DISRUPTIVE ECONOMIC OPPORTUNIES THROUGH QUANTUM SENSORS AND QUANTUM CLOCKS

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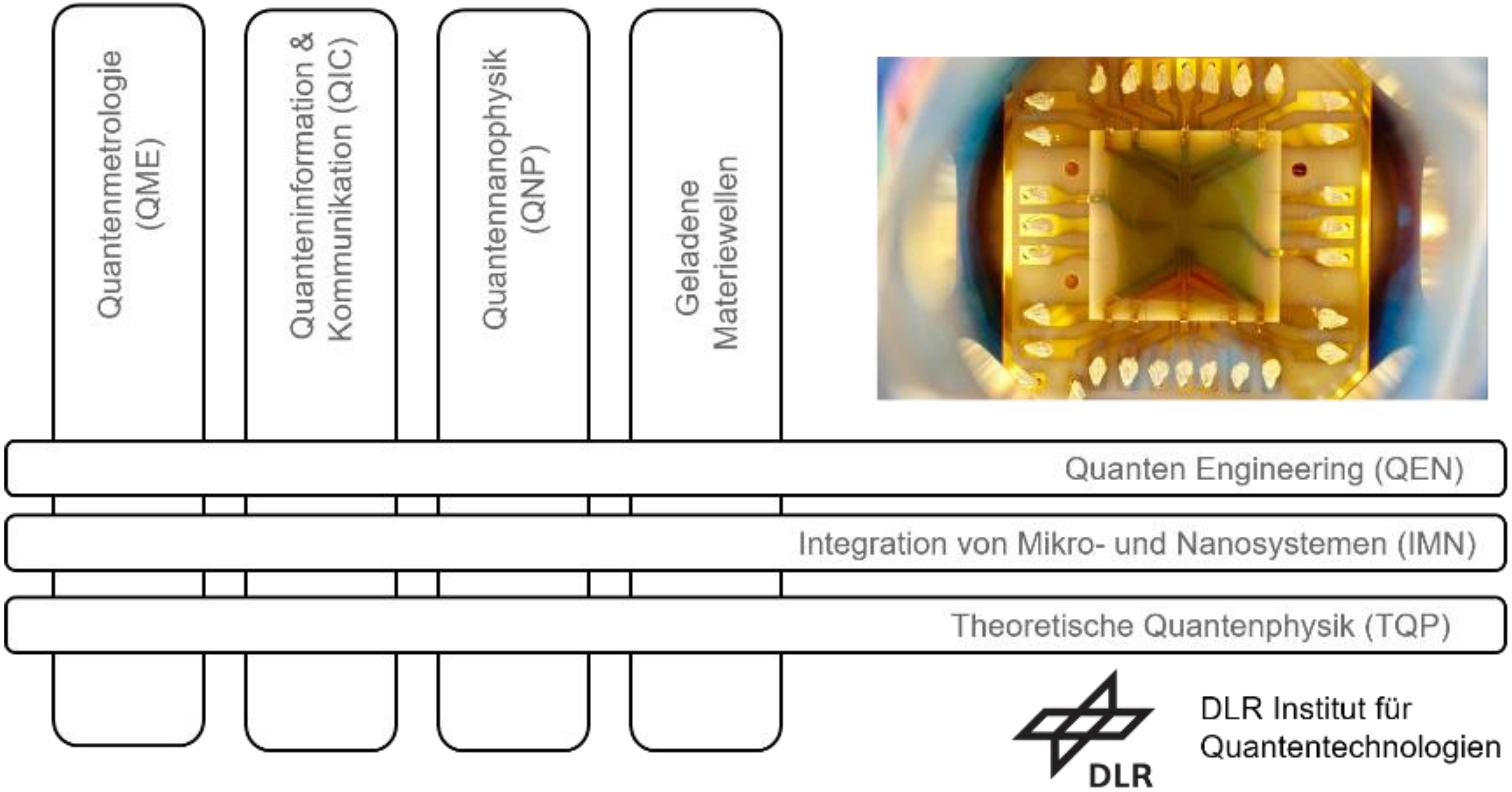
DLR

