Metrology meets Meteorology

CITAC: 2014 Best Paper award presentation

for

Applied Physics B 116:883–899 (2014)

Absolute validation of a diode laser hygrometer via
intercomparison with the German national primary water vapor standard

by

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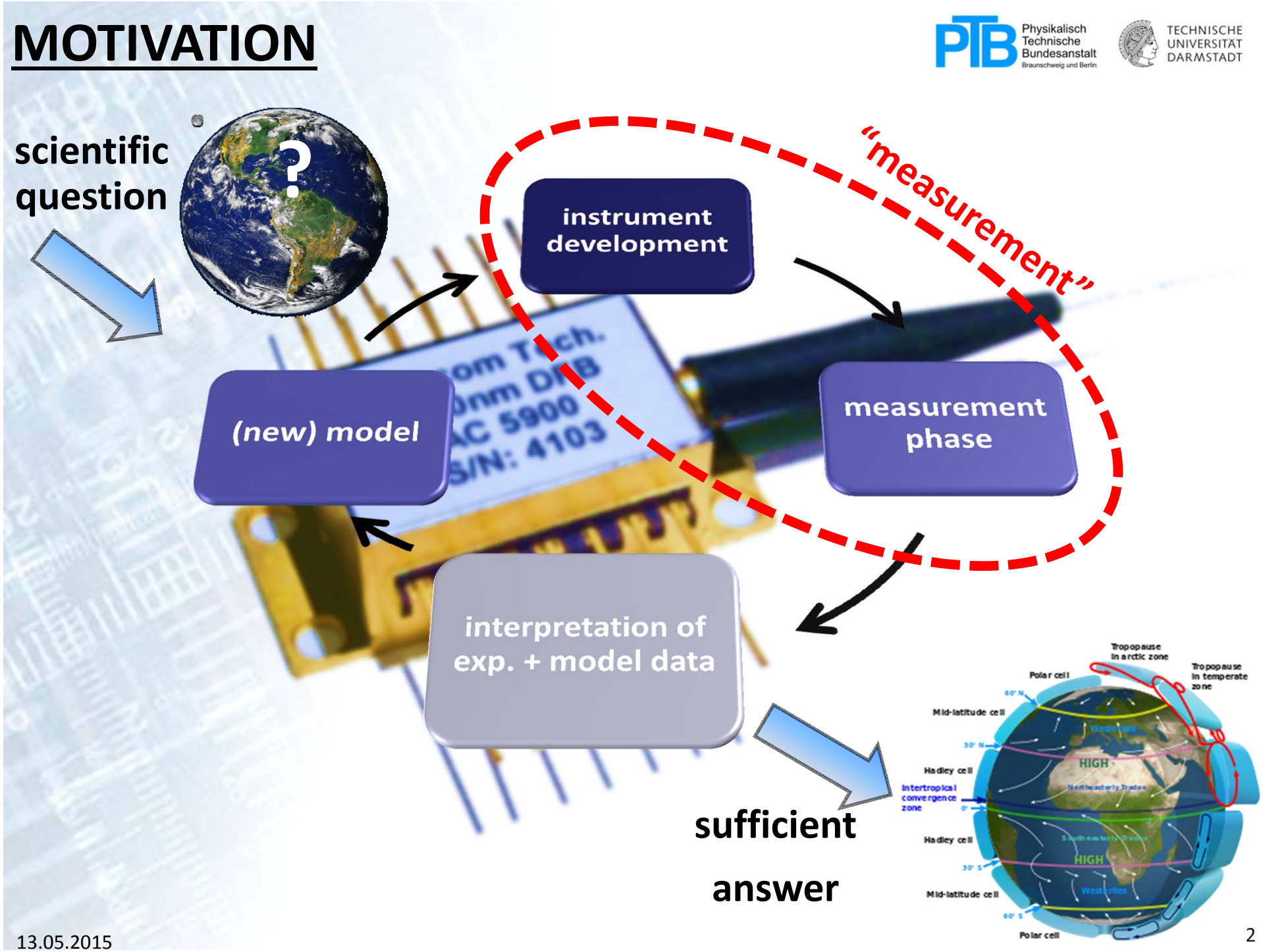
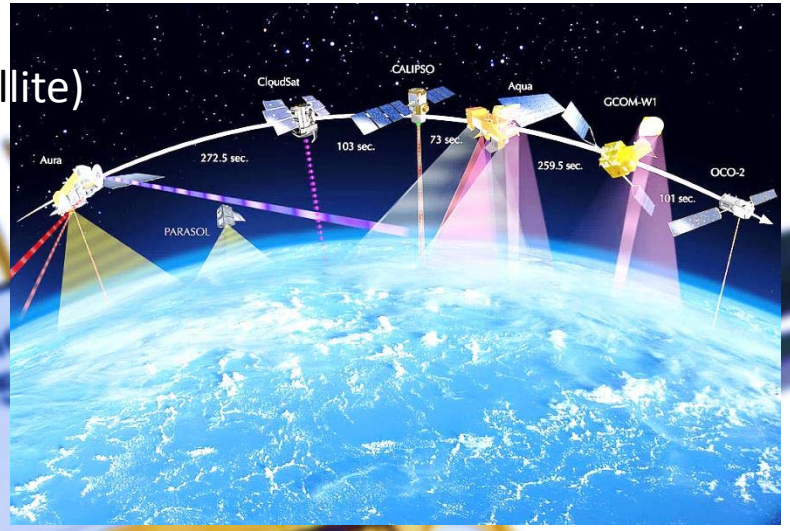
30th CITAC members meeting , 19 April 2015

MOTIVATION


scientific question
?
instrument development
"measurement"
(new) model
measurement phase
interpretation of exp. + model data
sufficient answer
Tropopause in arctic zone
Tropopause in temperate zone
Polar cell
Mid-latitude cell
Hadley cell
Intertropical convergence zone
Hadley cell
Mid-latitude cell
Polar cell
HIGH
HIGH

MEASUREMENTS
in atmospheric science

Remote sensing (ground /satellite)
validation
via
Airborne
In situ
measurements



lab input
(e.g. spectral ref data)
for
remote sensing

lab input
(e.g. spectral data)
and
lab validation
for
in-situ instrument

QUALITY of “field measurements” ?

Field instruments: Need for pragmatic solution ⇒ often far away from “metrology”

- link to the SI units ?
- traceability in general ?
- common evaluation, calibration, interpretation strategies ?
- well defined uncertainties calculations ?

