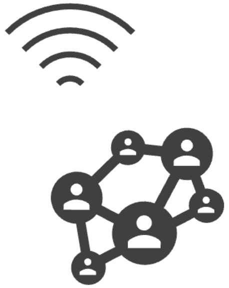
Q.Navigation Systems

- Constructing an Unjammable Navigation System -

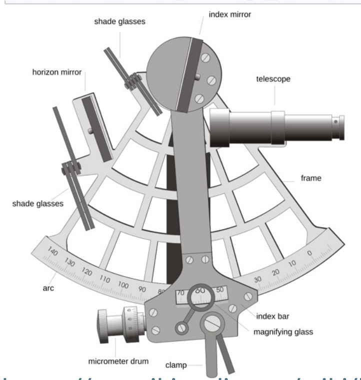
Adrian Huber

Intro Navigation Systems

https://en.wikipedia.org/wiki/File:GPS_Block_IIIA.jpg

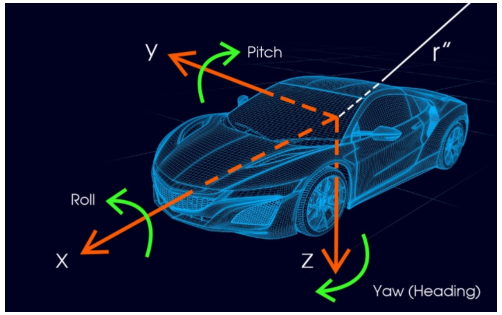


Global Positioning System (GPS)

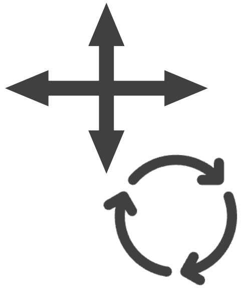


https://en.wikipedia.org/wiki/File:Marine_sextant.svg

Celestial Navigation



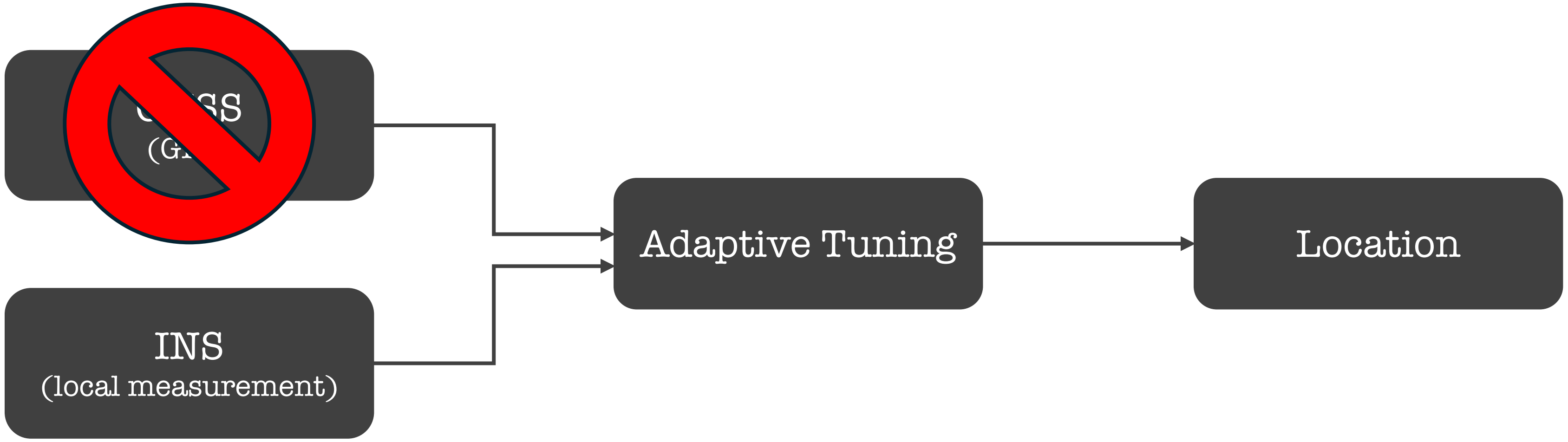
https://www.iconcox.com/news/facts-you-may-not-know-about-inertial-navigation-systems.html



Inertial Navigation Systems (INS)

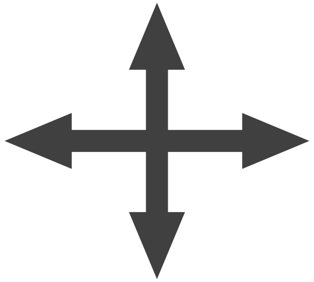
Intro Navigation Systems

GNSS-INS Architecture

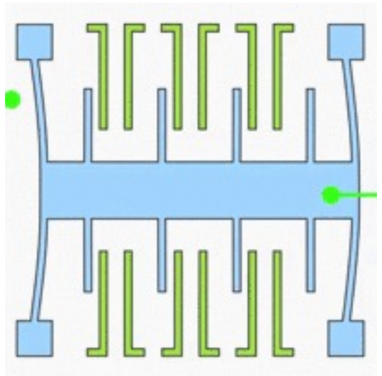


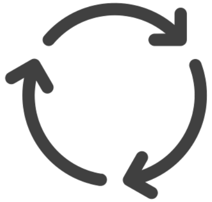
only system left! → has to work correctly!

