Development in FSI at NPL

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Outline

NPL
National Physical Laboratory

- Introduction
- Frequency scanning interferometry
- Multilateration
- NPL's new optical coordinate metrology system
- Motion and dual sweep corrections
- Results
- Current/Future work
- Summary & conclusions

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Introduction

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- Objective is to make a CMS that is:
  1. As accurate as possible
  2. Self-calibrating - built-in compensation for systematic errors
  3. Has built-in traceability to SI metre
  4. Gives on-line uncertainty estimation

Summary

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- **Coordinate Measurement System** operating over a **1 m^3 volume**.
- **Wide-field frequency scanning interferometry** to detect multiple targets simultaneously from multiple sensors.
- Four Wave Mixing to make measurements **insensitive to motion.**
- Measurements are **traceable** to the SI through use of a reference gas cell.
- **Multilateration** to calculate coordinate positions of both targets and sensors.
- The system is **self-calibrating.**
- Compensate for **systematic errors** with **full traceability**.
- **Sub 1 µm coordinate uncertainties** achieved.

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Conventional Frequency Scanning Interferometry (FSI)

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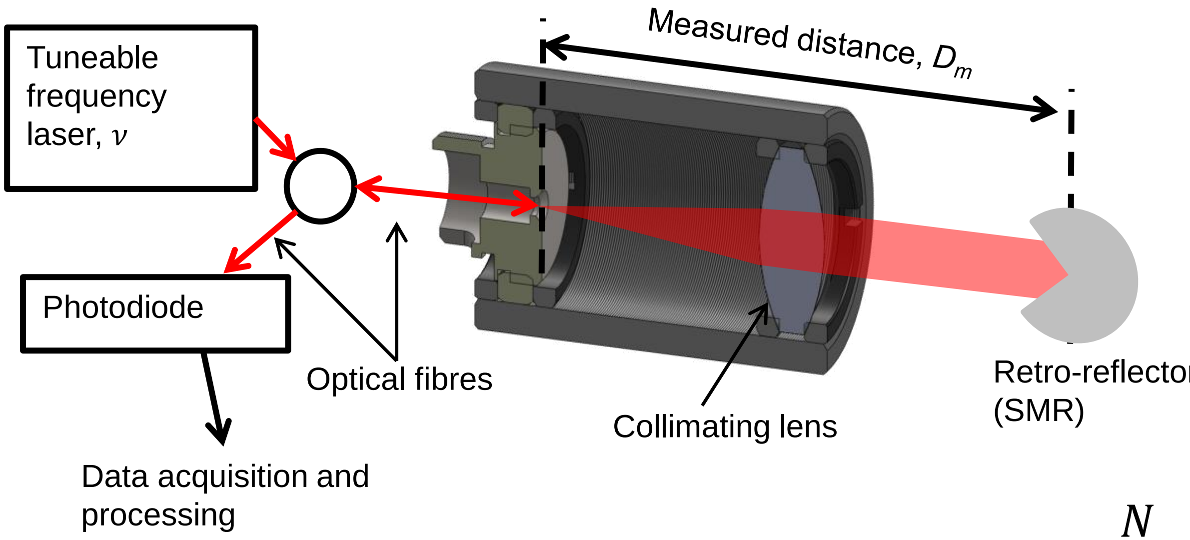
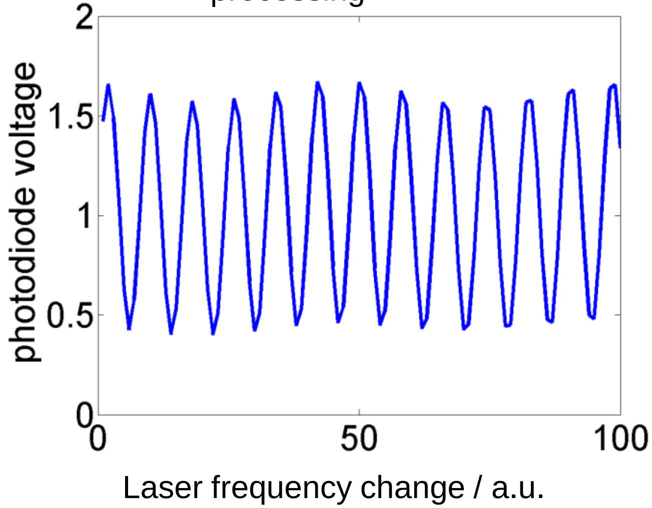


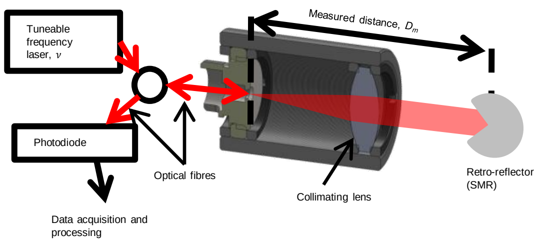


$$D = c\frac{N}{2\Delta\nu\, n}$$

D = measured distance
c = speed of light (defined)
N = Number of cycles of signal
$\Delta\nu$ = change in laser frequency
n = refractive index

Conventional Frequency Scanning Interferometry (FSI)

- How to measure $\Delta\nu$?
- Simultaneously measure the known length, *L*, of a reference interferometer



$$D = c\frac{N}{2\Delta\nu\, n}$$

$$D = L\frac{N}{m}$$

$$L = c\frac{m}{2\Delta\nu\, n}$$

D = unknown distance
L = known stable length
c = speed of light (defined)
N = Number of cycles of signal in unknown length, *D*
m = Number of cycles of signal in known length, *L*
$\Delta\nu$ = change in laser frequency

FSI advantages

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- Simple optics
  - Fibre feed & return – robust, remote operation
  - Many channels from one laser - cheap
- Robust absolute distance
  - No synthetic wavelength
  - Only one solution
- **Accuracy**
  - Can achieve sub 10^{-6} range uncertainty

