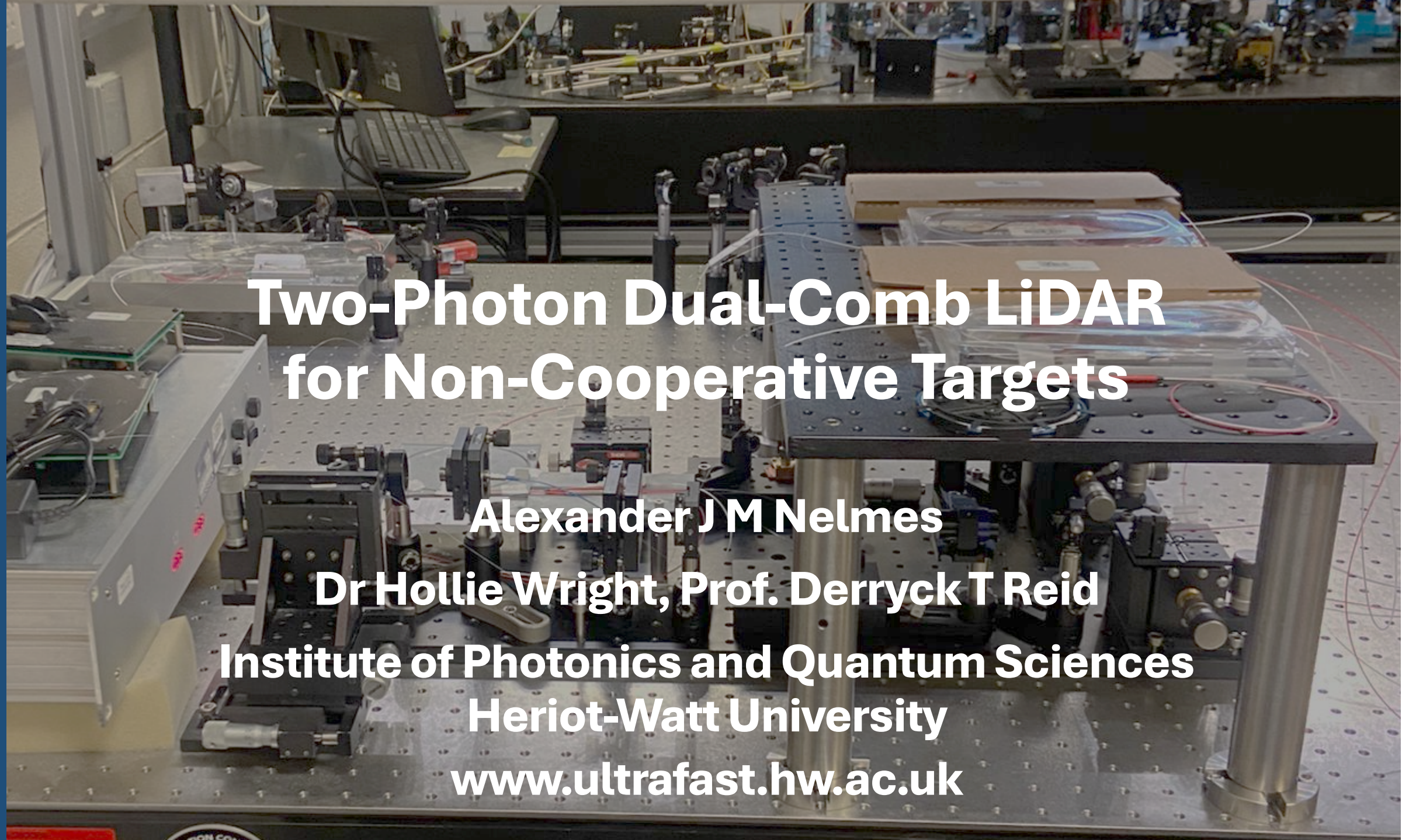

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Two-Photon Dual-Comb LiDAR for Non-Cooperative Targets

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Dr Hollie Wright, Prof. Derryck T Reid

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Outline

1. Introduction
   a. Overview
   b. Industrial Applications
2. Two-photon dual-comb LiDAR
   a. Optical Concepts
   b. Electrical operations
   c. Non-cooperative target measurements
3. Conclusion

Introduction – Overview: *Motivations*

- Absolute distance measurements
- Ranging at μm-level precision and at kHz-level update rate
- Using eye-safe lasers at a wavelength of 1550 nm

Two-photon dual-comb LiDAR

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Multi-target two-photon dual-comb LiDAR

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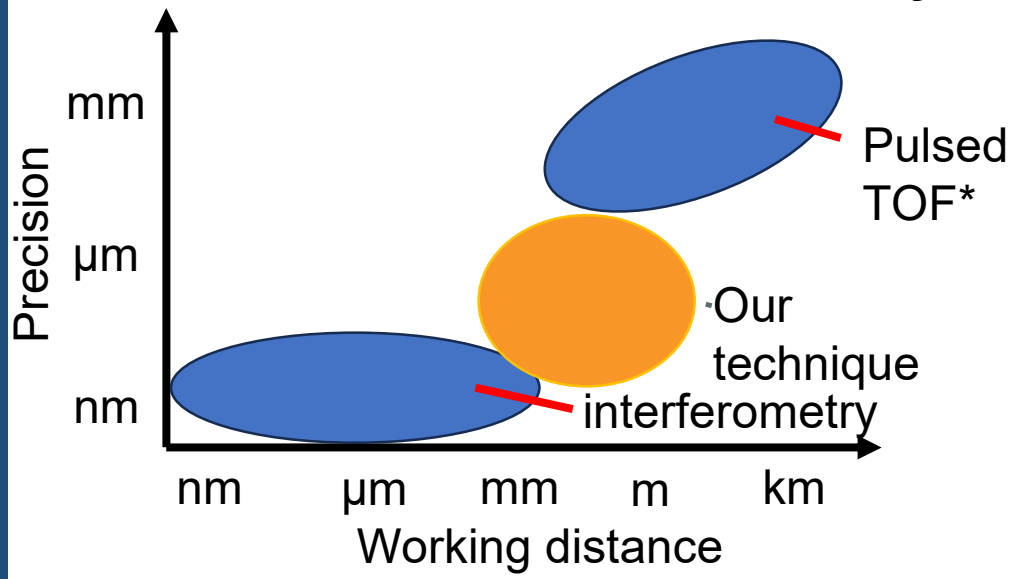
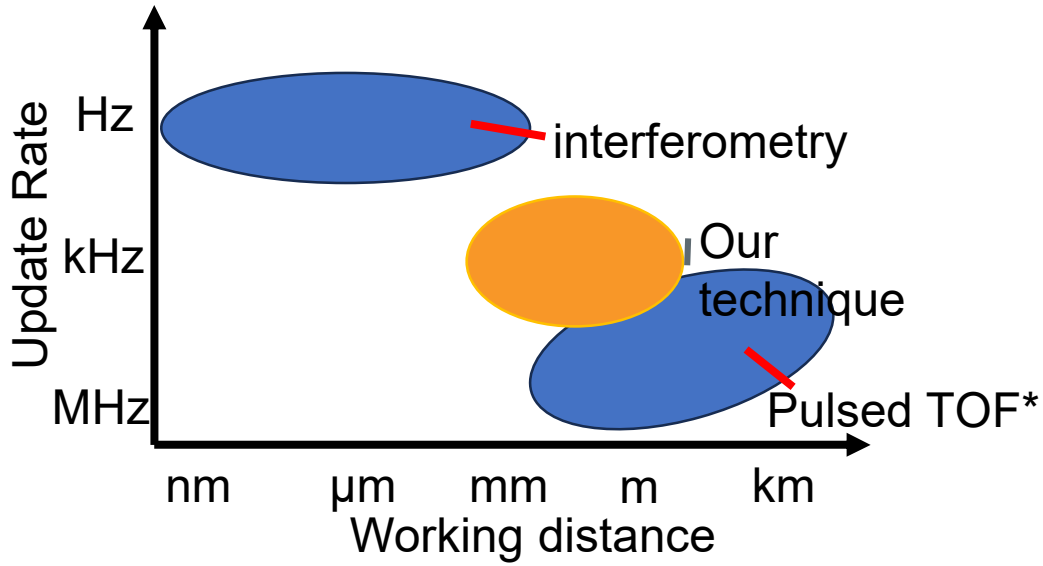
*H.Wright@hw.ac.uk