INS Core Components



Accelerometers
(Translation)

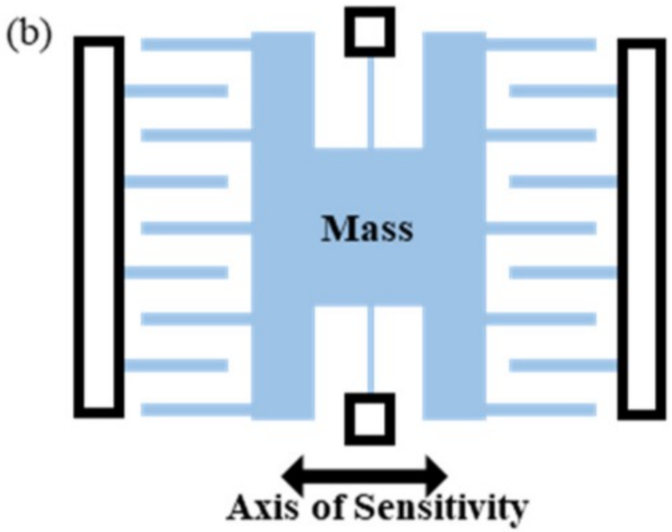




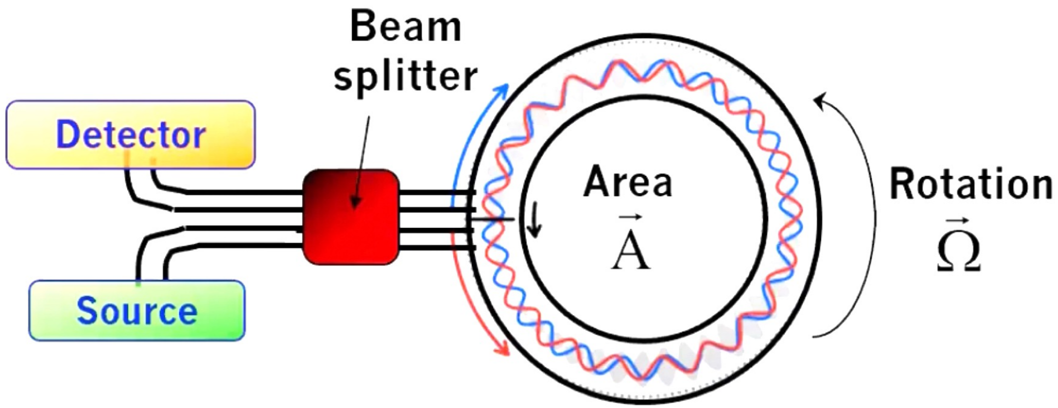
Gyroscopes
(Rotation)

Classical Implementations

some Examples:



(MEMS) Capacitive Accelerometer



(Optical) Gyroscopes using Sagnac Effect

Quality Comparison

<table>
<tr><th>Technology</th><th>Bias Stability (Accel)</th><th>Bias Stability (Gyro)</th></tr>
<tr><td>Mechanical (Servo Pendulum)</td><td>> µg</td><td>-</td></tr>
<tr><td>Optical Interferometric</td><td>~1 µg</td><td>~0.001–0.01 °/h</td></tr>
<tr><td>MEMS (Consumer)</td><td>100s of µg</td><td rowspan="2">~1–1000 °/h</td></tr>
<tr><td>MEMS (Tactical)</td><td>~50 µg</td></tr>
<tr><td>Hemispherical Resonator (HRG)</td><td>-</td><td>~0.001–0.01 °/h</td></tr>
<tr><td>Quantum - Cold-Atom</td><td>~0.07 µg (after 2 days!)</td><td>~0.0002 °/h</td></tr>
<tr><td>Quantum - Nuclear Magnetic Resonance (NMRG)</td><td>-</td><td>~0.02 °/h</td></tr>
</table>

Experiments showed up to 100x improvement

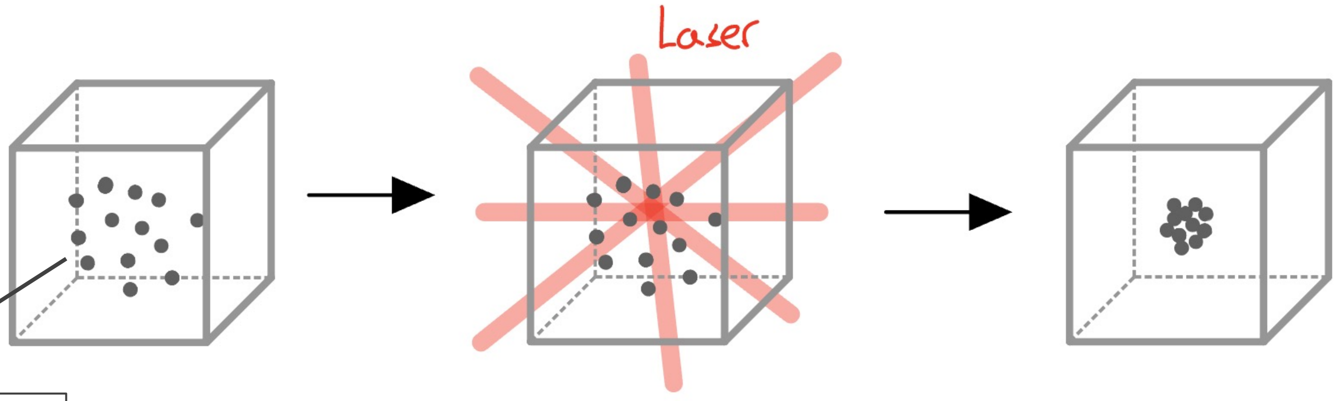
→Quantum Solutions seem promising!!!