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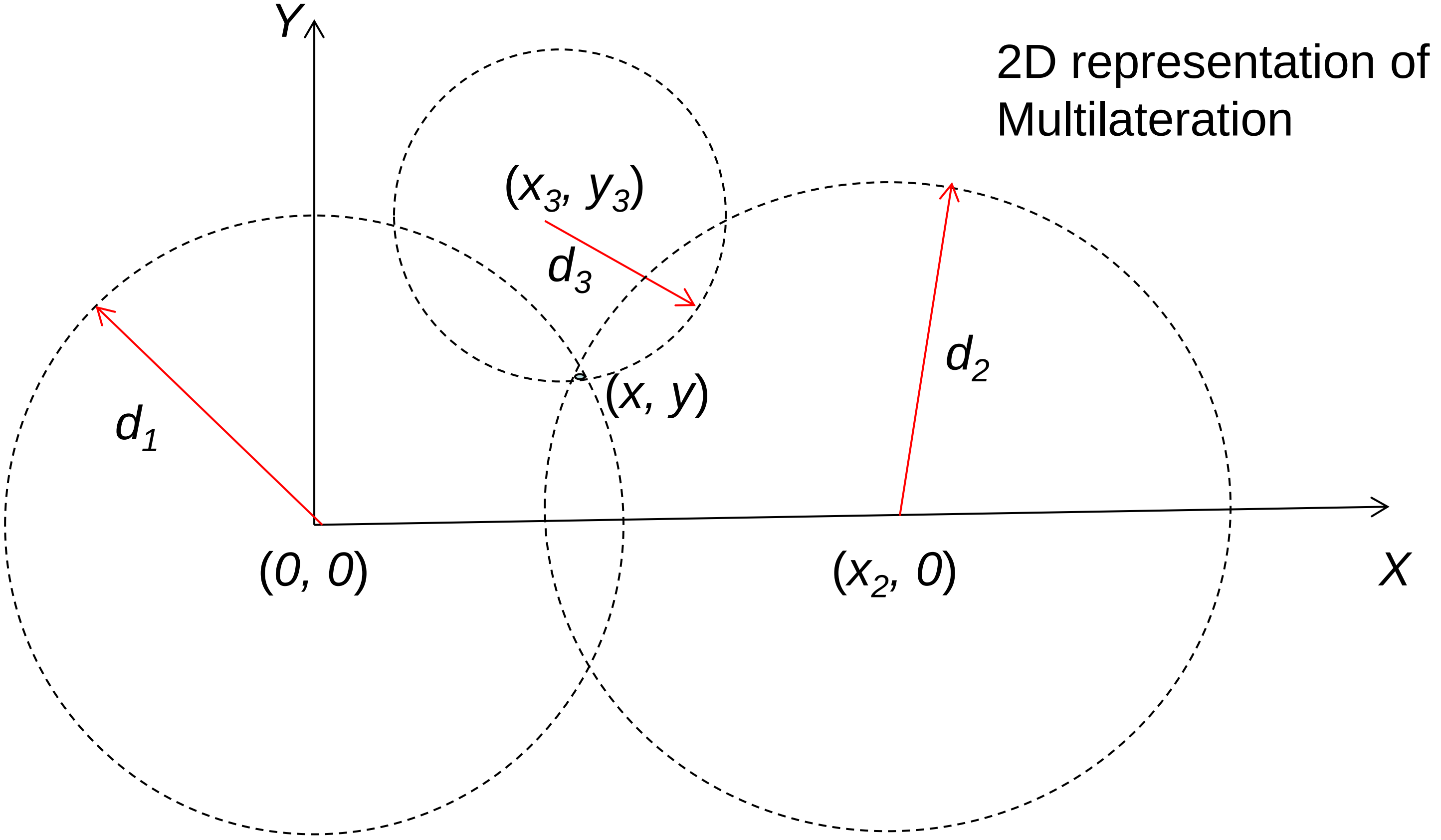
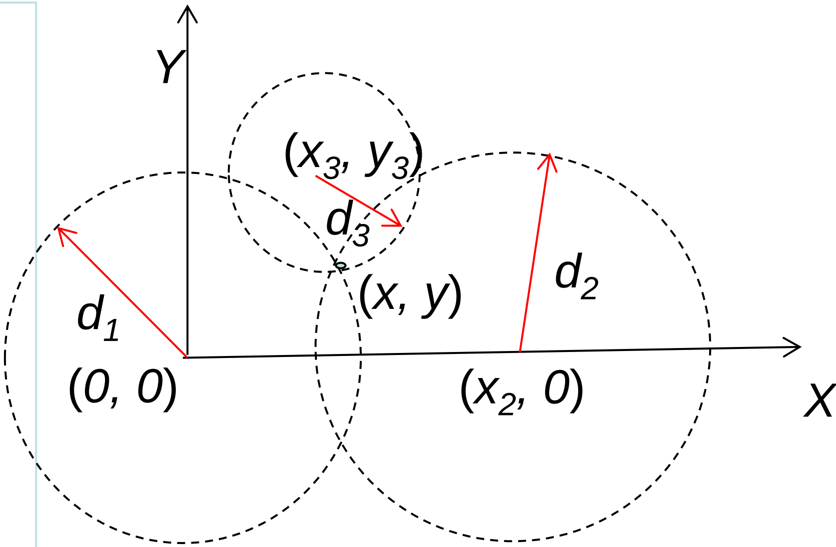
Multilateration…

- … is the process of determining absolute (or relative) locations of points by measurement of **distances** using the geometry of circles or spheres



