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Frequency Scanning Interferometry – traceable 3D coordinate metrology

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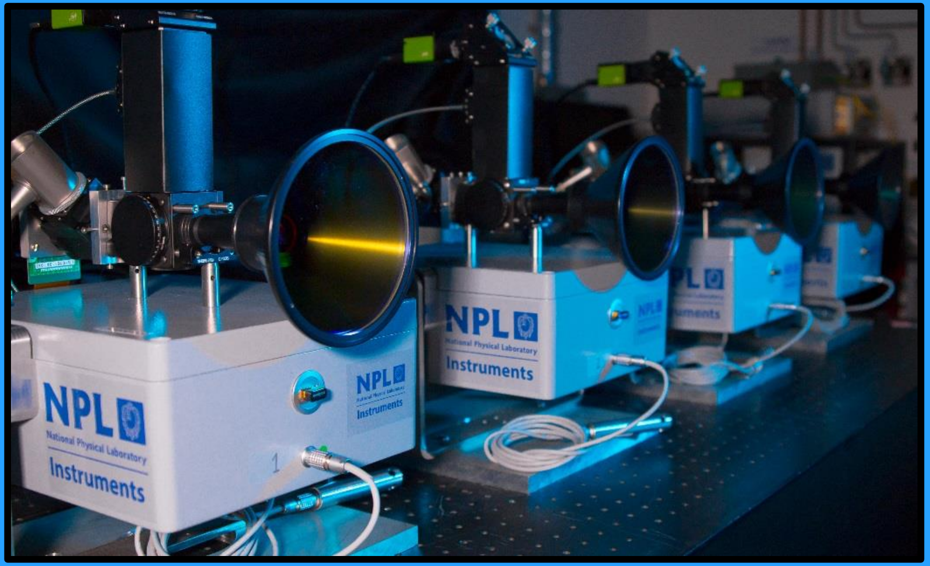

LUMINAR End of Project Meeting
2016, 19th May, NPL

Outline

- Introduction
- NPL’s Proposed Coordinate Metrology System
- Results
- Summary & Conclusions
- Future Work

Introduction

- How good is my instrument?
- How can I be sure my calibration is still valid?
- What’s my measurement uncertainty?

Introduction

- Objective is to make a CMS that is:
  1. As accurate as possible
  2. Measures multiple points simultaneously
  3. Self-calibrating - built-in compensation for systematic errors
  4. Has built-in traceability to SI metre
  5. Gives on-line uncertainty estimation
- Current project focus on proof-of-principle

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Proposed solution

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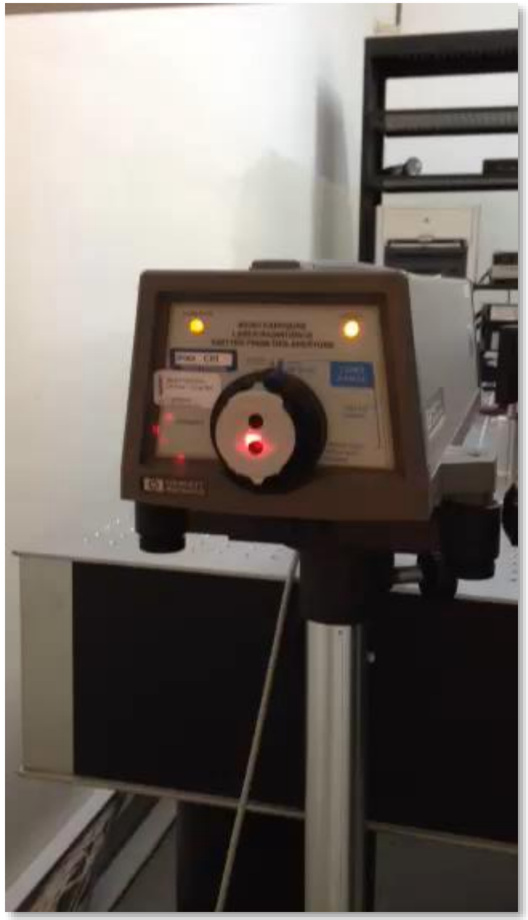
- Combination of:
  - Multilateration
    - calculates coordinates from distances
    - self calibrating
  - Frequency scanning interferometry
    - high accuracy range measurement



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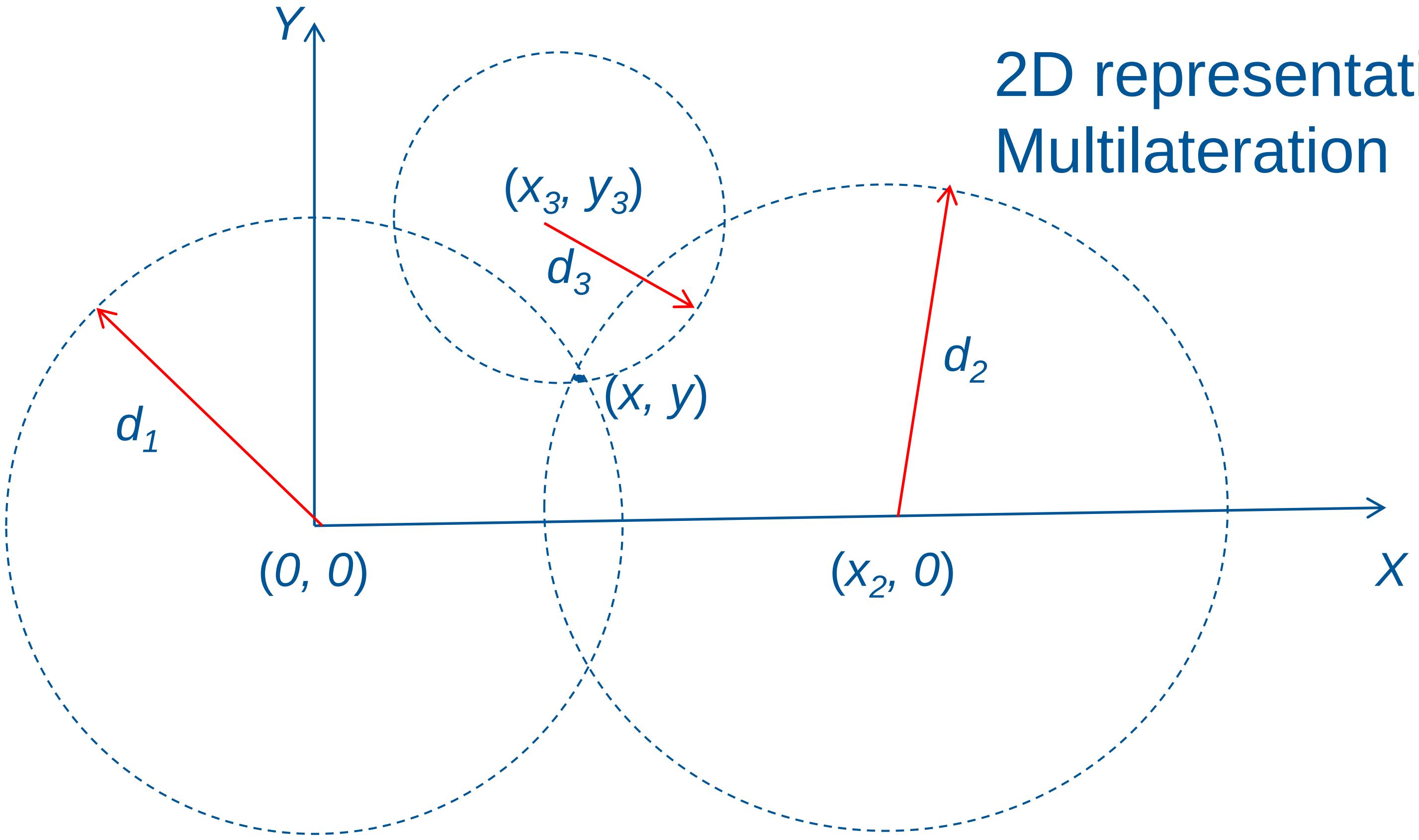
Multilateration…