→How do they work?

Cold-Atom Interferometry

Principle showed on a free-fall architecture

Cooling needed



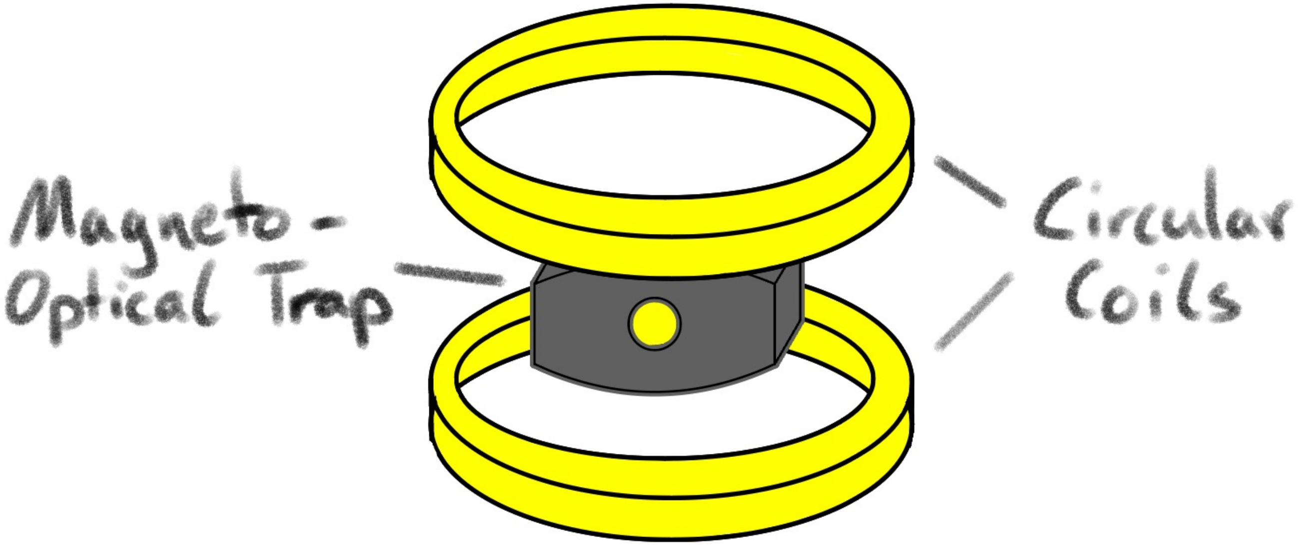
Typically Rubidium-87 or Cesium-133

Cooling near absolute zero
→ de-Broglie wavelength becomes signifficant!