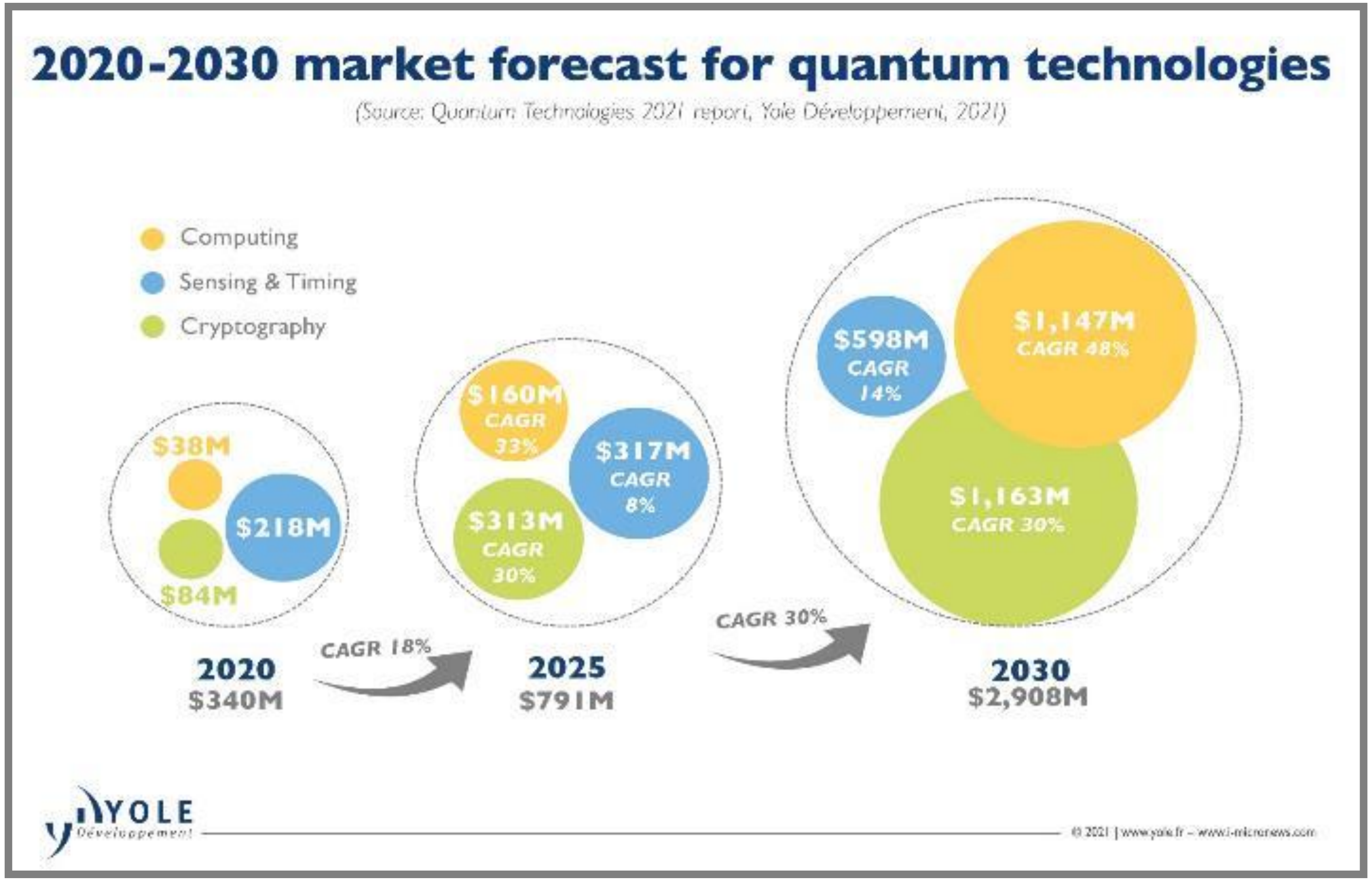
DLR-QT, Ulm

Divisions



Quantum Technologies

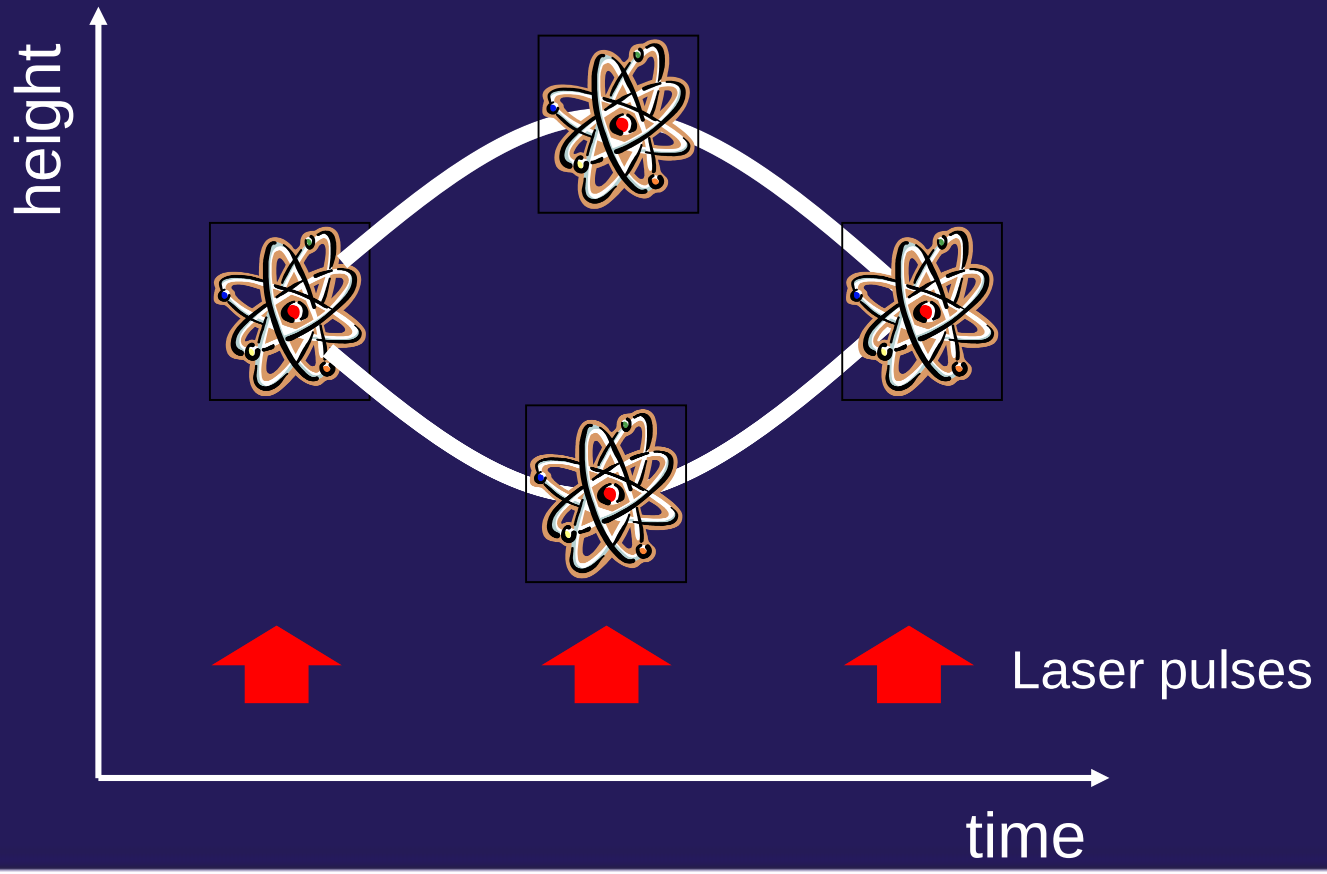
Growth Potential and Areas



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

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

Atomic Quantum Sensors: Atoms Manipulated by Lasers



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

UK Quantum Technology Hub Sensors and Timing

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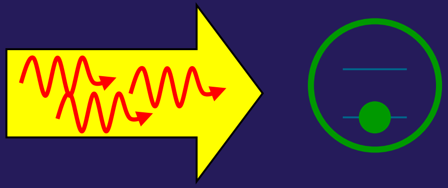
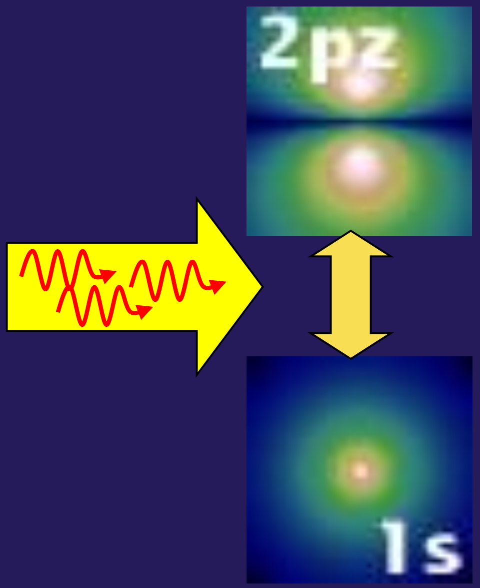
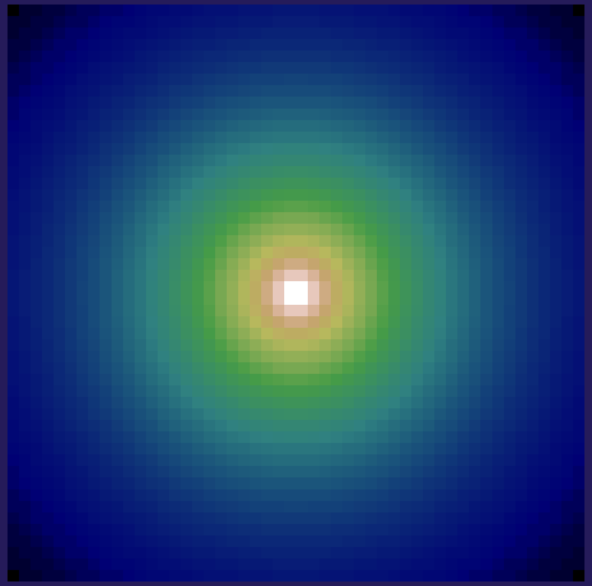
Atom-Light Interactions

