National Physical Laboratory

Bureau International des Poids et Mesures

Società Italiana di Fisica

Dimensional metrology in practice

Lecture 2 of 2 on length metrology

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Dimensional Metrology, NPL

New frontiers for metrology
Module I – Physical metrology
5 July 2019, Varenna Summer School

Contents of this presentation

- Interferometry
  - Comparing physical & optical lengths
  - Interference – basic theory
  - Simple interferometers
  - Narrow beam interferometers
  - Use of polarisation techniques
  - Fringe counting & its limitations
  - Wide field interferometers
  - Other interferometers for traceability (angle, straightness)
  - Interferometry traceability - additional requirements
- Fundamental principles
  - Abbe principle
  - Mechanical stability
  - Thermal stability
  - Alignment
  - Probe/surface interaction
  - Error separation techniques
  - Error mapping
- Applications

How to go from the metre definition to dimensional measurements?

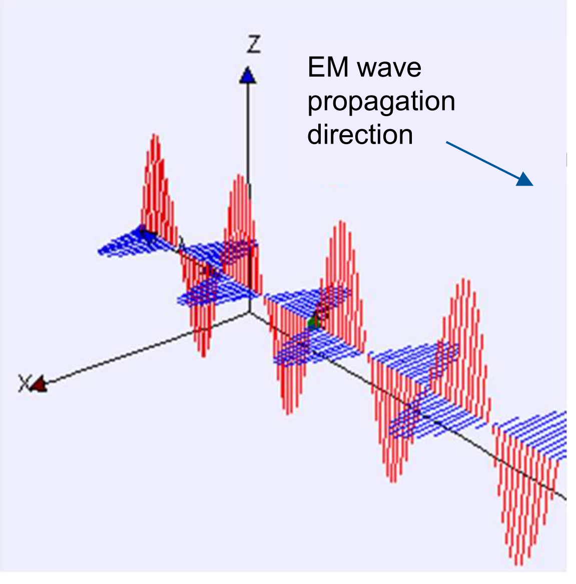
- How to make practical length measurements based on the *Mise en Pratique* of the metre definition?
- Every dimensional traceability chain contains measurements by interferometry
- Except:

  Measurements based on method 1 of the previous MeP

  - GPS/GNSS
  - electronic distance measurements (*e.g.* hand-held EDMs)

Interference of light waves

- **From EM theory, superposition of two waves**
  of the same frequency (homodyne) or very similar (heterodyne)
  usually from the same source (wavefront splitting or amplitude splitting)
  resulting pattern determined by phase difference



https://commons.wikimedia.org/wiki/File:Electromagneticwave3D.gif#/media/File:Electromagneticwave3D.gif

E is the electric field
B is the magnetic field
λ is the wavelength
f is the frequency
ω is the angular frequency
ϕ is the phase

$$\omega = \frac{2\pi}{\text{period}} = 2\pi f$$

Interference of two beams

Two EM waves:

$$E_1 e^{i(\varphi_1 - \omega t)} \text{ and } E_2 e^{i(\varphi_2 - \omega t)}$$

Superposing the beams at a location in space

$$E_T = E_1 e^{i(\varphi_1 - \omega t)} + E_2 e^{i(\varphi_2 - \omega t)}$$

We can measure the intensity of the resulting field rather than the field magnitudes, $I \propto \langle E_T^* E_T \rangle$

$$I(x, y) = E_1^2 + E_2^2 + 2E_1 E_2 cos(\varphi_1 - \varphi_2)$$

Or, in terms of intensities

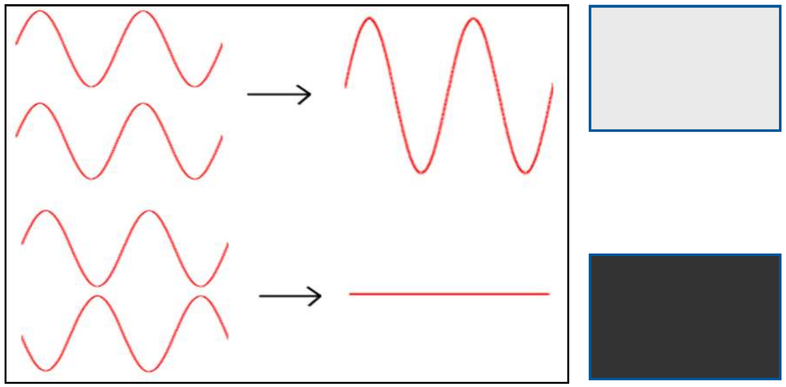
$$I(x, y) = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\varphi_1 - \varphi_2)$$

Simplified $\boxed{I(x, y) = a + b\cos(\Delta\varphi)}$

$\Delta\varphi = 2n\pi$ constructive interference (bright image)

$\Delta\varphi = (2n + 1)\pi$ destructive interference (dark image)

where $n = \{0, 1, 2, ...\}$

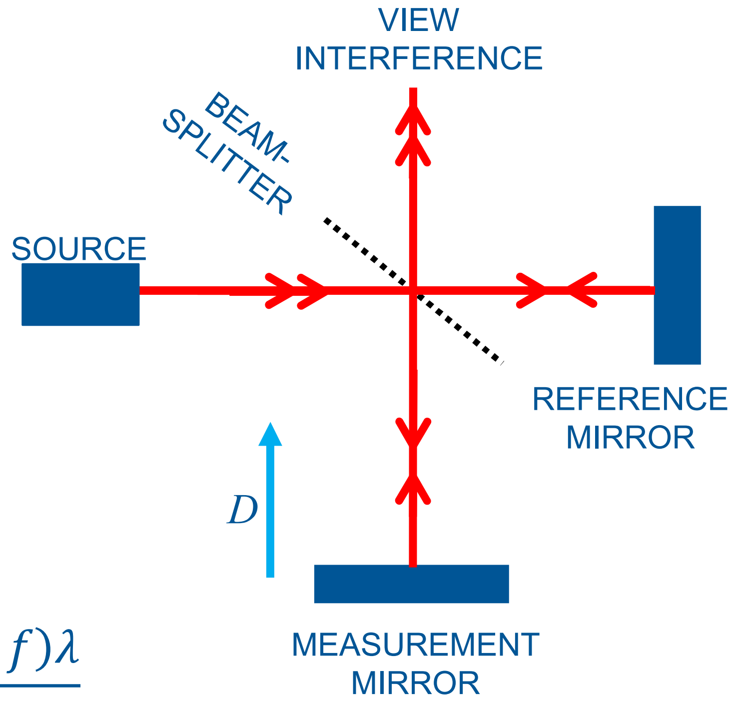


Observed intensity varies as $\cos(\Delta\varphi)$
Periodic in $\Delta\varphi = n2\pi$
Phase advance of 2π during path length of λ, *so …*

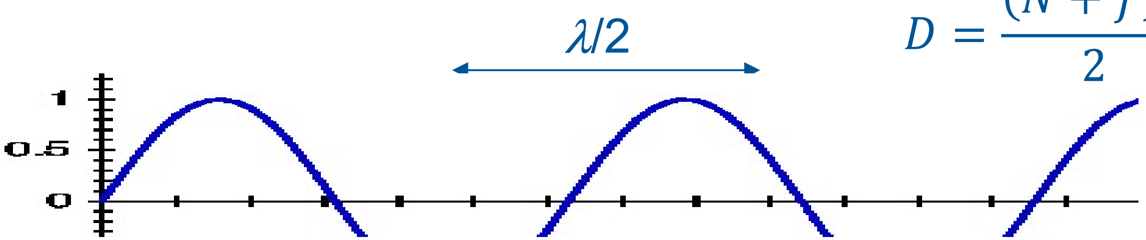
Observed intensity is periodic over path length difference of λ
Interferometry measures distances in units of wavelength

Simple interferometer

- Narrow beam (unexpanded laser)
- Amplitude splitting
- *Measurement* and *reference* arms
- Co-sinusoidal intensity variation at detector as one mirror moved *w.r.t.* other
- Double pass doubles the sensitivity, $\Delta\boldsymbol{\varphi} = 2n\pi, \Delta\boldsymbol{\varphi} \propto 2\boldsymbol{D}$ so every $\lambda/2$ = *fringe*



$$D = \frac{(N + f)\lambda}{2}$$



N = fringe **order**
f = fringe **fraction**

Interferometry basics

Summary of main concepts

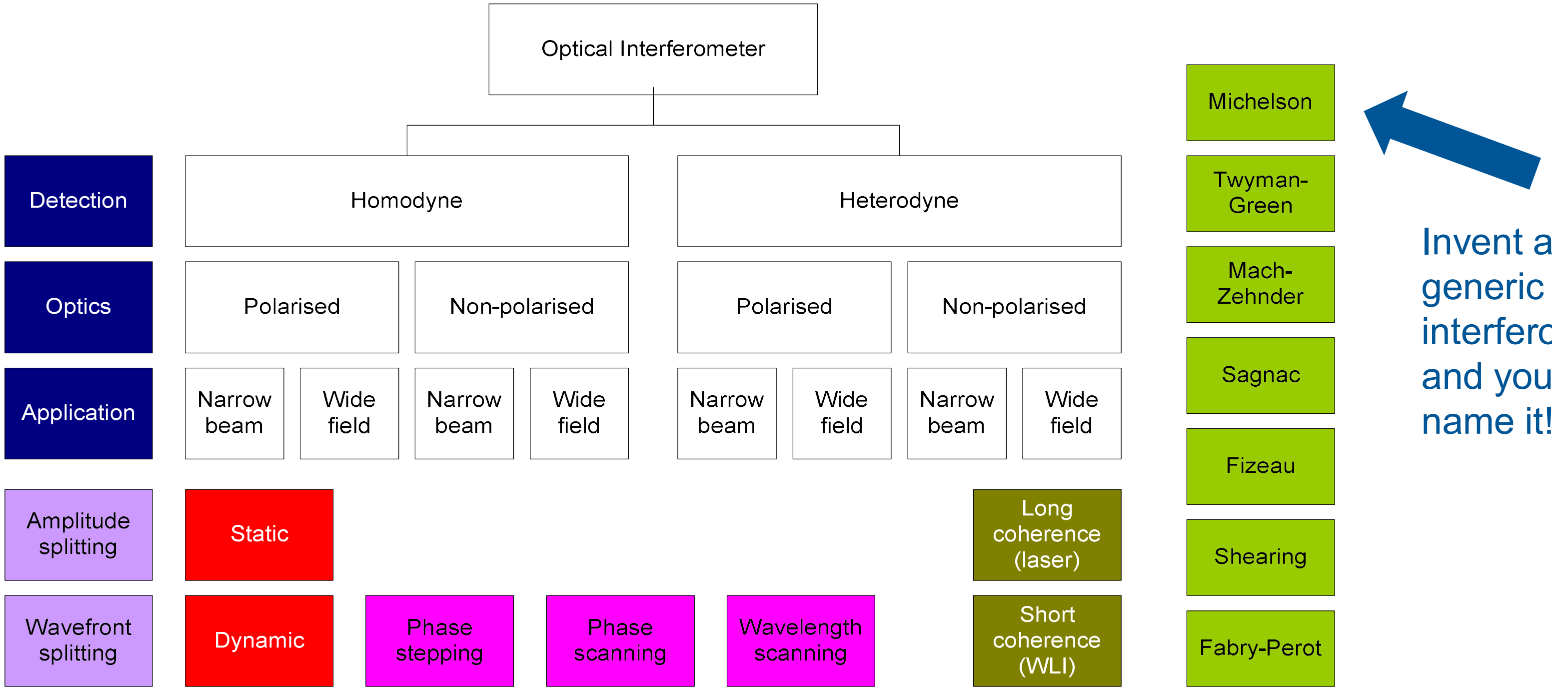
- Interference intensity shows phase difference $\Delta\varphi$
- $I(x, y) = a + b\cos(\Delta\varphi)$

