Air Temperature for Dimensional Metrology

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Overview

- Effects of Temperature on dimensional measurement
- Methods of compensation and correction
- Need for accurate temperature measurement
- Controlling laboratory spaces at NPL
- A slice of Raspberry Pi!

Dimensional Metrology

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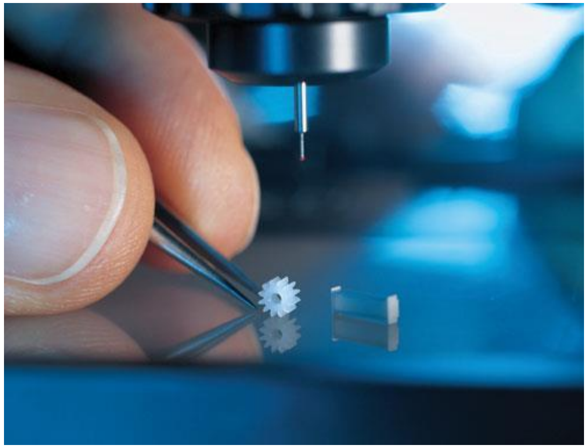
- The measurement of length over 1, 2 or 3 dimensions
- Ranges from the very small (sub nanometre) to large measurements (metre and kilometre plus)
- Measurements made traceable to the definition of the metre



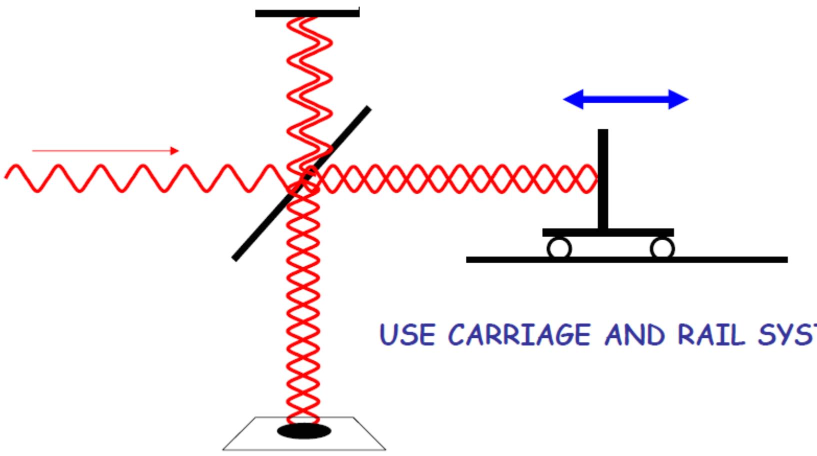
Definition of the metre

- The metre is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second.

  - 17th CGPM 1983 Resolution 1.

- This is practically realised through laser interferometry using frequency stabilised lasers which are frequency calibrated against atomic clocks.

Interferometry



- Measures the phase difference between a reference path and the measurement path

- Recombined beams interfere creating a fringe pattern

- Each fringe represents 1 wavelength difference between the length of reference and measurement paths

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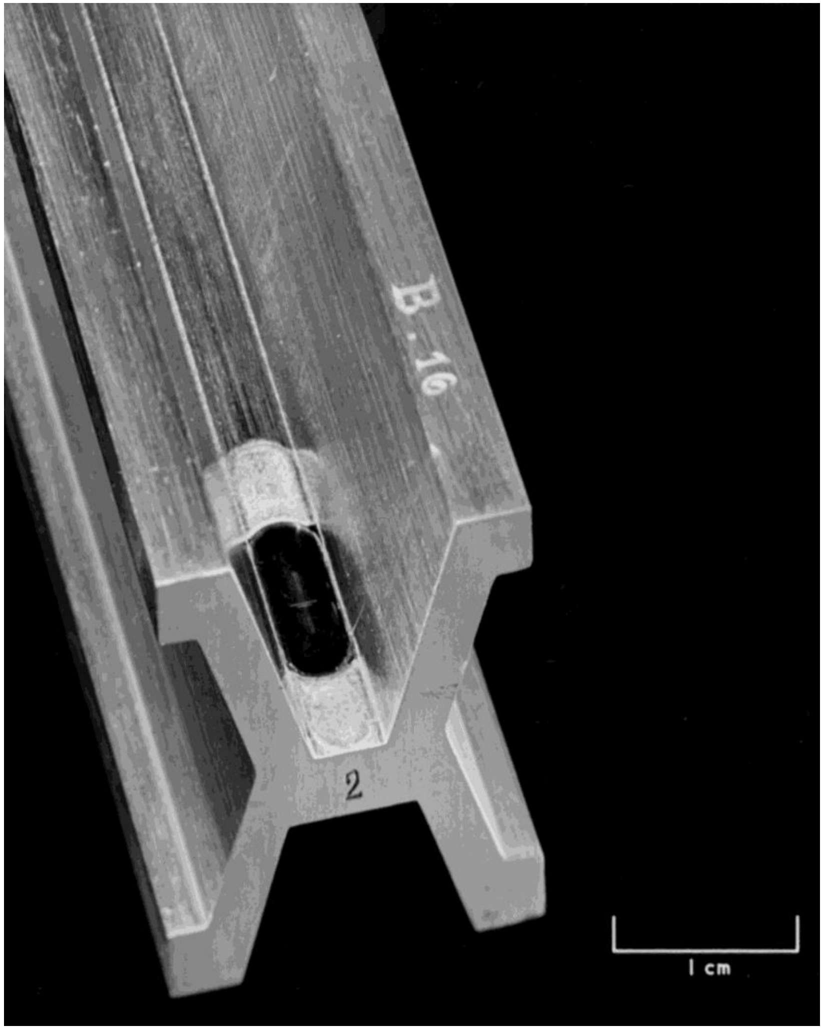
The Metre Bar