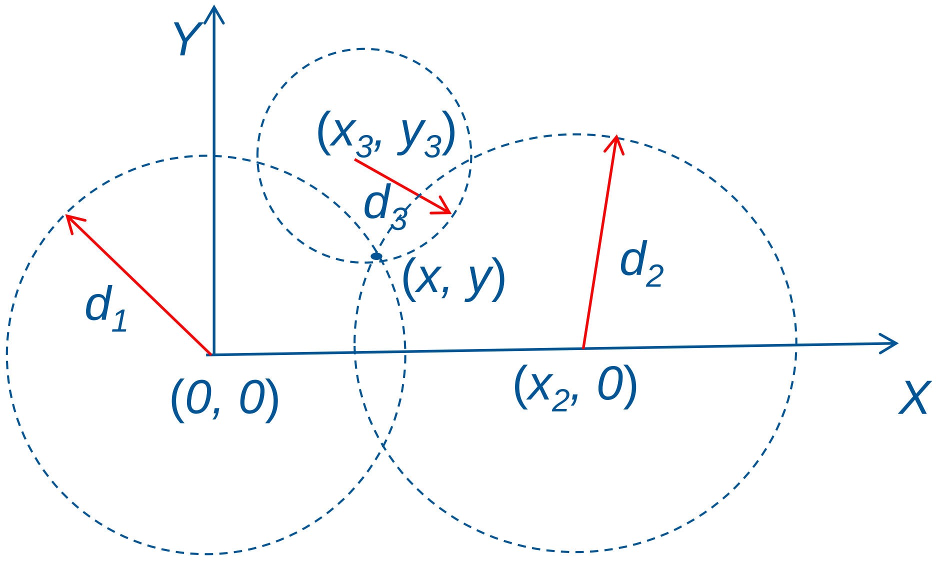
- … is the process of determining absolute (or relative) locations of points by measurement of **distances** using the geometry of circles or spheres



2D representation of Multilateration

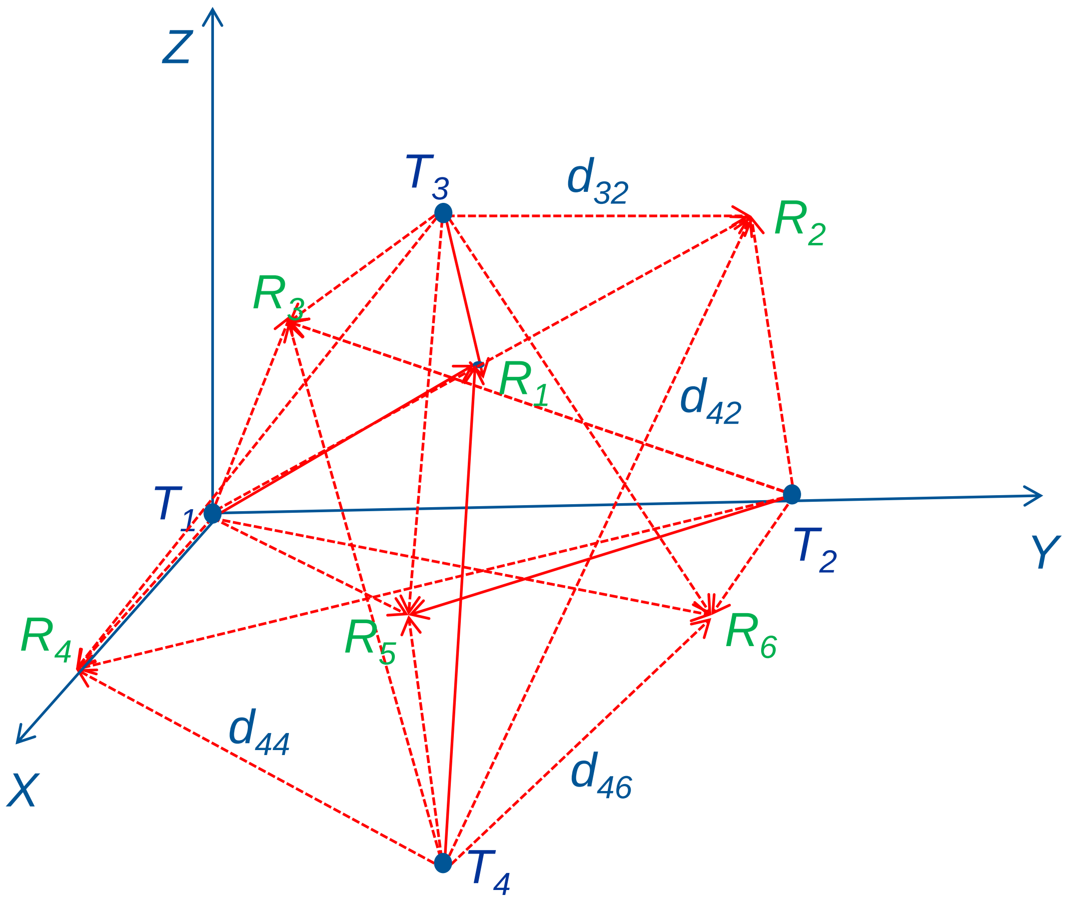
Multilateration

- *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

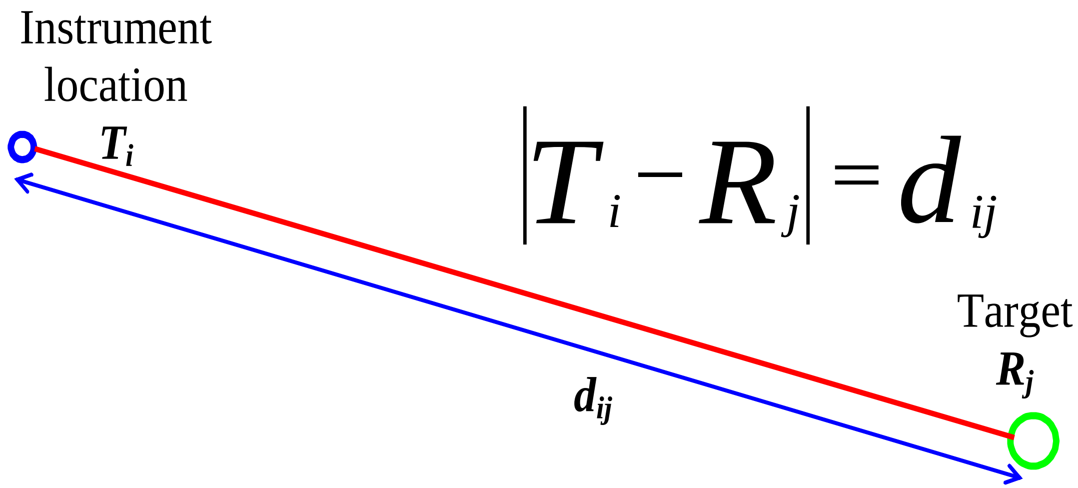
- Add a **fourth** instrument at a fourth location, and
- Measure ranges to **multiple** targets



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

- 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**
  - Coordinate uncertainty ≈ range uncertainty



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

(i = 1, …, M)
(j = 1, …, N)