  cosine variation with phase, with 2 extremes:

  dark = destructive (out of phase)

  light = constructive (in phase)
- Phase ∝ optical path length travelled
- Interference fringes spaced at $\lambda/2$
- $D = \frac{(N+f)\lambda}{2}$
- Knowing λ, counting or guessing *N*, measuring *f*, gives *D*

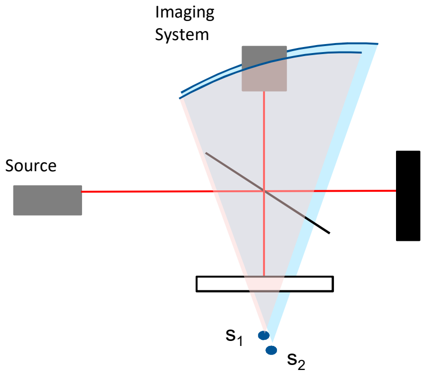
Interferometer types

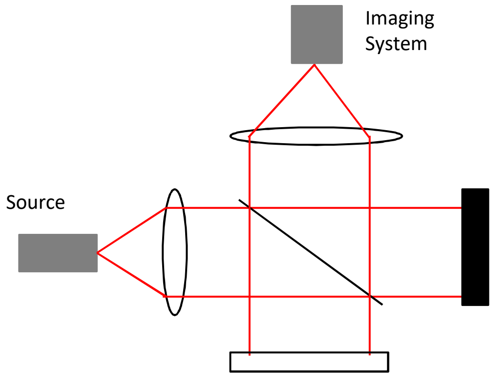


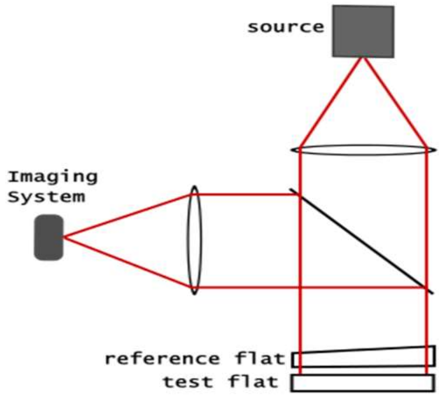
Invent a new generic type of interferometer and you got to name it!

Optical layouts

Common amplitude splitting interferometers







Michelson

Most common interferometer

Un-collimated beams

Fringes of different shape depending on path difference and mirror tilt (circles, conic sections, straight)

Fringes localised at mirrors or infinity when using extended source

Twyman-Green

Collimated (expanded) Michelson

Straight fringes

Double path – double sensitivity

Often used in surface metrology

Long paths require good coherence length (temporal coherence) such as lasers or stabilised lasers

Fizeau

Collimated (expanded) Michelson

Can have long common path

Short uncommon path

Double pass – double sensitivity

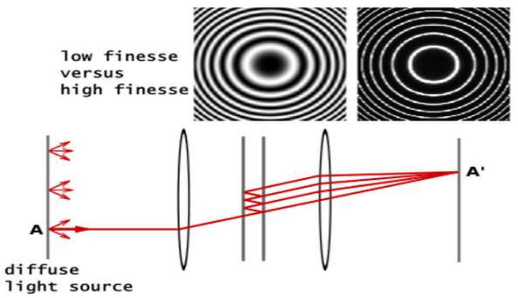
Often used in surface metrology

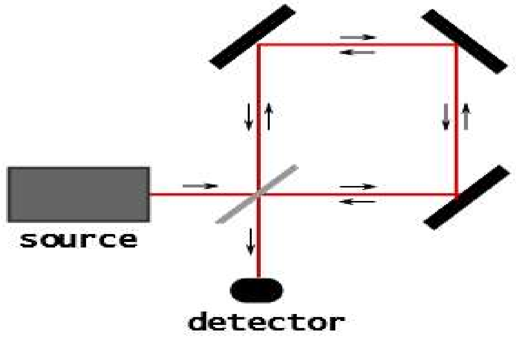
Works well with sources of lower coherence length *e.g.* discharge lamps, broader band sources (white light)

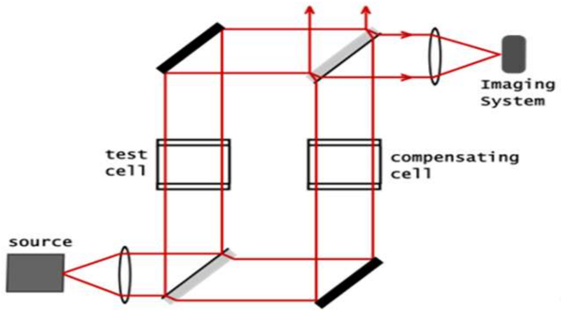
https://en.wikipedia.org/wiki/Interferometry

Optical layouts

Common amplitude splitting interferometers







Fabry Perot

Multiple reflections

Highly sensitive to thickness of 'cavity'

Can control *finesse* by changing reflectivity – higher R gives higher *finesse* (or 'Q')

Sagnac

Counter-propagating beams

Common path

Rotation sensing (angular velocity)

Based on invariant value of *c* in all frames (special relativity)

Also can be formed from an optical fibre ring to make fibre-optic gyroscope

Mach Zehnder

Separated path Fizeau/Twyman-Green

Single pass, balanced reference arm (*c.f.* test arm)

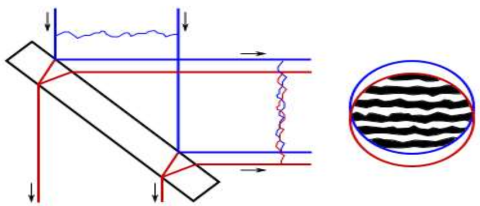
Good for 2D imaging of refraction and other phase-effects

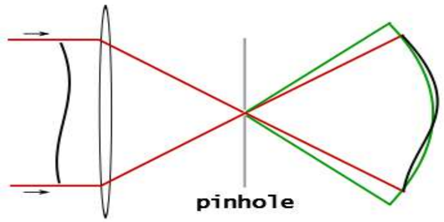
Used in holography and many quantum experiments

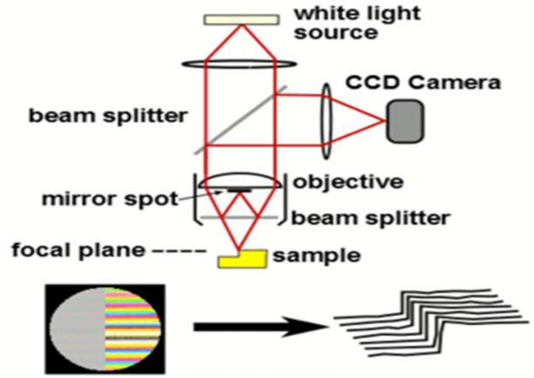
https://en.wikipedia.org/wiki/Interferometry

Optical layouts

Other common interferometers







Lateral shearing

Simple singular optic – self fringing

Sensitive to collimation

Used for setting focal length in collimators (fringe rotate with change in de-collimation)

Usually uses wedged plate

Point diffraction

Common path interferometer – generates own reference beam

Focused to give Airy disc at pinhole in semi-transparent filter

Zeroth order beam transmitted

Interferes with reduced intensity transmitted beam from entire wavefront

Good in vibrational environments

White light

Broadband light source

Very short coherence

Fringes only at (near) equal path lengths (reference arm = test arm)