- In 1889 the first international definition of the metre was:

The length of the International prototype metre, at the temperature of melting ice, shall henceforth represent the metric unit of length



Effects of temperature

- There are two main ways in which varying temperature affects dimensional measurement

1. Thermal expansion of materials

2. Variation of refractive index of air

1. Thermal Expansion

- Almost all materials expand when heated and contract when cooled

- Measuring the same dimension at a different temperature will give a different result if no correction is applied.

2. Variation of Refractive Index

- Laser frequency calibrations are converted to the vacuum wavelength. The refractive index of the air is needed to calculate the wavelength during the measurement to obtain a meaningful result.

- Refractive index of air varies with temperature, pressure and humidity.

- A difference in refractive index between reference and measurement path will produce a length error.

- Changes in refractive index during a measurement will create an apparent lengthening or shortening of the measurement.

Compensation and Correction

1. Thermal Expansion

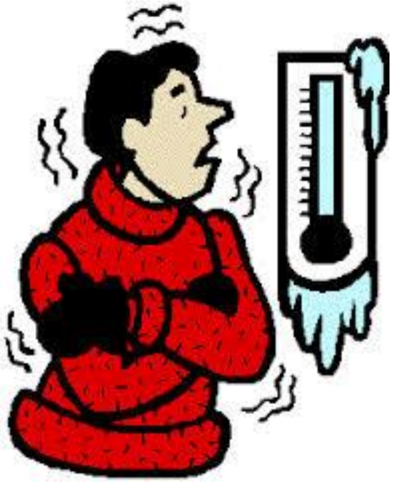
- Corrected to a standard temperature using a material's coefficient of thermal expansion (CTE) and the measured temperature of the artefact
- The bigger the temperature measurement uncertainty, the greater the length uncertainty
- Because CTE is not exactly known it leads to an additional uncertainty that increases with temperature deviation.

Standard Temperature

- Standard temperature for dimensional measurements defined by ISO 1.

- *The standard reference temperature for geometrical product specification and verification is fixed at 20 °C.*

- Dimensional Metrologists come out of the Cold!



Close temperature control Laboratories at NPL

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- Dimensional laboratories at NPL are environmentally controlled to achieve a stable air temperature of 20 °C ± 0.1°C.
- If instruments are allowed to drift in temperature they may permanently distort so temperature maintained 24/7
- Laboratories are also humidity controlled to
  45 % ± 5 % R.H.

Compensation and Correction

2. Refractive Index of Air

- For interferometry to be meaningful the refractive index of air (n_{air}) must be known in real time.
- n_{air} can be measured using a refractometer.
- It can also be calculated using modified Edlén equation based on air temperature, pressure and humidity.

Edlen Equation

$$(n-1)\times 10^{-8} = \left(8342.54 + \frac{2606147}{130-\sigma^2} + \frac{15998}{38.9-\sigma^2}\right)\times$$

$$\left(\frac{p}{96095.43}\right)\left(\frac{1+10^{-8}(0.601-0.00972t)p}{1+0.0036610t}\right)$$

$$-R(8.753+0.036588t^2)(0.037345-0.000401\sigma^2)$$

1 °C change of temperature results in change of 9.3×10^{-7} in refractive index

Need for accurate temperature measurements

Thermal control/metrology	10^{-7}
Alignment Refractive index	10^{-8}
Fringe subdivision	0.1 nm
Realisation/definition of the metre	10^{-11}

Instrument requirements

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Highest accuracy measurements

- Temperature uncertainties better than 0.05 °C
- Must be able to produce long term logs
- Typical cost £4-5k
- Usually only one or two steps removed from primary realisation instruments

For intermediate accuracy systems in industry these are too expensive but most cheaper systems lack sufficient resolution.

