PTB‘s refractive index compensated absolute 3D laser meter

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Overview:

- Introduction
- Refractive index compensation
- 3D-Lasermeter (IFM mode)
- Results in air conditioned and harsh environment
- ADM mode of 3D-Lasermeter
- Results of ADM mode
- Conclusion

Introduction

- 3D metrology based on speed of light (laser tracker, LaserTracer) is affected by air refractive index

- In harsh environments several µm/m uncertainty is possible

- Within LUMINAR a device was proposed with:
  - 3D capability like a LaserTracer
  - intrinsic compensation of air refractive index
  - fringe counting mode (IFM) like LaserTracer
  - absolute distance measurement (ADM) mode like several laser trackers
  - uncertainty $10^{-7}\,l$, even in harsh conditions

- Result: 3D-Lasermeter

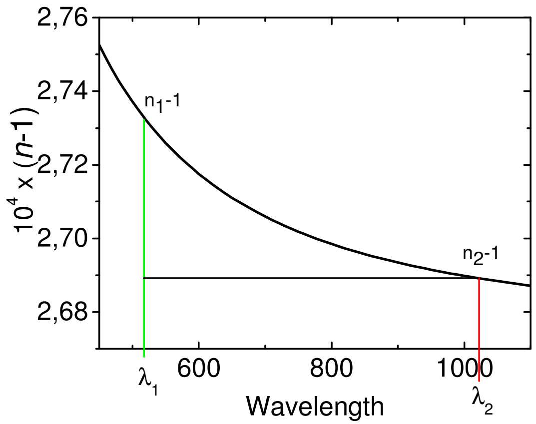
Standard Interferometry:

- Measurement of optical path l with frequency stabilised laser $\Rightarrow l_0 = n\,l$
- Measurement of temperature, air pressure, humidity, (CO_2) $\Rightarrow$ refractive index n
- Distance: $l = l_0/n$
- Uncertainties from measurement of air parameters:

Parameter	Refractive index change
Temperature Δt = +1 °C	-1×10^{-6}
Pressure Δp = +1 hPa	$+2.7 \times 10^{-7}$
Relative humidity ΔRH = +1 %	-1×10^{-8}

Refractive index compensated interferometry:

- Measurement of optical path with two wavelengths $\Rightarrow l_1, l_2$



- 1) $l = l_1 - A(l_2 - l_1)$, *A* constant (dry air)
  $A \approx 65$ for 532 nm + 1064 nm
  uncertainties in $(l_2 - l_1)$ are scaled by 65!

- 2) Measurement of partial pressure of water vapour $\Rightarrow p_w$
  Distance $l = f(l_1, l_2, p_w)$ (independent on temperature and pressure)

- 3) From $l_1 = n_1 l$ and l refractive index n_1 can be calculated: $n_1 = l_1 / l$
  From n_1, pressure p, and p_w the temperature can be derived

Refractive index compensation by two colour interferometry

Influence of changes in the air parameters:

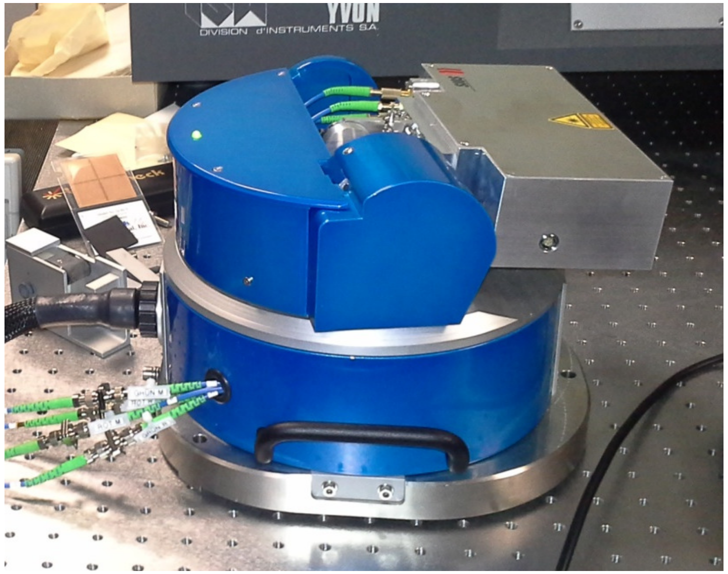
Parameter	**Standard**	**Compensated**
Temperature Δt = +1 °C	-1×10^{-6}	---
Pressure Δp = +1 hPa	$+2.7 \times 10^{-7}$	---
Relative humidity ΔRH = +1 %	-1×10^{-8}	-2.4×10^{-8}

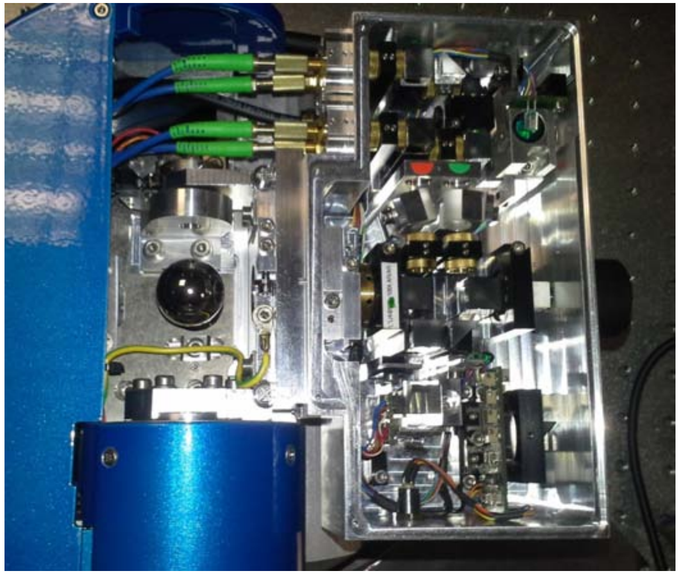
$\Rightarrow$ Theoretically independent on temperature and pressure, but more sensitive to relative humidity

$\Rightarrow$ Uncertainty enhanced by factor A: $l = l_1 - A(l_2 - l_1)$
(≈ 65 for “optical“ wavelengths, ≈ 21 for “synthetic wavelengths“ at 532 nm/1064 nm)