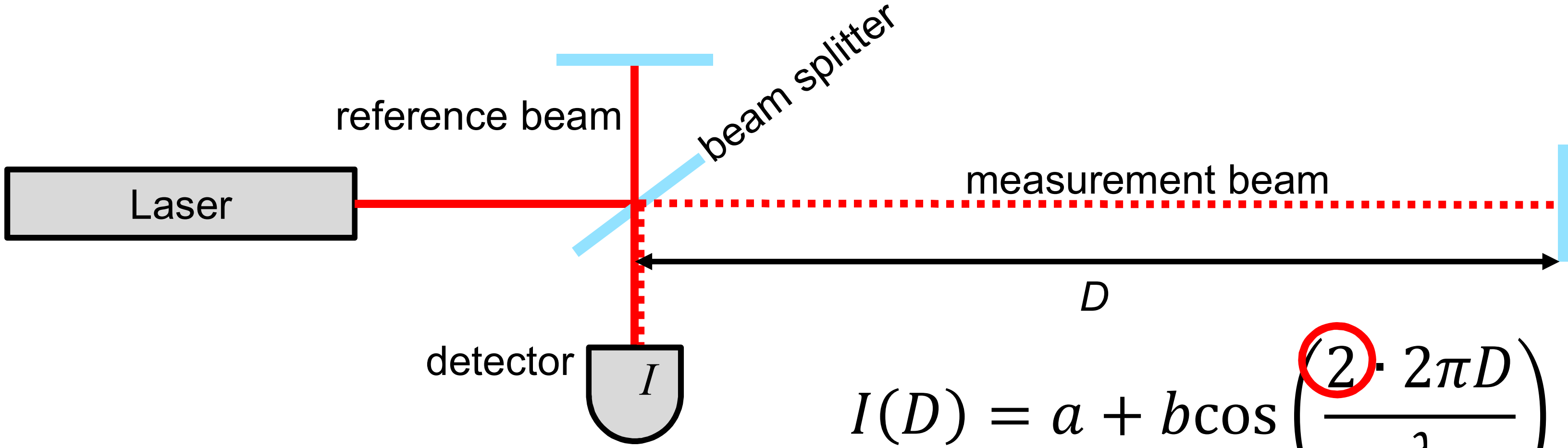
Can use to locate a surface's position

Central fringe dark or light depending on number of phase changes on reflection

https://en.wikipedia.org/wiki/Interferometry

Homodyne displacement interferometer

Single fringe resolution, ~300 nm



$$I(D) = a + b\cos\left(\frac{2 \cdot 2\pi D}{\lambda}\right)$$

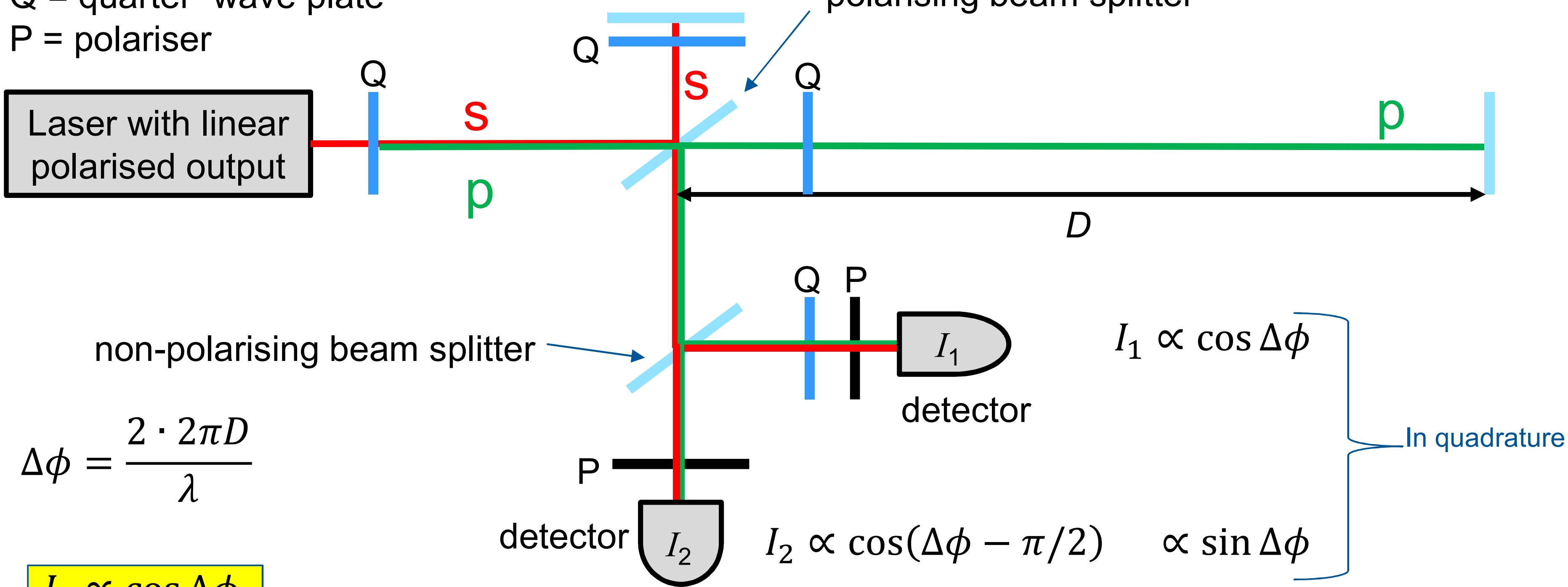
Interference fringes spaced $\lambda/2$ apart = 633 nm/2 = 317 nm

Difficult to interpolate to sub-fringe resolution:

- Instantaneous intensity *vs.* drift in $\boldsymbol{a}$ and/or $\boldsymbol{b}$ as laser power changes
- Stray light, *etc*.
- Cannot determine direction

Polarised homodyne interferometer
Sub-fringe interpolation

Q = quarter wave plate
P = polariser



$$\Delta\phi = \frac{2 \cdot 2\pi D}{\lambda}$$

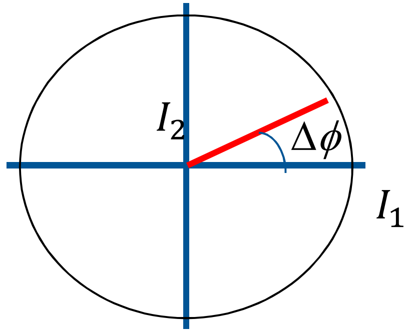
$$I_1 \propto \cos\Delta\phi$$
$$I_2 \propto \sin\Delta\phi$$

Both detectors see combination of s and p

Quadrature counting (homodyne)

Sub-fringe phase interpolation

$$I_1 \propto \cos \Delta\phi$$
$$I_2 \propto \sin \Delta\phi$$

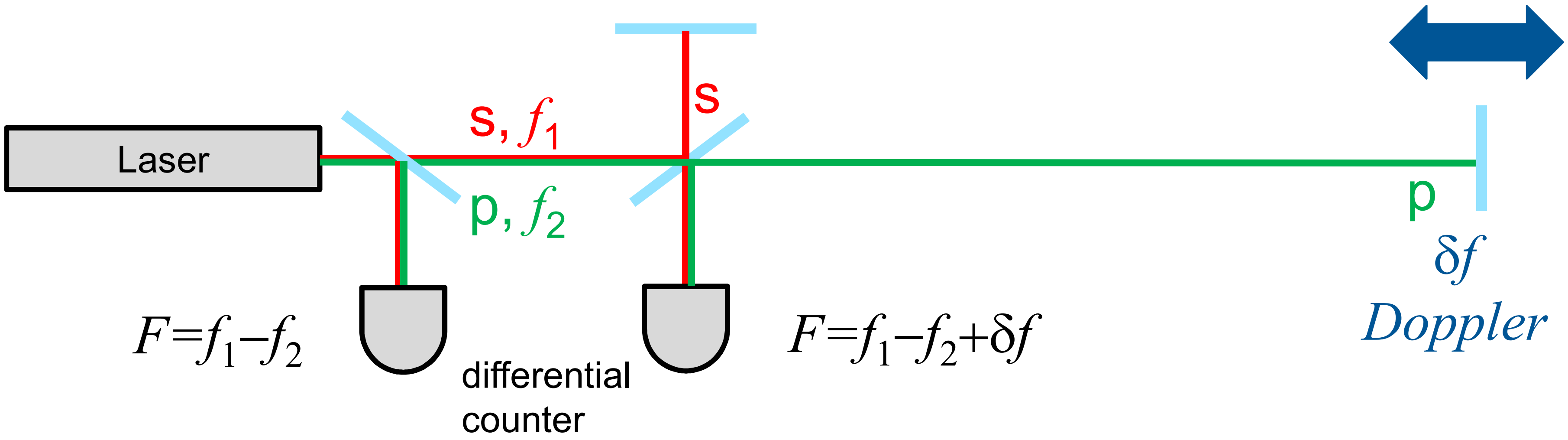


$$\Delta\phi = \tan^{-1}\left(\frac{I_2}{I_1}\right)$$

- Instantaneous resolving of sub-fringe phase
- Direction available from fringe crossing order & phase
- Fringe crossing can trigger *integer counts*
- Multi-fringe, fringe-interpolating displacement
- But… subject to non-linearities, phase quadrature errors requiring correction (‘Heydemann’)

Heterodyne interferometers

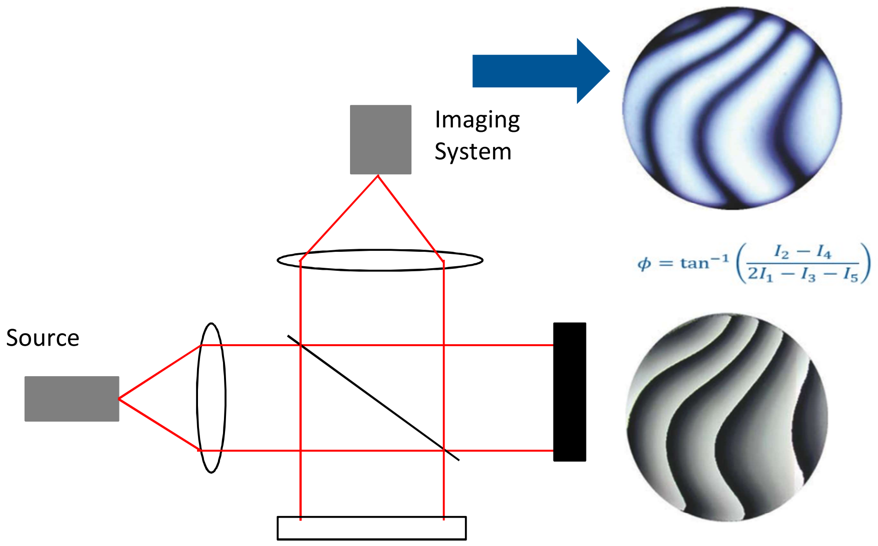
Beams with differing wavelengths



s and p polarisations have different optical frequencies, f_1, f_2
Differential counter: 0 if stationary, + or – if mirror moving
Output of differential counter gives velocity (with direction)
Integration over time gives displacement in wavelength units

Wide field interferometers

Optical testing

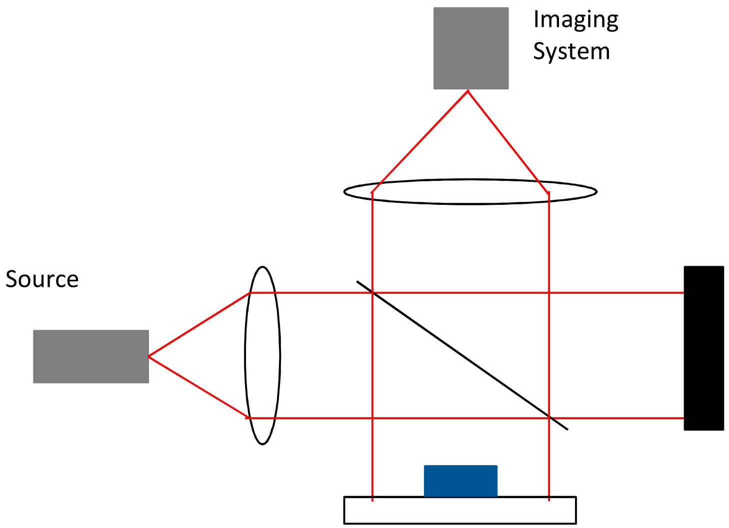


- Fringes are height contours spaced $\lambda/2$
- Static evaluation tricky
- Phase-stepping/scanning achieved by varying one optical path, *e.g*. PZT pushing the reference mirror
- Many algorithms to recover phase, but all give phase modulo 2π
- Have to cope with 2π discontinuity at fringe boundaries – add or subtract 1 fringe (2π)
- Cannot cope (easily) with step changes at the surface
- Range limited by camera resolution (at least 2 pixels/fringe)

