QUANTUM SENSORS AND TIMING FOR REAL-WORLD APPLICATIONS

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UK National QT Hub in Sensors and Timing
Funders, Partners and Collaborators

EPSRC funding £59.5M, collaborative projects with over 85 companies: £150M

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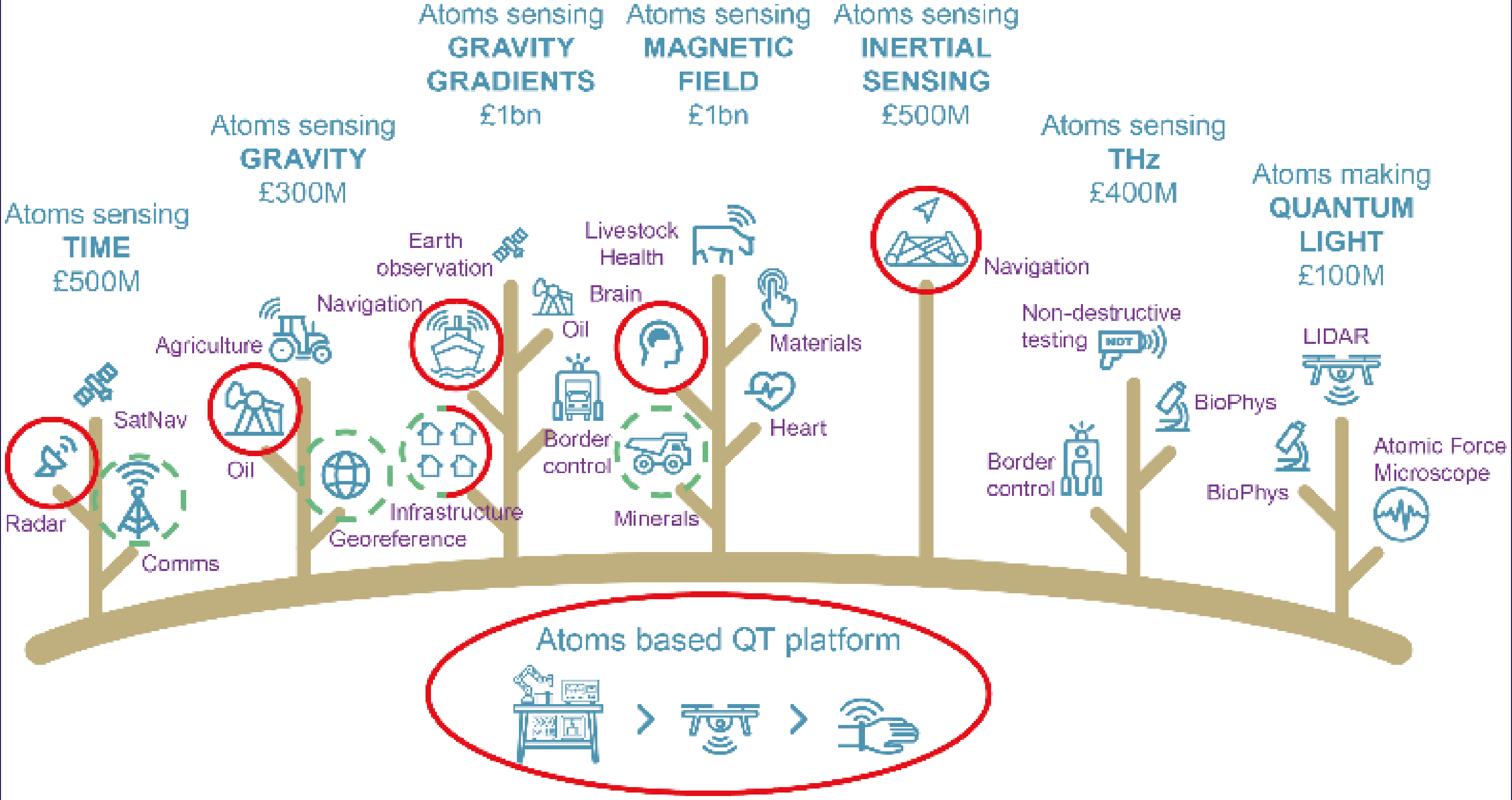
Roadmap to Applications



For Atom Interferometry, see also: Nature Reviews Physics **1**, 731 (2019)

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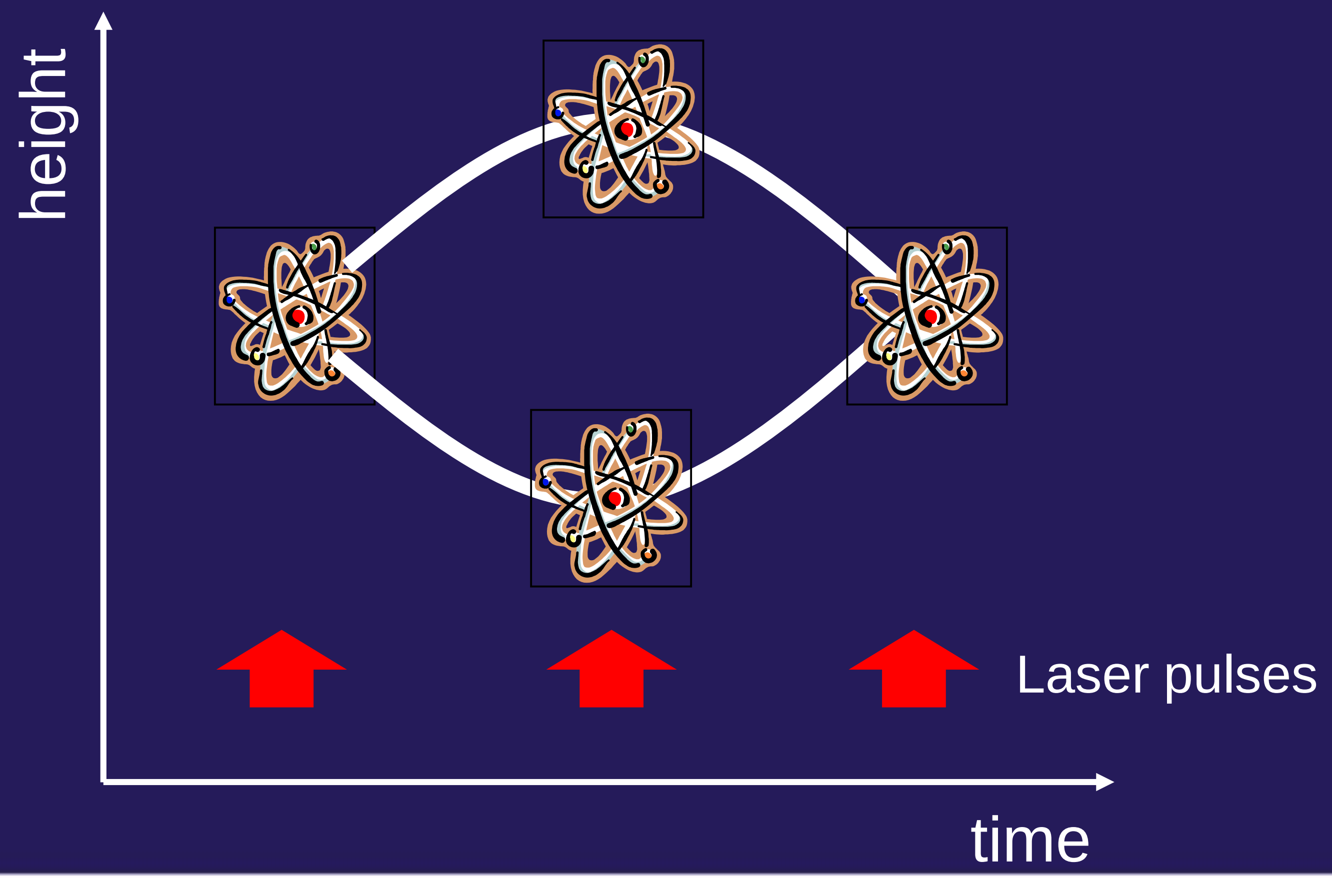
Atomic Quantum Sensors: Atoms Manipulated by Lasers



Unprecedented sensitivity for measuring gravity, rotation, time and magnetic fields

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Selected Quantum Sensor Applications

Sensing into the ground

Underground risk in infrastructure projects
→ **0.5% GDP**

Sensing brain function

Dementia: 1% GDP
ADHD: 1% GDP

Sensing small objects in the air

29M drones by 2021

Sensing position and movement

~7% GDP

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Sensors and Timing

The World Economic Forum has recognised **Quantum Sensing** as one of the top 10 emerging technologies for 2020

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Gravity Gradients for Construction

Underground risk in infrastructure projects
→ **0.5% GDP**

Drainage

Voids leading to sinkholes

Badger setts

Leakage from canals and reservoirs

Mineshafts

Density of mine entries in an urban setting, West Midlands. (Topography based on Ordnance Survey mapping © Crown Copyright and Database Right 2011). Ref: *Geoscientist* April 2016.