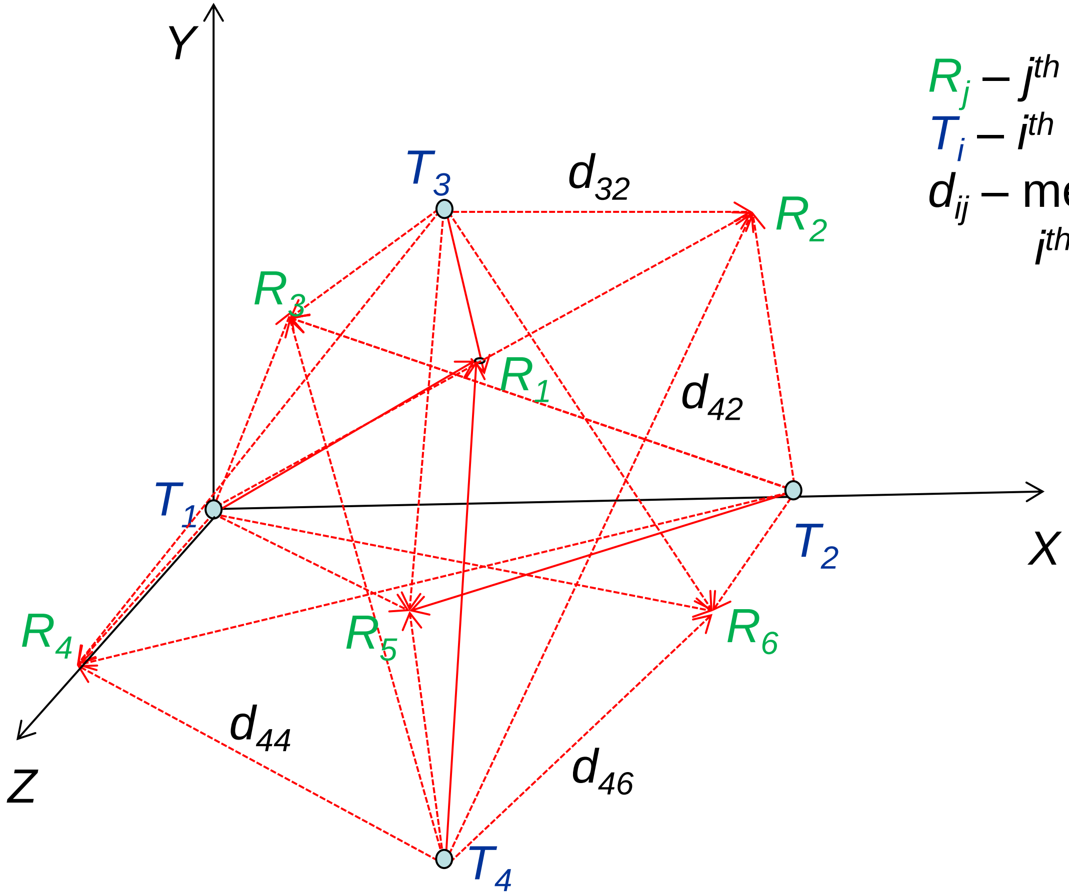
Multilateration

- *If instrument locations are known e.g.*
  - Origin
  - Distance x_2 along x axis
  - On X-Y plane at (x_3, y_3)
- Then measurements d_1, d_2 and d_3 are sufficient to locate uniquely target coordinates (x, y)
- In 3D and if instrument locations are **not known**, we need more information…



Multilateration

- Add a **fourth** instrument at a fourth location, and
- Measure ranges to **multiple** targets



R_j – j^{th} target coordinates
T_i – i^{th} Instrument coordinates
d_{ij} – measured distance from i^{th} instrument to j^{th} target

Multilateration

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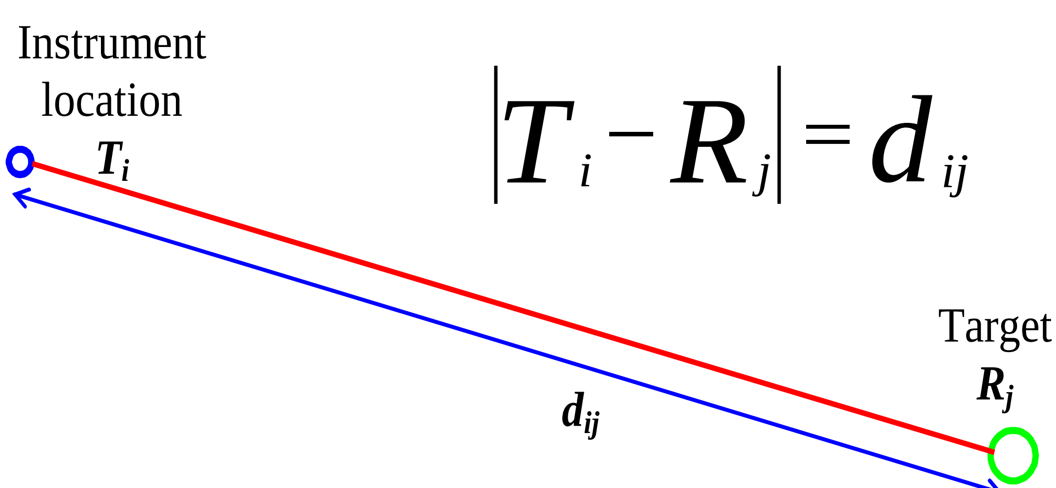
- Determine coordinates by measuring range, d_{ij} from M instrument locations, T_i, to N targets located at coordinates R_j.
  - **Self-calibrating** if $M \geq 4$ and $N \geq 6$
  - Increasing N, M gives data redundancy -> **uncertainty estimates**
  - **Traceable to SI** (if d_{ij} is traceable)
  - Can extend model equation to include other **systematic factors** – and **compensate** for them with full **traceability**
  - Can achieve coordinate uncertainty ≈ range uncertainty



$$\left| T_i - R_j \right| = d_{ij}$$

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

M number of instruments
N number of targets

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Divergent beam interferometry