Images: Thalmann (METAS)

Coping with steps > $\lambda/2$

Multiple wavelength interferometry for step heights

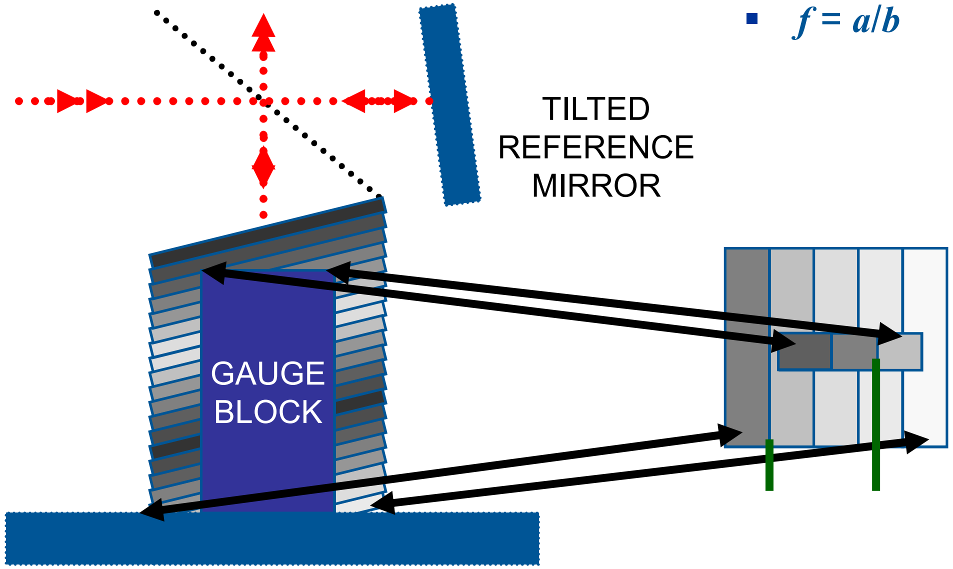


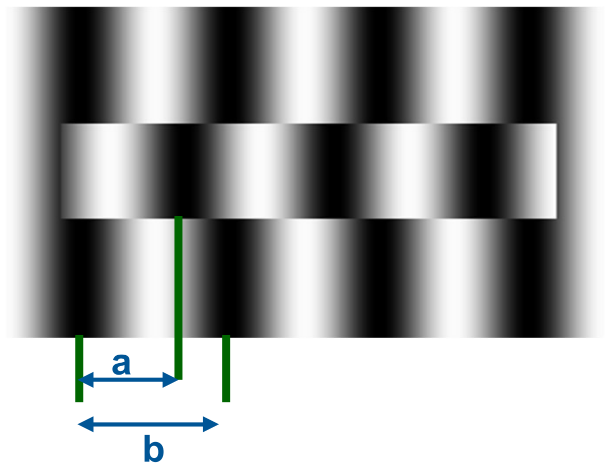
- Surface with a step height *e.g*. 10 mm
- *e.g*. gauge block attached to a flat surface
- Fringe discontinuity >> 2π
- How many fringes (2π) to add/subtract?

Image: Thalmann (METAS)

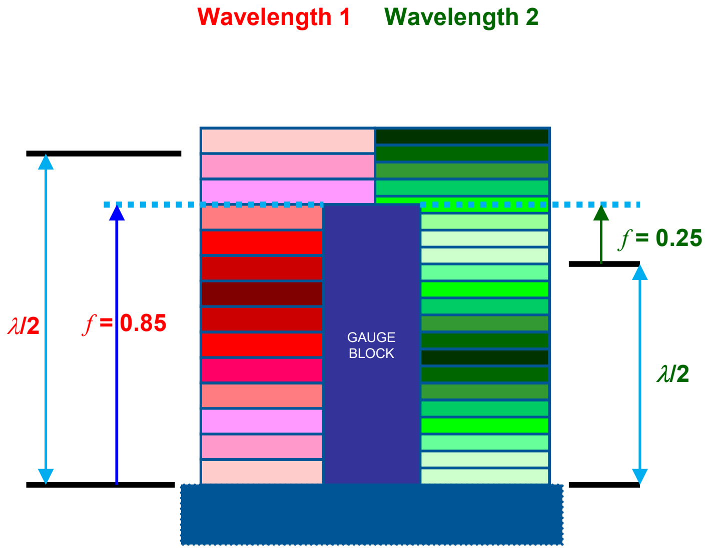
Measure fringe fractions at two wavelengths

- Tilt the reference mirror to obtain more fringes
- Illuminate with one wavelength and grab image (or phase step)
- Illuminate with second wavelength (different colour) and grab image (or phase step)
- Look at fringe fractions, f, for both cases
- $f = a/b$





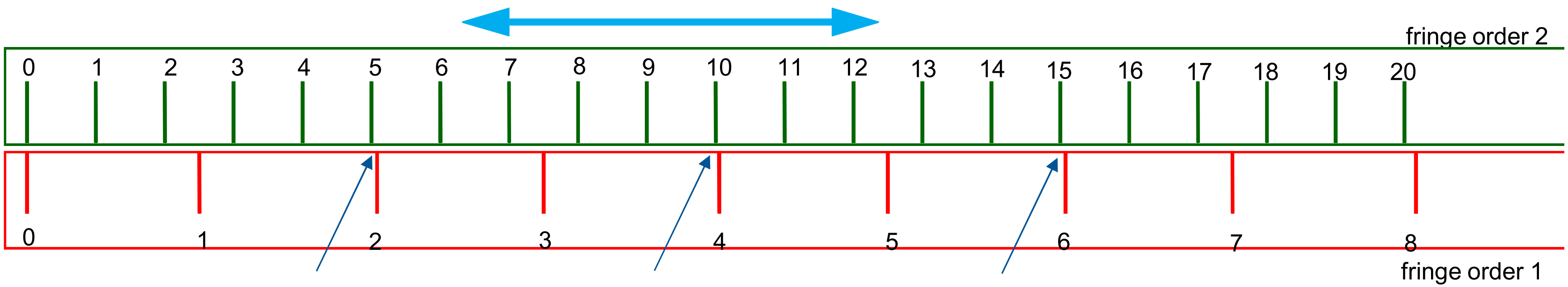
Conceptual view of measurement



$$L = (N_1 + f_1)\frac{\lambda_1}{2}$$

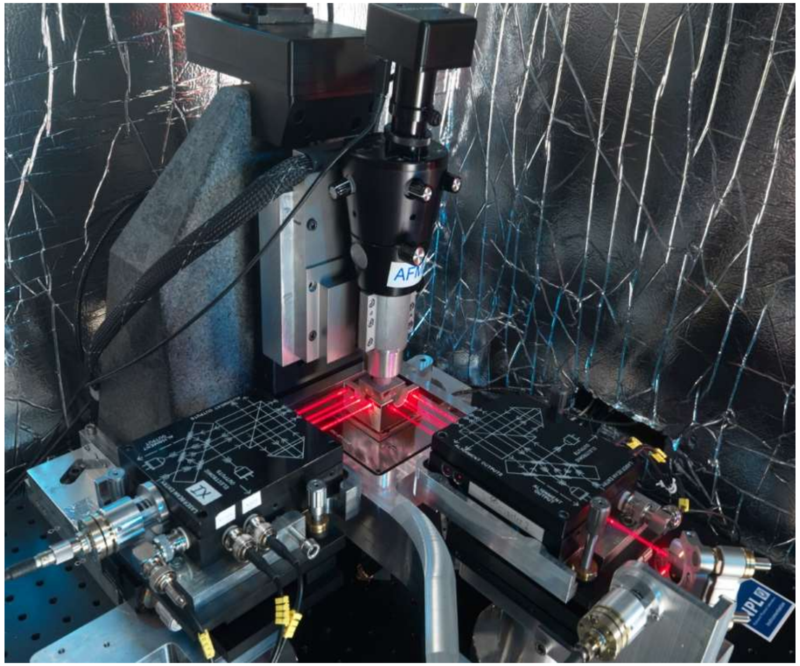
$$L = (N_2 + f_2)\frac{\lambda_2}{2}$$

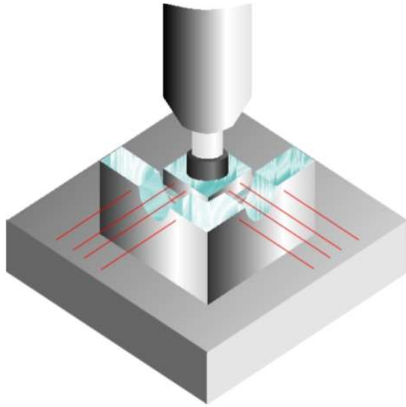
- Know $\boldsymbol{\lambda_1}$ and $\boldsymbol{\lambda_2}$
- Measure $\boldsymbol{f_1}$ and $\boldsymbol{f_2}$
- Have an estimate for $\boldsymbol{L}$
- From $\boldsymbol{L}$, estimate likely range of N_1 and from that estimate the corresponding range of N_2
- Look for solutions for $\boldsymbol{L}$ that match within the likely range
- Ensure $\text{range} < \frac{1}{2}\frac{\lambda_1\lambda_2}{\lambda_1 - \lambda_2}$ for unique solution



Traceable nanometrology

The metrological atomic force microscope





Mirror fixed to PZT tube

Mirror on stage that holds sample

Both are 3 sided orthogonal mirrors

Optical interferometers measure the relative displacement of the AFM tip and the sample in x, y and z axes.

