DISRUPTIVE APPLICATIONS ENABLED BY QUANTUM SENSORS AND CLOCKS

Heraeus Workshop

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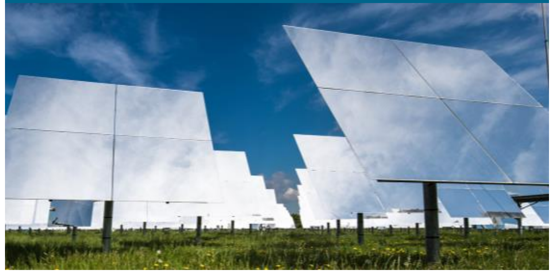
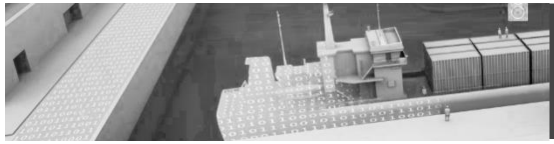
GERMAN AEROSPACE CENTER (DLR)

Research, technology and knowledge transfer for a sustainable future and to strengthen Germany as a location for science and business

Research Center + Space Agency + Project Management

AERONAUTICS	SPACE	ENERGY	TRANSPORT
			



SECURITY
civil security & defence research

DIGITALISATION, QUANTUM TECHNOLOGY AND SYSTEM MODELLING

- Europe's largest research centre for aeronautics and space
- Close cooperation with academia, research, business and industry
- BMWK is the primary funding ministry, BMVg provides institutional funding, BMI, BMU and others provide project funding

DLR sites

- **54 institutes and facilities across 30 sites**
  - 8 research stations
  - 4 international offices
- **More than 10.000 employees**
  - ~ 5.800 Scientific Staff
- **Budget: ~ 1.100 Mio. €** (2021)
  - ~ 550 Mio. Third-Party Funding

DLR Institute for Satellite Geodesy and Inertial Sensing

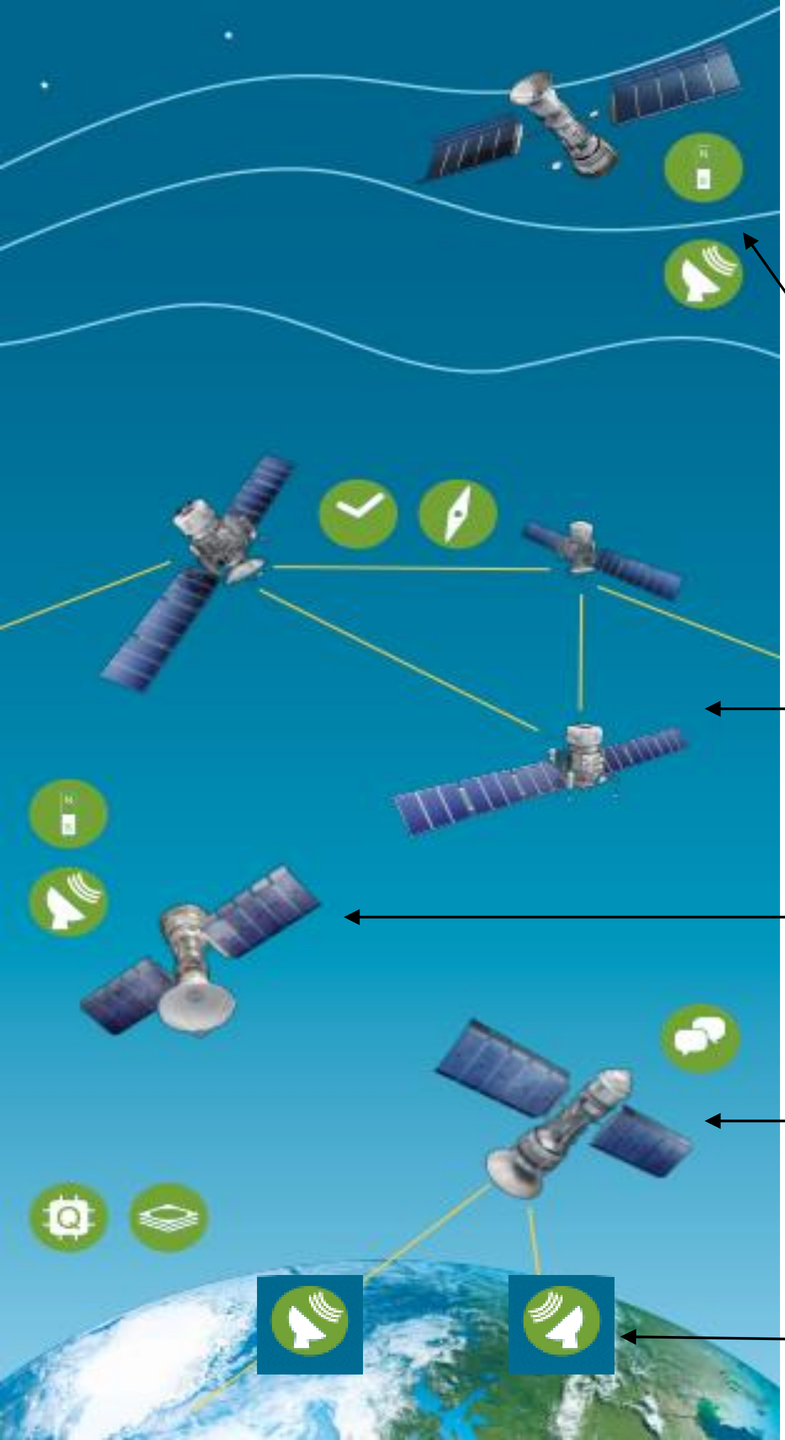
DLR Institute for Quantum Technologies

Quantum Technology Institutes
(also: DLR Quantum Computing Initiative)

DLR Institute for Communication and Navigation
Galileo Competence Center

Institute for Quantum Technologies

Quantum technologies for Space



Data for ionosphere-troposphere-models
(quantum magnetometers and accelerometers)

Global Navigation Satellite Systems, resilient time
(quantum clocks)

Earth observation, resilient communication
(quantum RF receivers)

Gobal networks with advanced quantum functionality
(quantum communication, authentication, client computing)

Space traffic management, Space asset monitoring
(Quantum oscillators and clocks for radar)

UN proclaimed 2025 as:

INTERNATIONAL YEAR OF
Quantum Science
and Technology

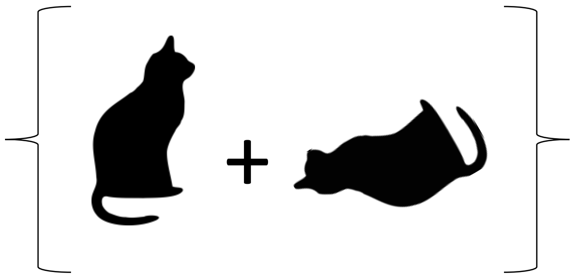
100 years of quantum is just the beginning...

[International Year of Quantum Science and Technology (quantum2025.org)](quantum2025.org)

Quantum 2.0

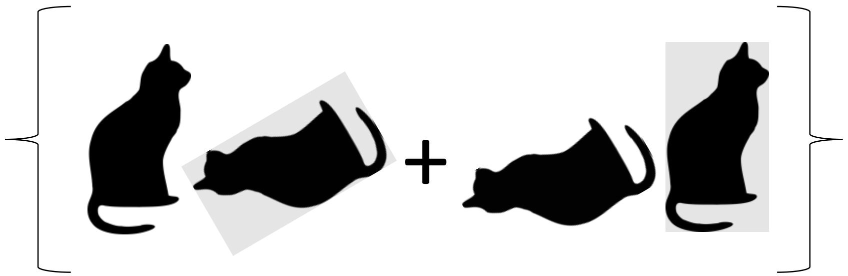
Superposition and Entanglement

Superposition



Particles simultaneously in several states
→ Schrödinger cat

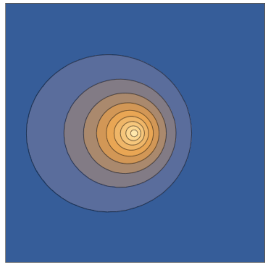
Entanglement



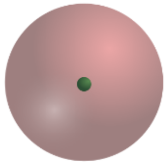
„Superposition involving several particles“

Example: Superposition in an Atom

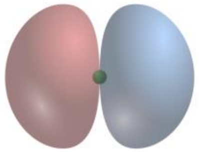
Oscillating Electron Cloud



$= \frac{1}{\sqrt{2}} \Big\{$



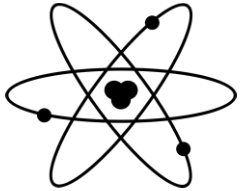
$+$



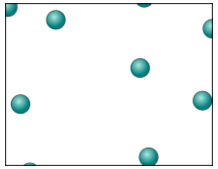
$e^{-i\frac{\Delta E}{\hbar}t} \Big\}$

Ingredients for Quantum Technologies

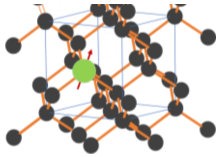
Quantum Particles + Control



Atoms / Ions

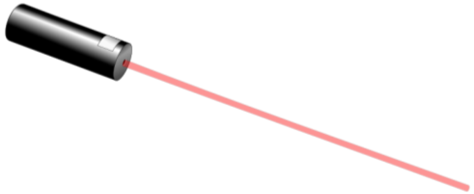


Natural Atoms

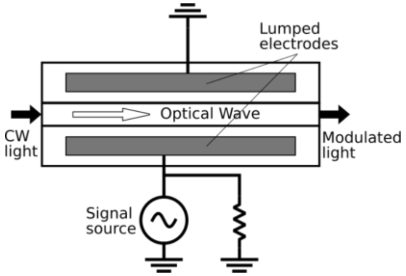


Artificial Atoms

Photons



Laser- or RF Pulses

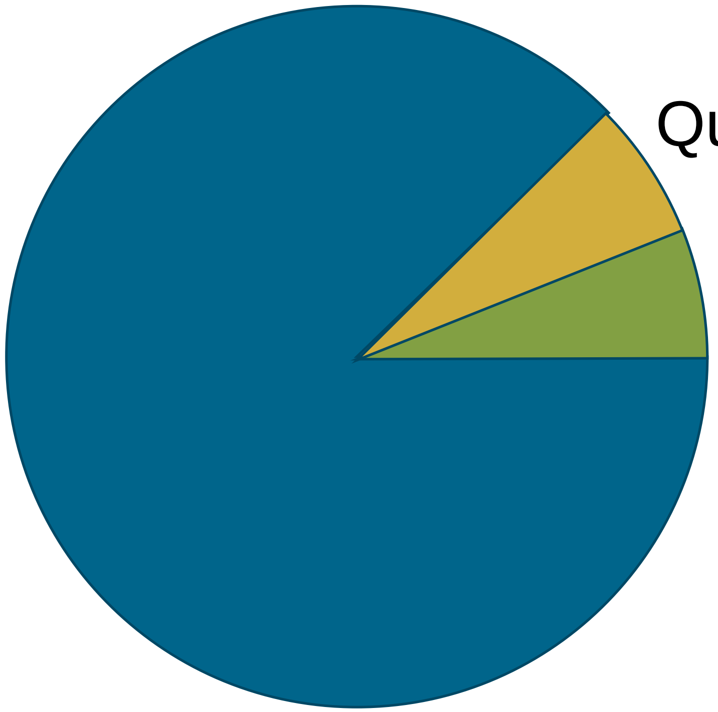


Nonlinear crystals
Photonics

Electronics
Software
Shielding
Packaging
User interface
…

Quantum Technology Applications and Markets

Market estimates in 2024 (source: McKinsey Quantum Technology Monitor, 2023)



Overall economic impact much larger (e.g. estimate for QC in 2035: $620B-$1270B)

Quantum Sensor Applications and their Impact

How important are sensors?