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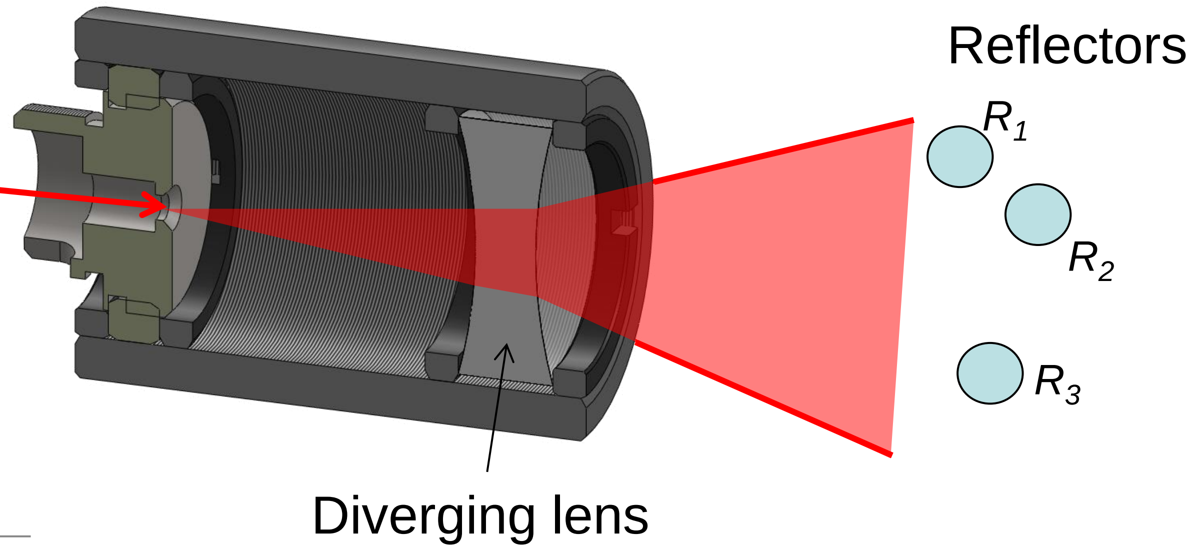
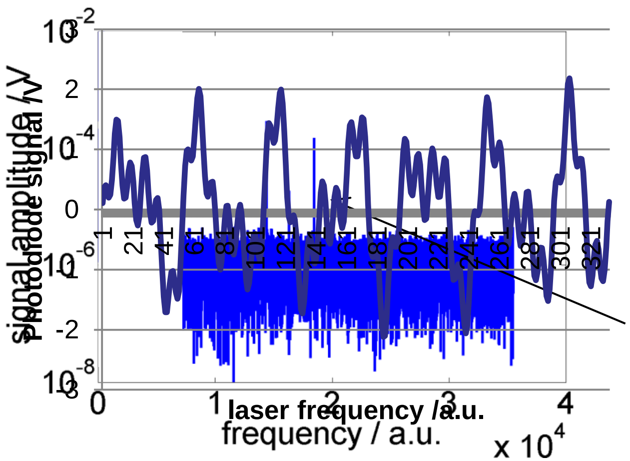
Variable Frequency Laser, ν

