 1 W corresponding to more than 10 mJ per pulse at a repetition rate of 100 Hz.

While airborne measurements are still pending, ground-based validation using both ozone sondes and ozone DIAL has successfully been performed and demonstrates the potential of this system.

1. INTRODUCTION

Stratosphere-troposphere exchange (STE) is a key controlling factor for the ozone budget in the upper troposphere (UT) and water vapor variability in the lower stratosphere (LS). The water vapor and ozone flux across the tropopause has a large impact on atmospheric chemistry and the Earth`s radiation budget and therefore the understanding of the relevant processes is important for our ability to predict climate change [1].

Despite their importance, the transport processes and their contribution to the constituent distribution in the UTLS are still inadequately understood. Therefore, more measurements in the tropopause region to assess the dynamical, chemical and radiative coupling between stratosphere and troposphere are required.

In general, a commonly used technique to investigate mixing between stratosphere and troposphere is tracer correlation. Aircraft in-situ measurements have provided insight into these processes by correlating trace species that strongly contrast in their stratospheric and tropospheric abundance such as ozone and carbon monoxide e.g. [2], [3], [4], [5].

Ozone and water vapor are also considered to be complementary tracers since stratosphere and troposphere have significant contrast in ozone (high in the former, and low in the latter) and water vapor (low in the former, and high in the latter) [6].

Simultaneous measurement of O_3 and H_2O profiles in the tropopause region with high accuracy and high spatial resolution would therefore constitute a major step forward helping to assess STE. From the ground, it is difficult to measure UT water vapor, however, ozone lidars have been employed for STE investigations [7], [8]. Airborne in-situ measurements can only provide one-dimensional data. Thus, airborne DIAL measurements of ozone and water vapor appear very promising, since they can provide mixing lines along 2-dimensional cross-sections.

In order to meet this goal, a new lidar system called AMALFI (**Ama**lgamated **L**idars for the Measurement of Trace Gas **F**luxes **i**n the Atmosphere) has been developed that modifies the H_2O-DIAL WALES already existing at DLR [9] by an additional ozone channel.

This system was designed to fly on the German research aircraft HALO, a Gulfstream G550.

2. REQUIREMENTS

The original WALES transmitter [9] consists of two identical laser systems that both comprise a near-infrared frequency converter pumped by a diode-pumped Nd:YAG laser at a repetition rate of 100 Hz. Each transmitter sequentially generates two of the four wavelengths in the vicinity of 935 nm to measure water vapor from the boundary layer to the LS. The NIR frequency converters are based on optical parametric oscillators and are attached as front-end modules to the pump lasers (see Figure 1). This system has been successfully operated during many flight campaigns on the DLR Falcon aircraft and recently also on HALO.

For the AMALFI system the goal was to replace one of the NIR frequency converter modules by an ultraviolet frequency converter.

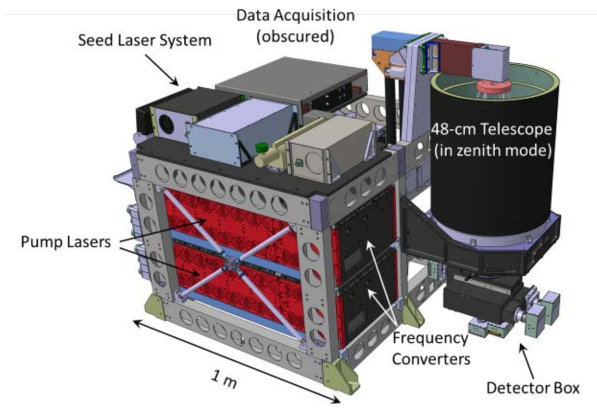

Figure 1. Construction design of the WALES lidar. For the combined measurement of water vapor and ozone one of the near-infrared frequency converters at the front end of the pump laser is exchanged against a UV frequency converter to generate the wavelengths relevant for ozone.

Since these modules have a volume of 300x412x256 mm^3 the UV transmitter necessarily had to meet this footprint (see Figure 2).