M number of instruments
N number of targets

Multilateration

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 $N \geq 6$
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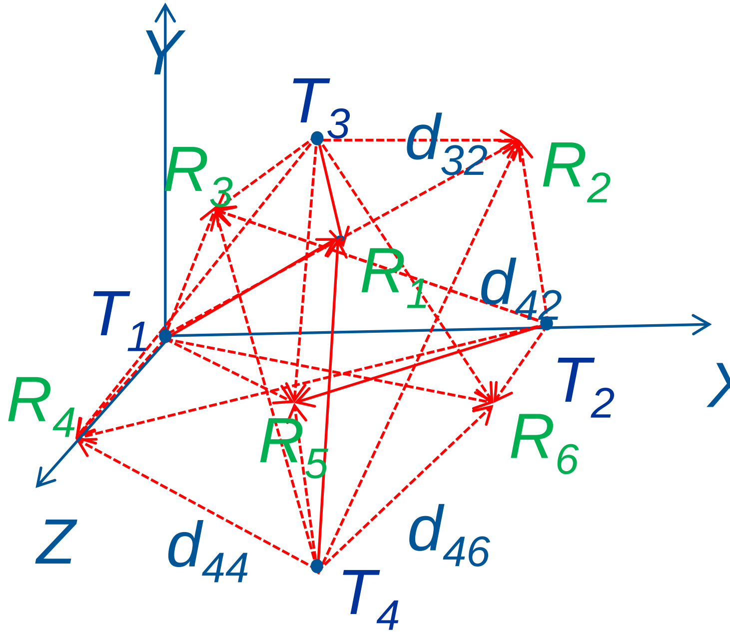
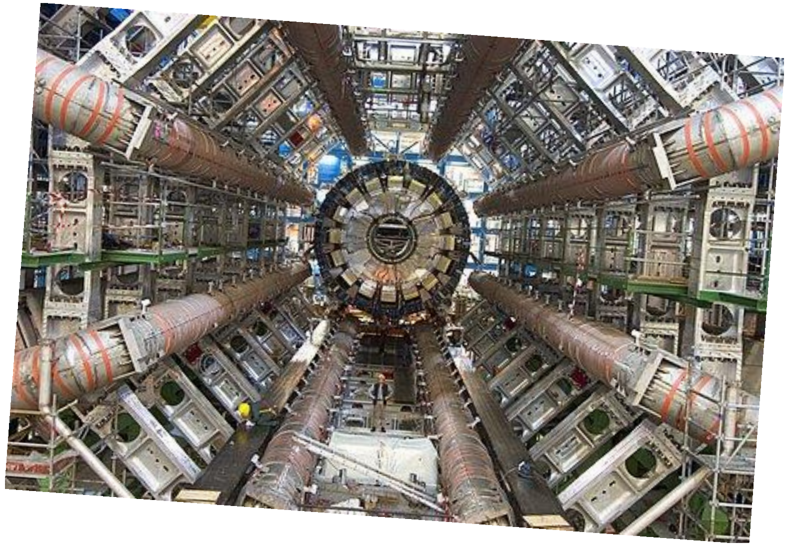
- **Traceable to SI** (if d_{ij} is traceable)
- Can extend model equation to include other **systematic factors** – and **compensate** for them with full **traceability**
- Can achieve coordinate uncertainty ≈ range uncertainty

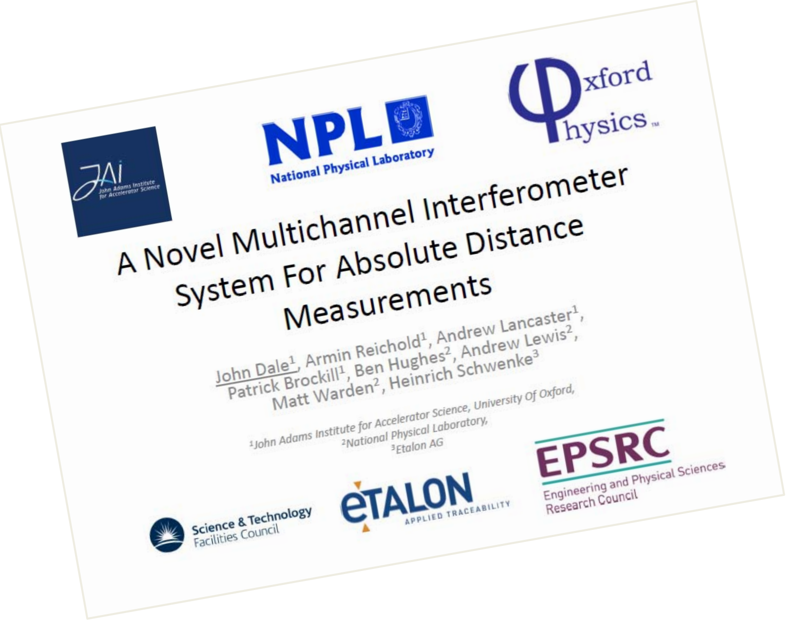


How do we determine absolute distance to multiple targets simultaneously?

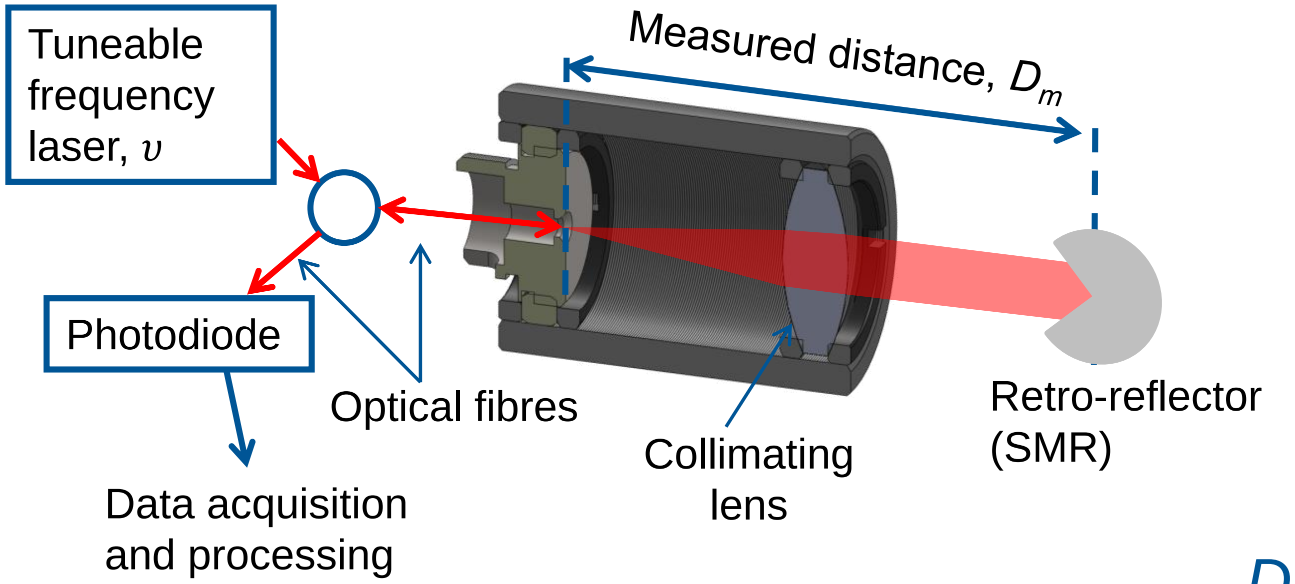
Frequency Scanning Interferometry

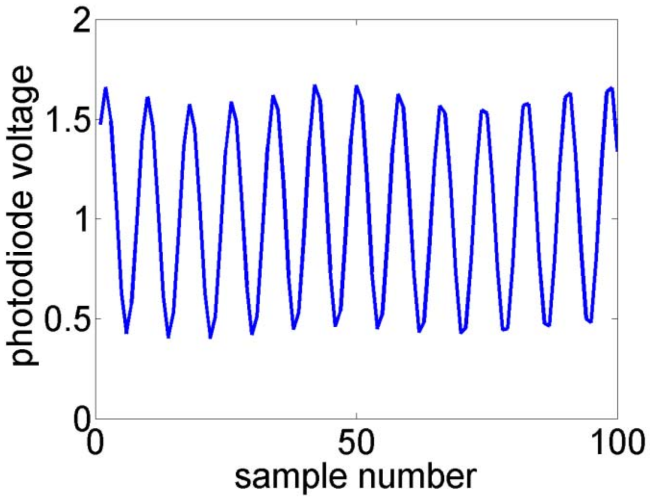
- Developed extensively at Oxford University
  - ATLAS
  - Oxford/NPL/Etalon presented recent developments at LVMC 2012
- Similar to laser radar technology





Conventional Frequency Scanning Interferometry (FSI)