Photodiode

Fourier transform

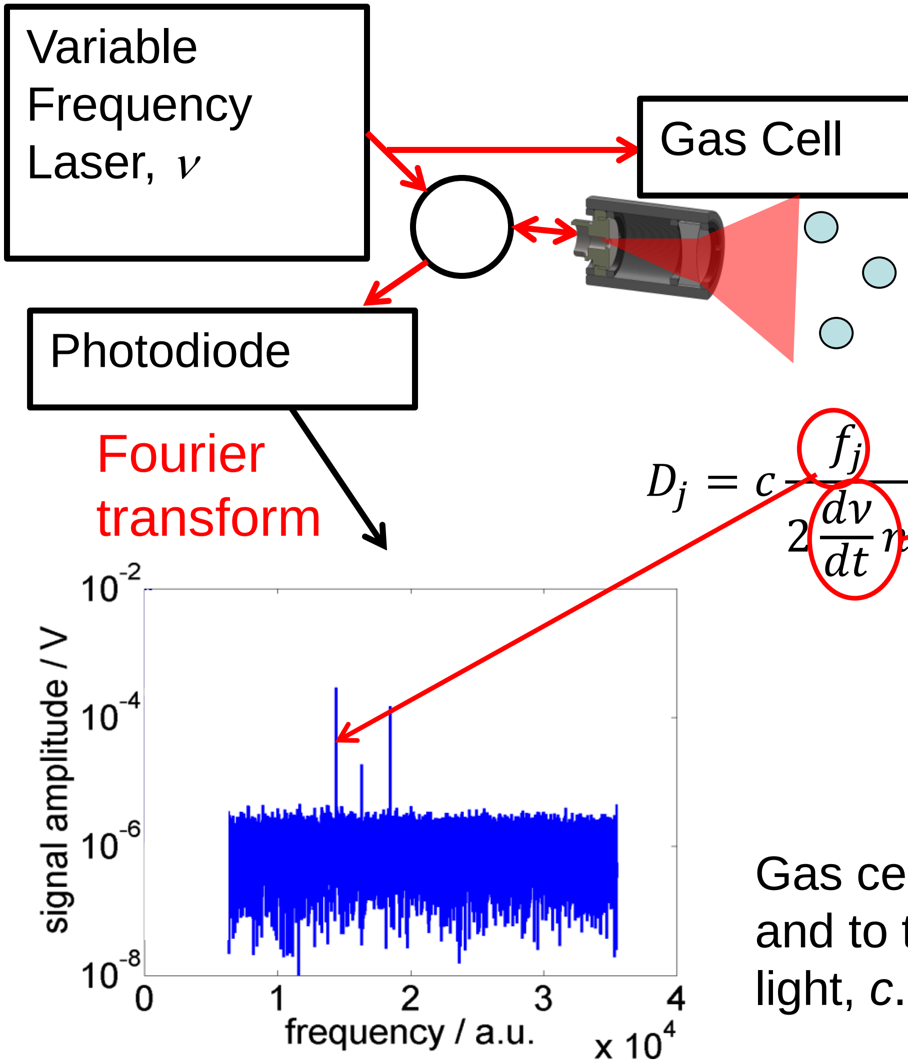


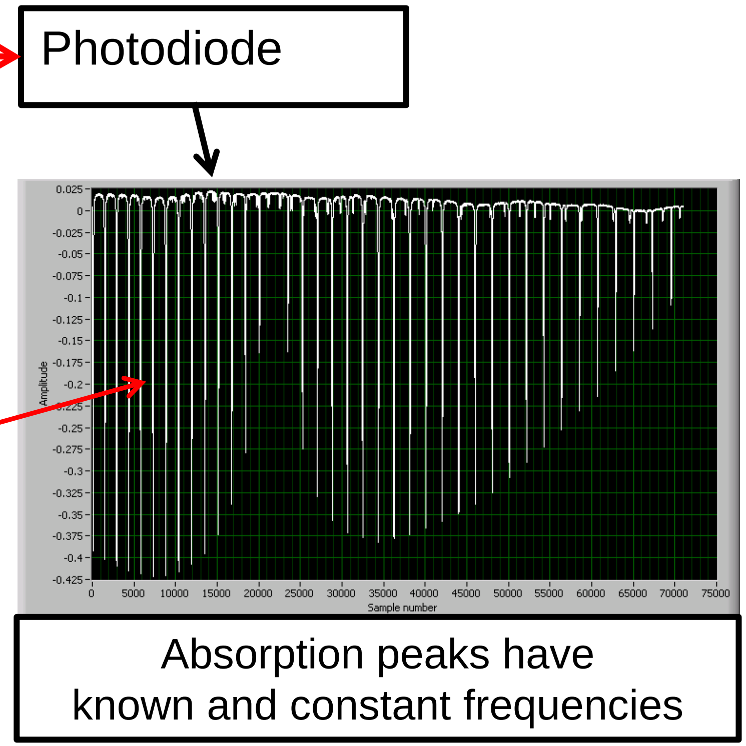
$$D_j = \frac{c\, f_j}{2\left({}^{dv}/_{dt}\right) n}$$



Each target shows up as a separate peak in the frequency domain

Traceability to SI: Gas Cell Frequency Reference





Gas cell provides **traceability** to the second and to the metre via the defined speed of light, *c*.

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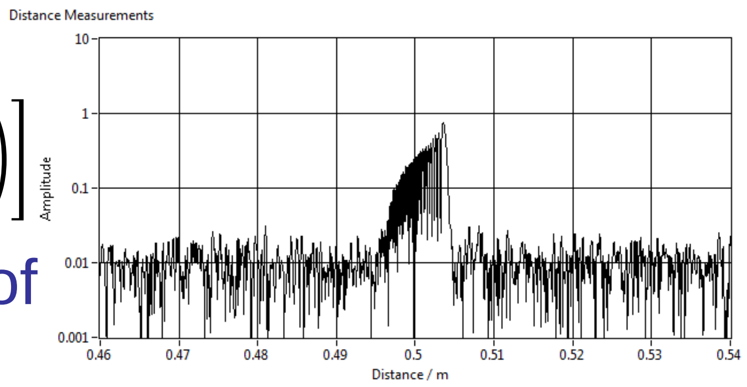
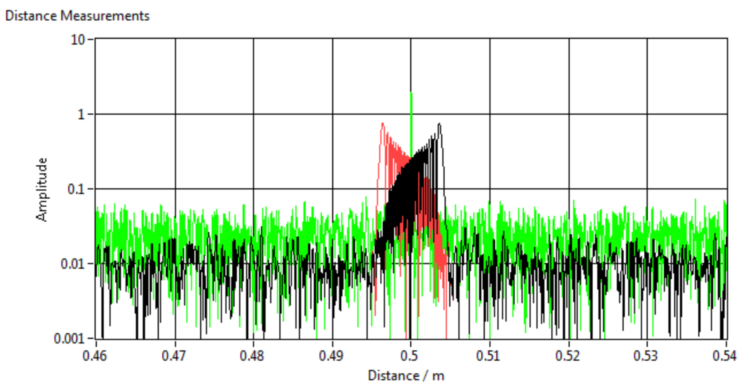
Motion in FSI Measurements

- Finite measurement time ~ 6ms

$$I(t,\tau) = A.\cos\left[2\pi\left(\alpha\tau(t)t + f_0\tau(t) - \frac{\alpha\tau(t)^2}{2}\right)\right]$$

- $\tau(t) = D/c$ is the round-trip time of the interferometer – varies with *t* and scaled by f_0 – big effect !
- α = rate of change of laser frequency
- f_0 = laser frequency at $\mathrm{t} = 0$
- Use a 2nd swept laser source
  - $\alpha_1 = -\alpha_2$, and $f_{0,1} \approx f_{0,2}$





$$I_1(t,\tau).I_2(t,\tau) = \frac{1}{2}A_1.A_2.\{\cos(4\pi\alpha_1\tau(t)t) + \cos\left(4\pi f_{0,1}\tau(t)\right)\}$$