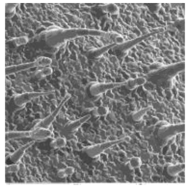
- What sensors did you use today?

Disruptive consequences of new sensors

Sensors and clocks are enabling system capabilities with large economic impact

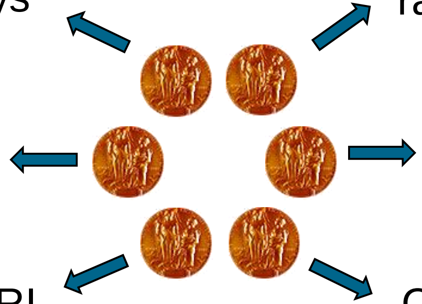
- Historic examples based on sensor-related Nobel Prizes

X-rays



Electron Microscope

MRI



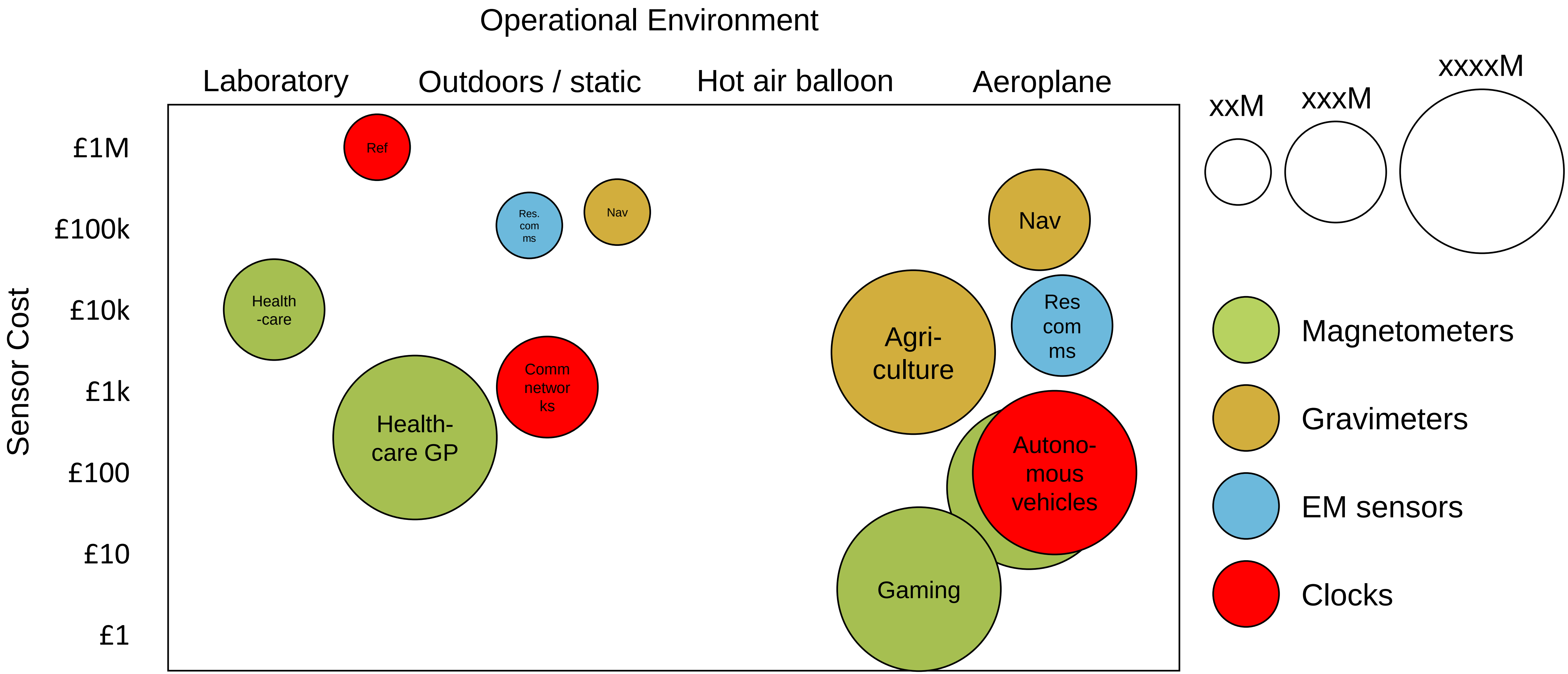
Aperture synthesis in radioastronomy → SAR Radar

Giant Magnetoresistance → Hard Drives

CCD

Potentially Accessible Quantum Sensor Markets

Key Drivers: Robustness and Cost



Magnetometers for Healthcare

Epilepsy: 60M people worldwide

Dementia: 1% GDP

Schizophrenia: 1% of population

Trauma: 100.000 / year in UK

What is "good enough"?

What are the barriers QT could overcome?
→ Adaptation to head size
→ Movement while measurement
→ System cost

Several commercial sensors available:
e.g. QuSpin with <15 fT/Hz$^{-1/2}$, 3-100Hz bandwidth
→ This allows 5-10 times SNR enhancement over SQUID-MEG
→ Good enough

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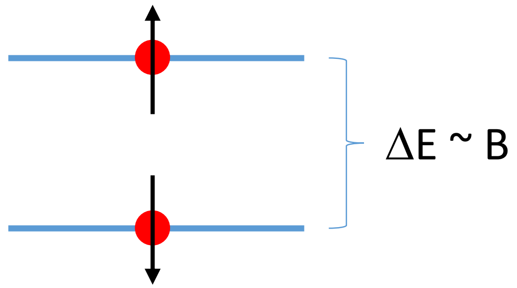
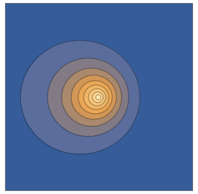
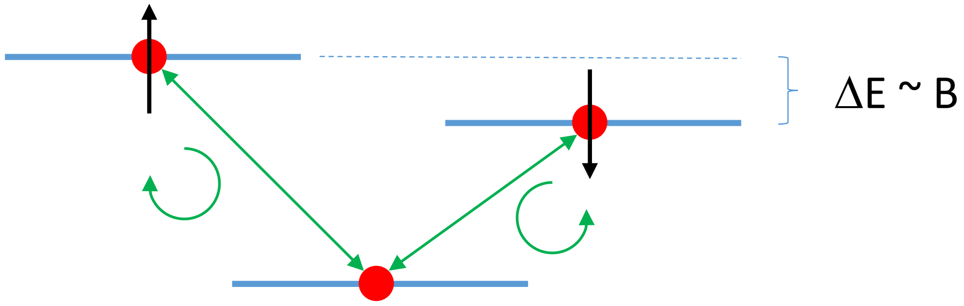
Quantum Magnetometers

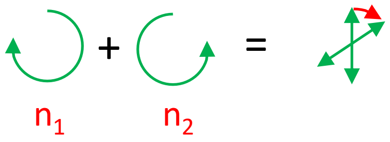
Superposition of energy levels depending on external magnetic field





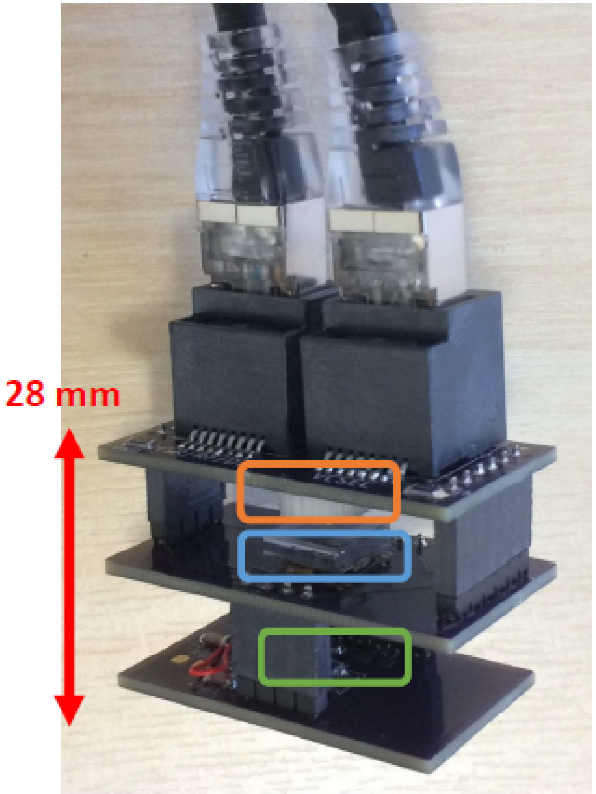
Oscillation frequency depends on magnetic field



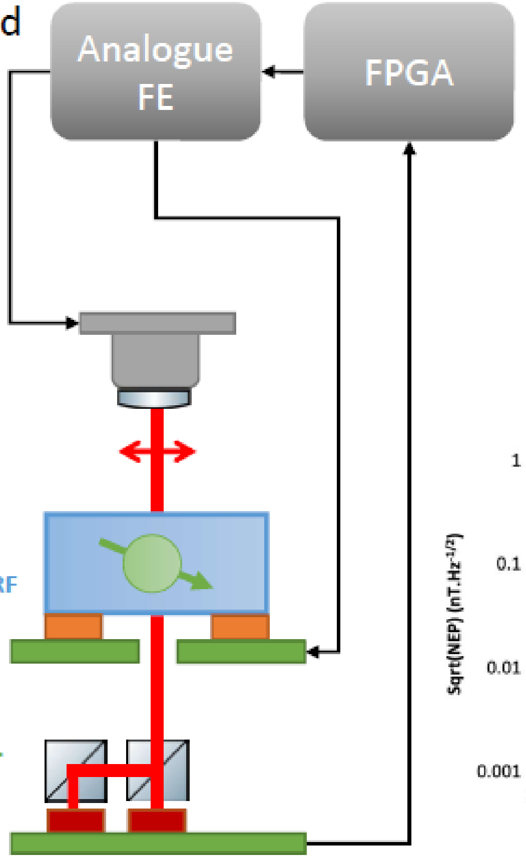


Rotation of polarization

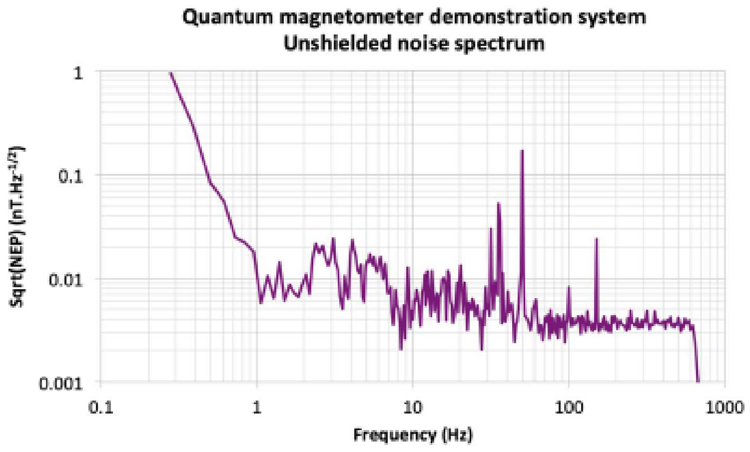
Miniaturisation of atomic magnetometers



- 75 cm^3 sensor head
- 60 g weight
- 5 W power



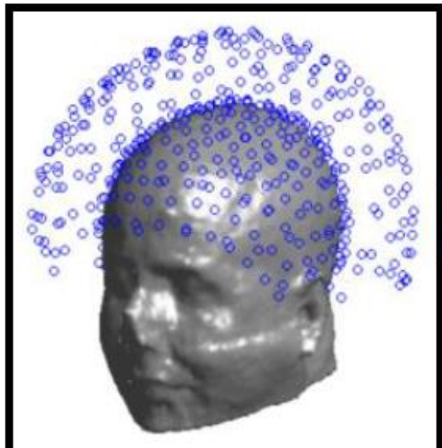
- High sensitivity
  - ~$pT.Hz^{-1/2}$
  - 0.1 ppm in Earth's field