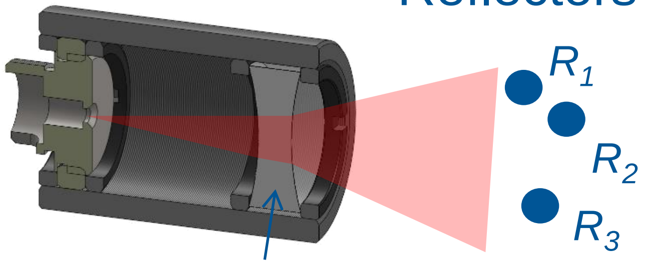
$$D = c\frac{N}{2\Delta\nu}$$

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

Measuring multiple targets simultaneously

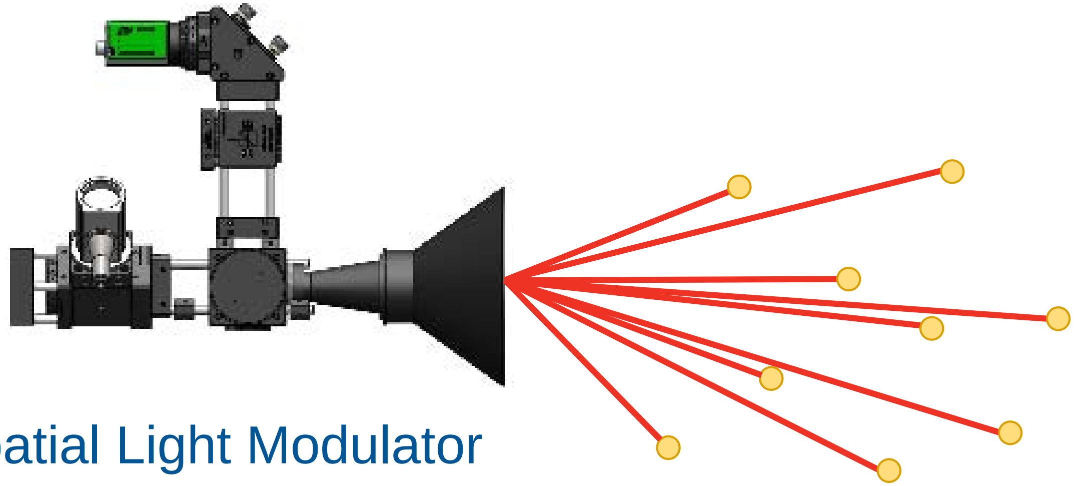
Short range
- Divergent lens system
- Cheap sensor heads

Reflectors



Diverging Optics

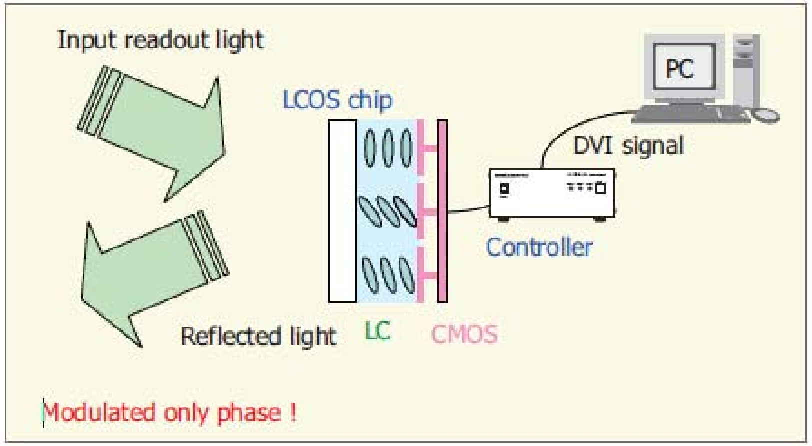
Long range
- Near-collimated beams
- Multiple beams
- Steerable beams with tracking

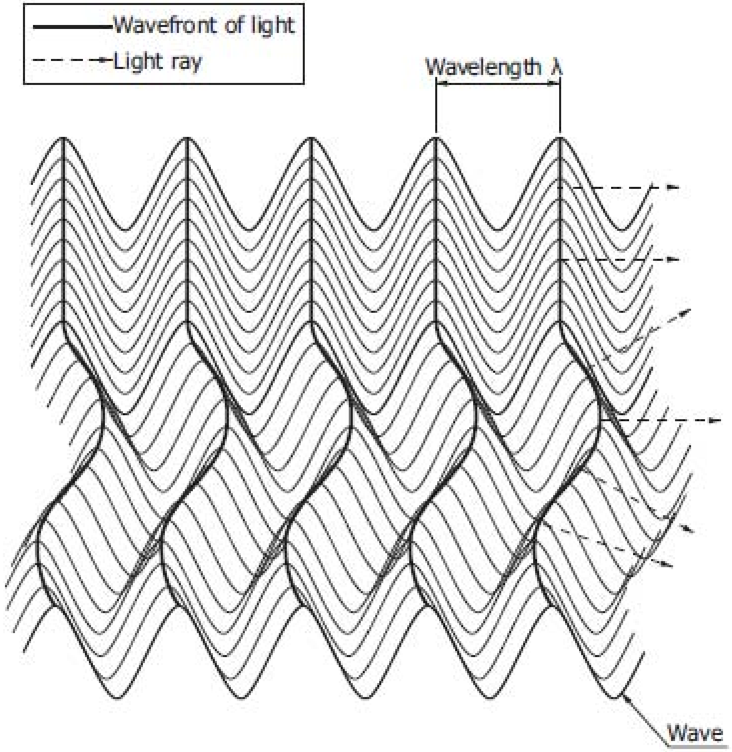


Spatial Light Modulator + Optics + Camera

Measuring multiple targets simultaneously

- Key component is the SLM





NPL's Proposed Coordinate Metrology System

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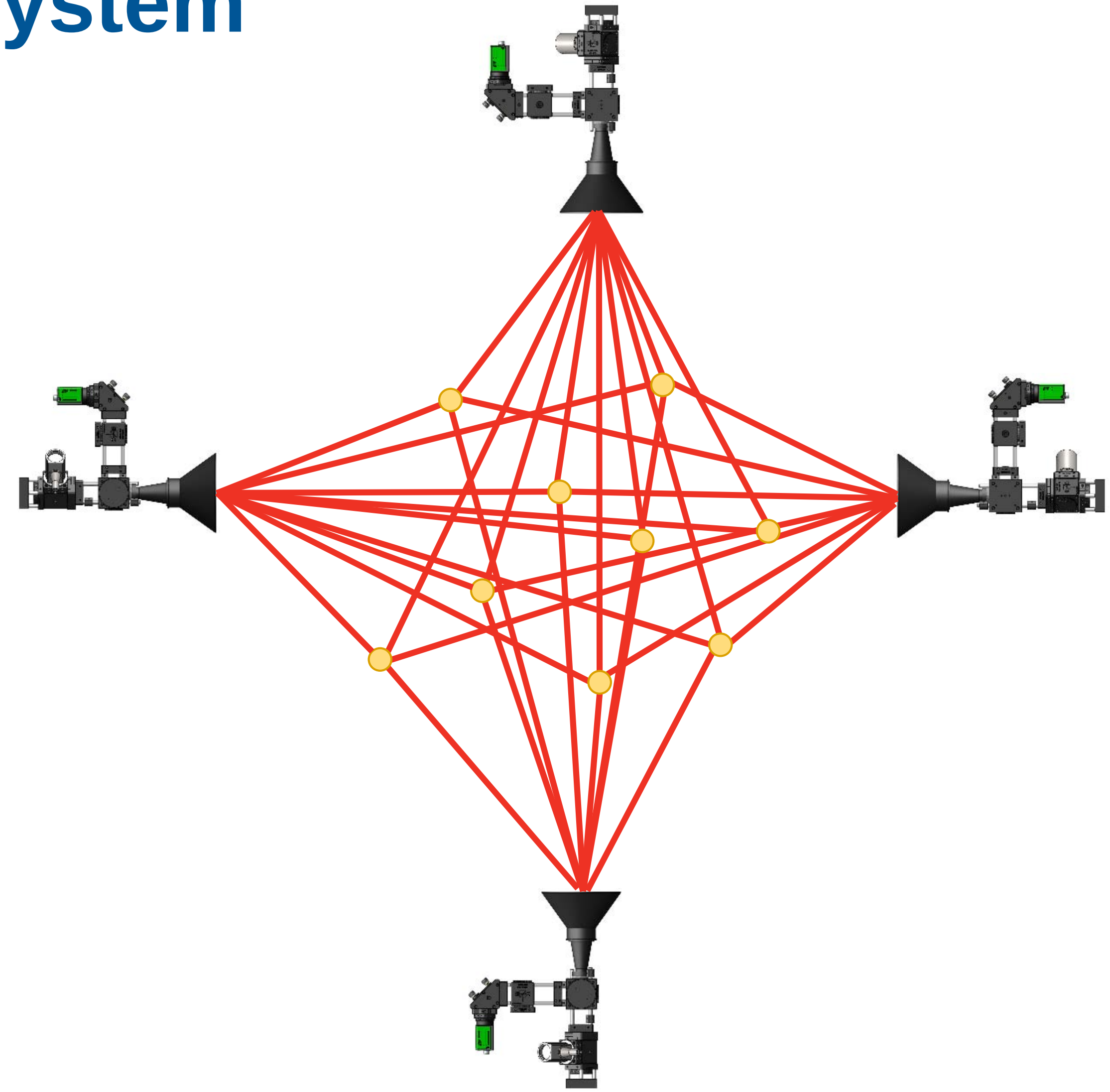
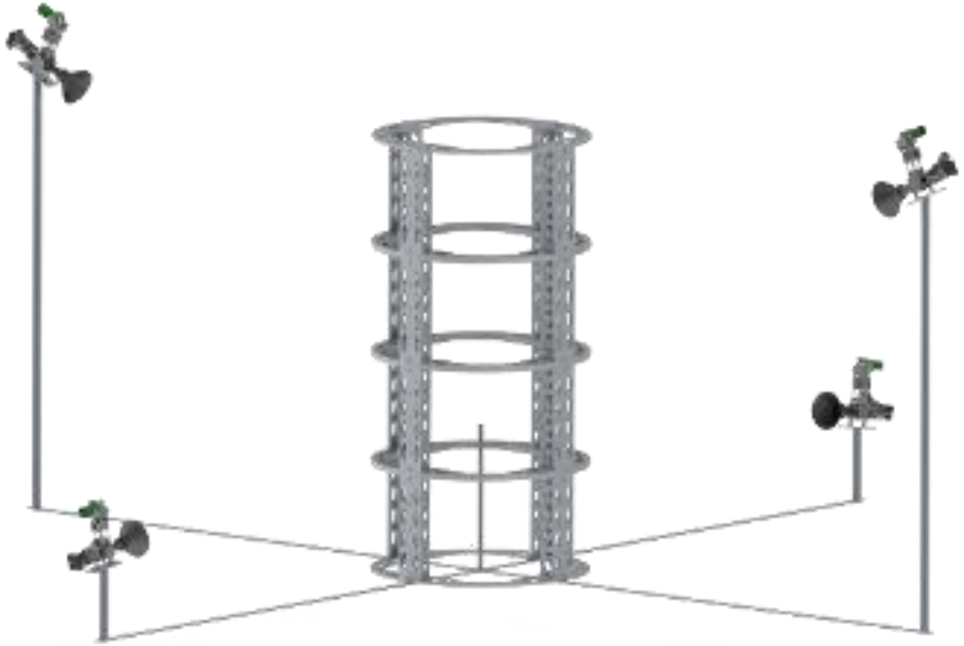