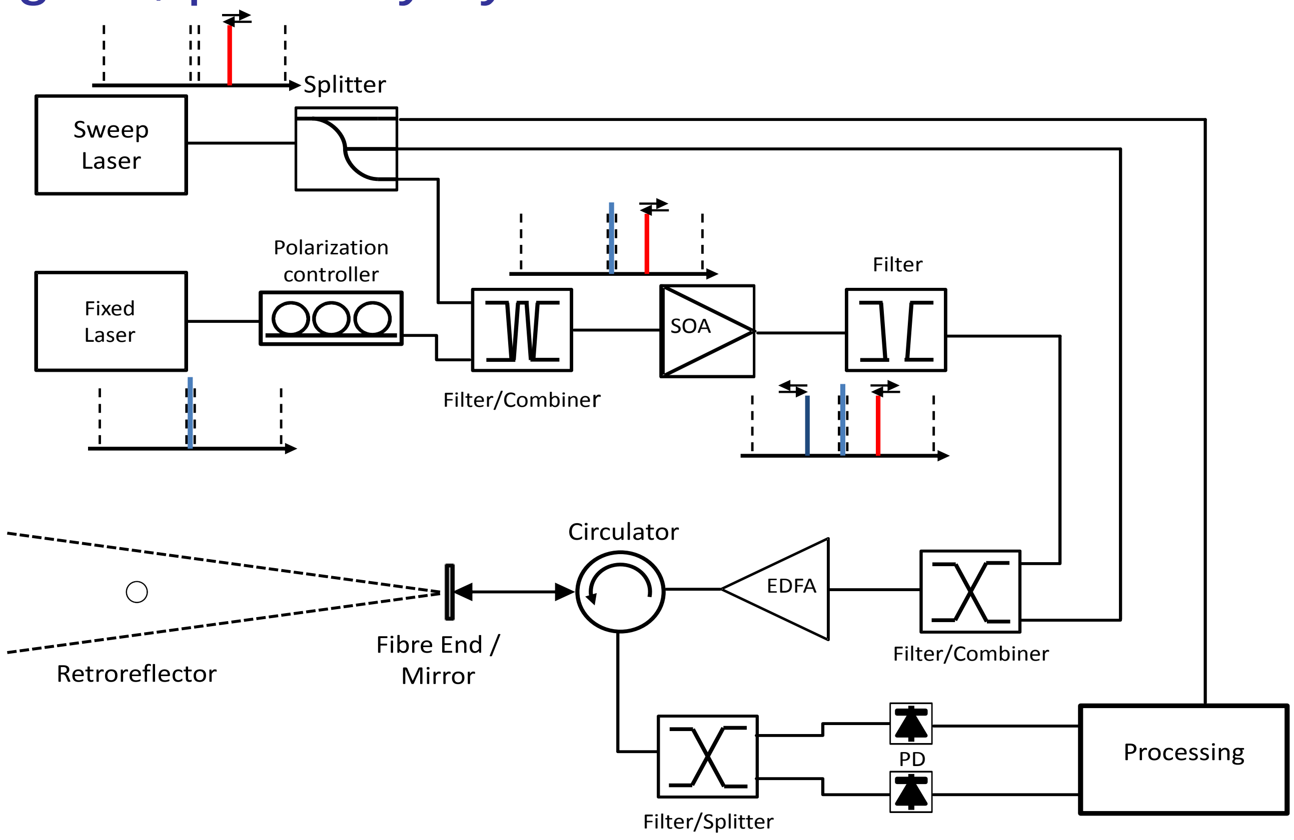
Motion compensation

- Second laser
  - Expensive
  - Synchronisation issues

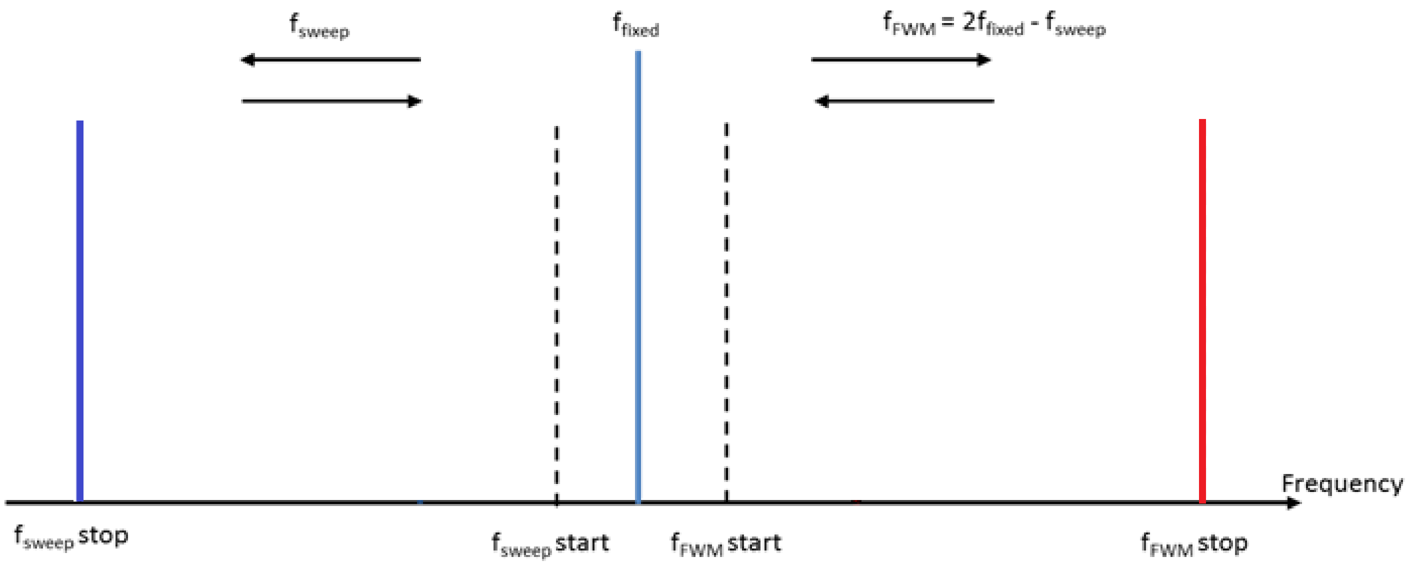
- Use up and down sweep
  - Not measuring the same movement
  - Not a perfect correction

Motion compensation

- Use Four Wave Mixing to generate a second swept frequency source from the original swept laser
- Generated sweep goes in opposite direction to the original, perfectly synchronised