Our focus: ⇨ **Improving atmospheric water vapor measurements**

Water vapor in environmental sciences/meteorology :

- very important for
  - atmospheric radiative balance (most **important greenhouse gas**)
  - Important **correction factor** for many other **atmospheric sensing techniques** (strongest atmospheric constituent with the highest variability)
  - very important **simulation parameter** for **climate models**
  - atmospheric chemistry (⇒ OH)
  - Cloud + aerosol formation (phase transition water/ice)
  - Weather + agriculture industry
  - …

BUT:

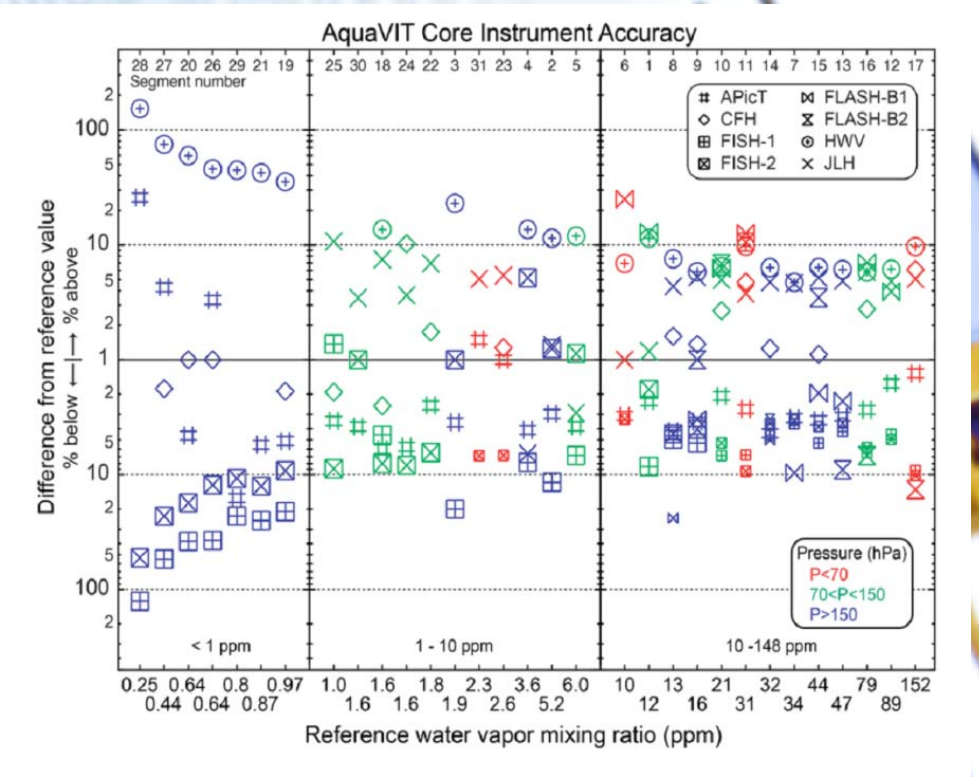
- even in static H_2O lab conditions ± **10% inconsistency** = “state of the art”
- in airborne campaigns: local, dynamic deviations up to **30%** are not unusual

WHY is there a need for improvement ?

(in airborne hygrometry)

e.g. AquaVIT-I in 2008

(blind comparison of world best airborne hygrometer)



(D. W. Fahey et al, AMTD, 2014)

→ **Inconsistency span: 20%**

reanalysis + correction of huge data sets

(e.g. MOZAIC)

Atmos. Chem. Phys. Discuss., 14, 18905–18942, 2014
www.atmos-chem-phys-discuss.net/14/18905/2014/
doi:10.5194/acpd-14-18905-2014

Atmospheric Chemistry and Physics Discussions
Open Access

This discussion paper is/has been under review for the journal Atmospheric Chemistry and Physics (ACP). Please refer to the corresponding final paper in ACP if available.

Technical Note: Reanalysis of upper troposphere humidity data from the MOZAIC programme for the period 1994 to 2009

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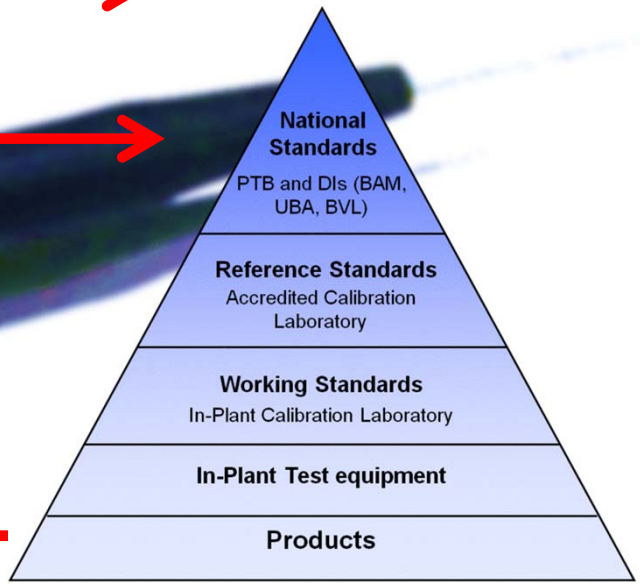
OUR philosophy

Meteorology ← **HOW TO LINK ?** → **Metrology**

?



Direct operation of an metrological airborne transfer standard in the field , i.e. on board of an research aircraft

STATE of development in 2011

(awarded paper)

Appl Phys B (2013) 110:249–262
DOI 10.1007/s00340-012-5143-1

Applied Physics B
Lasers and Optics

named "SEALDH – 0"

Validation of an extractive, airborne, compact TDL spectrometer for atmospheric humidity sensing by blind intercomparison

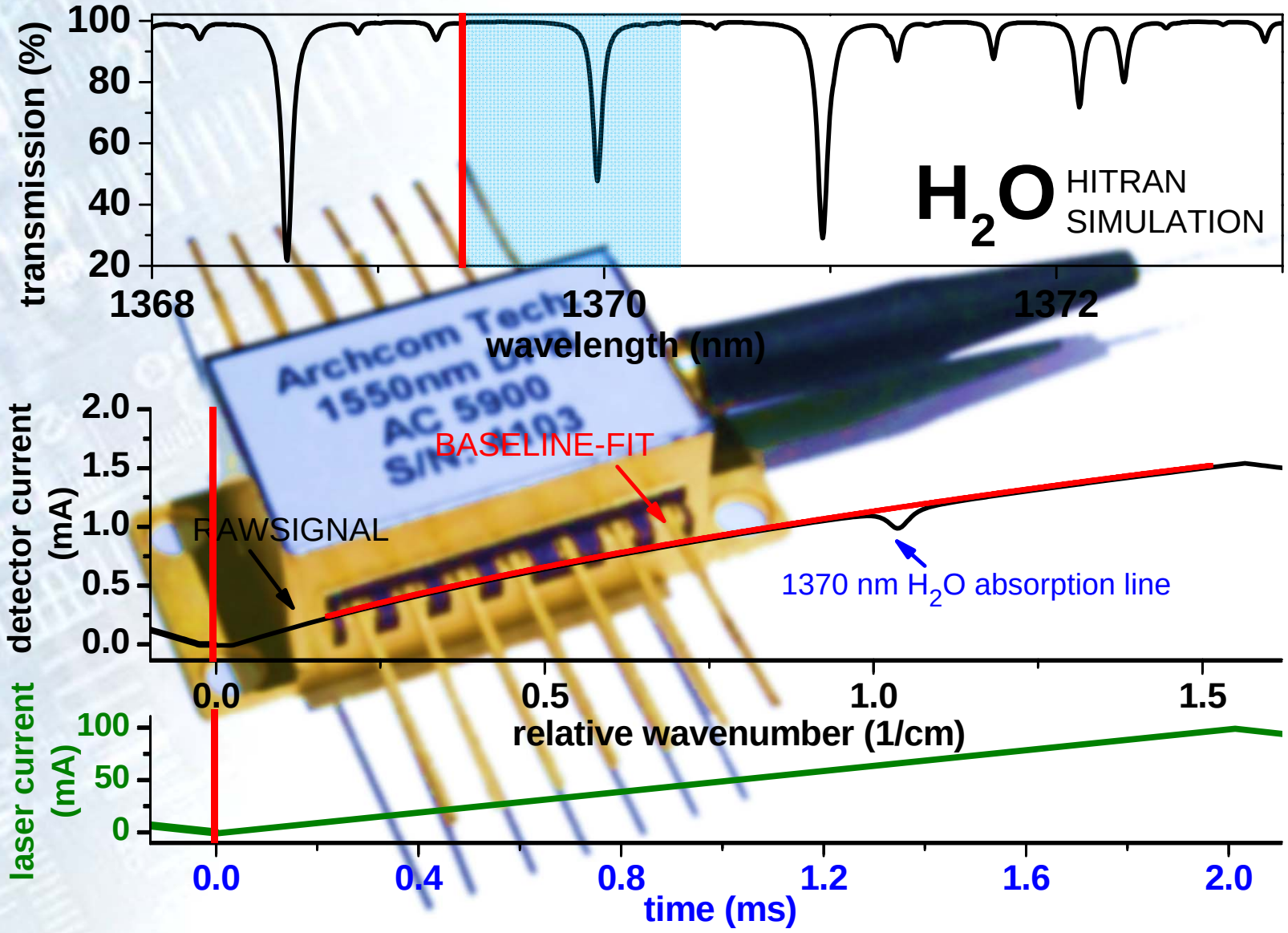
B. Buchholz · B. Kühnreich · H.G.J. Smit · V. Ebert