Collaboration: physics, civil engineering, geophysics, industry

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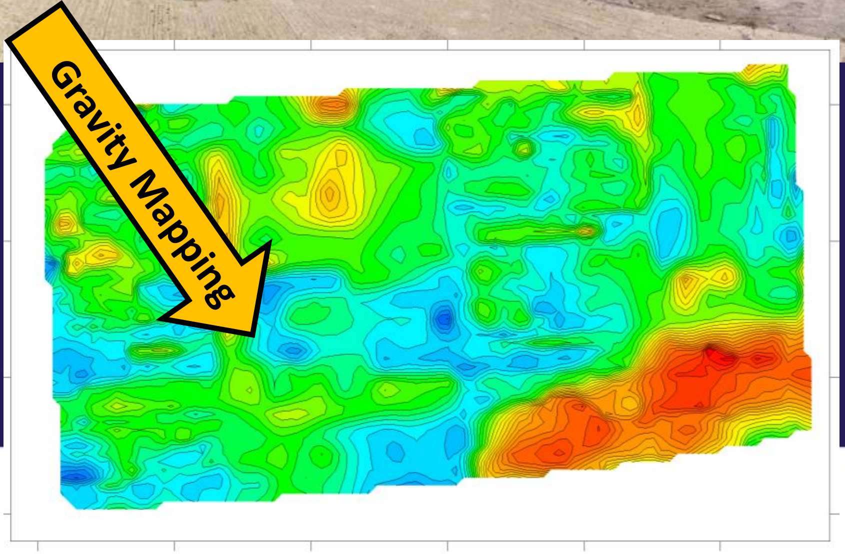
Microgravity Surveys and their Limitations

Example: Brown Field Site Survey



Classical microgravity sensors are sufficiently sensitive to deliver useful information!

BUT:
They take 5-10 min/measurement point

Sensor drift needs to be corrected by periodically returning to a calibration point

In this example: 1 month for 1 ha with 3 sensors and 4 persons

→ Commercial uptake hindered by cost of operation, not the sensitivity of the instrument

RSK

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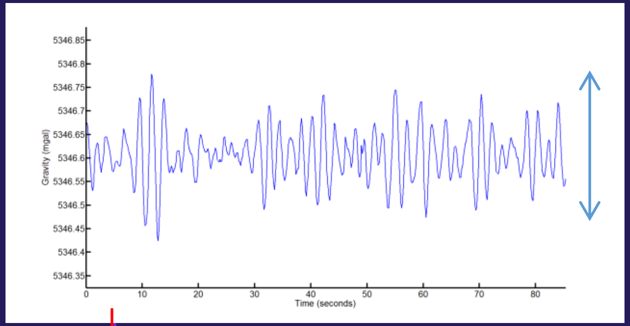
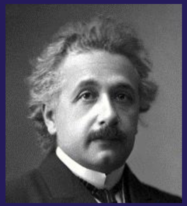
Why do Gravity Measurements take so much Time?

- Acceleration vs gravity



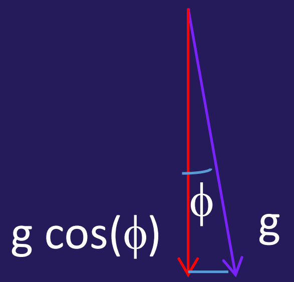


30-100 ng

Requirement to achieve 1 ng

Minutes / point

- Tilt



0.001° alignment

Better gravity sensors only provide calibration benefits, not lower measurement time/point !!!