Cold-Atom Interferometry

Principle showed on a free-fall architecture

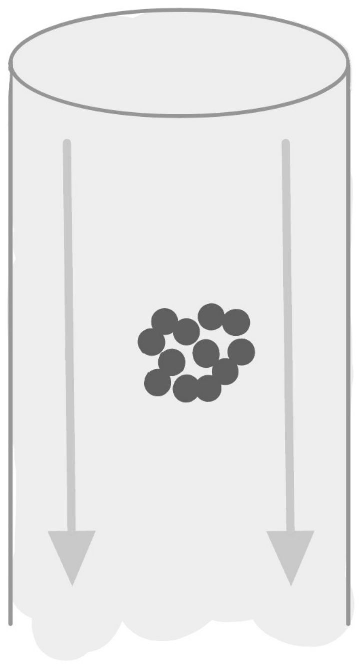
Atoms are held in magneto-optical trap



Cold-Atom Interferometry

Principle showed on a free-fall architecture

1. Step: Atoms enter free fall

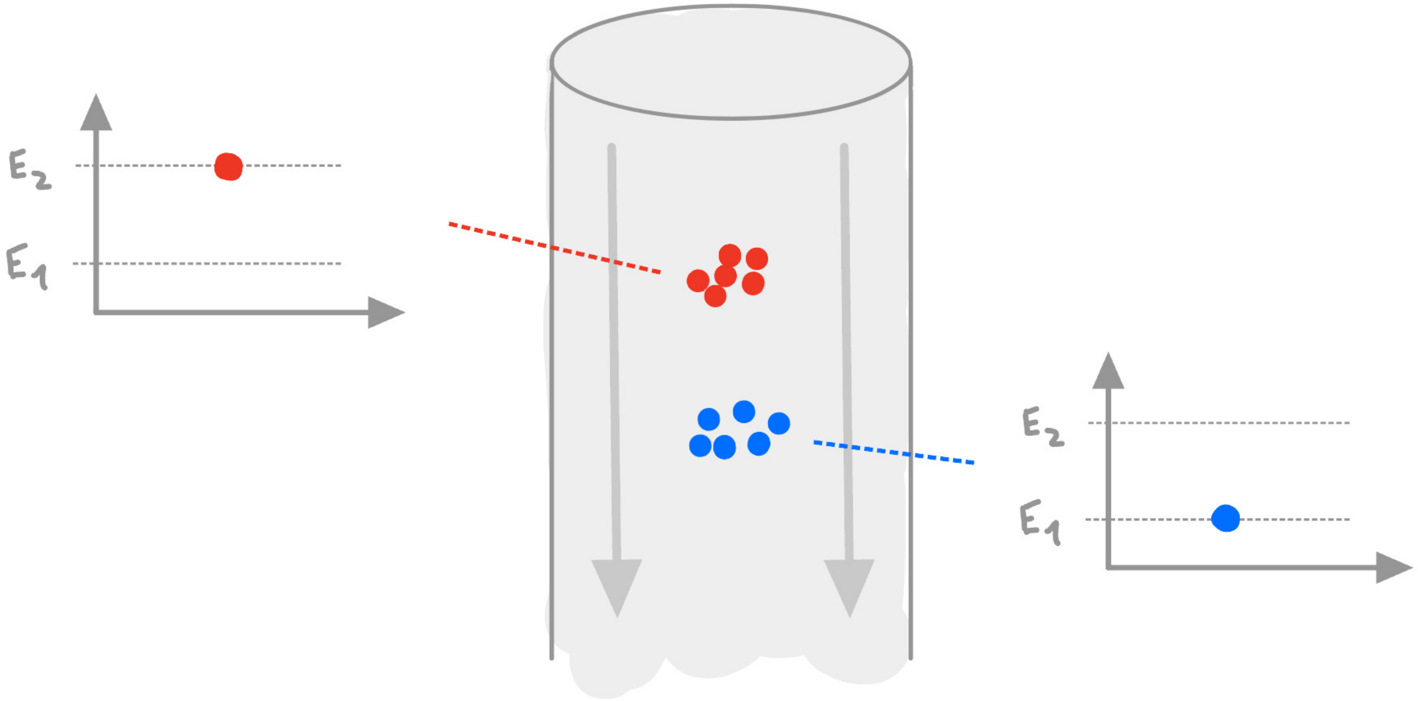


→ Free from external forces, except for gravity + intertial effects

Cold-Atom Interferometry

Principle showed on a free-fall architecture

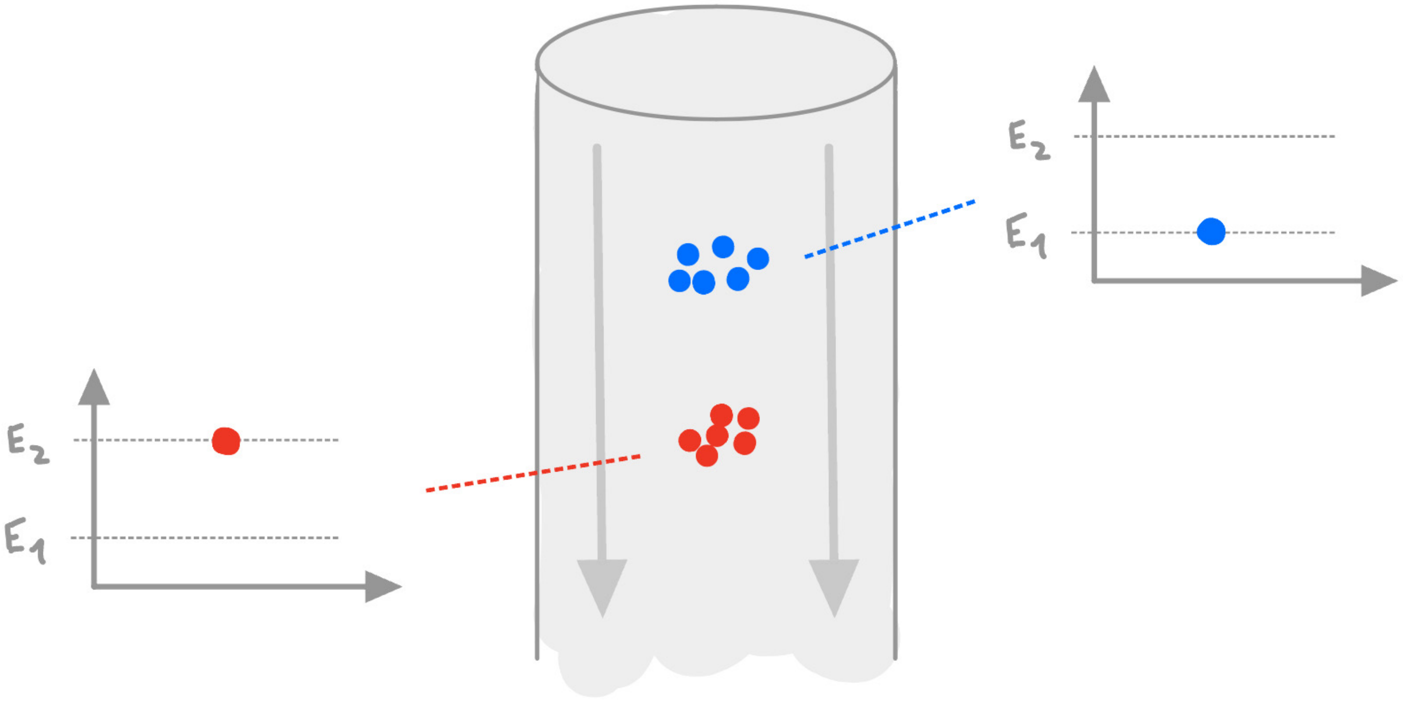
2. Step: First Pulse (π/2 - ”Beam Splitter”)

