SPIE

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Multilateration CMM: First steps

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The requirements

- **Next generation of medium sized CMM**
  - ≥ 0.5 m x 0.5 m x 0.5 m volume
  - ≤ 0.5 µm uncertainty
- **Large scale metrology**
  - (1 m … 50 m)
  - 1 x 10^{-6} accuracy (or better)
- **Large CMM/Machine tool verification**

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Chosen solution - Multilateration

- **Multilateration** is defined as a measuring system that determines either two or three dimensional coordinates by combining only length measurements made from fixed points.

- For two dimensional work, a minimum of two lengths are required, for three dimensional work a minimum of three lengths are required (hence the alternative name of **tri-lateration**).

- More lengths provide **redundant** measurements – used for uncertainty estimating and system parameter determination, or coping with beam breaks.

- Tracking laser interferometers (‘laser trackers’) suitable for 3D work, if the accuracy can be improved.

Multilateration - advantages

Multilateration using laser trackers:

- ensures that the Abbe criterion is always fulfilled (all displacements are, by definition, along the measurement axes);
- avoids necessity of using angle encoders with their relatively poor uncertainties;
- offers flexibility and extensibility of the measuring volume or configuration;
- uses a ‘virtual’ metrology frame, separate from the motion systems;
- uses data redundancy for increased confidence or monitoring.

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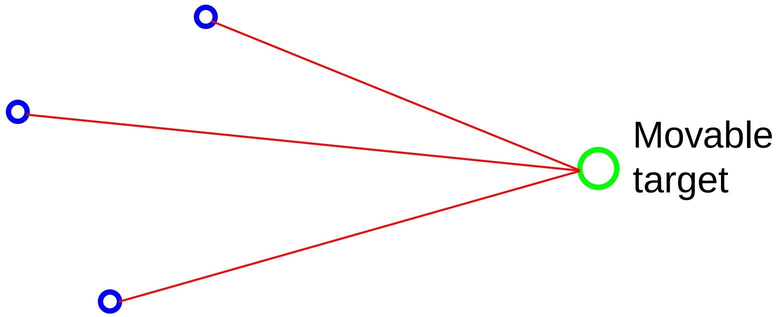
Multilateration with > 3 stations

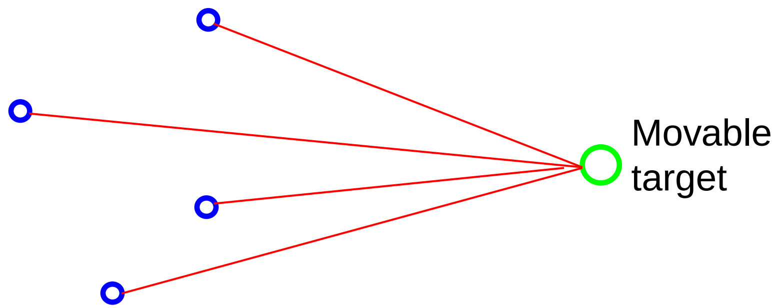
Fixed measuring stations with **known** positions



Tri-lateration:

immediate solution

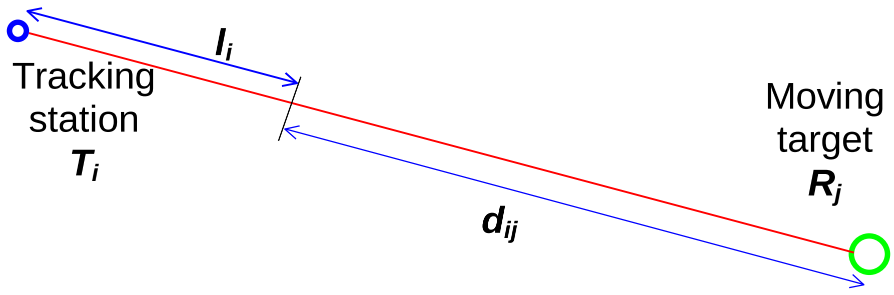
Fixed measuring stations with **unknown** positions



Multi-lateration:

make several measurements before solution is attained

Multilateration system - parameters



Geometrical relationship between centres of tracking stations and targets

T_i centre of i^{th} tracking station

R_j centre of target in its j^{th} position

l_i initial offset for i^{th} tracking station

d_{ij} displacement of target measured by the i^{th} tracker when target is in its j^{th} position