Aim for an operating volume of 10 m x 10 m x 5 m and uncertainty of < 50 µm



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Extracting signals from multiple targets

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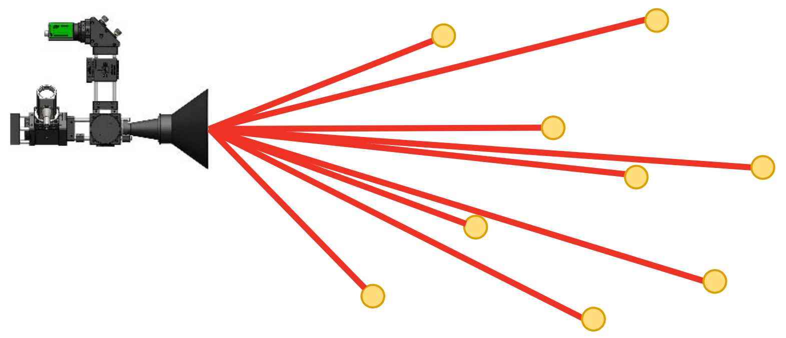

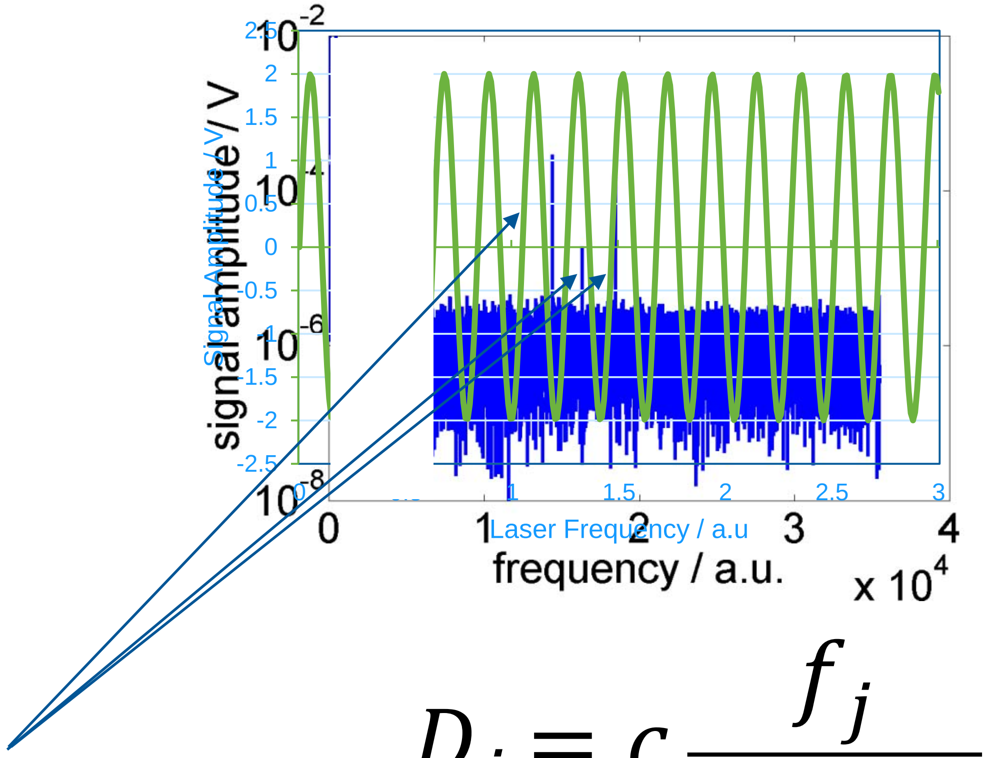

Fourier transform

$$D_j = c\,\frac{f_j}{2\,{dv}/{dt}}$$

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

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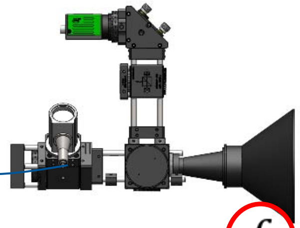
Traceability to SI: Gas Cell Frequency Reference