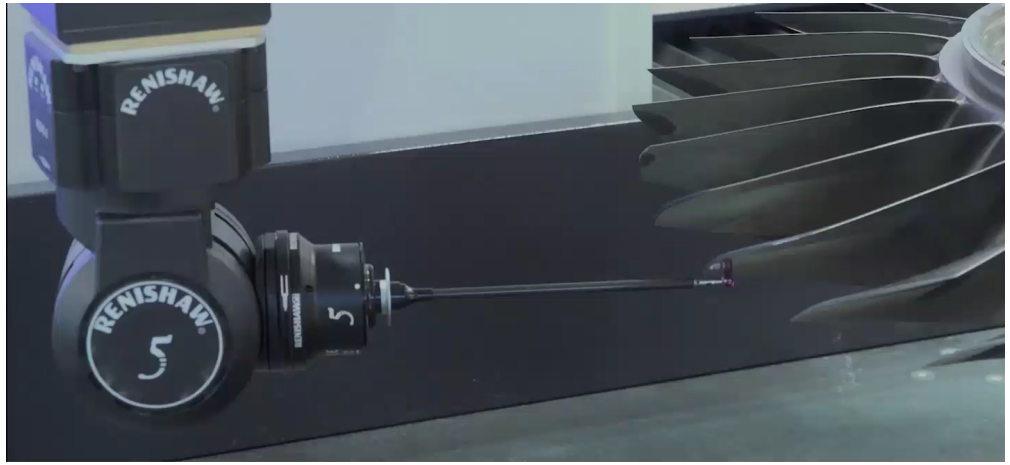
Optical Ranging Tools for Industry

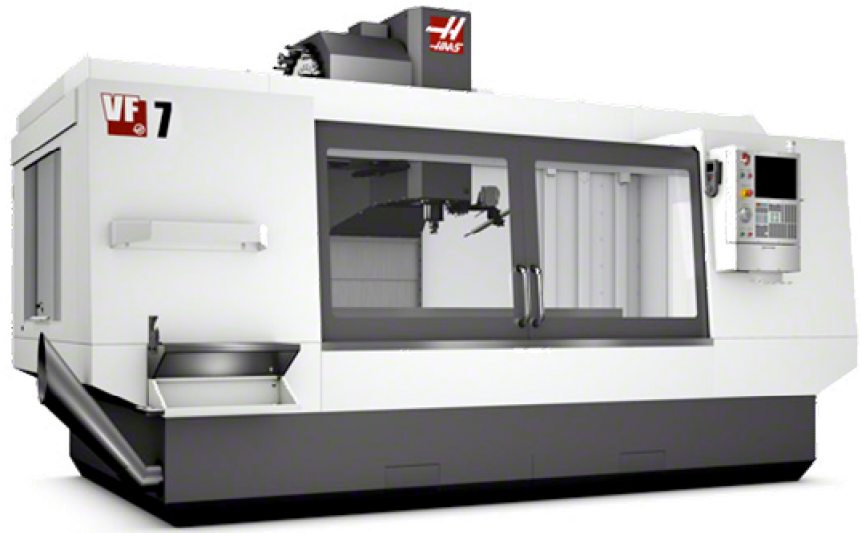




Introduction– Industrial Applications:
Applications in Industrial Metrology

- Industrial priorities —
  - absolute distance measurement
  - robust to beam interruption
  - µm-level precision
  - rapid (kHz) update rates
- Machine-tool calibration
  ⟹ coordinate measurement machines (CMMs) or manufacturing robots
- Machine-tool motion verification
  ⟹ direct measurement of the end-effector (tool tip) instead of motor encoders
- Important for both Cartesian machines (e.g. CNC milling) and non-Cartesian machines (e.g. robot arms, hexapods)

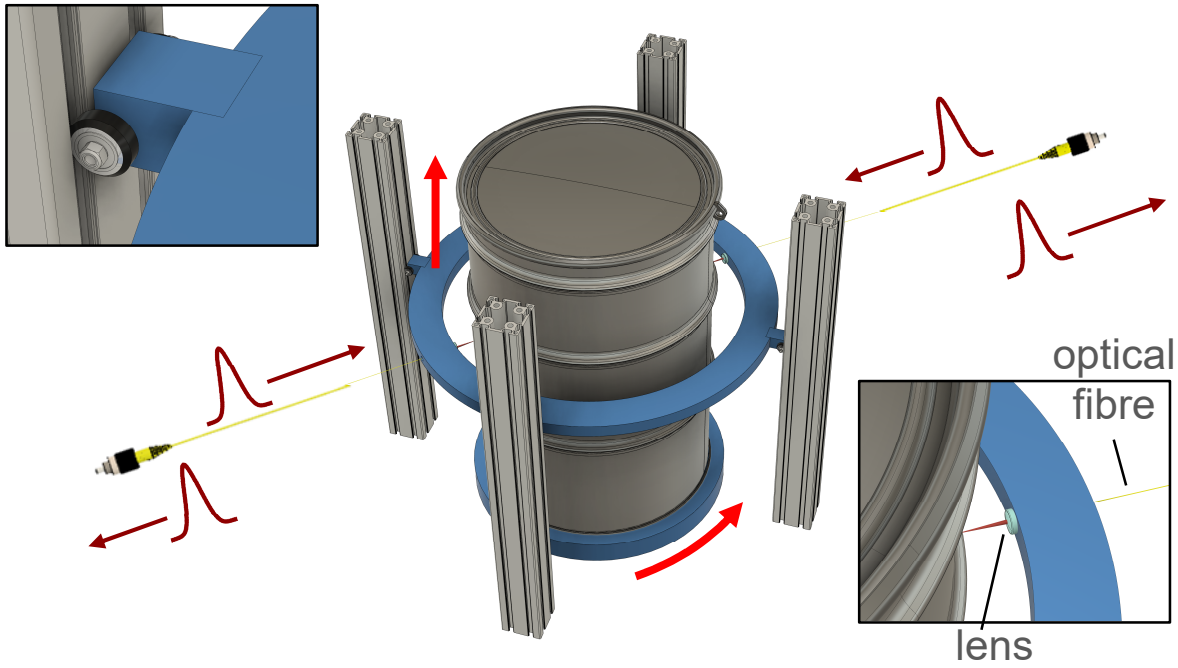




Introduction– Industrial Applications:
Nuclear security and defence work

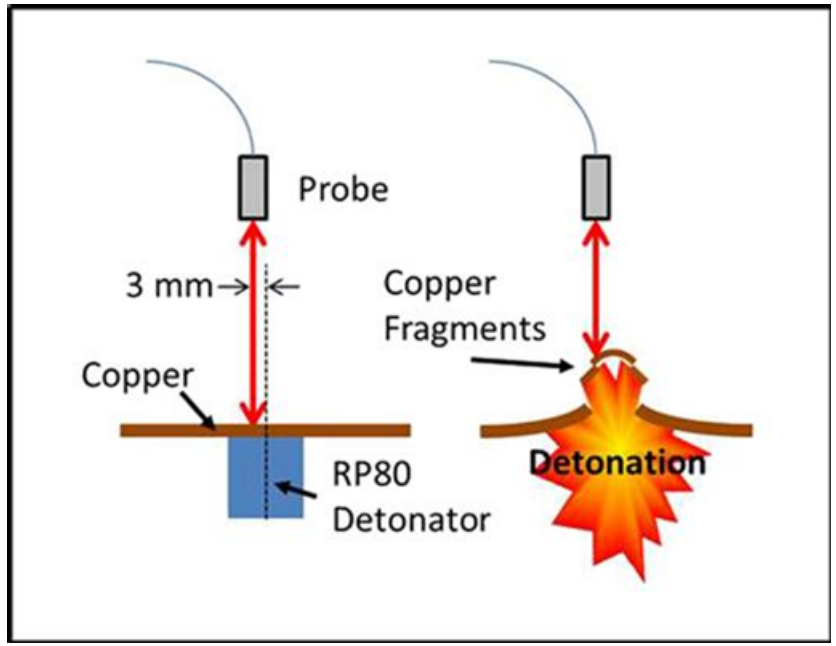
Dimensional Characterisation

- Aiming for accuracy <5 μm
- Alternative to touch probes / interferometry
- Characterisation of non-cooperative objects



Characterisation of Explosives

- Typically use pole-doppler velocimetry.

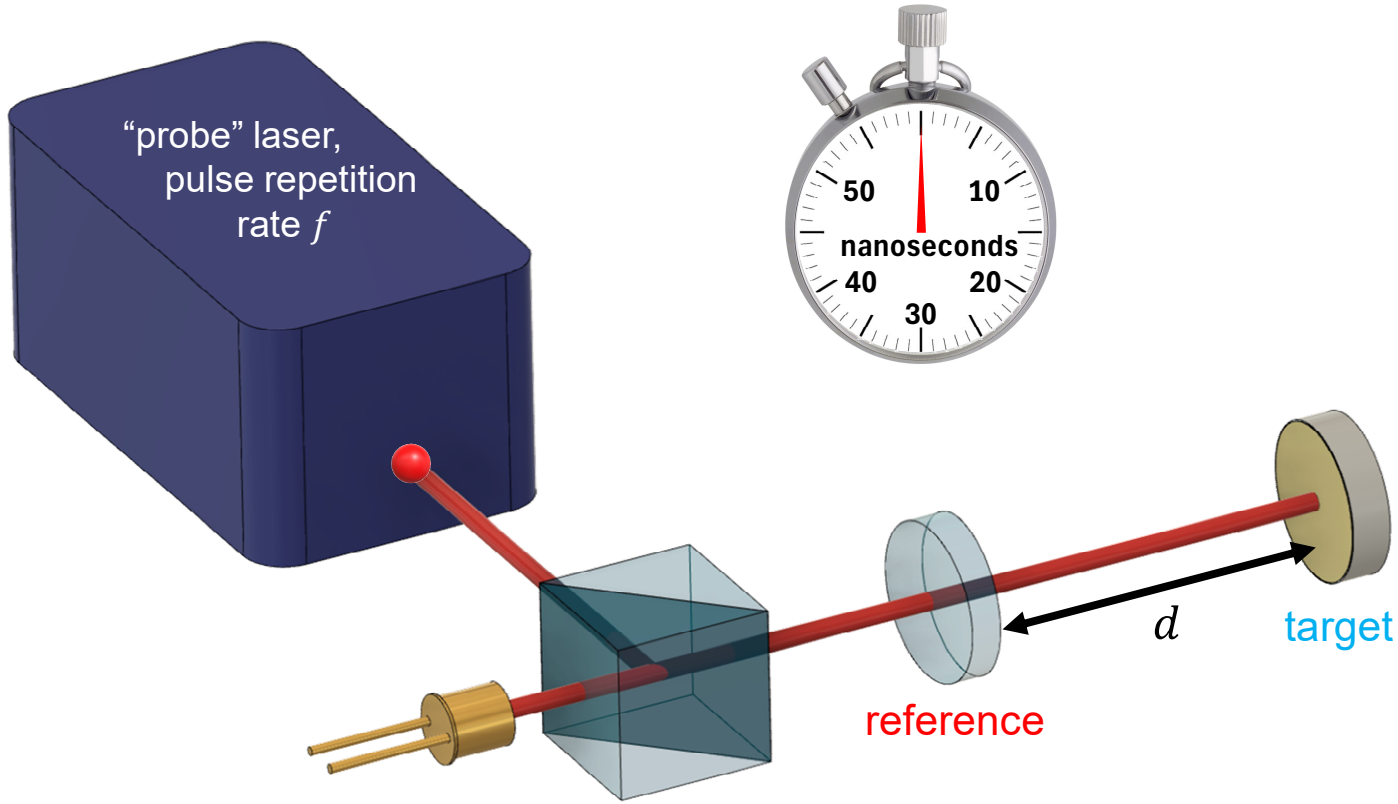


LaLone, *et al.* Rev. Sci. Inst, 2015

- Require high-repetition-rate lasers to enable sufficiently high-speed measurement (≈20 μs acquisition time).