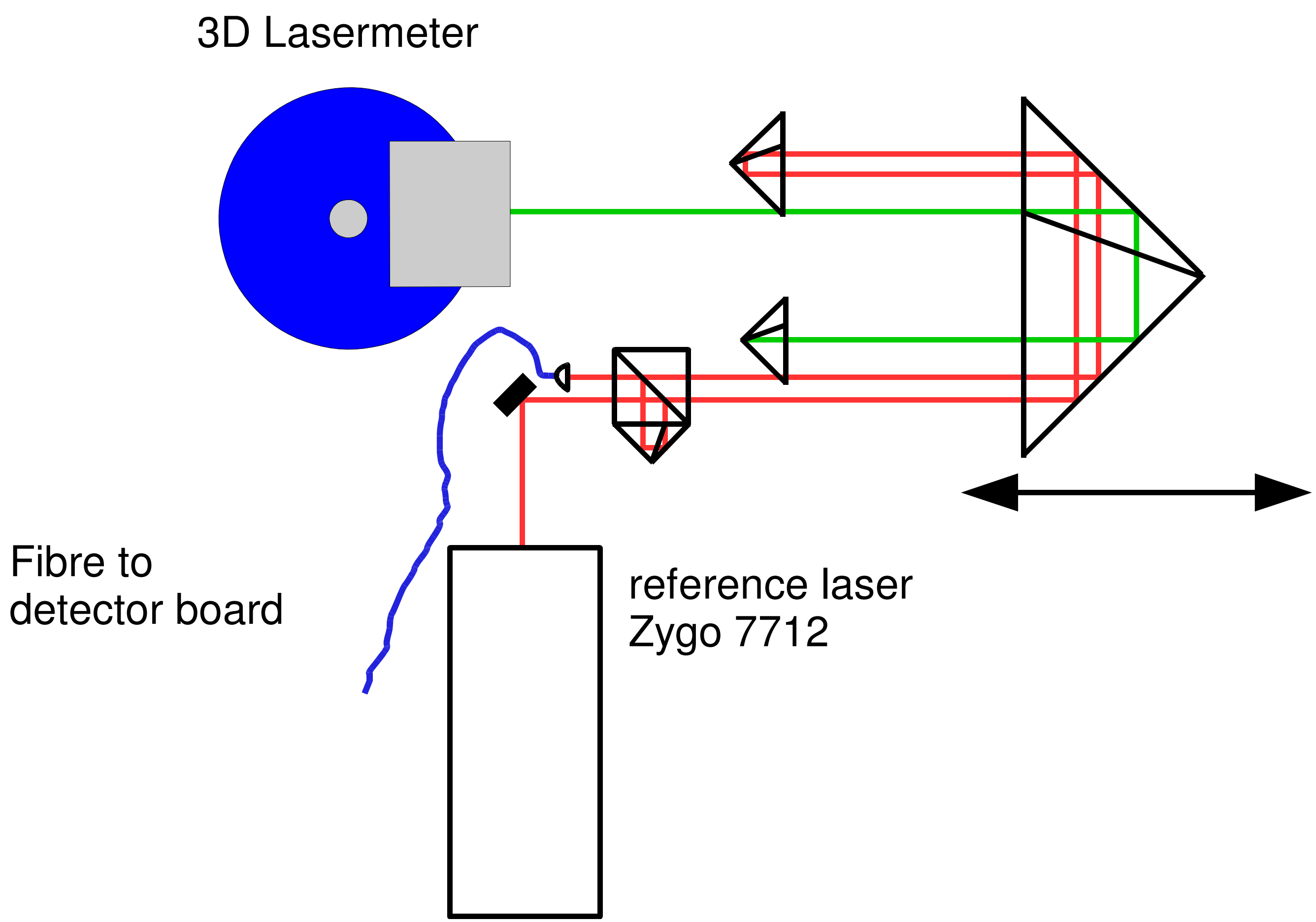
3D-Lasermeter

- Similar design like LaserTracer
- IFM mode: frequency doubled Nd:YAG laser (1064 nm + 532 nm)
- Frequency stabilised on Iodine absorption line
- Heterodyne interferometer





Comparison with PTB 50 m comparator (geodetic base)



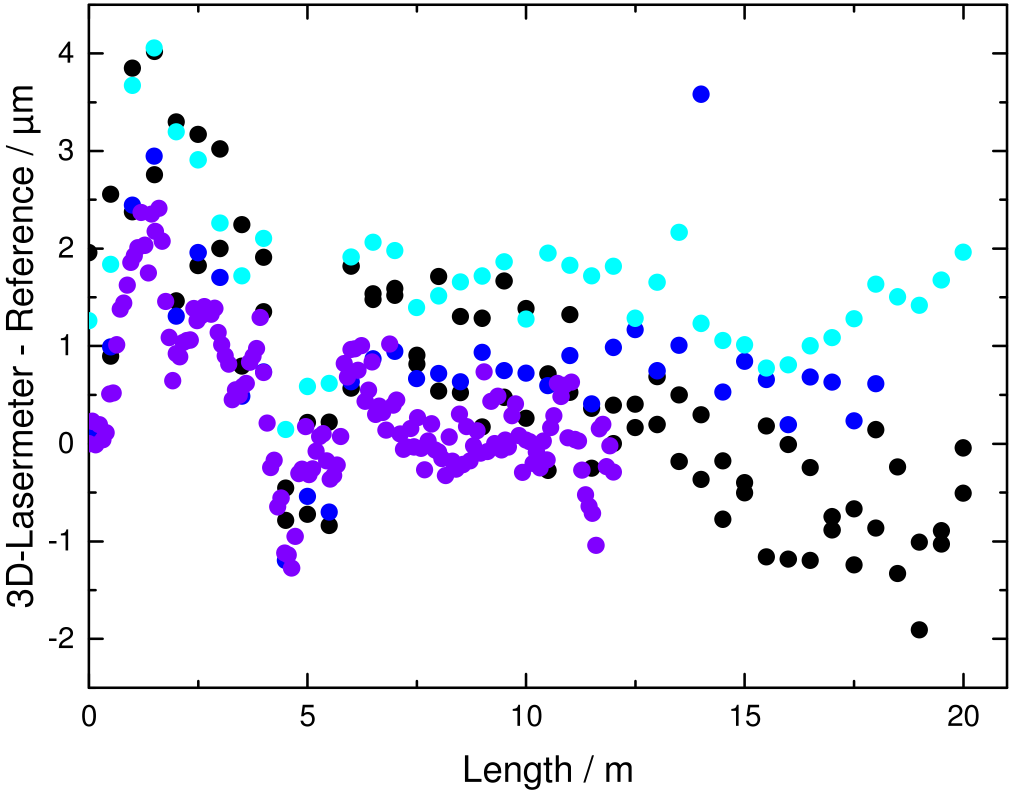
Comparison with HeNe interferometer with folded beam path.

Tracking is switched off.

Comparison with PTB 50 m comparator (geodetic base)

May 2015

Tracking off

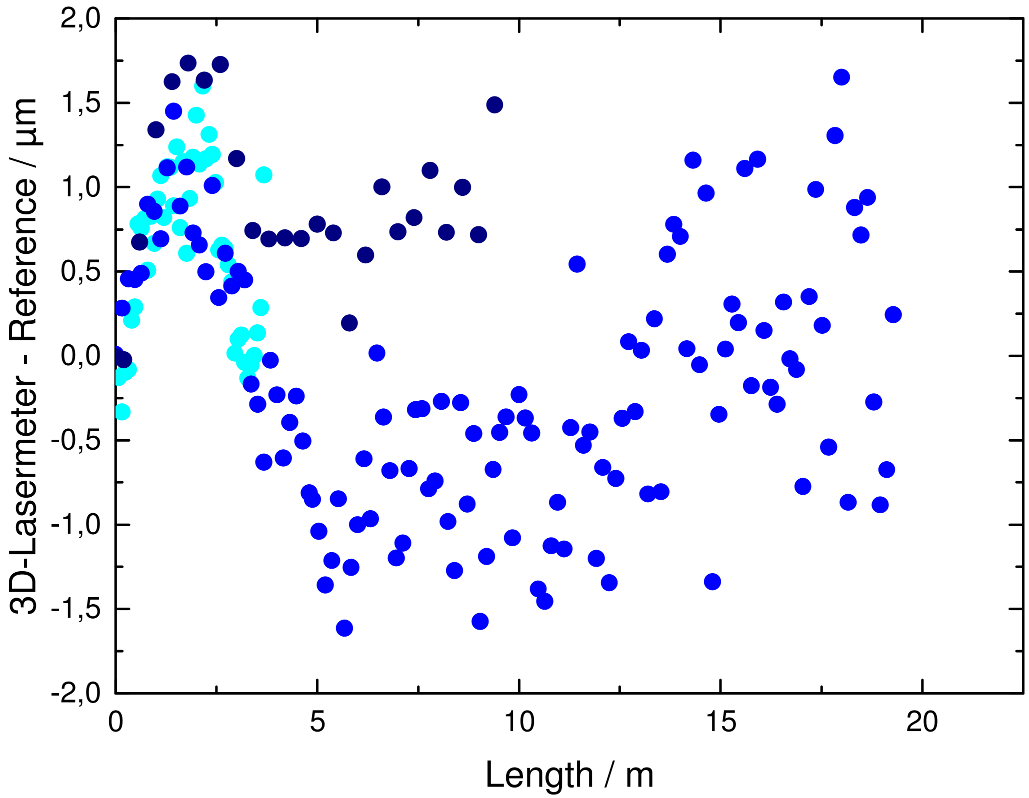


- Systematic deviations around 2 m ??
- Otherwise within ±2 µm up to 20 m

Comparison with PTB 50 m comparator (geodetic base)