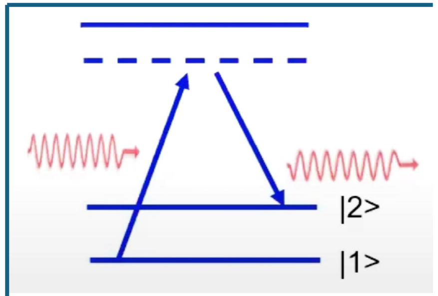


Cold-Atom Interferometry

Principle showed on a free-fall architecture

3. Step: Second Pulse (π - ”Mirror”):



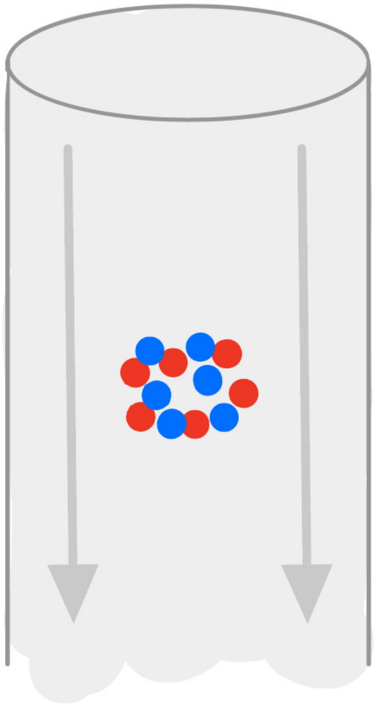


Stimulated Raman transmission

Cold-Atom Interferometry

Principle showed on a free-fall architecture

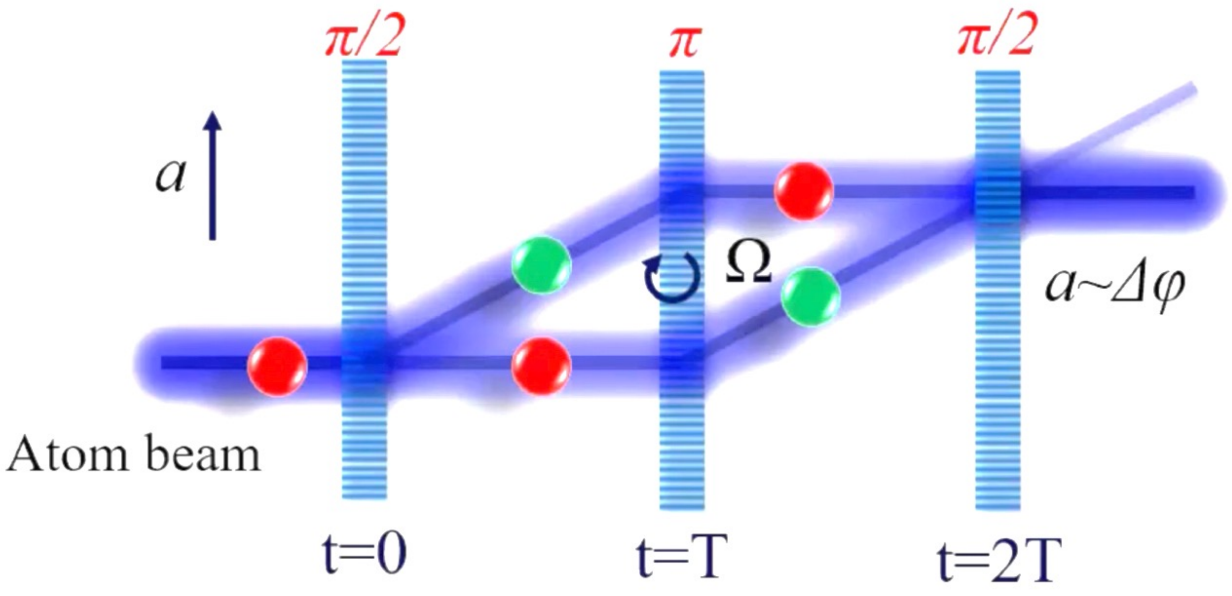
4. Step: Third Pulse (π/2 - ”Recombiner”)



→ Overlaps two paths which causes interference
→ Measurement of the pattern afterwards

Cold-Atom Interferometry

Steps visualized together:



$\Delta\phi = k_{eff} \cdot a \cdot T^2$

$\Delta\phi = \frac{2 * m}{\hbar}\, \Omega \cdot A$

Different Architectures

free-fall ⟺ guided

Other Implementations

- Trapped Ion Interferometers
- Nuclear Magnetic Resonance Gyroscopes (NMRG)
- Nitrogen-Vacancy Diamond Gyroscopes

→ But Cold-Atom Interferometry is the most established !