Turn off and not use the scanning PZT as it is highly non-linear

Images: Yacoot (NPL)

Interferometry in air

Refraction and refractive index

Refractive index (n)

Issue when operating in air (not vacuum)

n = 1.000 2XX XXX

Dispersive

Reduces speed of light & wavelength

Uncompensated → wrong distances

$$\lambda = c/f \qquad c = c_{vac}/n$$

$$\lambda = \lambda_{vac}/n$$

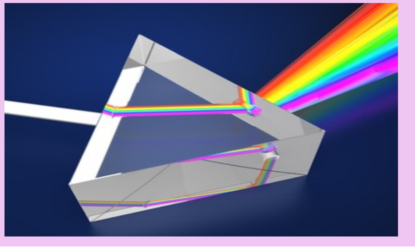
Refraction

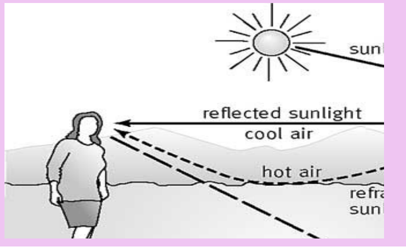
Occurs at change in refractive index or
in a refractive index gradient
e.g. Earth air pressure & temperature gradient

Dispersive

Bends light beams

Uncompensated → wrong direction





Images: Wikipedia

Refractive index details

- See lecture 1 for more information

Fundamental principles & techniques of dimensional metrology

- Abbe principle
- Mechanical stability
- Thermal stability
- Alignment
- Probe/surface interaction
- Error separation techniques
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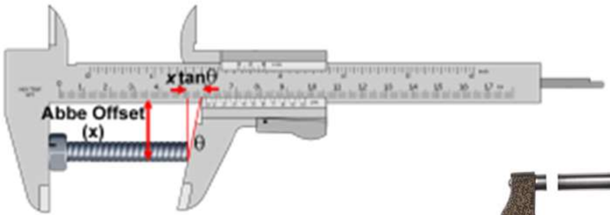
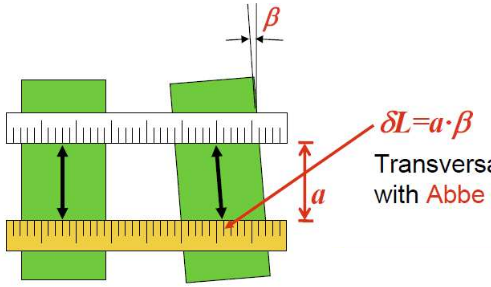
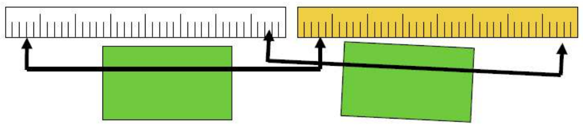
Abbe principle

- Measurement scale is not in line with the object being measured – Abbe offset, x
- Straightness of axis or sloppy fit of calliper causes angle between jaws, θ
- Length measurement error $\delta L \approx \theta x$
- Eliminate by aligning scale coaxially with part, or compensate my measuring x and θ





Transversal comparator with Abbe offset a



Longitudinal comparator

Minimise Abbe offset where possible or compensate

Images: Thalmann (METAS)

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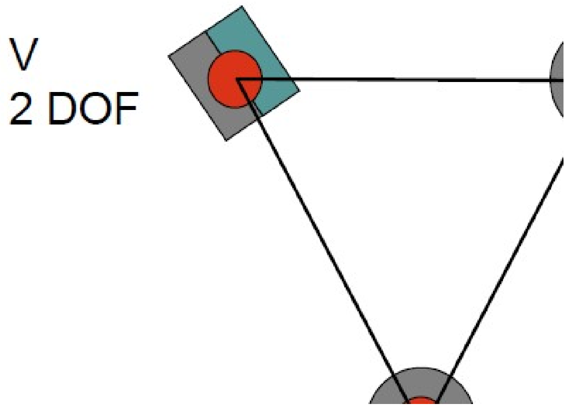
Mechanical stability

Kinematic mounting

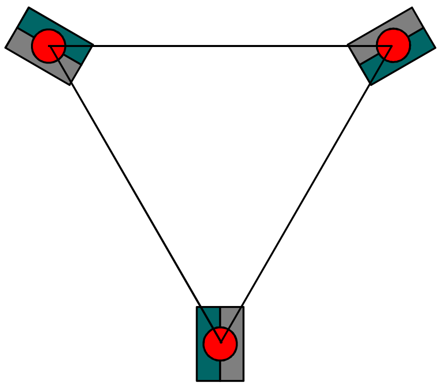
- Assume: nothing is perfectly flat, contact is at microscopic level, possible motion gives errors
- Ideally, 6 constraint contact: 3 position, 3 rotation
- Concept of kinematic mounting

Kelvin coupling



Guaranteed centre of rotation (cone)

Maxwell coupling

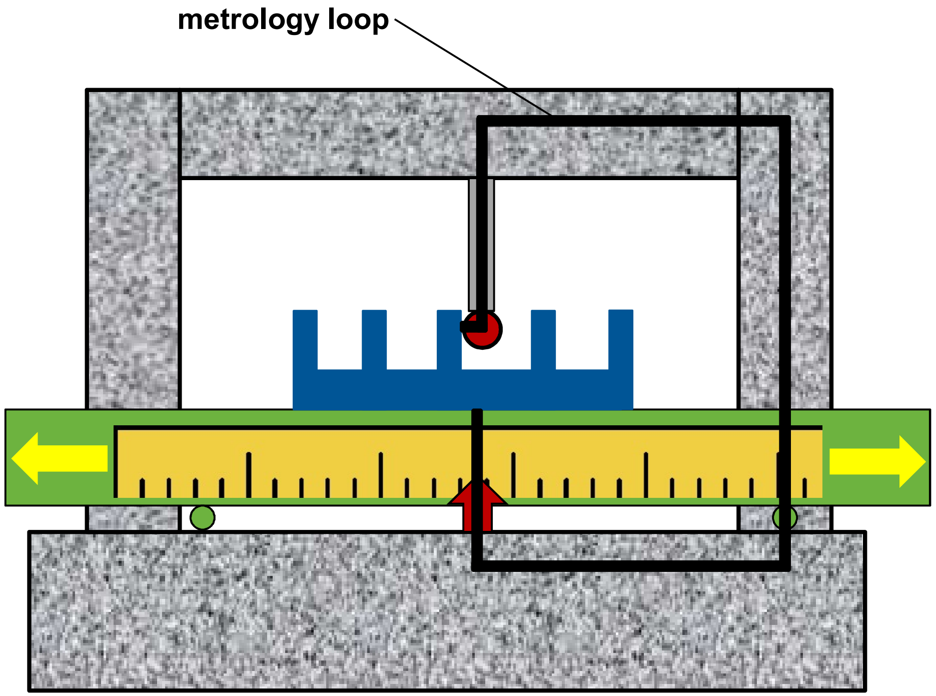


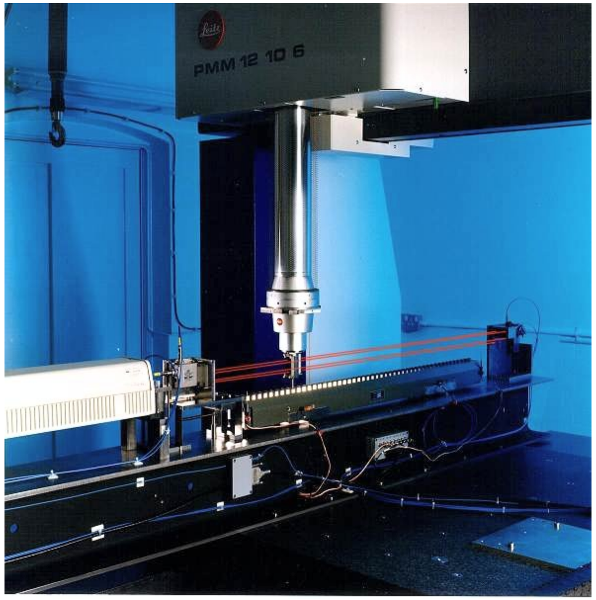
Thermally stable centre point

Utilise correct kinematic mounting

Mechanical stability

Stiffness, high resonance frequency, stable metrology loop

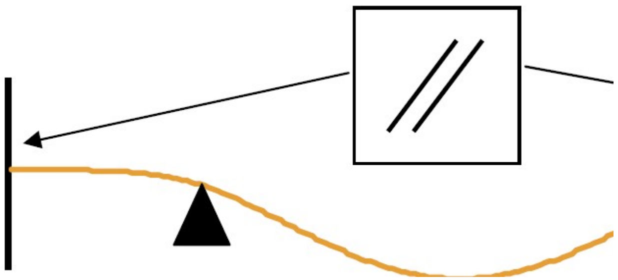




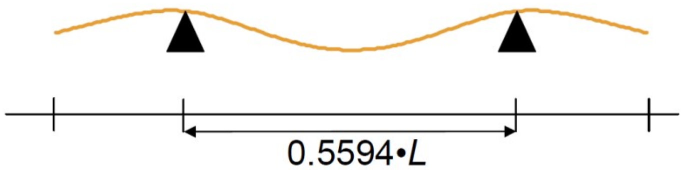
The metrology loop must be stable or measured

Mechanical stability

Gravitational bending



desire parallel end faces
e.g. gauge blocks
Airy points



desire minimum total length change
e.g. line scales
Bessel points

Correct support needed for artefact and parts of instrument

Images: Thalmann (METAS)

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Thermal expansion
Gravitational bending

Thermal expansion coefficients, α, (standard values)

Steel	11.5×10^{-6} K^{-1}	Quartz	0.5×10^{-6} K^{-1}
Aluminium	25×10^{-6} K^{-1}	Zerodur	0.03×10^{-6} K^{-1}
Tungsten carbide	4.3×10^{-6} K^{-1}	ceramic	5.5×10^{-6} K^{-1}

ISO 1 – 'reference temperature for dimensional metrology is 20 °C'

Correct measurement result to 20 ° C using $\boldsymbol{L}_{20} = \boldsymbol{L}_{\mathrm{T}}[1 + \boldsymbol{\alpha} \cdot (20\ ^\circ\mathrm{C} - \boldsymbol{T})]$

But, $\boldsymbol{u}(\boldsymbol{\alpha})/\boldsymbol{\alpha} \approx 10\ \%$!

