A new acoustic method for determination of the effective air temperature for length interferometers

Virpi Korpelainen, Björn Hemming, Heikki Lehto and Antti Lassila
Centre for Metrology and Accreditation (MIKES)
Lönnrotinkatu 37, 00181 Helsinki, Finland
Phone: +358 9 616 761, Fax: +358 9 616 7467
E-mail virpi.korpelainen@mikes.fi

MIKES - Metrology

Introduction

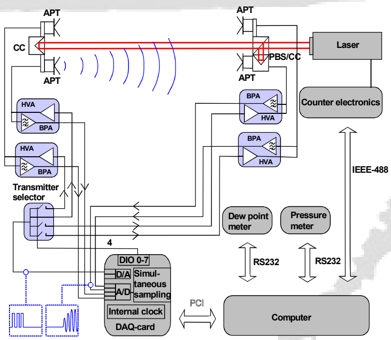
- The wave length of laser light in a medium ➔ the scale for interferometric distance measurements
  - ➔ the real-time refractive index of air (n) along the laser beam path is needed
  - ➔ n is function of air temperature (t), pressure (p), humidity (mole fraction of water vapour, x_w) and CO_2 mole fraction (x_c)
- The n is usually determined
  - using environmental sensors with Edlen formula [1, 2]
  - with interferometric refractometers
  - high accuracy can be reached with both methods in excellent laboratories
  - measurements only at single points
  - ⇓ Fast temperature changes and temperature gradients cannot be measured
  - ⇓ Errors in order of magnitude 1 - 10 µm/m under severe conditions
- A new acoustic method for measurements of the average temperature along the laser beam path (i.e. the effective air temperature, t_{eff}) is described

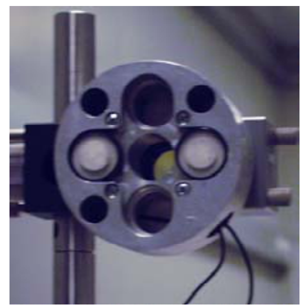
Setup

- Distance measurement (l)
  - heterodyne laser interferometer
- Time of flight of ultrasound (tof) measurement
  - two pairs of piezo transducers (APT)
  - short ultrasound burst of 50 kHz is transmitted and received in turn
  - FFT cross correlation algorithm

➔ $c = l/tof$

- The speed of sound (c) is two thousand times more sensitive to air temperature than the n. c is also a function of p, x_w and x_c.
  - ➔ $t_{eff} = f(c, p, x_w, x_c)$
  - ➔ Edlén ➔ n_{eff}
- Acoustic and interferometric measurements are done
  - symmetrically
  - simultaneously
  - over the same distance
  - ➔ t_{eff} and n_{eff} along the beam path





Equation

$$t_{eff} = b_0 + b_1 c + b_2 x_w + b_3 x_w^2 + b_4 x_w^3 + b_5 p + b_6 x_c + b_7 x_w c$$

- Fitted to
  - measured speed of 50 kHz ultrasound
  - Cramer equation for speed of sound [3]
  - dispersion relation [4]
- Validated by large set of differential speed of sound measurements over temperature range 19 - 22°C and humidity range 16 - 51%RH

	Coefficient	
b_0	-540.0160	°C
b_1	1.630328	°Cs/m
b_2	86.74	°C
b_3	972	°C
b_4	-27400	°C
b_5	-0.000000111	°C/Pa
b_6	145	°C
b_7	-0.5150	°Cs/m

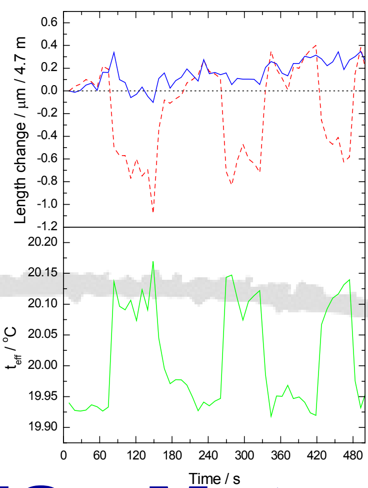
Uncertainty budget

Component		u_c/mK
Equation		15
Speed of sound	10 mm/s	18
Repeatability	8 mm/s	
Distance	51 µm	
Abbé error	10 µm	
Offset	50 µm	
Length scale	1 µm	
Time of flight	0.3 µs	
Time scale	6 ns	
Echoes	0.3 µs	
Pressure	5 Pa	10^{-3}
Humidity (x_w)	120 ppm	10
CO_2 mole fraction	50 ppm	7
Combined standard uncertainty		25

Test measurements

- The fixed distance was measured with laser interferometer
- The path was disturbed three times by electric radiator

- Changes in the t_{eff} ~0.2°C (——)
- Change in uncorrected l ~0.2 µm/m (------)
- Change in acoustically corrected l ~0.04 µm/m (——)



Conclusions

- Acoustic method gives effective t for interferometer; time and place are equivalent to interferometric measurement
- Large temperature gradients and fast temperature changes can be compensated.
- Accuracy of interferometric length measurements can be increased by acoustic method
  - ➔ high accuracy length measurements in laboratory conditions
  - ➔ industrial applications in workshop conditions
- Uncertainty of the setup: 25 mK and ~0.03 µm/m for t_{eff} and l.

Acknowledgements

Leonid Mihaljov (Data EVM Ltd) is thanked for co-operation and his original idea of the acoustic method. The project is partly funded by Finnish technology agency (TEKES).

References

[1] Edlén, B., *Metrologia*, **2**, 71-80, 1966.
[2] Bönsch, G. and Potulski, E., *Metrologia*, **35**, 133-139, 1998.
[3] Cramer, O., *J.Acoust. Soc. Am.*, **93**, 2510-2516, 1993.
[4] Morfey, C.L. and Howell, G.P., *J. Acoust. Soc. Am.* **68**, 1525-1527, 1980.

MIKES - Metrology