$(i = 1, \ldots, M)$

$(j = 1, \ldots, N)$

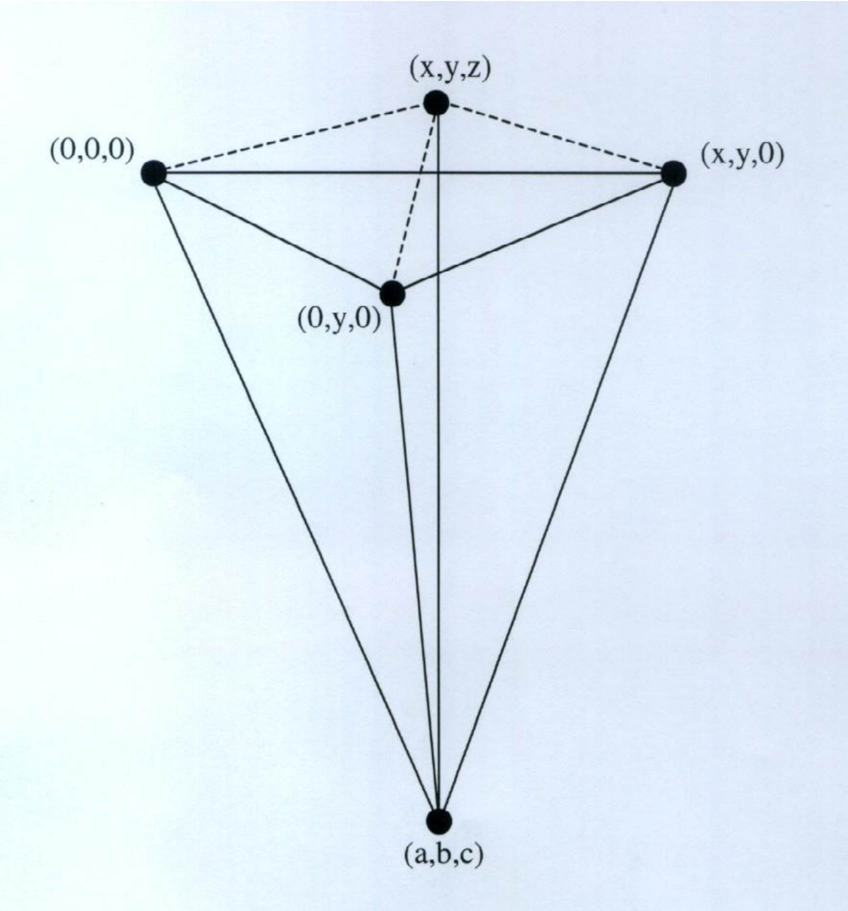
M number of tracking stations

N number of measurements

$$\left|T_i - R_j\right|^2 = \left(l_i + d_{ij}\right)^2$$

Number of measurement points for solution

Consider 4 tracker stations and 1 target



- 1 measurement
  - **6** station coordinates unknown (*x,y,z*)
  - **4** initial length offsets unknown
  - **3** target coordinates unknown (*a,b,c*)
  - ***4*** *lengths known (tracker measurements)*
- 2 measurements (move target)
  - same station coordinates
  - same initial offsets
  - **3** more target coordinates unknown
  - ***4*** *new lengths known (from trackers)*
- *n* measurements
- **6** + **4** + **3*n*** *(unknown)* = ***4n*** *(known)*
- So when ***n*** **> 10**, the system collects information with increasing data redundancy