The most expensive equation in dimensional metrology

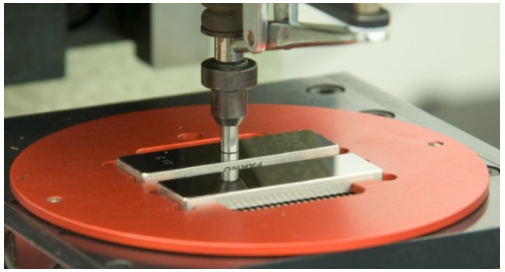
Unless you measure α and know the object temperature very well…
Measure as close as possible to reference temperature 20 °C
Or use 'tricks'

Thermal expansion

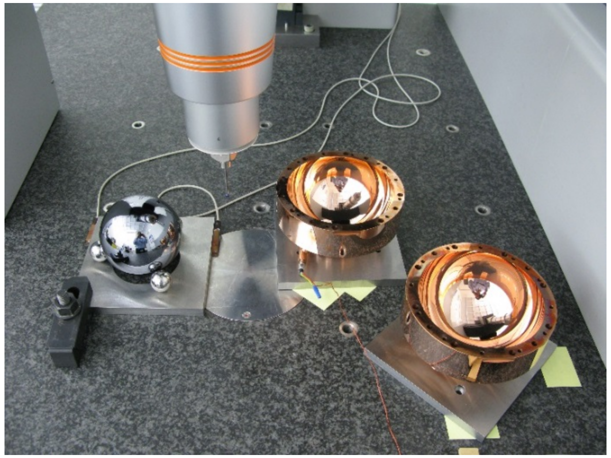
'Tricks' to minimise problems

Match (CTE × *L*) for thermal stability

- Thermally controlled environment (ideally just the volume local to the instrument)
- Compact and thermally compensated instruments (metrology loops)
- Fast measurements(low drift)
- Low and constant power consumption, reduce operator's influence
- Use of low expansion materials: Invar, Super-Invar, Zerodur, Carbon fibre reinforced epoxy...
- Use comparison/substitution methods between objects of similar materials



Two gauge blocks:
- Same material
- Same length
- Same (~) temperature



Images: Various (NPL)

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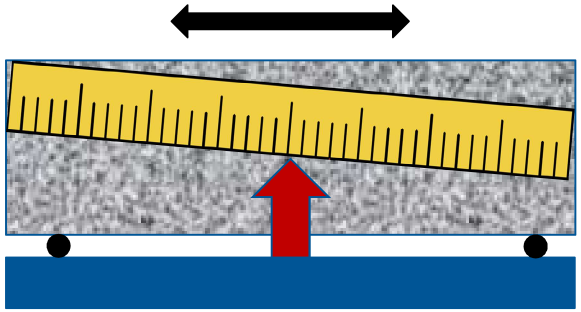
Alignment

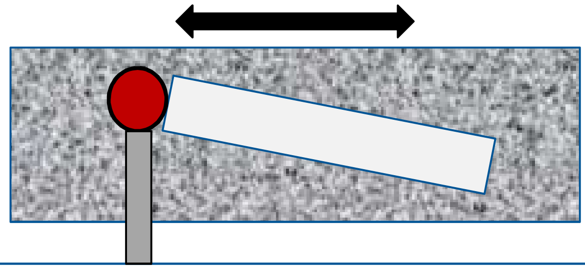
Avoiding excessive cosine errors

- Cosine error $\delta L = L(1 - \cos\alpha) \approx \frac{1}{2}\alpha^2 L$
- Messing up the alignment is obvious on macro-scale!
- Rule of thumb:
- 1 mm in 1 m is 0.5 ppm error in L
- Precision dimensional metrology often demands $u(L)/L < 5 \times 10^{-9}$ and this requires < 10 µm misalignment over 1 m

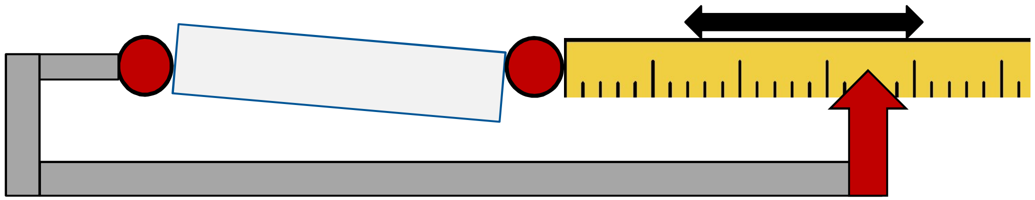
‘Design for align’



Scale not parallel to movement **scale cosine error**



Artefact not parallel to movement **artefact cosine error**



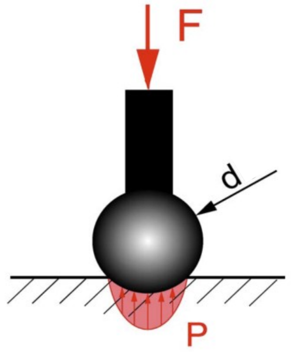
Artefact not parallel to scale **artefact cosine error**

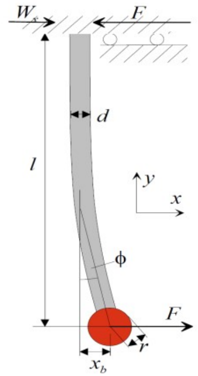
Fundamental principles & techniques of dimensional metrology

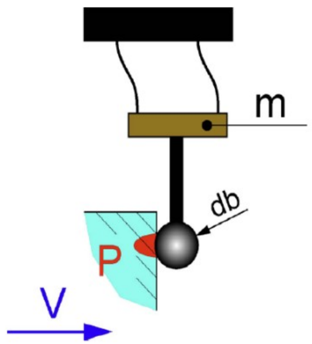
- Abbe principle
- Mechanical stability
- Thermal stability
- Alignment
- Probe/surface interaction
- Error separation techniques
- Error mapping

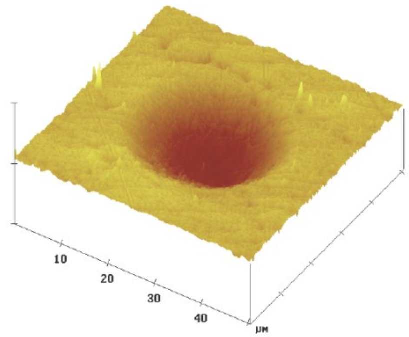
Probe-surface interaction

Common to all contact-based measuring systems









Hertzian compression, a

$$a = \frac{1}{2}\left(\frac{3}{F}\left(\frac{1-\nu_1^{\,2}}{E_1}+\frac{1-\nu_2^{\,2}}{E_2}\right)\right)^{2/3}\left(\frac{1}{d}\right)^{1/3}$$

E_1, E_2 are elastic moduli
ν_1, ν_2 are Poisson ratios

Stylus bending:
- *rotation*
- *displacement*

Dynamic forces
Impact on surface approach
Plastic deformation

Use small forces, small masses, low speed
Elastic compression correction by calculation or extrapolate to zero force from several forces

Images: Thalmann (METAS)

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CJ Evans, RJ Hocken, WT Estler,
"Self-calibration: Reversal, redundancy, error separation, and absolute testing"
Annals of CIRP 45(2) 1996

DOI: 10.1016/S0007-8506(07)60515-0

Primary measurement methods

Separation of errors from form elements

- Classical form elements are intrinsically defined:
  - straight line
  - plane
  - circle
  - cylinder
  - sphere
  - angles

- Primary measurement methods are based on error separation
  - separate the machine form error from the test object
  - several overall techniques:
    - reversal
    - multi-step
    - multi-artefact
    - circle closure

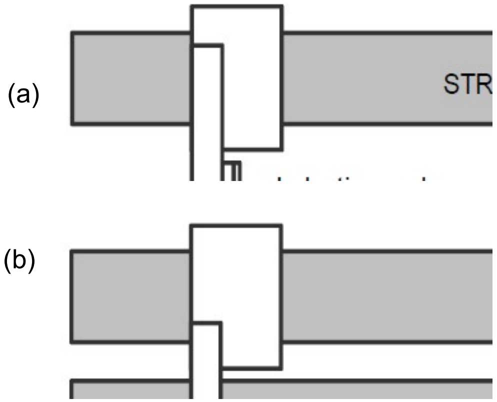
- (Freeform measurements are thus more difficult)

Error separation by reversal

Invert the probing direction and the part

Reversal can remove machine form errors

Straightness



measured profiles

$p_a(x) = s_2(x) - s_1(x)$

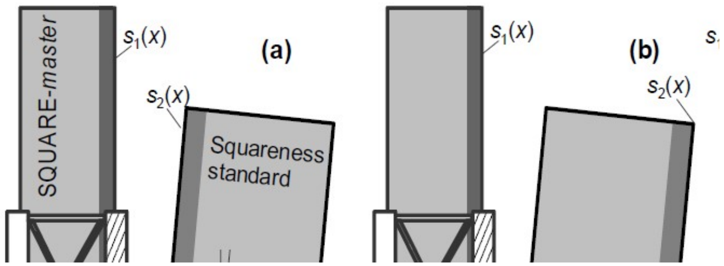
$p_b(x) = s_2(x) + s_1(x)$

straightness deviations

DUT: $s_1(x) = ½[p_b(x) - p_b(x)]$

Instrument: $s_2(x) = ½[p_b(x) + p_b(x)]$

Squareness



α_1, α_2 are squareness of machine and part

measured profiles

$p_a(z) = s_2(z) - s_1(z) + (\alpha_1+\alpha_2-\alpha_3)\cdot z$

$p_b(z) = s_2(z) + s_1(z) + (\alpha_2-\alpha_3+\alpha_1)\cdot z$

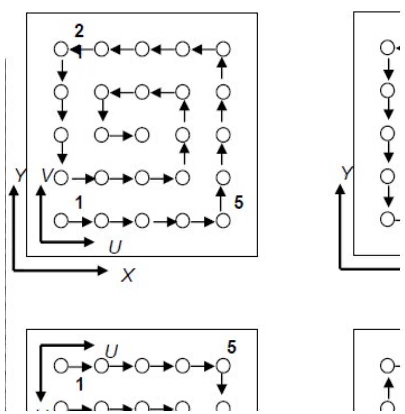
$p_c(z) = s_2(z) + s_1(z) + (\alpha_2+\alpha_3+\alpha_1)\cdot z$

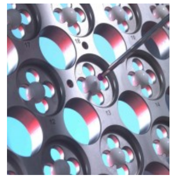
$s_1(z) = \alpha_1\cdot z = ½[p_c(z) - p_a(z)]$

$s_2(z) = \alpha_2\cdot z = ½[p_b(z) + p_a(z)]$

$\alpha_3\cdot z = ½[p_c(z) - p_b(z)]$

CMM ballplate
4-fold reversal





Four-fold rotation is equivalent to:

- two line reversals (x y axes)
- two squareness reversals

Determines:

- position errors of balls
- CMM axes squareness
- CMM axes straightness

Repeat for other CMM axes

Images: Thalmann (METAS)