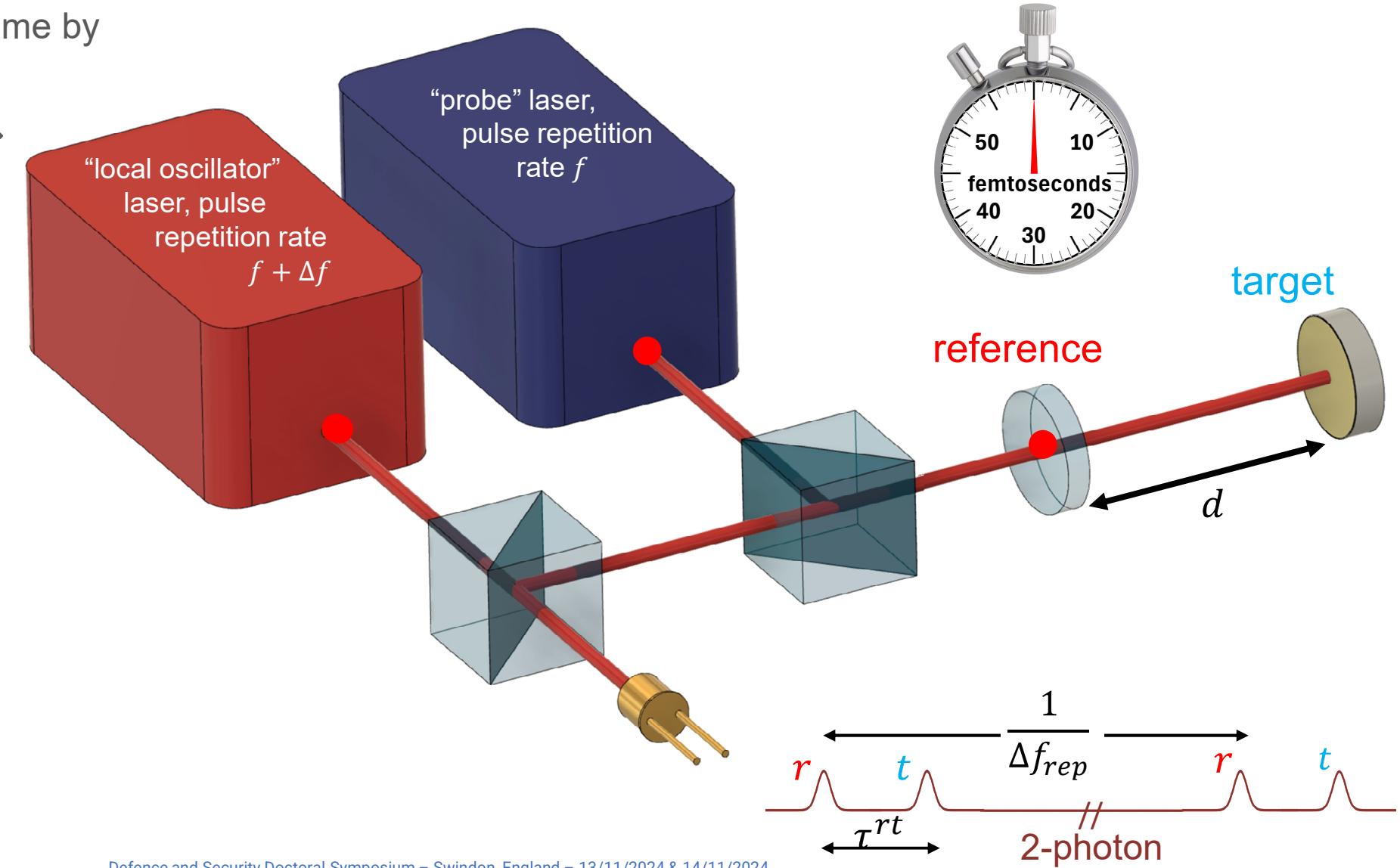
Two-photon dual-comb LiDAR – Optical Concepts:
Conventional time of flight LiDAR

- Conventional LiDAR uses a pulsed laser + time-of-flight to measure distance.
- Pulses from reference and target optics start and stop the clock.
- Typical LiDAR electronic timers (≈50 ps resolution) limit precision to cm.

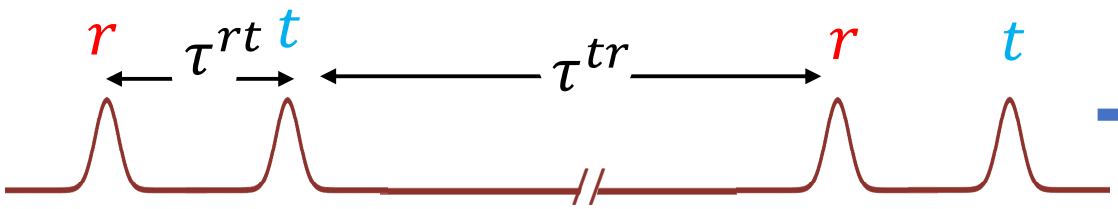


Two-photon dual-comb LiDAR – Optical Concepts:
Two-photon dual-comb LiDAR

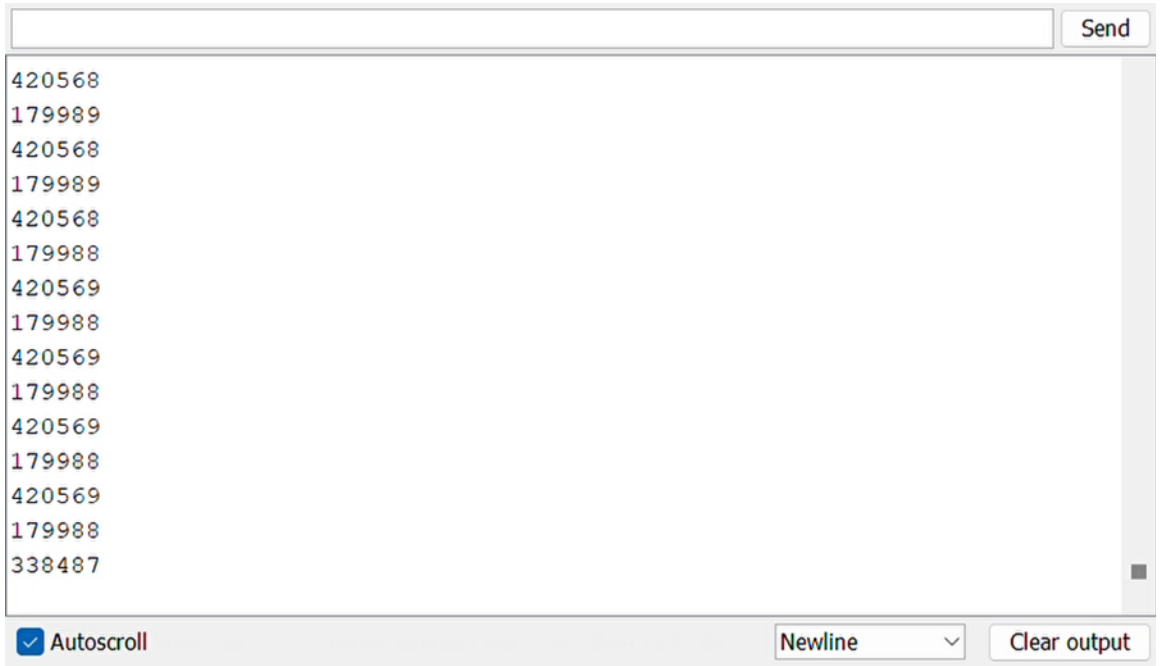
- Dual-comb measurement "stretches" optical time by factor $f/\Delta f$
- Same electronics ⇒ **100-nm precision!**



Two-photon dual-comb LiDAR – Electrical operations:
Electronic time tagging

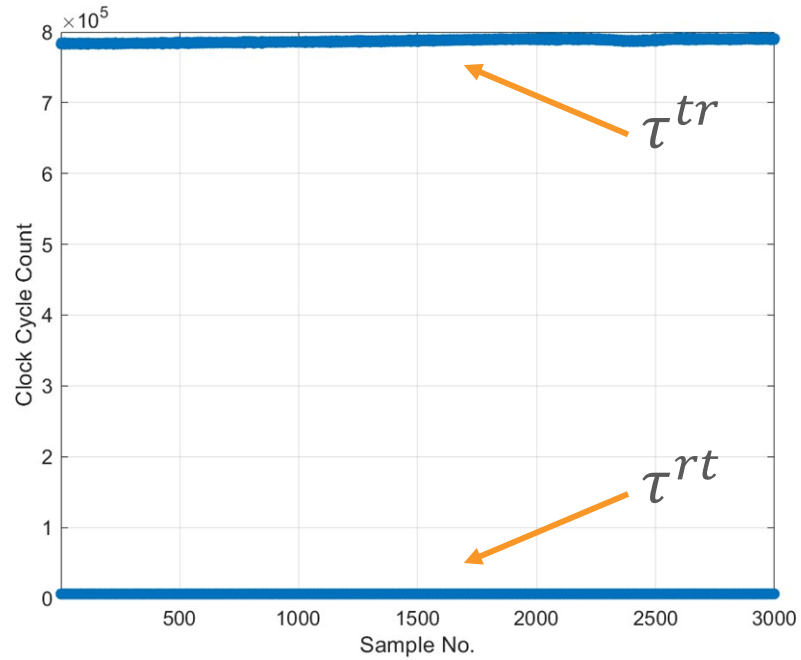


- Arduino Teensy 4.0 counts internal 600 MHz clock cycles
- Saves and resets the count when a rising edge is detected
- Timing resolution = internal clock duration = 1.67 ns