Quantum Advantages

- Low bias drift and high scale factor stability
- Self-Calibrated
- Quantum "headroom" for future performance enhancements:
  SNR → 1/sqrt(N)
  quantum projection limit → 1/N

→ Short: exploitation of atom stability and well-defined properties by fundamental constants

Comparison

Comparison of other metrics…

Technology	Size	Weight	Power	Cost
Mechanical (Servo Pendulum)	10-20 cm	1-2 kg	1-5 W	$10k-20k
Optical Interferometric	5-15 cm	0.5-1 kg	1-3 W	$5k-15k
MEMS (Tactical)	<2 cm	<50 g	<0.5 W	$100-1k
MEMS (Consumer)	<5 mm	<1 g	<0.1 W	$1-30
Quantum (Cold-Atom)	**Few liters**	**10-35 kg**	**50-200 W**	**>$300k**

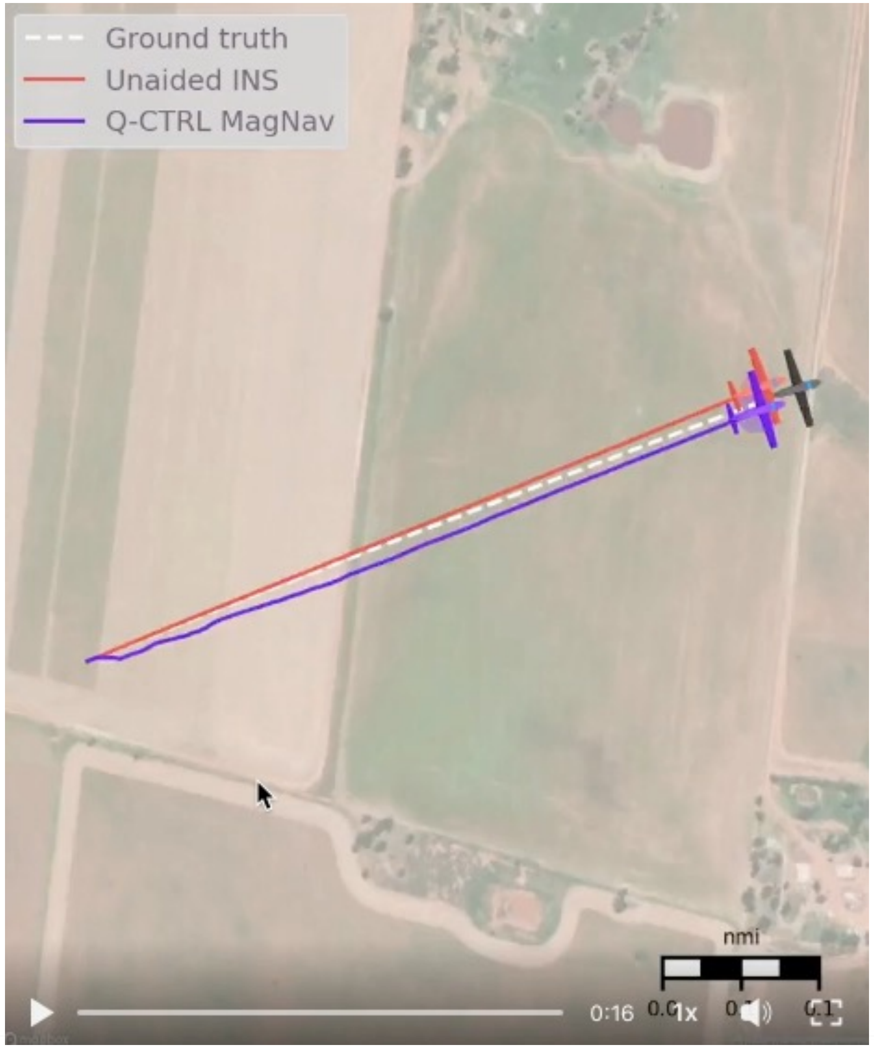
→ Only quality is better!