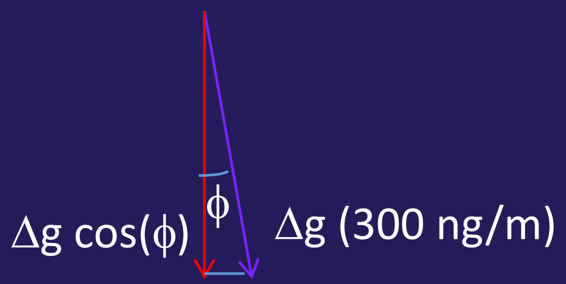
Solution: Gravity Gradiometry

Requirement to achieve 1 ng/m

- Suppression of Accelerations

As fast as your instrument
→1 s / point

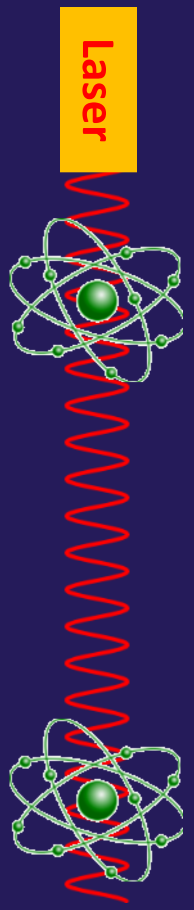
- Reduced Tilt Sensitivity



3^o alignment

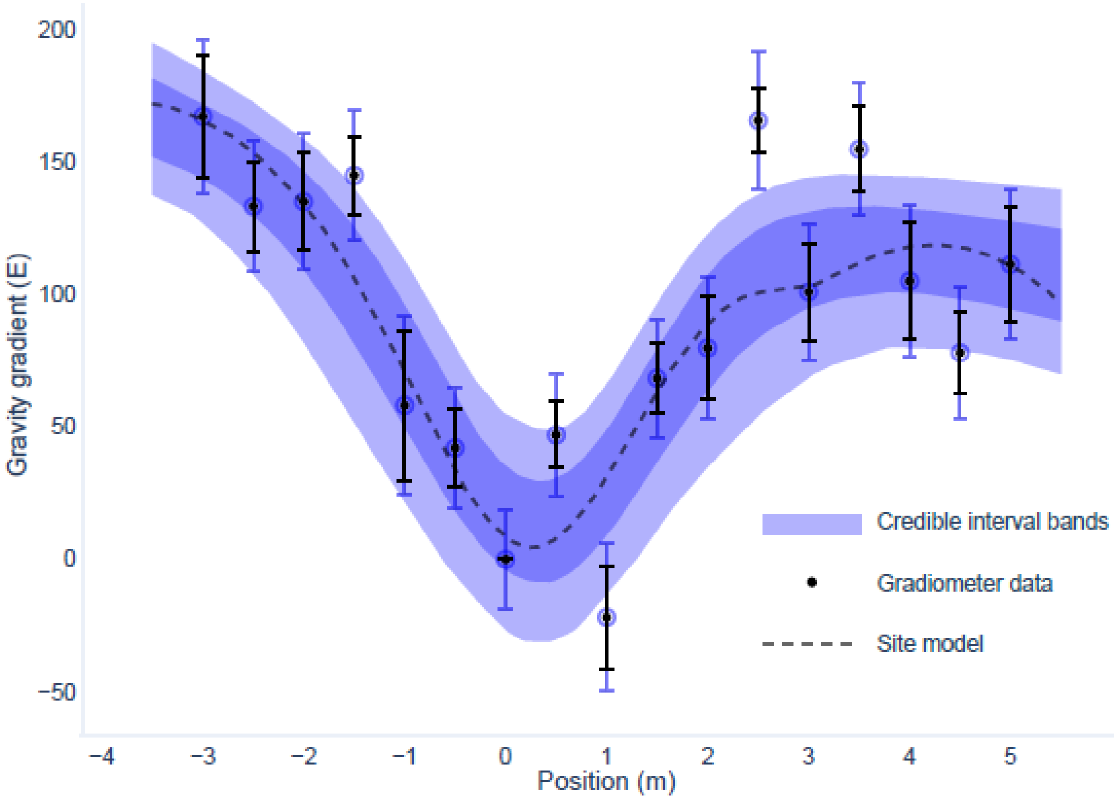
Common laser beam

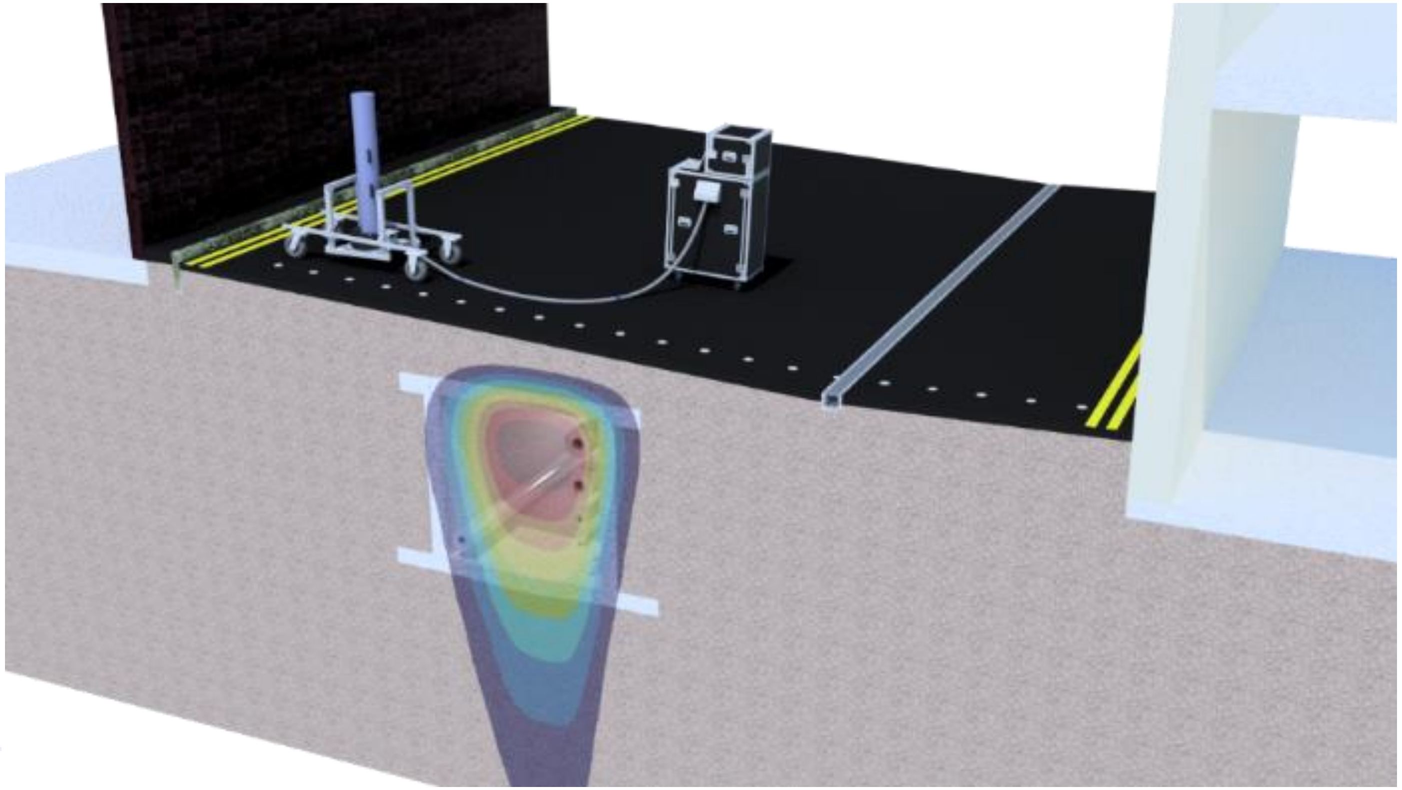
Near-Perfect acceleration suppression and alignment in Atom Interferometry



Tunnel detection with quantum gradiometry

- Survey over tunnel



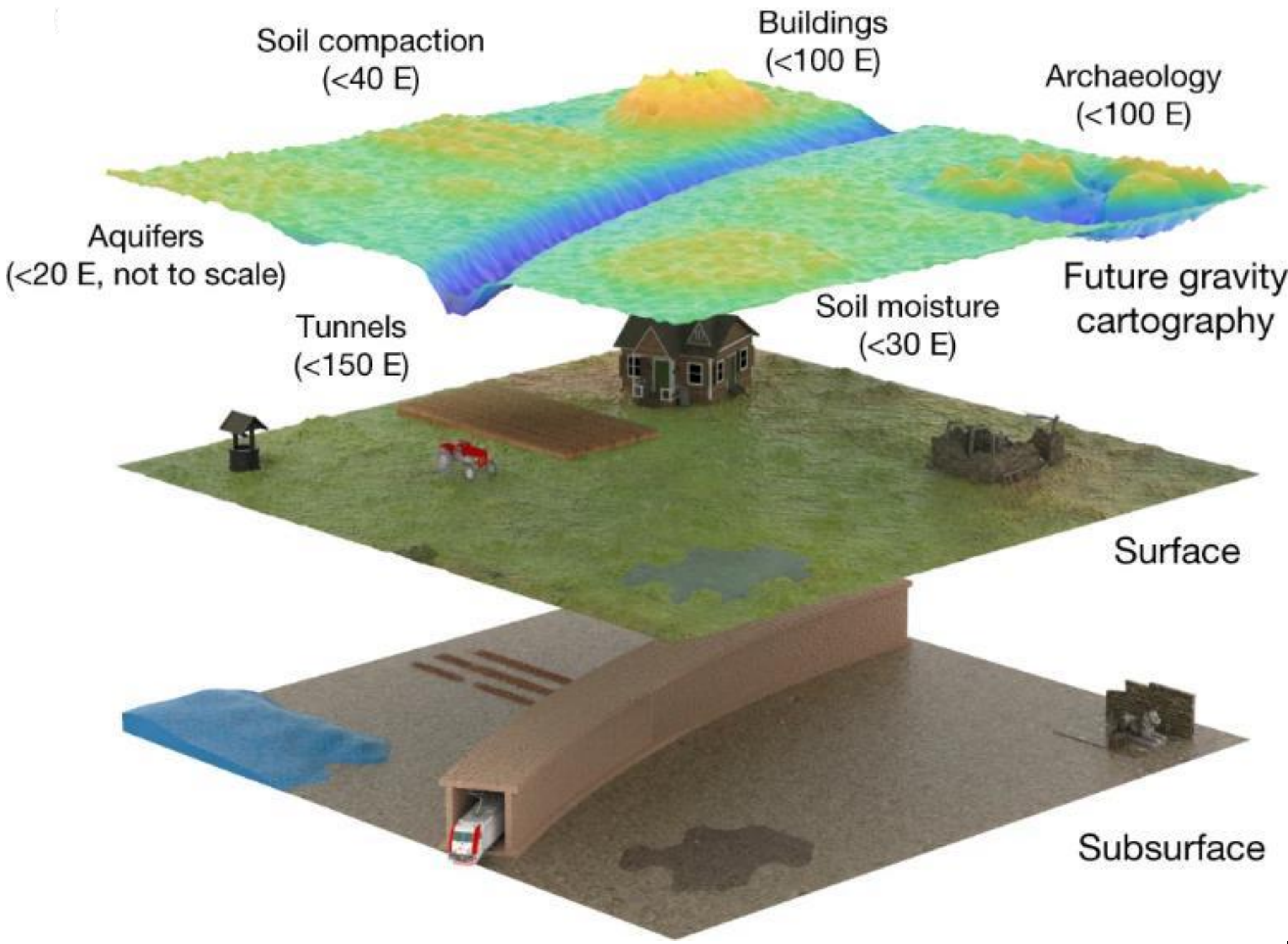


Tunnel centre localised to: ±0.19 m, horizontal; -0.59/+2.3 m, vertical

Nature **volume 602**, pages590–594 (2022)

Enabling Gravity Cartography

- Relevant to a range of applications, including:
  - Water monitoring
  - Infrastructure
  - Archaeology
  - Agriculture
  - Navigation



Towards compact sensors

- Person-portable and moving platform devices underway

CASPA

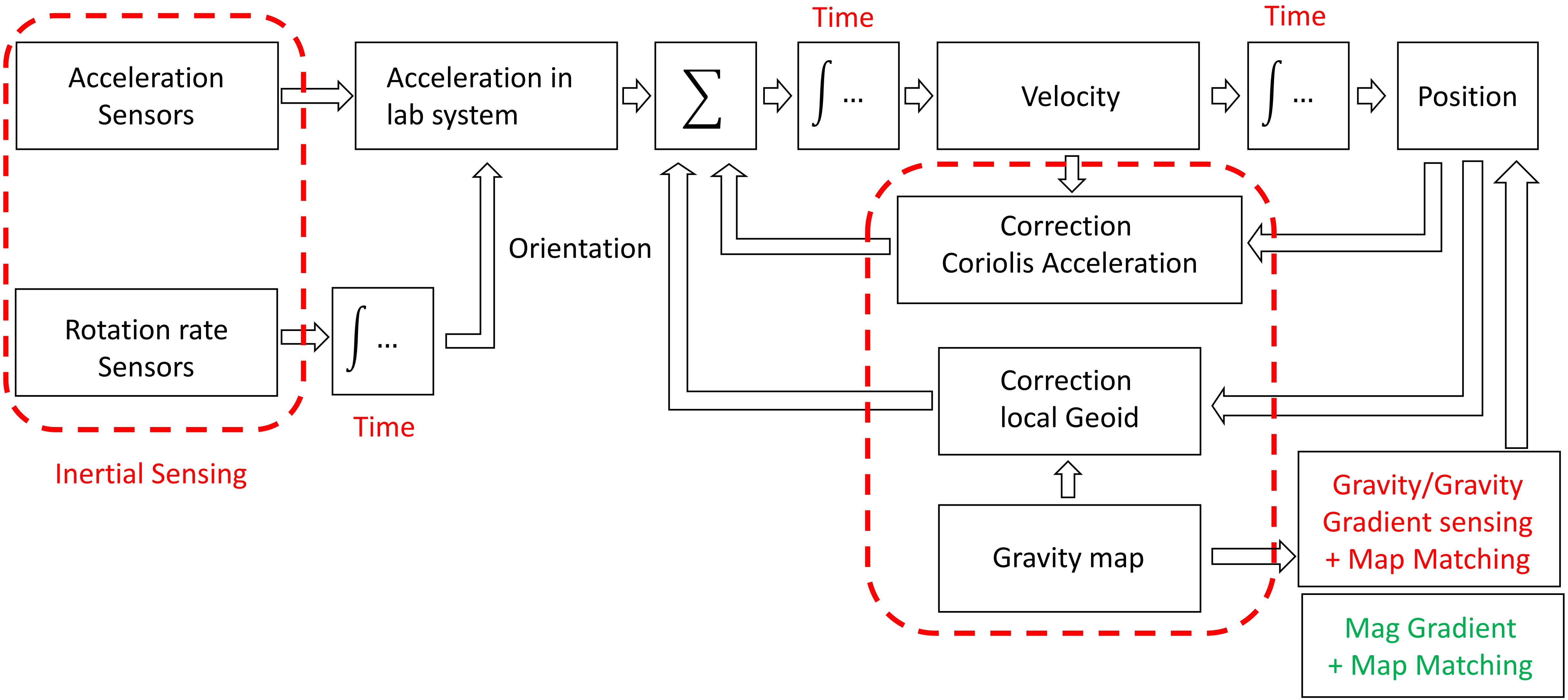
MOT on UAV

MOT in 50 m borehole

Exploitation in new start-up:

Delta g limited

Schematic Setup of a Quantum Navigation System



Quantum Sensors and Timing: Opportunities in PNT

Map Matching for Positioning

Gravity gradient

Magnetic Fields

→ Providing absolute position without any communication (including under water)

→ Collision alert (?)