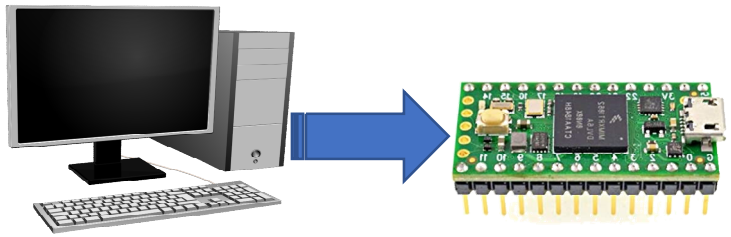
- "Time-tagged" pulses provide distance measurement:

$$d = \frac{c f_{rep}}{2} \cdot \frac{\tau^{rt}}{\tau^{rt} + \tau^{tr}}$$

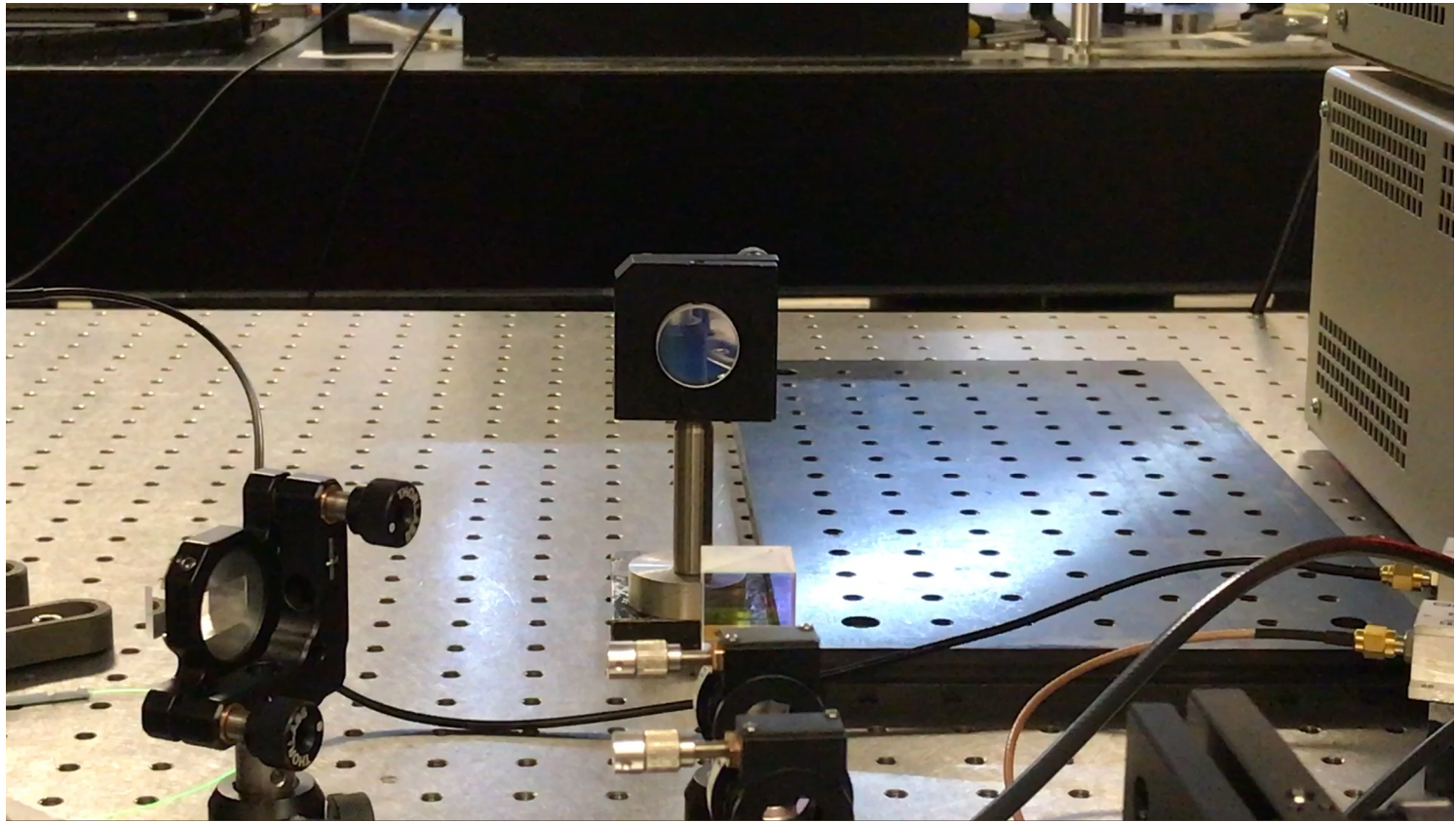


Two-photon dual-comb LiDAR – Electrical operations:
Real time data and data burdens

- Ultra-efficient data collection.
- Allows real time data results
- E.g. 25s of data costs:
  - 21GB for digitizer,
  - few 100kB for Teensy.



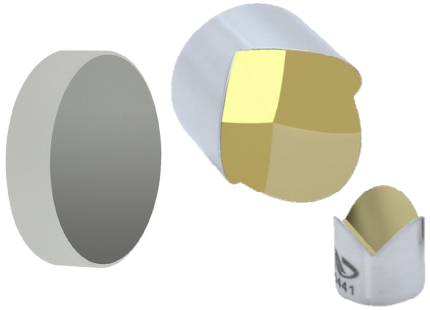
£10K+ £20

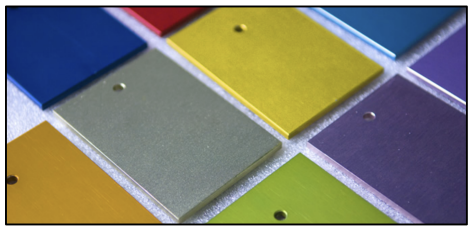


Two-photon dual-comb LiDAR – Uncooperative Target Measurements

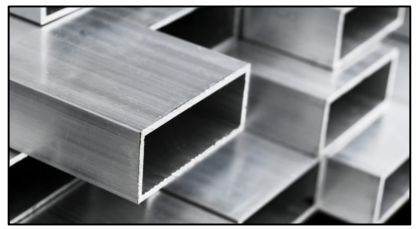
Towards non-cooperative targets

- Previous targets were mirrors / retroreflectors—what performance can we get from metal targets?





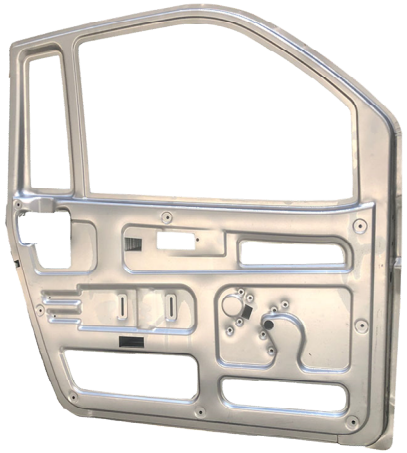
anodised



bare

painted

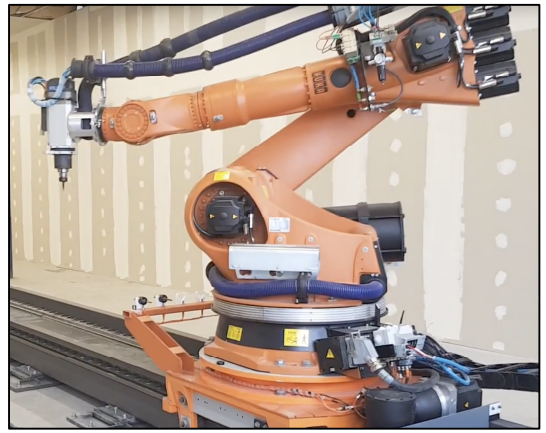
- Success in measuring non-cooperative targets will enable more potential applications…



Artefact characterisation

Explosive Shock Physics

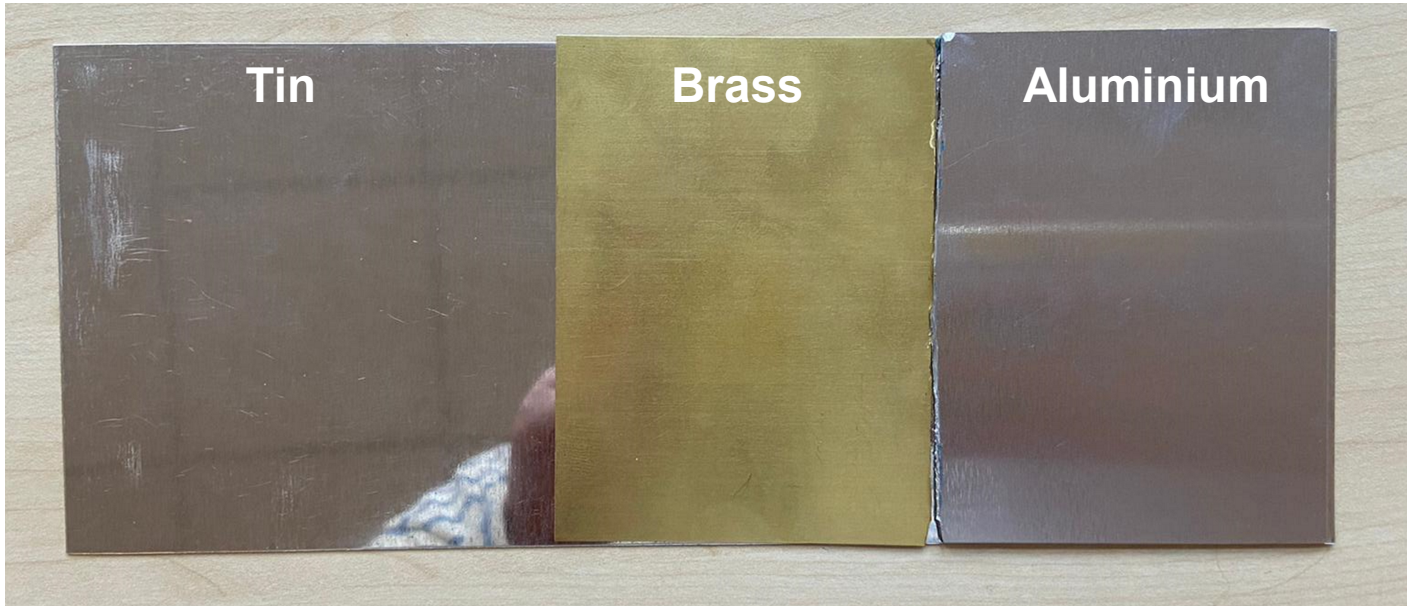
External position tracking of cartesian machines