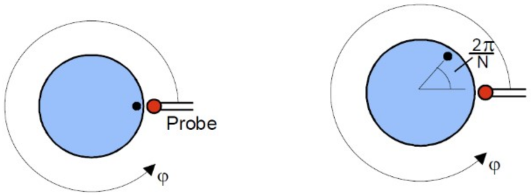
Error separation

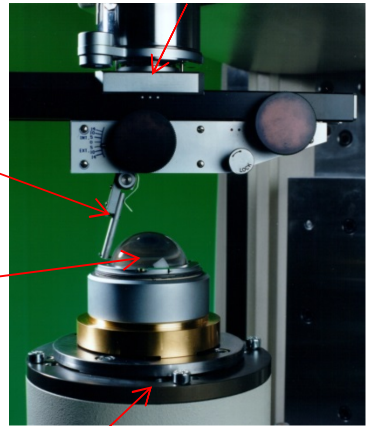
Multi-step roundness

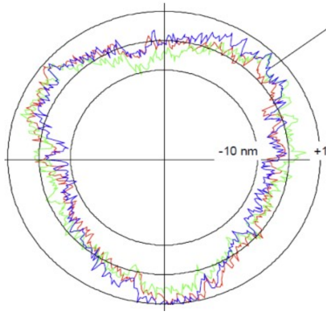
Machine spindle accuracy 20 nm – 30 nm
Roundness standard accuracy ~ 40 nm
Roundness profile is combination of both errors

<u>Multi-step</u>

Measure at initial alignment (rotate spindle)
Repeat (N =1, … 5 or higher)
    Repeat:
        Rotate indexing stage by $2\pi/N$
        Measure again (rotate spindle)
    Until alignment is back at start
Until N is high enough
Separate out errors (except unresolved)
For N = 24, still 4 % of harmonic errors remain







Multi-step good but slow.
Use pseudo-random steps, Fourier series of signal and in frequency domain to speed up technique

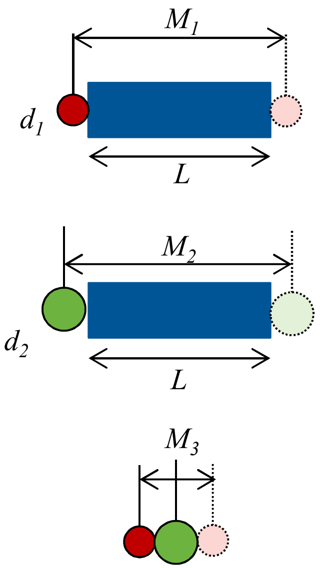
Images: Thalmann (METAS), Flack (NPL)

Error separation

More reversals!

Absolute flatness achievable but slow
Can use liquid surface as pseudo perfect flat

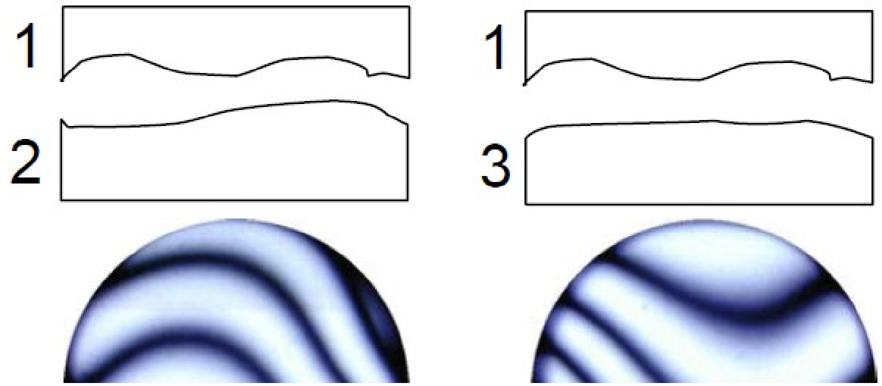
Probe ball reversal



$M_1 = d_1 + L$
$M_2 = d_2 + L$
$M_3 = d_1 + d_2$

$d_1 = [M_1 – M_2 + M_3]/2$

Three flat test
(in a Fizeau interferometer)



$I_1 = S_1 + S_2$ $I_2 = S_1 + S_3$ $I_3 = S_2 + S_3$

$S_1(x) = [I_1(x)+I_2(x) – I_3(x)]/2$

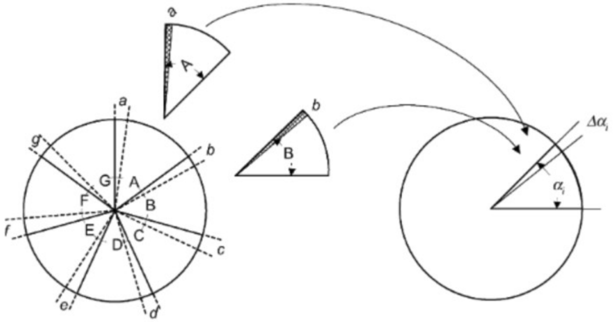
Insufficient information for 2-D problem
over both $I_k(x,y)$ and $S_k(x,y)$
But there is one line of reversal across all
three interferograms (x –axis)
Use this line to transfer known profile to full surface

Images: Thalmann (METAS)

Error separation

Full closure on circle for angle calibrations

- Based on principle that all angles in a circle (or polygon) sum to 2π (360°)



(a) Circle 1 (b) Circle 2

7 sided polygon (or circle)
Angle intervals: A, B, C, D, E, F, G each with small error: a, b, c, d, e, f, g

Sum of all angles must be 360°, hence sum of all errors must be zero
Compare all intervals with a second circle interval of size α_1 which has small error $\Delta\alpha_1$ to obtain seven differences $x_1, x_2, \ldots, x_7$

$\Delta\alpha_i - a = x_1$ $\Delta\alpha_i - b = x_2$ $\Delta\alpha_i - c = x_3$ $\Delta\alpha_i - d = x_4$
$\Delta\alpha_i - e = x_5$ $\Delta\alpha_i - f = x_6$ $\Delta\alpha_i - g = x_7$

$$a + b + c + d + e + f + g = 0$$

$$7\Delta\alpha_i - (a + b + c + d + e + f + g) = x_1 + x_2 + \ldots + x_7$$

$\Delta\alpha_i = [x_1 + x_2 + \ldots + x_7]/7$ and $\mathrm{a} = \Delta\alpha_i - x_1$ *etc.*

Methods exist using:
multiple autocollimators and rotary table
single autocollimator and indexing table with rotary table

Precision autocollimators have limited range so may cause problems with indexing tables

Image from: Yandayan *et al. Prec. Engg.* 26 (2002) 414-424

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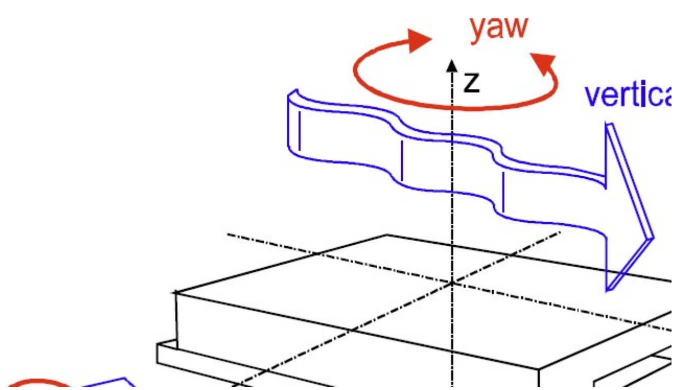
Error mapping

A priori error separation (using external tool)



Error map of Coordinate Measuring Machine

For each of 3 axes:

- 3 translational errors
  - Txx = Px position error
  - Txy, Tx,z: straigntness error
- 3 rotation errors:
  - Rxx: roll
  - Rxy: pitch
  - Ryz: yaw

3 angles between axes

21 error files for map of motion errors

Techniques for error mapping:

- Multiple ball-plate reversals
- Laser interferometer with additional optics (angle, straightness)
- Laser tracer measuring distance as probe makes traversals
- Traditional artefacts (squares, straight edges, *etc.*)

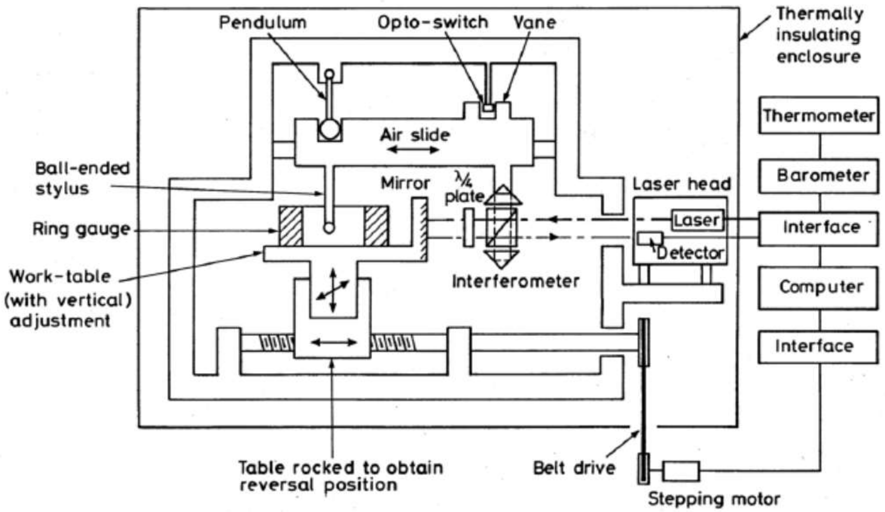
Error mapping useful only if machine is stiff and has repeatable and reproducible errors

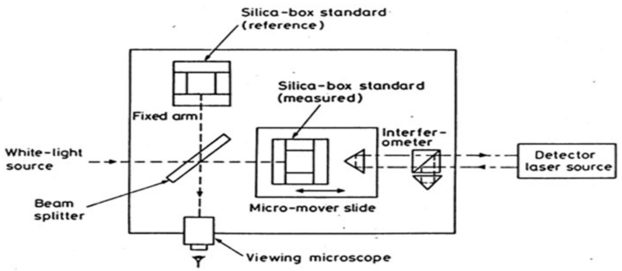
Examples of dimensional measuring instruments

- Internal diameter measuring machine
- Length bar interferometric comparator
- Step gauge machine