Received: 20 February 2012 / Revised version: 26 May 2012 / Published online: 7 September 2012

Abstract Accuracy, precision, repeatability and long-term stability, are the most important requirements to enable reliable airborne humidity measurements, which are needed for climate models or to validate e.g. remote sensing instrumentation like satellites. However, various hygrometer artifacts which depend on the individual sensor principle and the application profile frequently cause problems and significantly complicate the hygrometer choice. Sensor inter-

800 hPa, 10 to 8000 ppmv H_2O). Its absolute accuracy was investigated via blind intercomparison with two reference FPHs and a LAFH. Without any calibration of SEALDH, i.e. without a comparison to a water vapor standard, we achieve an excellent agreement with the reference sensors, with an average systematic offset (over all three days) of $-3.9\ \% \pm 1.5\ \%$, which is fully consistent with the sensor's uncertainty bounds.

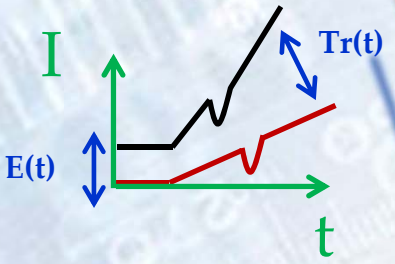
TDLAS PRINCIPLE

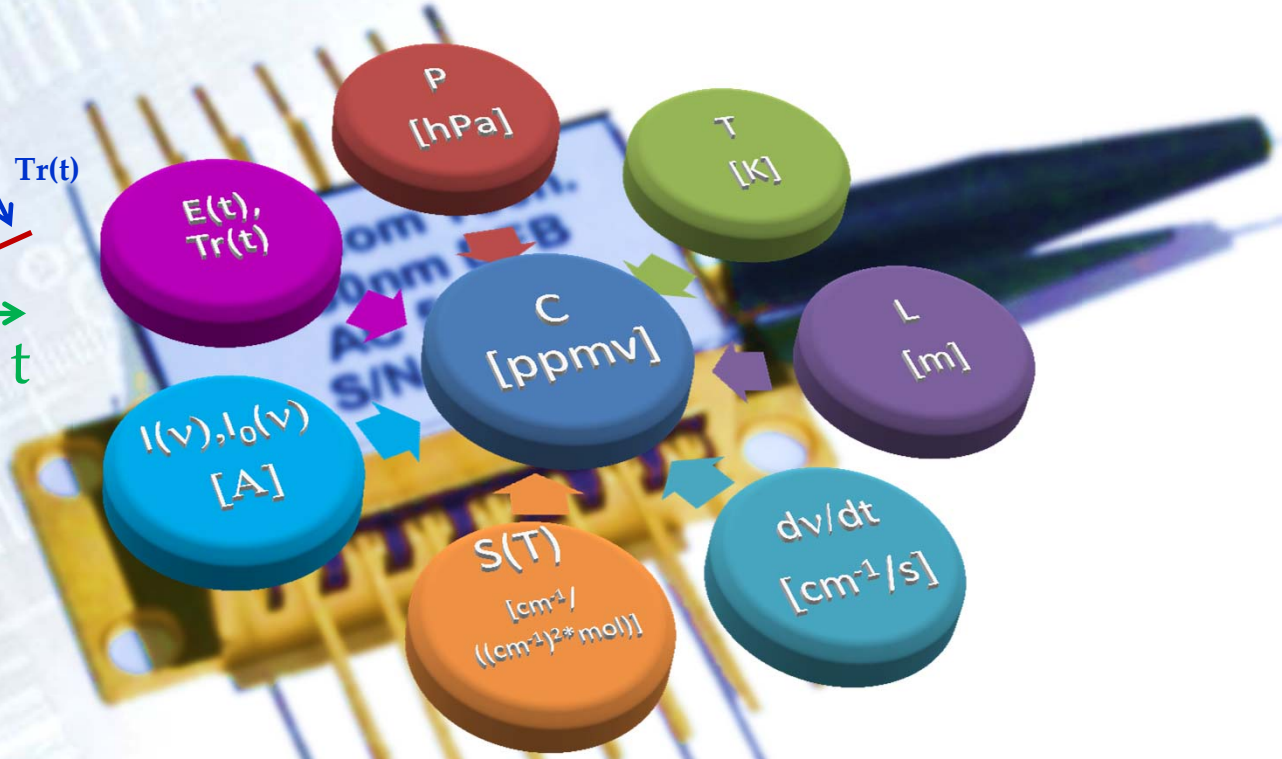


DIRECT TDLAS EVALUATION

Extended Lambert-Beer-law

$$I(\lambda) = E(t) + I_0(\lambda) \cdot Tr(t) \cdot exp[-S(T) \cdot g(\lambda - \lambda_0) \cdot N \cdot L]$$





