Mid-IR Laser Spectrometer for Balloon-borne Lower Stratospheric Water Vapor Measurements

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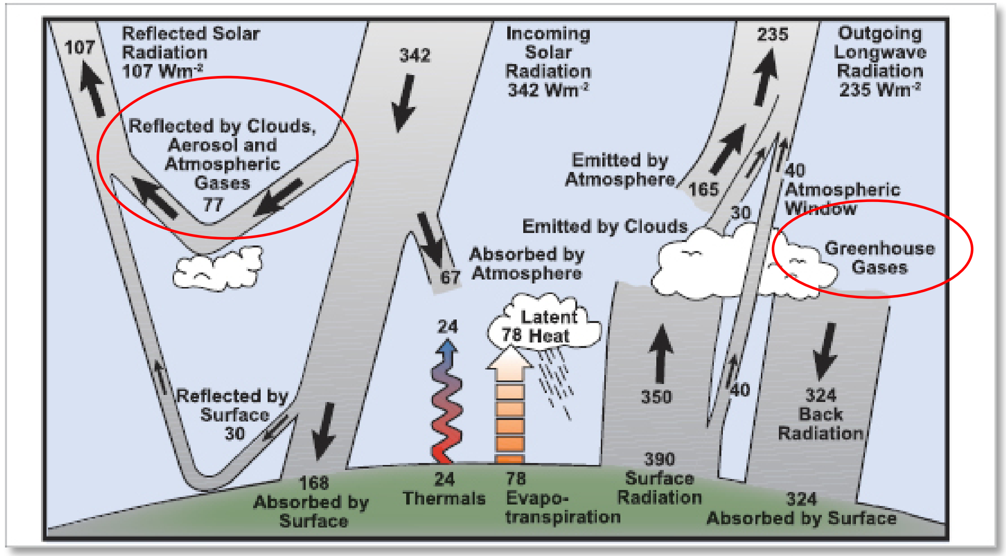
H_2O at Upper Troposphere/Lower Stratosphere (UTLS)

- Understanding the Earth's radiative balance.

Short wave radiation

Reflection by clouds

Cloud microphysics



Kiehl and Trenberth (1997)

Long wave radiation

Absorption (Greenhouse gas)

Trends? Feedback mechanisms?

Important to accurately know the water vapor concentration in the UTLS, i.e., 8-20 km altitude.

Challenges for H_2O measurement:

- **Low abundance:** 2-10 ppmv H_2O
- **Low** ***p*** <100 mbar; **low** ***T*** 210 K (-60°C)
- **Stickiness** of H_2O

Requirements and State of the Art

Requirements for an ideal in-situ instrument:

High spatial **resolution**
(few meters, i.e., 1 Hz)

high **accuracy** (<5 %)
(→ selectivity, sensitivity, precision, SI traceability)

Frequency and **flexibility** of measurements
(mass <4.5 kg)

In-situ H_2O instruments – current situation:

- CFH/FPH: standard method, but uses R23 as cooling liquid (Vömel et al., 2016)
- FLASH-B: (Lyman-α) restricted to nighttime measurements (Lykov et al., 2009)
- Various other techniques (absorption spectroscopy, mass spec,…) exist, all to be deployed aboard **aircrafts** or **special balloon gondolae**. (cf. Rollins et al., 2014)

Goal & Strategy

Development of an

open-path miniaturized mid-IR direct absorption spectrometer

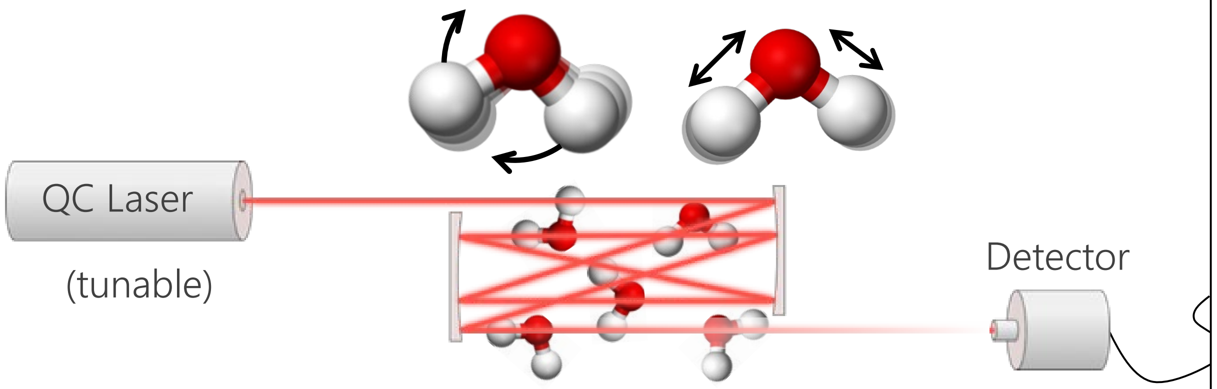
Ensures fast response and reduces contamination