Jan 2016

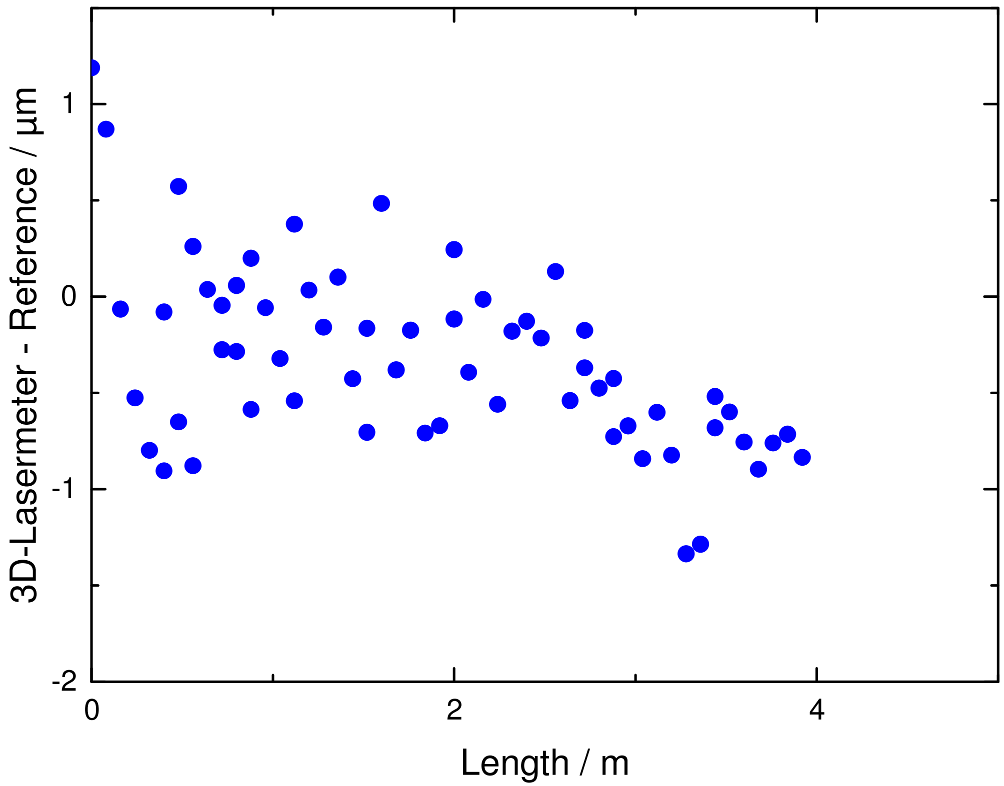
Tracking off



After optimisations:

- Systematic deviations around 2 m ??
- Scatter well below 1 µm on short path, otherwise within ±2 µm up to 20 m

Comparison with PTB 50 m comparator (geodetic base)

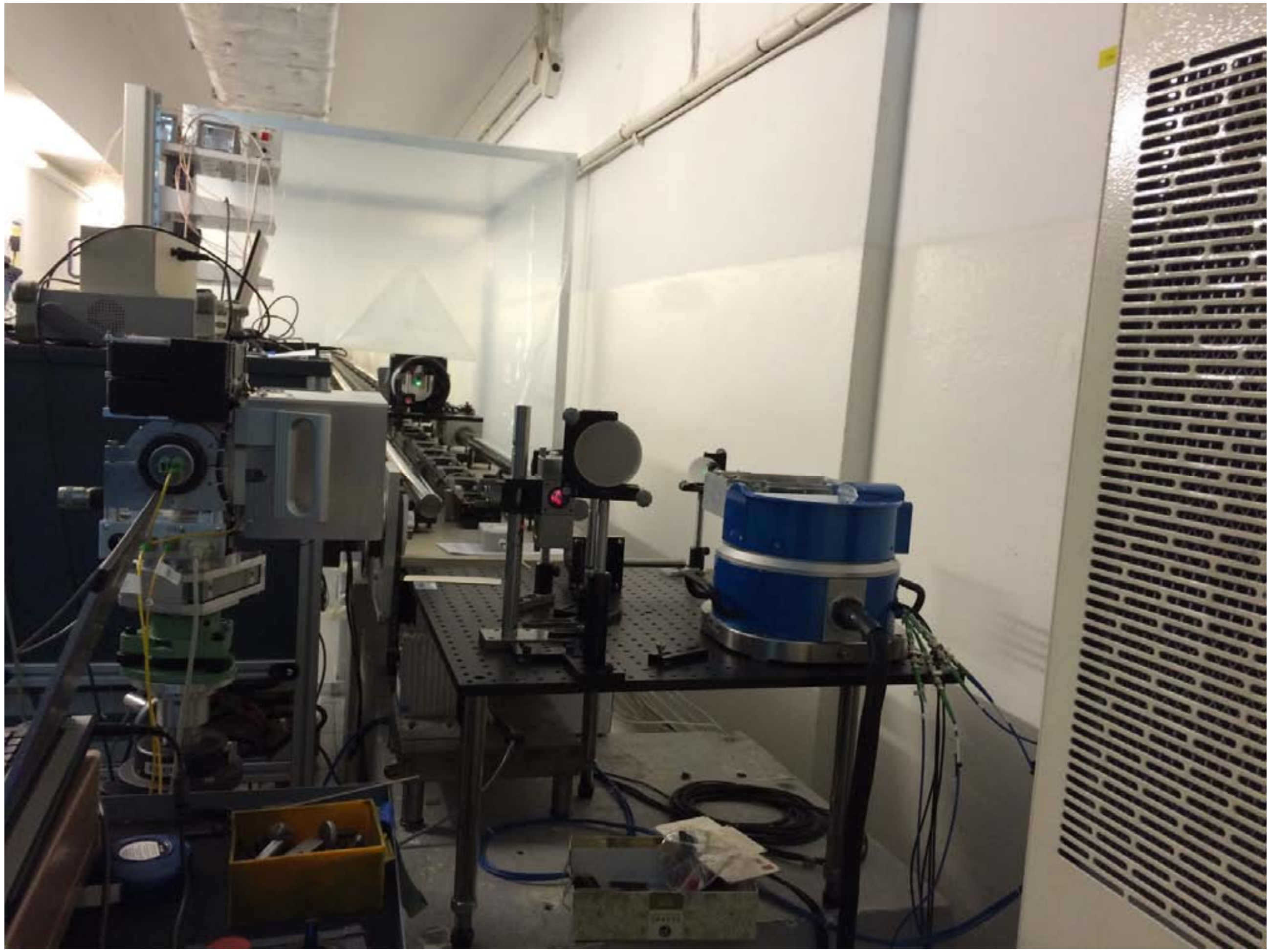


Jan 2016

Tracking on

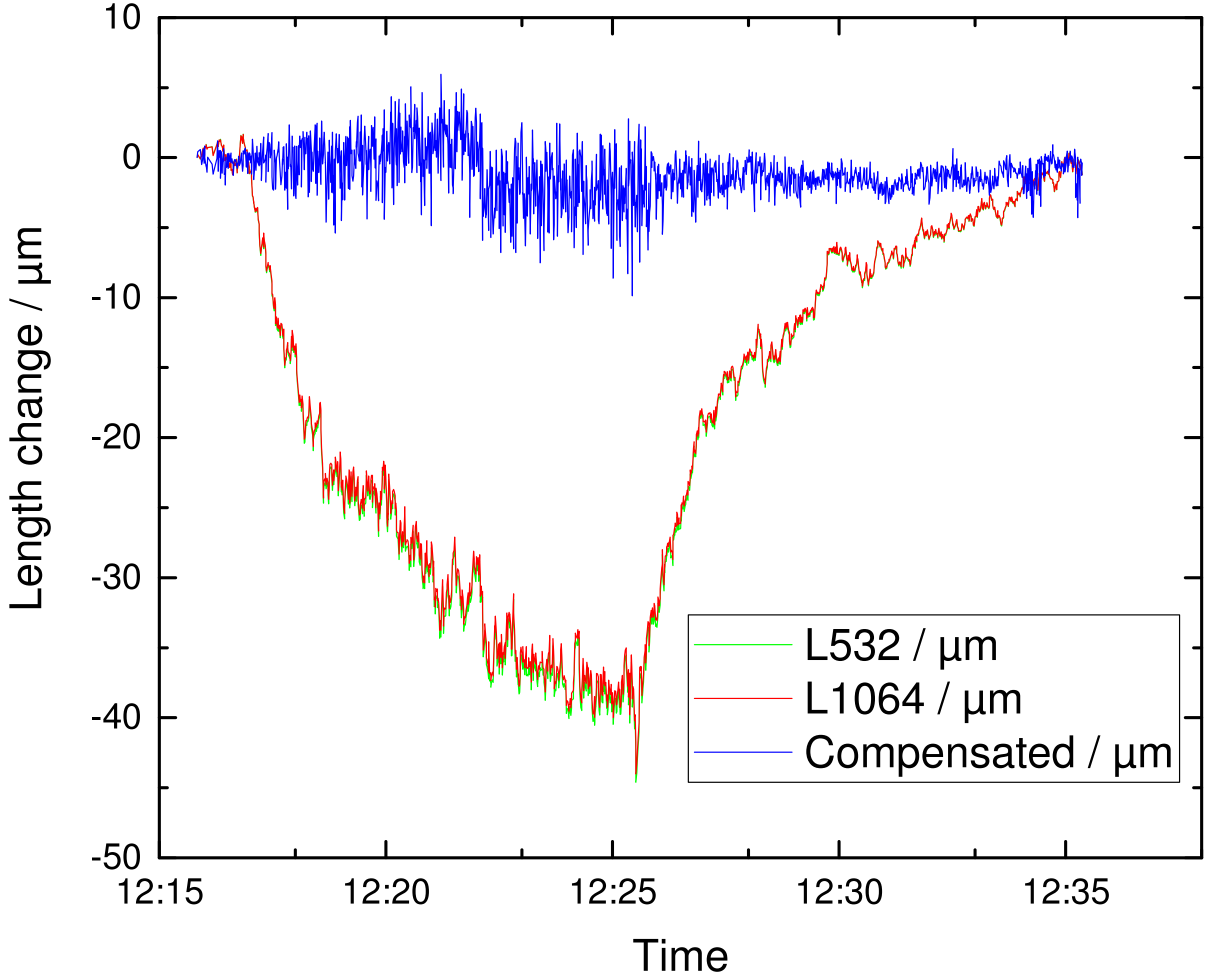
- Seems to be a curve in our rail
- Deviations not yet understood (no problems with interferometer calibrations)
- $U = \sqrt{(1\ \mu\text{m})^2 + (10^{-7} l)^2}$ for 1D, but why the effort?