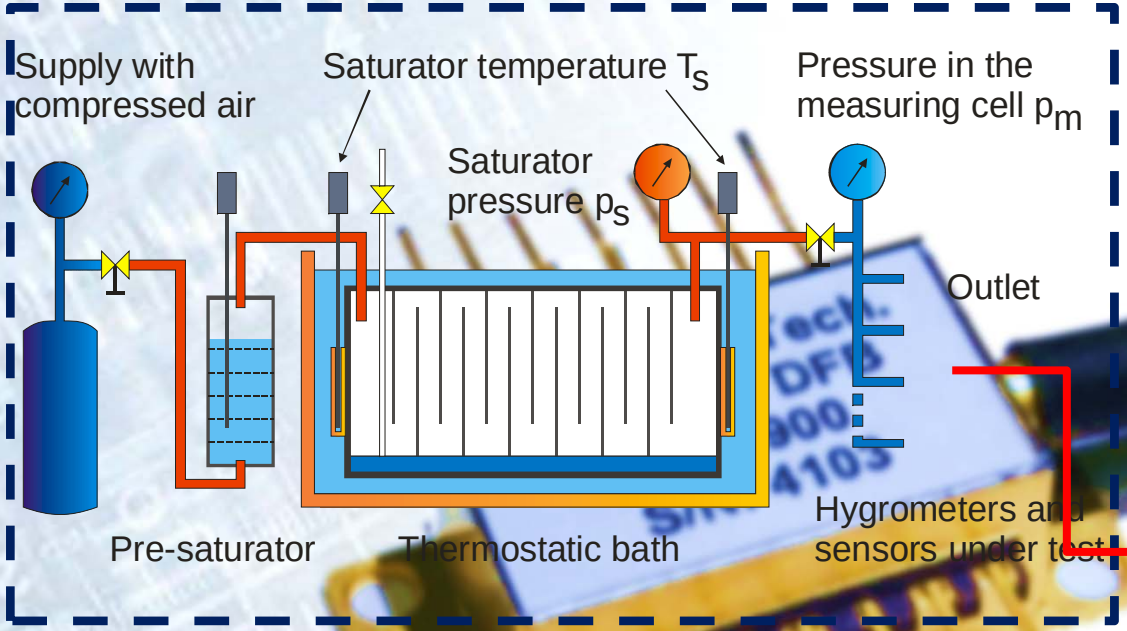
with ideal gas law: $c = \frac{k_B \cdot T}{S(T) \cdot L \cdot p} \int ln\left(\frac{I(\nu) - E(t)}{I_0(\nu) \cdot Tr(t)}\right) \frac{d\nu}{dt} dt$

measured parameters
constants
molecular line data

⇨ calibration free! …no need for calibration procedures … just validation

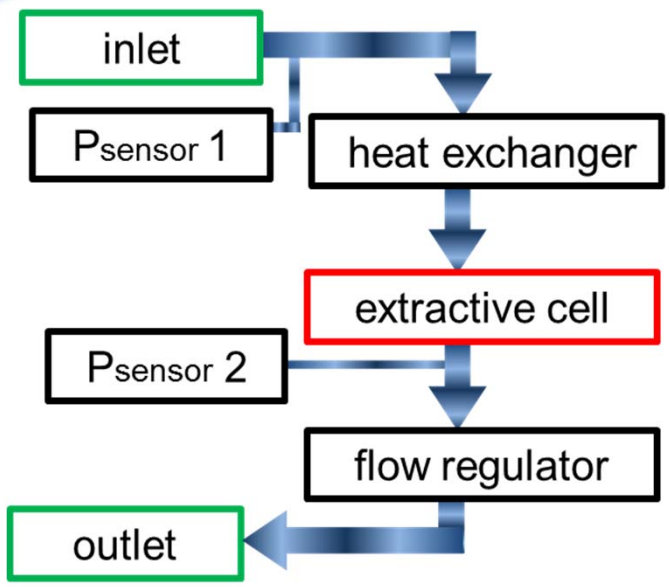
Intercomparison Setup

H_2O-SOURCE (National Primary Standard)



TDLAS-instrument (SEALDH-0)

- **1.4 µm Absorption Spectroscopy**
- **extractive, closed-path**
- **novel in-house development**
- **Absolute 1st principles instrument**
  - **No calibration needed !**