Allows flexible, balloon-borne deployment

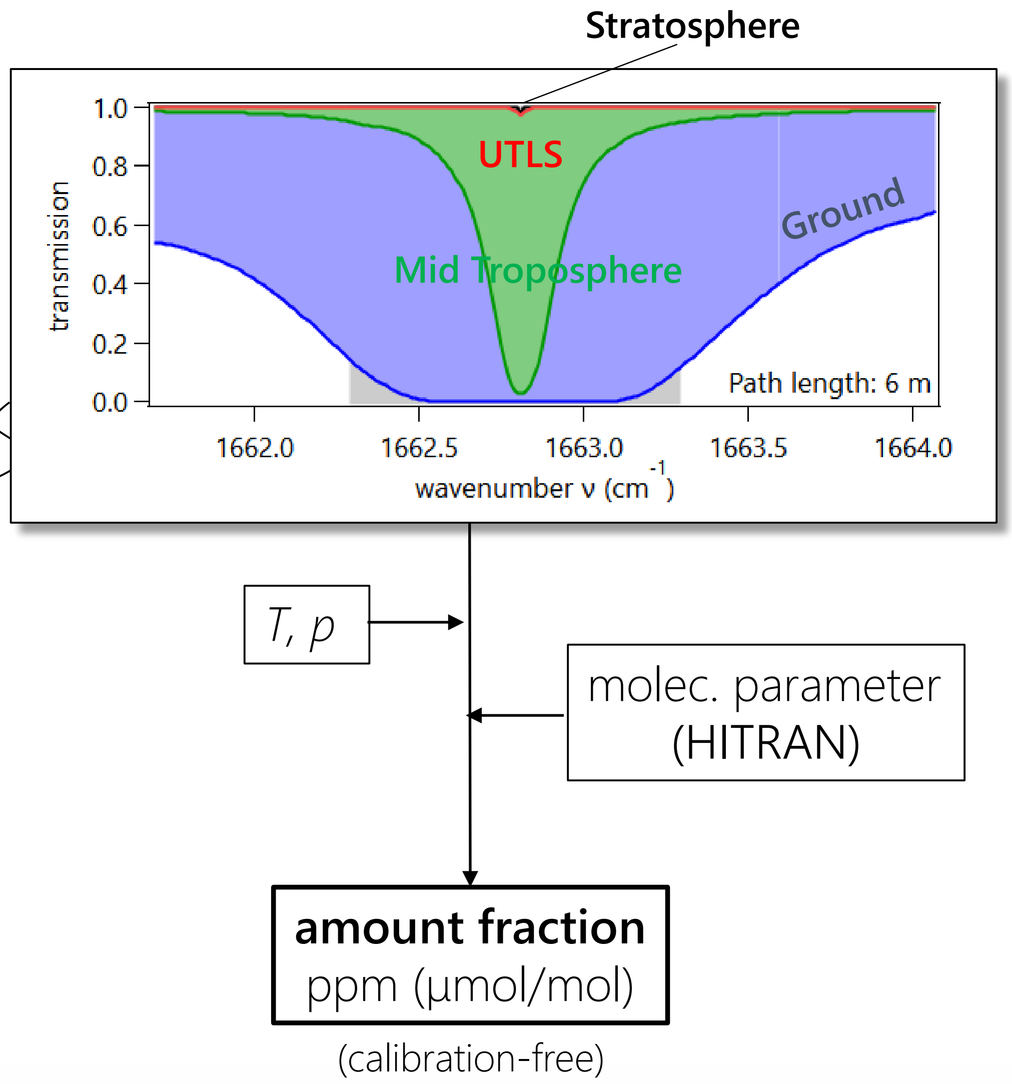
Delivers high accuracy and molecular specificity. The measurements are comparable and requires no calibration.

Direct Mid-IR Spectroscopy on H_2O

- **Direct tunable laser absorption spectroscopy**



In the mid-IR, only 6 m optical path length is required!

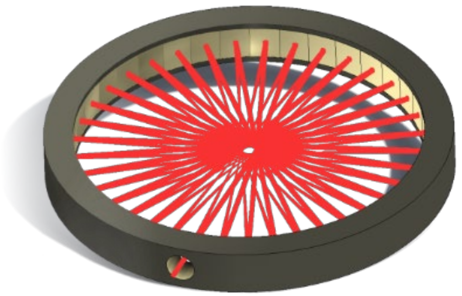


- **Properties of direct absorption spectroscopy:**

- fast response
- accurate & comparable
- calibration-free (e.g. Buchholz et al., 2017)

Miniaturization: Multipass Cell Design

- Segmented circular multipass cell (SC-MPC)