Harsh environment at GUM (Warsaw) 50 m comparator



Two housings with heating fans installed for simulating harsh environment

Harsh environment at GUM (Warsaw) 50 m comparator

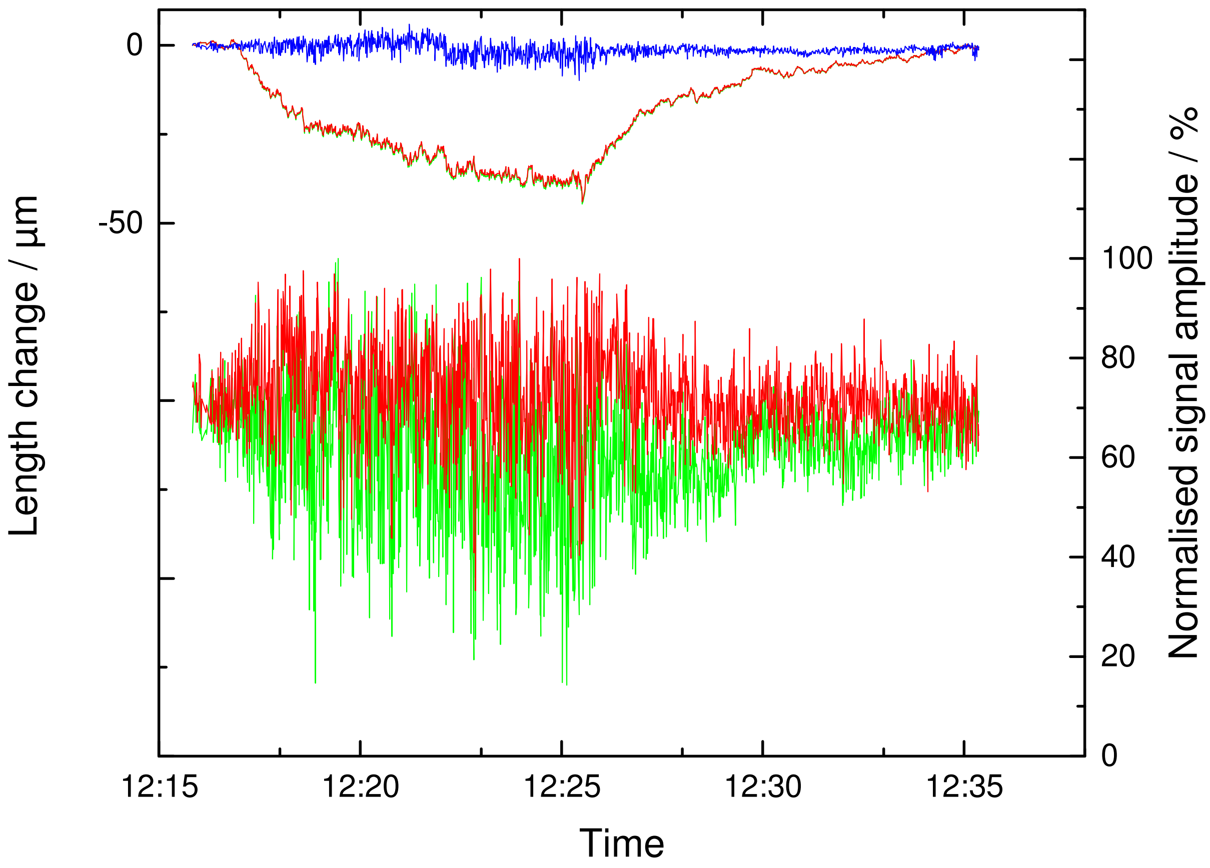


Length ≈19 m

Raw optical path length changes with temperaure

Compensated result remains constant, but with larger scatter during turbulences

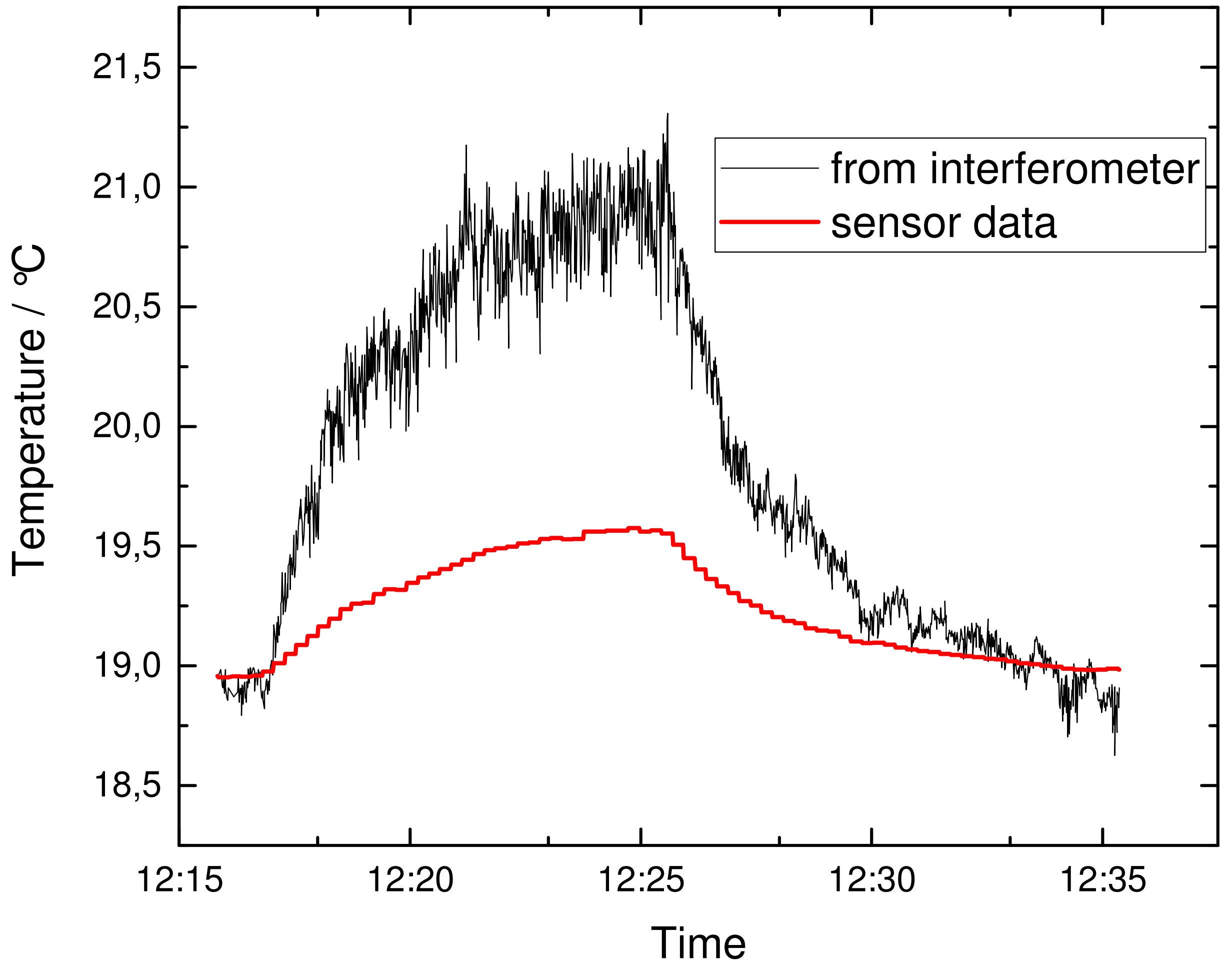
Harsh environment at GUM (Warsaw) 50 m comparator