Inertial Sensors for Navigation

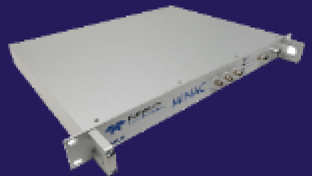
Acceleration and Rotation

→ Low drift

→ Low bias

→ Ingredients for INS

Clocks for Timing



→ On board holdover

→ GNSS spoofing alert

→ Time references

→ Transportable time

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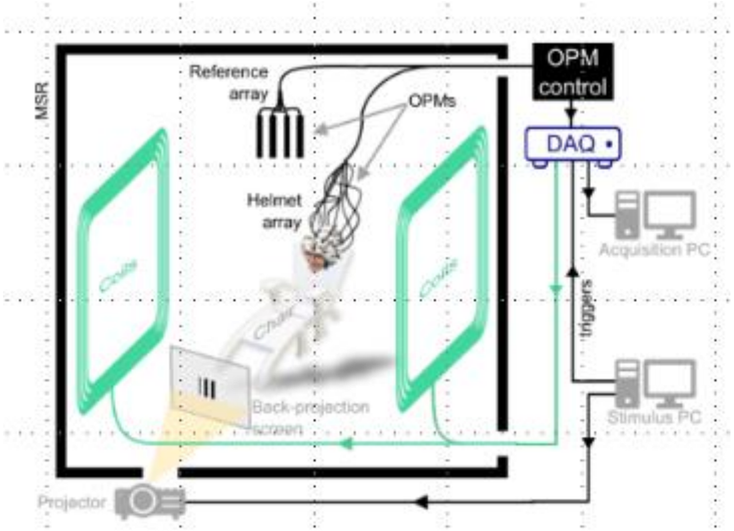
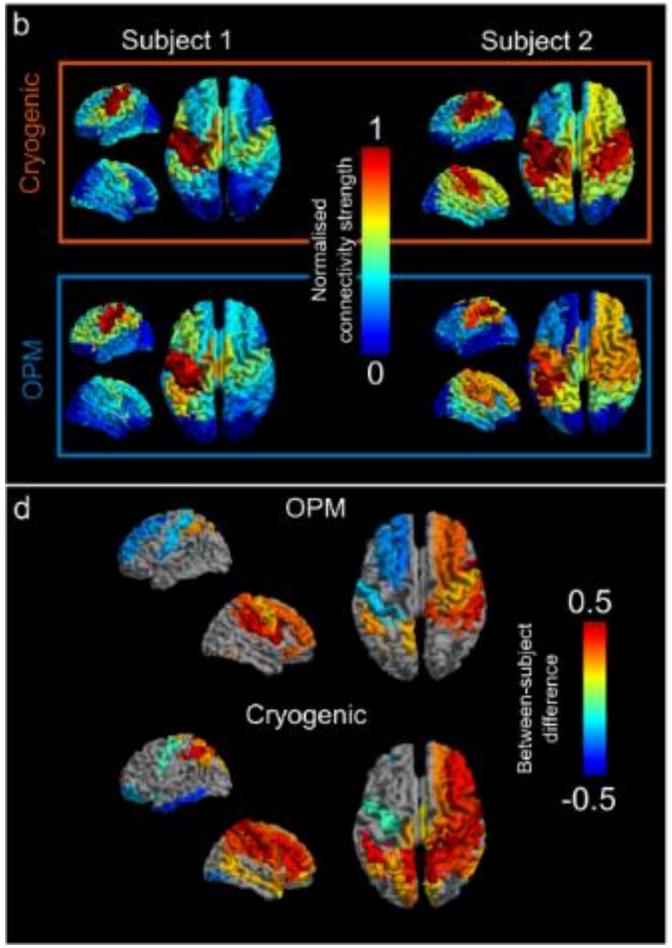
Quantum-Magnetoencephalography – Spin off from QT



Cerca:
Joint venture spin-off between Magnetic Shields and Nottingham University
Founded in 2020

First systems delivered internationally
£6M turnover in first year
>£50M requests for quotations



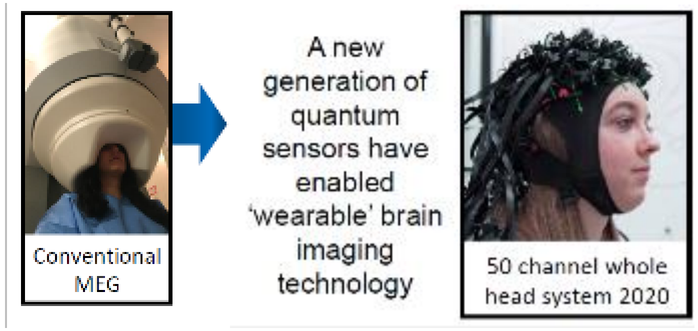
Impact Opportunities:

Epilepsy: 60M people worldwide

Dementia: 1% GDP

Schizophrenia: 1% of population

Trauma: 100.000 / year in UK



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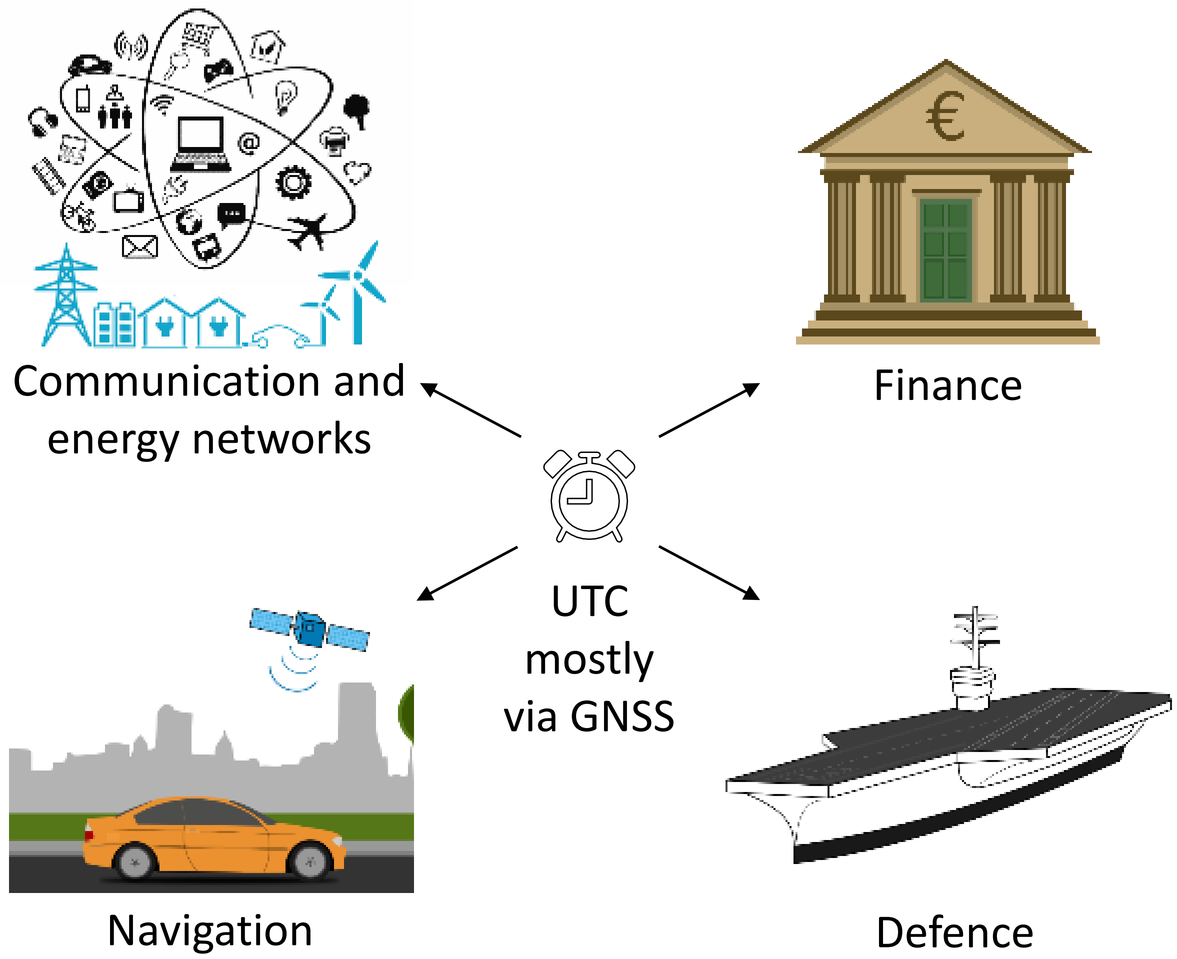
Quantum Clocks Potential to Change Business Models