Current Challenges

- **Size, Weight, and Power (SWaP)**
  require vacuum chambers, lasers, and control electronics
    - Environmental Sensitivity
    - Complexity and Cost
- **Low Bandwidth and Dead Time**
  atom interferometer cycles take roughly 0.1-1 seconds which leads to "dead time" between measurements
- **Dynamic Range**
  can saturate or lose contrast under large rotations or accelerations, creating a trade-off between sensitivity and dynamic range

Q-CTRL

Announcement



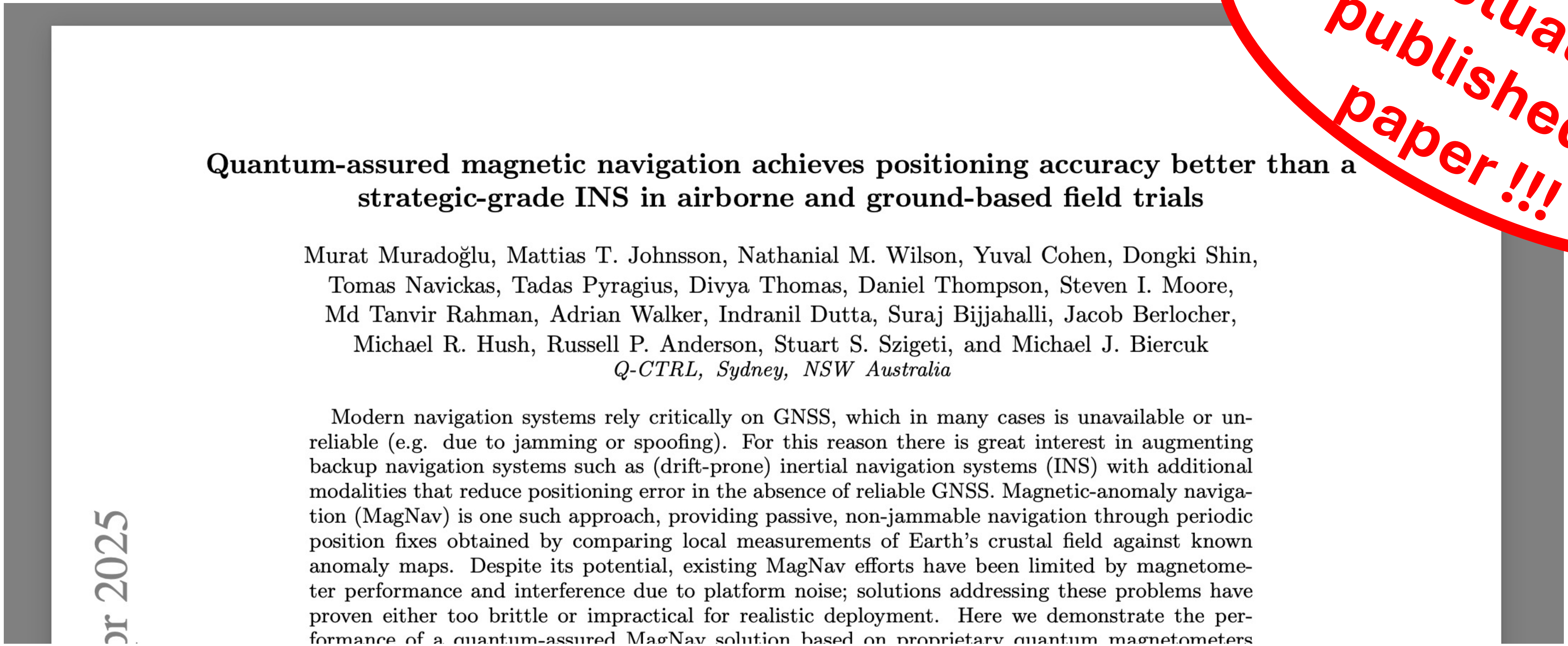
10. April 2025

- 46× better accuracy than strategic-grade INS
- Achieved final positioning error of just 22m (0.006% of flight distance)
- Works in high-noise environments
- Successful tests in both airborne (~19,000 ft) and ground vehicles
- System combines quantum magnetometer with denoising algorithms

https://www.linkedin.com/posts/rpanderson_another-view-of-the-quantum-assured-navigation-ugcPost-7317657934031638530-zuqq?utm_source=share&utm_medium=member_desktop&rcm=ACoAAEcJ-mYBe3VekgqvTTV7W_sixP5BTYovnfY

Q-CTRL Magnetometer

Actually published a paper !!!



Quantum-assured magnetic navigation achieves positioning accuracy better than a strategic-grade INS in airborne and ground-based field trials