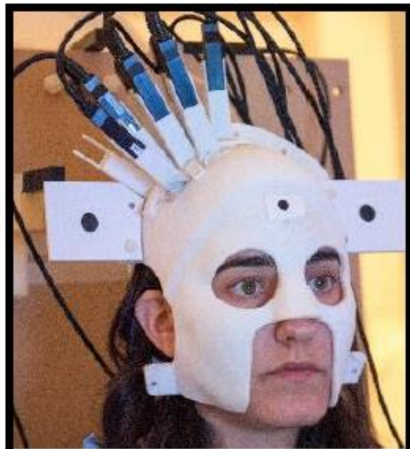
University of Nottingham
UK | CHINA | MALAYSIA

OPM-MEG development – 2015 – 2019 - Adaptation to Head Size


Conventional MEG


On scalp MEG simulations 2016


Single channel recording 2017


First wearable OPM array 2018


First paediatric helmet 2019


First VR-MEG recording 2019

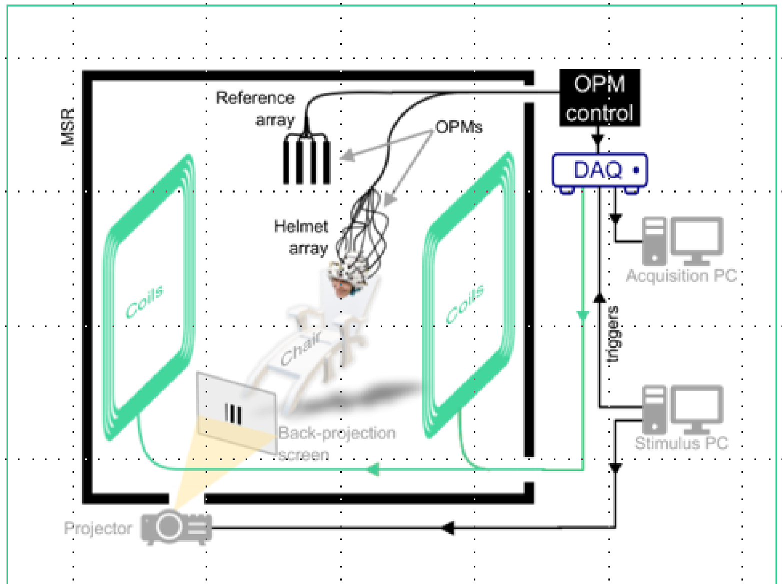

First Gen II OPM recordings 2019


First simultaneous OPM/EEG 2019


50 channel whole head system 2020

A new generation of quantum sensors have enabled 'wearable' brain imaging technology

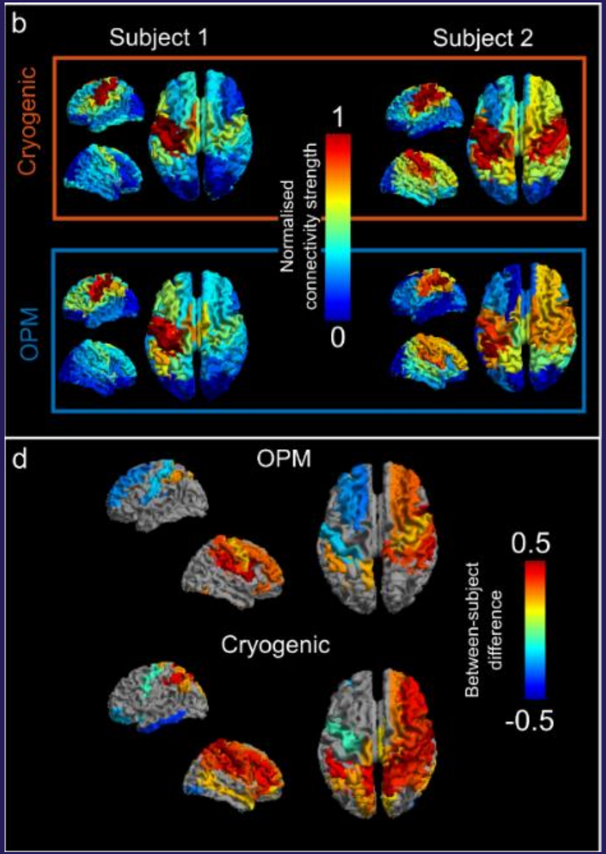
Its here NOW: Commercial Offering



Cerca's market offering:

- Integrate system components into one OPM-MEG system
- Test and validate system
- Single point of contact for customer
- Provide warranty for integrated system

Joint venture between University of Nottingham and Magnetic Shields Ltd.



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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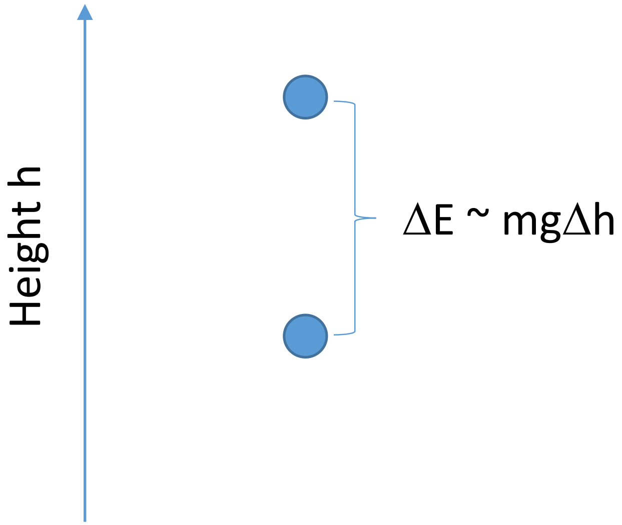
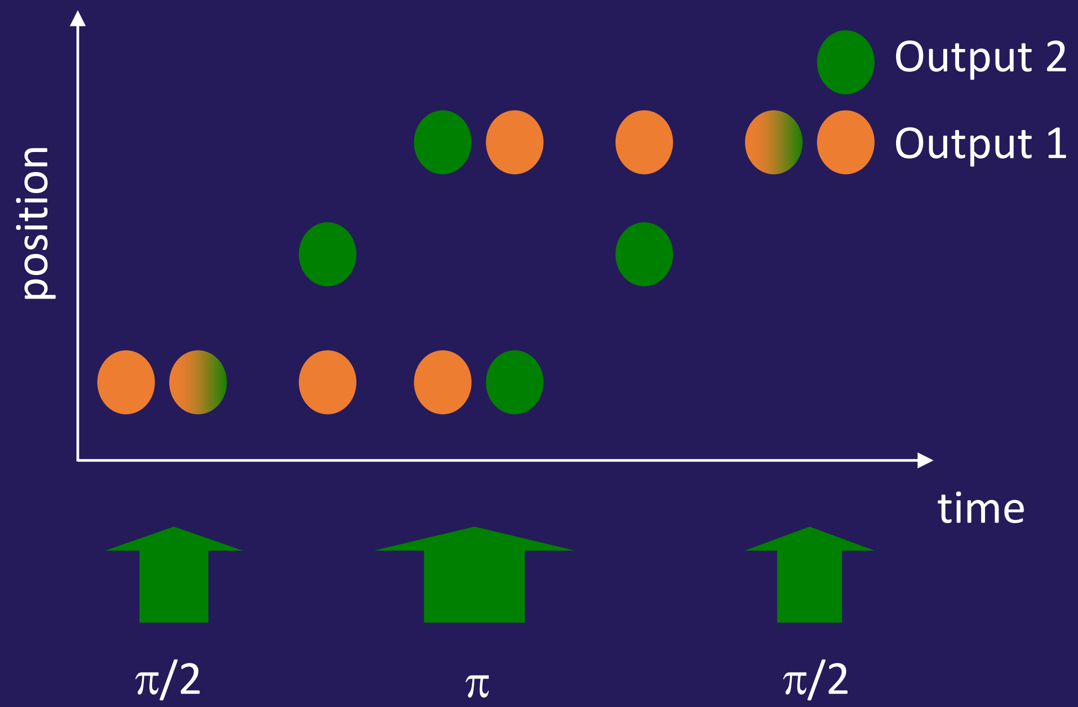
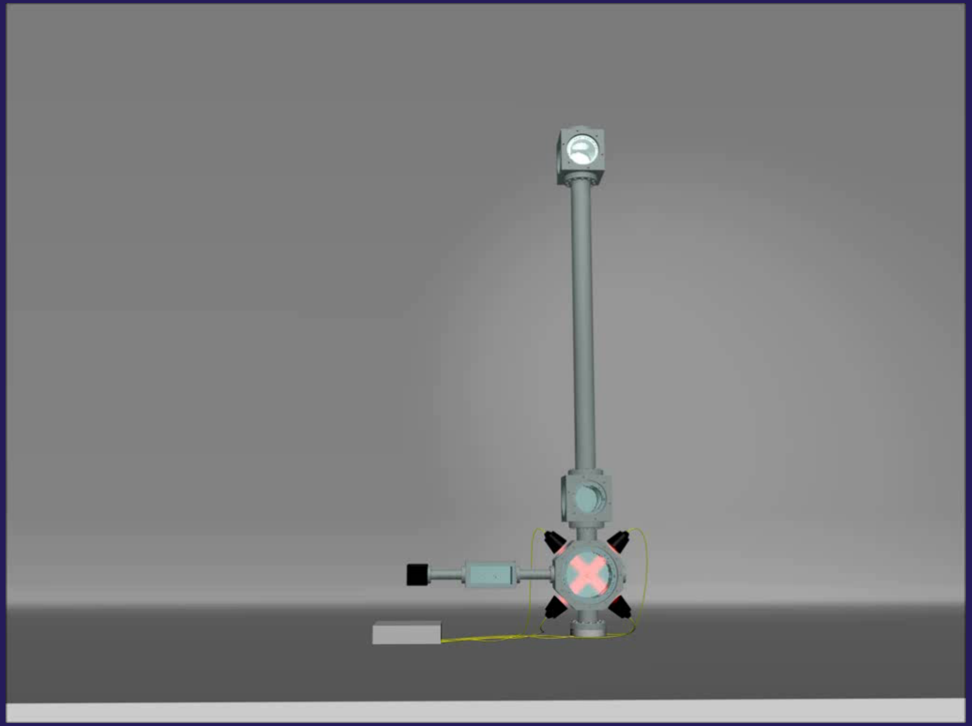
Quantum Gravimeters / Inertial Sensors

Potential difference leads to different phase evolution



Atom Interferometer





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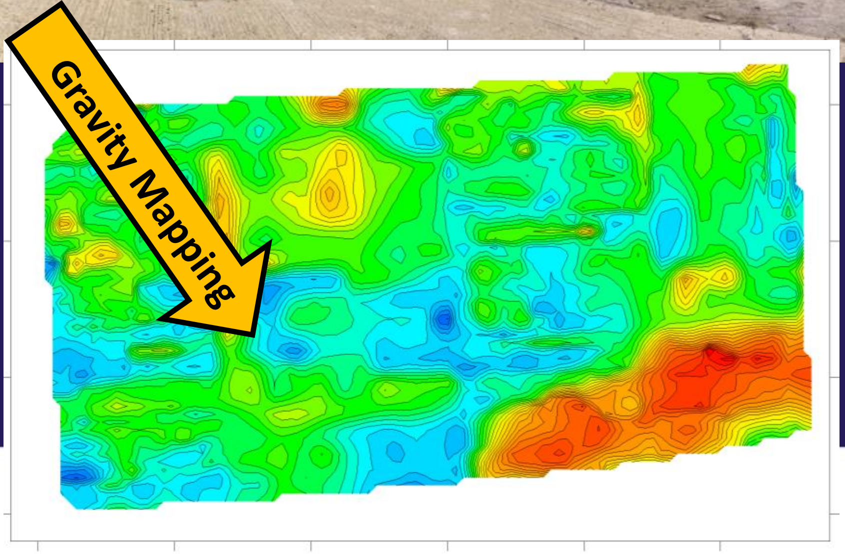
Microgravity Surveys and their Limitations

Example: Brown Field Site Survey



RSK

UNIVERSITY OF BIRMINGHAM

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

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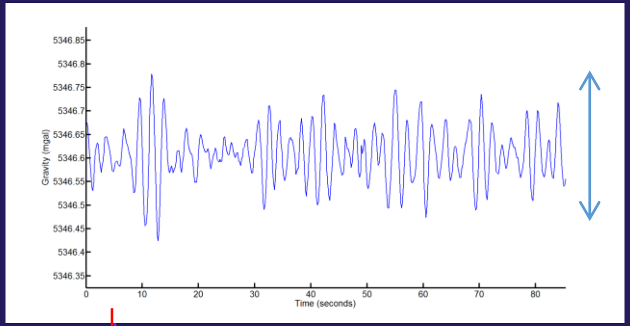
Why do Gravity Measurements take so much Time?