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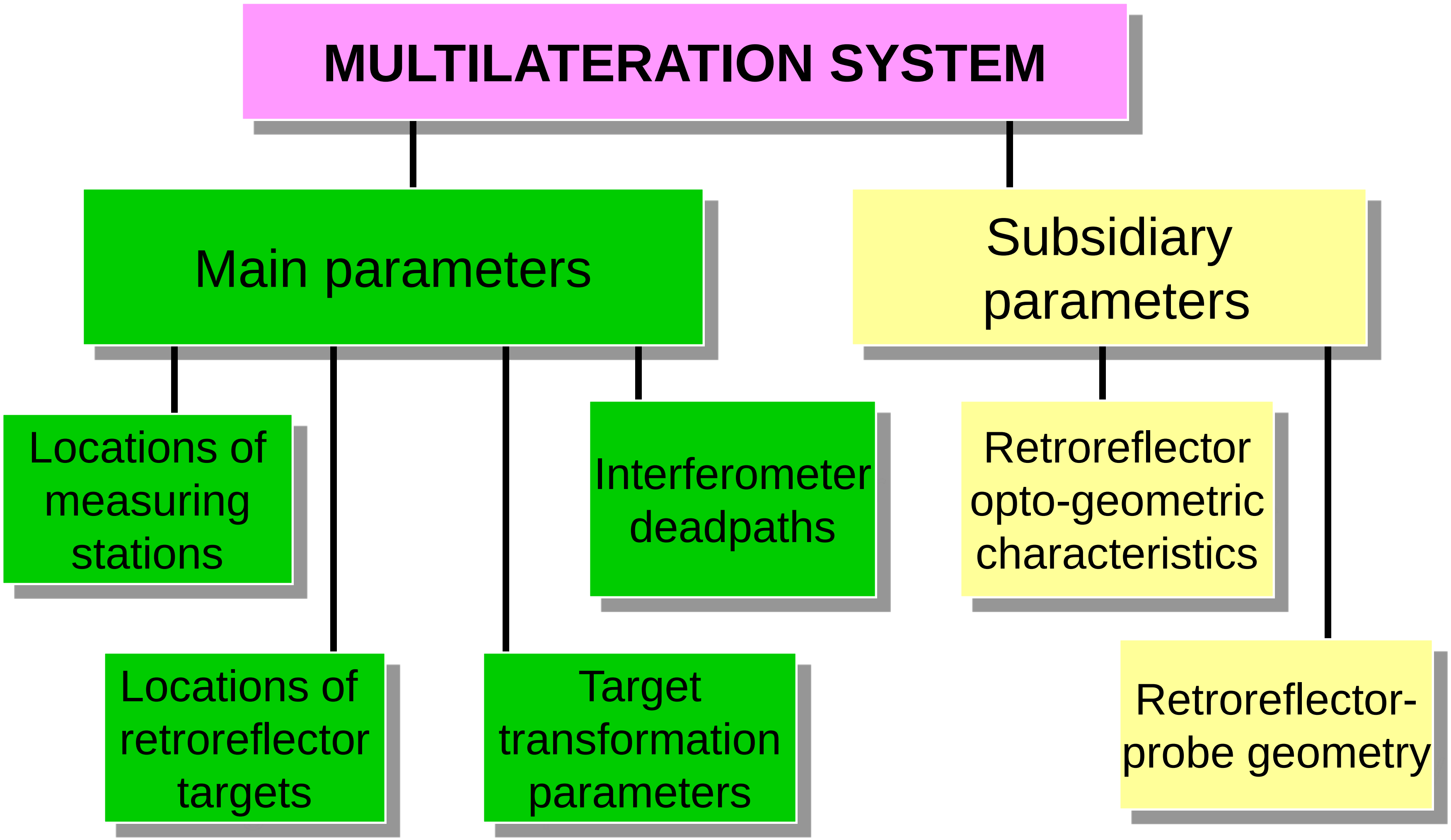
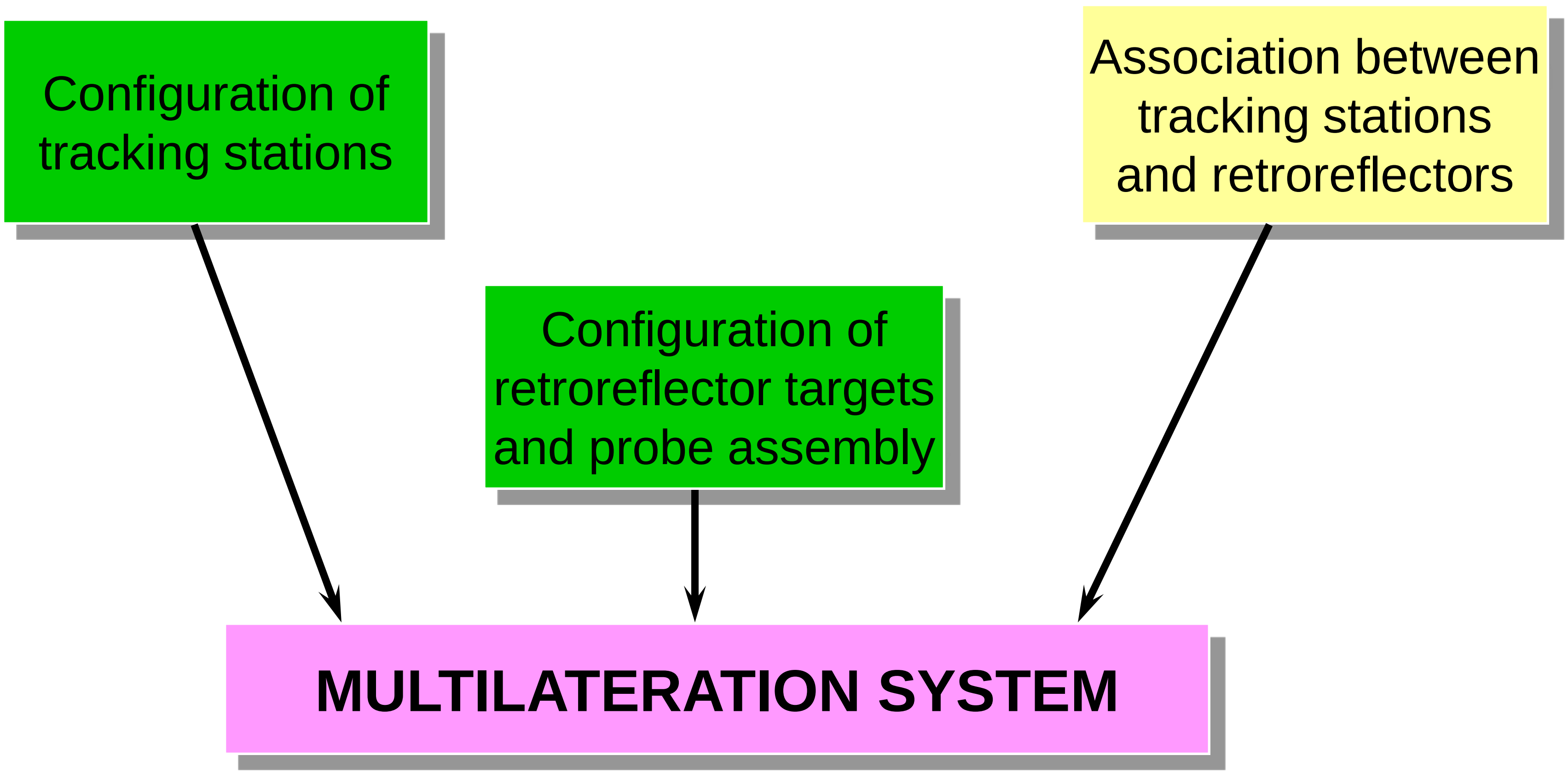
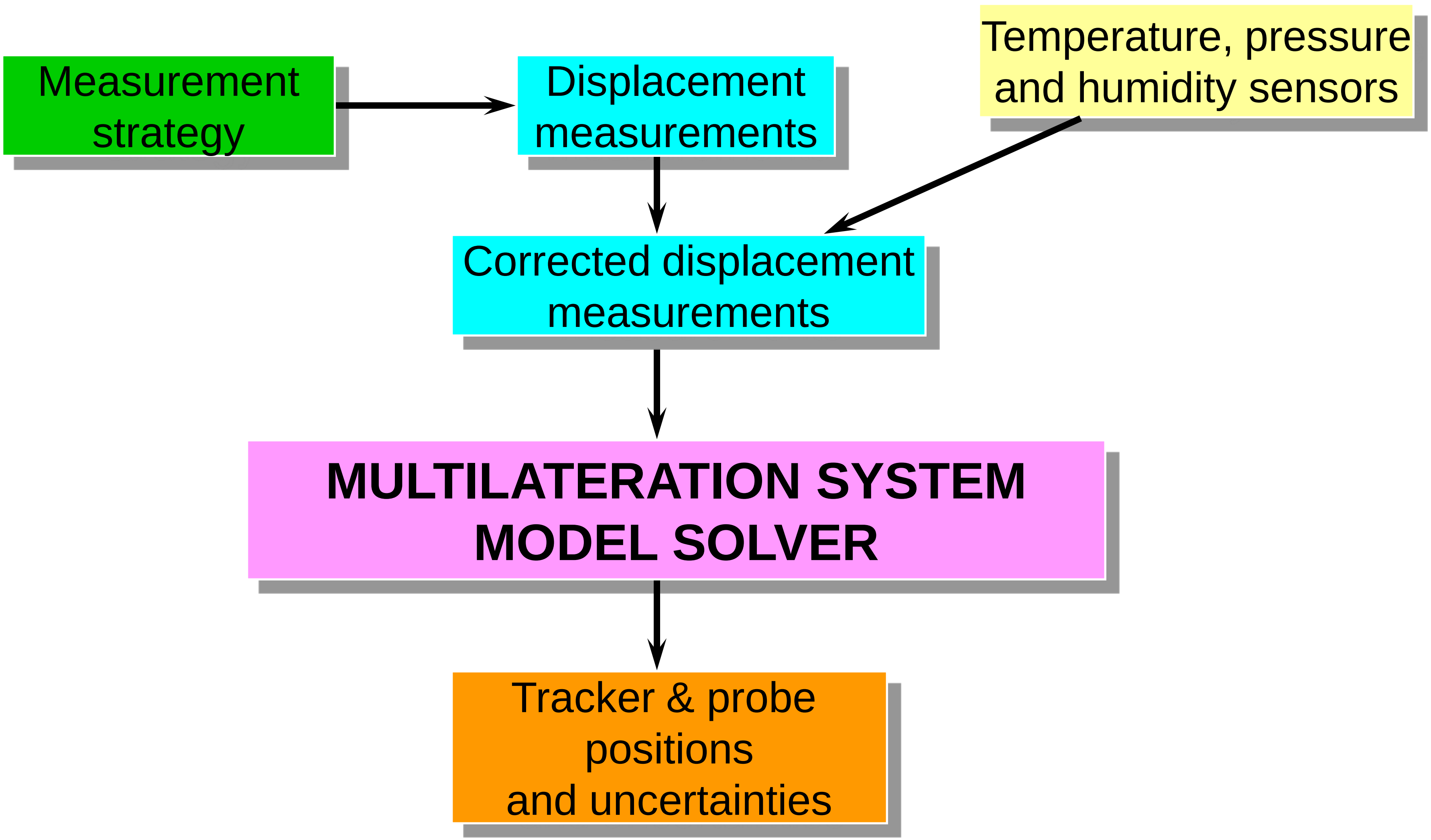
System parameters