Length ≈19 m

Scatter during turbulences probably due to signal amplitudes.

Harsh environment at GUM (Warsaw) 50 m comparator



Length ≈19 m

Temperature from sensors 1.5 °C off: we believe in interferometer (constant length)

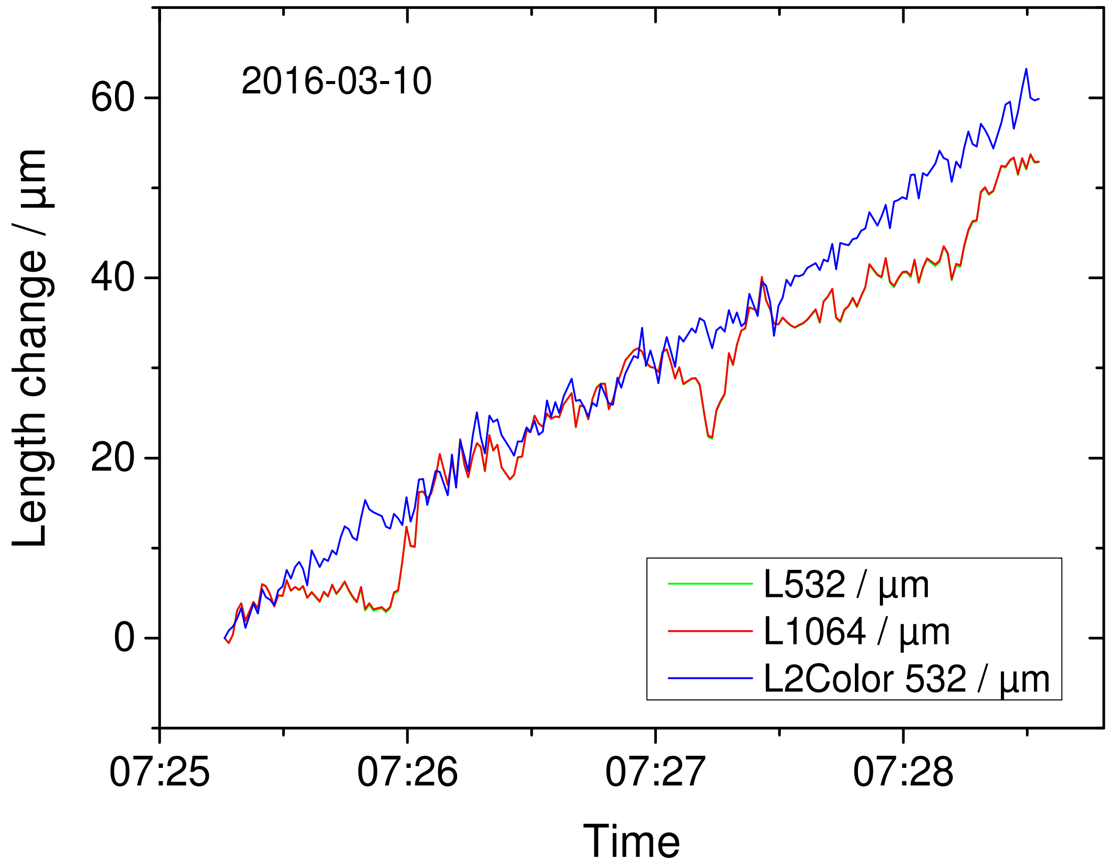
Measurements at Airbus in Filton, March 2016

- Measurements in building Q7 on a 44.7 m path
- No interferometric reference, only sensor data for temperature, pressure, humidity
- Evaluation of data:
  - length uncorrected and refractivity compensated
  - air index change (no absolute values)
  - temperature change (no absolute values)

  (for absolute values of air index and temperature the absolute optical path lengths must be known)

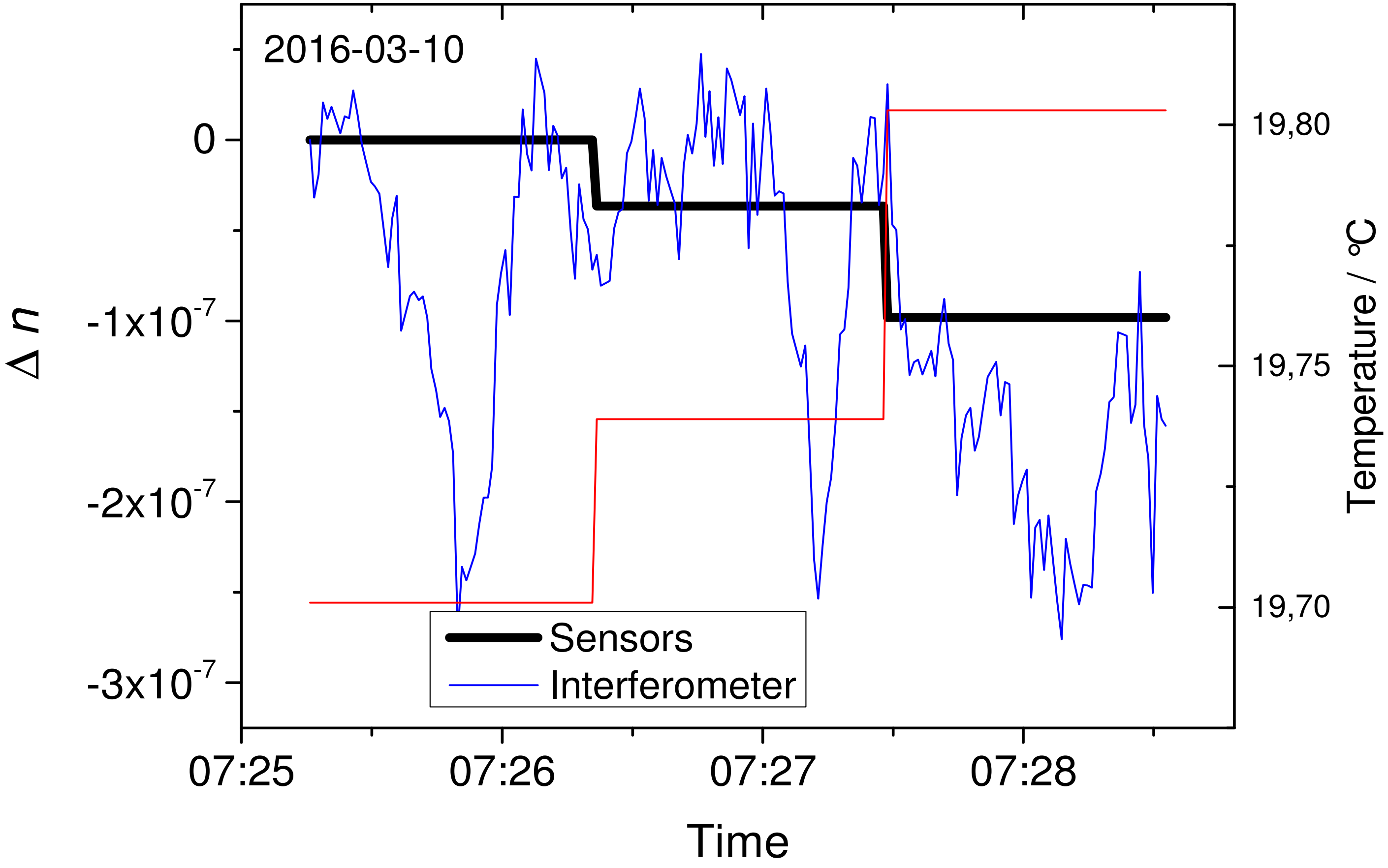
Karl Meiners-Hagen

Measurements at Airbus in Filton, March 2016



Moderate turbulences: corrected length follows a straight line, uncorrected does not.

