Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

Intrinsic refractivity compensation for high-accuracy distance metrology in manufacturing environments

K. Meiners-Hagen[1], T. Meyer[1], G. Prellinger[1], W. Pöschel[2], D. Dontsov[2], K. Rost[1], K. Wendt[1], and F. Pollinger[1]

[1]Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany

[2]SIOS Meßtechnik GmbH, Am Vogelherd 46, D-98693 Ilmenau, Germany

Motivation

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- required: (sub) ppm accuracy
- challenge: complex working environments

Optical distance measurement in air

- problem: knowledge of refractivity

$$\frac{\partial L}{\partial T} \cong -1\times10^{-6}\, l\,/\,K$$
$$\frac{\partial L}{\partial p} \cong +3\times10^{-7}\, l\,/\,mbar$$
$$\frac{\partial L}{\partial RH} \cong -1\times10^{-8}\, l\,/\,\%\,RH$$

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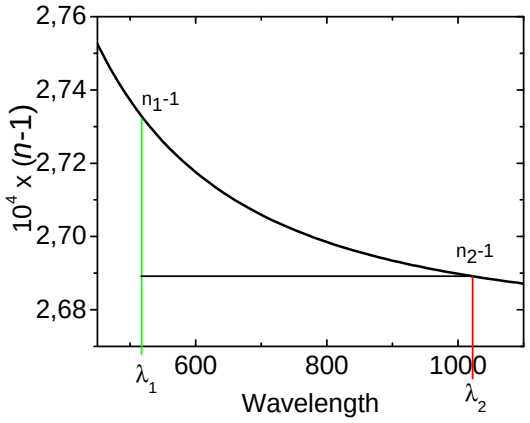
In-situ refractivity compensation



$$l = l_1 - A(l_2 - l_1) \qquad A = \frac{n_1 - 1}{n_2 - n_1}$$

knowledge of dispersion
+
measurement with two well-defined wavelengths
+
Relative humidity (MU 4 %RH)

⇩

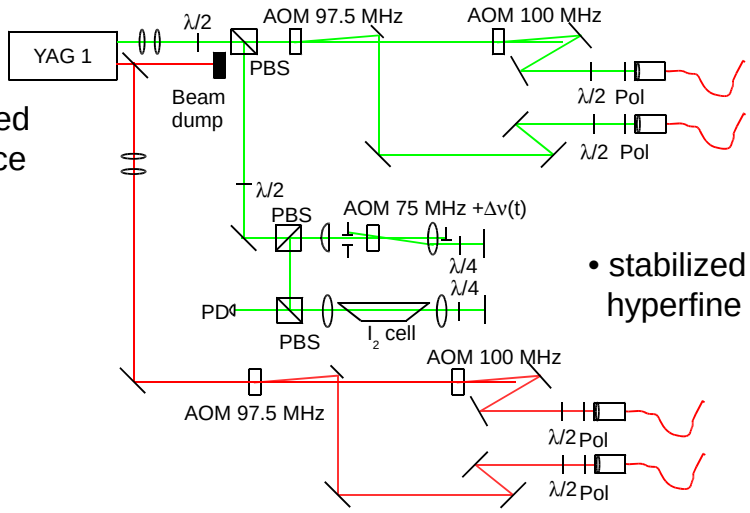
„geometrical length“

But unfavourable uncertainty scaling (A ~ 20 – 140) !

Earnshaw and Owens, IEEE J. Quant. Electron. ***3****, 544 (1967)*
Meiners-Hagen & Abou-Zeid, MST 19, 084004 (2008)