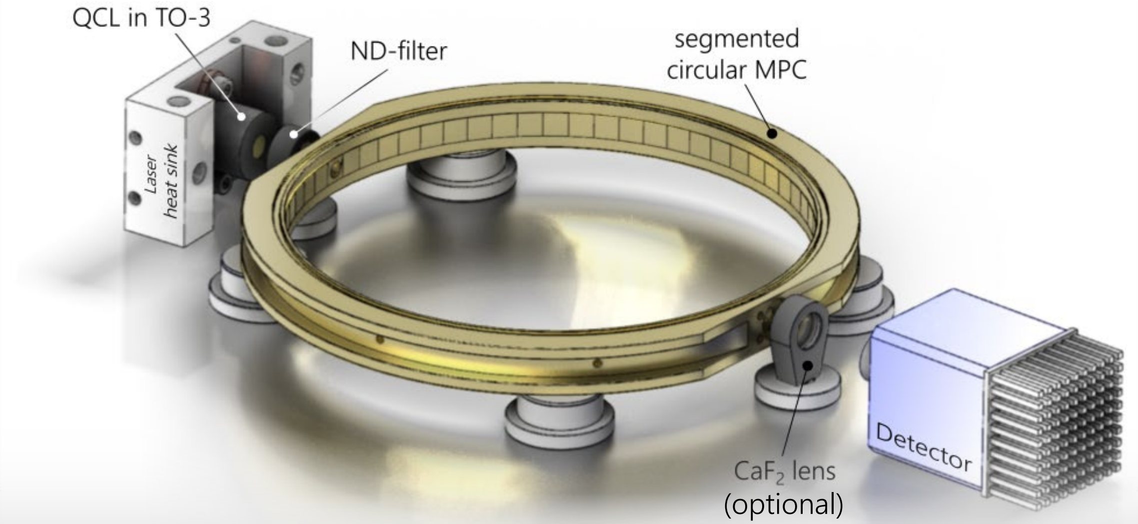
+ rotationally symmetric
+ lightweight (<150 g)
+ adjustable OPL

- **Specifically developed MPC for compact applications:**

  - Laser & detector can directly be mounted on the MPC
  → **very compact optical setup**!

  - Ideal geometry for **open-path** measurements

- Optical setup: basic concept



Graf et al., *Opt. Lett.* 43, 11 (2018)

The QCLAS Instrument

Integration of the presented concept in an integrated, standalone instrument

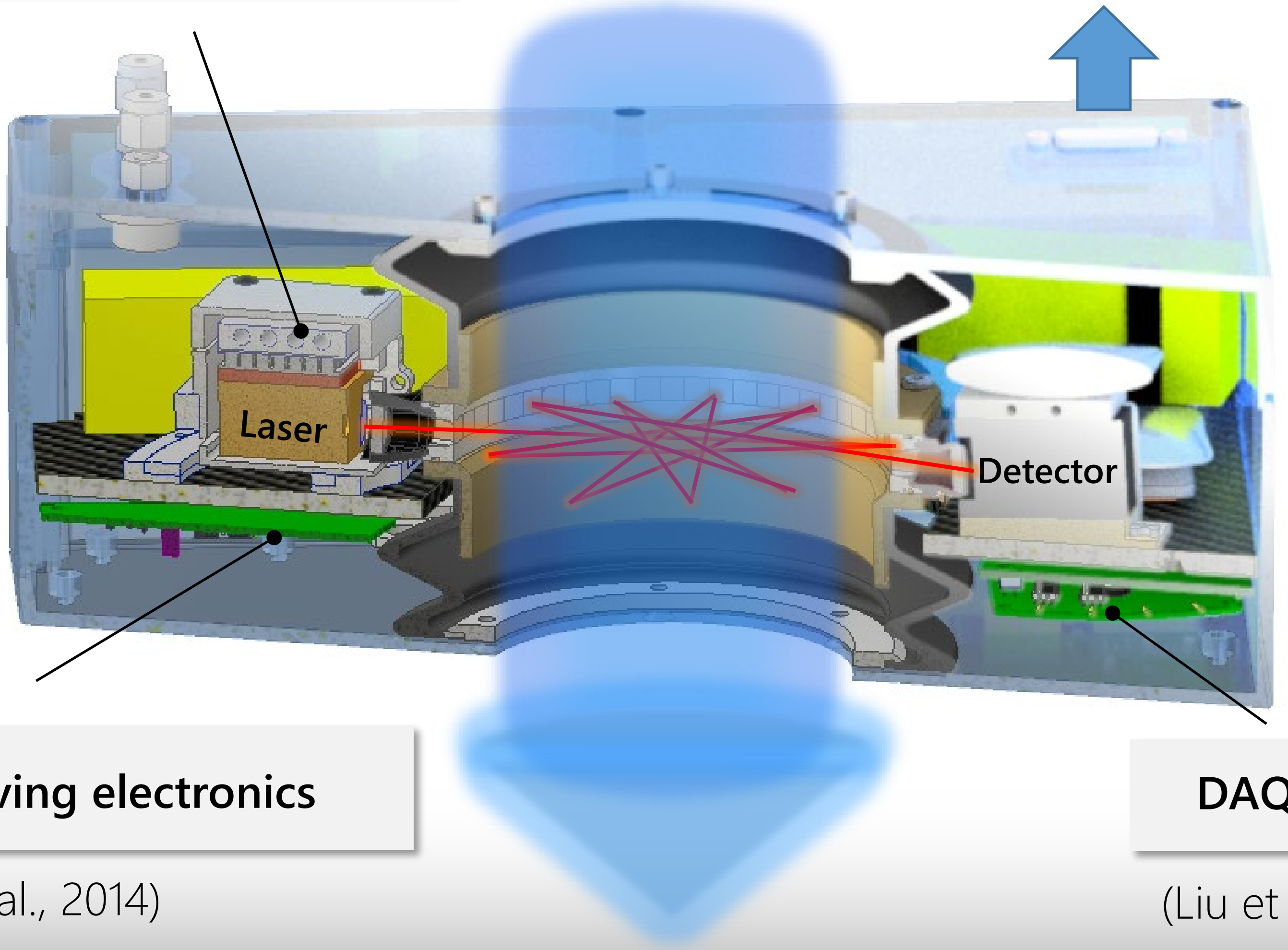
Further details in:

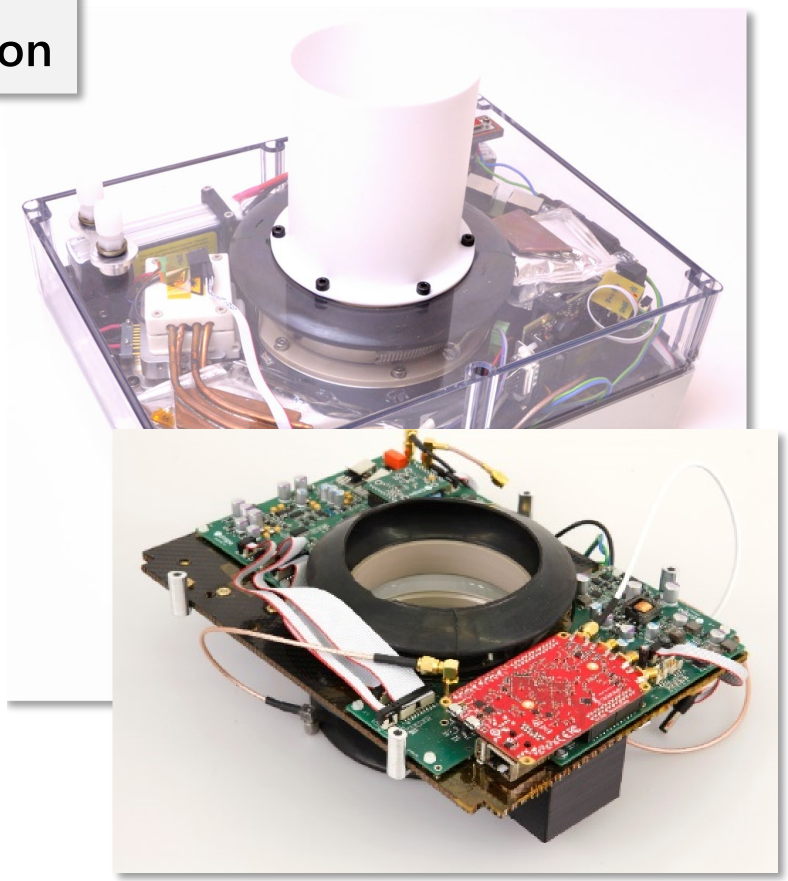
Graf et al., 2020, *in preparation for AMT*

H_2O QCLAS for UTLS water vapor measurements

Thermal management system

Software for
Communication & Evaluation





Laser driving electronics

DAQ & Storage

(Fischer et al., 2014)

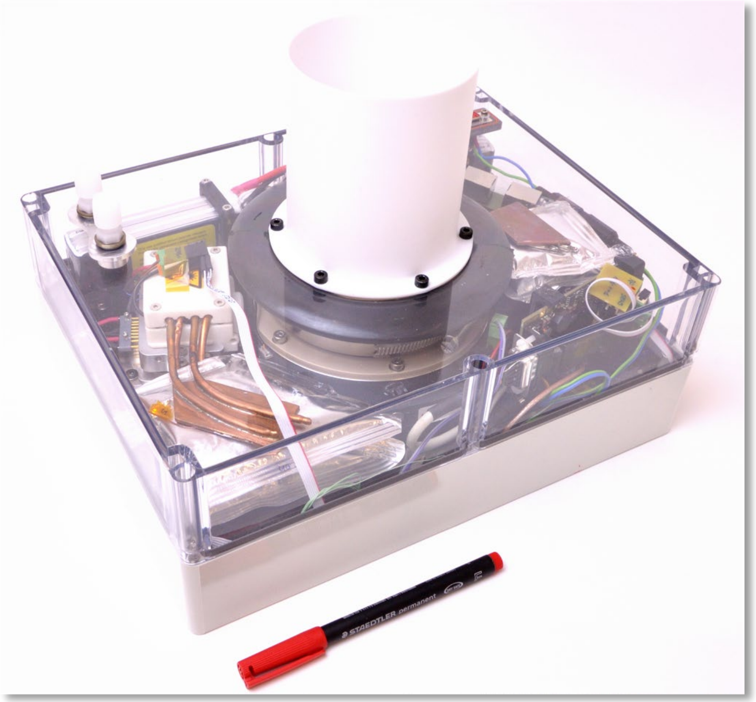
(Liu et al., 2018)