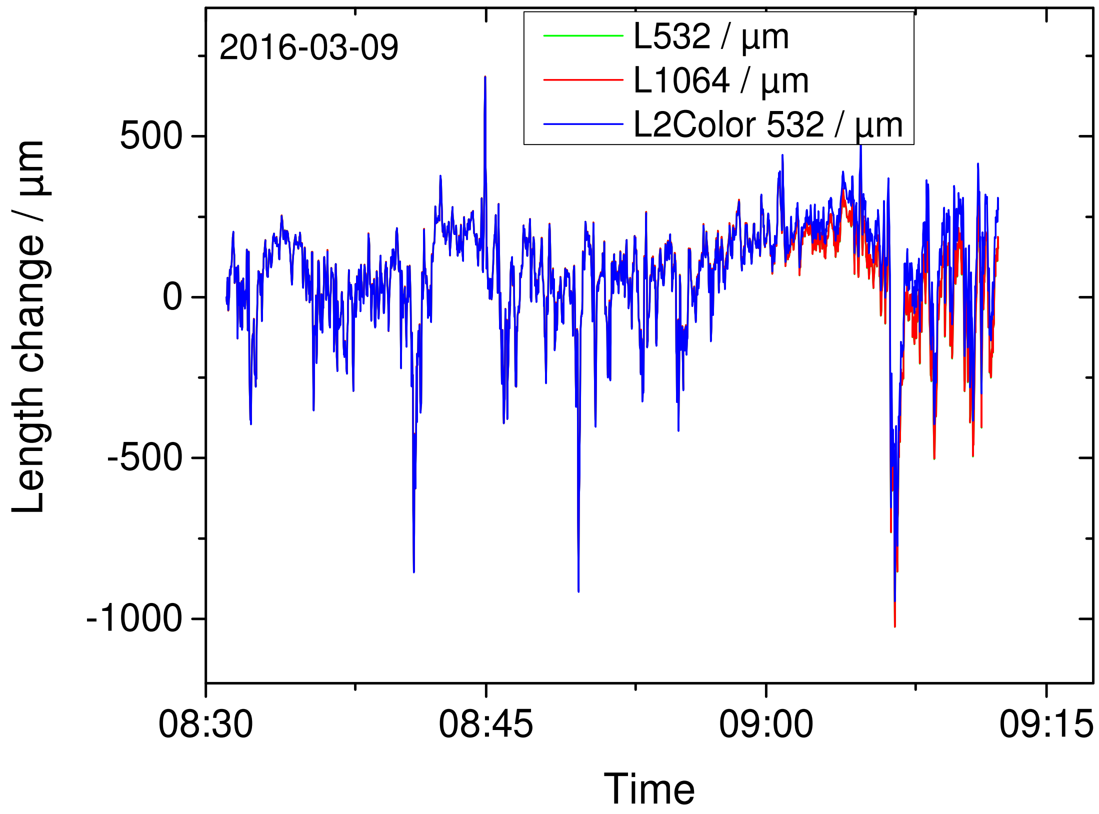
Measurements at Airbus in Filton, March 2016



Refractive index change and measured temperature:

Sensors can‘t follow the refractive index (measurement cycle and thermal delay)

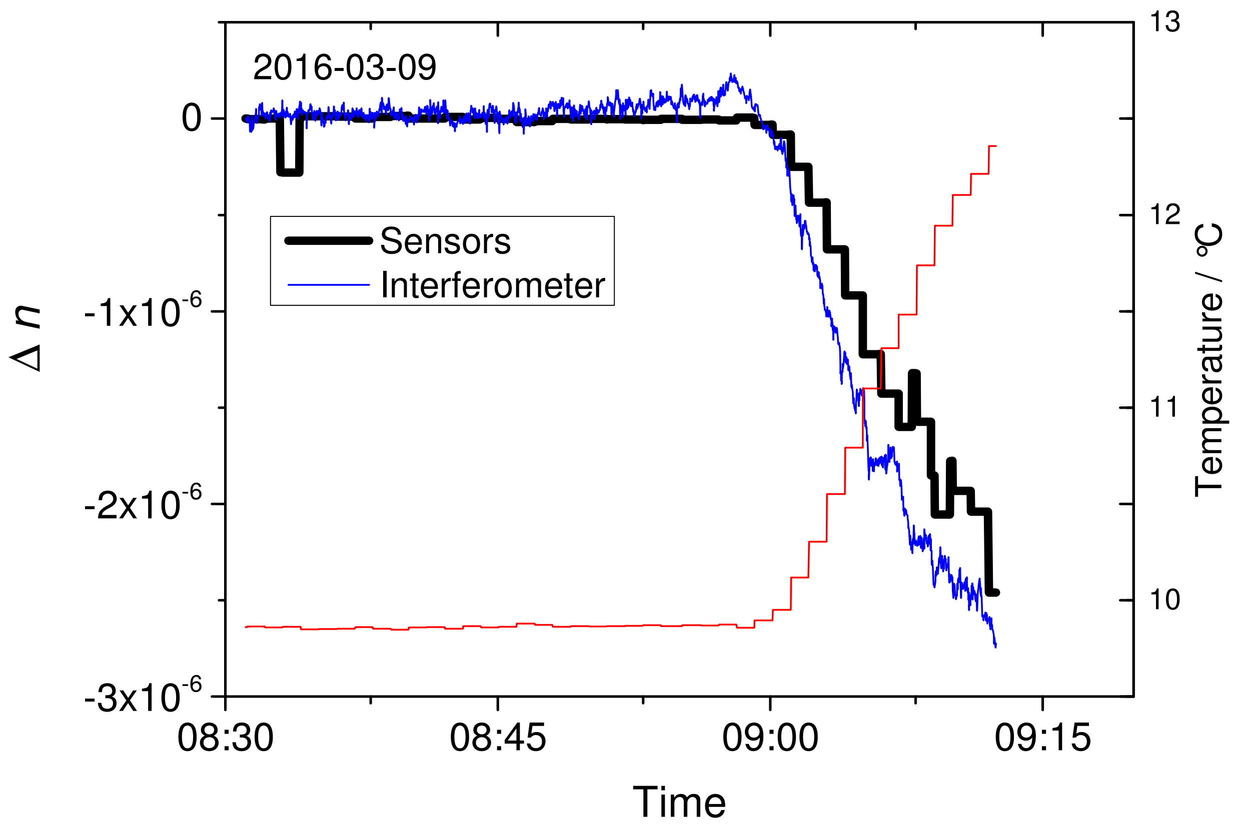
Measurements at Airbus in Filton, March 2016



Heating of building turned on at 09:00

(Windy morning, up to 1 mm movement of the structure)