- Acceleration vs gravity

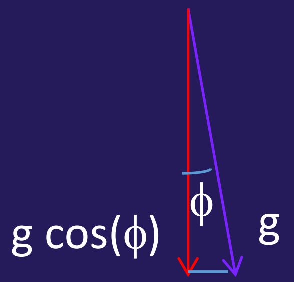


30-100 ng

Requirement to achieve 1 ng

Minutes / point

- Tilt



0.001° alignment

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

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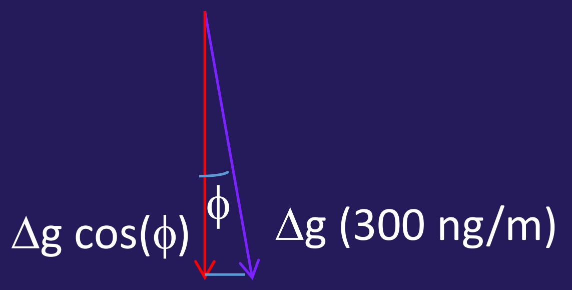
Solution: Gravity Gradiometry

Requirement to achieve 1 ng/m

- Suppression of Accelerations

As fast as your instrument
→1 s / point

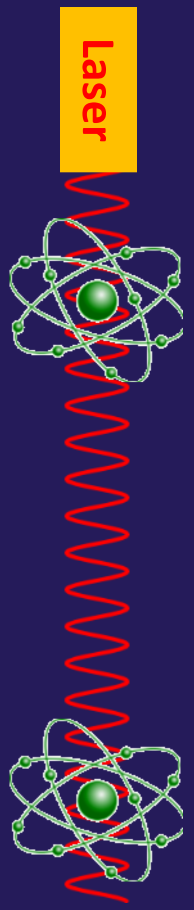
- Reduced Tilt Sensitivity



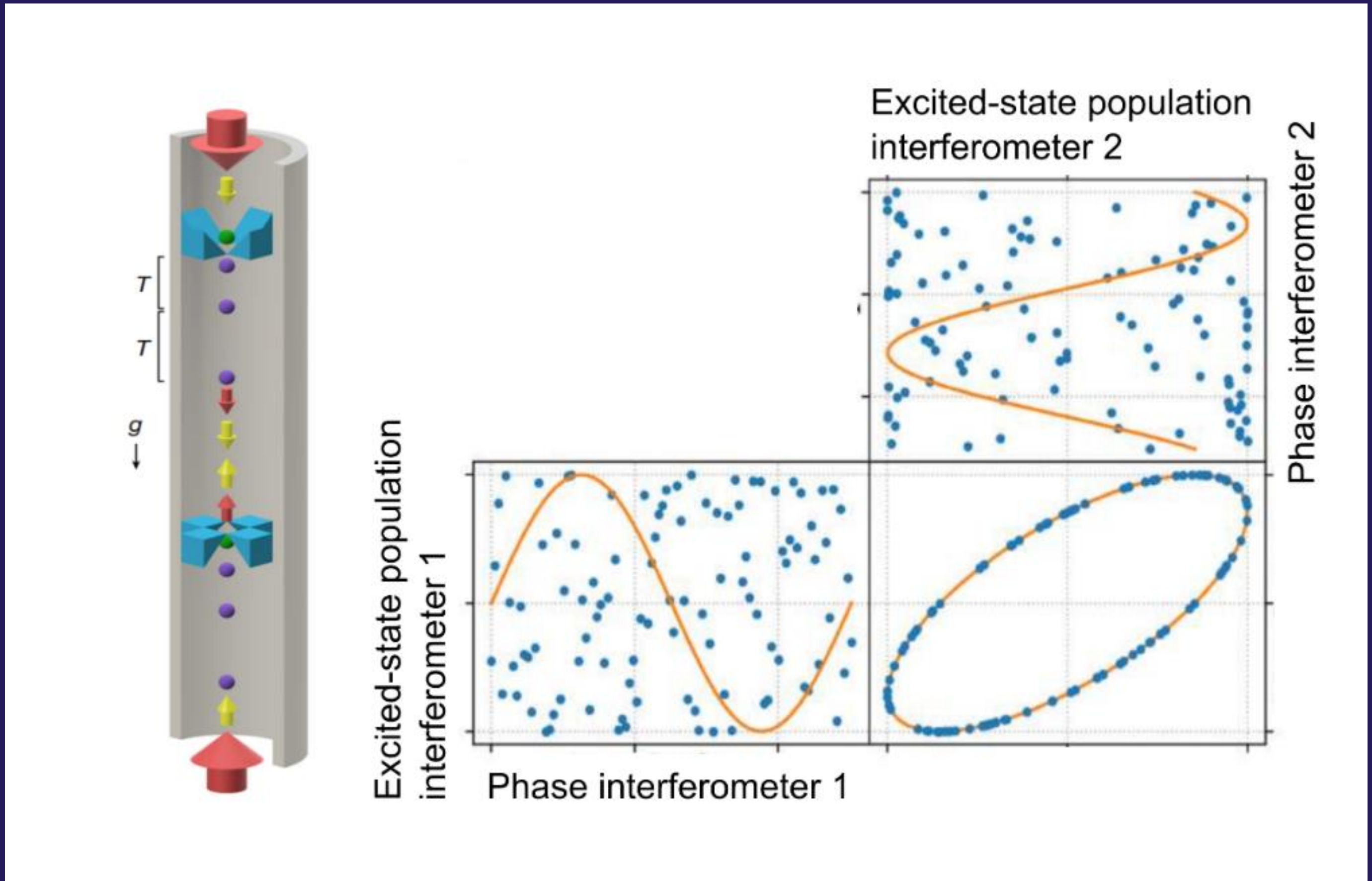
3^o alignment

Common laser beam

Near-Perfect acceleration suppression and alignment in Atom Interferometry



Solution: Gravity Gradiometry



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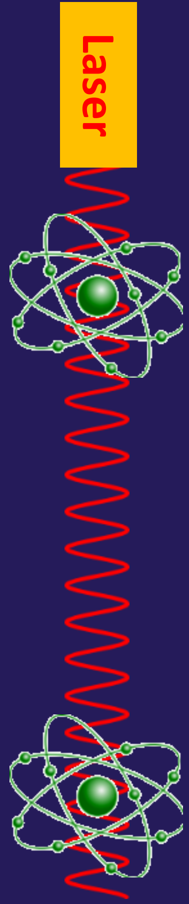

Nature **volume 602**, pages590–594 (2022)

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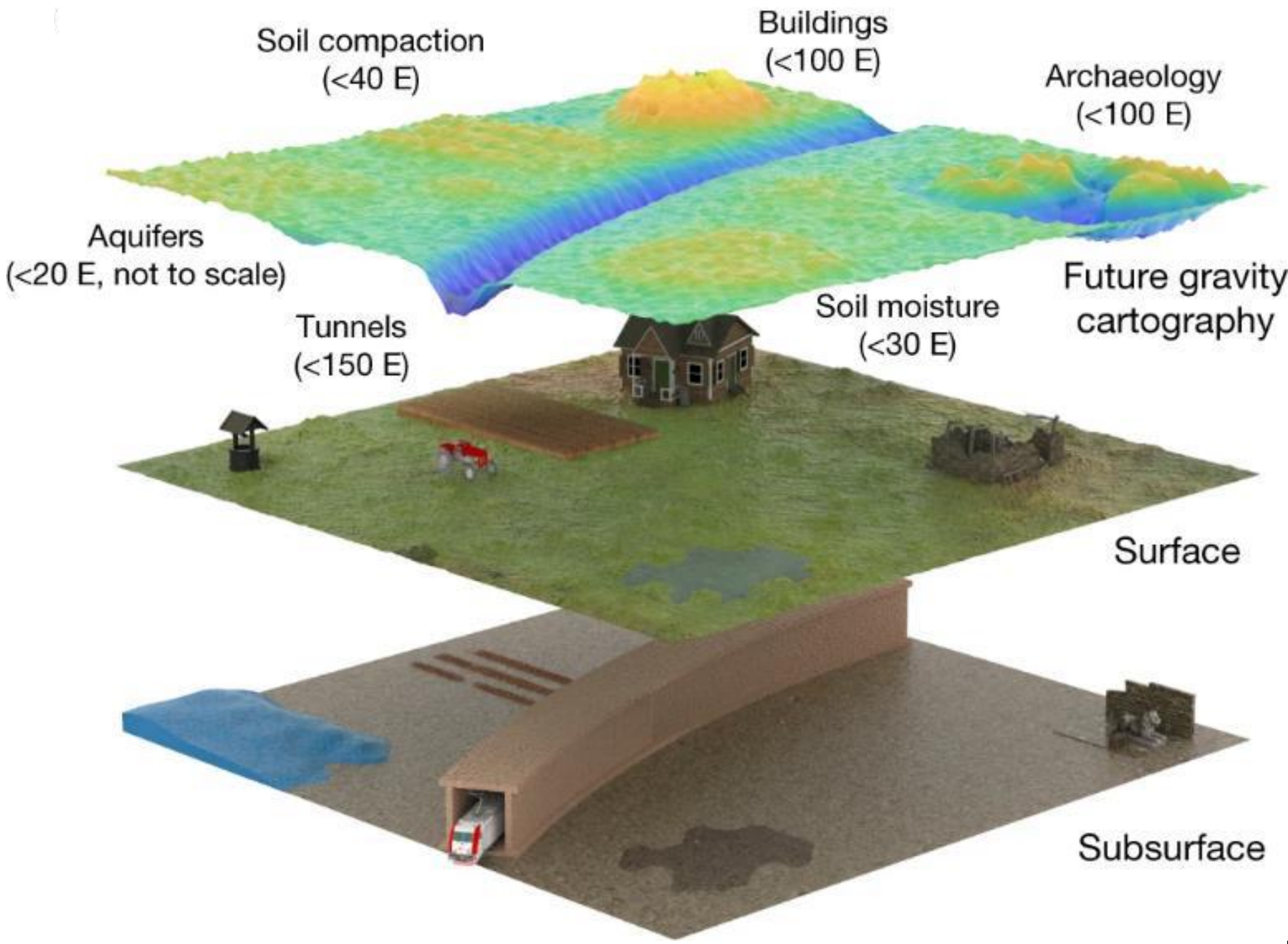
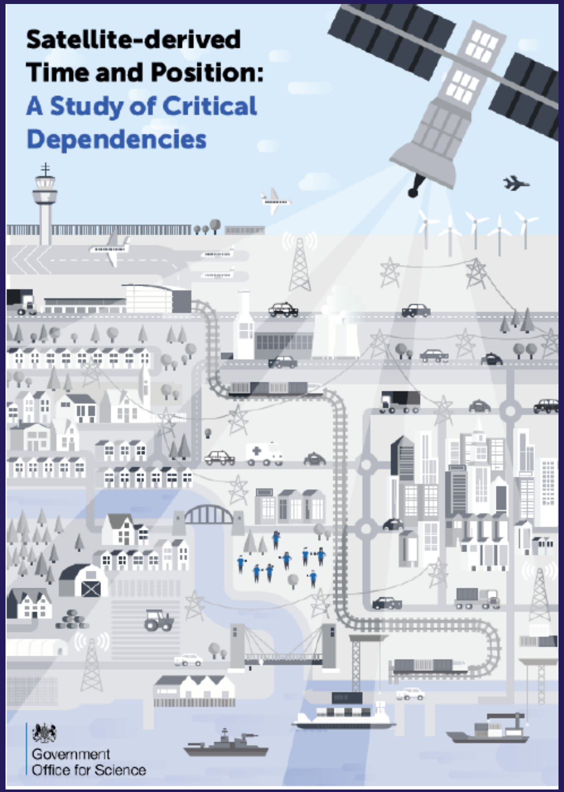
Enabling Gravity Cartography