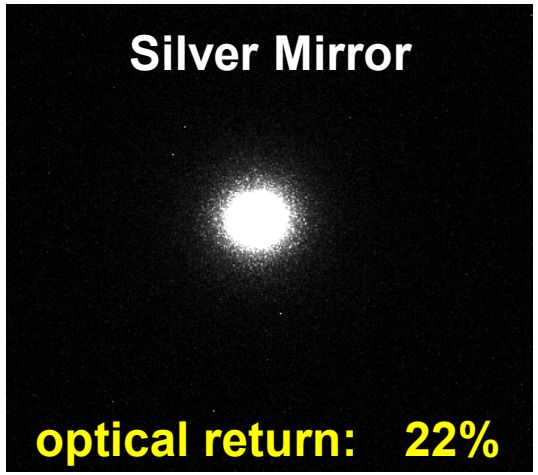


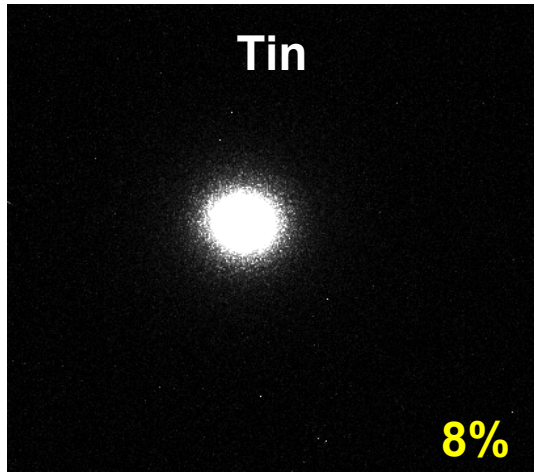
External position tracking of non-cartesian machines

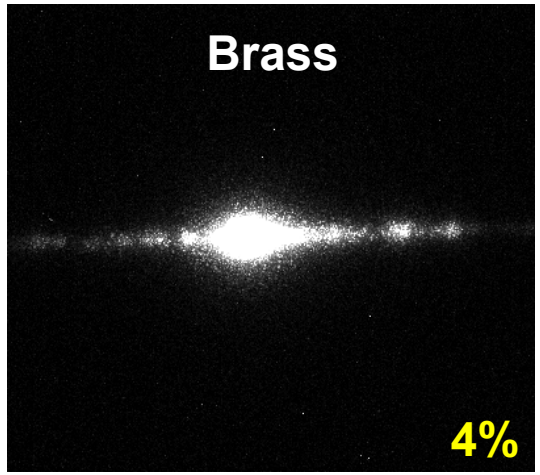
Two-photon dual-comb LiDAR – Uncooperative Target Measurements

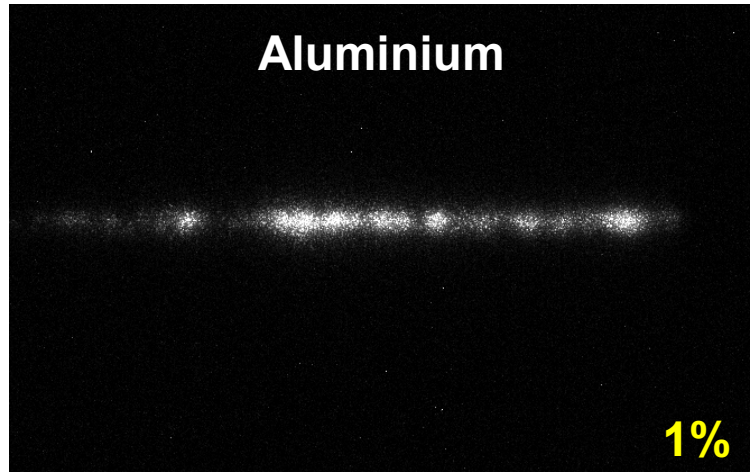
Non-cooperative targets: tin, brass and aluminium







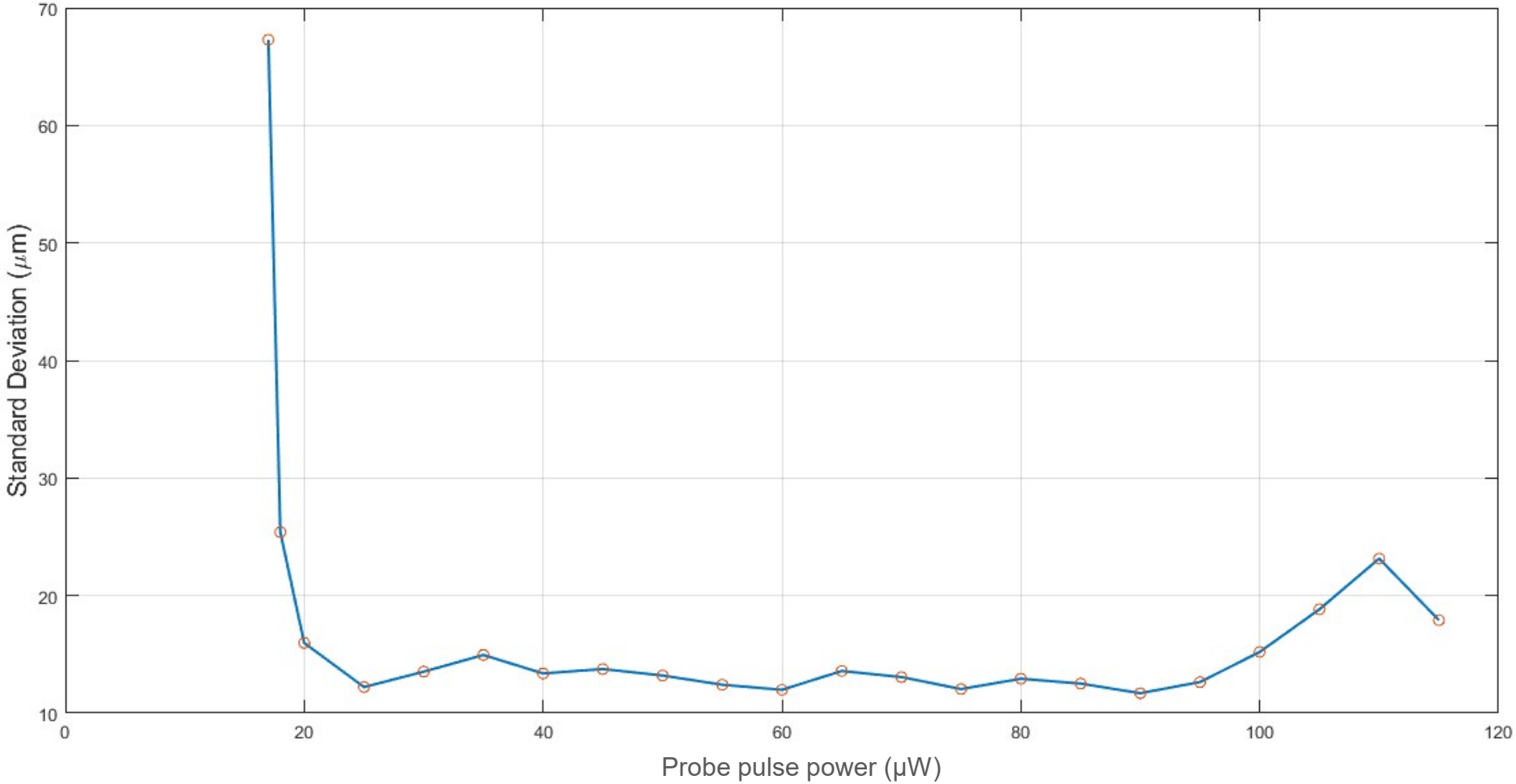




Two-photon dual-comb LiDAR – Uncooperative Target Measurements

Impact of return power on precision

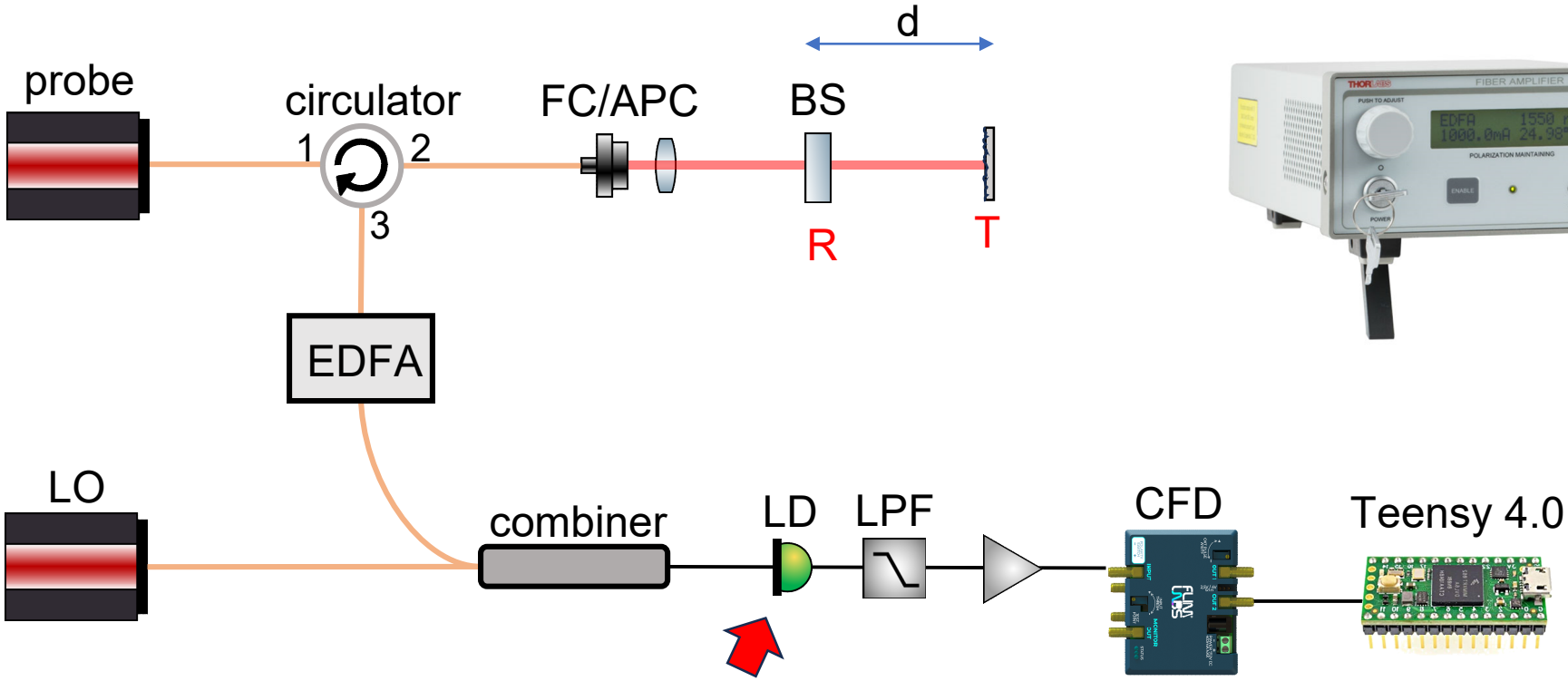
- Initial results (October 2024).
- Work in progress to investigate dependence on probe **and reference** pulse powers.