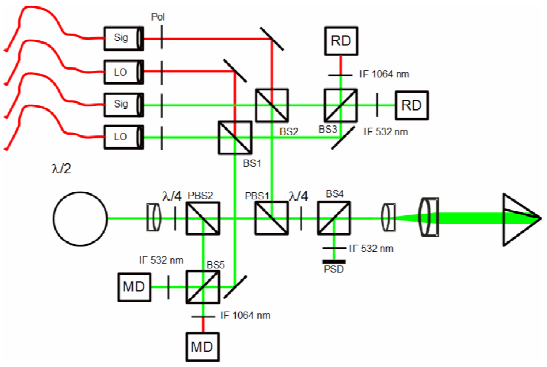
Two-color heterodyne interferometer

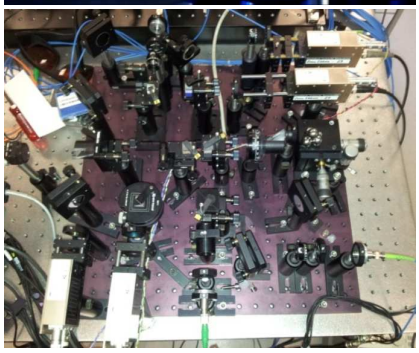
- frequency-doubled Nd:YAG as source



- stabilized on iodine hyperfine transition

Self-tracking interferometer head



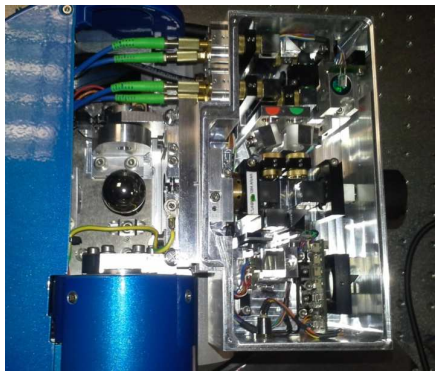


- Heterodyne interferometer in (self-tracking) LaserTRACER® design

Patents DE 10 2010 032407 (2011), DE 10 2015 203 697 (2013)

3D Lasermeter

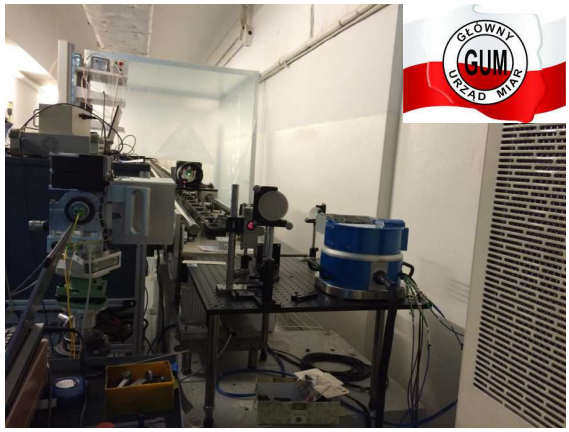
- Miniaturized interferometer head
- Works as self-tracking, counting refractivity-compensating interferometer
- Based on LaserTRACER® mechanics design



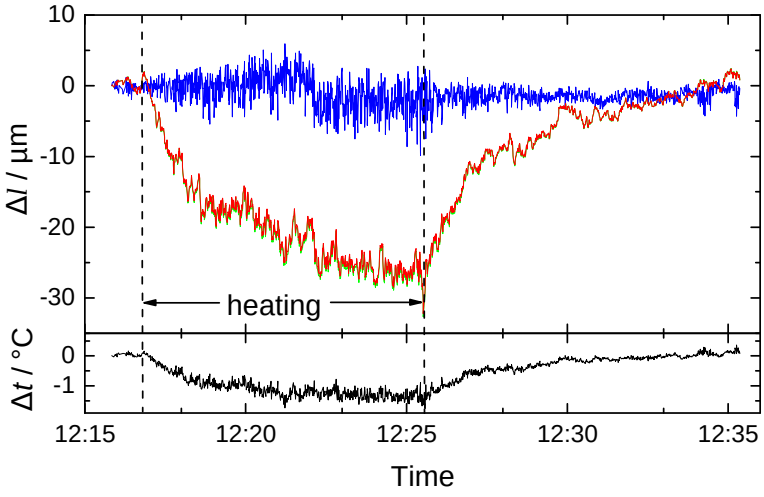
Patents DE 10 2010 032407 (2011); DE 10 2015 203 697 (2013)

