Metrology meets Meteorology

CITAC: 2014 Best Paper award presentation for
Absolute validation of a diode laser hygrometer via intercomparison with the German national primary water vapor standard
by
B. Buchholz\textsuperscript{1,2}, N. Böse\textsuperscript{1}, V. Ebert\textsuperscript{1,2}

\textsuperscript{1}Physikalisch-Technische Bundesanstalt Braunschweig, Germany
\textsuperscript{2}Center of Smart Interfaces, Technische Universität Darmstadt, Germany

30th CITAC members meeting, 19 April 2015
MOTIVATION

scientific question

instrument development

measurement phase

(interpretation of exp. + model data

sufficient answer
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

13.05.2015
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 H₂O 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)
- reanalysis + correction of huge data sets (e.g. MOZAIC)

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

→ **Inconsistency span: 20%**
**OUR philosophy**

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

Direct operation of a metrological airborne transfer standard in the field, i.e. on board of a research aircraft.
STATE of development in 2011

(awarded paper)

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: 25 May 2012 / Published online: 7 September 2012
© The Author(s) 2011. This article is published with open access at Springerlink.com

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 H2O). 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 % ± 1.5 %, which is fully consistent with the sensor’s uncertainty bounds.

named “SEALDH – 0”
TDLAS PRINCIPLE

H2O HITRAN SIMULATION

RAW SIGNAL

BASELINE-FIT

1370 nm H2O absorption line

detector current (mA)

laser current (mA)

transmission (%)

wavelength (nm)

relative wavenumber (1/cm)

time (ms)

H2O

1368 1370 1372

178 20 40 60 80 100

119 91

wavelength (nm)

HITRAN

SIMULATION

TDLAS

PRINCIPLE

13.05.2015

B. Buchholz
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: \[ c = \frac{k_B \cdot T}{S(T) \cdot L \cdot p} \int ln \left( \frac{I(v) - E(t)}{I_0(v) \cdot Tr(t)} \right) \frac{dv}{dt} \, dt \]

measured parameters constants molecular line data

calibration free! ...no need for calibration procedures ... just validation
Intercomparison Setup

H₂O-SOURCE (National Primary Standard)

Supply with compressed air
Pre-saturator

Thermostatic bath

Saturator temperature Tₛ
Saturator pressure pₛ

Pressure in the measuring cell pₘ

Outlet

Hygrometers and sensors under test

TDLAS-instrument (SEALDH-0)
• 1.4 µm Absorption Spectroscopy
• extractive, closed-path
• novel in-house development
• Absolute 1ˢᵗ principles instrument
• No calibration needed!

interconnection:

Pressure

inlet

Pₘ

heat exchanger

extractive cell

flow regulator

outlet

Pₛ

13.05.2015
Validation Procedure

here: 5 different $\text{H}_2\text{O}$ concentration levels during validation

B. Buchholz et al.

13.05.2015 B. Buchholz
RESULT

relative deviation from primary standard

Sophisticated further explanation

deviations explainable as spectroscopic effect

⇒ see awarded paper

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 H₂O 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)

⇒ metrology meets meteorology requirement for field applicability
CONCLUSION

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, ...

13.05.2015

B. Buchholz
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 without any calibration!

18 month time span of validation at national primary humidity standard

18 month long-term stability: (600-8000 ppmv, 65-1000hPa)
\[ \mu = -0.17\% \text{ and } \sigma = 0.31\% \]
OUTLOOK (unpublished further results)

at traceable low H₂O Standard

100 - 1200 ppmv

September 2013 at THG
H₂O concentration

20 - 100 ppmv

September 2013 at THG
H₂O concentration

difference: Δ = 0.35 %
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)

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

**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

B. Buchholz