H_2O spectrometer for UTLS water vapor measurements

- **QCLAS for UTLS**

  - \>2 h **autonomous** operation
  - Fully **integrated** driving electronics and batteries
  - **On-board** data acquisition & storage

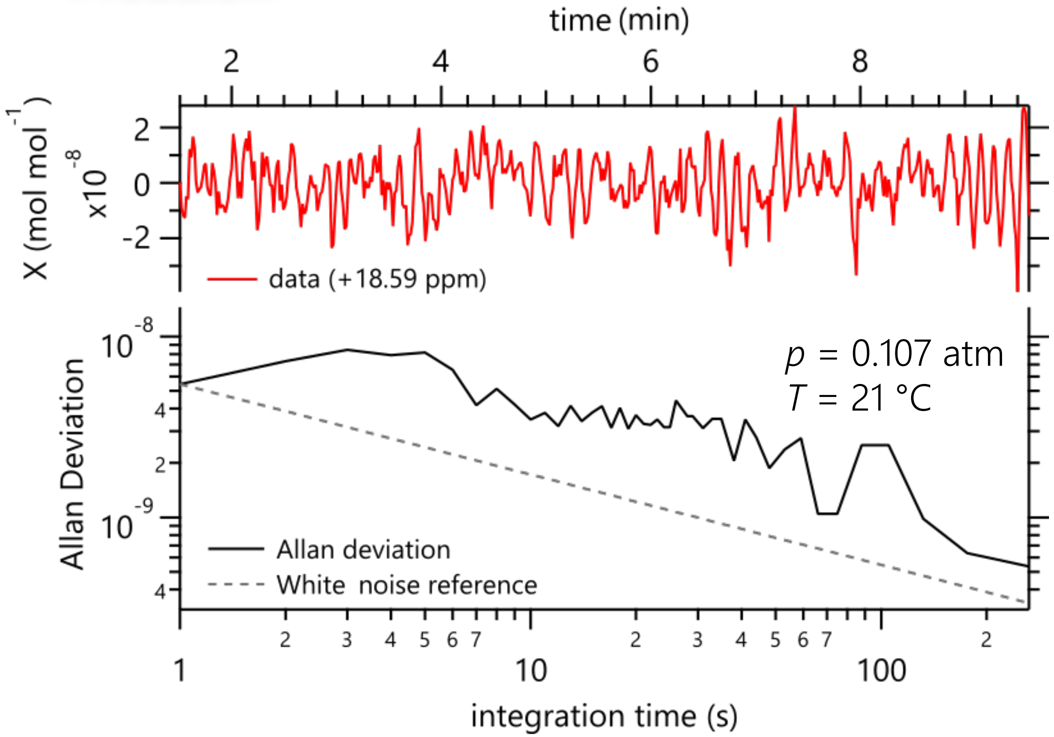
Total weight	3.8 kg
weight spectrometer only	2.6 kg
power consumption	15 W
gas exchange rate (5 m/s ascent speed)	40 l/s
acquisition rate	1 Hz



Open-path QCLAS (quantum cascade laser-based direct absorption spectrometer)