Harsh environment verification

- Comparisons at 50 m comparator bench in Warsaw, Poland, at GUM
- Two housings with heating fans installed for simulating harsh environment
- 38 temperature sensors distributed along the bench



Verification under harsh conditions

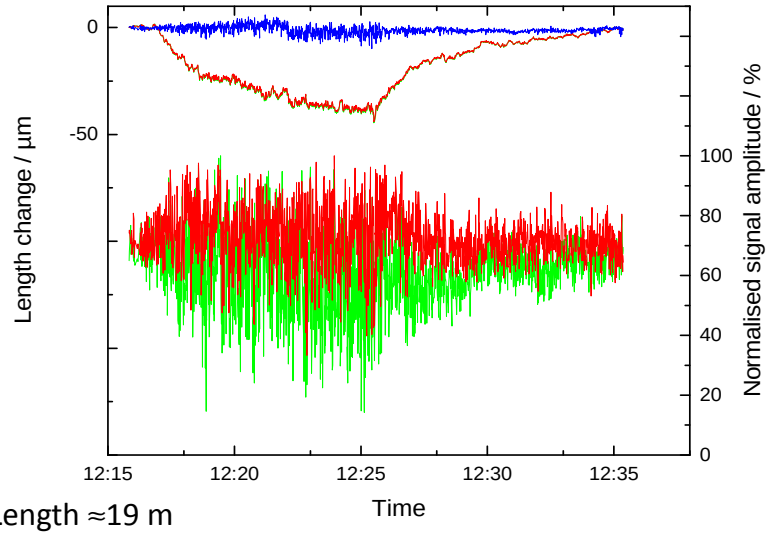


- Intrinsically compensated measurement values remain constant
- Classically compensated measurement values change significantly

☺

Meiners-Hagen et al., Opt. Expr. 24, 24092 (2016)

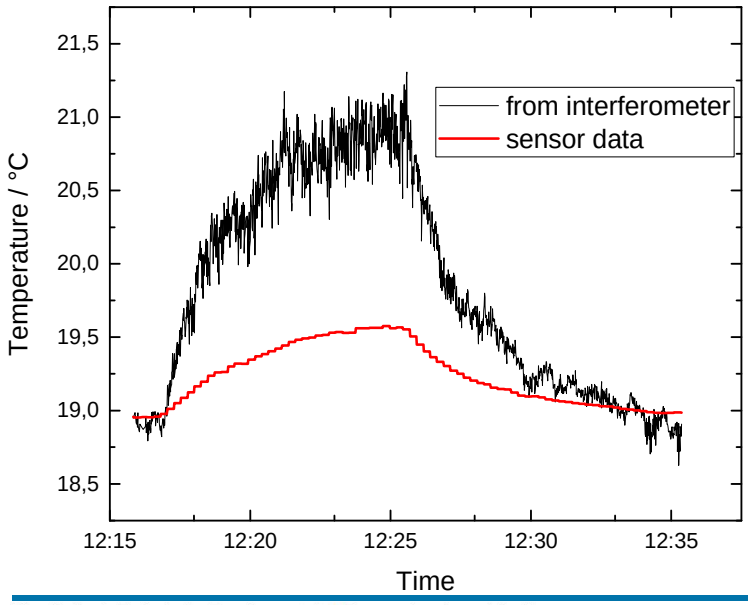
… but standard deviation increases ?



Length ≈19 m

- Correlated with signal amplitudes
- Beam path fluctuations due to turbulence limits