System:
- two-level atom
- resonant laser beam

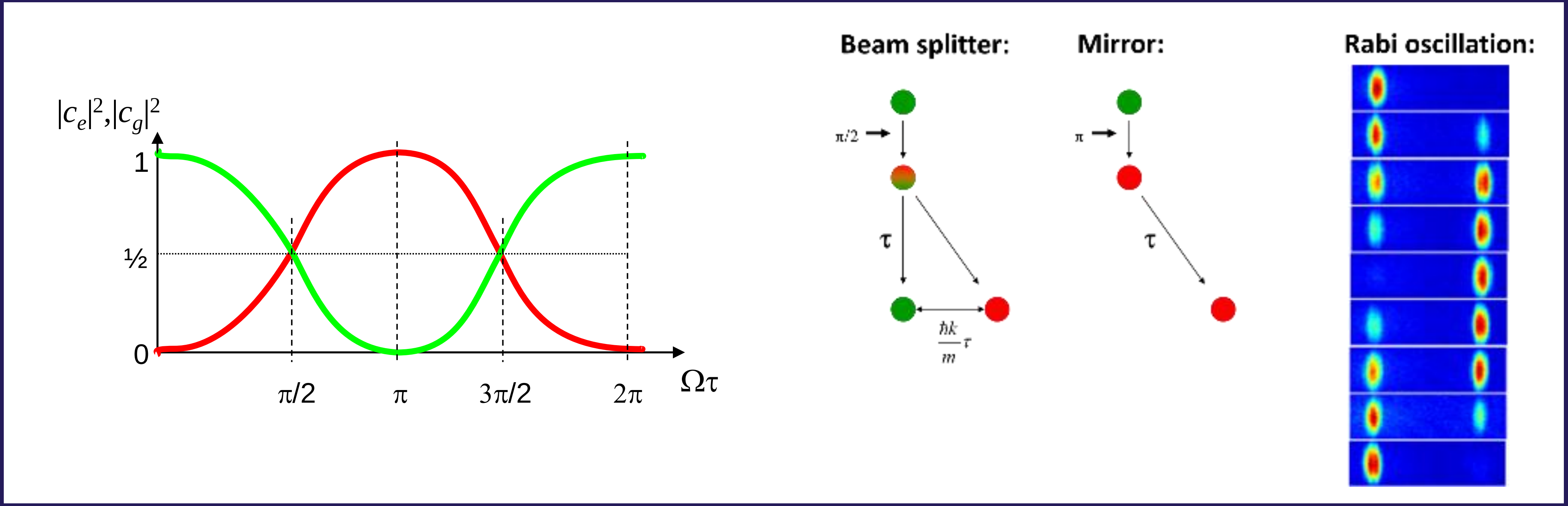




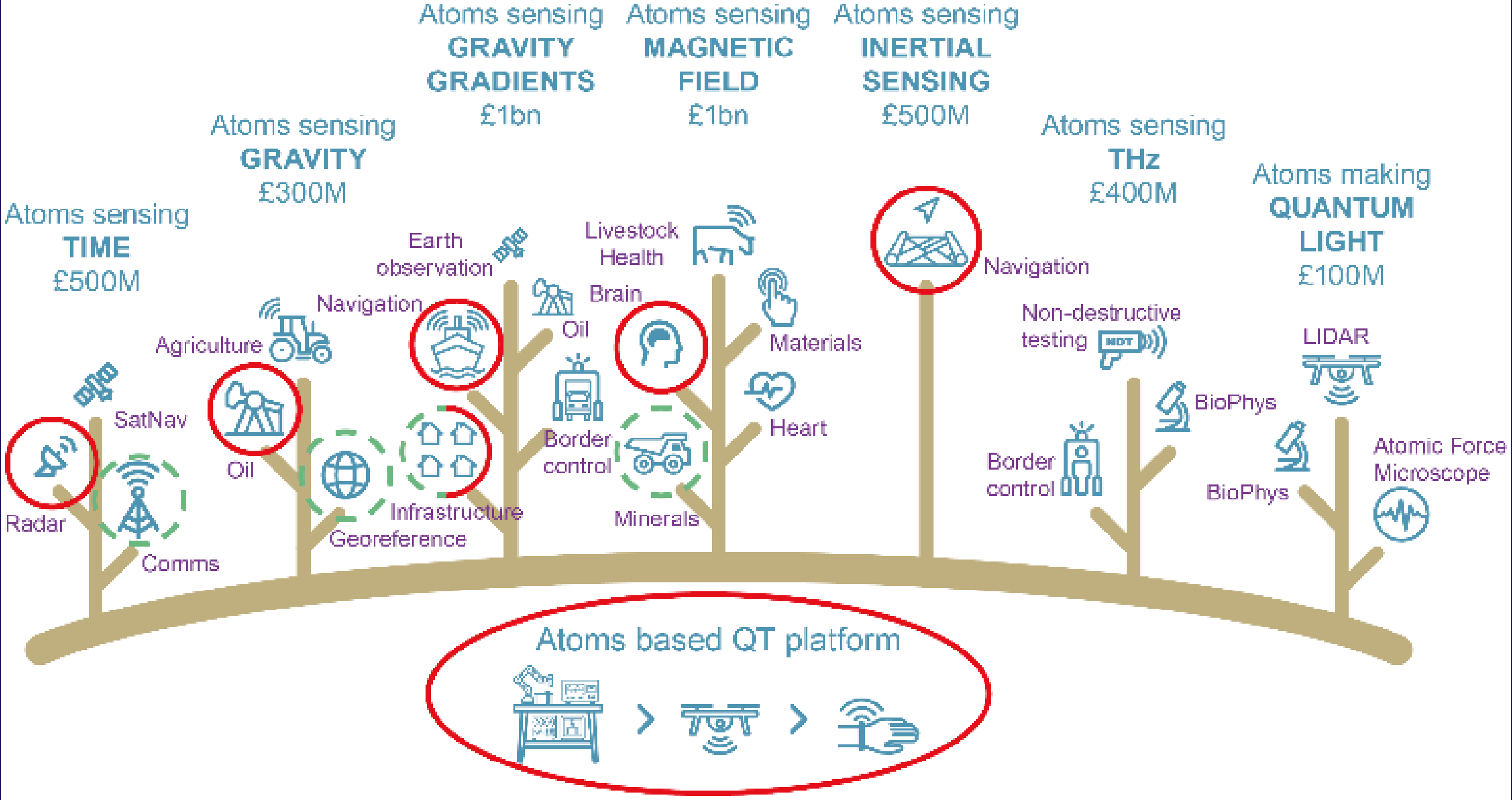


animation and images from: http://iff.physik.unibas.ch/~florian/rabi/rabi.html

Atom-Light Interactions



Roadmap to Applications



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

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

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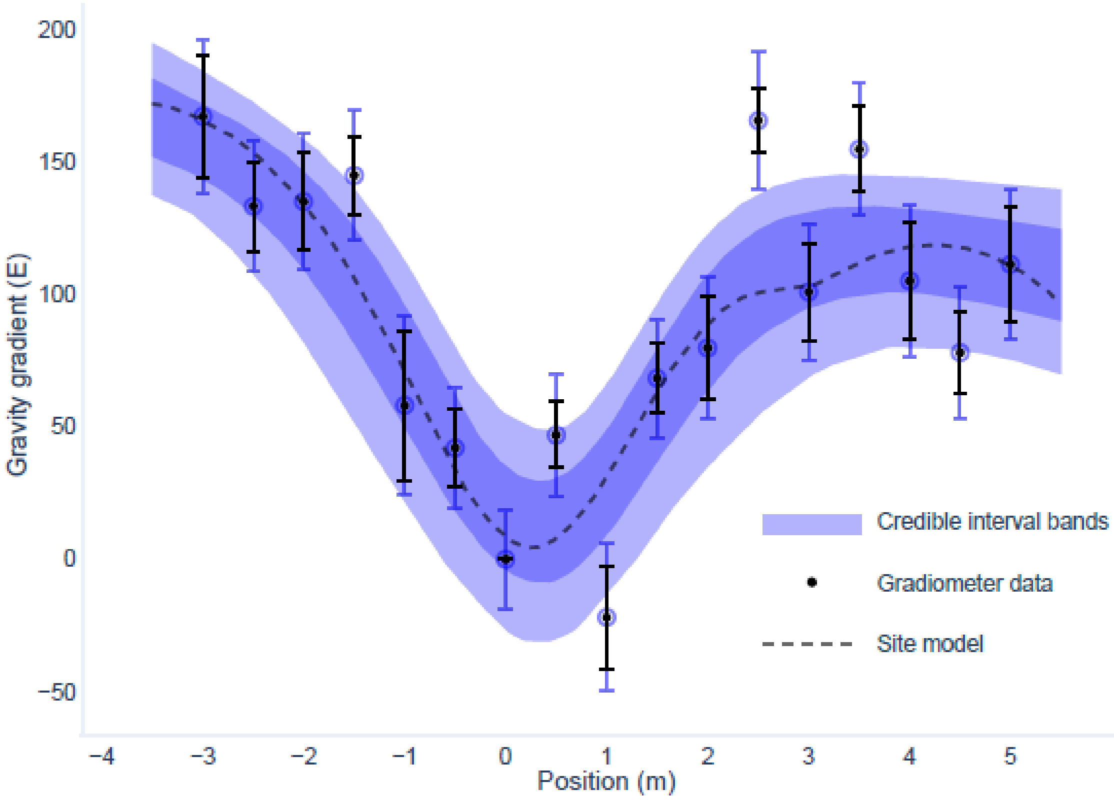
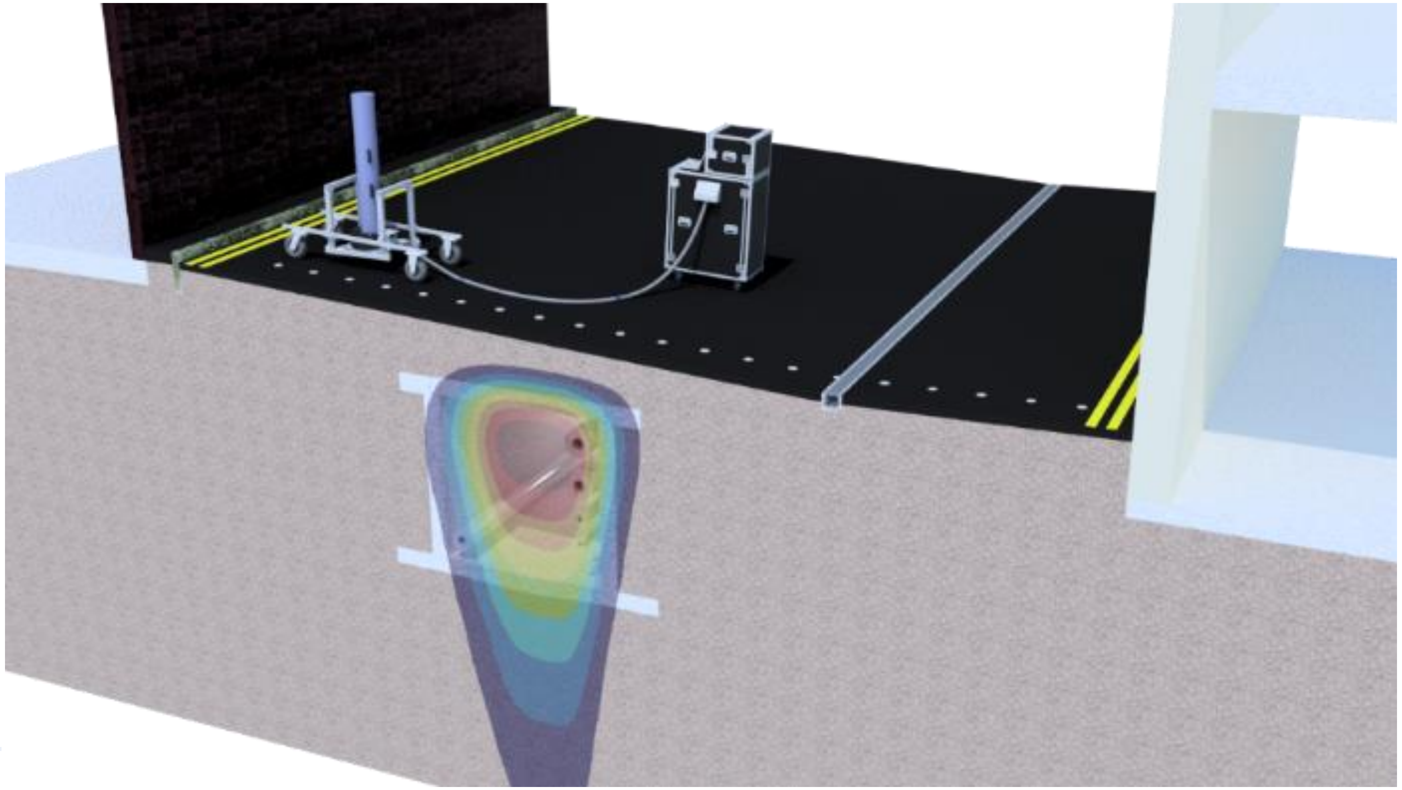
World first detection for quantum gradiometry