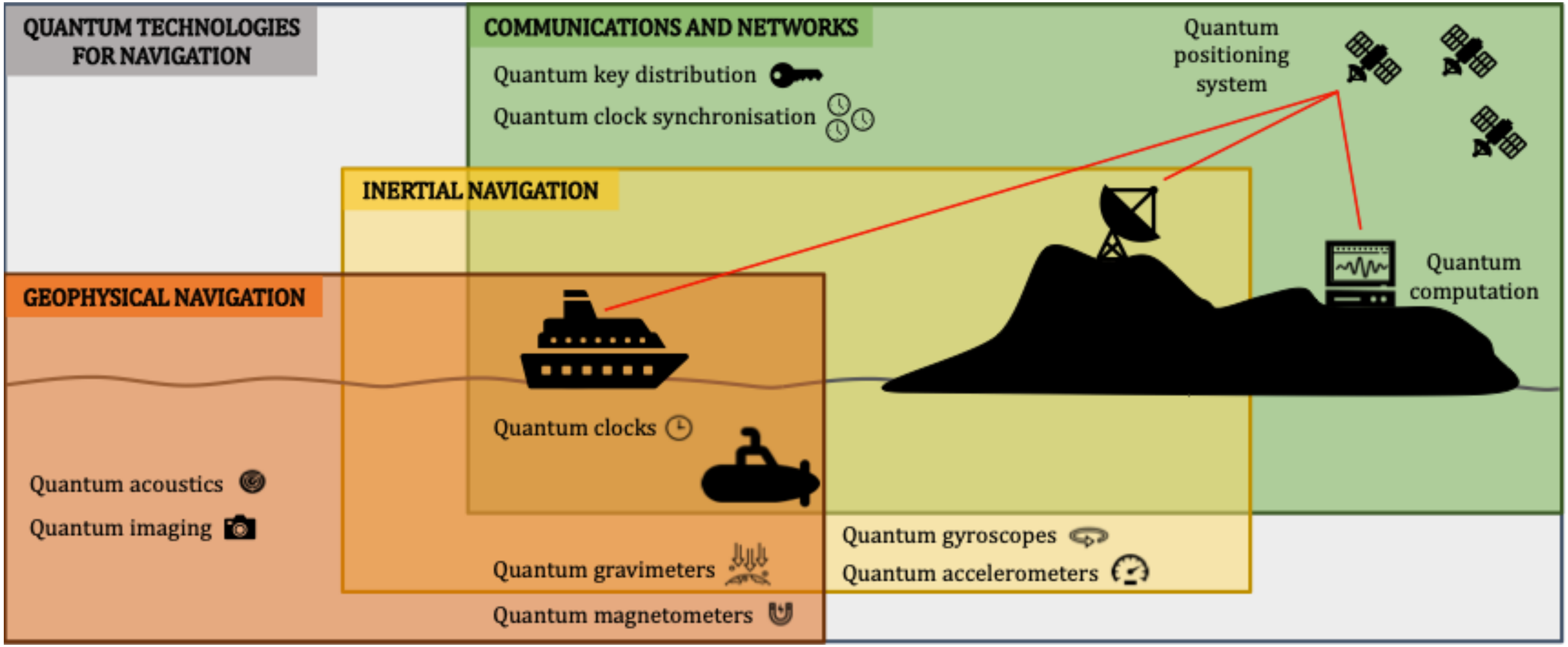
Murat Muradoğlu, Mattias T. Johnsson, Nathanial M. Wilson, Yuval Cohen, Dongki Shin, Tomas Navickas, Tadas Pyragius, Divya Thomas, Daniel Thompson, Steven I. Moore, Md Tanvir Rahman, Adrian Walker, Indranil Dutta, Suraj Bijjahalli, Jacob Berlocher, Michael R. Hush, Russell P. Anderson, Stuart S. Szigeti, and Michael J. Biercuk
Q-CTRL, Sydney, NSW Australia

Modern navigation systems rely critically on GNSS, which in many cases is unavailable or unreliable (e.g. due to jamming or spoofing). For this reason there is great interest in augmenting backup navigation systems such as (drift-prone) inertial navigation systems (INS) with additional modalities that reduce positioning error in the absence of reliable GNSS. Magnetic-anomaly navigation (MagNav) is one such approach, providing passive, non-jammable navigation through periodic position fixes obtained by comparing local measurements of Earth's crustal field against known anomaly maps. Despite its potential, existing MagNav efforts have been limited by magnetometer performance and interference due to platform noise; solutions addressing these problems have proven either too brittle or impractical for realistic deployment. Here we demonstrate the performance of a quantum-assured MagNav solution based on proprietary quantum magnetometers

https://arxiv.org/pdf/2504.08167

Overview QNS

Many other promising approaches....

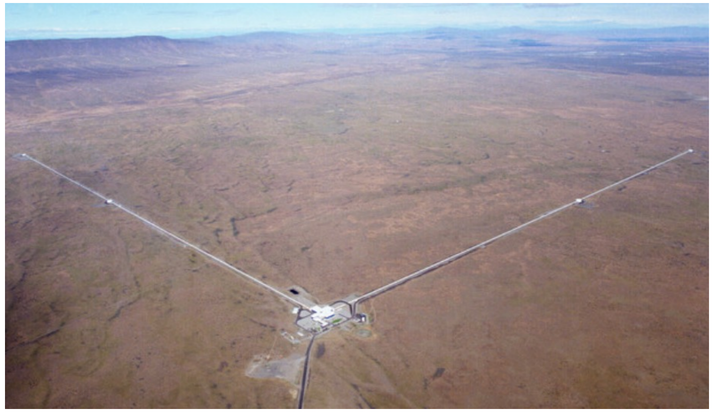


https://arxiv.org/pdf/2310.04729

Applications

GPS free → Unjammable

https://esut.de/2024/10/meldungen/54021/strategische-u-boot-kooperation-deutschlands-u-boot-technologie-im-indischen-ozean/



https://www.geekwire.com/2016/gravitational-wave-detection-earns-ligos-founders-3-million-breakthrough-prize/

https://www.france24.com/en/live-news/20241013-spacex-will-try-to-catch-giant-starship-rocket-shortly-before-landing

Thanks!