Two-photon dual-comb LiDAR – Uncooperative Target Measurements

Amplified detection

- Common transmit / receive geometry with in-path reference reflector
- Amplify weak reflections in EDFA to recover signal strength
- EDFA necessitates fiberised system



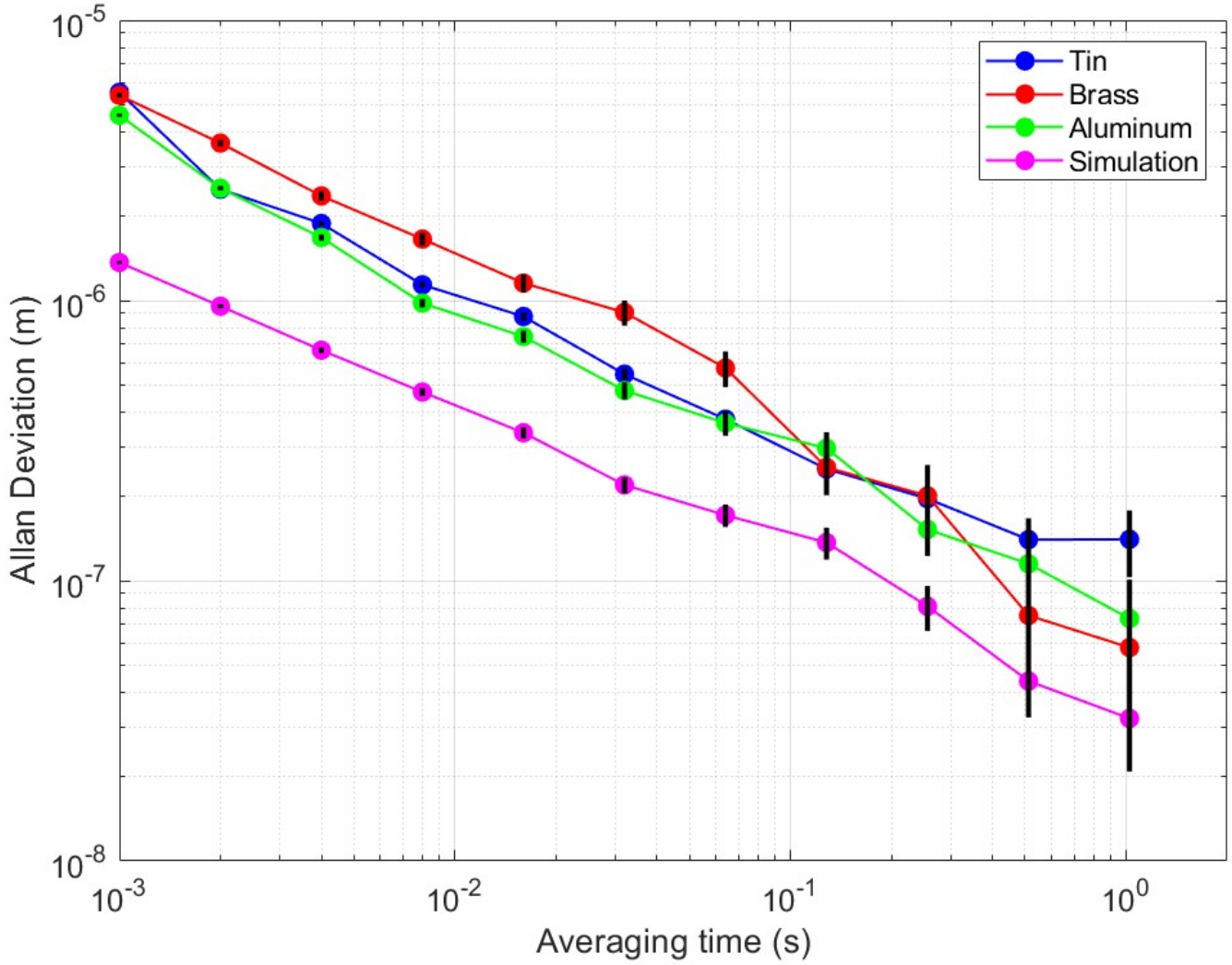
- Laser diode (LD) detector: Reid *et al.*, Appl. Opt. **37**, 8142 (1998);
  Sterczewski *et al.*, Nature. Commun. **14**:3339 (2023).

Two-photon dual-comb LiDAR – Uncooperative Target Measurements

Measurement precision

- Allan deviations for measurements from tin, brass and aluminium at $\Delta f_{rep} =$ 1 kHz

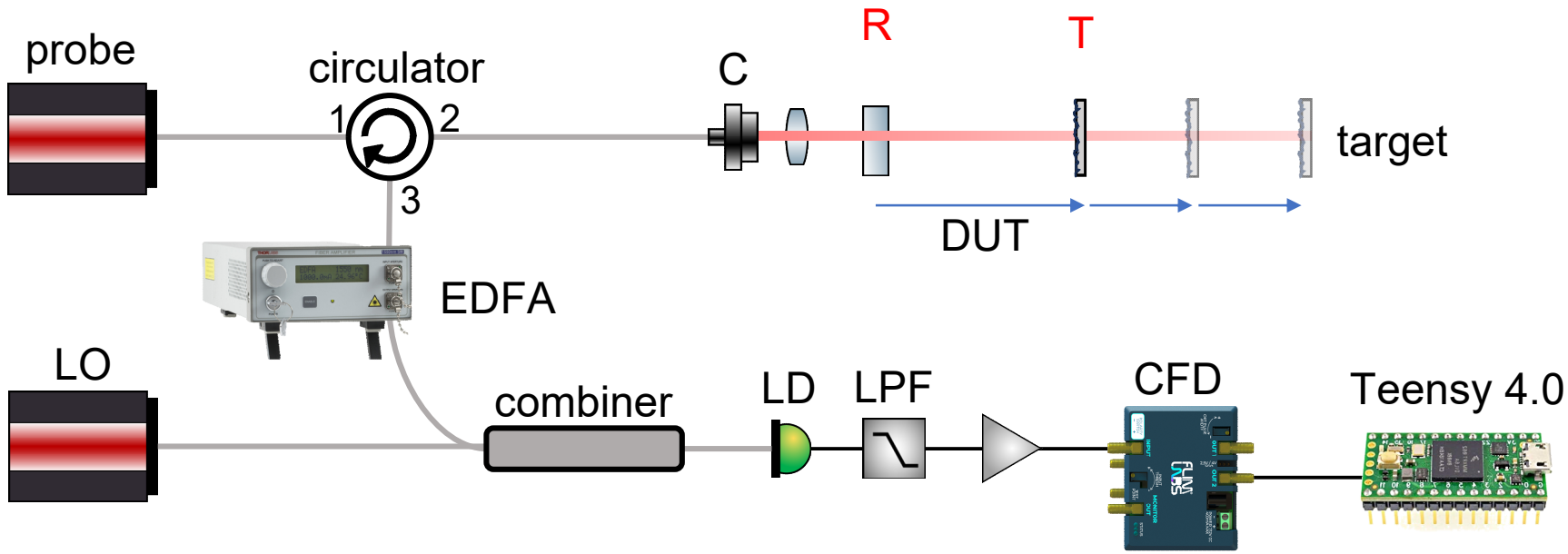
	Single-shot (μm)	1-sec aver. (nm)
Tin	5.5	141
Brass	4.6	73
Aluminium	5.4	58
Timing-limited precision	1.4	32