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



Gravity Sensors for Navigation



~7% GDP

Motivation: GNSS Vulnerabilities

- Reduced precision in cluttered spaces
- Does not work indoors, underwater, or underground
- Can be easily jammed or spoofed

Collaboration: physics, materials science, electrical engineering, industry

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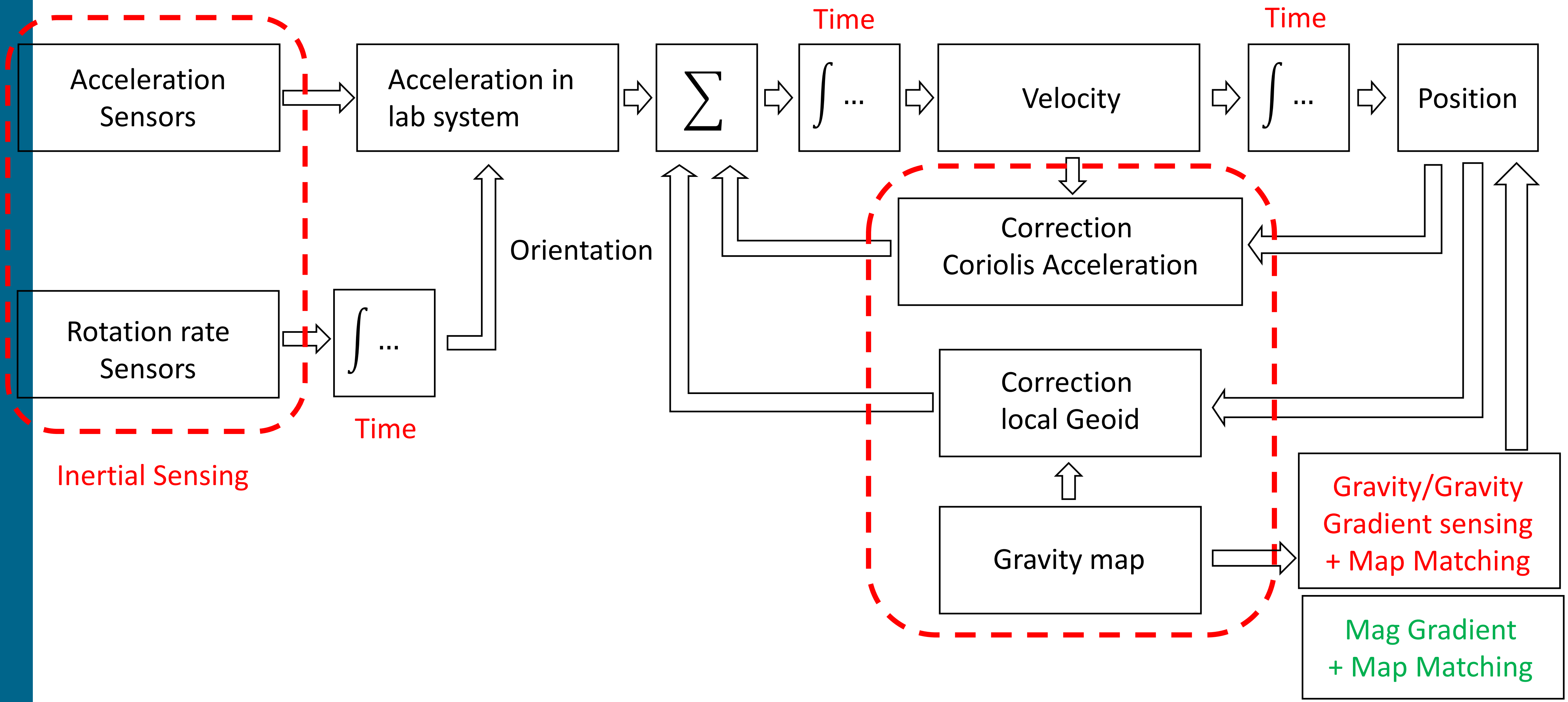
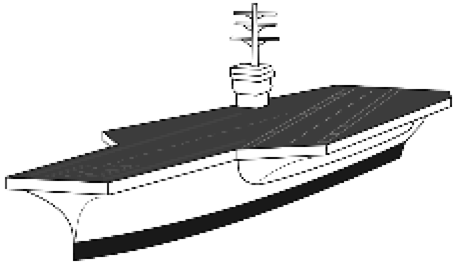
Schematic Setup of a Quantum Navigation System

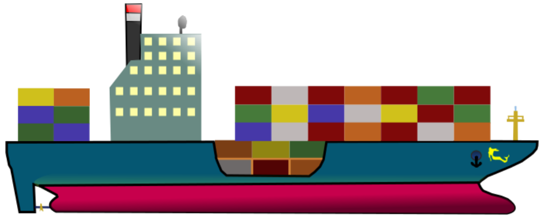


Market Roadmap for Quantum Navigation Systems

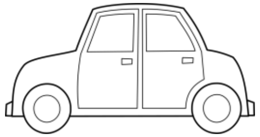
Cost and regulatory requirements as key drivers



Strategic platforms



Autonomous ships and underwater vehicles

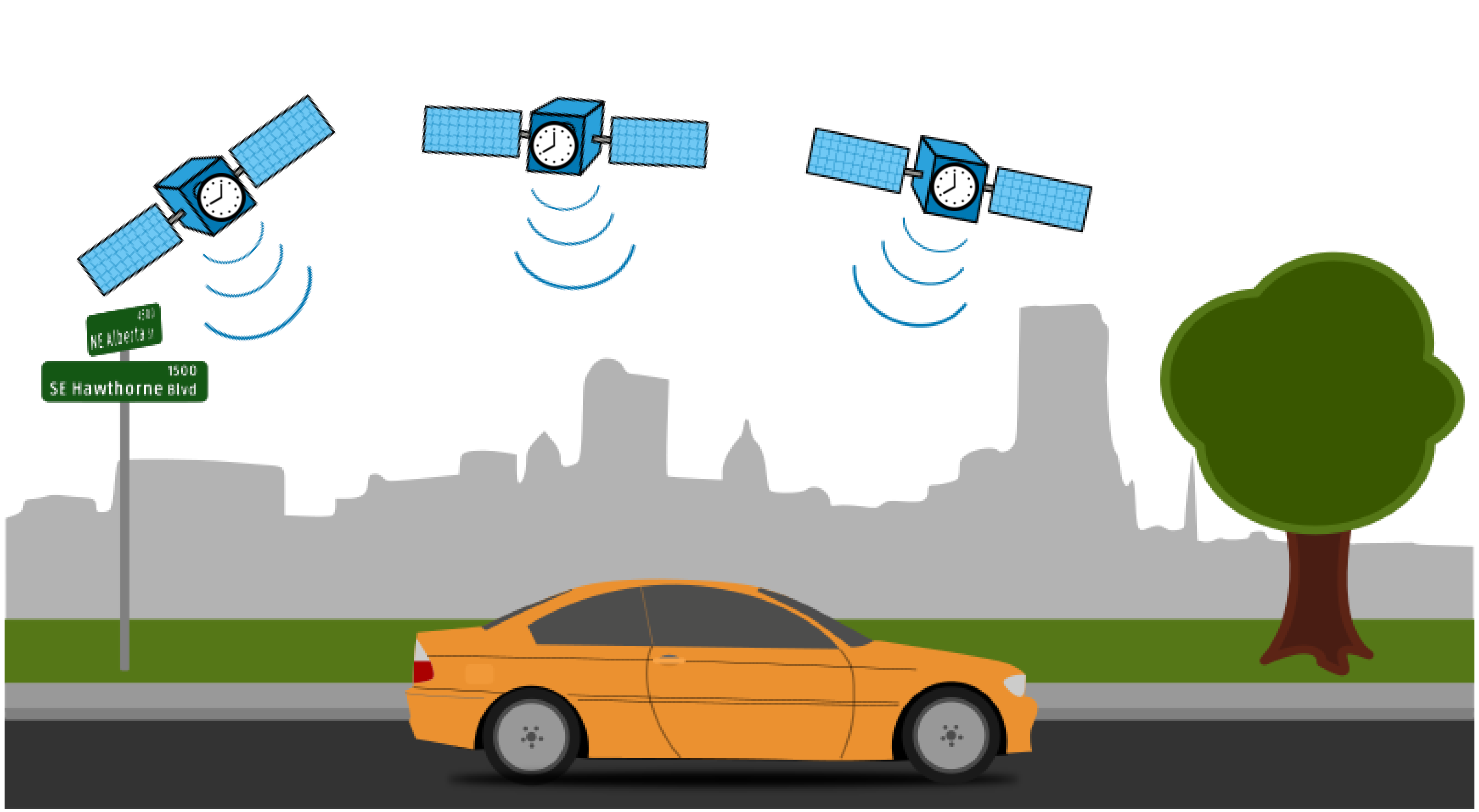


Autonomous vehicles

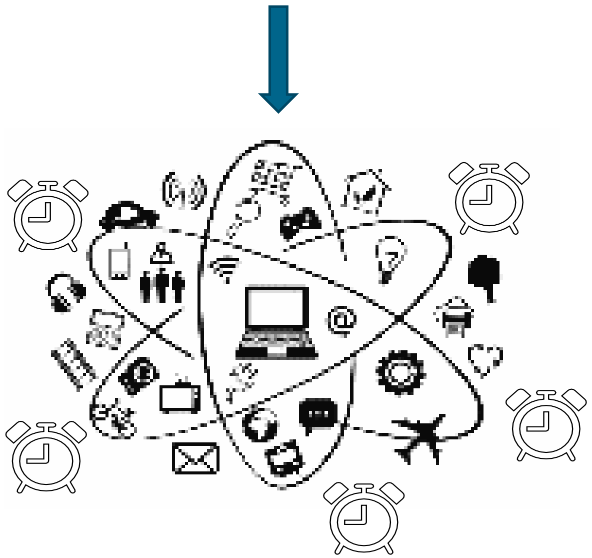
	2030	2040	2050
Unit cost	xM€	xxxk€	xxx€
Market volume	xxM€	xxxM€	xxxxxM€

Quantum 2.0 for Navigation and Time

Quantum clocks are powering current global satellite navigation systems



Navigation

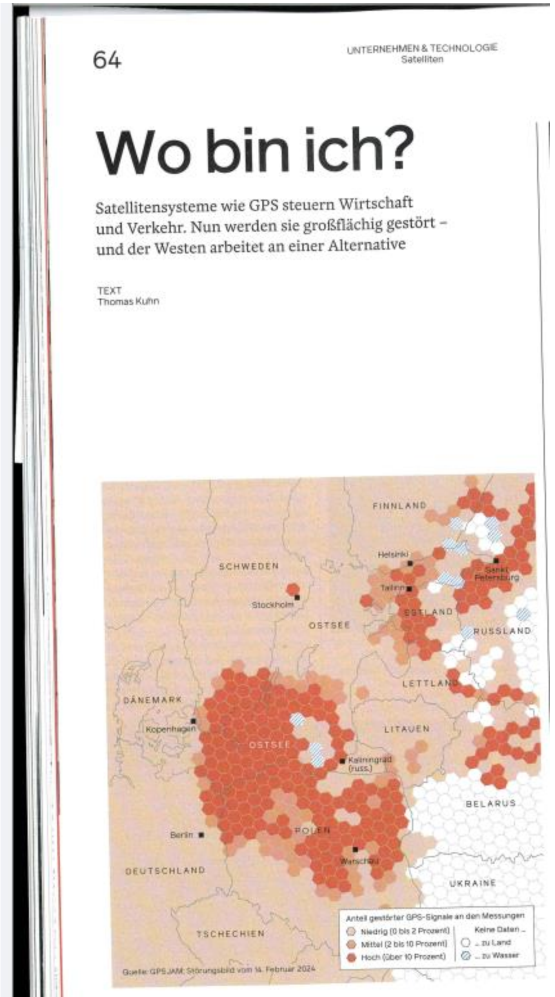


Synchronisation

Impact: 5-10% of GDP

GNSS critical dependencies

Need for independent alternatives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UNTERNEHMEN & TECHNOLOGIE
Satelliten

Wo bin ich?