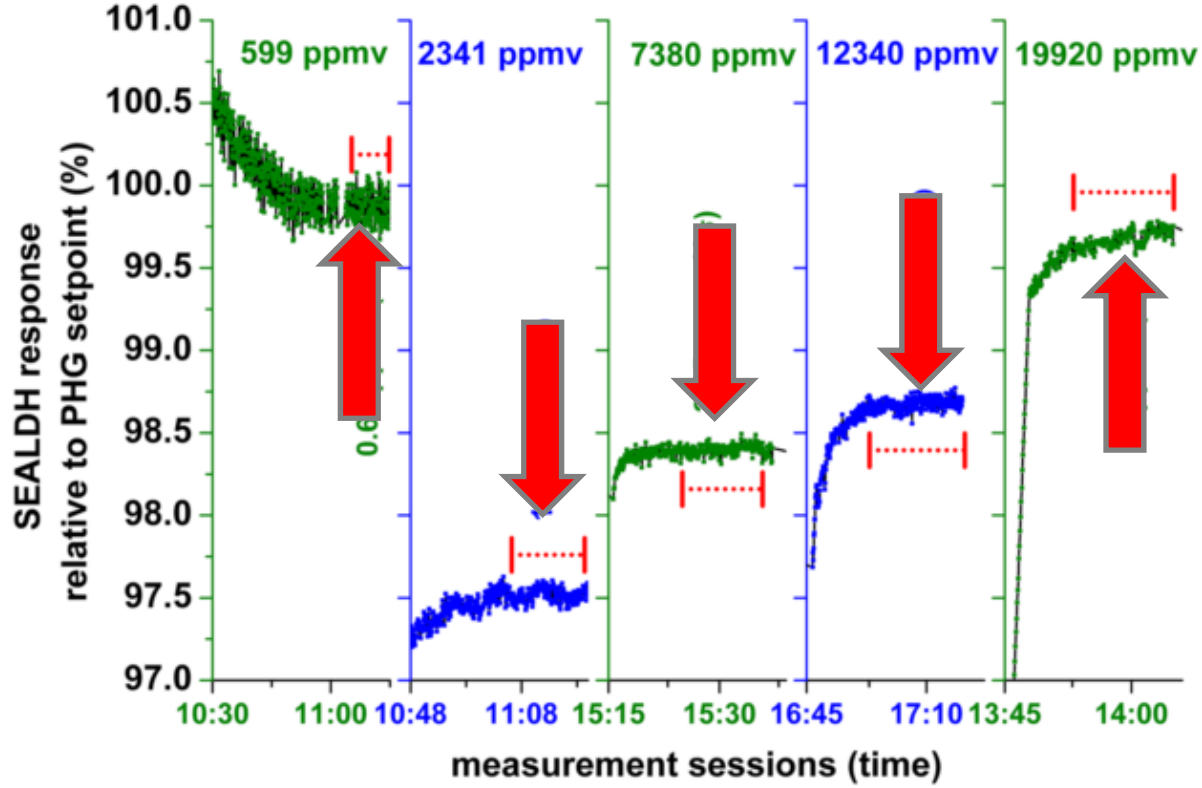
Validation Procedure

Physikalisch Technische Bundesanstalt Braunschweig und Berlin

TECHNISCHE UNIVERSITÄT DARMSTADT

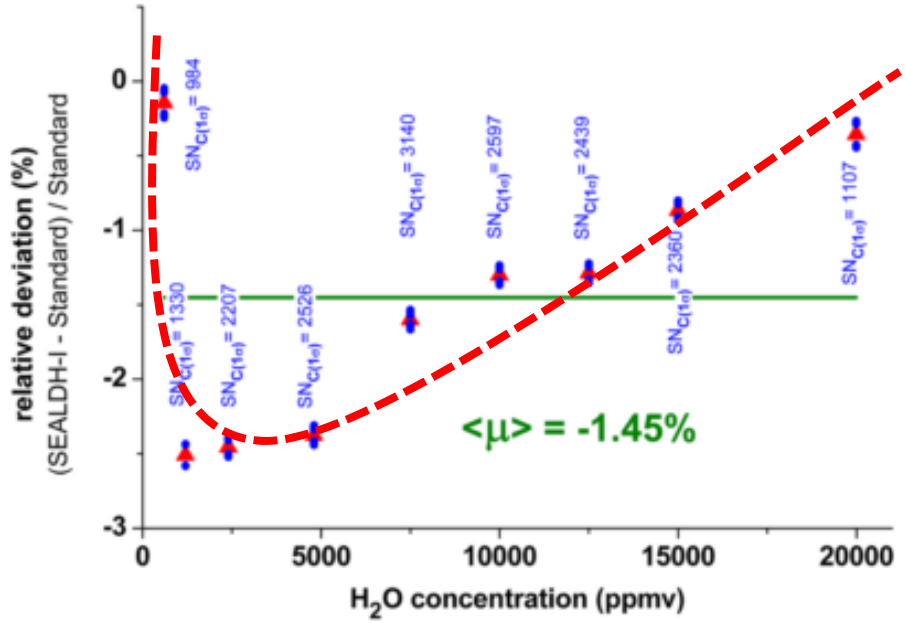
here: 5 different H_2O concentration levels during validation

B. Buchholz et al.

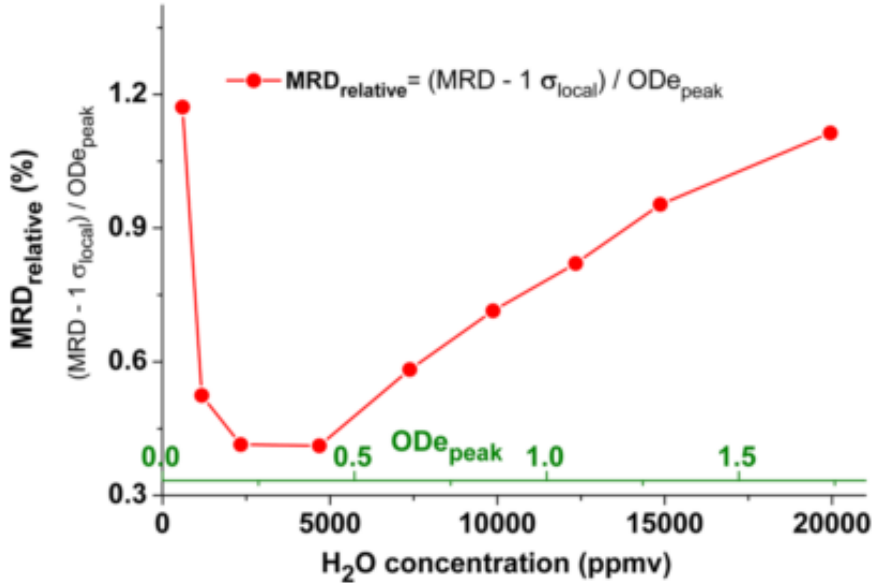


RESULT

relative deviation from primary standard



Sophisticated further explanation



deviations explainable as spectroscopic effect

➔ see awarded paper

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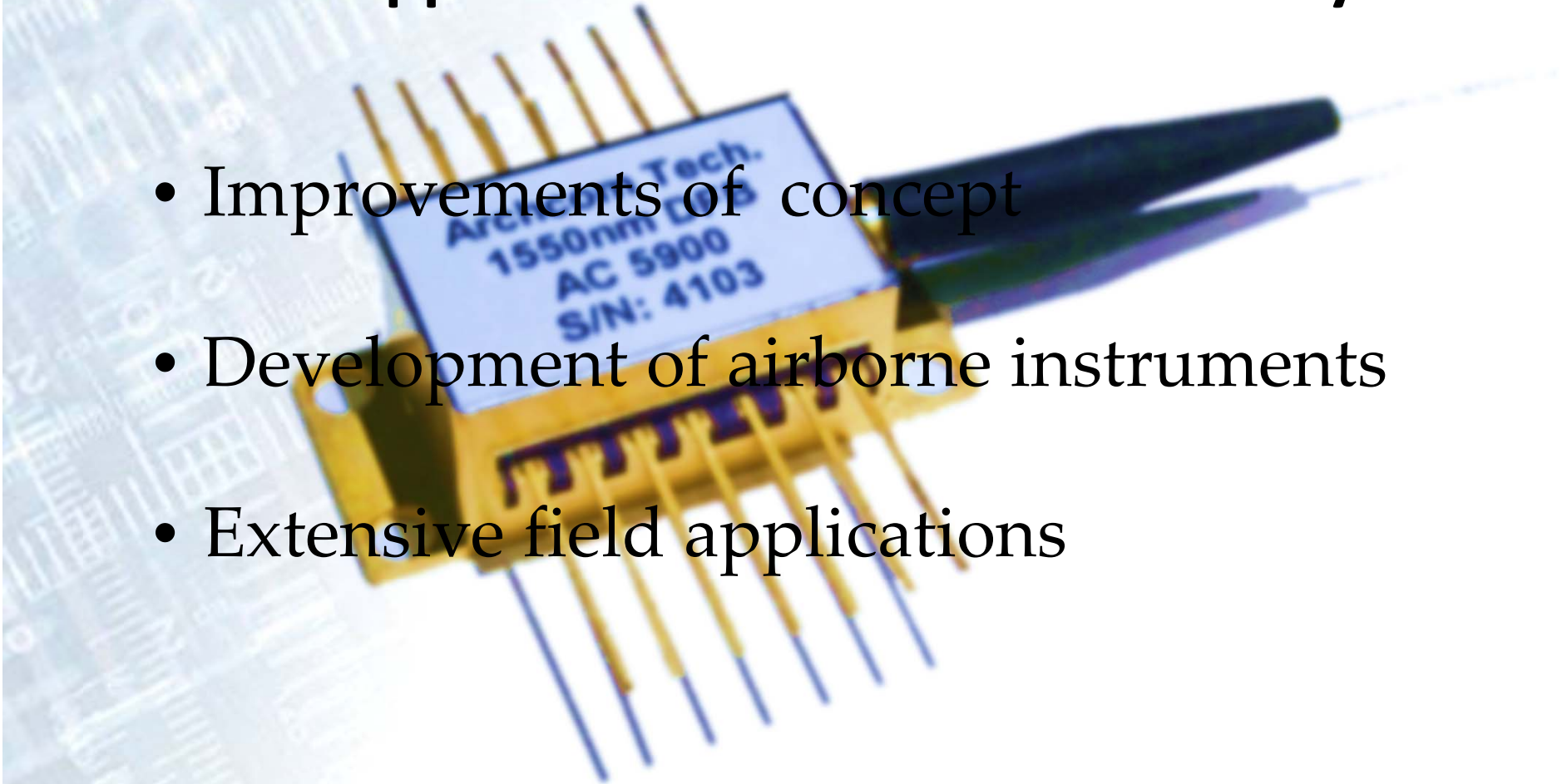
WHAT happened between 2011 und today ?