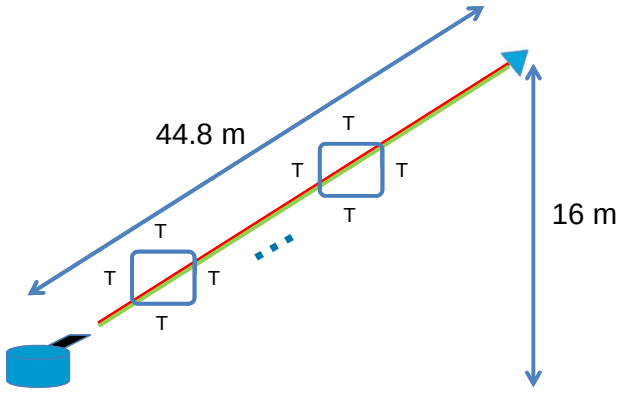
On the limits of sensor networks I



Length ≈19 m

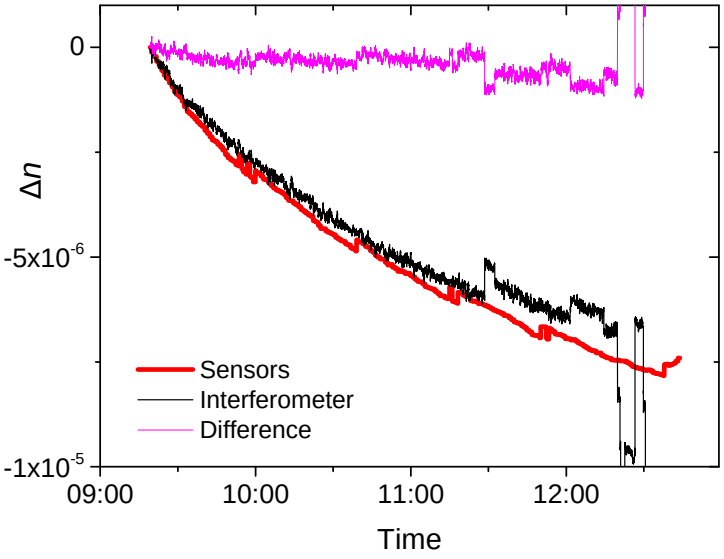
- Localized heat sources and associated inhomogeneity difficult to capture and interpret correctly
- Temperature from sensors 1.5 °C off

Verification under industrial conditions



- campaign at a test facility of Airbus, Filton, UK
- target in 16 m height, optical path 44.8 m
- reference temperature by 48 sensors in 12 frames

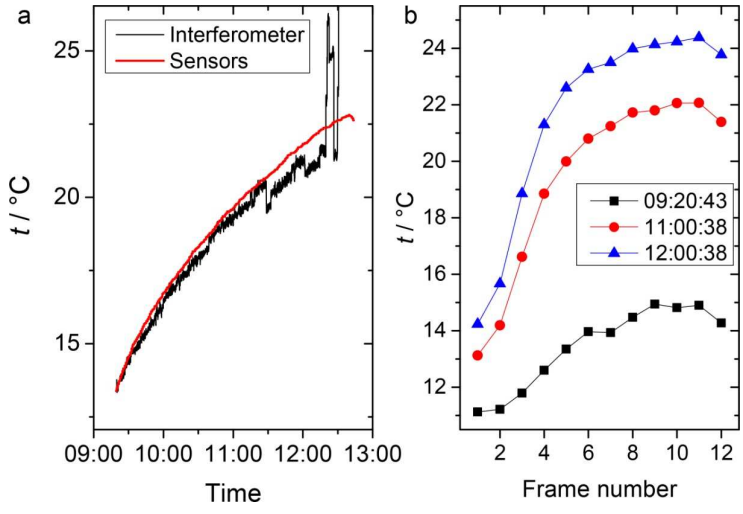
Monitoring refractivity index changes



- $n_{optical} - n_{sensor} < 5 \times 10^{-7}$ (as long as interferometer stable)
- "steps" in reference network correspond to pressure sensor resolution

Meiners-Hagen et al., Opt. Expr. 24, 24092 (2016)

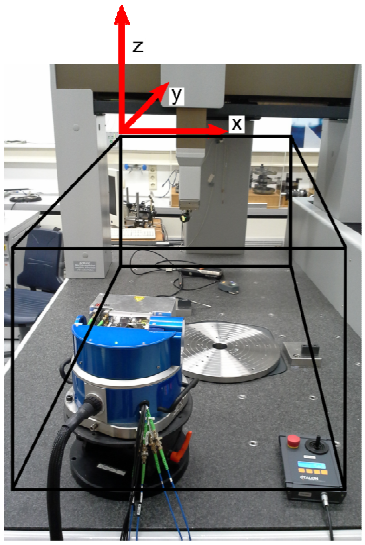
On the limits of sensor networks II



- fits to temperature sensor arrangement
- typical "imperfect" sensor network design