Satellitensysteme wie GPS steuern Wirtschaft und Verkehr. Nun werden sie großflächig gestört – und der Westen arbeitet an einer Alternative

TEXT
Thomas Kuhn

Wirtschaftswoche 10, 2024


NATIONAL ARCHIVES

FEDERAL REGISTER

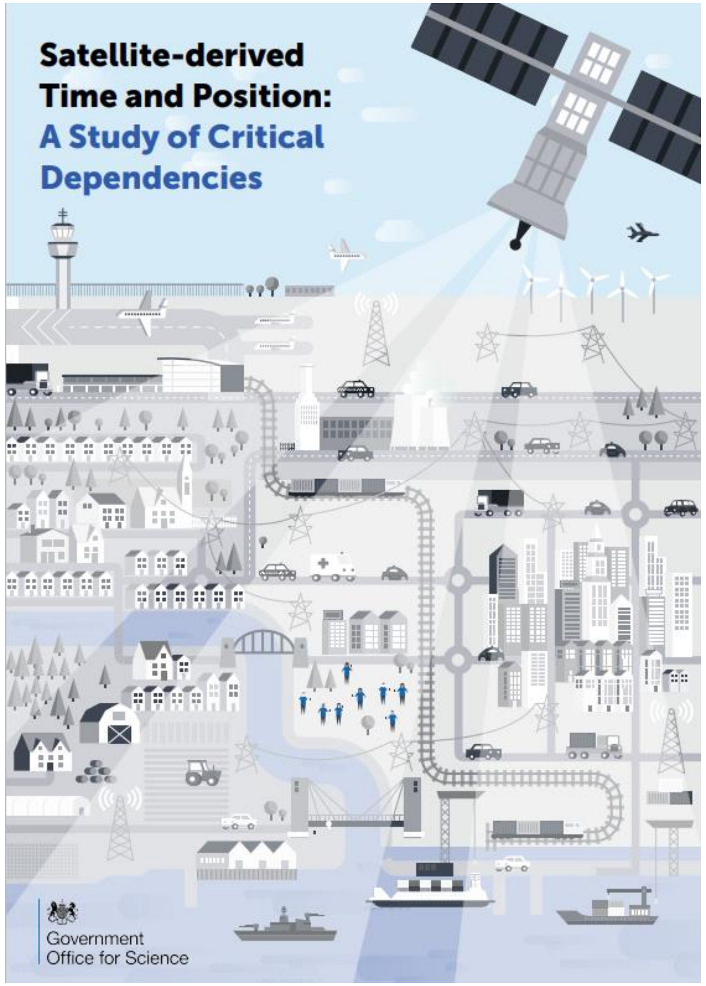
The Daily Journal of the United States Government

Presidential Document

Strengthening National Resilience Through Responsible Use of Positioning, Navigation, and Timing Services

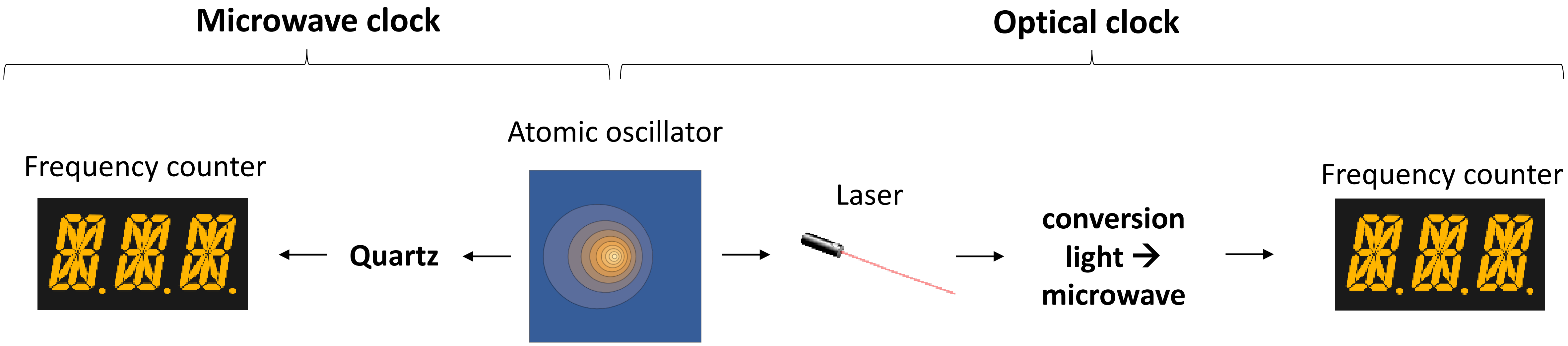
A Presidential Document by the Executive Office of the President on 02/18/2020

UK Blackett Report 2018



Microwave clocks (old) and optical clocks (new)

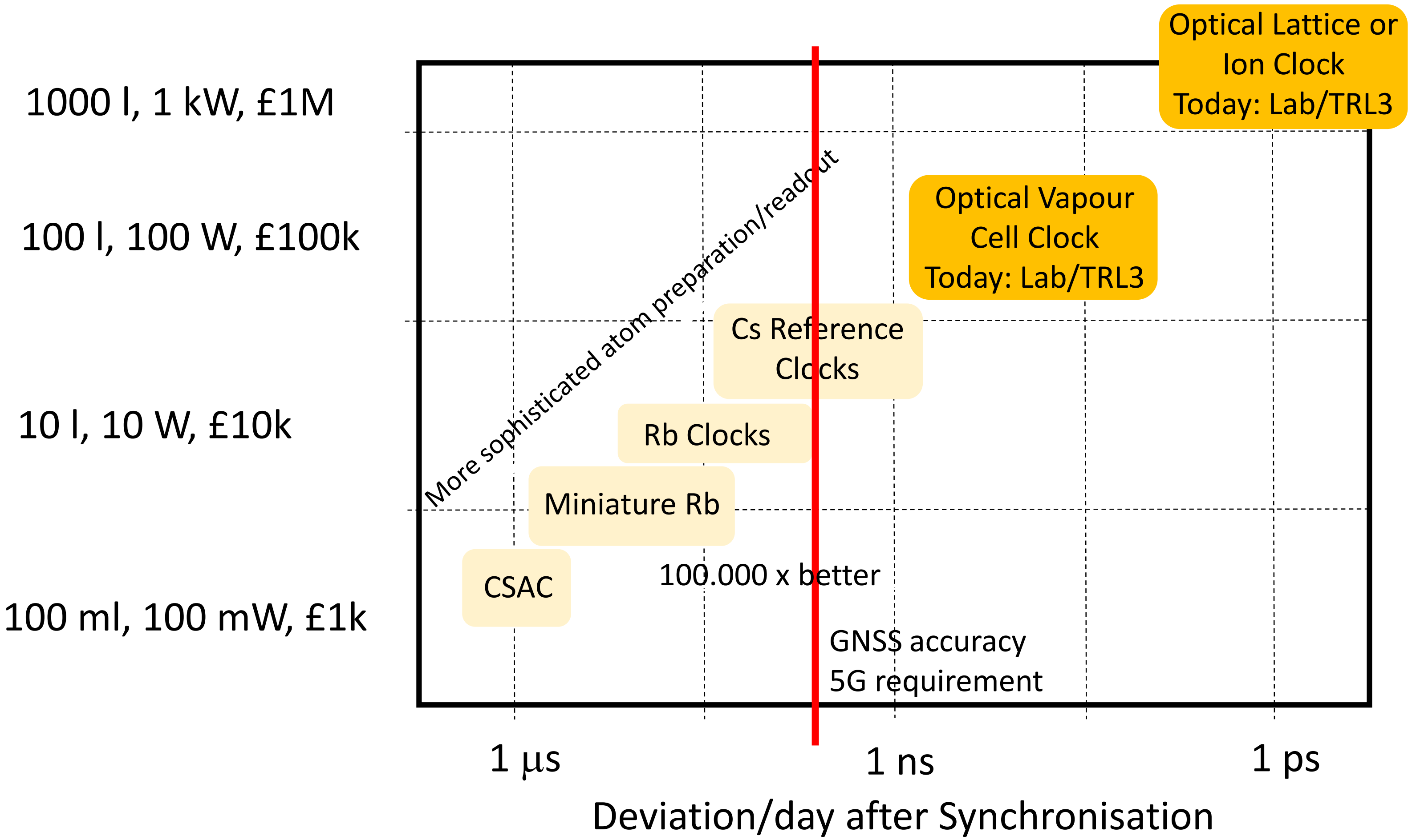
Optical clocks allow higher precision and faster synchronization



Disruptive: 100x better synchronisation as compared to GNSS
Lower phase noise than Quartz-oscillators

Why are Optical Clocks Disruptive?

So far: “linear” relationship between SWAP-C and stability



Why are Optical Clocks Disruptive?