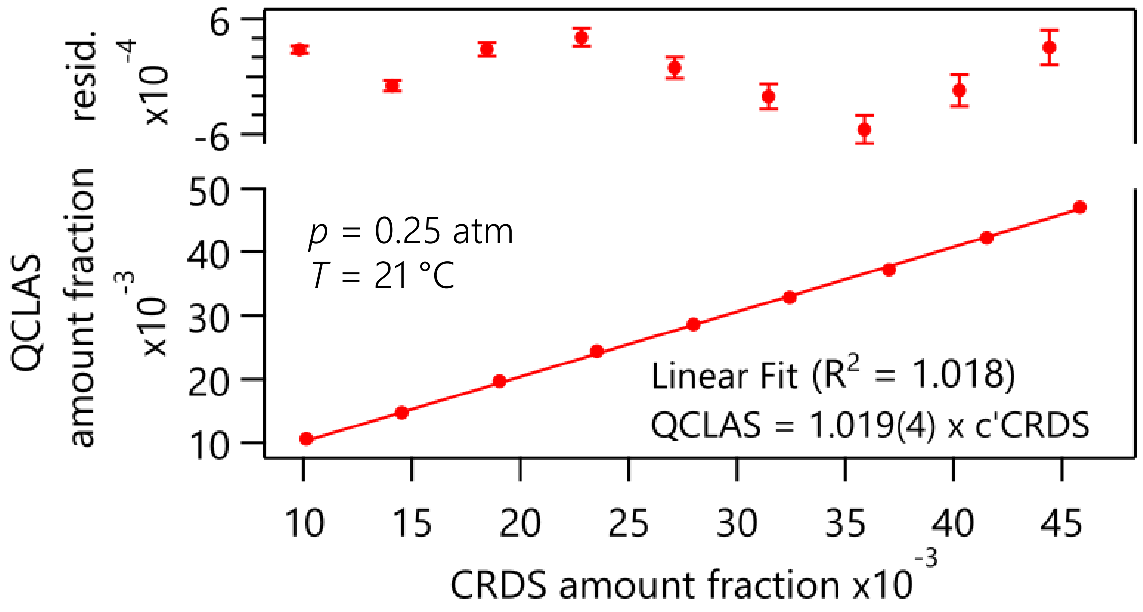
Lab-based Characterization

Precision



Precision at 1 Hz:
5.5 ppb (0.03%)

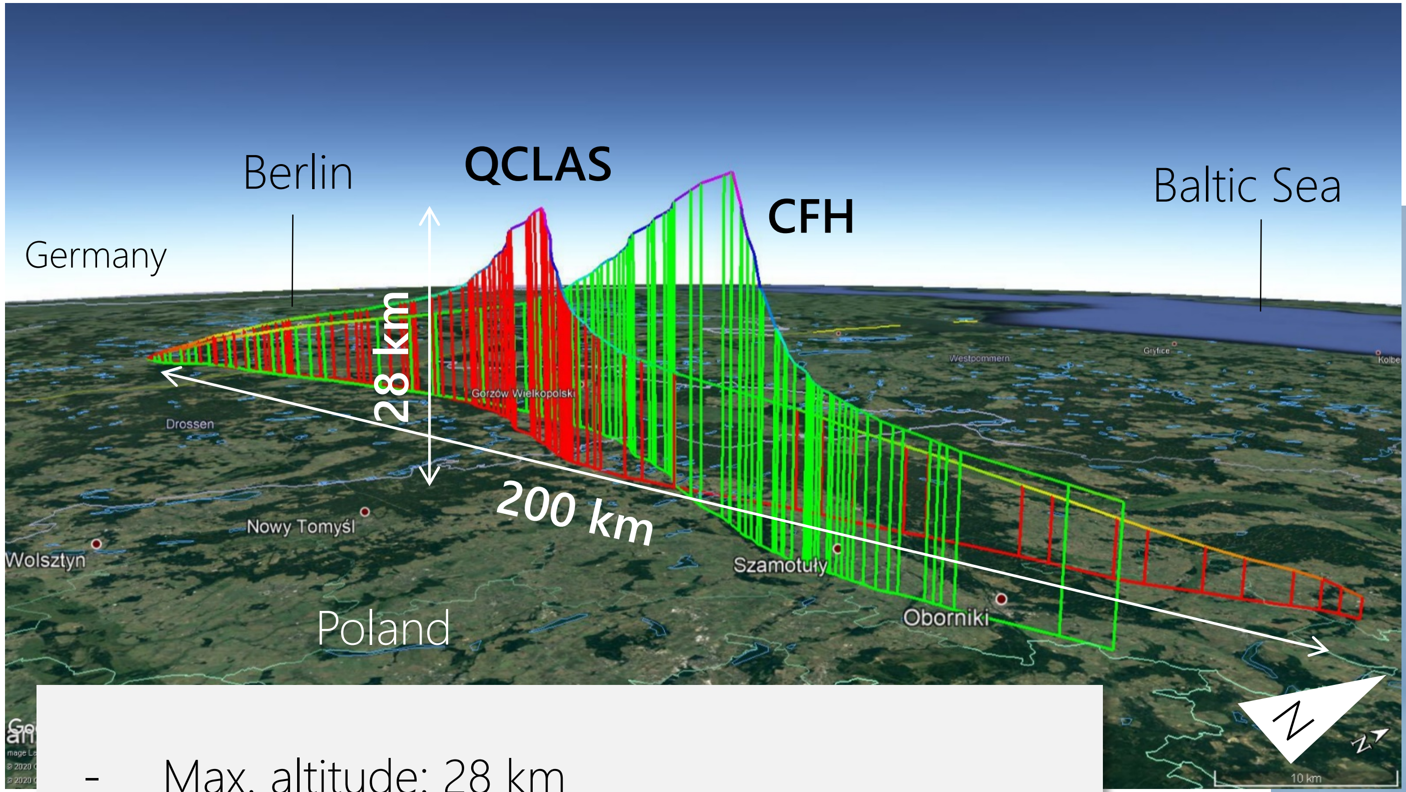
Accuracy (Comparison to CRDS)