Measurements at Airbus in Filton, March 2016

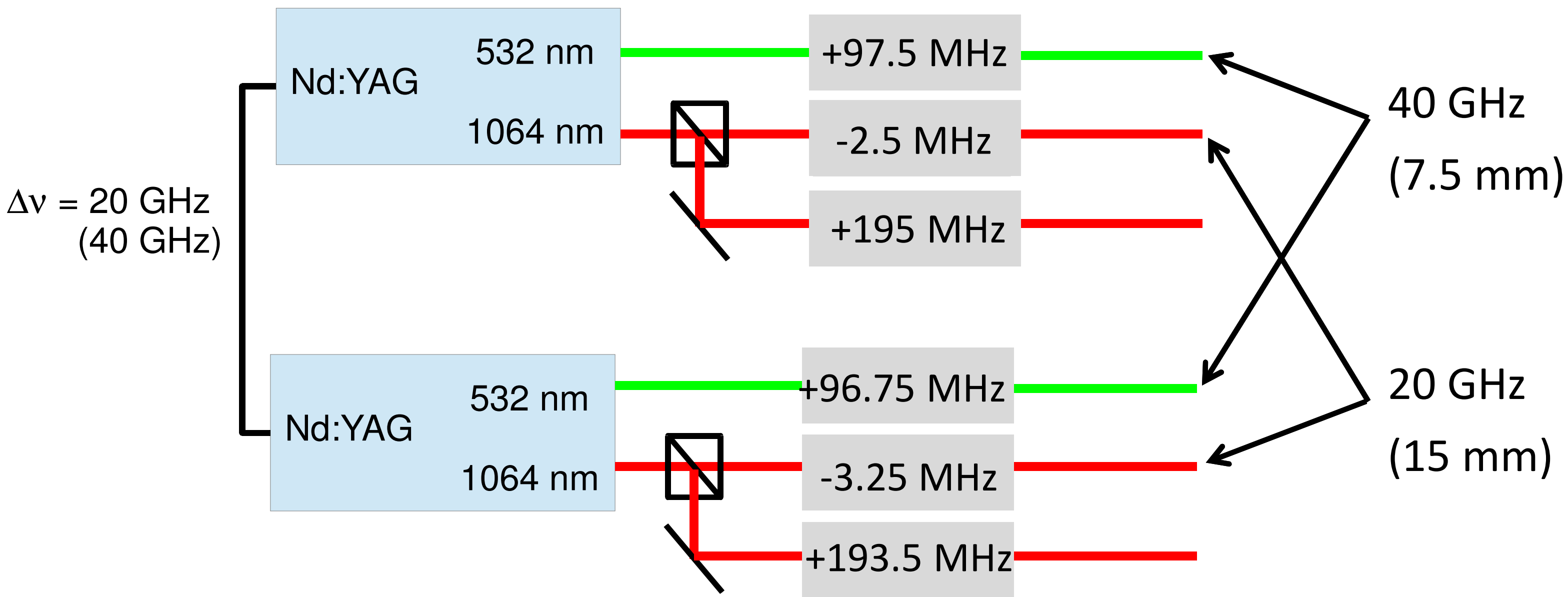


Refractive index difference within 5x10^{-7} during heating

Possible reason: temperature distribution (lowest 5 m path had no sensors)

ADM mode

- Two frequency doubled Nd:YAG lasers (1064 nm + 532 nm)
- Phase locked wih 20 GHz (1064 nm) / 40 GHz (532 nm) offset
- Generation of additional frequencies with frequency shifters (AOM)



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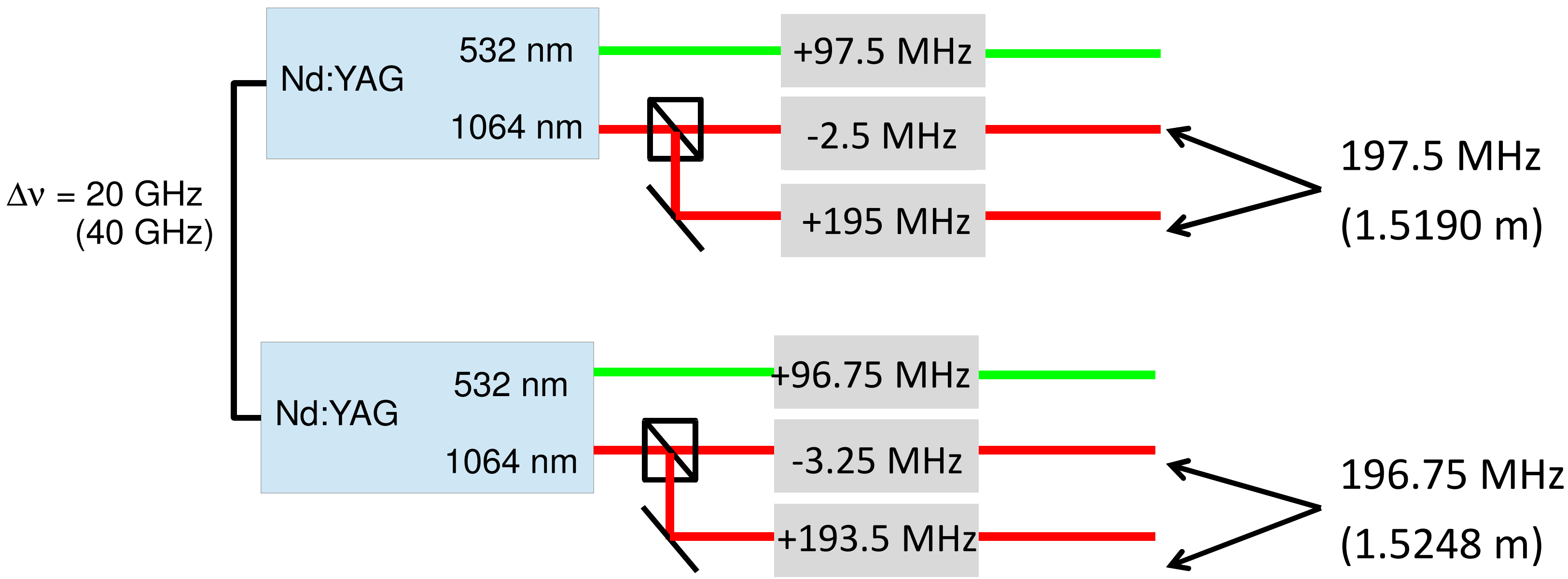
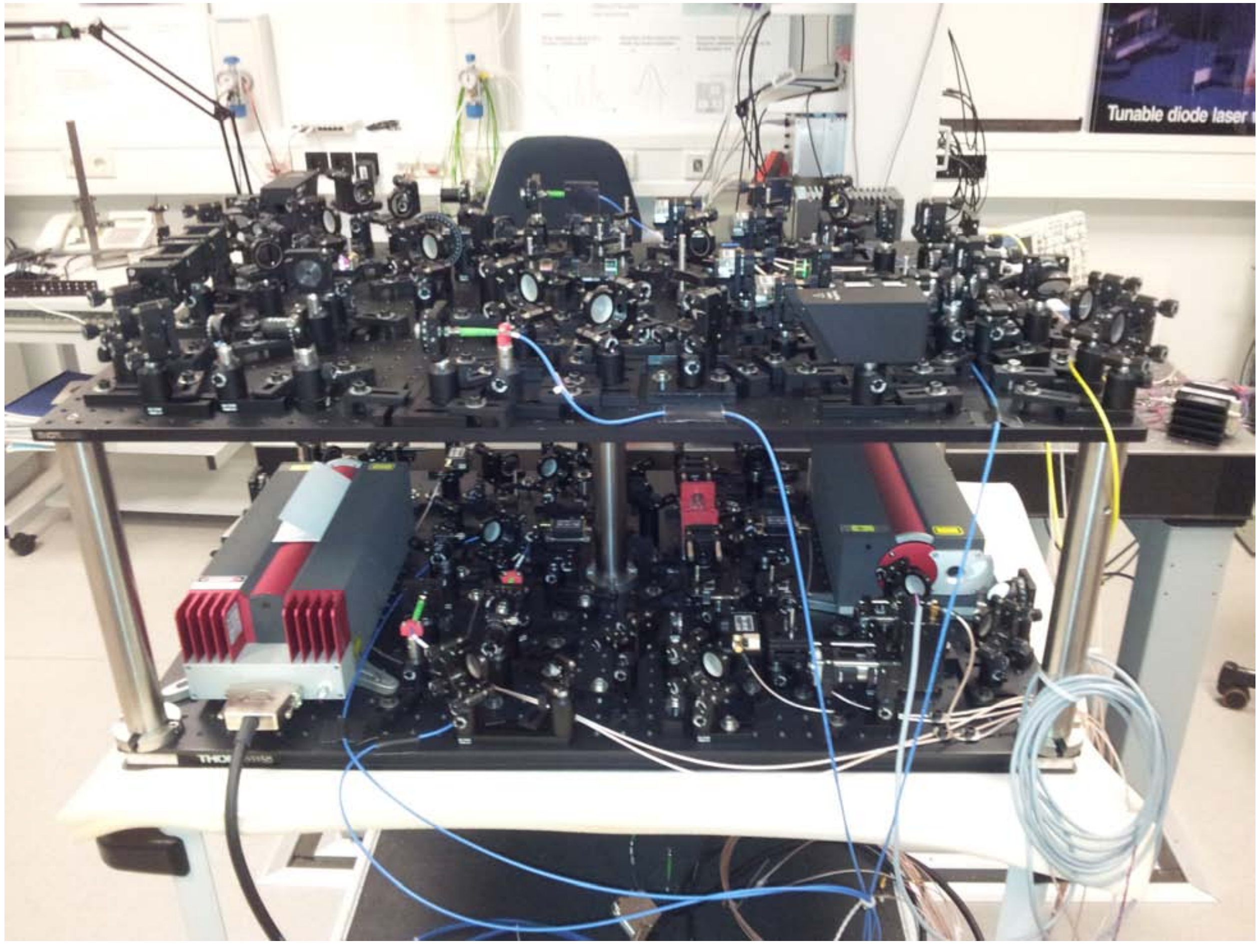