- Survey over tunnel

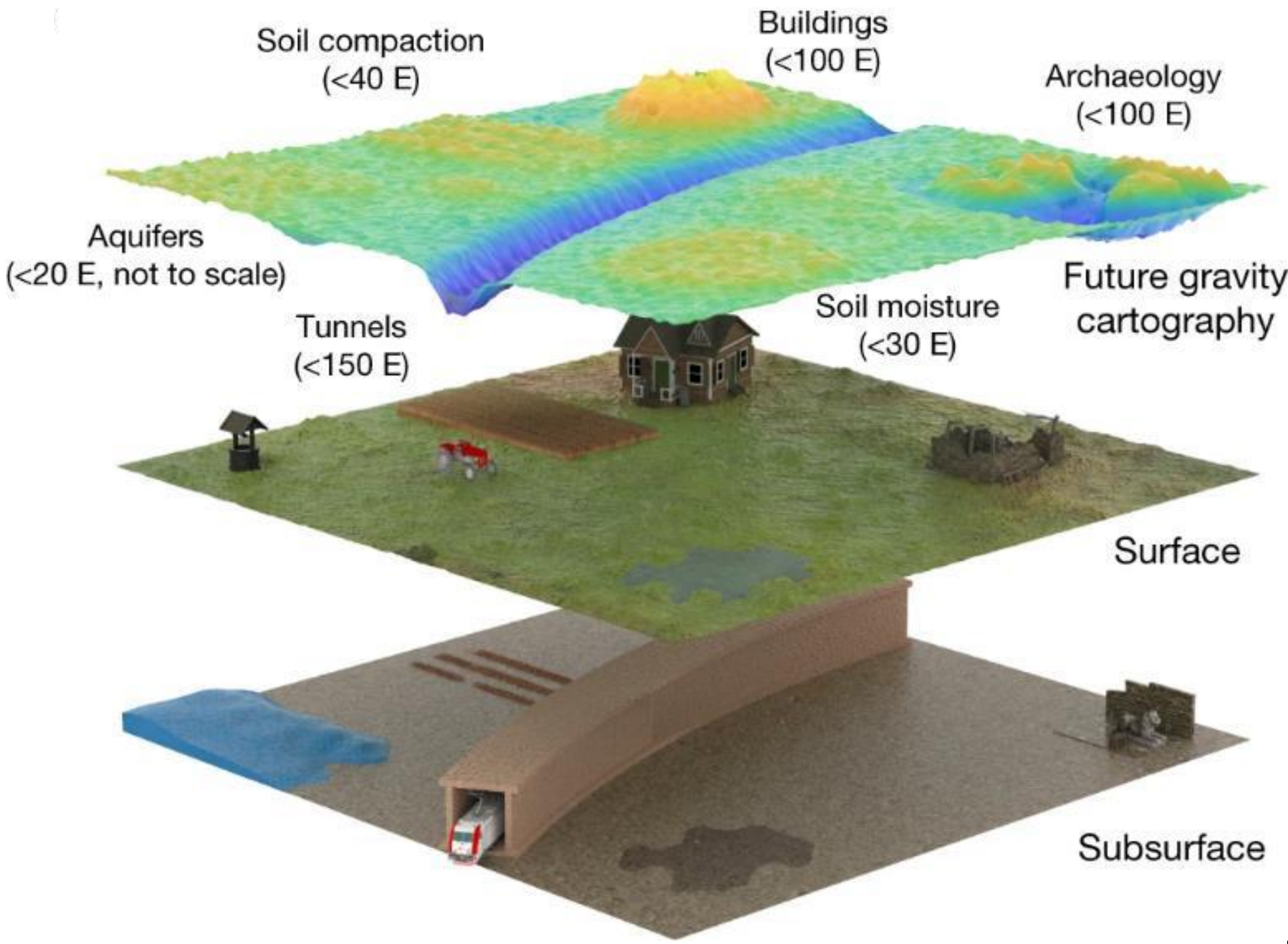




Tunnel centre localised to: ±0.19 m, horizontal; -0.59/+2.3 m, vertical

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

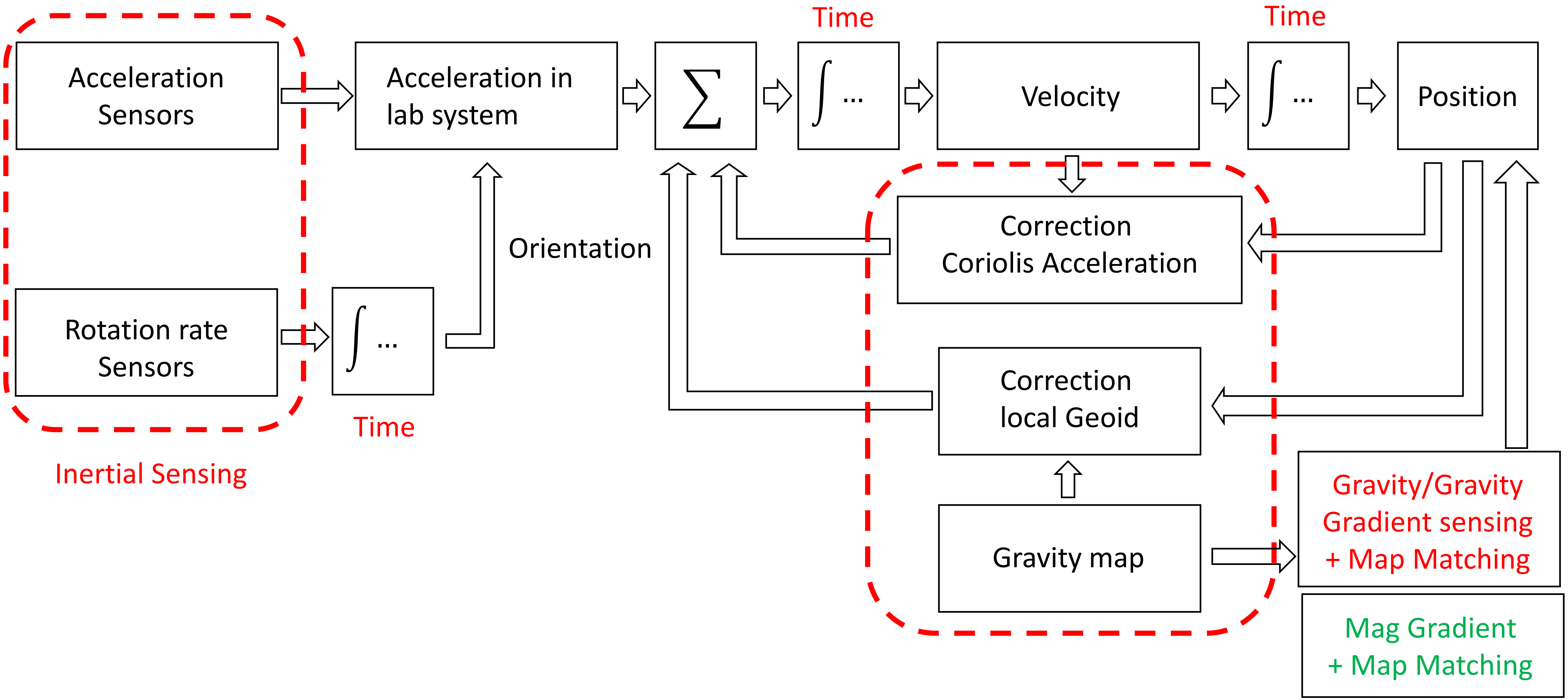
MOT on UAV

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

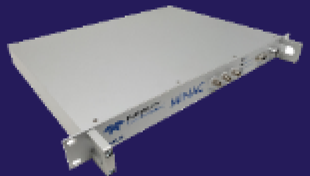
→ Providing absolute position without any communication (including under water)
→ Collision alert (?)

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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UK National Quantum Technologies Programme

One Navigation System Example: TERPROM


TERPROM® DIGITAL TERRAIN SYSTEM

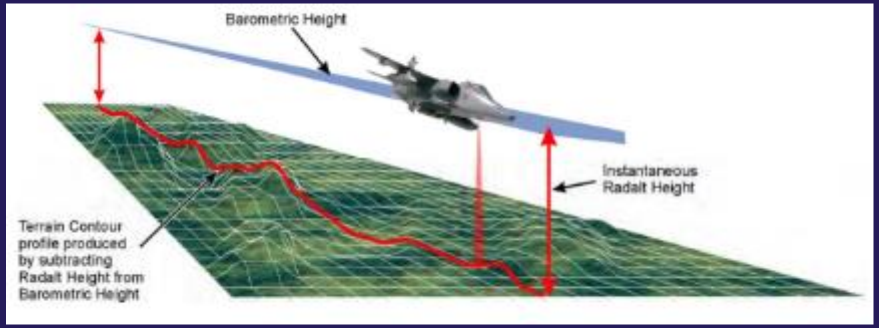
MISSION PROVEN, GPS-DENIED TERRAIN REFERENCED NAVIGATION

Enables aircraft to fly demanding missions more safely and effectively in all weather conditions, day and night

KEY FEATURES

- Terrain referenced navigation
- Predictive ground collision avoidance system
- Obstruction warning and cueing
- Database terrain following
- Passive target ranging
- ATAC (Advanced Terrain Avoidance Cueing)

https://www.collinsaerospace.com/-/media/project/collinsaerospace/collinsaerospace-website/product-assets/marketing/t/terpromr/terpromr-digital-terrain-system-fixed-wing.pdf?rev=14709802dc674d959f4fd9e787f2b2bc



https://www.whatdotheyknow.com/request/491019/response/1182168/attach/3/Segment%20005%20of%20AP3456%20Tablet%20Vn%2010p0%202018Redacted.pdf?cookie_passthrough=1