Variable Frequency Laser, ν

Gas Cell

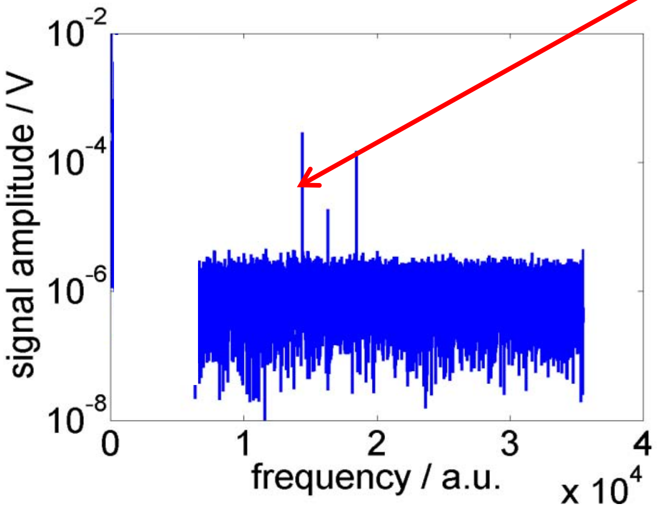
Photodiode



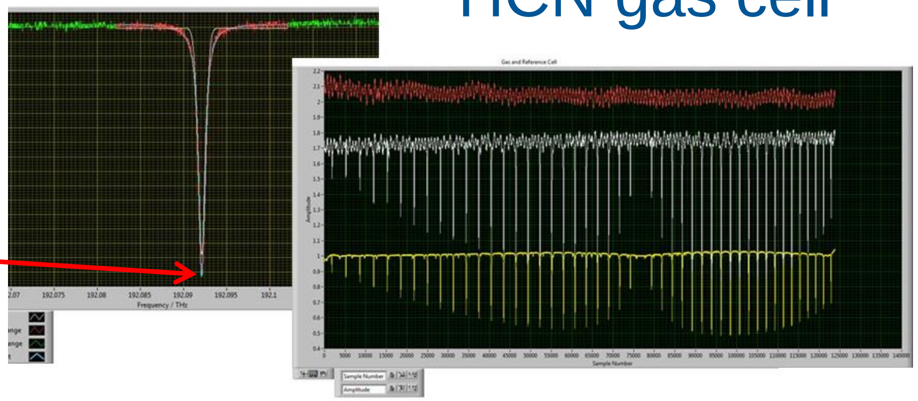
Photodiode

Fourier transform

$$D_j = c\frac{n_j}{2\Delta\nu} = \frac{f_j}{2\frac{d\nu}{dt}}$$



HCN gas cell



Absorption peaks have known and constant frequencies

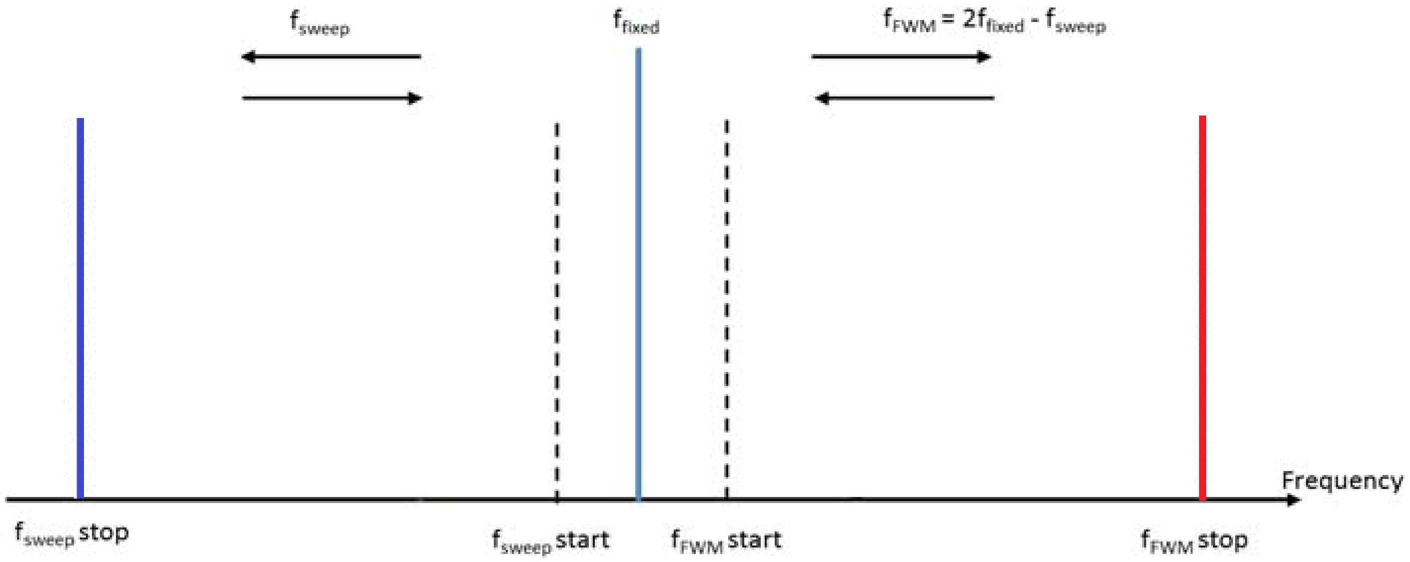
Gas cell provides **traceability** to the second and to the metre via the defined speed of light, *c*. **Uncertainty of ~ 1 ppm**

Vibration compensation

- Conventional solution is to use two lasers; one sweeps up, the other down in frequency
  - Expensive
  - Ideally need to synchronise the sweeps
- We use (degenerate) Four Wave Mixing (FWM)
  - A non-linear optical effect
  - Takes pump laser (fixed frequency, F_1), signal laser (tuneable, F_2) generates new signals,

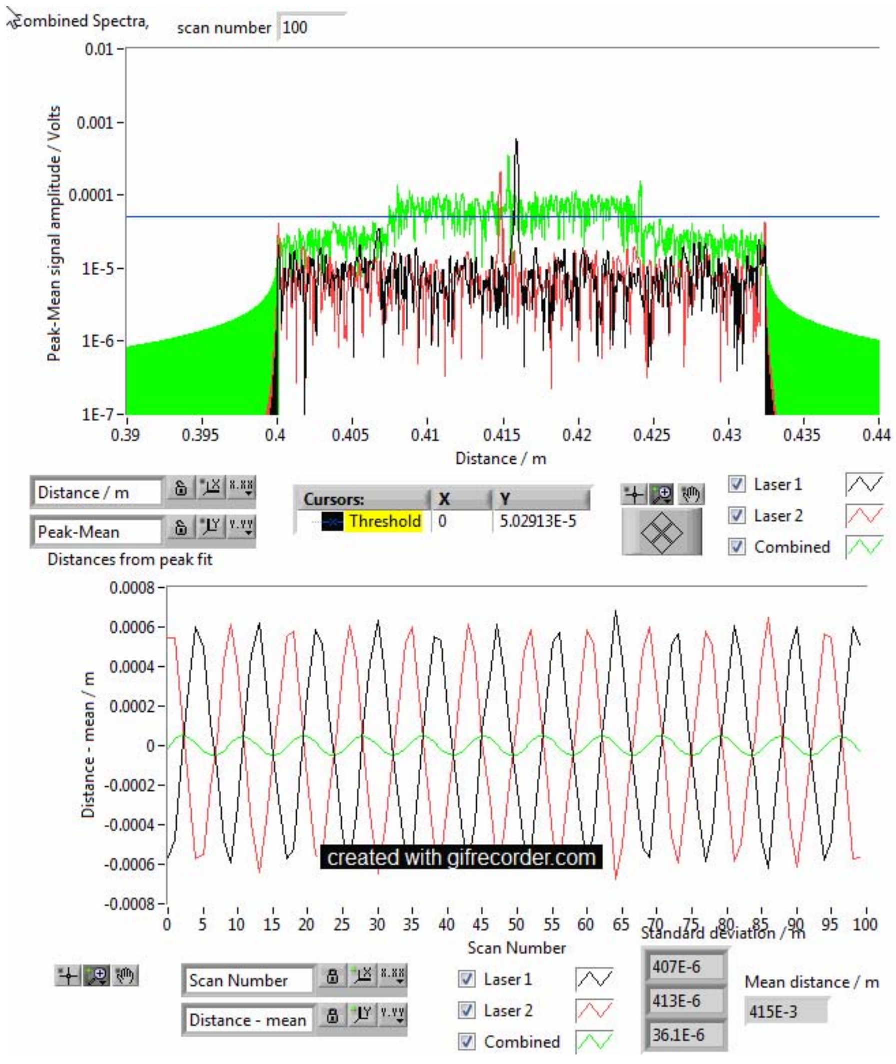
$$F_{3,4} = 2F_1 \pm F_2$$

Vibration Compensation

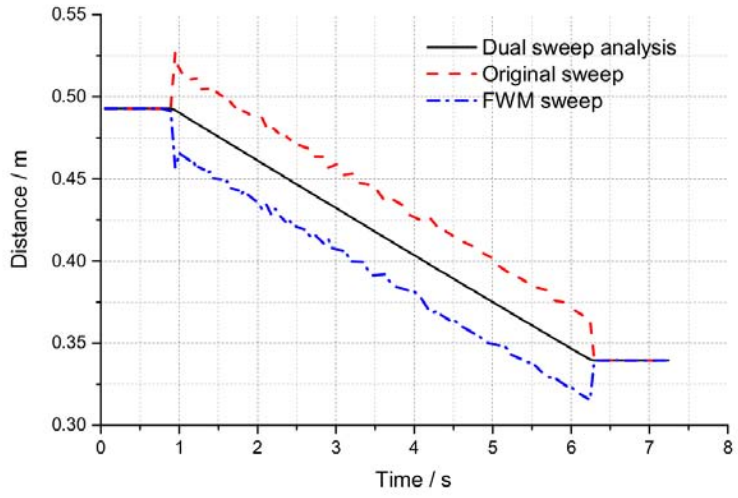


- Fixed frequency DFB laser – 1564.3 nm
- Original laser - 1530 → 1560 nm
- FWM generated - 1565 → 1600 nm
- Filter out unwanted fixed frequency wavelength