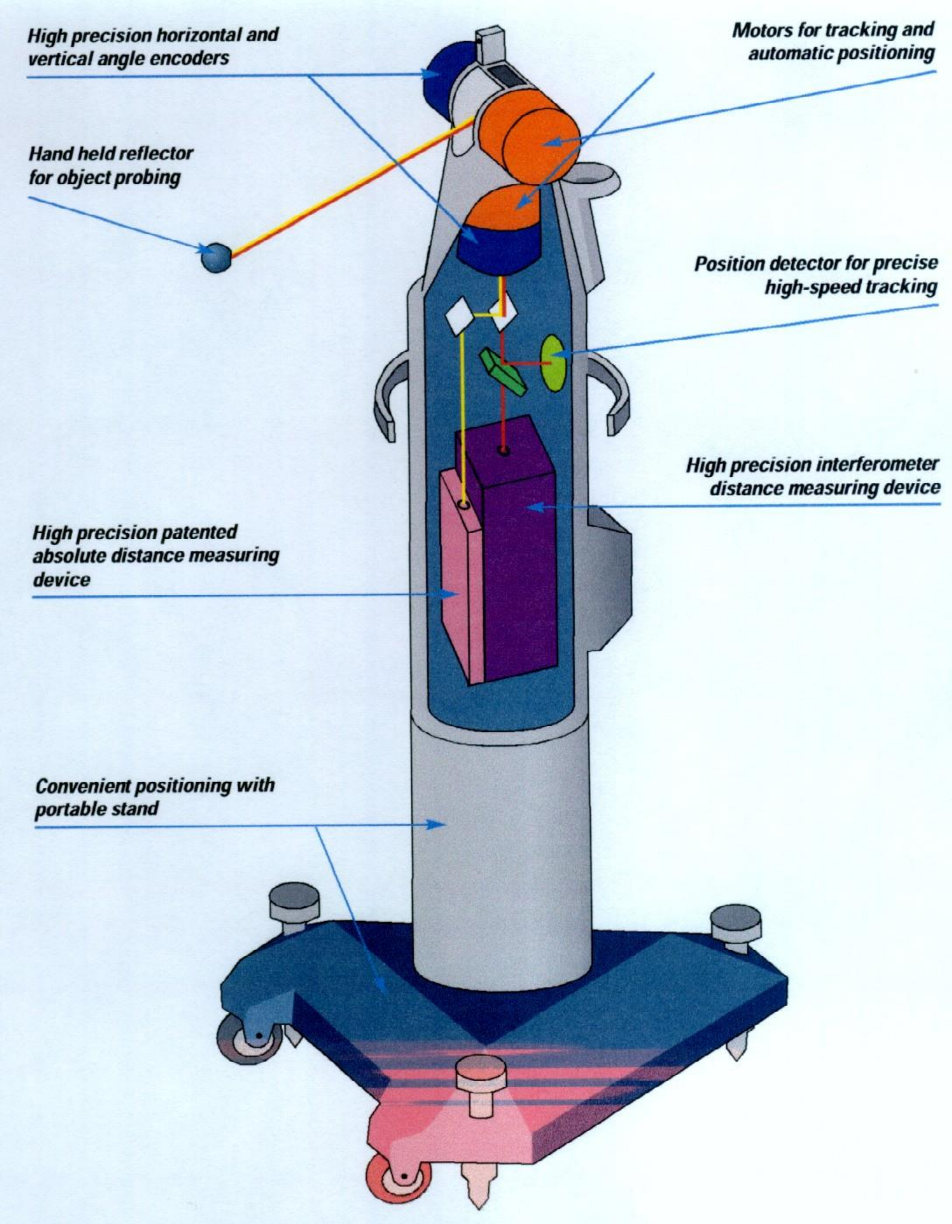
System specification



System operation



Hardware choice: Commercial laser trackers ?



Laser interferometer accuracy ~ 1 ppm,

Angle encoders accuracy ~ 10 ppm

Good for long range

Not so good for short range, low uncertainty

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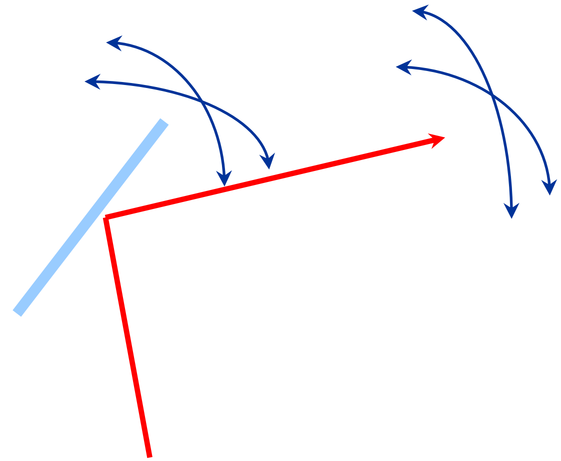
Uncertainty – beam steering

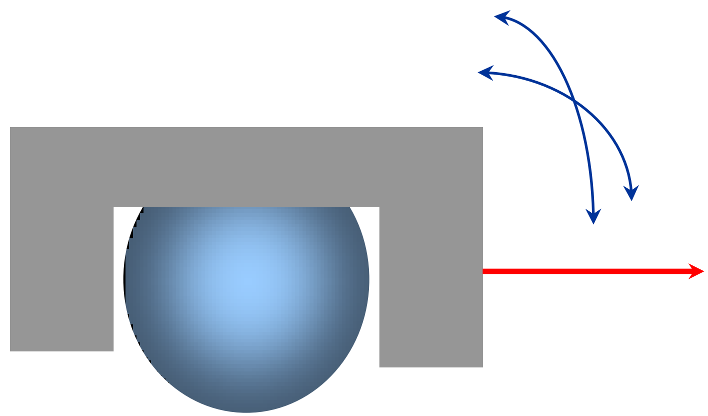
Tilting mirror errors:

- Misalignment of rotation axes
- Misalignment of reflecting point on surface



Spherical bearing errors:

- Automatic alignment of axes



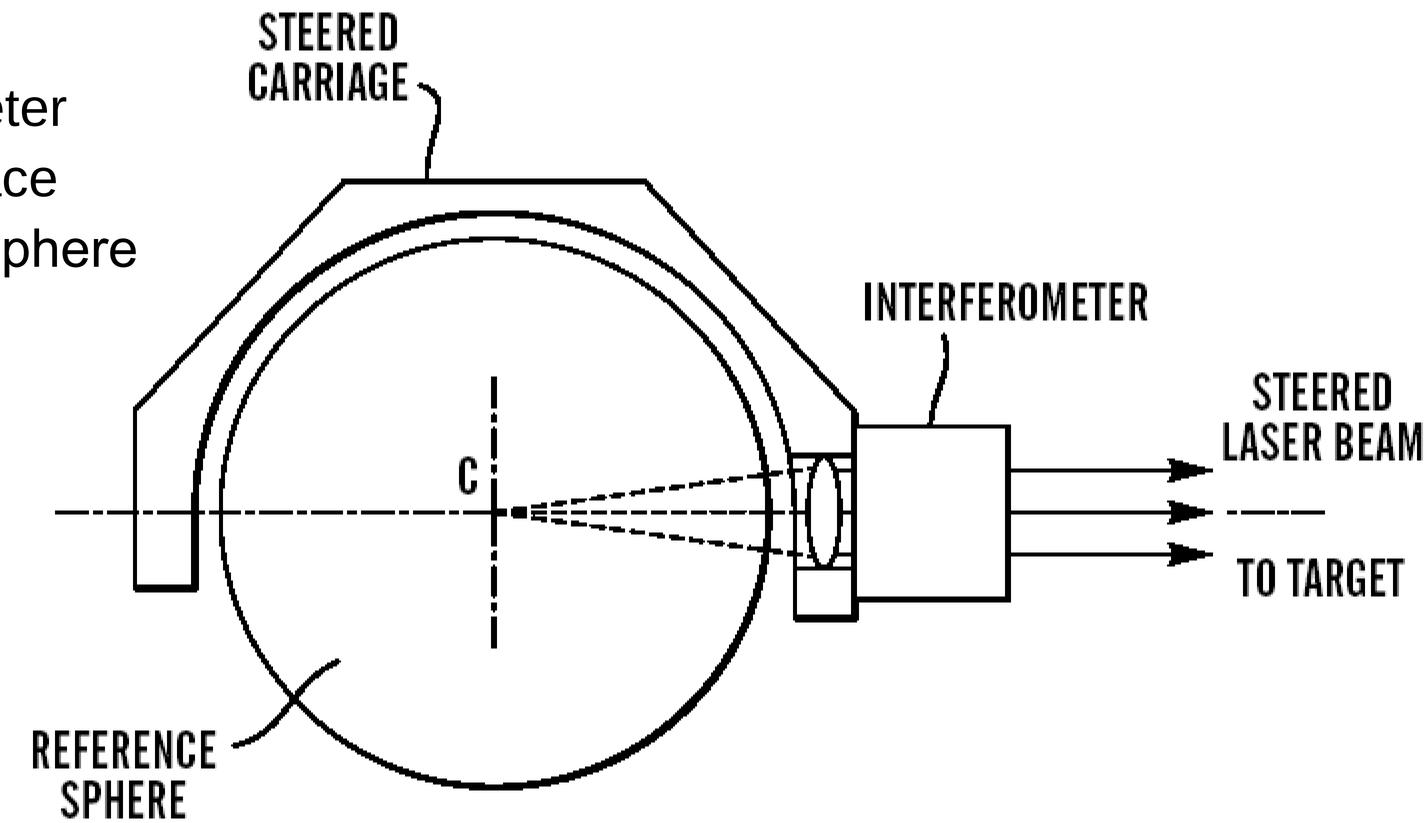
But…

- Relative motion along axis is possible depending on quality of sphere and air bearing

Reduction of beam steering errors

Combined bearing and interferometer reference

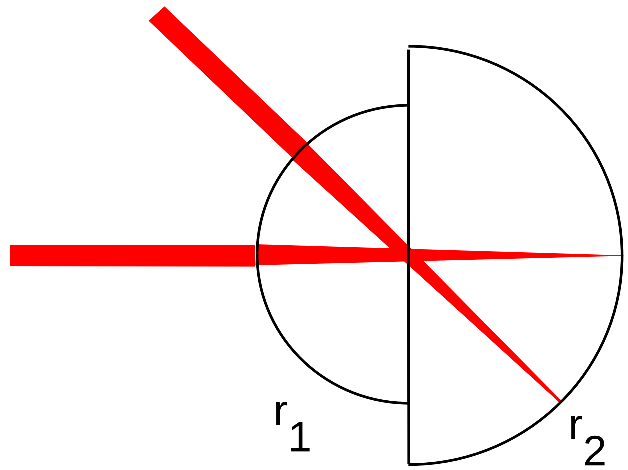
- Spherical bearing
- Integrated interferometer
- Datum is sphere surface
- …or virtual centre of sphere



Uncertainty - retroreflector

Hemi-spherical retro-reflector (cat’s eye)