Timing today: Centralized model



Timing via Global Navigation Satellite Systems:

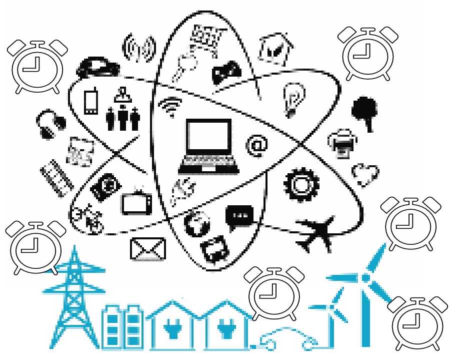
+ „Free“ to use
+ Worldwide availability
+ 30 ns within UTC

→ Widespread use in industry and critical national infrastructure

- Can be easily spammed or spoofed
- Is not available everyehere (e.g. underwater)
- Risk to critical infrastructure in case of conflict
- Potential limits to communication

Quantum Clocks Potential to Change Business Models

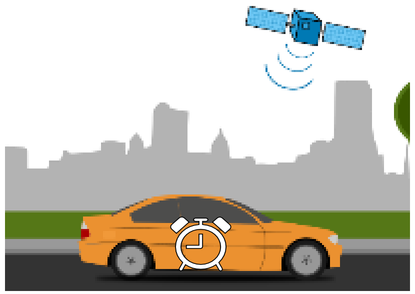
Timing future: „Edge“ model



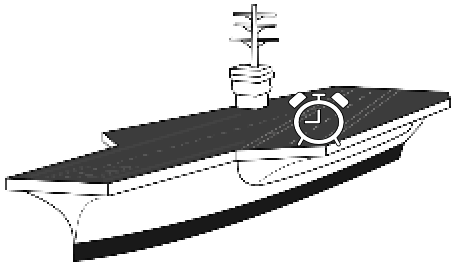
Communication and energy networks

Finance

Local timing with synchronization



Navigation



Defence

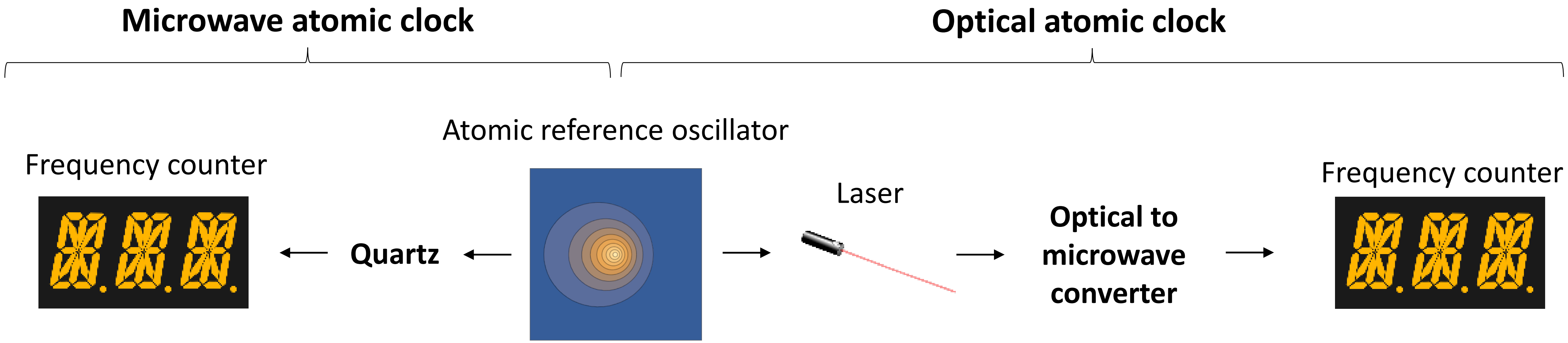
Quantum „Edge“ Timing:

- + Resilience
- + Network architectures with higher bandwidth and better energy efficiency
- + Architectures for safe autonomous vehicles
- + Improved air and space surveillance

- - Not „free“ to use
- - Will need 10-15 years of development to reach full potential

Microwave (old) and Optical (new) Quantum Clocks

A quantum clock replaces the manmade frequency reference in a classical clock (e.g. a pendulum) with an atom



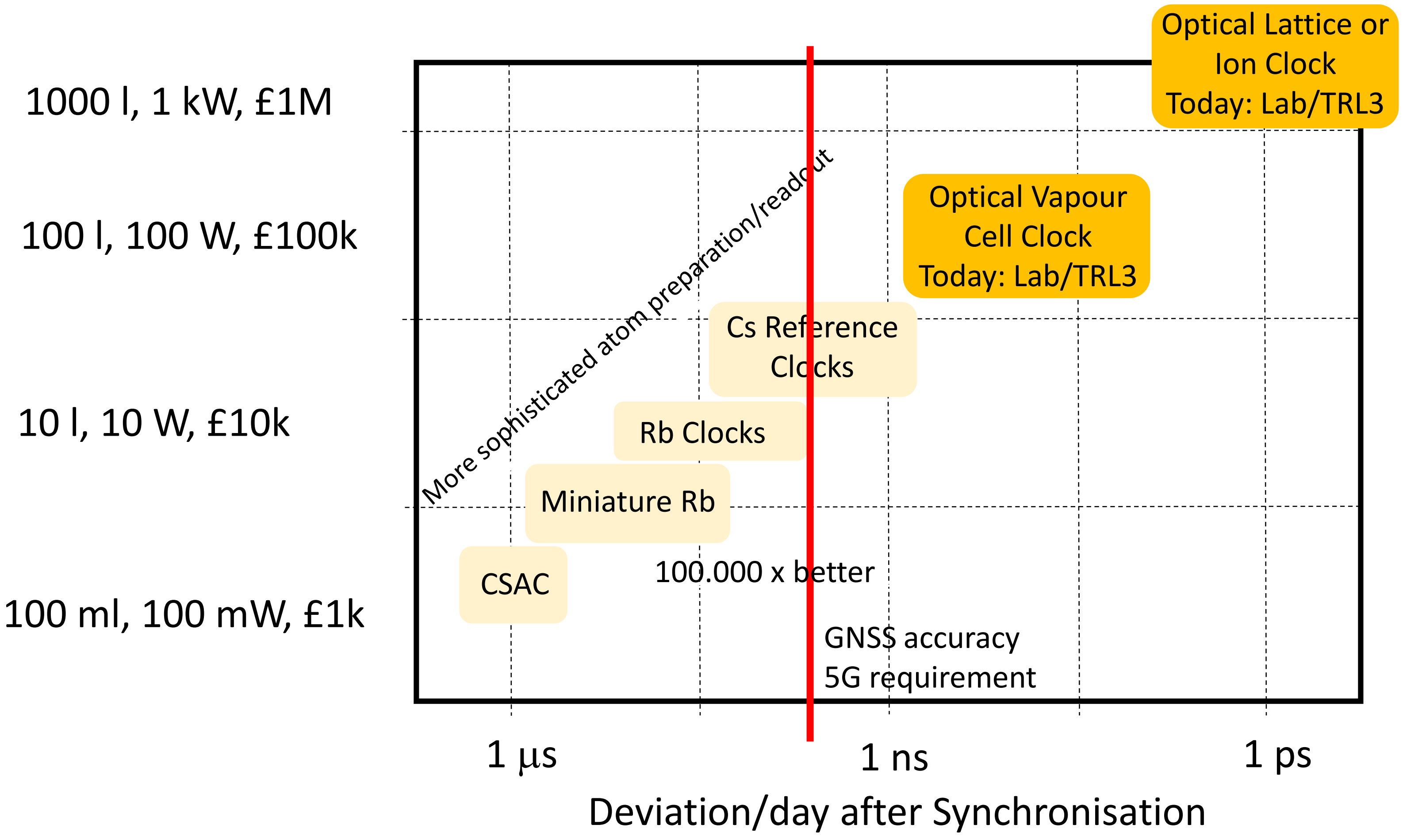
Microwave atomic transition is used to discipline a quartz oscillator

Optical atomic transition is used to discipline a laser

100.000 higher frequency
→ faster sychronization & higher precision

Why are Optical Clocks Disruptive?