Vibration / Motion Compensation



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



Target moving at 100 mm/s

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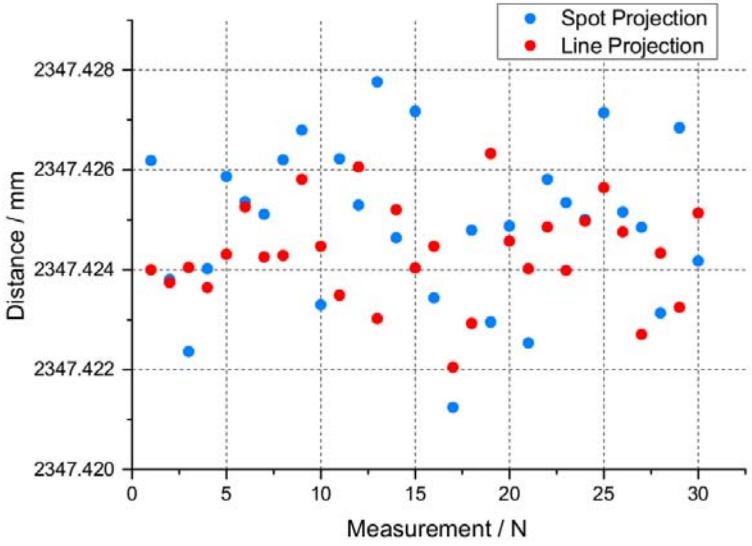
Absolute Distance Measurements

Divergent beam
- Maximum distance ~1 m
- Maximum FoV ~ 60

Original laser / µm	FWM laser / µm	Combined analysis / µm
3.8	3.7	0.4

Standard deviation of 100 distance measurements taken of a stationary target at ~ 0.51 m

Long range system
- Maximum distance > 12 m
- Maximum FoV > 70°
- Greater SNR



Spot projection/ µm	Line projection/ µm
1.5	1.0

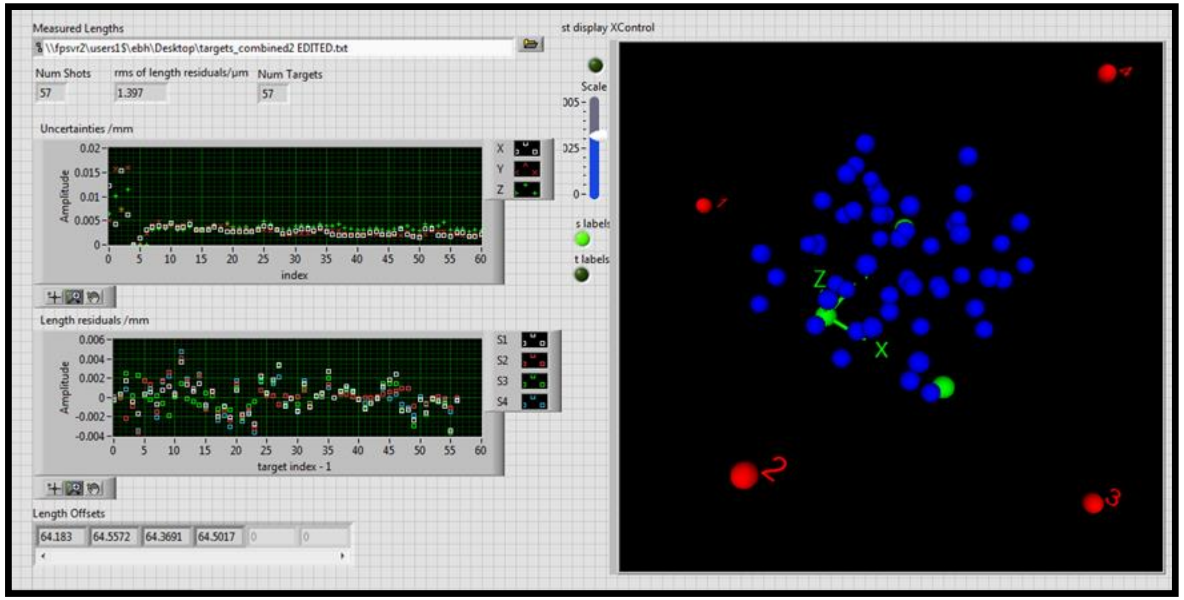
Standard deviation of 30 distance measurements taken of a stationary target at ~ 2.35 m

30 distance measurements taken of a stationary target at ~ 2.35 m

Multilateration Results - Divergent Beam

- Measurement volume of
- ~ 0.75 x 0.75 x 0.75 m
- Coordinate uncertainties of < 5 µm achieved
- RMS length residuals of 1.4 µm

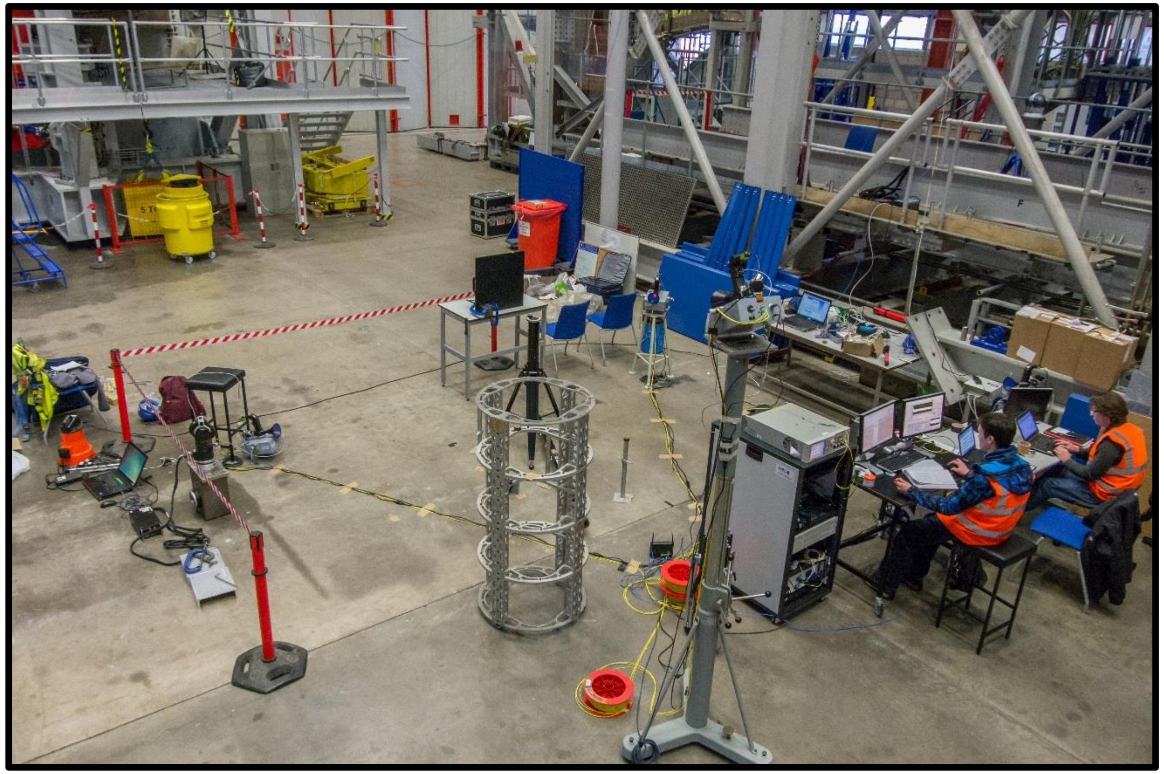
- Vibration compensation applied
- But measurements taken sequentially due to SNR issues with FWM