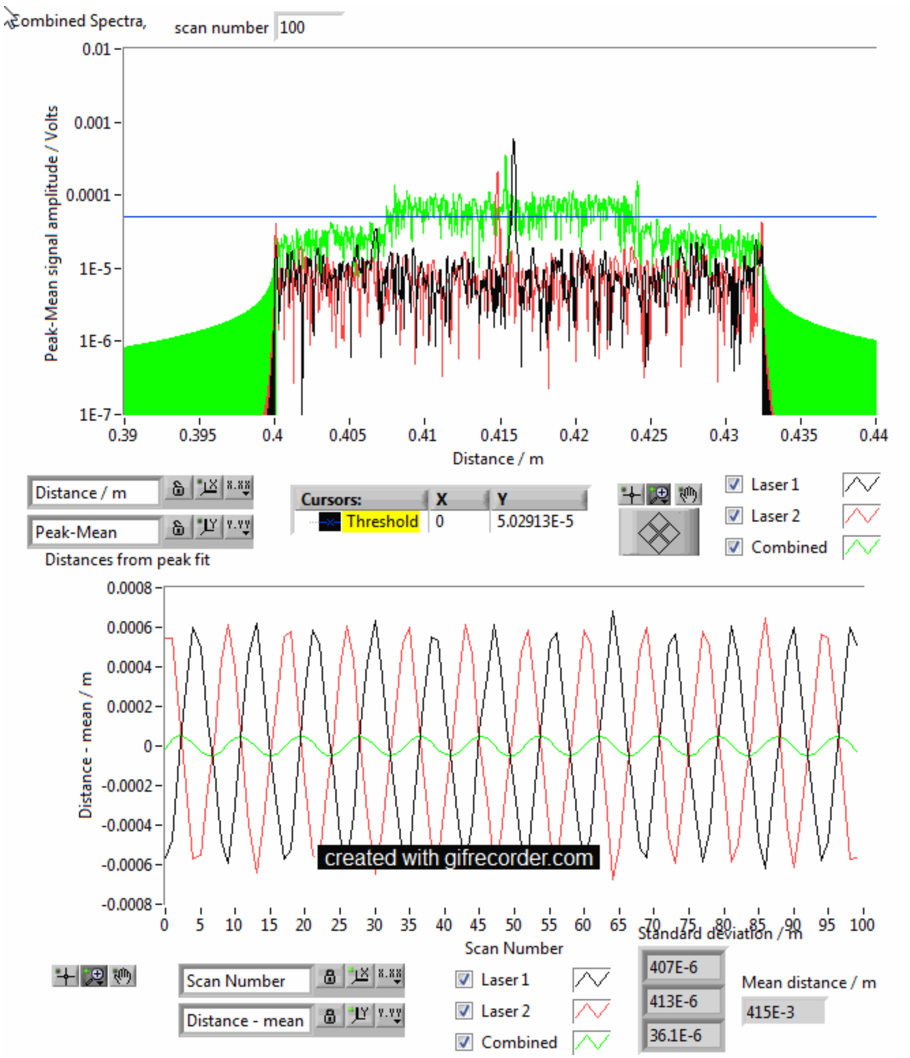


Four Wave Mixing



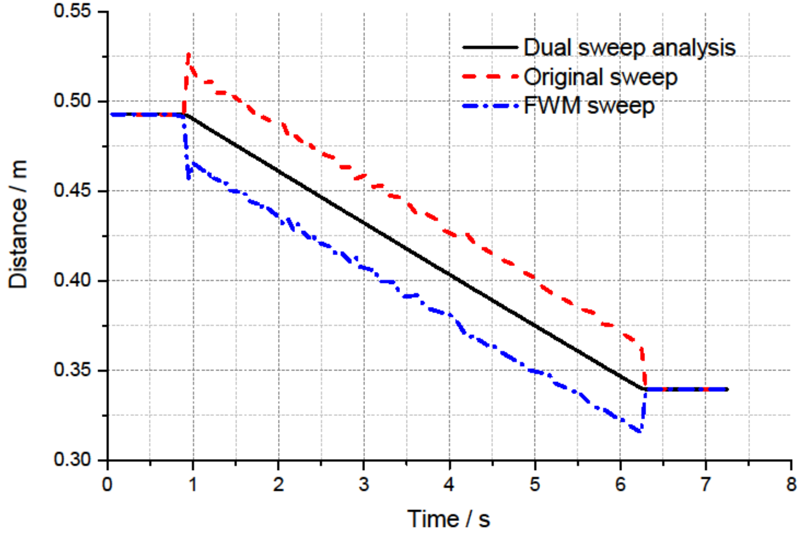
- Fixed frequency DFB laser – 1545 nm
- Original laser - 1550 → 1560 nm
- FWM generated - 1540 → 1530 nm
- Filter out unwanted fixed frequency wavelength

Motion tolerant measurements



- Piezoelectric actuator
- 2 Hz frequency
- 0.1 mm amplitude
- Individual sweep amplitudes: 1.3 mm
- Combined sweep amplitude: 0.1 mm

Motion sensitivity



Target moving at 100 mm/s

Table: Standard deviation of 100 distance measurements taken of a stationary target

Original laser measurement / µm	FWM generated measurement / µm	combined analysis measurement / µm
3.8	3.7	0.4
3.9	3.6	0.4
3.8	3.5	0.4
3.7	3.6	0.4

To achieve high accuracy measurement in non-laboratory environments, dual sweep analysis is essential!