So far: "linear" relationship between SWAP-C and stability



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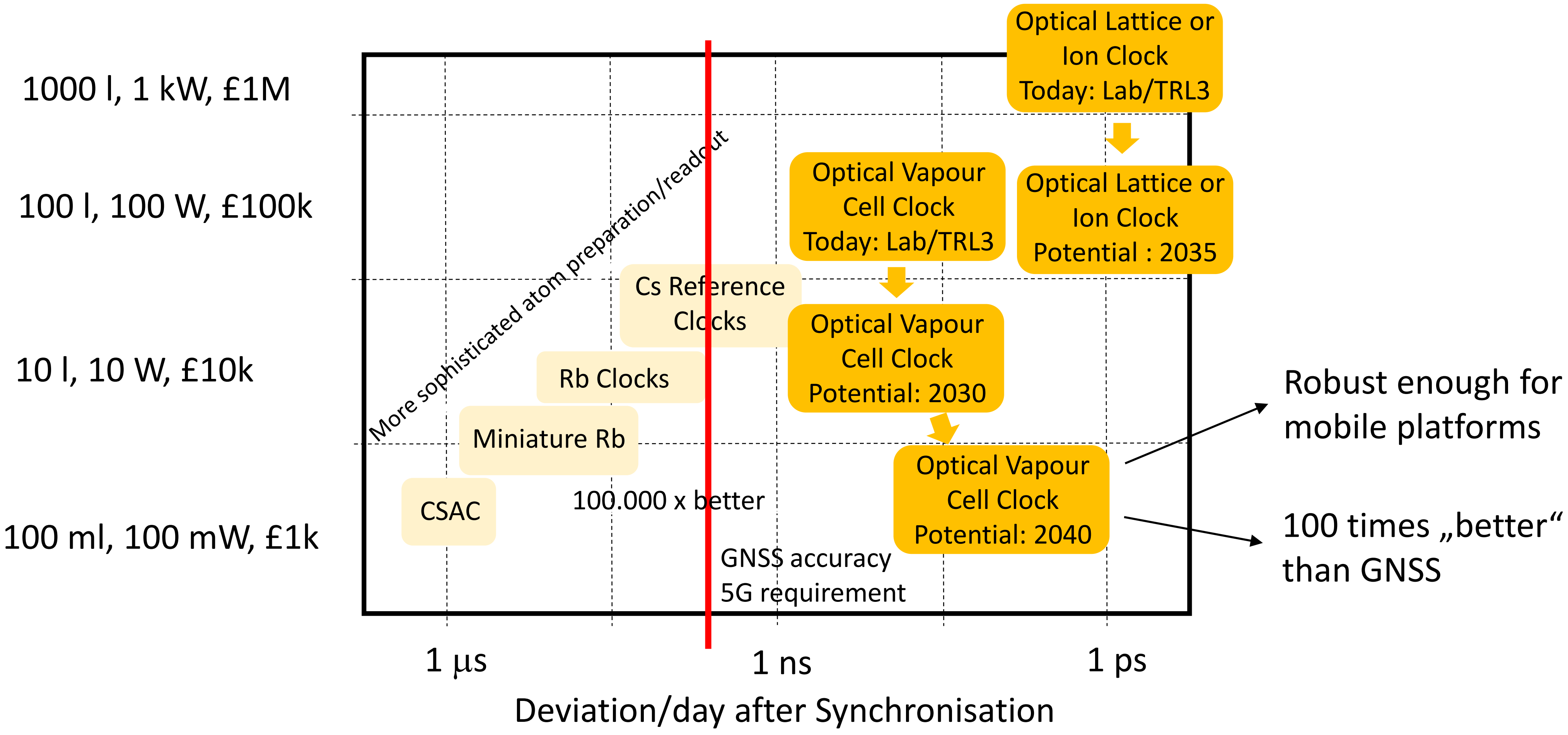


DLR-QT Optical Clock Technology

DLR

Iodine optical vapour cell clock

GPS Solutions (2021) 25:83
https://doi.org/10.1007/s10291-021-01113-2

Table 1 Summary of the key figures of the different optical clock technologies, together with the corresponding figures of the Galileo RAFS and PHM

	References	Galileo RAFS Orolia datasheet (2016)	Galileo PHM Leonardo datasheet (2017)	Ca beam Shang et al. (2017)	I_2 MTS Schuldt et al. (2017); Döringshoff et al. (2019)	Rb MTS Zhang et al. (2017)	Rb TPT Martin et al. (2018)	Sr Lattice clock Bongs et al. (2015); Origlia et al. (2018)	Ca single ion clock (Delehay and Lacroute 2018; Cao et al. 2017)
Frequency stability (in RAV @ integration time τ)	1 s	3×10^{-12}	2×10^{-12}	5×10^{-14}	6×10^{-15}	1×10^{-14}[a]	4×10^{-13}	n/s	n/s
	10 s	1×10^{-12}	3×10^{-13}	2×10^{-14}	3×10^{-15}	4×10^{-15}[a]	1×10^{-13}	1×10^{-16}	6×10^{-15}
	10^2 s	3×10^{-13}	7×10^{-14}	5×10^{-15}	2×10^{-15}	3×10^{-15}[a]	4×10^{-14}	4×10^{-17}	2×10^{-15}
	10^3 s	6×10^{-14}	2×10^{-14}	2×10^{-15}	2×10^{-15}	n/s	1×10^{-14}	1×10^{-17}	6×10^{-16}
	10^4 s	3×10^{-14}	7×10^{-15}	n/s	3×10^{-15}	n/s	5×10^{-15}	4×10^{-18}	2×10^{-16}
	10^5 s	Long-term drift $< 10^{-10}$ / year	Long-term drift $< 10^{-15}$ / day	n/s	$< 2\times10^{-14}$	n/s	n/s	n/s	n/s
	10^6 s			n/s	n/s	n/s	n/s	n/s	n/s
	Longest reported (continuous) τ (s)			1600	700,000	600	180,000	30,000	30,000
Clock transition frequency/wavelength		6.8 GHz	1.4 GHz	657 nm	532 nm	420 nm	778 nm	698 nm	729 nm
Clock transition natural linewidth				0.4 kHz	300 kHz	1450 kHz	330 kHz	6 mHz	140 mHz
SWaP Budgets[b,c]	Mass (kg)	3.4	18.2	n/s	21 + 10[b]	10[d] + 10[b]	12[e] + 10[b]	< 250	n/s
	Power (W)	35	60[f]	n/s	44 + 66[b]	20[d] + 66[b]	25[e] + 66[b]	n/s	n/s
	Volume (l)	3.2	26.3	300 + 7[b]	33 + 7[b]	n/s	8[e] + 7[b]	< 1000	540
Complexity	# Lasers	n/a	n/a	2	1	1	1	5	6
	Vacuum chamber			Yes	No	No	No	Yes	Yes
	Cavity pre-stabilization	n/a	n/a	Yes	No	No	No	Yes	Yes
TRL		9	9	4	4-5[g]	4	4	4	4