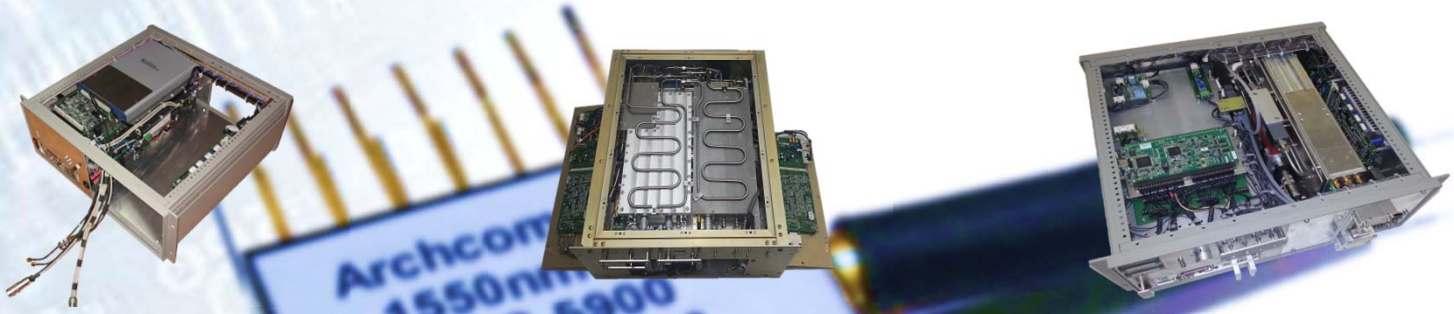
- Improvements of concept
- Development of airborne instruments
- Extensive field applications

2014 development status

New family of calibration-free, airborne H_2O transfer standards

SEALDH-0 => SEALDH-I; SEALDH-II; HAI-Ia; HAI-Ib

= CITAC Award



SEALDH-II

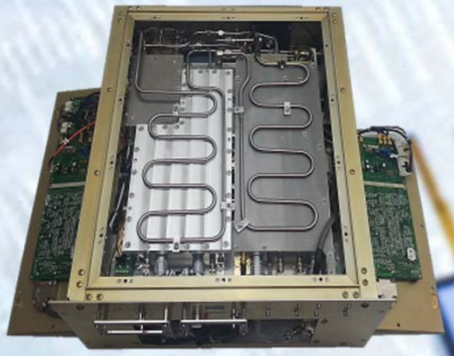
Selective Extractive Airborne Laser Diode Hygrometer

New, completely own development

- ✓ New **autonomous**, airborne, extractive, closed-path, absolute 1.4 µm **FIELD** TDL Hygrometer
  1st principles = calibration-free
- ✓ Metrological uncertainty: **4.3% , ± 3 ppmv**
- ✓ **< 3 % deviation to National Primary Standard** (over UTLS pressure range 200 - 1000 hPa)
- ✓ Extremely temperature stable **< 0.02% / K**
- ✓ ⇒ Very long-term stable **< 0.2% in 18 month**

CURRENT status

HAI: *Hygrometer for Atmospheric Investigations*

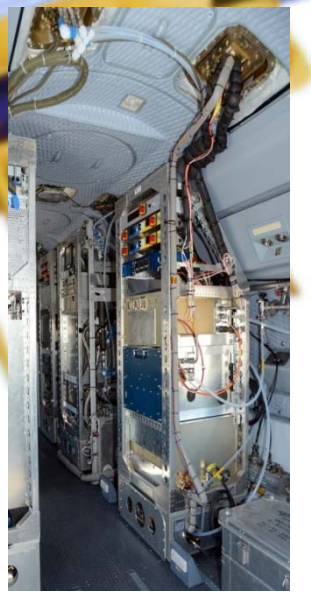


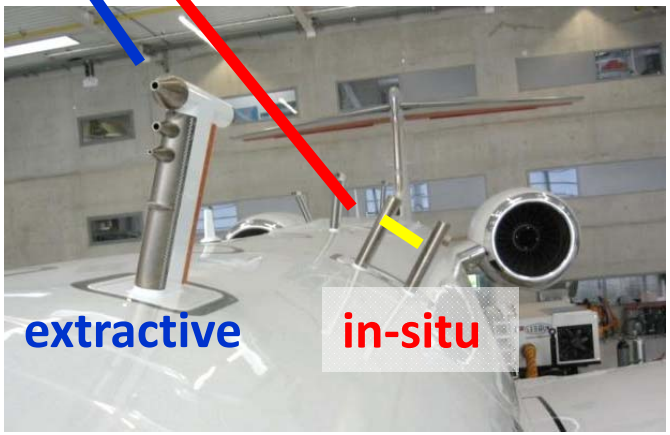
- new airborne multi-channel TDL Hygrometer

- highly accurate
- highly precise < 0.033 ppmv
- Very high speed: up to 120 Hz
- very large dynamic range 1- 40000 ppmv

- 1st airborne multi-phase instrument:
  vapor , total and ice water

- self validating, 1st principles = calibration-free
- Metrological uncertainty



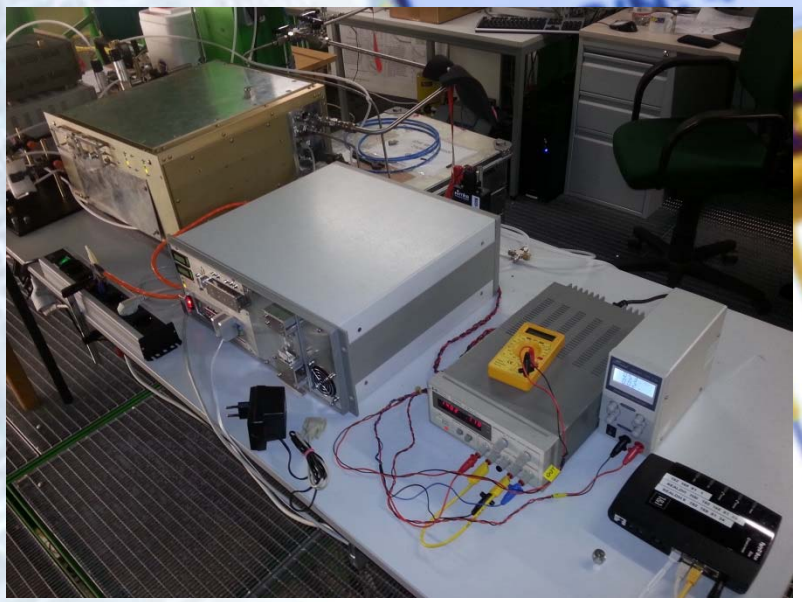


Extensive Field Applications

…many laboratory and airborne comparisons & campaigns

EUFAR DENCHAR (FZJ)
PHG-Comparison (PTB)
THG-Comparison (PTB)
AquaVIT-II (KIT)