The preferred lidar transmitter for ozone DIAL should be tunable in the ultraviolet spectral range as pointed out by many authors. Tunability allows optimizing the lidar wavelengths for a selection of the optimum absorption cross sections in order to improve the signal-to-noise ratio and to optimize the measurement range, as well as to minimize interferences with other molecules and measurement errors caused by aerosol extinction and gradients.

Careful analysis suggests that the optimum on-line wavelength for ozone detection in the UTLS range is about 300-305 nm with the preferred off-line wavelength being ~10 nm longer. In order to achieve the required accuracy and spatial resolution the design goal was to generate > 1W of average UV power.

While early UV-DIALs were based on dye laser systems [10] it is generally accepted that all-solid-state laser sources are the preferred choice for airborne operation. Potential, tunable solid-state laser sources are those that directly emit in the UV spectral range (such as Ce-doped lasers [11] or those that emit in the visible or near IR spectral range (e.g. Ti:sapphire lasers [12] or OPOs [13], [14], [15]) whose radiation is converted into the relevant spectral range using the techniques of nonlinear frequency conversion. Here, we decided to use a technique that has already been used to efficiently generate tunable UV radiation starting with a Nd:YAG laser as the pump: intracavity sum frequency mixing of a near-infrared OPO [13], [16]. This concept has already been proven to fly on a small aircraft [14] to measure ozone in the boundary layer. Those results, however, were obtained with pump lasers having low repetition rates of 10 Hz. One of the challenges here was to adapt this concept to the high average power of the WALES pump laser.

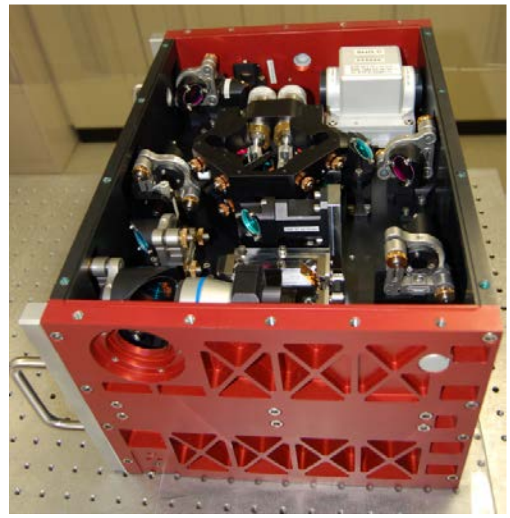

Figure 2. Photograph of the UV frequency converter module with open cover. The upper level contains all the optics (SHG module, beam steering and conditioning, and the UV-OPO), the lower level (obscured) comprises the temperature control for the second harmonic crystal, galvo scanner electronics, and spectrometer for wavelength control. The volume is 300x412x256 mm3 and the weight ~25 kg.

3. LAY-OUT OF THE UV FREQUENCY CONVERTER

The UV-OPO was designed as a four-mirror ring resonator consisting of two potassium titanyl phosphate (KTP) crystals in a walk-off compensated configuration. The OPO generates signal wavelengths around 740 nm. As the pump the second harmonic of the pump laser was generated to yield ~200 mJ of 532-nm pulse energy at a conversion efficiency approaching 60%. The second harmonic was split into two beams. The first one serves as the pump for the OPO process, the second one is injected into the cavity to serve as the pump for the sum-frequency mixing process to take place inside the OPO cavity. The SFM-crystal is a β-barium borate (BBO) crystal and generates the sum frequency of the OPO signal (698-780 nm) and the 532-nm second harmonic of the Nd:YAG laser which is coupled out of the cavity using appropriate dielectric mirrors.

All three crystals are attached to galvanometer scanners and wavelength tuning is achieved by their simultaneous rotation. Since this can easily be performed at a repetition rate of 50 Hz all wavelengths within the tuning range of this device can be addressed from pulse to pulse.

The continuous tuning range, within which UV energies of > 1Watt (10 millijoules of pulse energy) could be achieved, extended from ~302–316nm (Figure 3). Therefore, also the dual-DIAL technique to minimize interferences in the presence of aerosol layers [17], [18] can be applied as well as measuring profiles of sulfur dioxide.