Opt. Expr. 24, 24092 (2016)

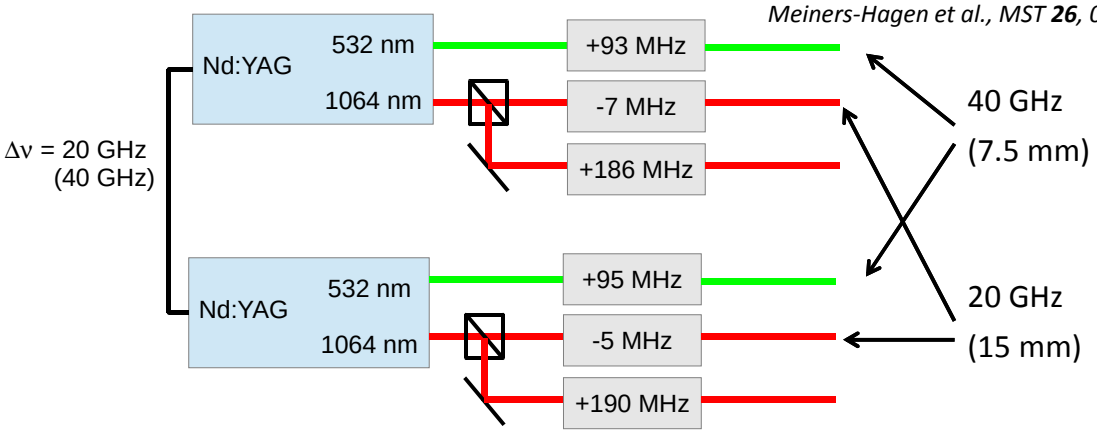
3D Lasermeter application at PTB



- intended use:
  calibration of large scale
  coordinate measuring machines

Absolute distance mode

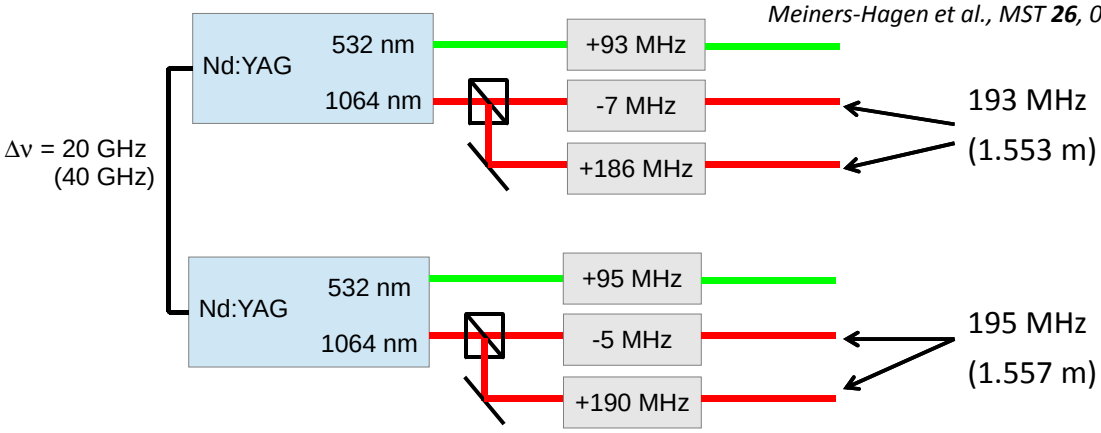
*Meiners-Hagen et al., MST **26**, 084002 (2015)*