Two-photon dual-comb LiDAR – Uncooperative Target Measurements

Precision over increasing standoff distance

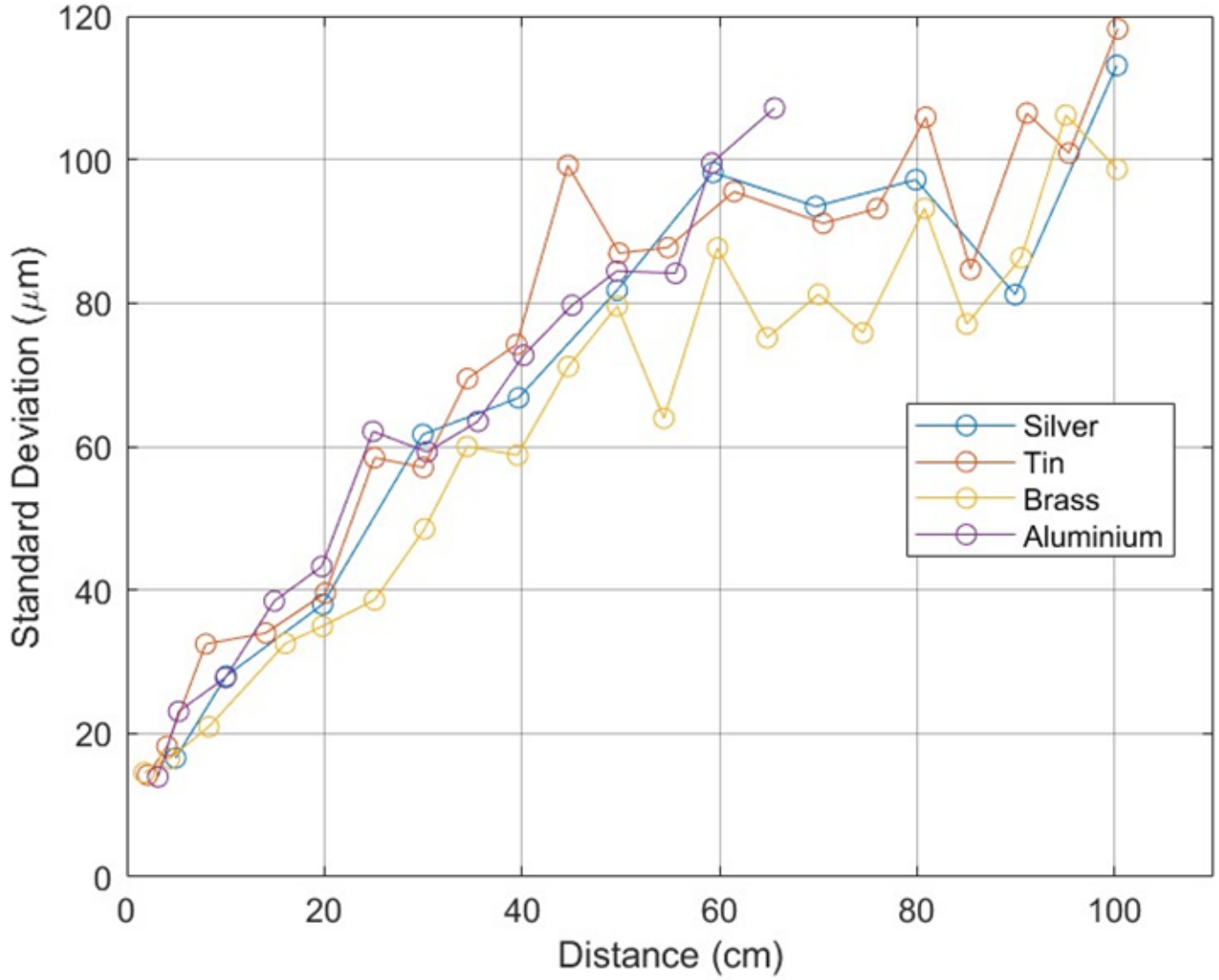
- Experiment to measure precision change over distance
- We noticed precision changed with the distance of the target in earlier work
- We believe this effect came from coupling inefficiencies due to fiberisation of our system



Two-photon dual-comb LiDAR – Uncooperative Target Measurements

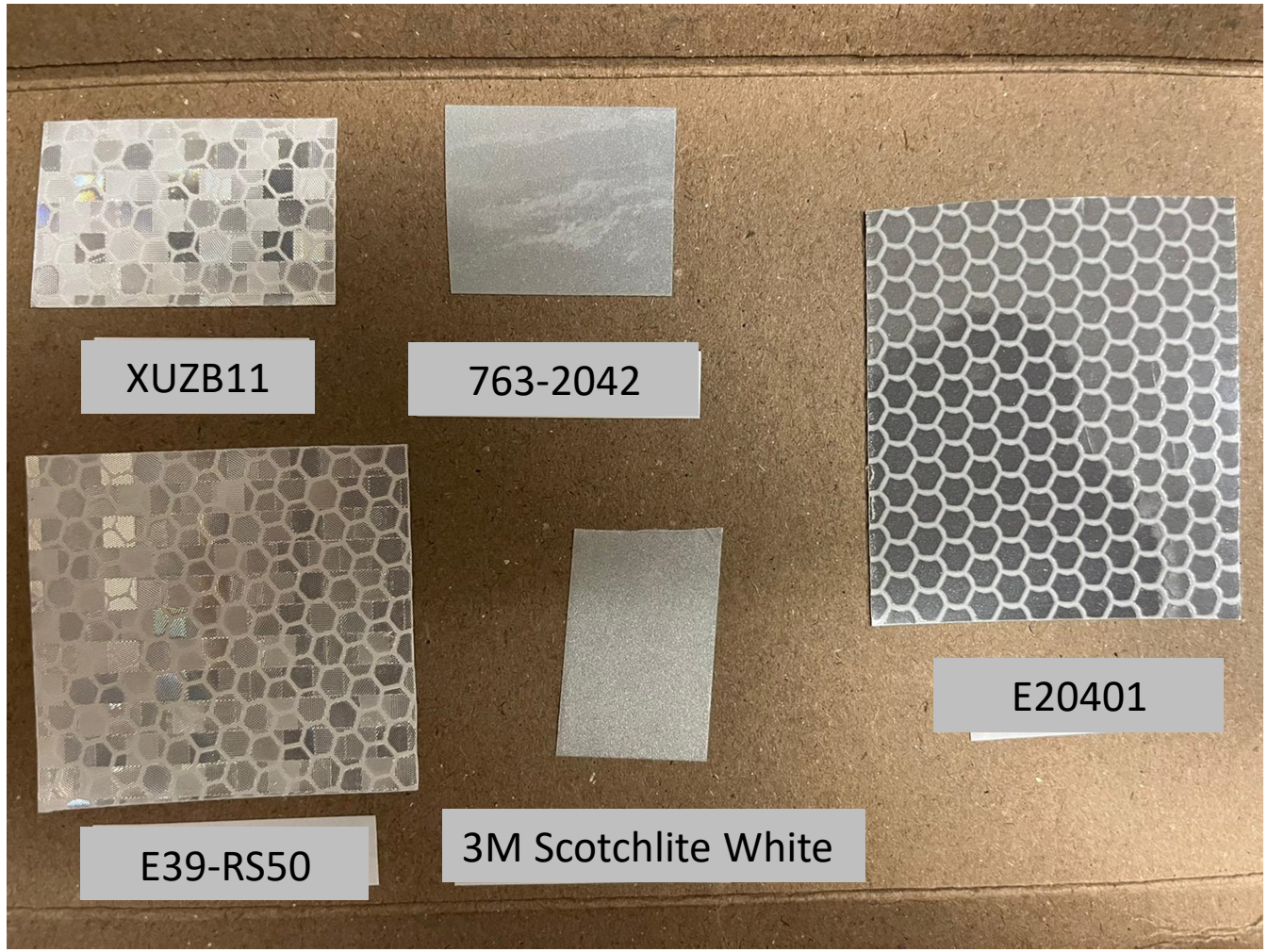
Metal targets

- A mirror was used as a control (marked Silver on the plot)
- Metals perform comparable to silver mirror
- Aluminium was most difficult metal to range
- A noticeable trend between distance and standard deviation



Two-photon dual-comb LiDAR – Uncooperative Target Measurements
Retroreflector tape

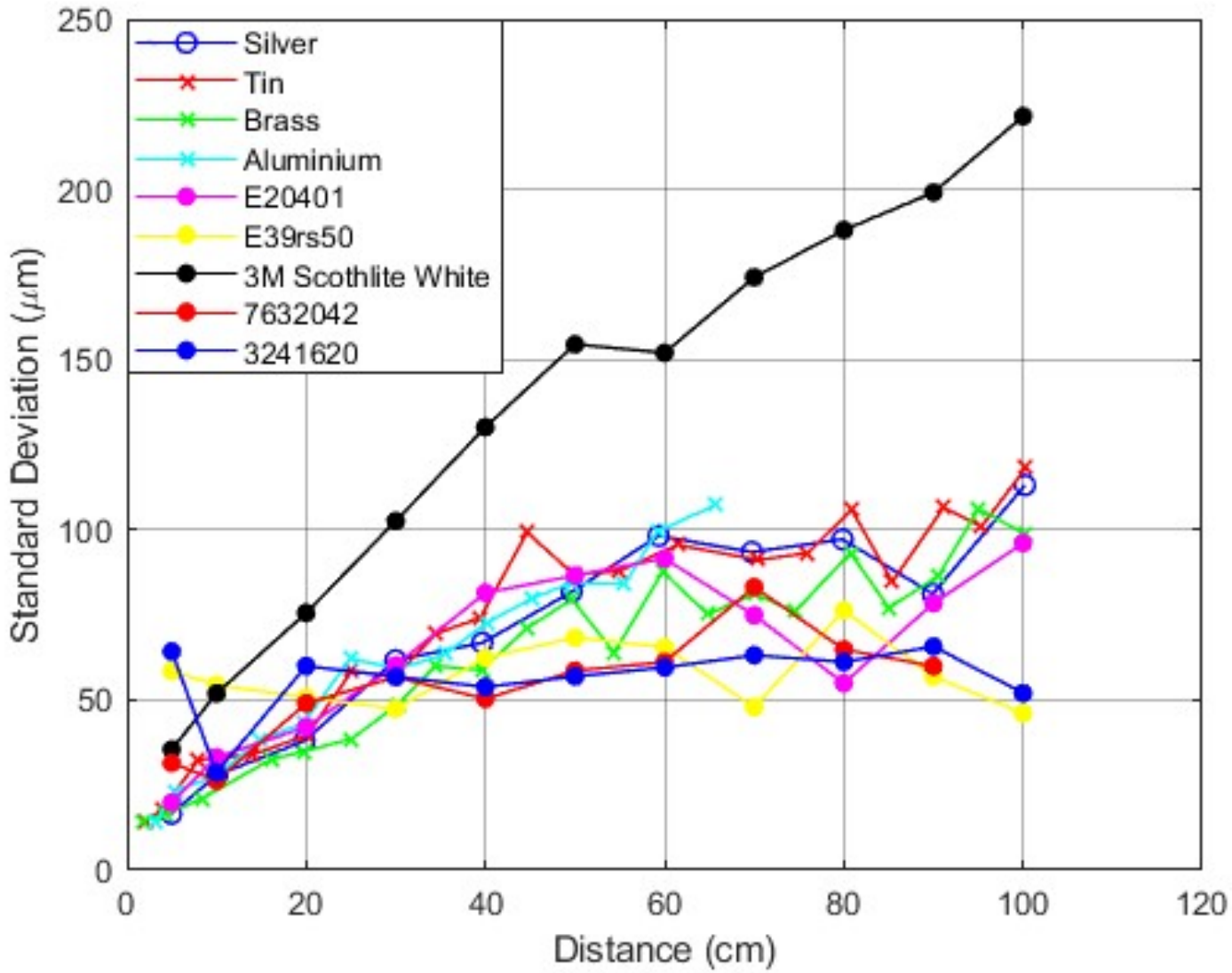
- As well as metal, retroreflective tapes were tested
- The tapes used were suggested by Renishaw PLC and AWE
- Commonly used in industry to aid in laser calibrations