Roadmap for Optical Clock Applications

Business Advantage through Quantum Timing


Credit: ESA

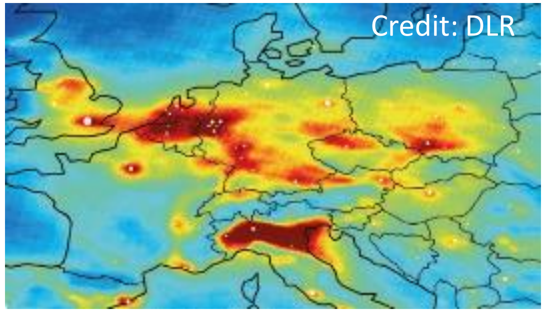
Next generation GNSS


Credit: DLR

Long distance 3d imaging radar

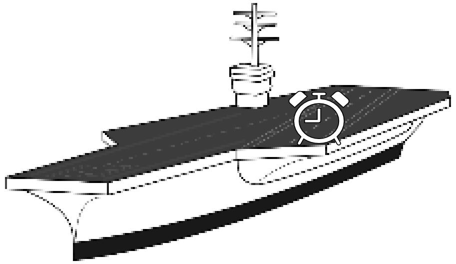

Credit: AdobeStock/J-mel

Urban airspace control


Credit: DLR

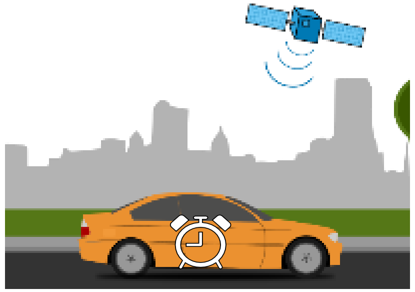
mm-level global height reference system

2030 2040 2050



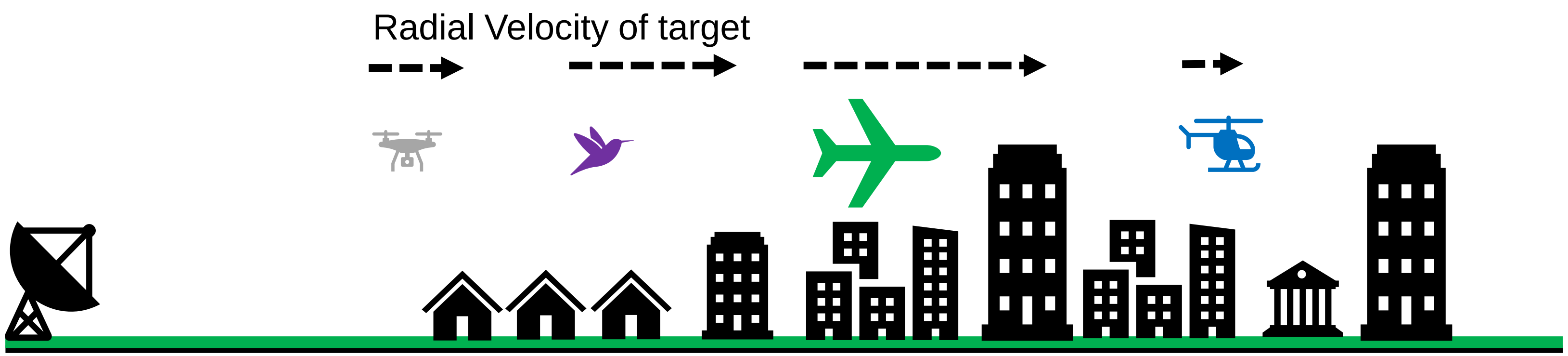
GNSS resilient operation

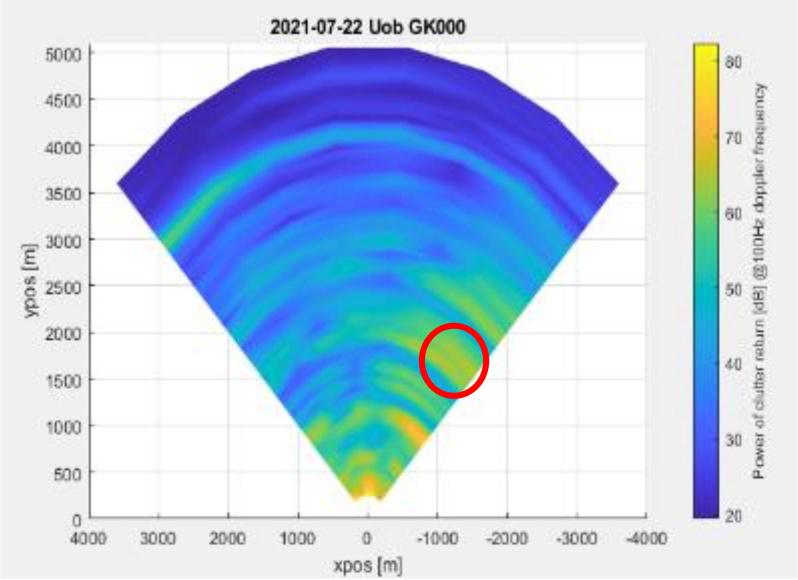
High bandwidth communication



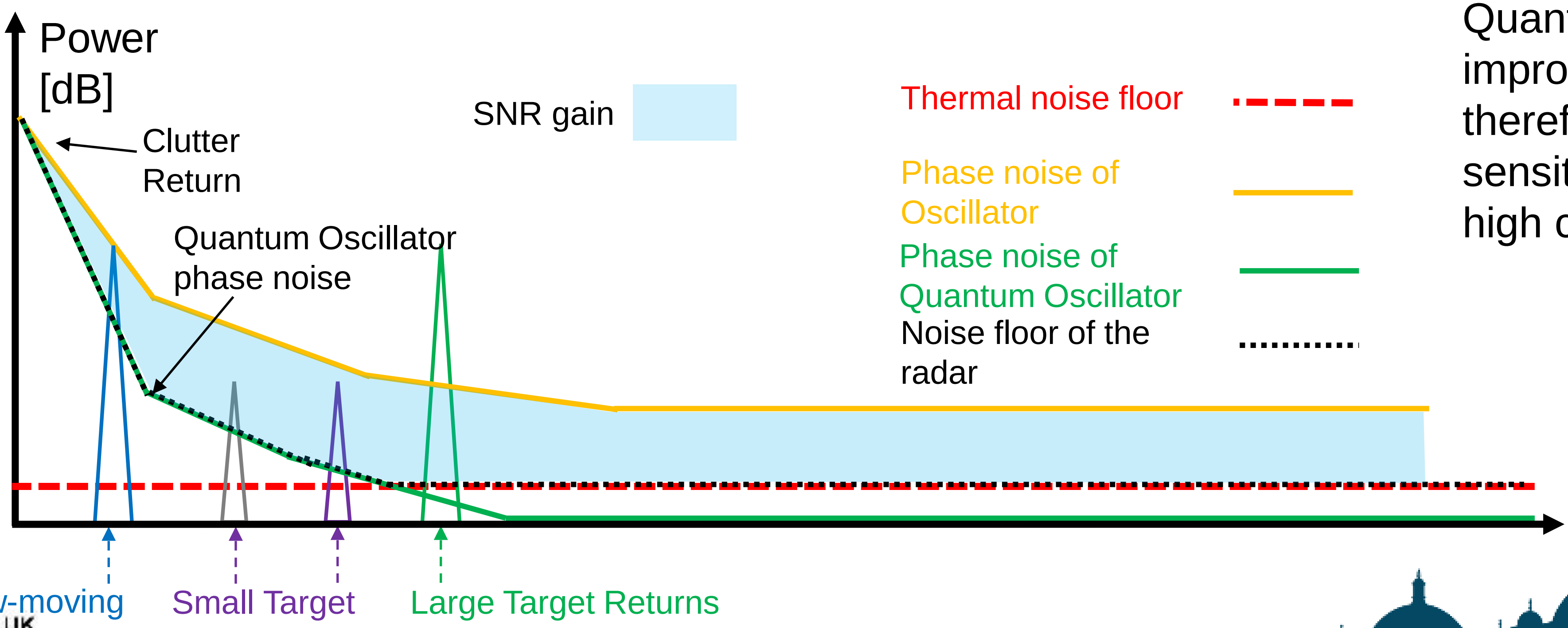
Autonomous vehicles

Noise limitations in the radar

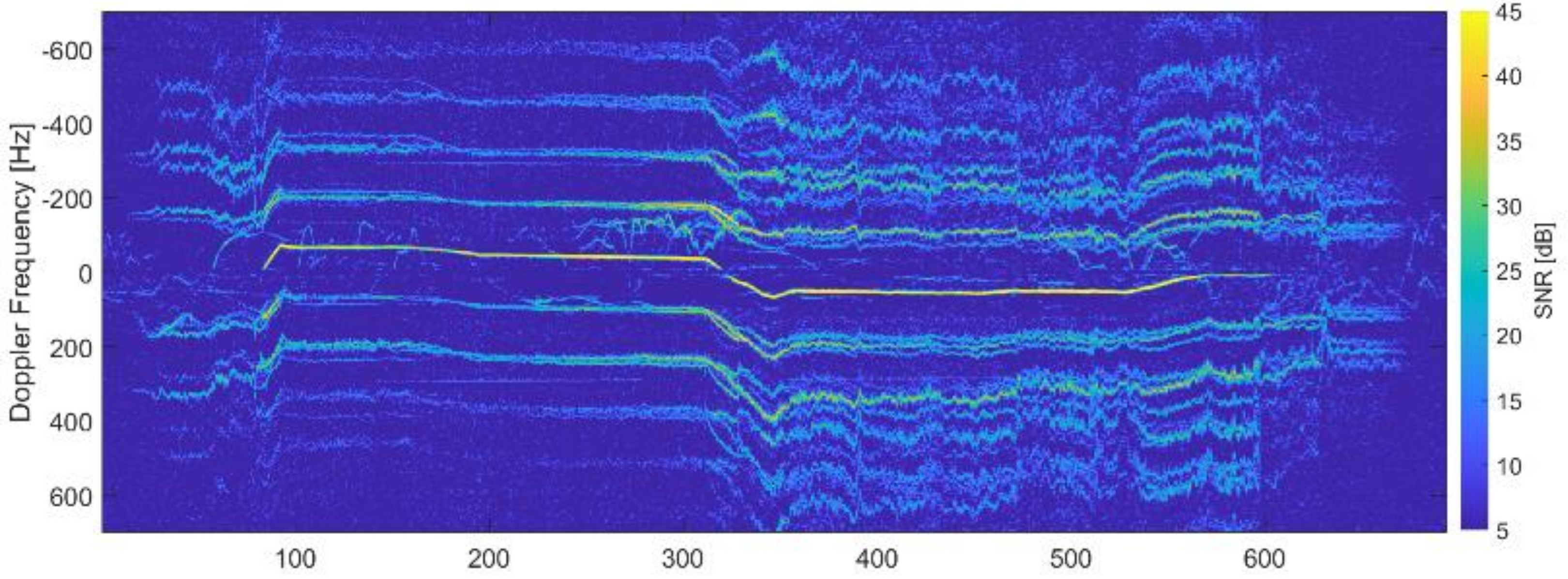




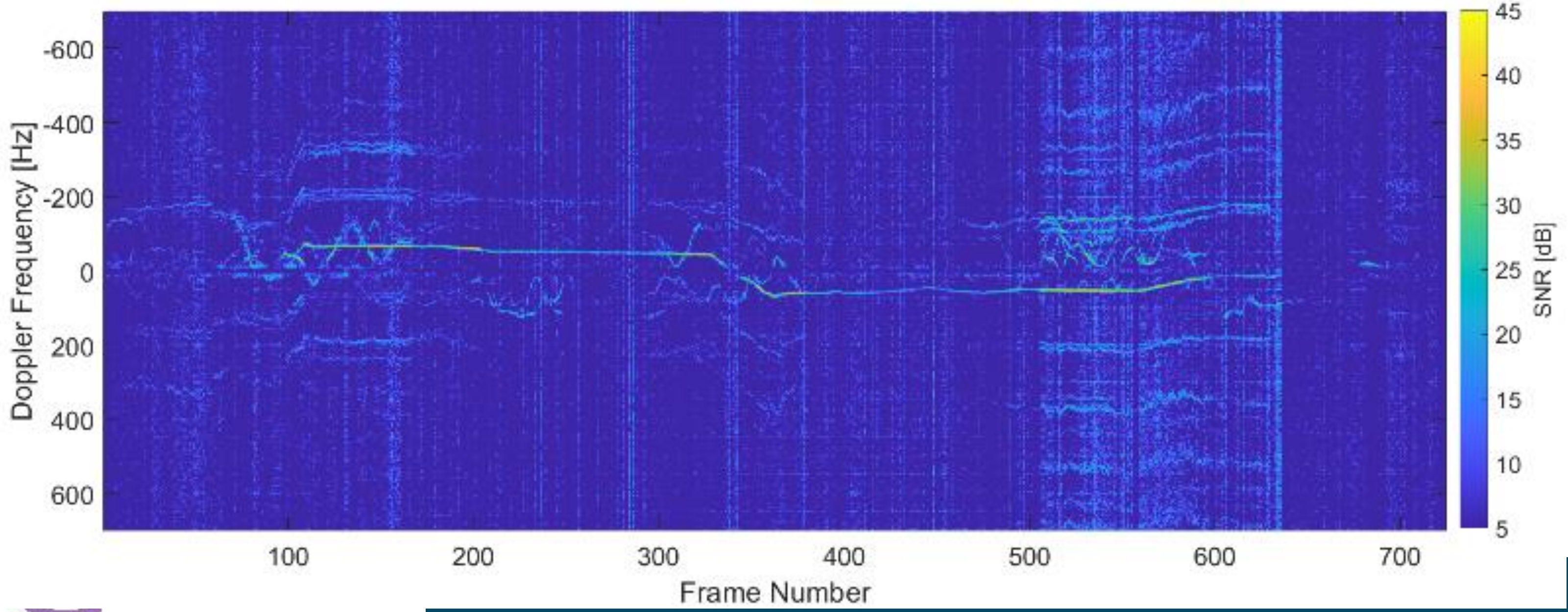
Quantum oscillators provide improved phase noise and therefore improve the sensitivity of the radar in high clutter regions