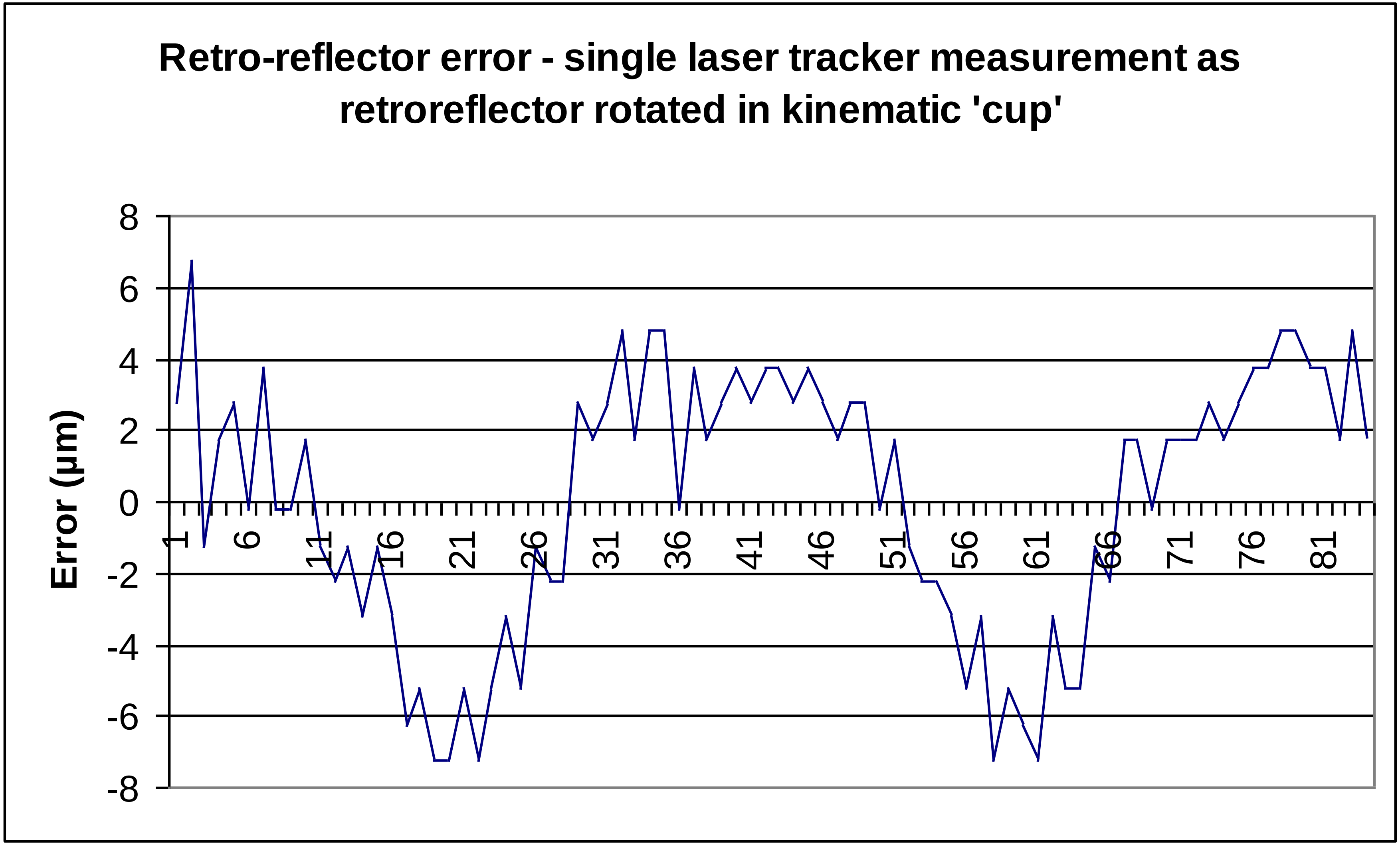
$$r_1 = (n-1)r_2$$



Uncertainty contributions

- Alignment of hemi-spheres
    - axial
    - radial
- Form error
- Aberrations

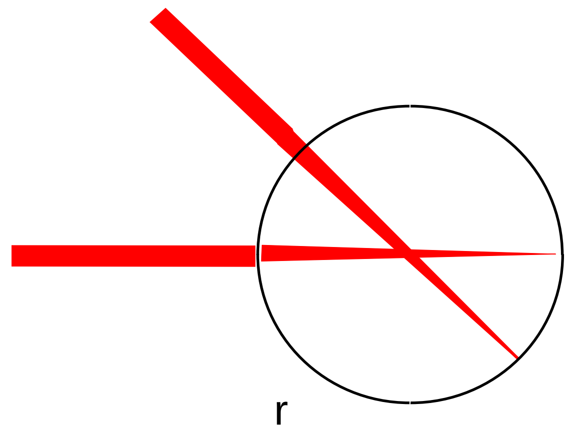
Uncertainty - retroreflector



Reduction of retroreflector errors

n = 2 retro-reflector

$r_1 = r_2 = r$

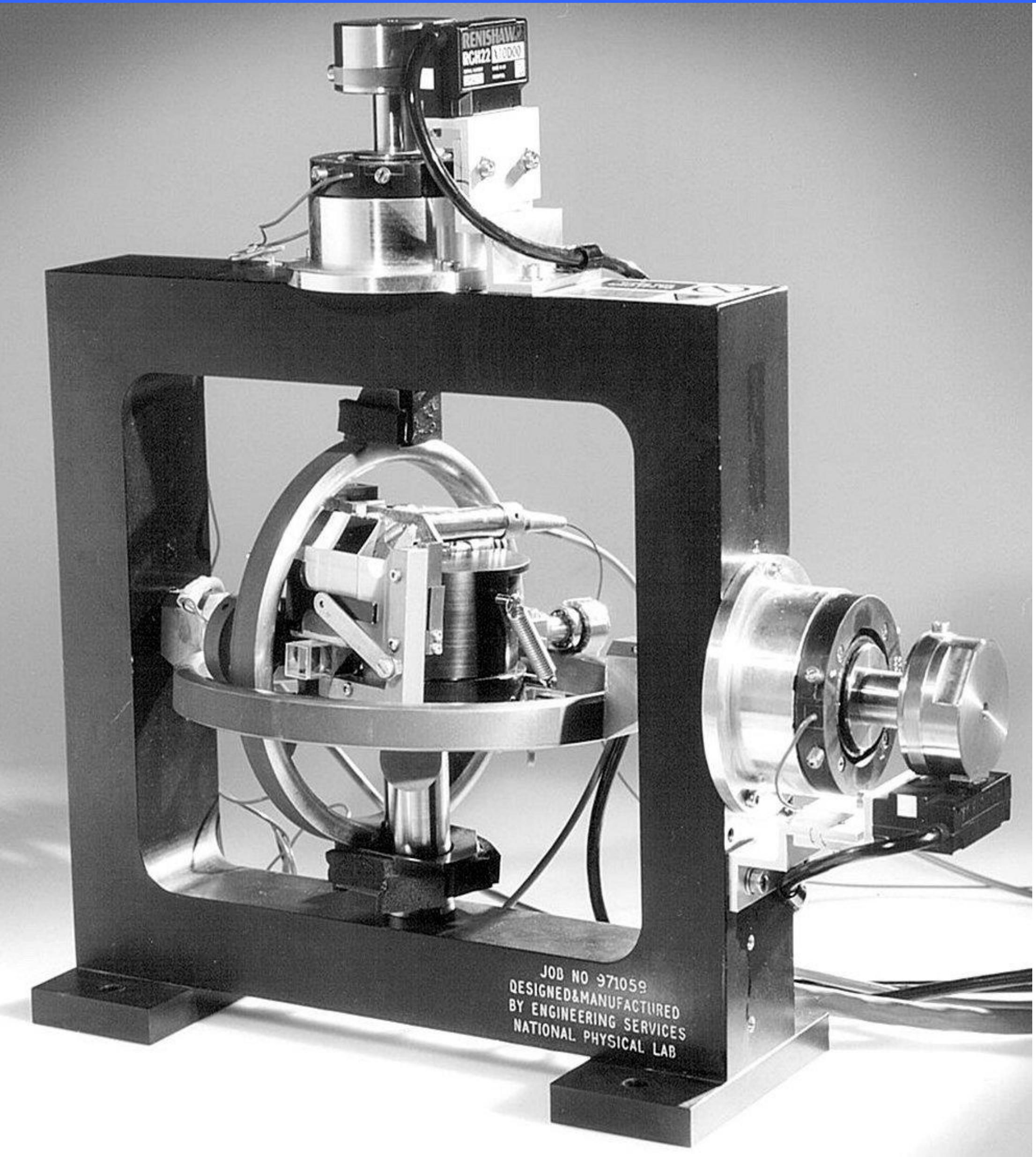


Uncertainty contributions

- Form error
- Homogeneity
- Aberrations

But…Wider angle of acceptance

NPL prototype high accuracy laser tracker



Features

- Precision sphere
  - 2-D bearing
  - retro-reflector
  - datum
- Integrated interferometer