Two-photon dual-comb LiDAR – Uncooperative Target Measurements

Variation of distance precision with range

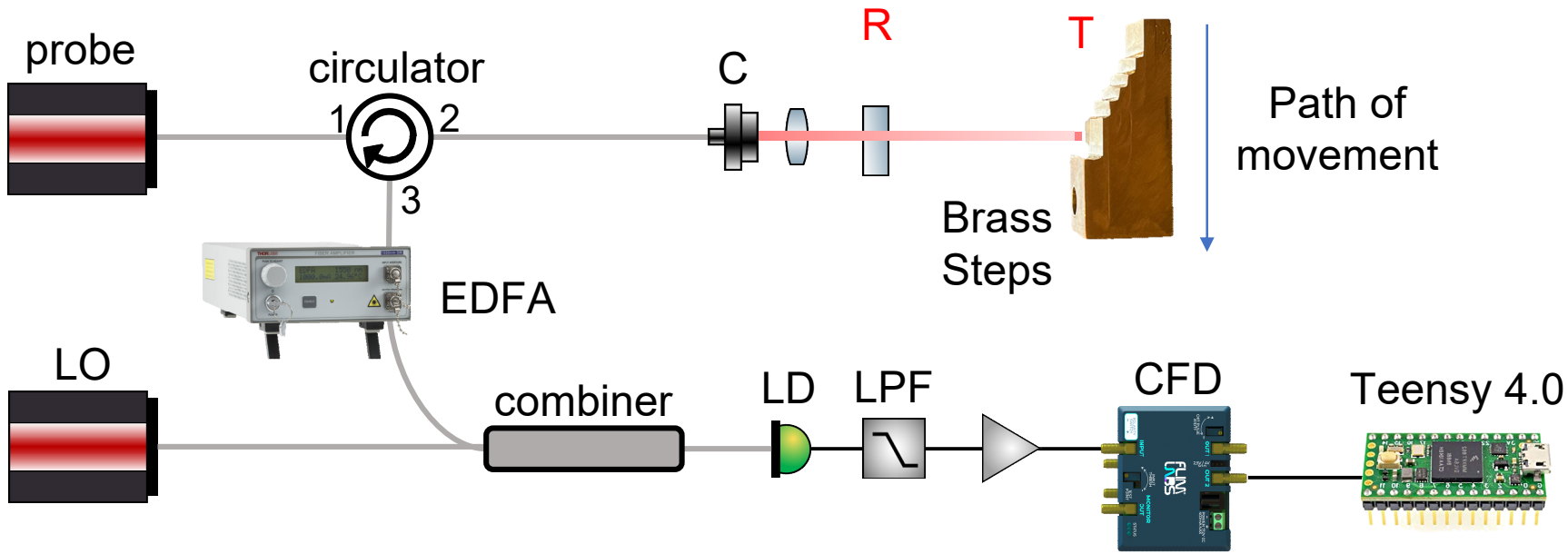
- A direct link to precision and target range is shown
- The retroreflective tape performance is equivalent to metal
- All materials precision worsened with increasing distance



Two-photon dual-comb LiDAR – Uncooperative Target Measurements

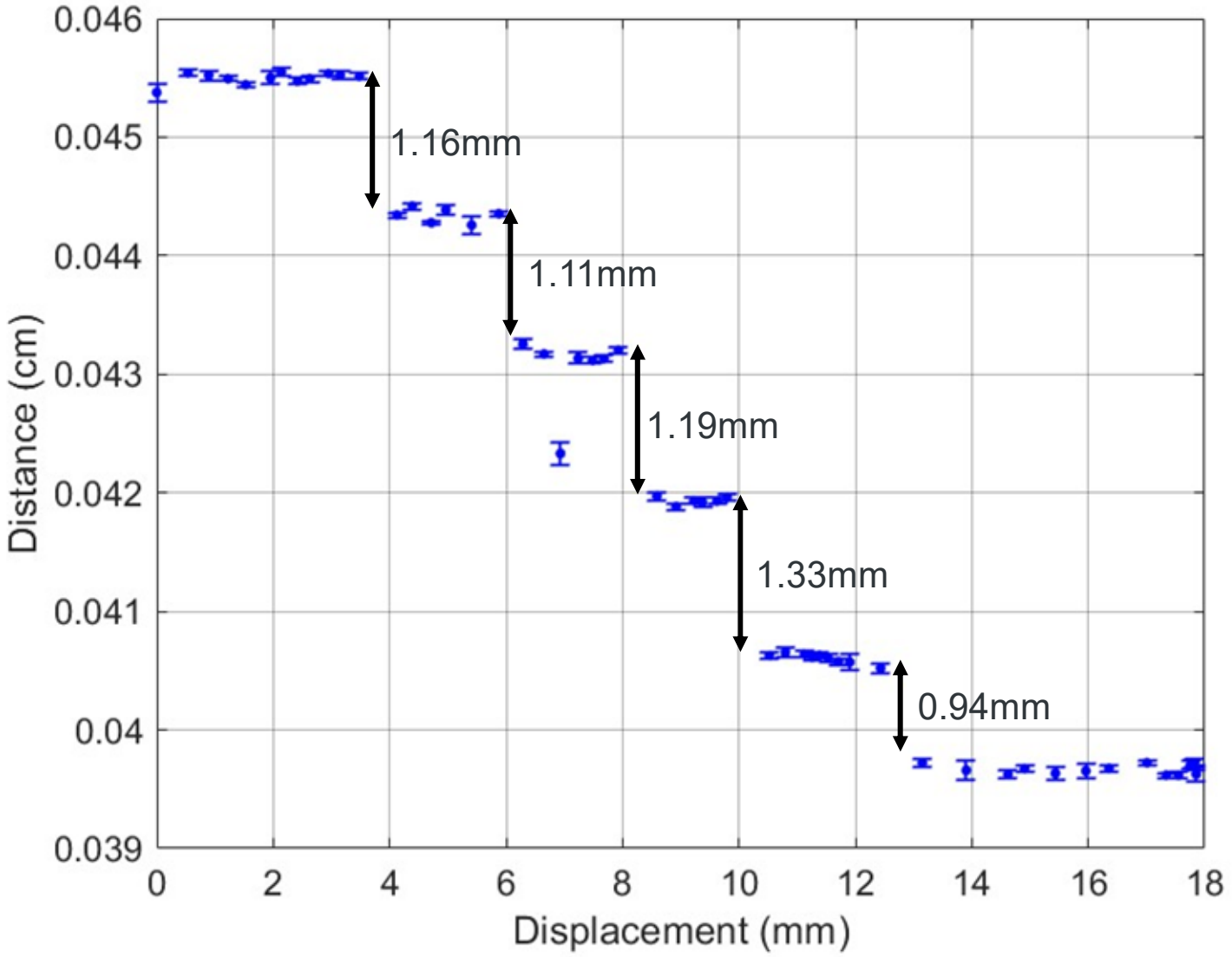
1-dimensional surface scanning

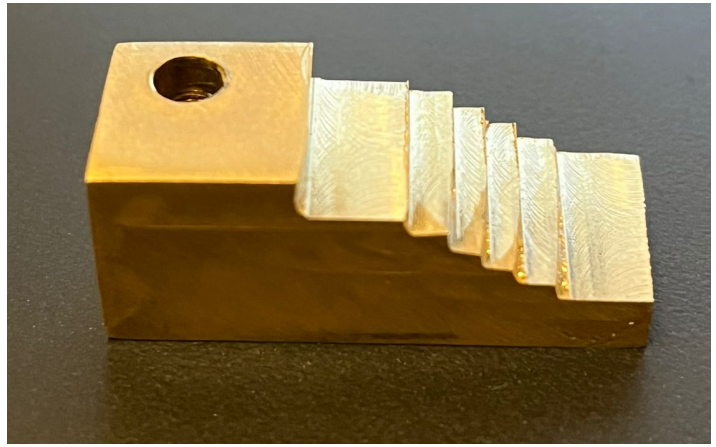
- Experiment designed to test surface scanning capability
- Each step was milled to be 1mm × 1mm
- If successful, allows work on 2-dimensional and 3-dimensional scanning to begin



Two-photon dual-comb LiDAR – Uncooperative Target Measurements

Extension to 2-dimensional profiling





Conclusions

- Demonstrated the ability to range multiple industry typical targets such as bare metals and retroreflectors.
- Instantaneous absolute precisions of a few μm possible.
- Sub-100-nm precisions possible from non-cooperative targets after 1 second of averaging.
- Proof-of-principle extension to 2-dimensional surface scanning.
- Represents a potentially powerful tool for supporting future MoD programmes in the realm of shock physics and industrial metrology.

Acknowledgements

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Wright, *et al.*, Optics Express **29**, 37037 (2021)
Wright, *et al.*, Optics Express **31**, 22497 (2023)