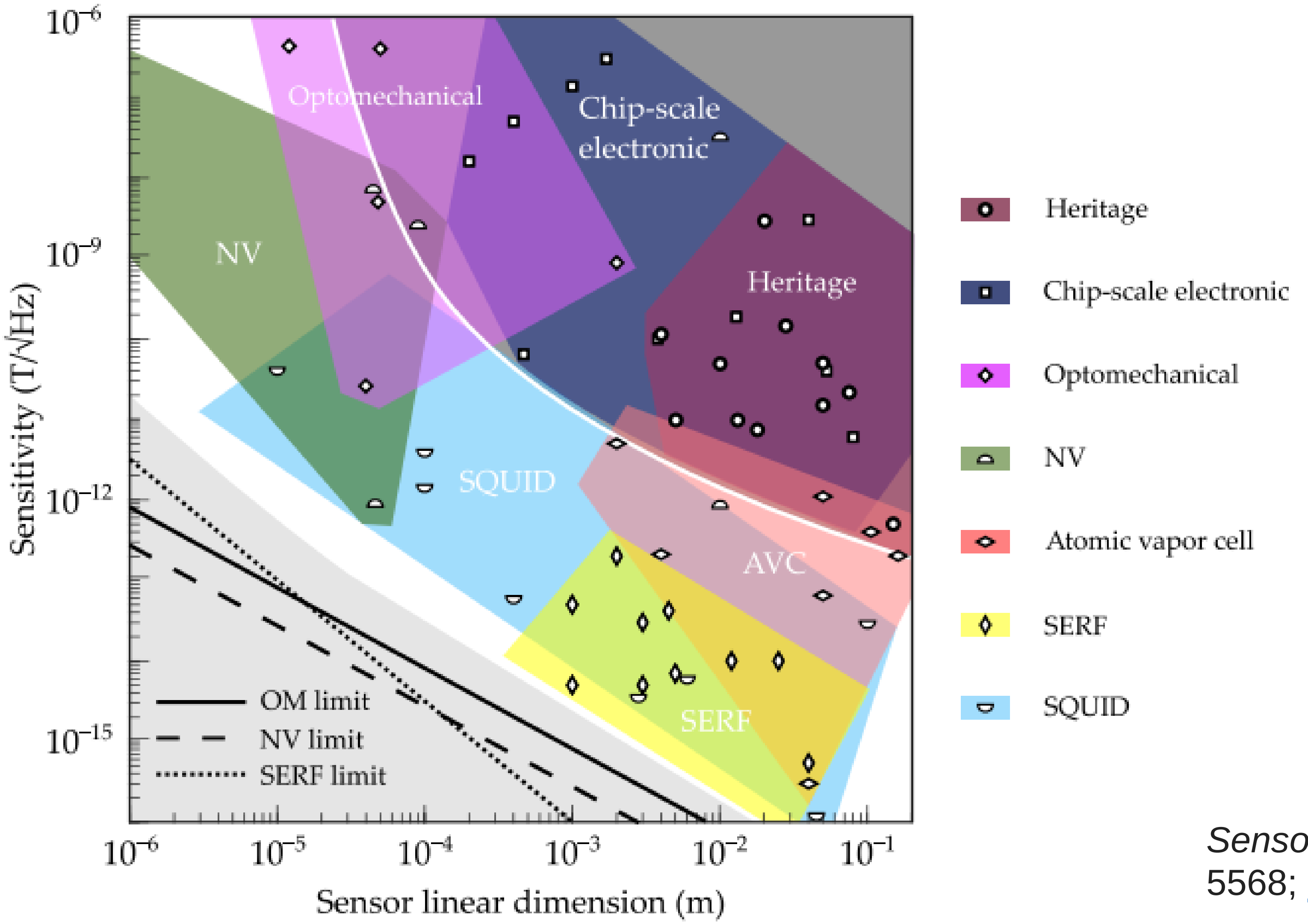
Radar Altimeter → Kalman Filter

IMU → Kalman Filter

Kalman Filter → Navigation Output

Magnetic Sensor Overview – Scale vs Sensitivity

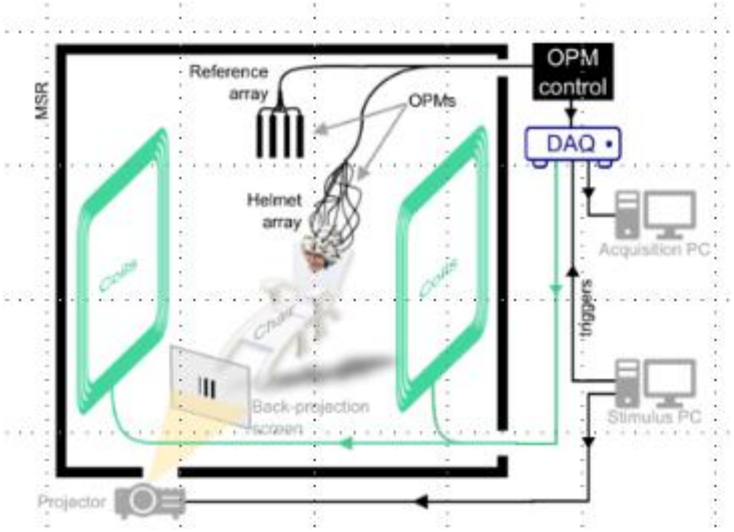
Sensors **2021**, *21*, 5568 16 of 27



Sensors **2021**, *21*(16), 5568; https://doi.org/10.3390/s21165568

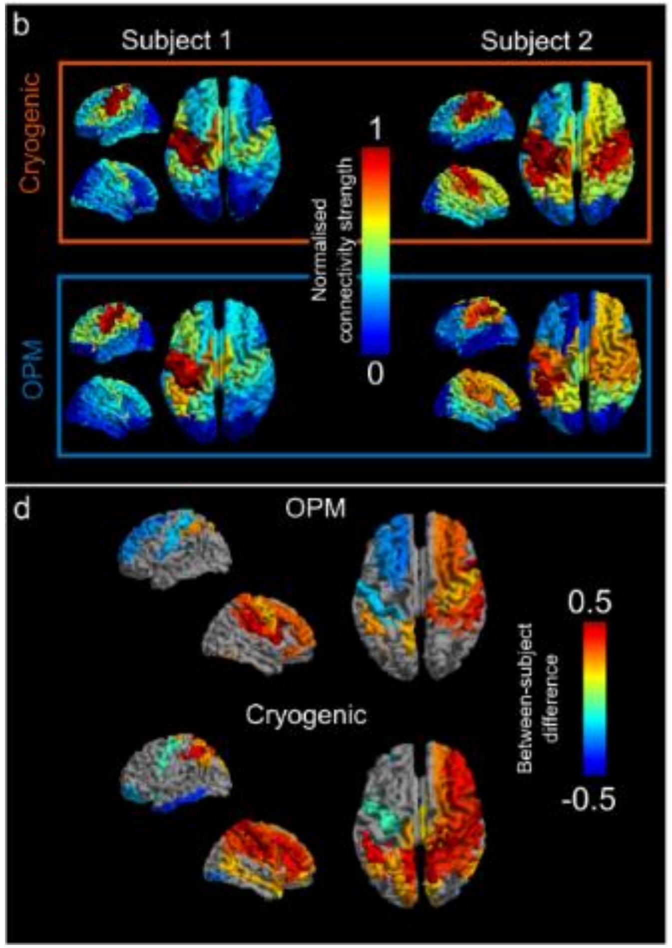
Quantum-Magnetoencephalography – Spin off from QT

cerca
Magnetics Limited



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



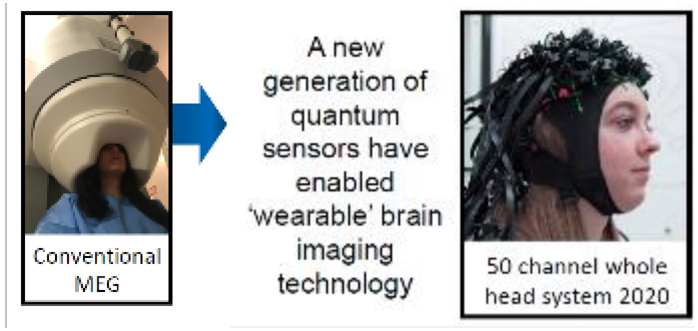
Impact Opportunities:

Epilepsy: 60M people worldwide

Dementia: 1% GDP

Schizophrenia: 1% of population

Trauma: 100.000 / year in UK



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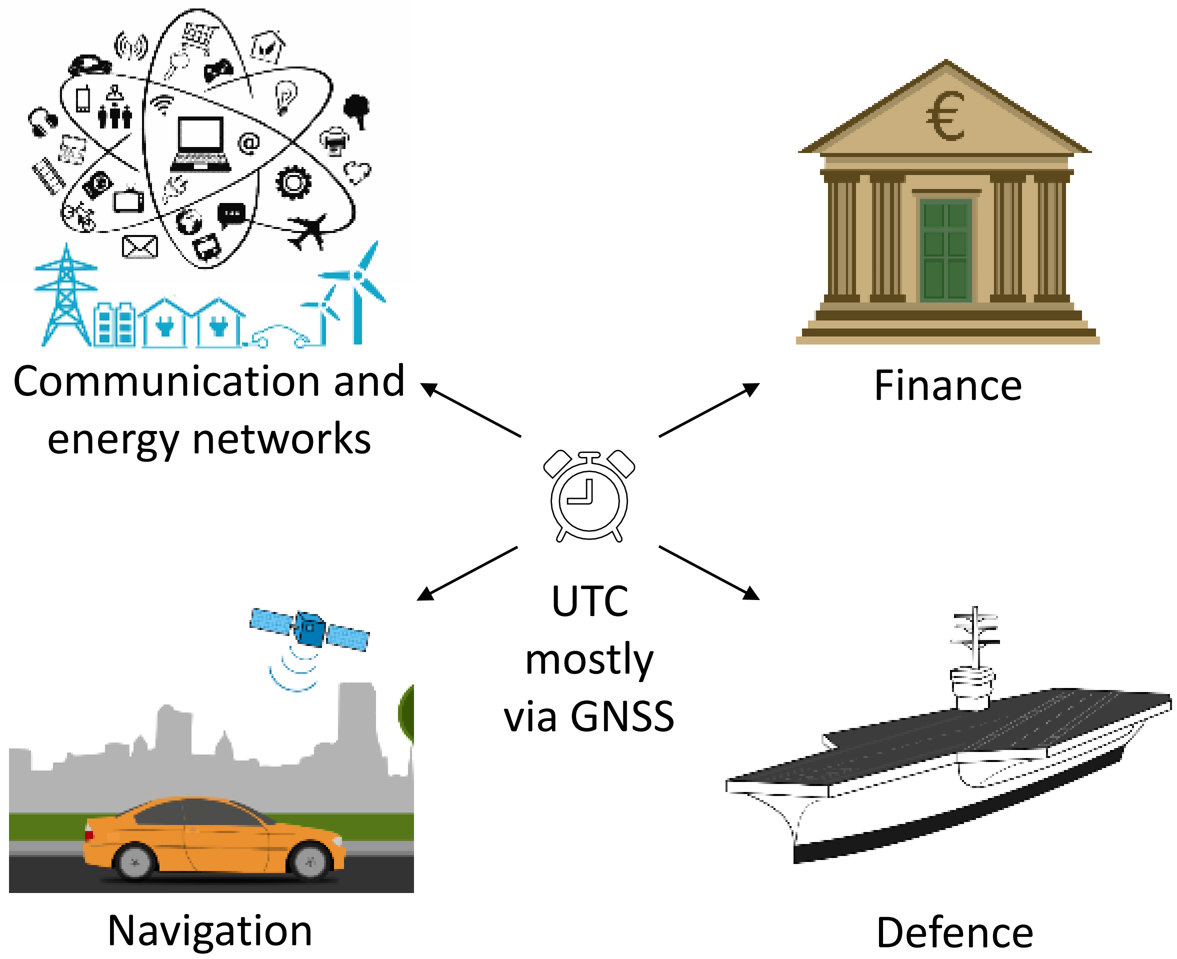
Quantum Clocks Potential to Change Business Models

Timing today: Centralized model



Timing via Global Navigation Satellite Systems:

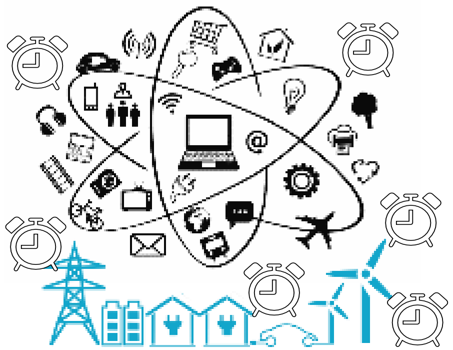
+ „Free“ to use
+ Worldwide availability
+ 30 ns within UTC

→ 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

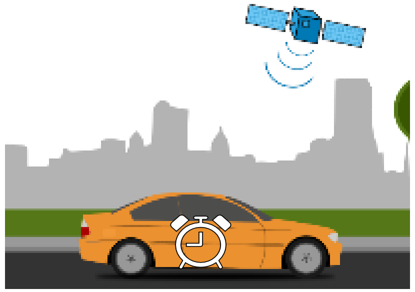
Timing future: „Edge“ model



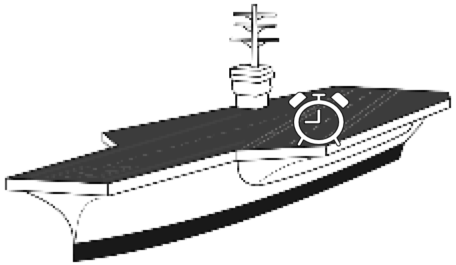
Communication and energy networks

Finance

Local timing with synchronization



Navigation



Defence

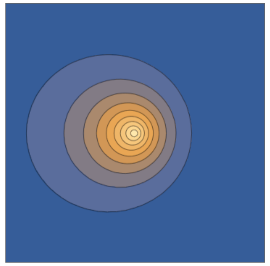
Quantum „Edge“ Timing:

+ 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

How do Quantum Clocks Work?