- Coarse distance by frequency scanning with AOM
- Uncertainty scaling bad: 7.5 mm/532 nm x 21.5 = **300 000**

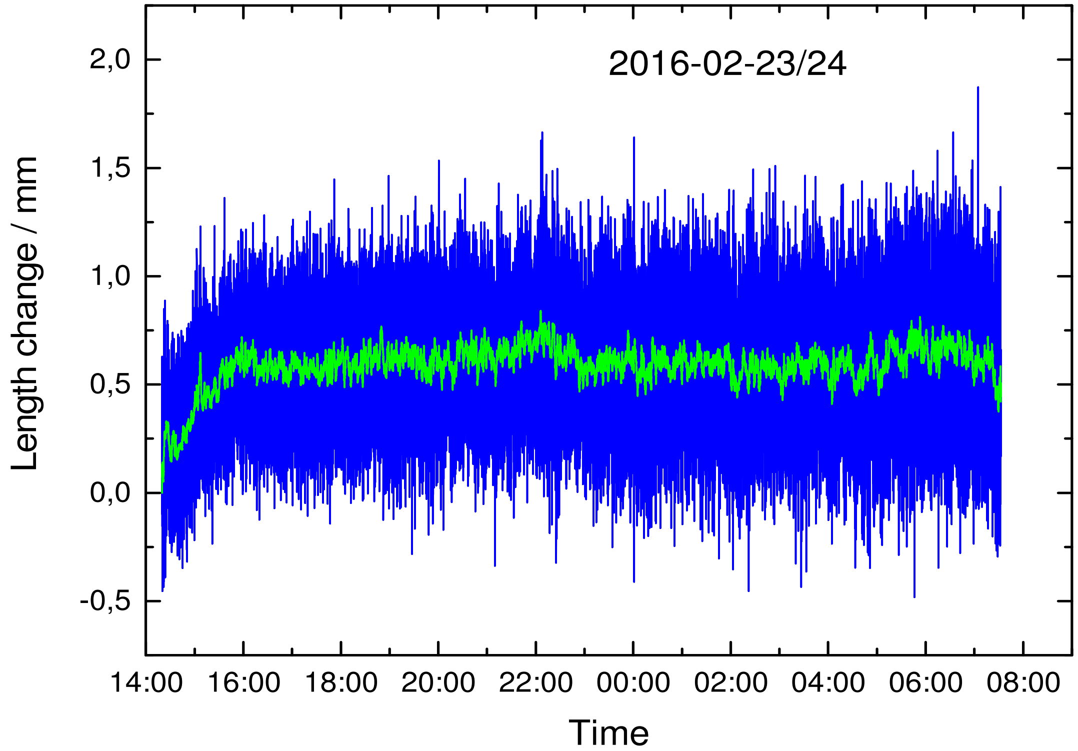
ADM mode

Light source, now on a trolley with laser shielding



90 cm x 60 cm
+ 19‘‘ rack

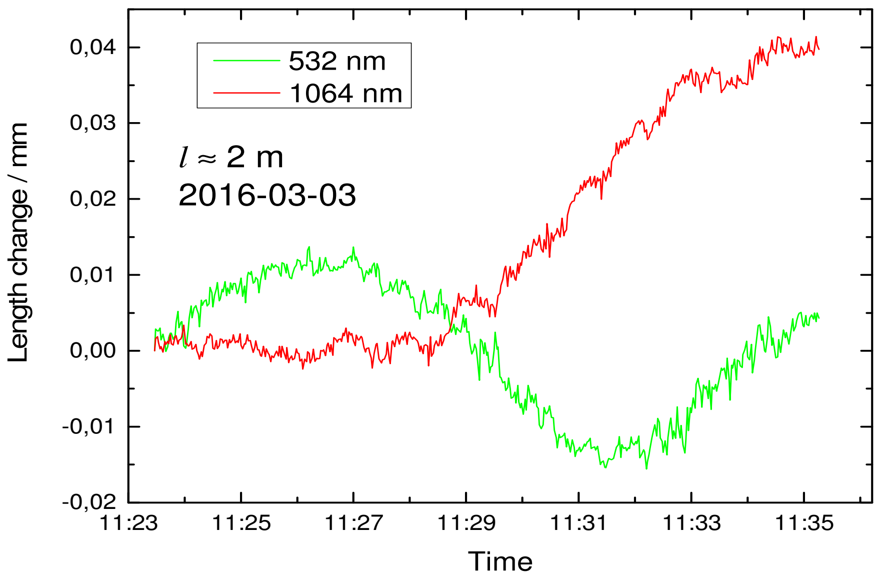
ADM mode



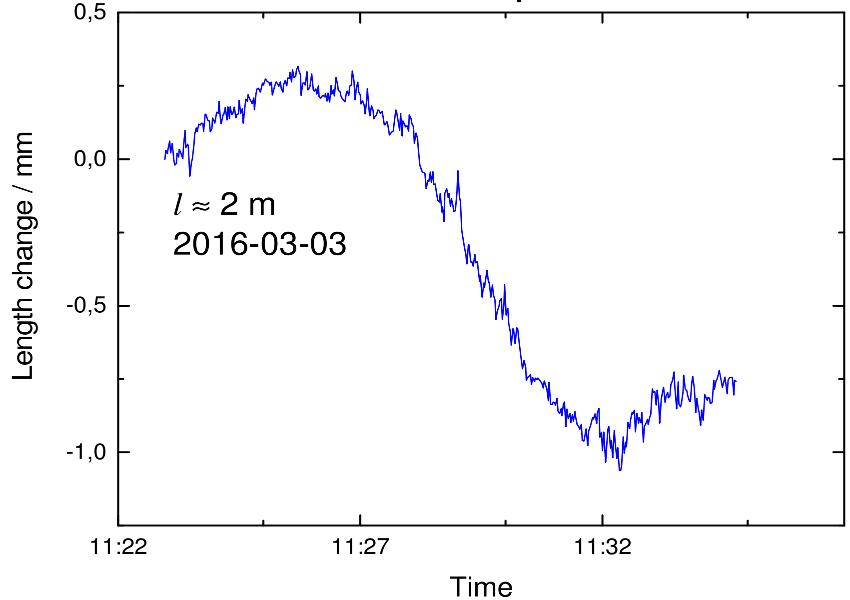
- Fixed 40 m path at 50 m comparator in PTB
- 10 seconds averaging: 60 µm standard deviation ⇒ 0.2 nm between four optical wavelength results

ADM mode

Raw data



Refractive index compensated result



- At Airbus with 2 m path length: >1 mm variation $\Rightarrow$ 3.3 nm between four optical wavelength results
- Problems with polarisation in the interferometer
- In JRP „Surveying“ the ADM mode works up to 864 m (<50 µm length independent standard deviation, $1 \times 10^{-7}\ l$)

Conclusions

- IFM measurements works with 1D uncertainty $U = \sqrt{(1\ \mu\mathrm{m})^2 + (10^{-7} l)^2}$

- Temperature range 9 °C to 22 °C verified, with gradients up to 10 °C

- 3D measurements at a CMM, 3D uncertainty around 3.5 µm

- ADM measurements suffer from problems with polarisation which were solved in the JRP “Surveying” project

- Outlook: investigation of temperature dependence of non polarising beam splitters

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