Better oscillator: more features



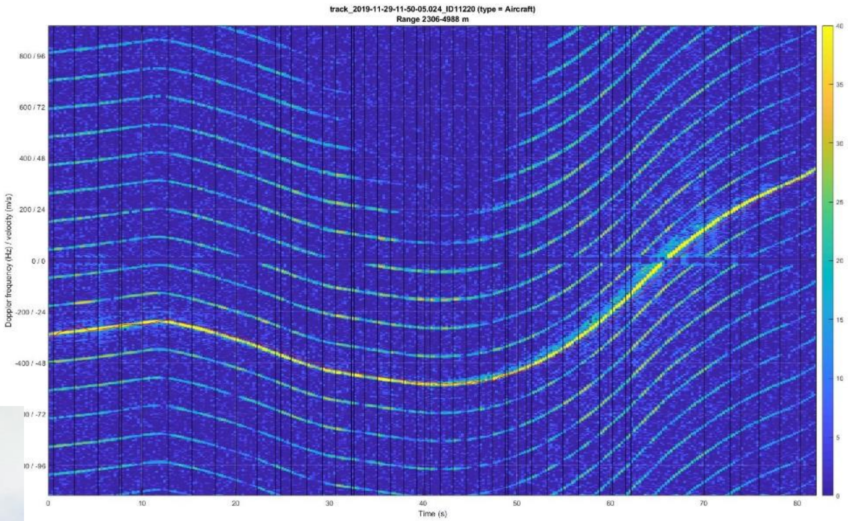
GK007
Monostatic
(Better oscillator)

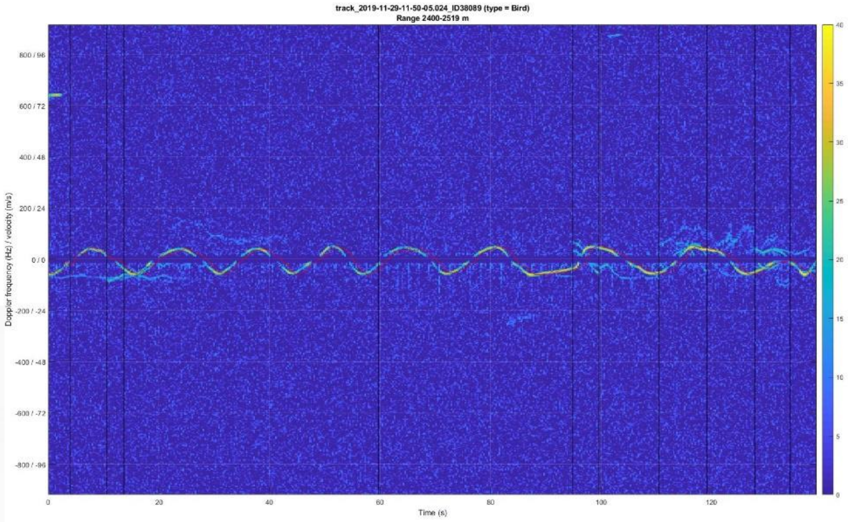


GK000
Monostatic

Discrimination via Micro-Doppler

Opportune targets – Light aircraft vs large bird





Radar Improvement with better Oscillator – Drone Tracking

Small Drone Tracked by two radar

Side-by-side comparison: Tracker output

Radar#1
Purple lines

Radar#2
Yellow Line - Better Phase Noise

misl

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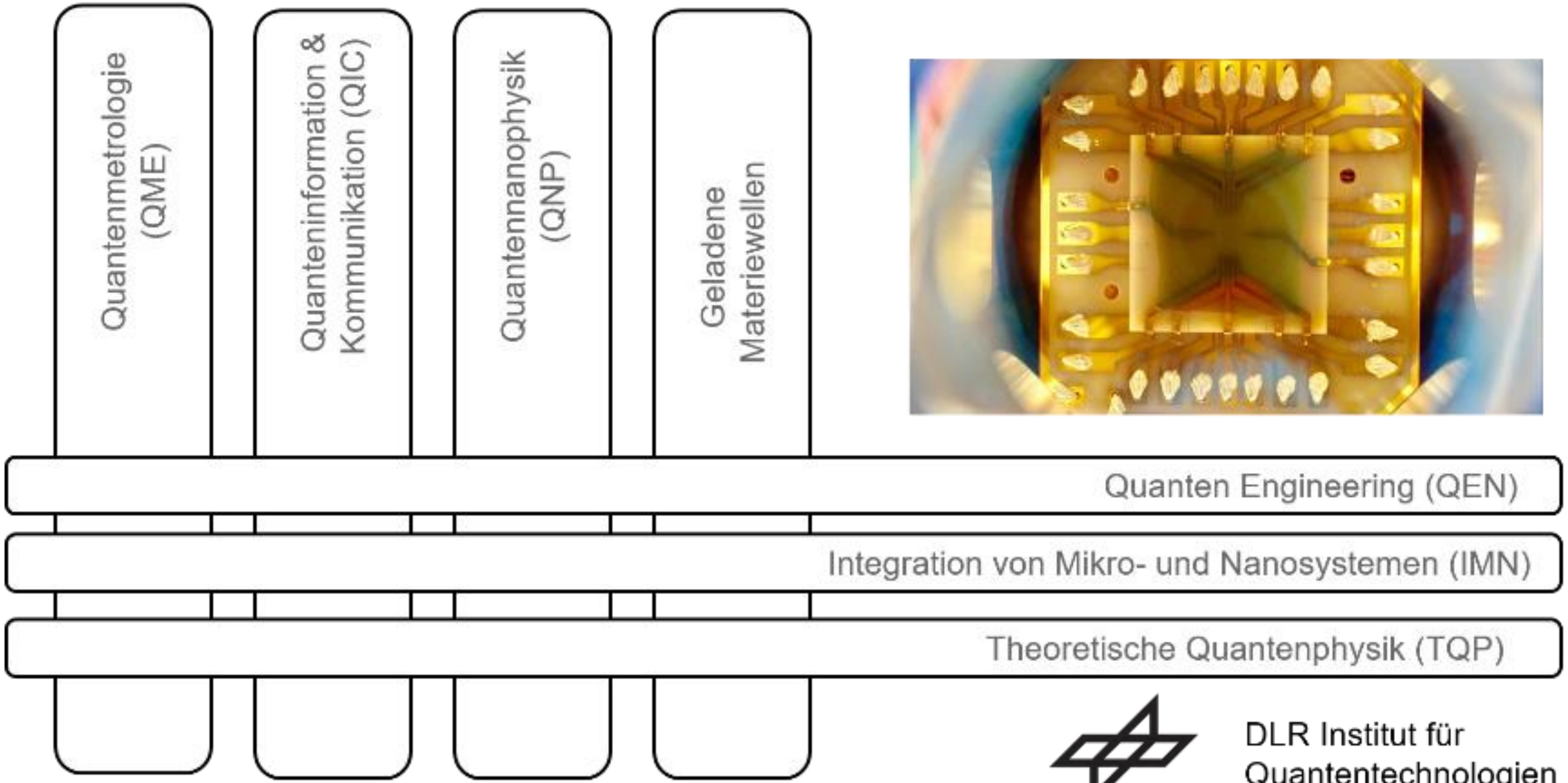
UK National Quantum Technologies Programme

DLR-QT, Ulm – Open for Collaboration

Divisions



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THANK YOU FOR LISTENING – QUESTIONS?