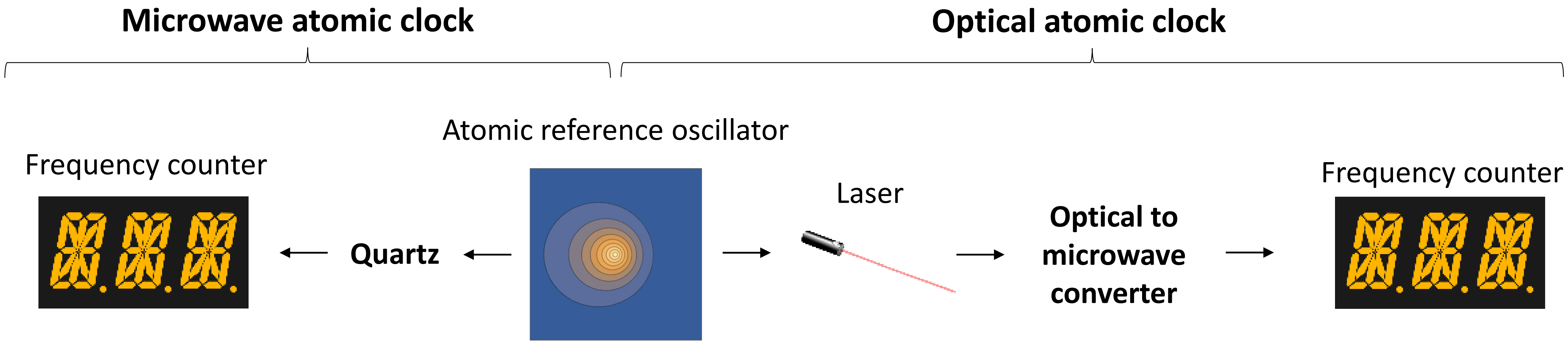
A quantum clock replaces the manmade frequency reference in a classical clock (e.g. a pendulum) with an atom



Always made the same by nature
Precision governed by the laws of physics

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



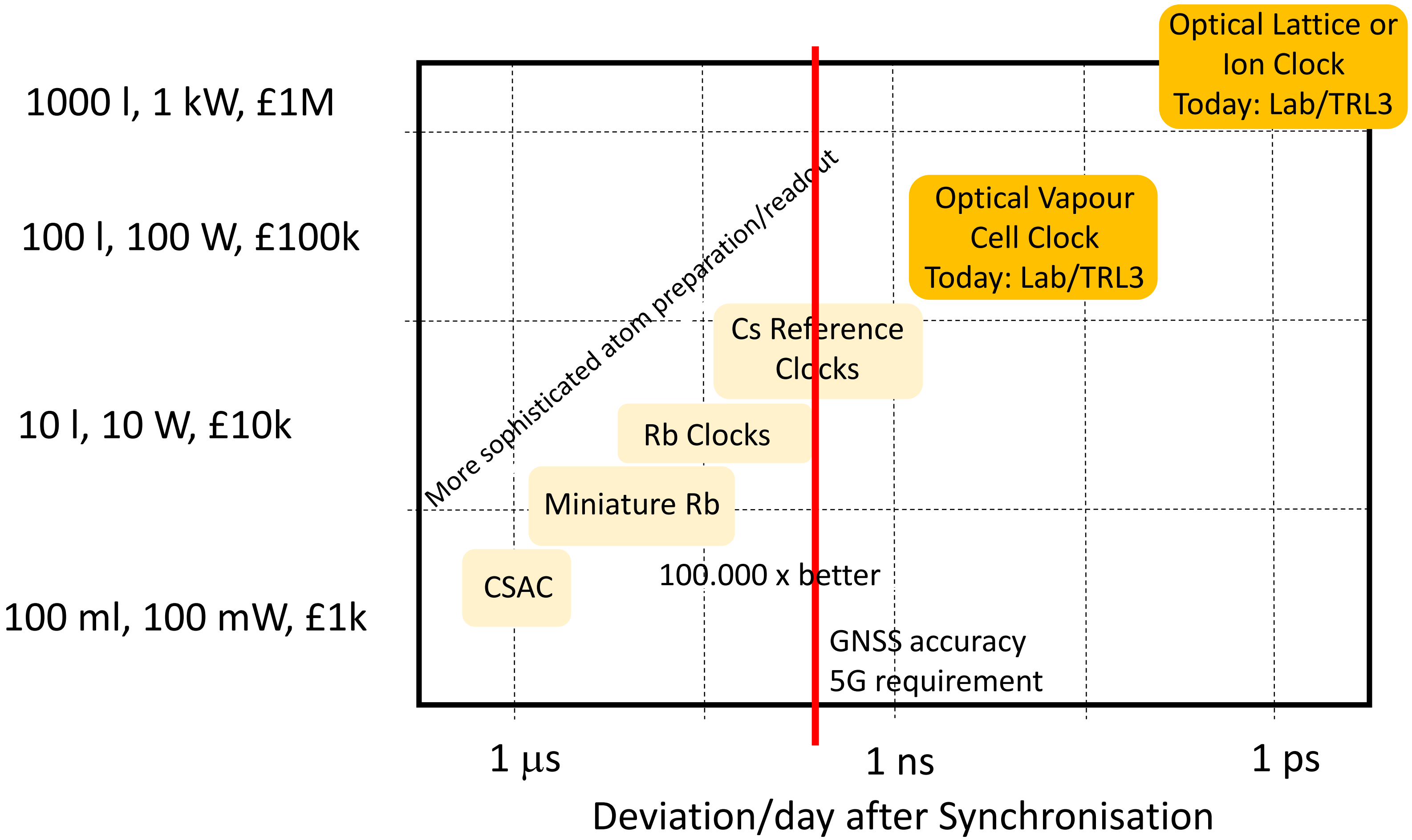
Microwave atomic transition is used to discipline a quartz oscillator

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



Some International Developments – Optical Clocks

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

		Galileo RAFS	Galileo PHM	Ca beam	I_2 MTS	Rb MTS	Rb TPT	Sr Lattice clock	Ca single ion clock
	References	Orolia datasheet (2016)	Leonardo datasheet (2017)	Shang et al. (2017)	Schuldt et al. (2017); Döringshoff et al. (2019)	Zhang et al. (2017)	Martin et al. (2018)	Bongs et al. (2015); Origlia et al. (2018)	(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^{-14a}	4×10^{-13}	n/s	n/s
	10 s	1×10^{-12}	3×10^{-13}	2×10^{-14}	3×10^{-15}	4×10^{-15a}	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^{-15a}	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

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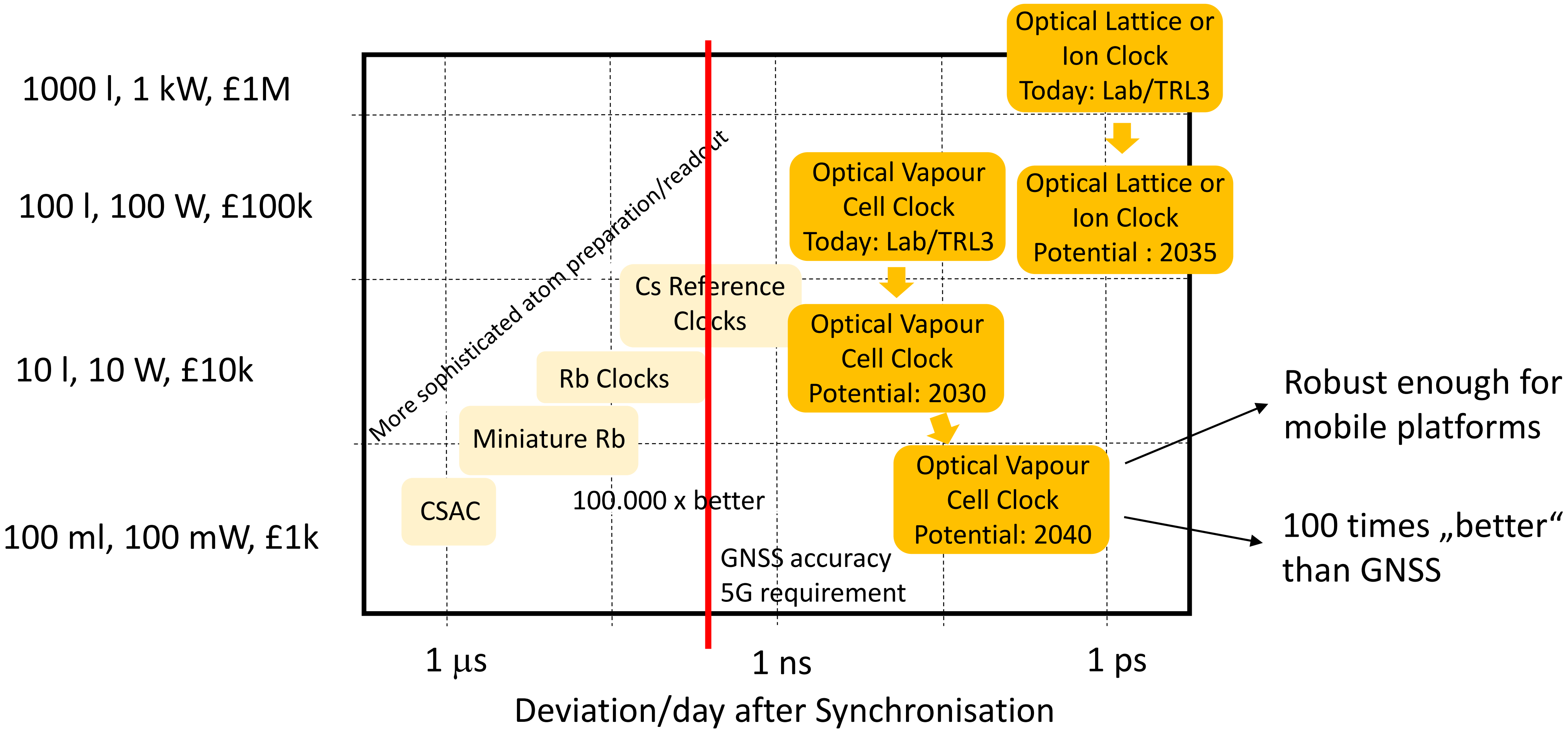
So far: "linear" relationship between SWAP-C and stability