Graphical output of sensor-target positions and associated uncertainties

Multilateration Results - Long Range Airbus

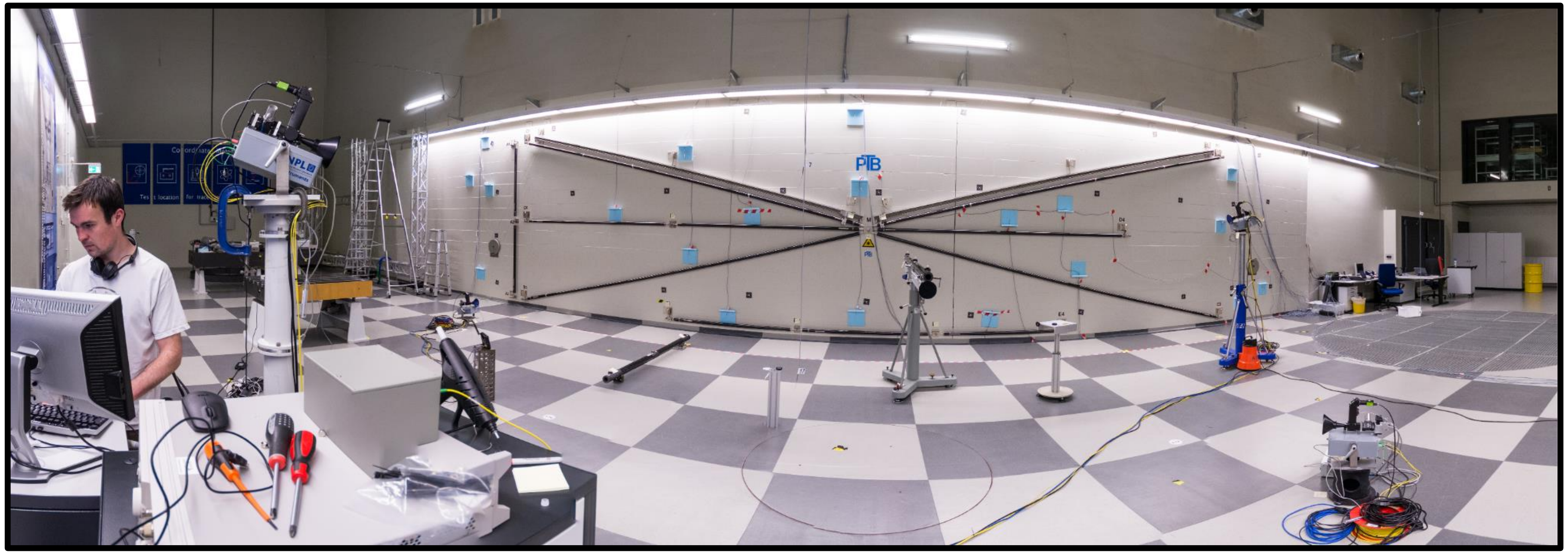
- 5 x 5 x 3 m measurement volume
- Uncertainties of ~100 µm
- Difference from laser tracker for 2.3 m artefact of ~90 µm
- Targets measured sequentially
- No vibration compensation



Test setup at Airbus with 4 sensor heads and 12 targets

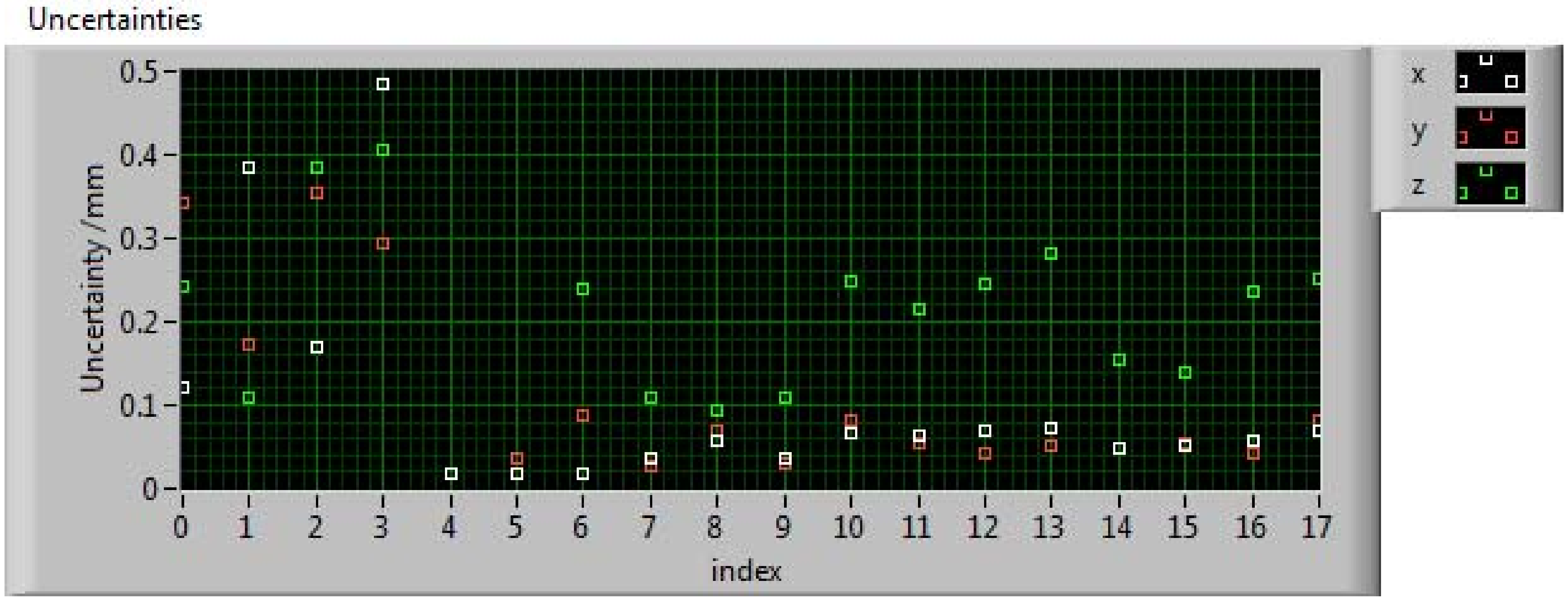
Multilateration Results – Long Range

PTB - Decommissioned Nuclear Reactor



- 10 x 5 x 2.5 m measurement volume
- 4 sensor heads, 15 targets
- Targets measured simultaneously
- Max distance = 8.328 m
- Min distance = 3.240 m
- Angular FoV = 70°

Multilateration Results – Long Range
PTB - Decommissioned Nuclear Reactor



- Measurement uncertainties:
- x , y ~ 100 µm, z ~ 300 µm
- Difference with tracker measured artefact ~ 50 µm – 150 µm

- No vibration compensation
- Spot projection, not line projection
- No optical distortion correction
- Poor geometry / redundancy

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Summary and Conclusion

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- Prototype *proof-of-concept* system constructed
- Two types of sensor developed
  - Short range (simple diverging lens)L
  - Long range (SLM + optics + camera)
- Repeatability < 0.5 µm for short range system
- Multi-beam steering over wide angular range using SLM
- FWM for synchronised dual laser sweep generation – vibration/motion compensation
- Simultaneous FSI to multiple targets over large volume from multiple sensors demonstrated
- Traceability through direct, *in-situ* calibration against a gas absorption cell with an uncertainty of 1 ppm.
- Multilateration determines un-known system parameter, currently sensor locations and offsets as well as target coordinates
- Currently achieving uncertainties ~ 100 µm (but lots of improvements coming)
- Three patents pending

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Future Work
Lots to do!

- Improve mechanical stability of sensors
- Fix FWM – vibration/motion compensation
- Improve optics for long-range sensor
- Software improvements/integration
- Implement optics calibration in multilateration solution – improve accuracy
- Develop (much) faster data acquisition system – increase measurement speed, implement target tracking
- …..

Thank you

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National Measurement System

EMRP
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Programme of EURAMET

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