Simple construction

- Gimbal drives
- Bearing pads
- Interferometer on flexure stage

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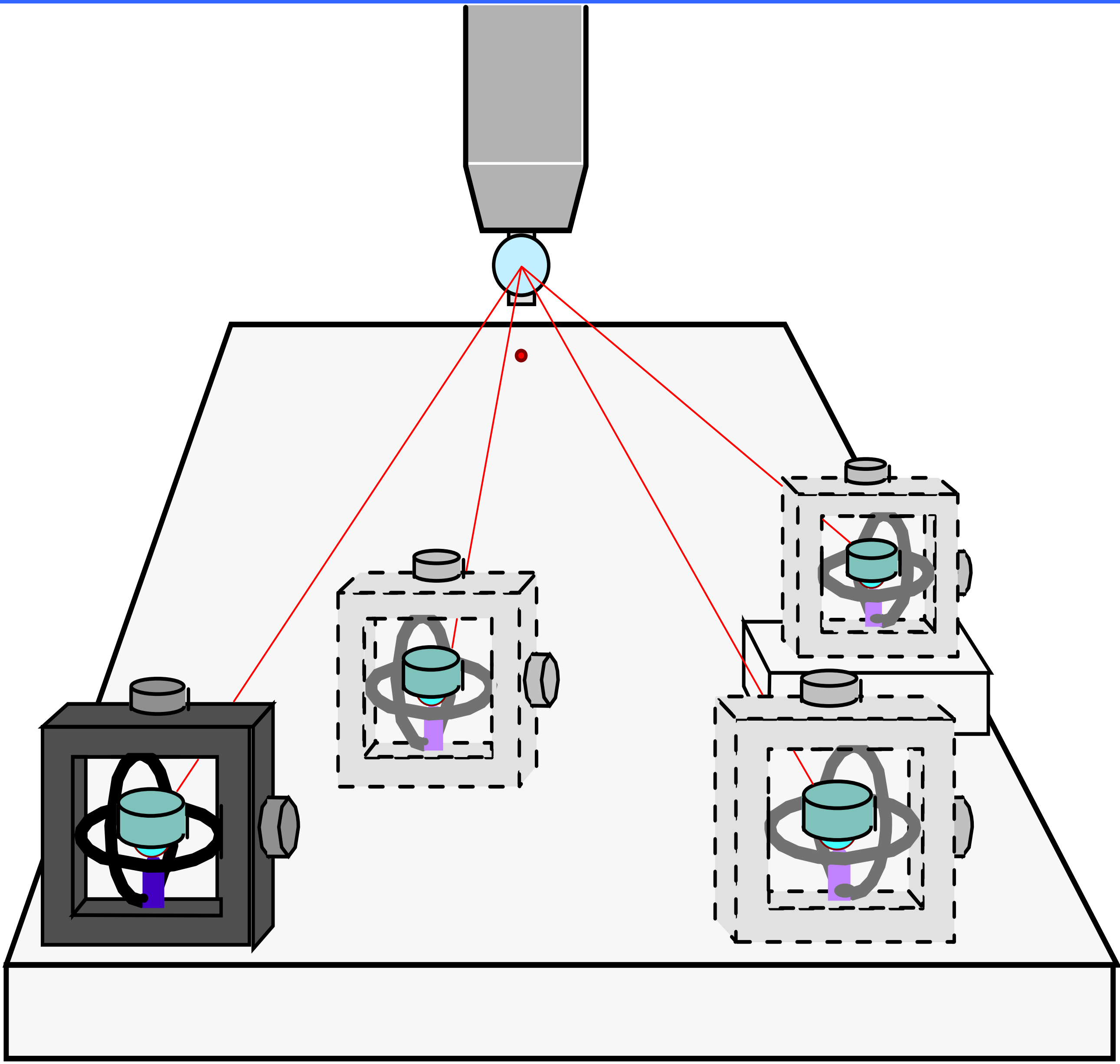
Multilateration simulation with 1 tracker



- Only 1 tracker available
- Mounted in 4 positions

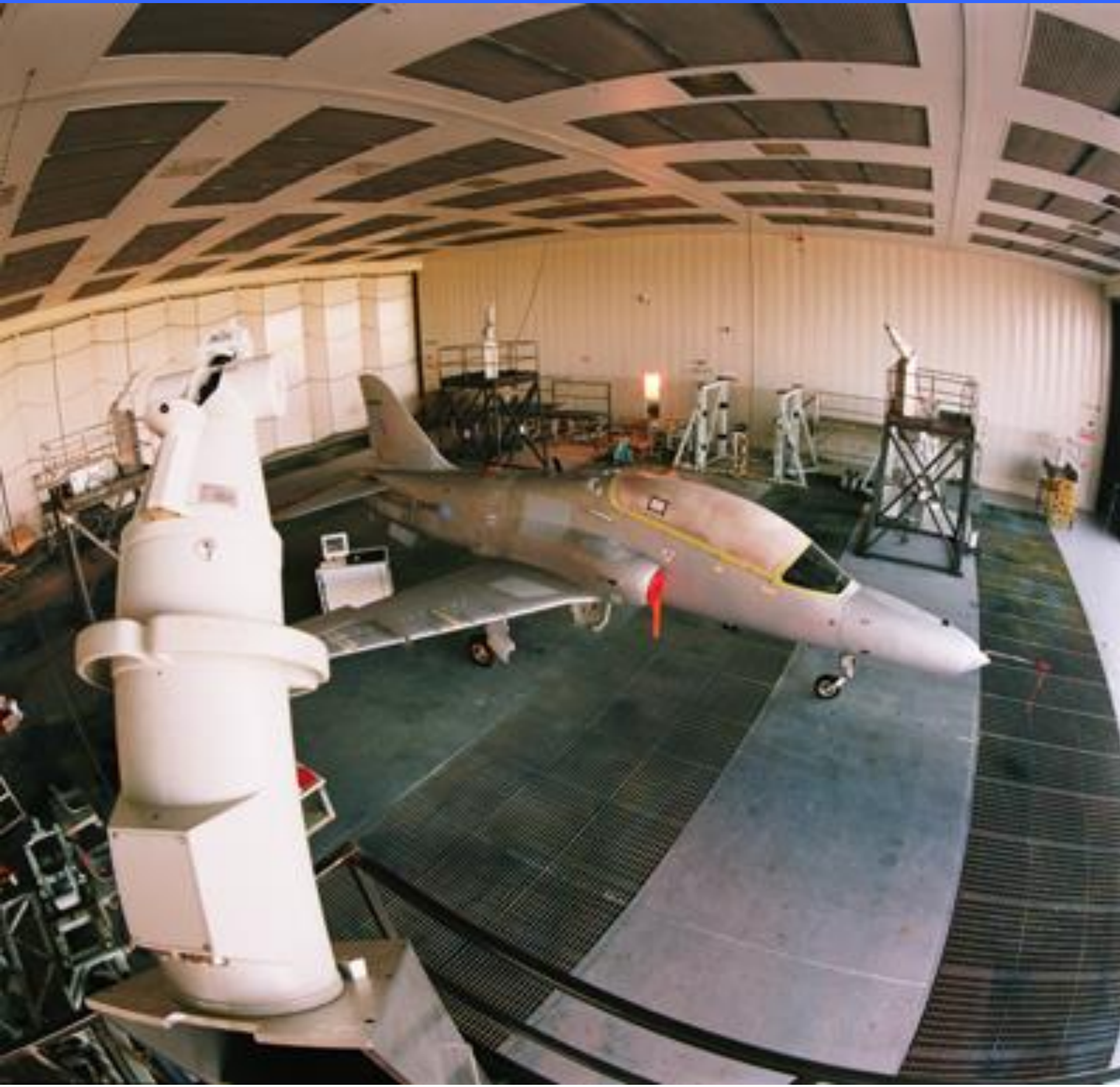
- *combined* uncertainty of the tracker displacement measurements *and* the CMM repeatability is of the order of 200 nm (*k = 1*)
- CMM repeatability:

  X-axis: 100 nm

  Y-axis: 150 nm

  Z-axis: 250 nm

Software Trial – BAe Systems



- NPL multilateration software
- 4 commercial laser trackers
- Commercial retroreflector
- Synchronised data acquisition
- Measuring volume
  ~ 10 x 10 x 0.5 m
- Standard uncertainty of
  ~1 ppm obtained for fit of
  data to model
- 10 x improvement on single
  tracker uncertainty

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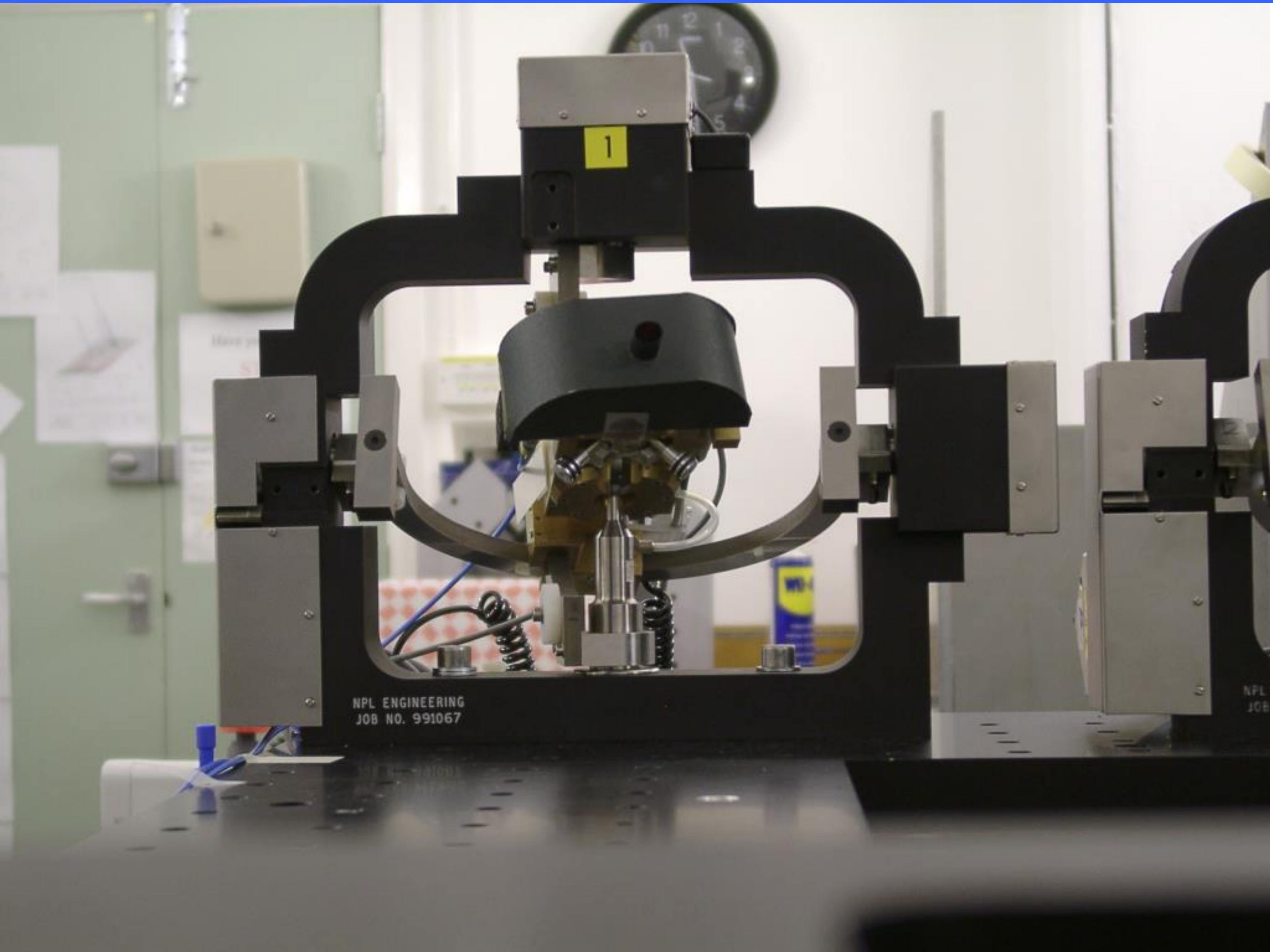
NPL high accuracy laser tracker



Features

- Air bearing
- Angle sensors
- Remote control
- Re-targeting
- Networked
- 4 trackers built

Multilateration CMM – 4 trackers

Data

- Probe movements of 400 mm measured with CMM and trackers
- CMM & trackers agree on displacement to within 100 to 200 nm

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Application – in situ measurements

Demo

- Measure air bearing ‘puck’ on mirror surface
- Measure aspheric surfaces, metres in size

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Application – machine tool error mapping

CONCLUSION / SUMMARY

Multilateration CMM

- Experiments indicating 1 ppm accuracy achieved, up to D=400 mm (more verification continues)
- Good integration between CMM and trackers
- Software: operational, verified, beam-breaks and re-targeting OK
- Trackers operate up to 3 to 4 m path length (servo tuning)
- Applications other than as a Coordinate Measuring Machine:
    - CMM verification
    - Machine tool verification
    - Measurement of large structures

Acknowledgements

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