EUFAR DENCHAR IFIC (LearJet 35A)
AIRTOSS-ICE – I (LearJet 35A)
AIRTOSS-ICE – II (LearJet 35A)
TACTS (Gulfstream G550)
ESMval (Gulfstream G550)
ML-CIRRUS (Gulfstream G550)
ACRIDICON (Gulfstream G550)



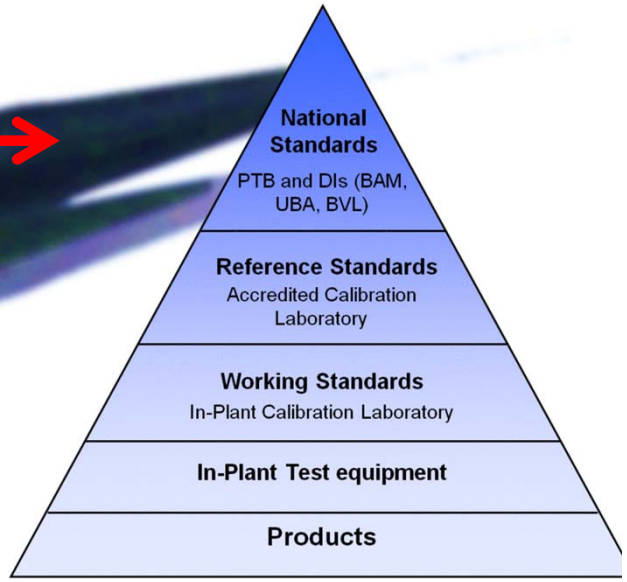
⇒ **metrology meets meteorology requirement for field applicability**

CONCLUSION

Meteorology

SEALDH-0
SEALDH-I
SEALDH-II
HAI-Ia
HAI-Ib

Metrology



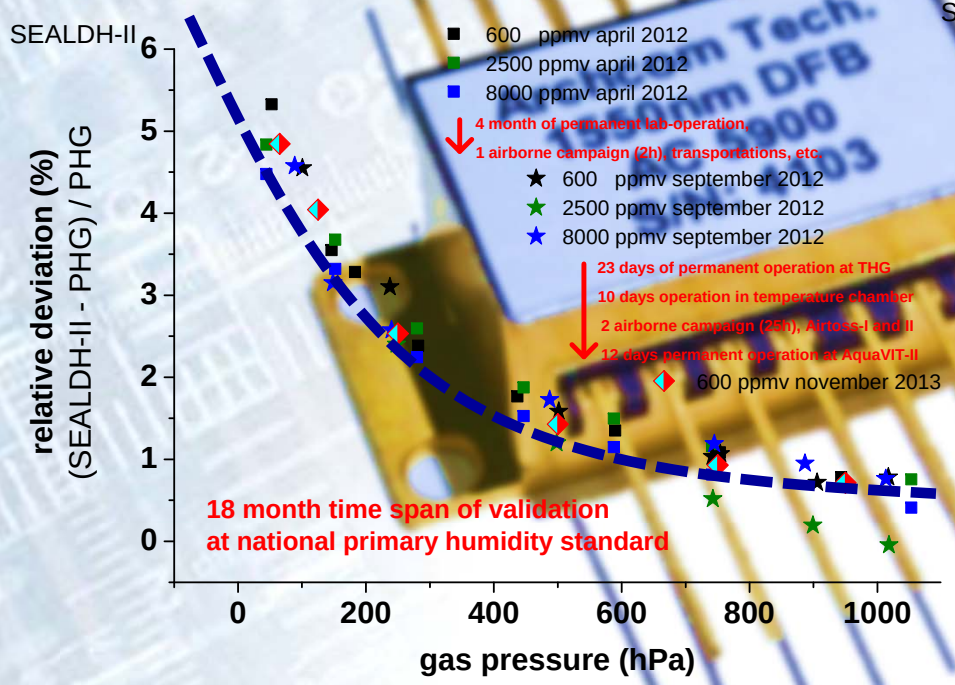
Linking Metrology and Meteorology on the highest level …
..while taking into account all typical airborne restrictions and requirements - such as:
Robustness, low maintenance, stand-alone, high reliability, …
highly accurate and fast measurements, …
airborne certification issues, ...

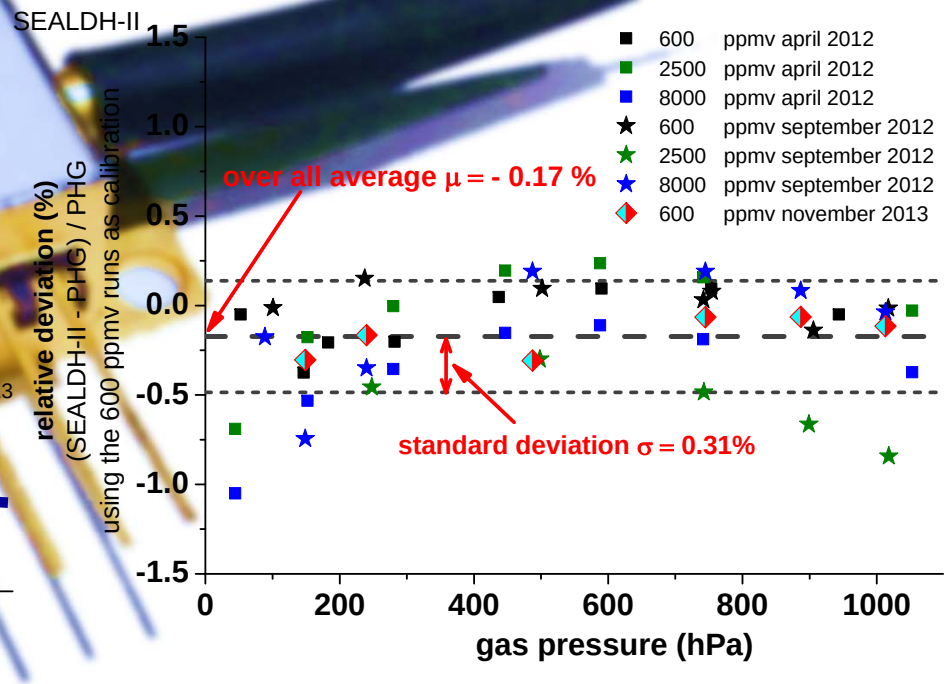
OUTLOOK (unpublished further validation)