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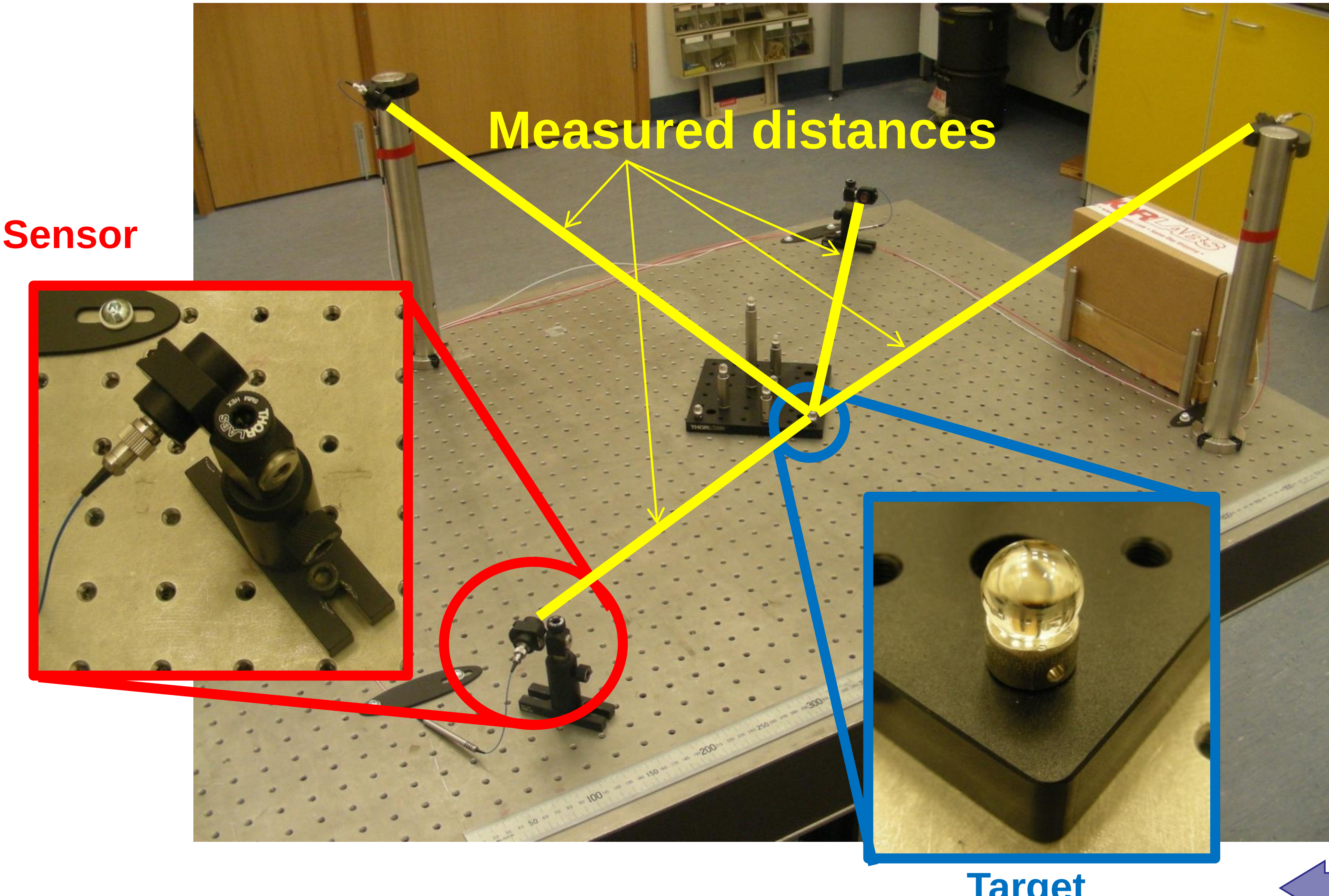
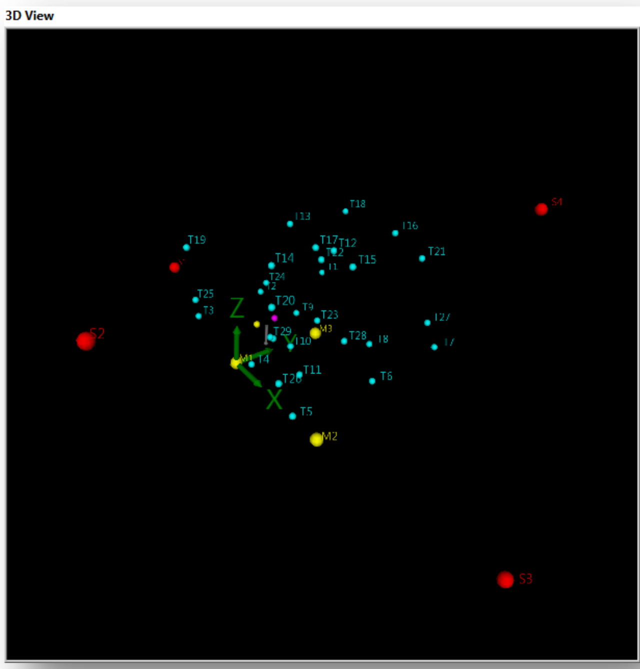
Multilateration using divergent beam interferometry

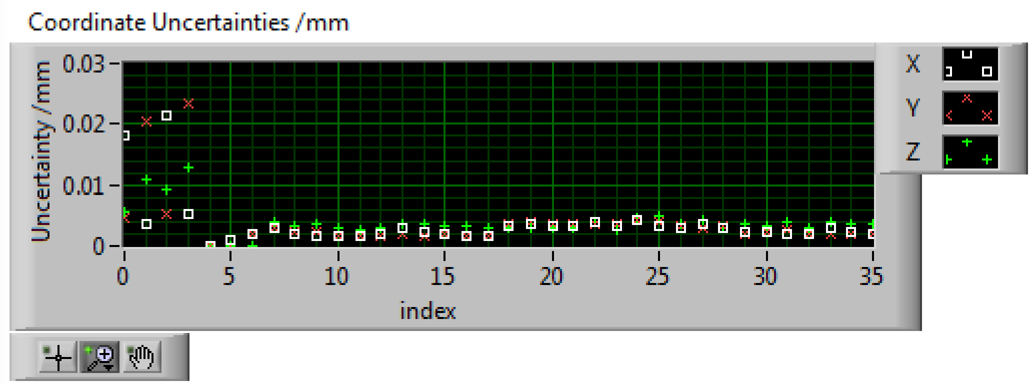


More equipment under the table

Multilateration Results

- RMS length residuals of 1.4 µm
- Coordinate uncertainties of < 4 µm





(Target measurements taken individually, drift compensation implemented)

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Current / Future Work

- Extend to larger volume (5 - 10 m^3)
- Reduce FWM Noise
- Correspondence problem
- Extend FSI scanning range
- Identify and investigate any un-modelled systematic errors
- Online multilateration computation

Summary and Conclusion

National Physical Laboratory

- **Coordinate Measurement System** operating over a **~0.5 m^3 volume**.
- **Wide-field frequency scanning interferometry** to detect multiple targets simultaneously from multiple sensors.
- Four Wave Mixing to make measurements **insensitive to motion.**
- Measurements are **traceable** to the SI through use of a reference gas cell.
- **Multilateration** to calculate coordinate positions of both targets and sensors.
- The system is **self-calibrating.**
- Compensate for **systematic errors** with **full traceability**.
- **~ 1 µm coordinate uncertainties** achieved.

Thank you