The maximum conversion efficiency from the 1064-nm pump to the UV was as high as 4%.

The bandwidth in the UV was measured to be of the order of 0.03 nm. In order to accurately monitor the wavelengths, part of the signal radiation was transmitted to a fiber-coupled spectrometer (integrated in the lower level of the frequency converter module, see Figure 2) optimized for the wavelength range between 610-790 nm. During long-time measurements over several hours the wavelength did not deviate by more than 0.03 nm.

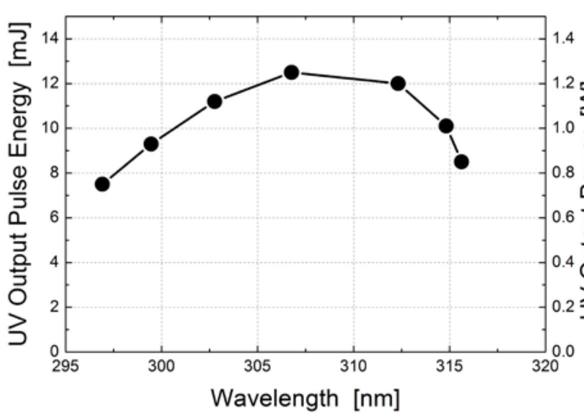

Figure 3. UV output power and pulse energy as function of the wavelength.

4. VALIDATION RESULTS

Due to scheduling issues we have not yet been able to operate the AMALFI system onboard the HALO aircraft. Instead, ground based validation exercises were carried out to demonstrate the performance of the newly developed ozone DIAL.

For this purpose we compared our ozone DIAL measurements with both ozone (Brewer-Mast) sondes and ground-based lidar at the meteorological observatory of the German Weather Service (DWD) at Hohenpeissenberg which is part of the Network for the Detection of Atmospheric Composition Change (NDACC) and which is located at a distance of ~38 km from our measurement site. We found a very good agreement of the measurements (Figure 4).

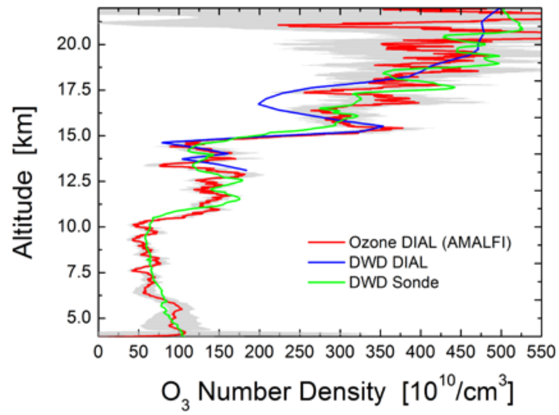

Figure 4. Comparison of the ozone profiles measured with the new UV lidar to the Brewer-Mast sonde and the NDACC lidar at Hohenpeissenberg on April 20, 2011. The tropopause level was at 10.4 km. The shaded area gives the statistical error of the measurement.

A simulation of the expected statistical error under these conditions with the actual result showed an agreement within a few percent. Taking into account that the measurement geometry is very different from airborne operation where the UTLS is much closer to the lidar, we meet the expected precision, indeed, which is 10% for 300 m vertical and 15 km horizontal averaging, respectively.

5. SUMMARY

A new ozone lidar has been developed that complements the existing DLR water vapor DIAL and thus enables to simultaneously measure profiles of H_2O and O_3 in the upper troposphere and lower stratosphere. Once airborne, this system will be able to study stratosphere-troposphere exchange by means of tracer correlation along 2-dimensional curtains.

The total weight of the lidar is ~500 kg, and thus approximately only 1/6 of the possible scientific payload of the HALO aircraft, so that additional instruments can be deployed.

Due to its tunability and bandwidth this ozone DIAL is also capable for the application of the Dual-DIAL technique as well as for the measurement of sulfur dioxide profiles.

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