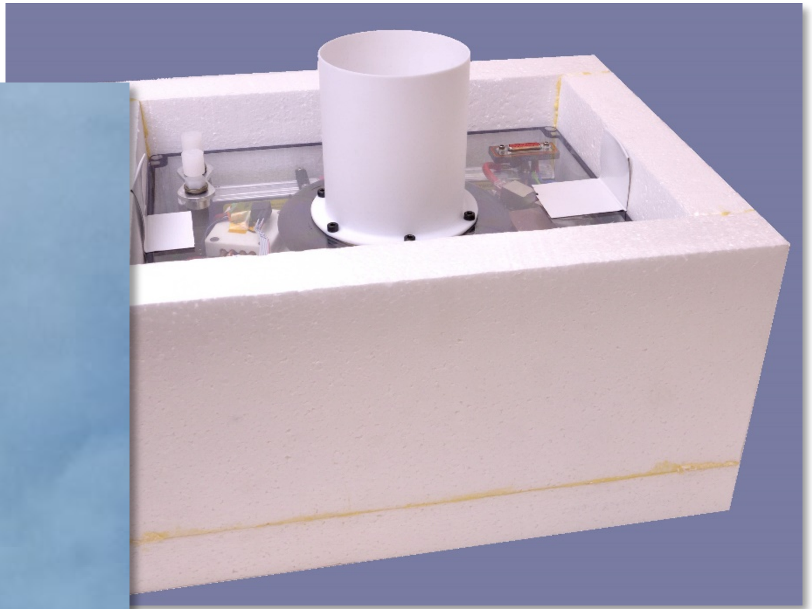
Accuracy:
2 %

First Balloon Flight from GRUAN Station Lindenberg

Parallel ascent of the novel QCLAS and CFH



- Max. altitude: 28 km
- Ascent and descent measurement
- 1 Hz (5 m) resolution
- Stable measurements even at $T_{outside}$ = -60 °C