Where Does DLR Stand?

DLR

Worldwide leading optical vapour cell clock

GPS Solutions (2021) 25:83
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	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
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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

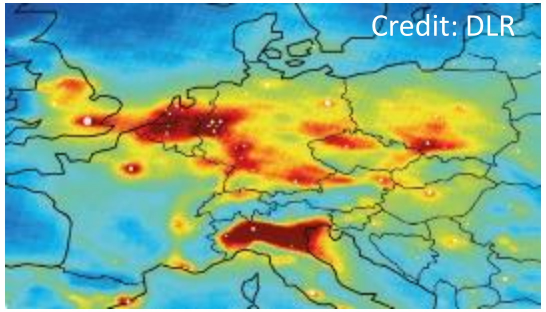
Business Advantage through Quantum Timing

Next generation GNSS

Long distance 3d imaging radar

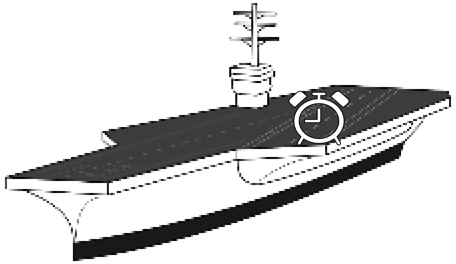
Credit: AdobeStock/J-mel

Urban airspace control



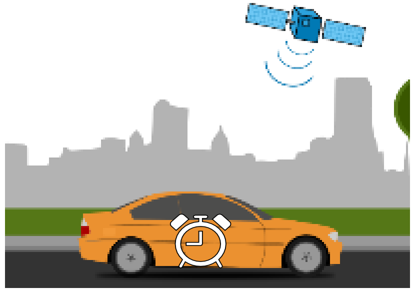
mm-level global height reference system

2030 2040 2050



GNSS resilient operation

High bandwidth communication



Autonomous vehicles

Timeline for Quantum Clocks providing Business Advantage

Advanced signal-based intelligence

Radar in cluttered environments

Long distance 3d imaging radar

mm-level global height reference system

2030 2040 2050

GNSS resilient operation with multi-month on board holdover

Urban airspace control

Low power high bandwidth communications

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UK National Quantum Technologies Programme

UoB ADRAN Testbed

- UoB ADRAN ADvanced Networked RAdar facility is enabling to
  - Benchmark conventional radar performance in challenging urban environment
  - Demonstrate the capability of network synchronisation through practical demonstration in radar under demanding realistic conditions
  - Only dedicated multistatic network radar testbed for urban surveillance

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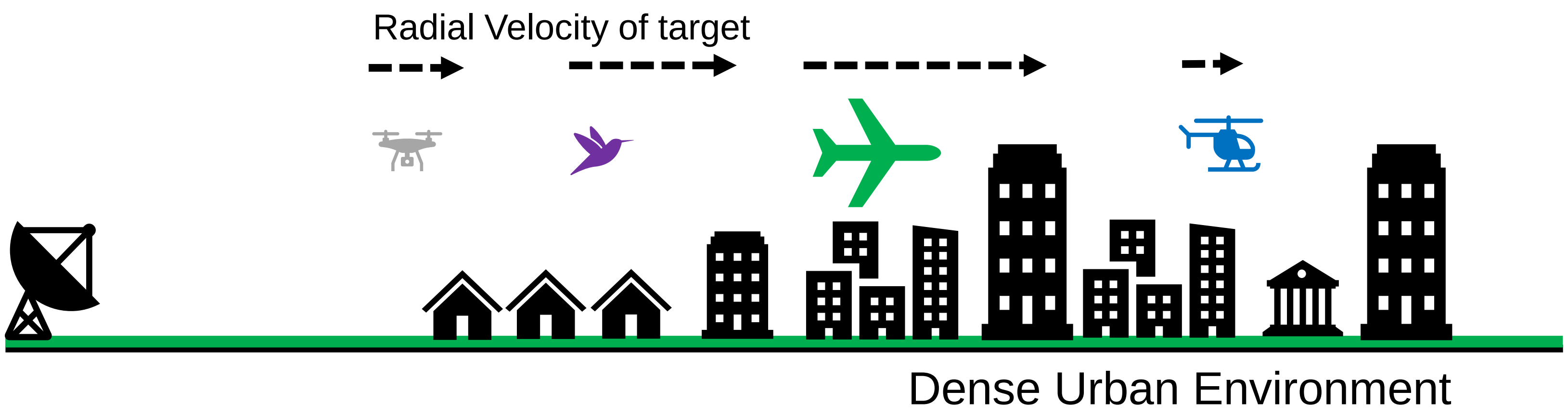
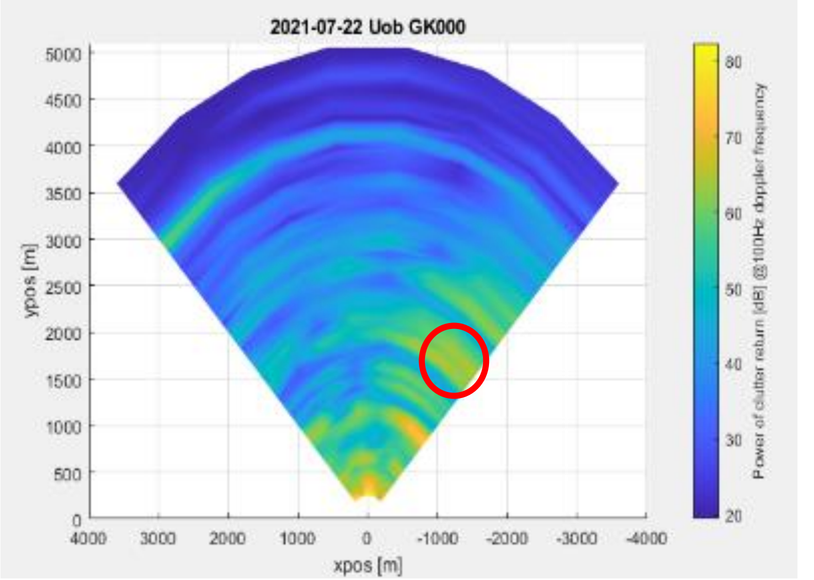
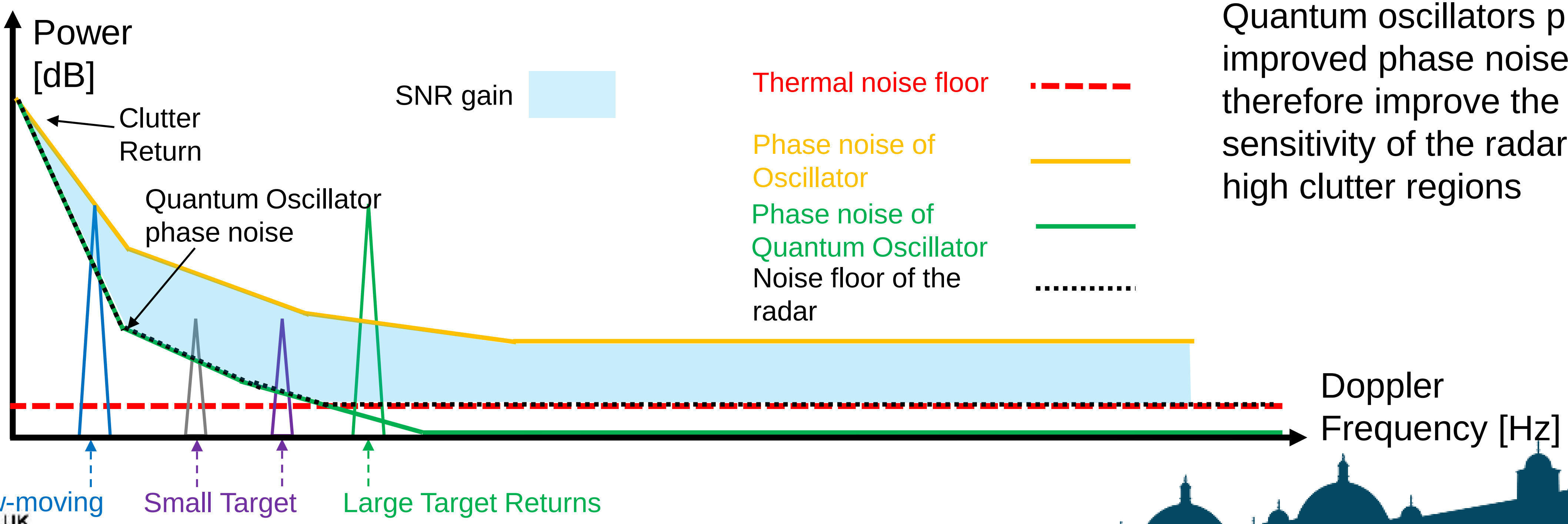
Noise limitations in the radar