Internal diameter measuring machine

Measure internal diameter of ring gauges





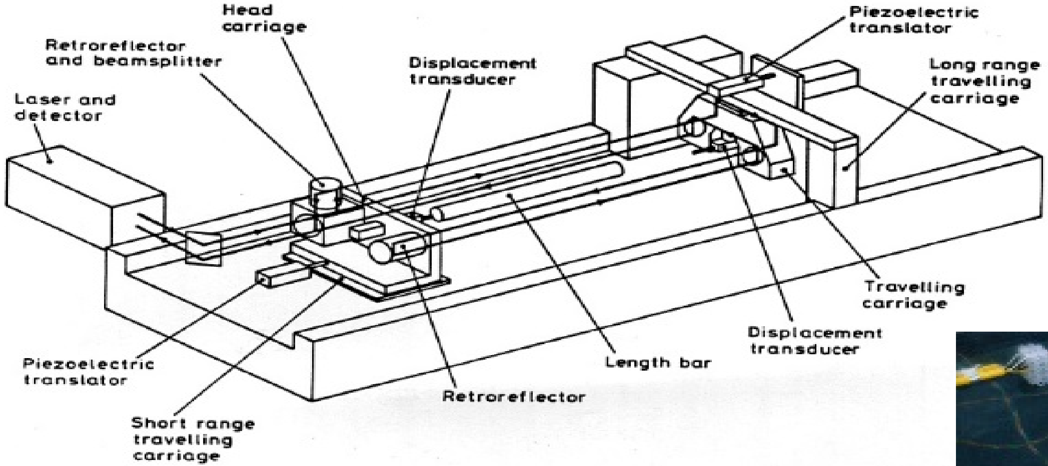
Images: Flack (NPL)

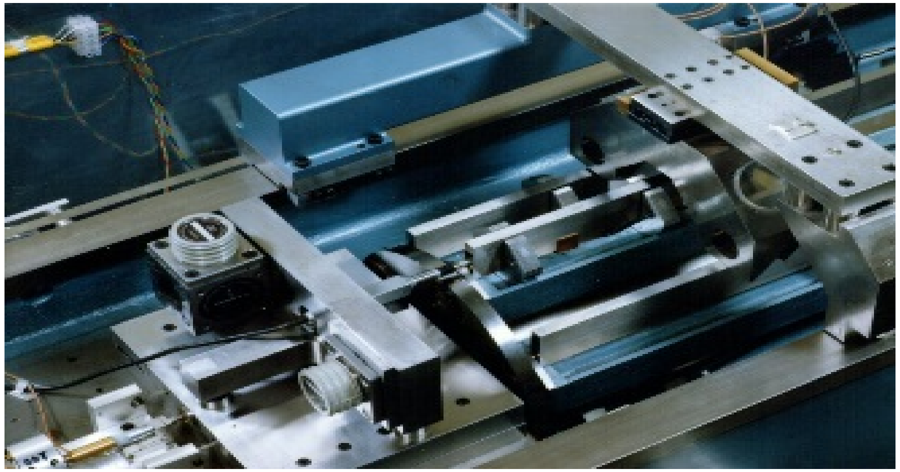
Secondary length bar interferometer

Measurement of end standards

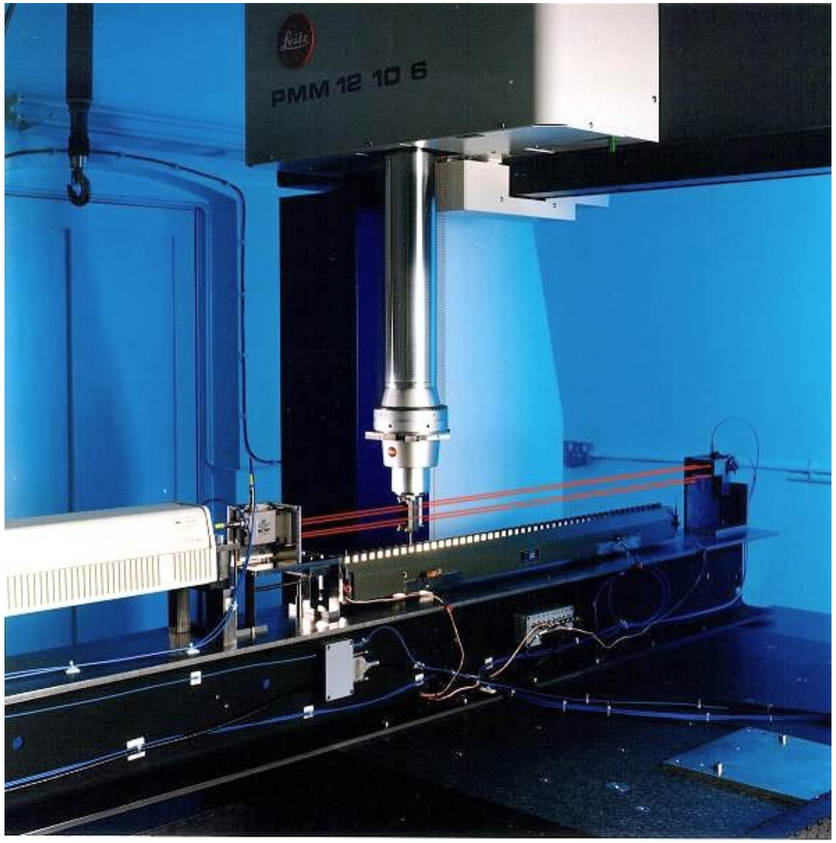
Length bar interferometric comparator

Compares bars using a laser for scale





Step gauge machine



Probe must move in/out of gaps – Abbe offset
Abbe offset correction:

- measure probe tilt using extra interferometer
- *a priori* Abbe offset measurement
- compute Abbe error correction

Commercial CMM used as motion device
Double pass interferometry
Twin interferometers (double ended)both: distance and tilt

- far interferometer is column reference

Refractive index correction

$U_{95}(L)$ = 100 nm + 3 × $10^{-9}L$ U_{95}(1 m) = 400 nm

Dimensional metrology outside the NMI

Countless real-world applications of dimensional metrology. Notable ones:

Big Science: alignment of magnetic sub-systems of the Large Hadron Collider successor to better than 10 µm accuracy every 200 m;

Nanoscience: extending the practical SI length scale to bio applications;

Aerospace: 100 µm uncertainty in full aircraft wing or wing jig measurements and

100 µm accuracy in gas turbine factory over temperature range of 10 ºC to 10 ºC;

Healthcare/lifescience: ability to perform traceable AFM scanning of e.g. DNA molecules in real time;

Energy: metrology of 3D micro-structured electrodes used for electricity storage in batteries for electric vehicles; wind turbine blade mould metrology;

Environment: long-term stable sensors at the µm level for engineering strain monitoring in protective structures (dams, bridges);

Astronomy: traceable aspheric and freeform metrology of large (50 m) optical telescope mirrors during manufacturing and servicing.

Aerospace industry – exemplar traceability user

Airbus A380 wing

Compensation for refractive index and turbulence effects in large factories

1000 kg extra metal in a large aeroplane!

(not just Airbus – industry-wide problem!)

Airbus A350 XWB wing

International supply chains require proper SI traceability

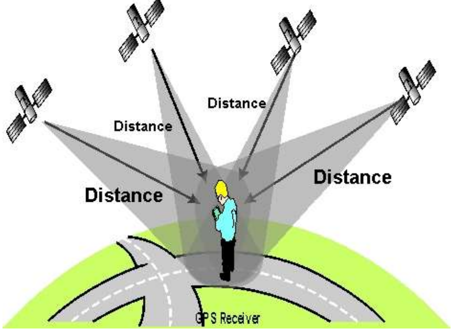
Metrology of difficult things in ‘poor’ environments

Force metrologists to develop new techniques

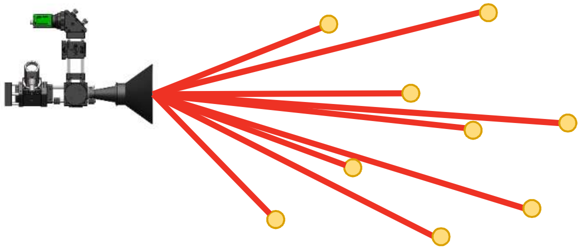
NPL OPTIMUM – 3D coordinate measurement system

Multilateration

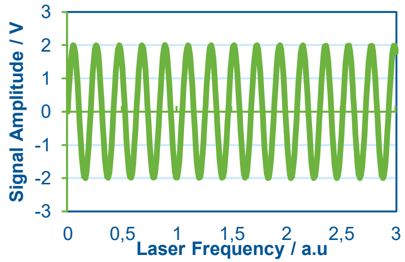
“Indoor GPS”



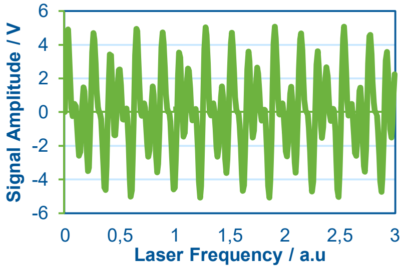
Frequency Scanning Interferometry



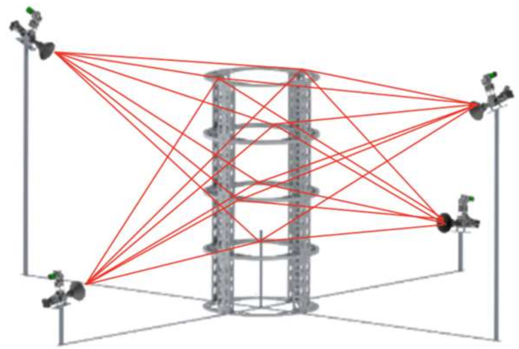
Single target



Multi-target



OPTIMUM

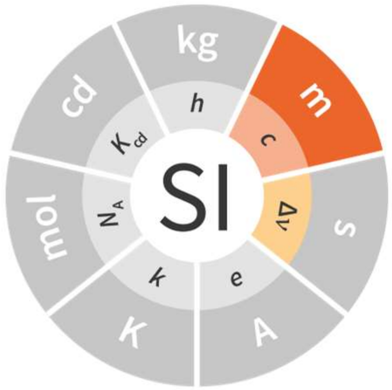


- Accurate (5×10^{-6})
- Real-time uncertainties, target-specific
- Traceable and self-calibrating (HCN gas cell (λ), *c.f.* on-board atomic clocks for real GPS)
- Dynamic with vibration tolerance

Images: Hughes (NPL)

Recap of lecture 2

- **The metre is defined based on the speed of light, *c*, and a time interval and is the basis for all dimensional metrology - however it is no longer the limiting factor determining measurement uncertainty.**



- Dimensional metrology has to cope with many issues including:
  - Refractive index
  - Alignment
  - Thermal
  - Gravity
  - Probe interactions
  - Dynamic stability
  - Imprecise, non-intrinsic measurands
  - Speed demands
  - Imperfect measuring machines
- Many solutions exist, but newer problems are arriving daily!

THANK YOU

NPL

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