Compact QCL Absorption Spectrometer for Balloon-borne Water Vapor Measurements in the Upper Atmosphere

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Abstract: We present a lightweight mid-IR spectrometer for accurate measurements of the H_2O concentration in the upper troposphere and lower stratosphere (UTLS) aboard meteorological balloons.

1. Introduction

Water vapor (H_2O) is the strongest greenhouse gas in the Earth's atmosphere, and it plays a key role in a multitude of processes that affect weather and climate. Particularly, H_2O in the upper troposphere and lower stratosphere (UTLS) is of great importance to the Earth's radiative balance, and it has a significant impact on the rate of global warming. Hence, accurate measurements of H_2O in the UTLS are crucial for understanding and projecting climate. Currently, the reference method used for in-situ measurements of UTLS H_2O aboard meteorological balloons is cryogenic frostpoint hygrometry (CFH) [1]. However, the cooling agent required for this technique (trifluoromethane) is phasing out as of 2020, due to its strong global warming potential. This represents a major challenge for the continuity of global, long-term stratospheric H_2O monitoring networks, such as the GCOS Reference Upper Air Network (GRUAN). As an alternative to CFH, we developed a compact instrument based on mid-IR quantum-cascade laser absorption spectroscopy (QCLAS) [2]. The prototype was already subject to in-flight validation, demonstrating excellent agreement with CFH in the troposphere, and successful operation in the lower stratosphere, up to 28 km altitude. Such outstanding capabilities open the perspective for future highly resolved, accurate, and cost-efficient soundings.

2. Methodology

Balloon-borne deployment provides low-cost access to the UTLS; however, it poses extraordinary constraints to the instrument in many aspects. In general, meteorological balloons ascend in the atmosphere at a rate of about 5 m/s, reaching up to a burst altitude of typically 30–35 km (pressure 5–10 hPa). During the flight, the payload experiences temperatures as low as −70 °C (−90 °C) at the mid-latitudes (tropical) tropopause, while the H_2O amount fraction varies from about 1–3 % on the ground to 4–6 ppmv in the stratosphere. The stable operation of a laser-based system under such harsh conditions is extremely challenging. To achieve the required robustness, while satisfying the stringent mass limitations associated with the balloon platform, many established concepts of spectrometer design, optics, and electronics have been systematically reconsidered. As a consequence, the instrument relies on a newly designed segmented circular multipass cell (MPC), consisting of a monolithic aluminum ring with 10.8 cm inner radius and containing 57 quadratic, spherically curved segments [3], which allows for 6 m optical path length in a very compact fashion. The collimated laser beam (wavelength 6 µm) is coupled to the MPC without the need for additional beam-shaping optics, resulting in a resilient optical setup suitable for mobile applications (Fig. 1a). Quick response and minimal interference by H_2O outgassing from surfaces are achieved by an open-path measurement strategy. An elaborate thermal management system, including phase-change materials as well as thermoelectric cooling, ensures excellent internal temperature stability despite of outside temperature variations up to 80 K. The instrument further benefits from considerable hardware optimization, including FPGA-based data acquisition and custom-developed power-economic laser driving electronics [4], resulting in a total power consumption of 15 W. The spectrometer, with a total weight of 3.9 kg, is a fully independent system, operating autonomously for the duration of a balloon flight (Fig. 1b).

3. Validation activities

The instrument underwent extensive stability assessments in a climate chamber as well as further validation experiments using dynamically generated water vapor mixtures. Finally, in collaboration with the German Weather Service (DWD), two successful test flights were conducted in Lindenberg, Germany. In the troposphere (altitudes < 12 km), the retrieved spectroscopic data show an excellent agreement (mean deviation 3 %) with the accompanying measurements by a standard CFH instrument (Fig. 1c). At higher altitudes, the quality of the spectral data remained unchanged, but interfering signal due to outgassed H_2O within the instrument enclosure prevented the accurate measurement of the stratospheric water vapor. Currently, a hardware adaptation is developed that eliminates such interfering internal signal. Further validations are planned in cooperation with the Swiss Federal Institute of Metrology (METAS), using SI-traceable reference mixtures with H_2O amount fractions below 20 ppmv and an uncertainty < 1%. The ultimate goal is to demonstrate the potential of QCLAS as a highly valuable technique for quantitative balloon-borne measurements of UTLS water vapor.

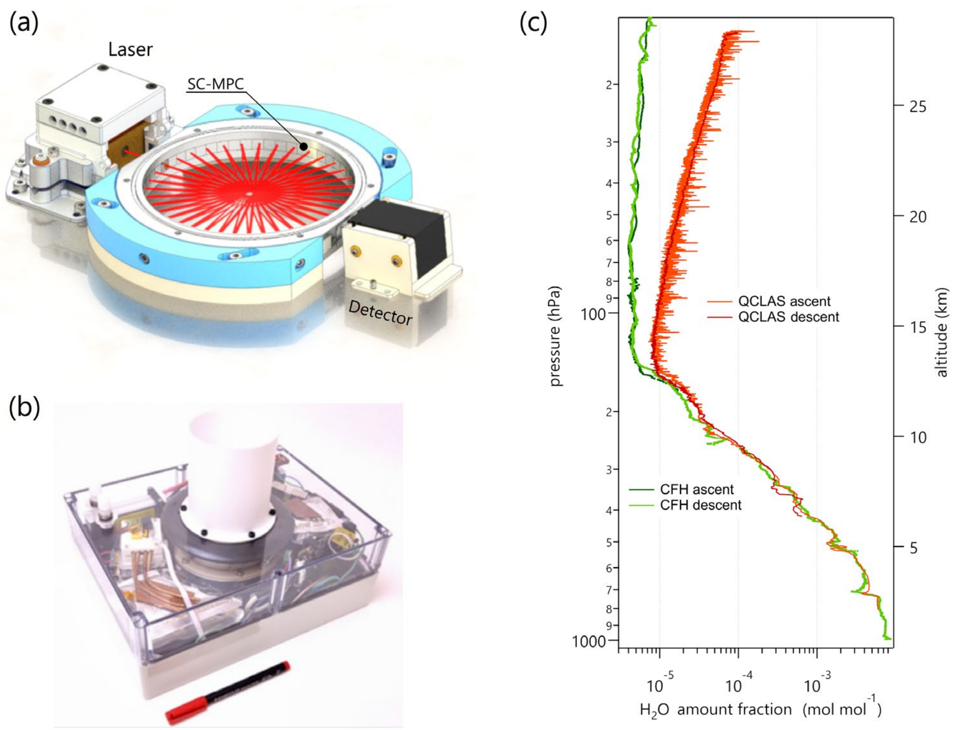

Fig. 1. (a) Schematic layout of the optical setup. (b) Fully assembled QCLAS instrument as deployed for the balloon flights. (c) Results of the balloon flight intercomparison with CFH conducted in Lindenberg (Germany) on 17 December 2019 (adapted from [2]).

4. References

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