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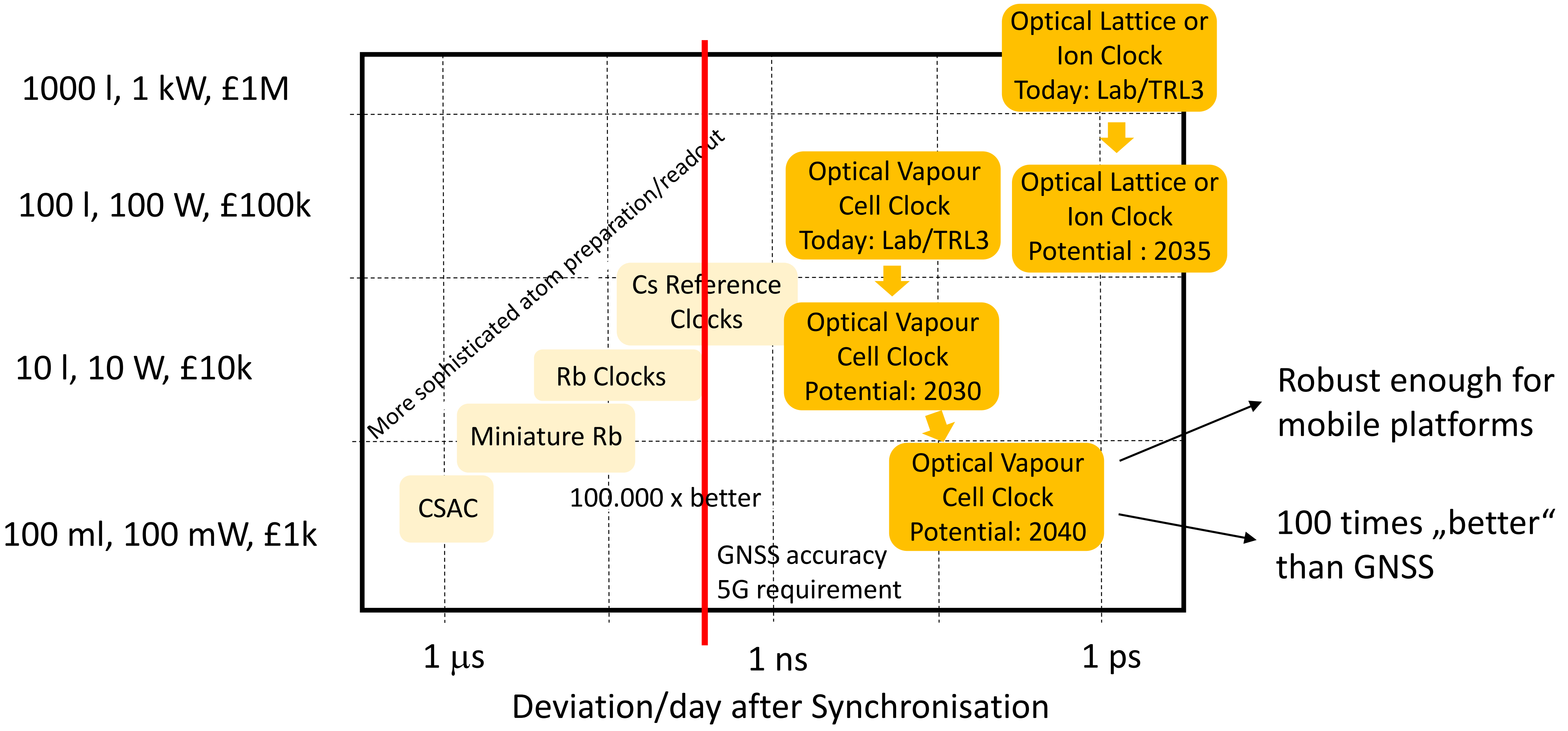


DLR-QT Optical Clock Technology

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

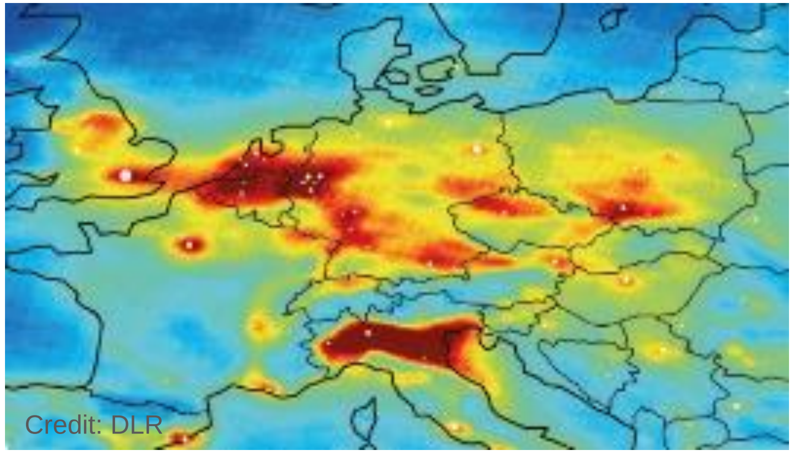
		Galileo RAFS	Galileo PHM	Ca beam	I_2 MTS	Rb MTS	Rb TPT	Sr Lattice clock	Ca single ion clock
	References	Orolia datasheet (2016)	Leonardo datasheet (2017)	Shang et al. (2017)	Schuldt et al. (2017); Döringshoff et al. (2019)	Zhang et al. (2017)	Martin et al. (2018)	Bongs et al. (2015); Origlia et al. (2018)	(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^{-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