long-term accuracy validation at mid humidity

again at primary standards

⇒ 18 month validation in three sessions





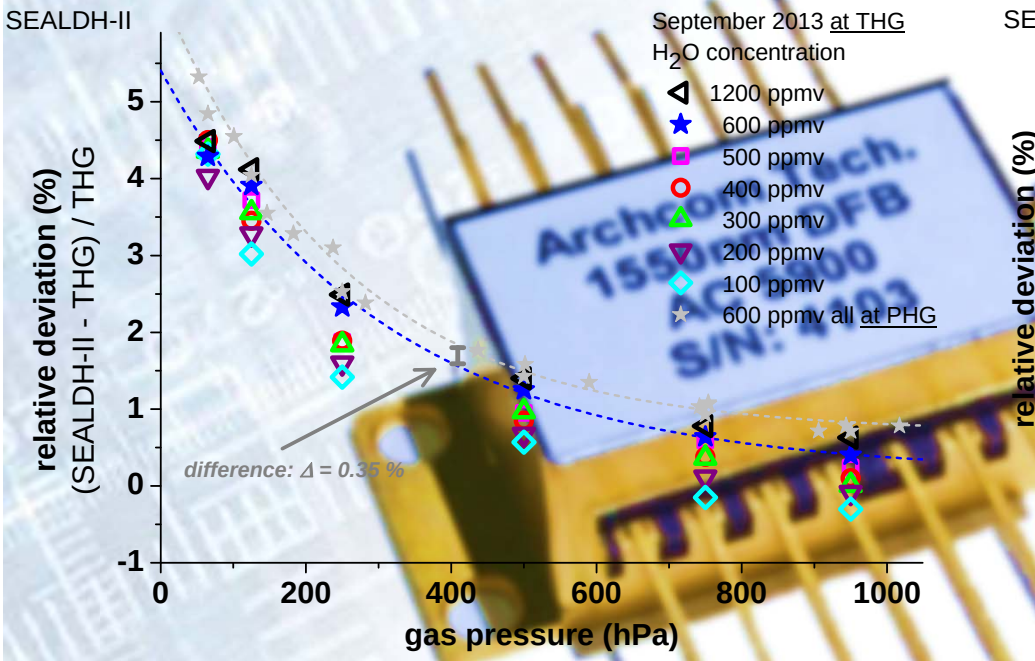
All SEALDH-II data are evaluated <u>without</u> any calibration !

18 month long-term stability:
(600-8000 ppmv, 65-1000hPa)
μ = -0.17% and σ = 0.31%

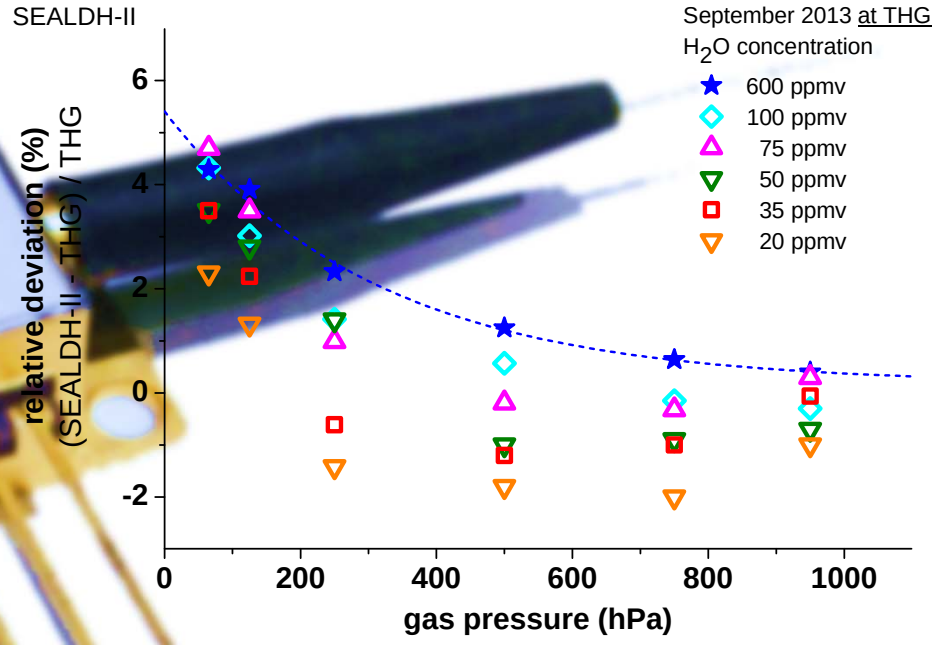
OUTLOOK (unpublished further results)

at traceable low H_2O Standard

100 - 1200 ppmv



20 - 100 ppmv



How to guarantee the accuracy under flight conditions ?

Full Instrument control

- online supervision of instrument status
- pro active inclusion of field testing and validation schemes

Full Validation

- robust metrological analysis
- field equivalent lab tests

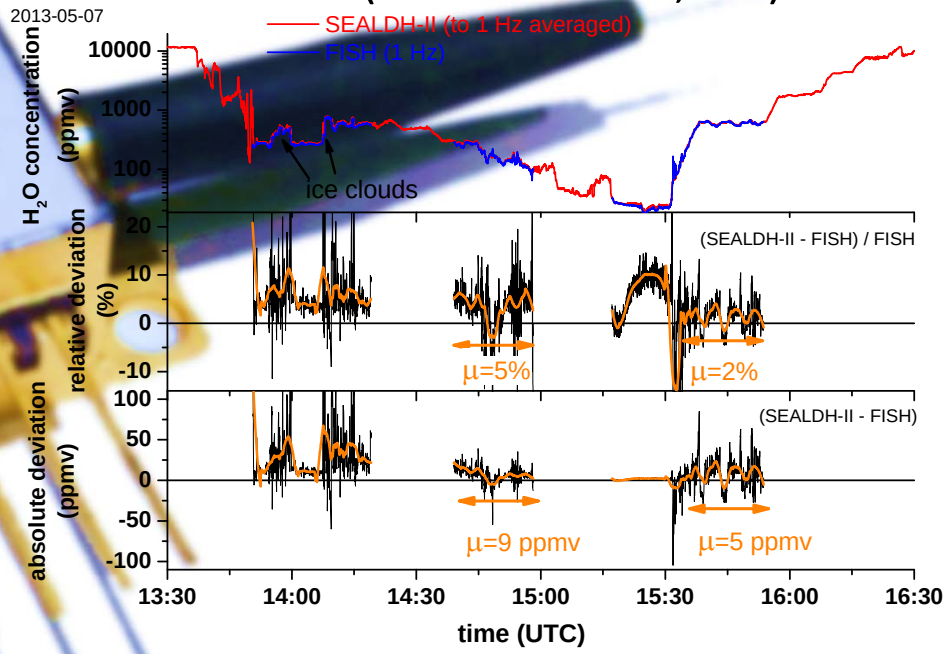
HOW does the data look like in detail ?

airborne operation of hygrometer

SEALDH-II is our new, airborne, calibration-free, wide range TDLAS hygrometer
(TDLAS = tunable diode laser absorption spectroscopy)

WVSS-II (PI: H. G. J. Smit, FZJ)

FISH (PI: M. Krämer, FZJ)



"uncertainties" & "errors"

SEALDH-II (4.3% ± 3 ppmv) Range 0-40000 ppmv 0-1200hPa

FISH (6% ± 0.15 ppmv) Range 0-1000 ppmv 0-500hPa

WVSS-II (5% ± 50 ppmv) Range 50-40000 ppmv 200-500hPa