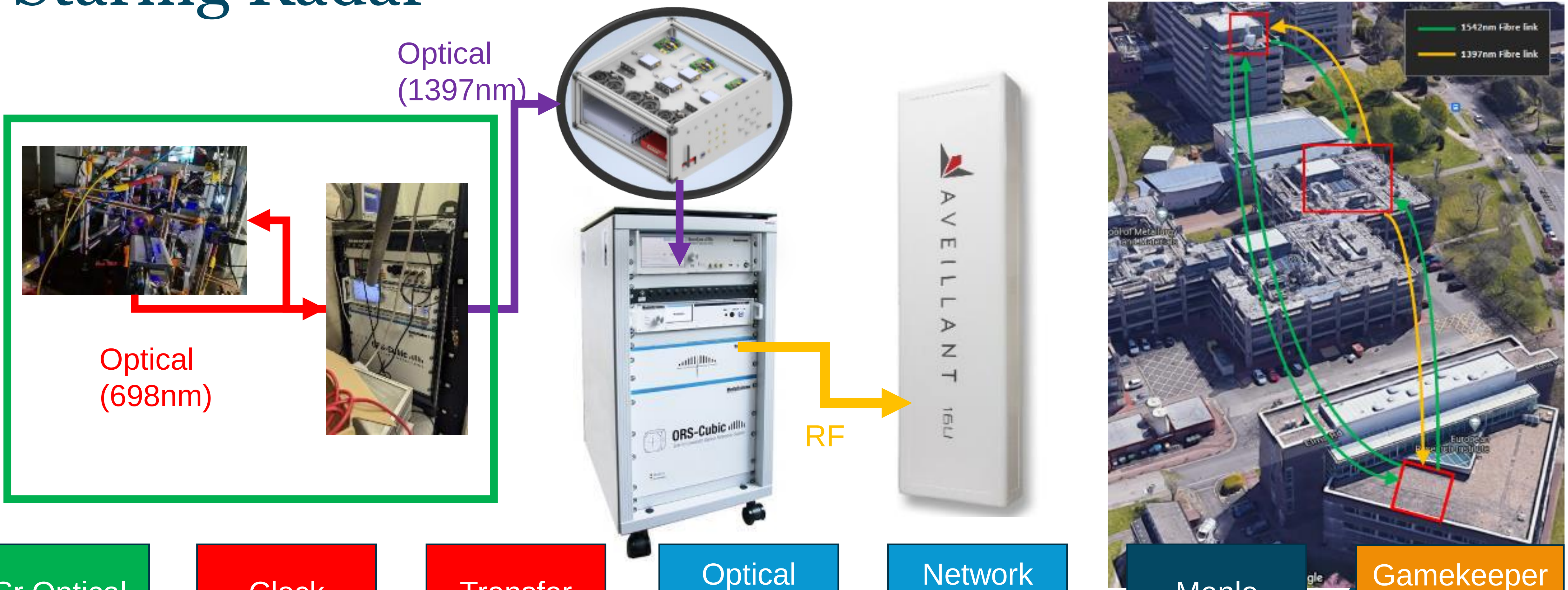




Quantum oscillators provide improved phase noise and therefore improve the sensitivity of the radar in high clutter regions

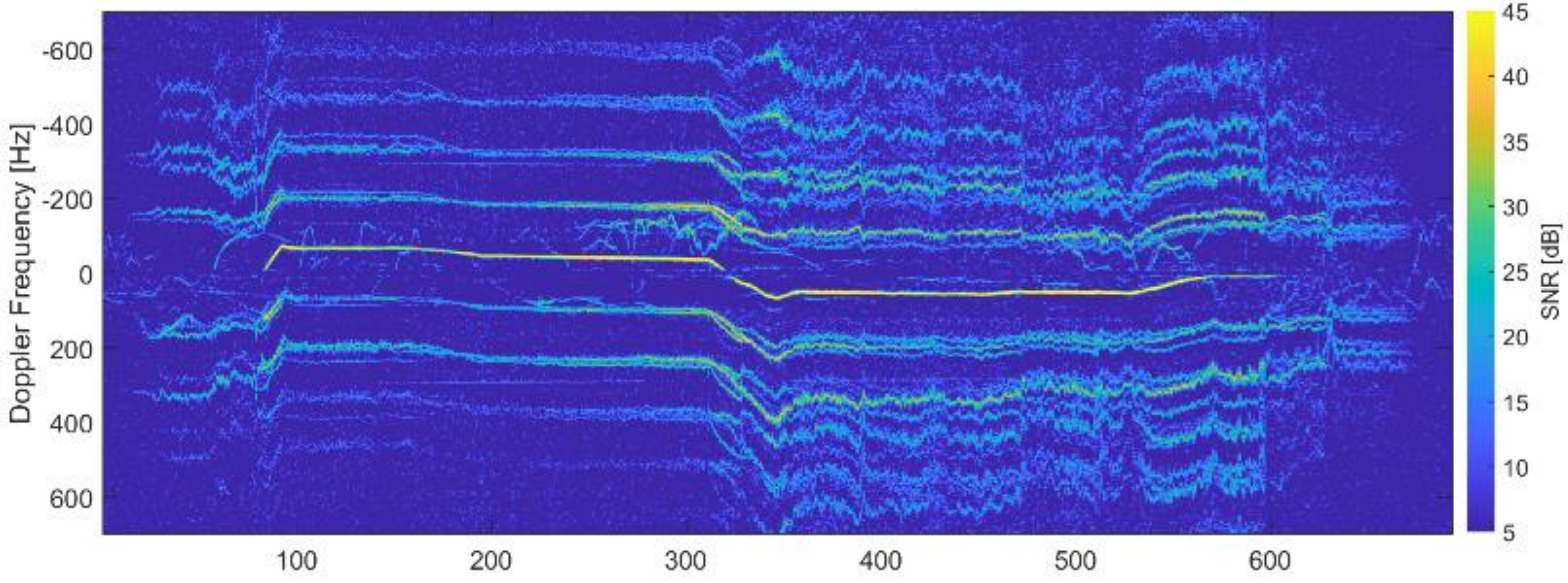


Components of the Quantum Enabled Staring Radar

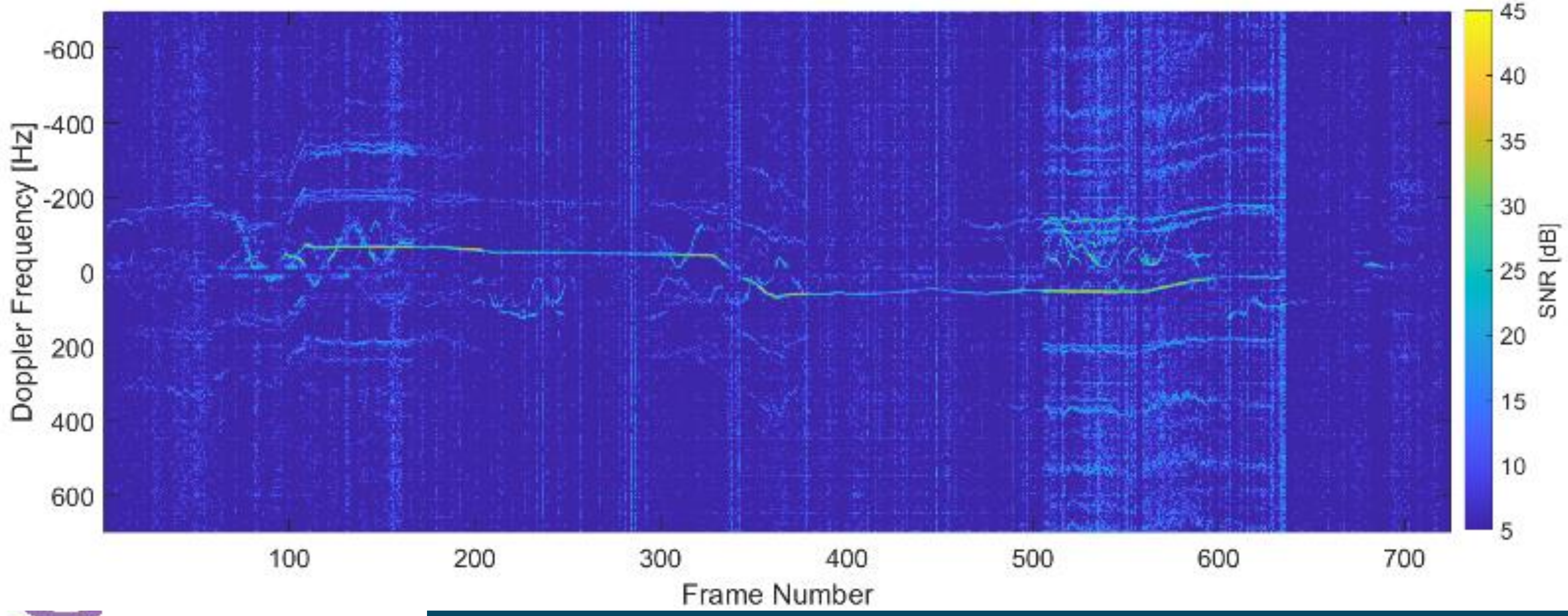


Sr Optical Clock → Clock Laser → Transfer Laser → Optical Fibre Network → Network Interface Node → Menlo MGU → Gamekeeper Staring Radar

Better oscillator: more features



GK007
Monostatic
(Better oscillator)



GK000
Monostatic

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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THANK YOU FOR LISTENING – QUESTIONS?