A refractivity-compensated absolute distance interferometer as prospective novel primary standard for baseline calibrations

Metrology for long distance surveying, IPQ, Caparica 2014

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Overview

JRPSIB60 “Metrology for long distance surveying”

One task for PTB: Absolute distance interferometer with internal compensation of the refractive index of air (TeleYAG).

Targeted uncertainty $10^{-7}$ / up to 1 km

- Multiwavelength interferometry
- Refractive index compensation
- Experimental set-up
- Results
- Conclusion and outlook
Multiwavelength interferometry

**Measurement principle**

- Combination of the phase information of more than one wavelength

😊 Range of non-ambiguity increases to half the synthetic wavelength

\[ \Lambda_{jk} = \frac{\lambda_j \lambda_k}{\lambda_j - \lambda_k} \]

😢 Uncertainties are scaled up quickly

\[ u(l_{jk}) \propto \frac{\Lambda_{jk}}{\lambda_j} \]
Refractive index compensation by two colour interferometry

**Standard Interferometry:**
- Measurement of optical path with frequency stabilised laser ⇒ $l_0$
- Measurement of temperature, air pressure, humidity, $(\text{CO}_2)$ ⇒ refractive index $n$
- Distance: $l = l_0/n$

**Refractive index compensated interferometry:**
- Measurement of optical path with two wavelengths ⇒ $l_1, l_2$
  - 1) $l = l_1 - A(l_2 - l_1)$, $A$ constant (dry air)
  - 2) Measurement of partial pressure of water vapour ⇒ $p_w$
    Distance $l = f(l_1, l_2, p_w)$ (independent on temperature and pressure)
    Optional calculation of temperature, if air pressure is known: $t = g(l_1, l_2, p, p_w)$
  - 3) In practice measurement of relative humidity and temperature of sensor ⇒ $p_w$
Refractive index compensation by two colour interferometry

Influence of changes is the air parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Standard</th>
<th>Compensated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature $\Delta t = +1 , ^\circ C$</td>
<td>$-1 \times 10^{-6}$</td>
<td>---</td>
</tr>
<tr>
<td>Pressure $\Delta p = +1 , hPa$</td>
<td>$+2.7 \times 10^{-7}$</td>
<td>---</td>
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<tr>
<td>Relative humidity $\Delta RH = +1 , %$</td>
<td>$-1 \times 10^{-8}$</td>
<td>$-2.4 \times 10^{-8}$</td>
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</tbody>
</table>

⇒ Theoretically independent on temperature and pressure, but more sensitive to relative humidity

⇒ Uncertainty enhanced by factor $A$: $l = l_1 - A(l_2 - l_1)$

($\approx 21$ for synthetic wavelengths at 532 nm/1064 nm)
Experimental set-up

- 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)

\[ \Delta v = 20 \text{ GHz (40 GHz)} \]
Experimental set-up

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**Nd:YAG**

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<td>Δν</td>
<td>20 GHz</td>
<td>(40 GHz)</td>
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</table>

- 7 MHz
- +93 MHz
- +186 MHz

193 MHz (1.553 m)

**Nd:YAG**

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+95 MHz
-5 MHz
+190 MHz

195 MHz (1.557 m)

For long range change of one AOM frequency (sequential measurement)
Experimental set-up
Experimental set-up

Heterodyne interferometer

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Karl Meiners-Hagen
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Experimental set-up

Heterodyne interferometer
Experimental set-up

Base plate from super Invar
Results
Stability measurement \((l \approx 0.5 \text{ m})\)

\[ l(\text{laser 1}) - l(\text{laser 2}) \text{ in nm} \]

Variations \(\approx 2 \text{ nm} \Rightarrow \approx 28 \text{ µm} \) for synthetic wavelength results
Beam splitter cubes:
Old set-up: 2 x 10 mm Linos 400 nm – 750 nm
Test set-up: 1 x 25 mm Linos
New set-up: 2 x 10 mm Thorlabs 700 nm – 1100 nm
(easier alignment with two BS)
Experimental set-up

Beam splitter plates:
Old set-up: 1" Linos 450 nm – 1100 nm
New set-up: ½" Thorlabs 350 nm – 1100 nm
Results
Stability measurement \( |l \approx 0.5 \text{ m}| \)

\[ l(\text{laser 1}) - l(\text{laser 2}) \text{ in nm} \]

Replaced beam splitters: Max. length – min. length: 0.9 nm \((12.6 \text{ µm})\)
standard deviation <0.1 nm \((1.4 \text{ µm})\)
Results
Comparison to HeNe reference interferometer, 4 measurements
(averaging time 0.164 s and 0.656 s)

- Reproducible results
- Deviations are from collimation of the beams,
  \( \Delta \lambda = 0.04 \text{ nm (532 nm)}, 0.08 \text{ nm (1064 nm)} \)

(calculations with Edlen equation)
Results
Comparison to HeNe reference interferometer, 2 measurements
(averaging time 1.64 s and 3.2 s)

Fibre collimators have to be replaced (alignment issues)
(calculations with Edlen equation)

(14 µm ⇔ 1 nm)
Results

Refractive index compensation: subtracting a linear fit from raw data

- Deviations < 200 μm for refractive index compensated ADM
- In linear part (20 m – 40 m) < 100 μm
Results
Comparison to HeNe reference interferometer
Only one measurement with 1.5 m synthetic wavelength

„Accident“ with software: averaging time only 200 µs (normally 0.16 s to 3.2 s)
Max. – Min. = 2 mm, allowed is \( \Lambda/4 = 3.75 \) mm
Conclusion

- We do not understand the effect of beam splitters on the results (not much, but scaled by 14,000)
- Now reproducible results up to 50 m, changes with collimation
- Scatter <10 µm ⇒ 0.7 nm from 0 to 50 m
  - 0.7 nm / 50 m = 1.4x10^{-11}
- With linear correction refractive index compensated ADM < 200 µm
- Overall scaling factor 21 x 14000 = 30000

Outlook

- Replacing the fibre collimators (easier alignment)
- Investigation of different beam splitters?
- Outdoor baseline measurements (PTB, Munich, Nummela)
A huge “Thank you” to

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• You for your attention