Commercial Opportunities through Quantum Clocks

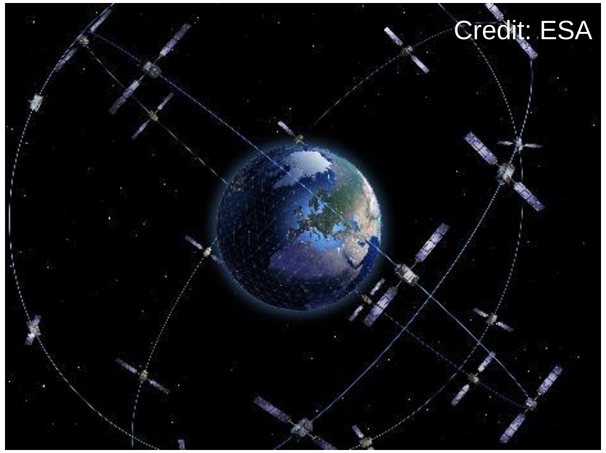
Communication

3D Radar

Urban Flight



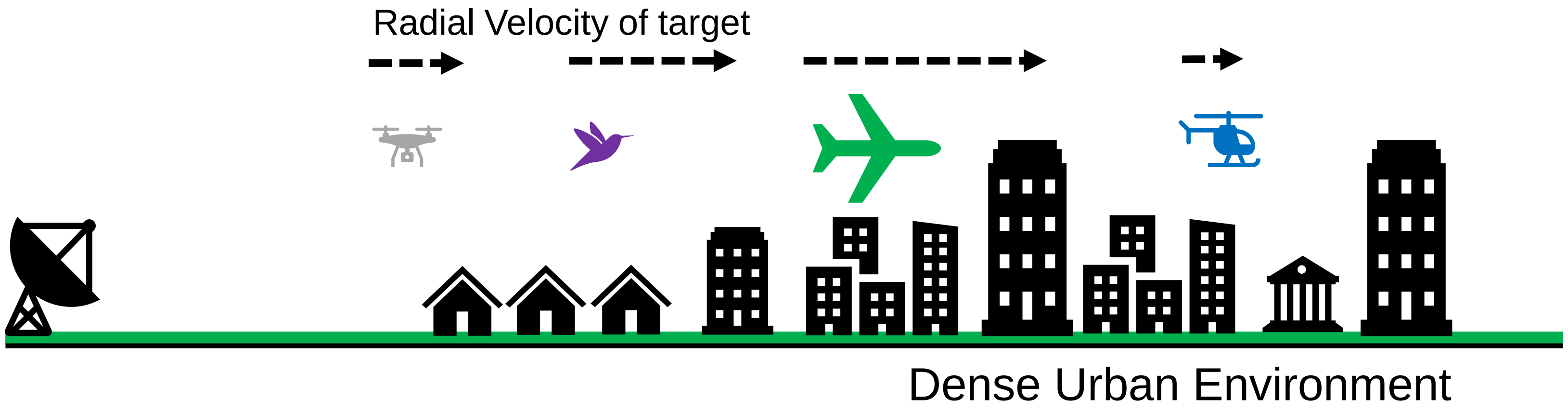
Global Height Reference

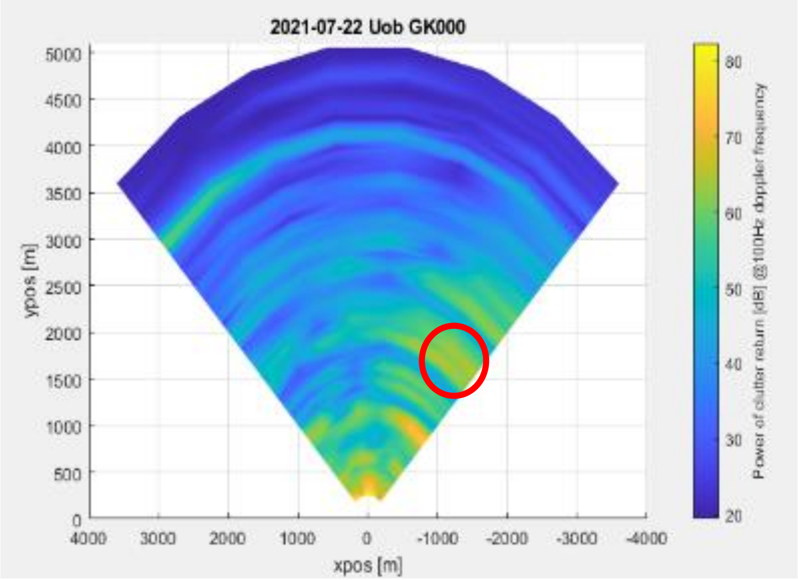


Satellite Navigation

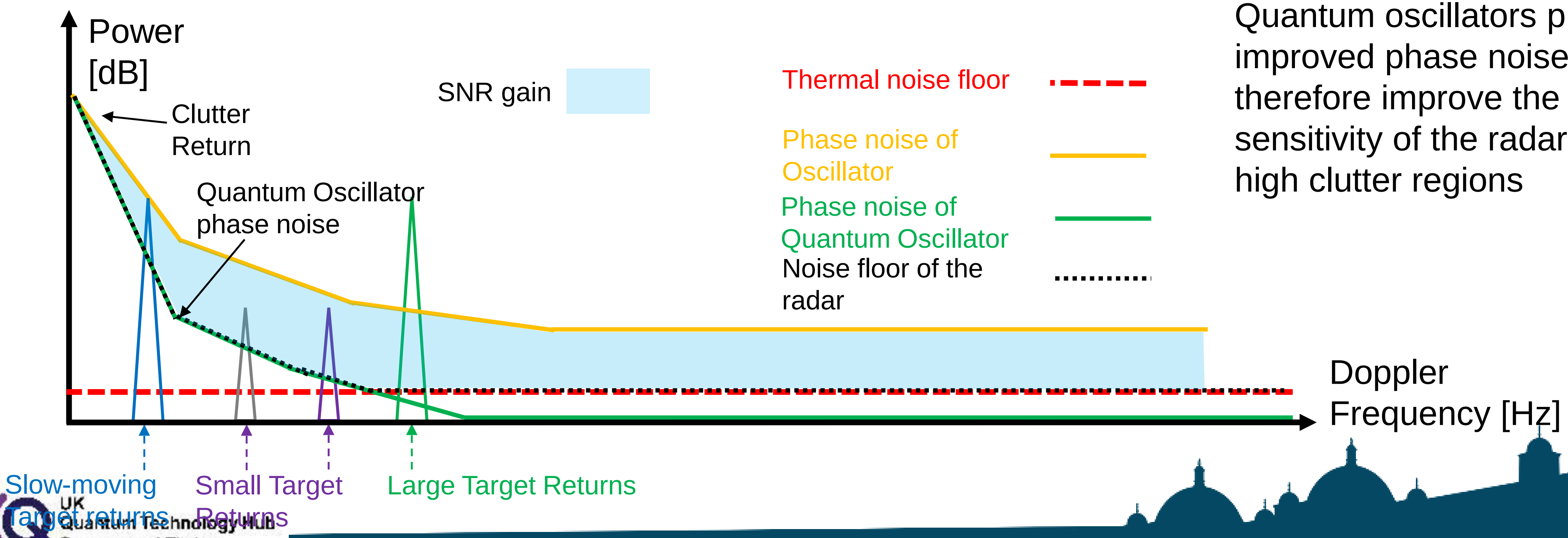
Autonomous Vehicles

Noise limitations in radar



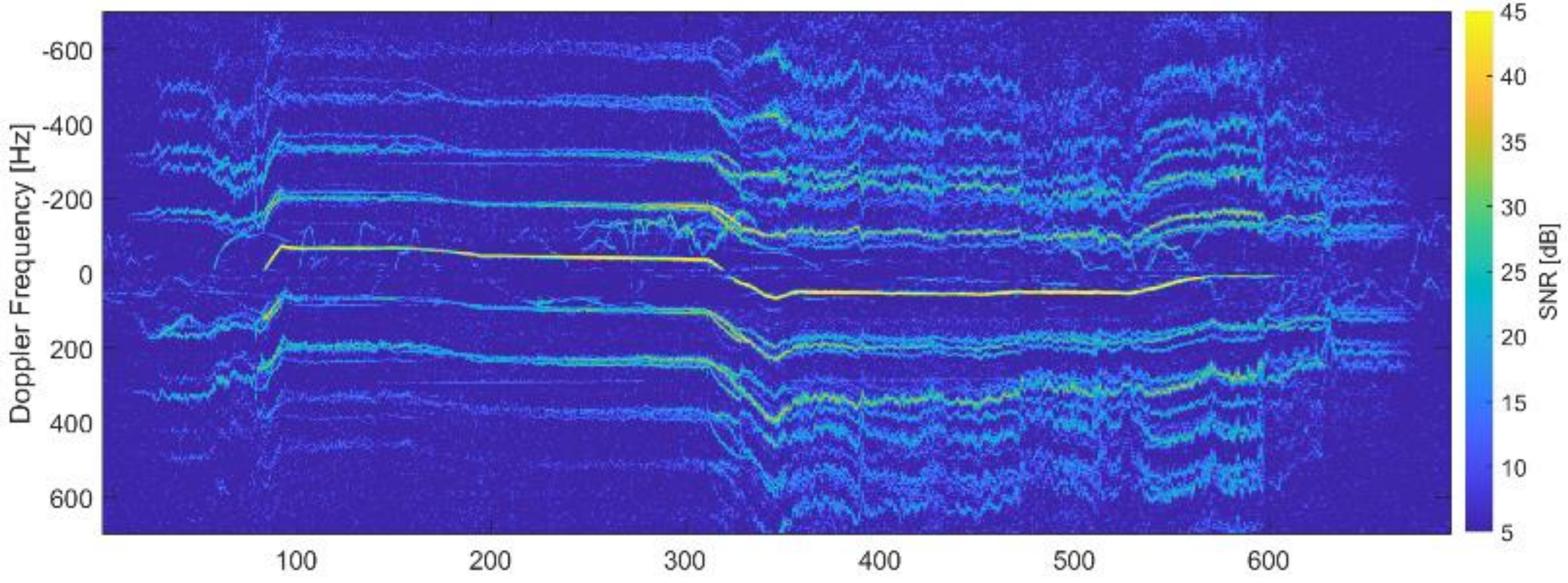


Quantum oscillators provide improved phase noise and therefore improve the sensitivity of the radar in high clutter regions

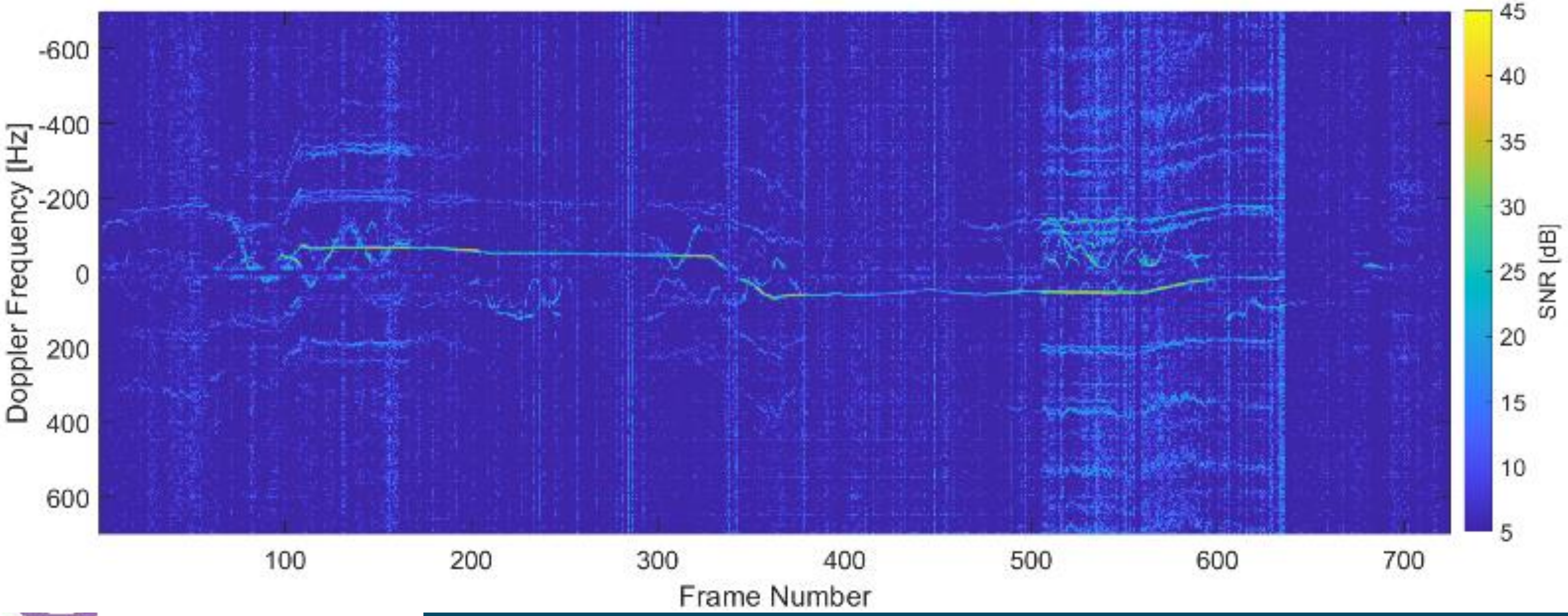


UK Quantum Technology Hub Sensors and Timing

Better oscillator: more features



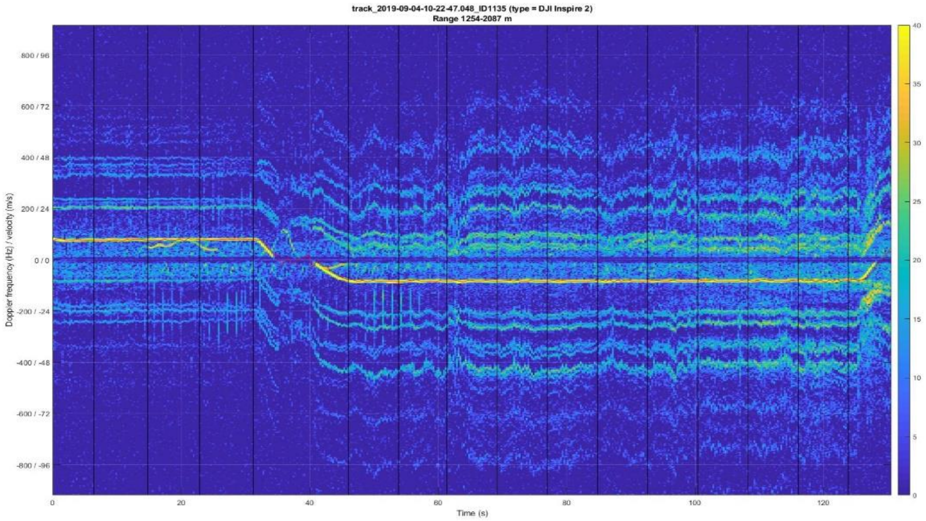
GK007
Monostatic
(Better oscillator)

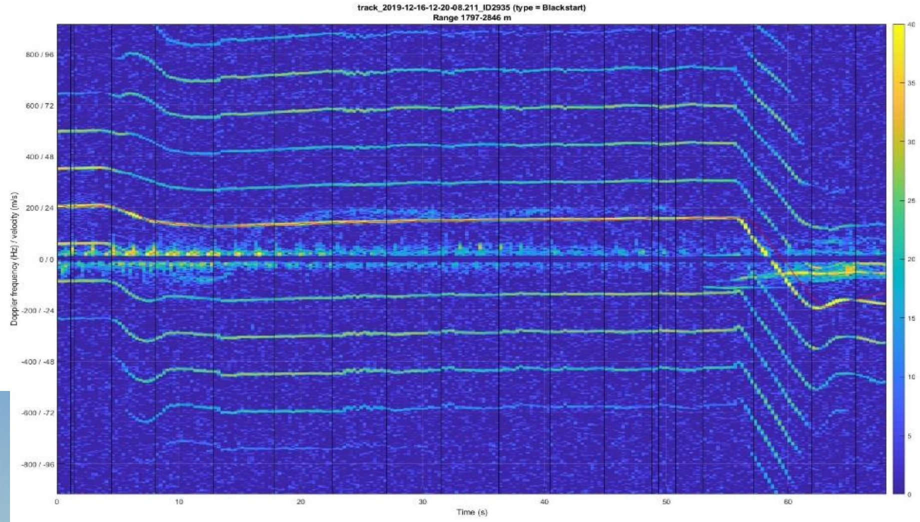


GK000
Monostatic

Discrimination via Micro-Doppler

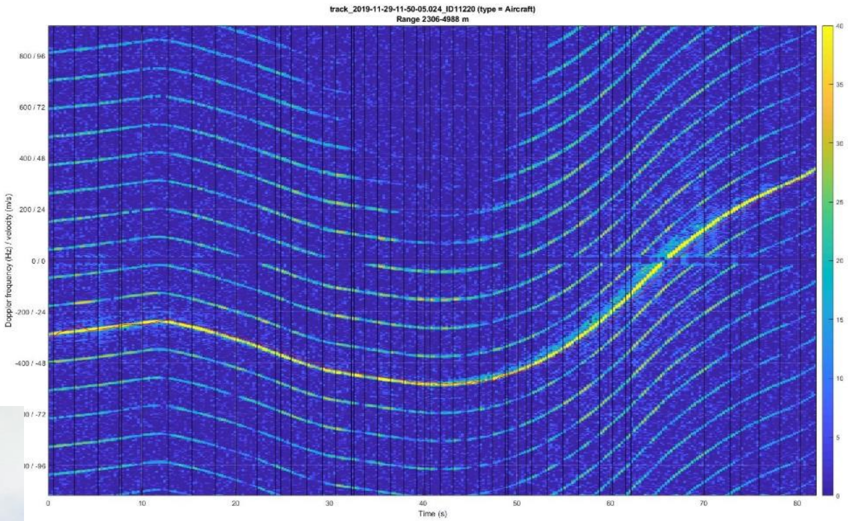
Rotary wing vs Fixed Wing

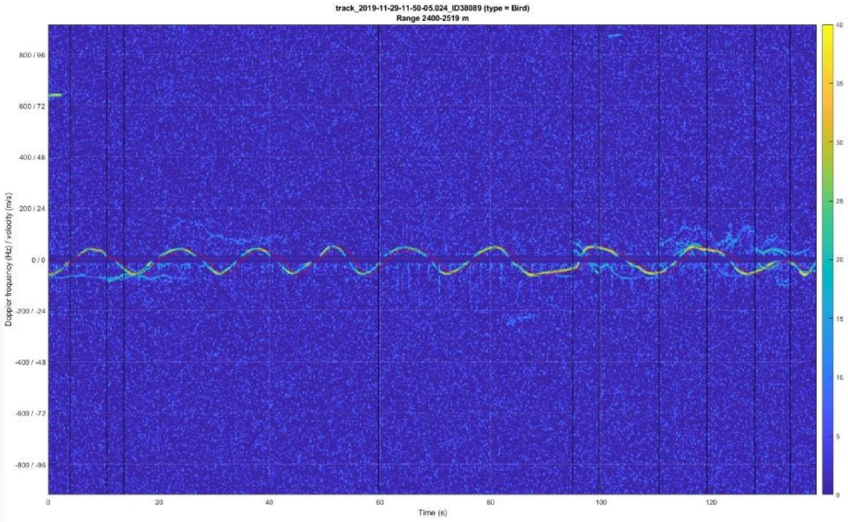




Discrimination via Micro-Doppler

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

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TECHNOLOGIES
PROGRAMME

Thank you for your attention

Questions?