Test Flights from MO Lindenberg

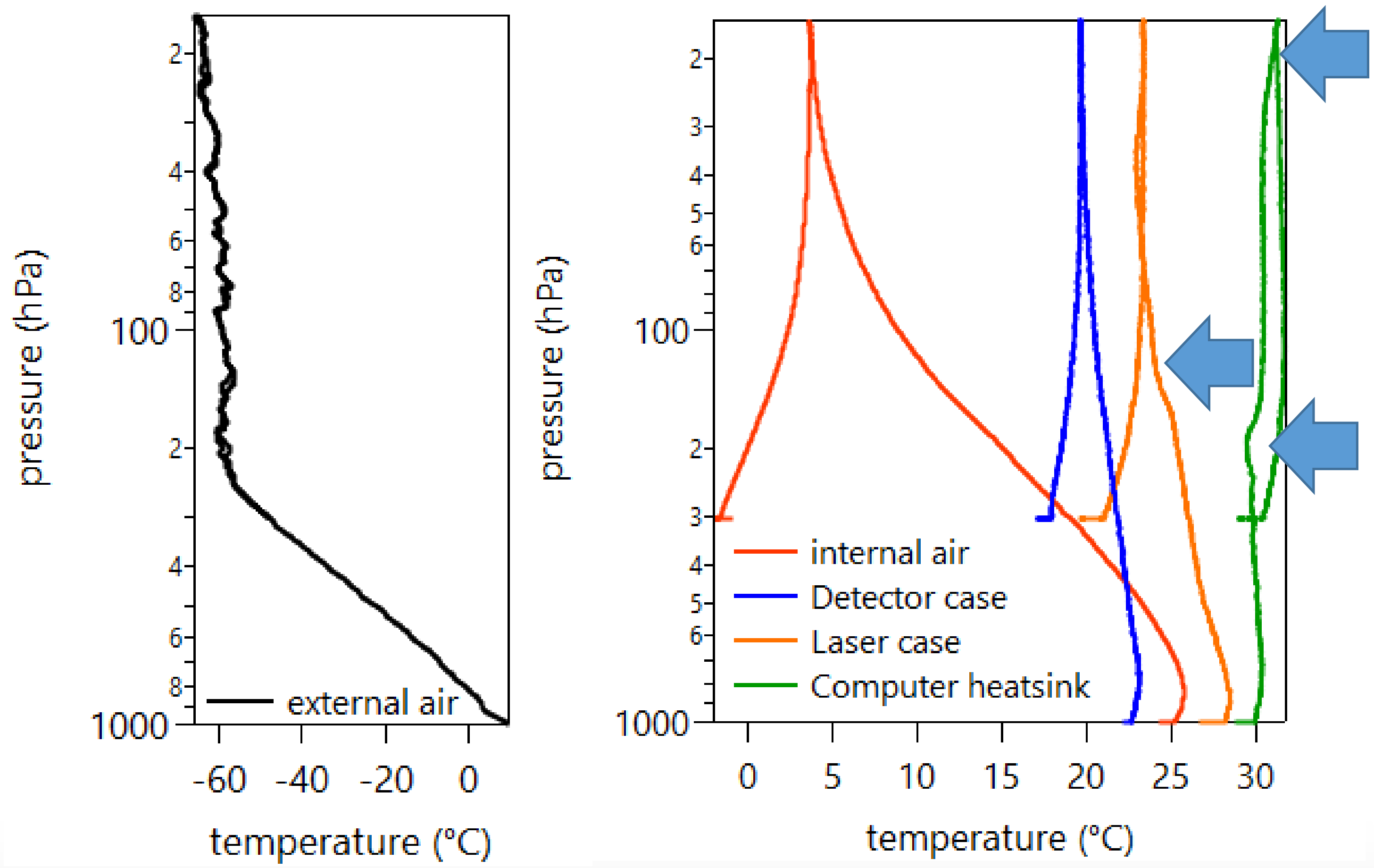
QCLAS ready for liftoff

Hooked on

Landing site

Test Flights from MO Lindenberg

- Temperature stability during flight



Critical electronics are contacted to **phase change material (PCM)** which increase the thermal inertia of the system and lead to a characteristic kink in the temperature evolution.

ΔT of the external air:
73 K

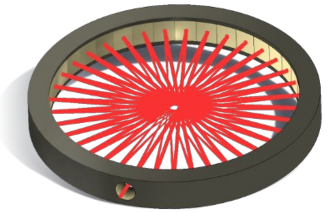
ΔT of laser-chip:
19 mK

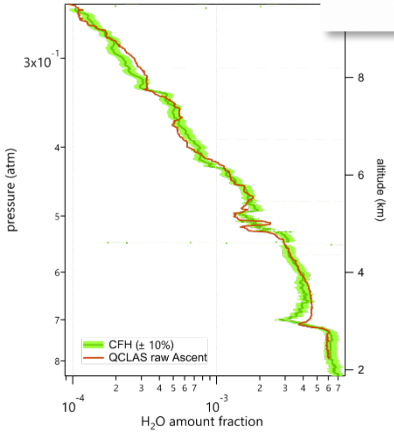
Conclusions

- **Integrated, standalone QCL spectrometer of 3.8 kg**
  - using SC-MPC to miniaturize the optical setup
  - specifically developed electronics

- **In-lab precision of 0.03% and 2% accuracy**

- **First-ever balloon-borne QCL spectrometer in the UTLS**
  - Excellent accuracy in the troposphere
  - Good relative agreement to CFH in the stratosphere





Further details in:

Graf et al., Mid-IR Laser Spectrometer for Balloon-borne Water Vapor Measurements in the UTLS, 2020, *in preparation for AMT*

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Resources

Empa
Materials Science and Technology

- B. Buchholz, A. Afchine, A. Klein, C. Schiller, M. Krämer, and V. Ebert. HAI, a new airborne, absolute, twin dual-channel, multi-phase TDLAS-hygrometer: Background, design, setup, and first flight data.
  Atmos. Meas. Tech., 10(1):35–57, 2017.

- M. Fischer, B. Tuzson, A. Hugi, R. Brönnimann, A. Kunz, S. Blaser, M. Rochat, O. Landry, A. Müller, and L. Emmenegger. Intermittent operation of QC-lasers for mid-IR spectroscopy with low heat dissipation: tuning characteristics and driving electronics.
  Opt. Express, 22(6):7014–7027, 2014

- M. Graf, L. Emmenegger, and B. Tuzson. Compact, circular, and optically stable multipass cell for mobile laser absorption spectroscopy.
  Opt. Lett., 43(11):2434–2437, 2018

- C. Liu, B. Tuzson, P. Scheidegger, H. Looser, B. Bereiter, M. Graf, M. Hundt, O. Aseev, D. Maas, and L. Emmenegger. Laser driving and data processing concept for mobile trace gas sensing: Design and implementation.
  Rev. Sci. Instrum., 89(6), 2018.

- A. Lykov, V. Yushkov, S. Khaykin, V. Astakhov, and V. Budovich. New version of balloon hygrometer for in situ water vapour measurements in the upper troposphere and lower stratopshere (FLASH-BM).
  Eur. Sp. Agency, (Special Publ. ESA SP), 700 SP:341–345, 2011

- A. W. Rollins, T. D. Thornberry, R. S. Gao, J. B. Smith, D. S. Sayres, M. R. Sargent, C. Schiller, M. Krämer, N. Spelten, D. F. Hurst, A. F. Jordan, E. G. Hall, H. Vömel, G. S. Diskin, J. R. Podolske, L. E. Christensen, K. H. Rosenlof, E. J. Jensen, and D. W. Fahey. Evaluation of UT/LS hygrometer accuracy by intercomparison during the NASA MACPEX mission.
  J. Geophys. Res. Atmos., 119(4):1915–1935, 2014

- H. Vömel, T. Naebert, R. Dirksen, and M. Sommer. An update on the uncertainties of water vapor measurements using Cryogenic Frostpoint Hygrometers.
  Atmos. Meas. Tech. Discuss., 9:3755–3768, 2016.