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

Absolute distance mode

*Meiners-Hagen et al., MST **26**, 084002 (2015)*



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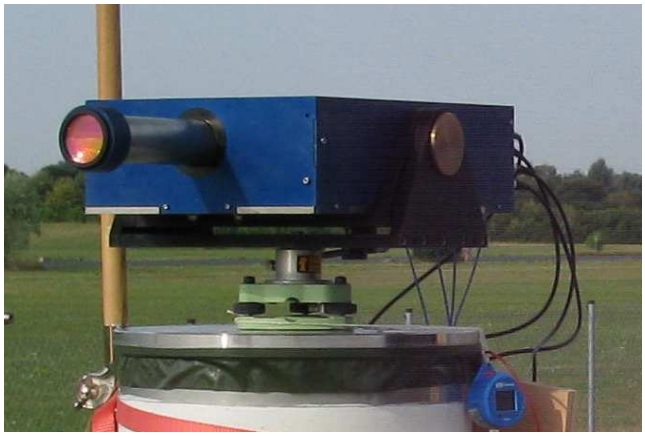
The TeleYAG distance meter



JRP SIB60 SURVEYING

- designed for geodetic length (~1000 m)
- heterodyne multi-wavelength interferometer

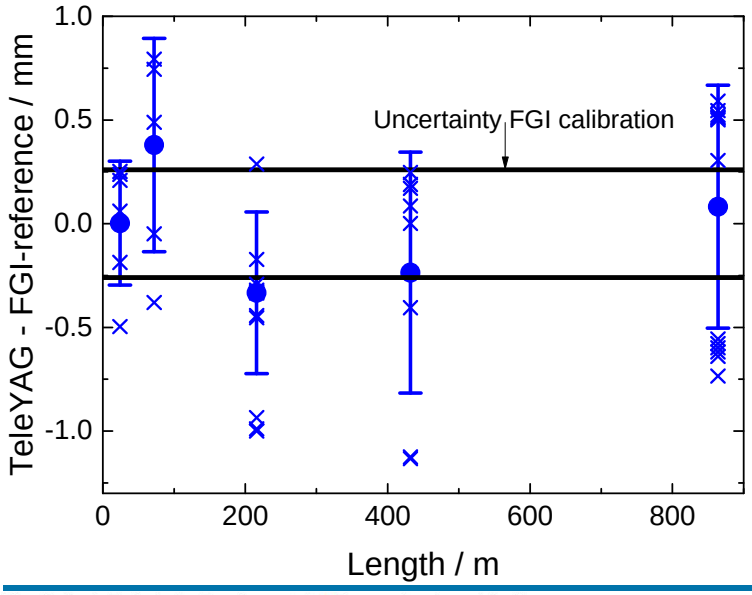
Meiners-Hagen et al., MST 26, 084002 (2015)

Long distance outdoor verification

- 6 very stable pillars (data history since 1930s)
- Distances 24 … 864 m, traceable by white light interferometry (Väisälä Interferometer)

J. Jokela, Veröff. FGI 154 (2014)

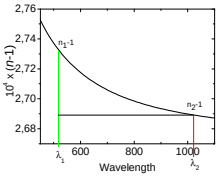
Refractivity-compensated results

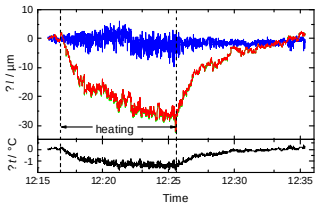


- Measurement time: 5 days
- Only sensor: humidity
- Refractivity-compensated results in sub-mm agreement with reference values

Conclusions

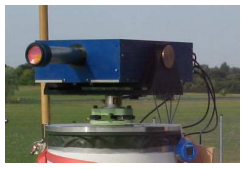
- realization of a refractivity-compensating self-tracking interferometer

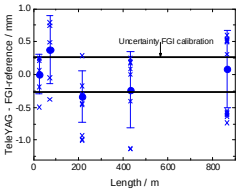




- successful verification in harsh environments

- refractivity-compensating length measurement up to 860 m





- turbulence as parameter determining the achievable uncertainty

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Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
Bundesallee 100
38116 Braunschweig

Dr. Florian Pollinger
Telefon: 0531 592-5420
E-Mail: florian.pollinger@ptb.de
www.ptb.de

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