A slice of Raspberry Pi

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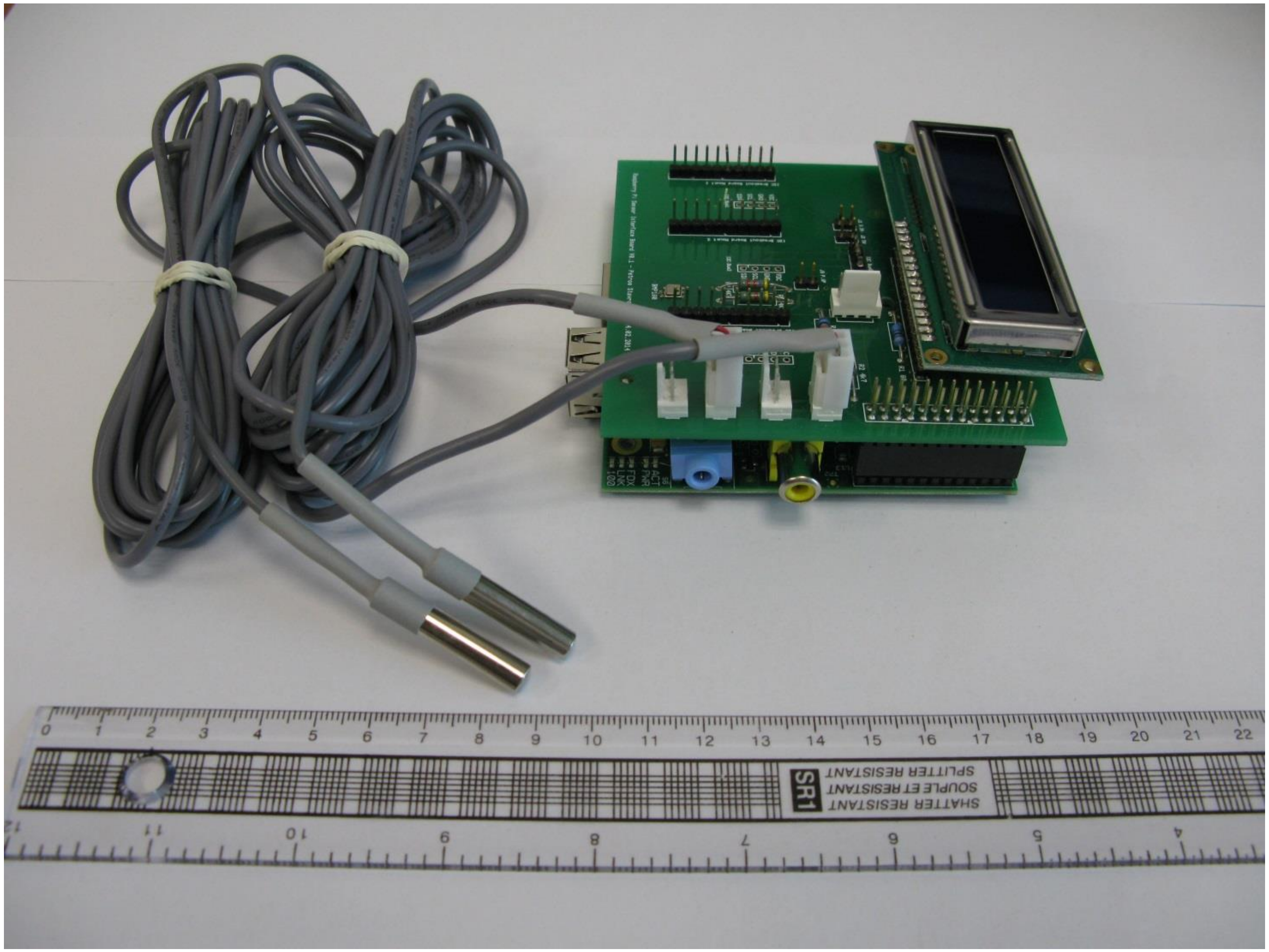

Raspberry Pi Environmental Logger

- Logger developed at NPL as a medium accuracy low cost device (cost approx £115).
- Based on Raspberry Pi basic computer
- Contains 2 temperature sensors with 0.06 °C resolution and accuracy over a relevant temperature range of approx 0.2 °C
- Also contains pressure and humidity sensors
- Logs data to a remote server and can send alerts if temperature specifications exceeded

Calibrating the Pi

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- The Raspberry Pi logger was calibrated in an environmental chamber at NPL at temperatures from 15 °C to 25 °C
- Temperature probe errors are within 0.04 °C
- Humidity sensor errors are within 1.4 % R.H
- Several of these devices are now in operation around NPL

Summary

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- Temperature is the primary limiting factor to length measurement accuracy

- Errors due to thermal expansion and refractive index influence the achievable uncertainty

- Accurate temperature measurement and control are essential.

- For lower accuracy systems the raspberry pi logger provides good measurement capability at low price

Thank You

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Any Questions?