

Quantum Sensors for Complementary PNT and Resilient Communications

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Quantum sensors
are devices that exploit quantum phenomena
to measure physical quantities.

Compared to traditional sensors, quantum sensors may provide:

Improved Performance

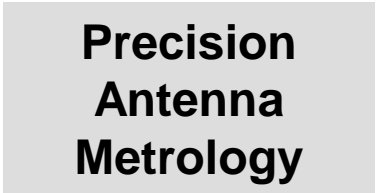
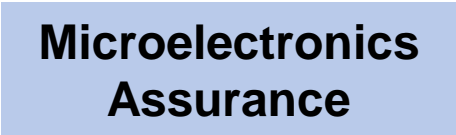
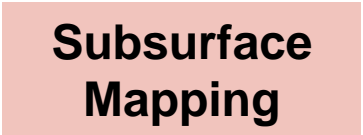
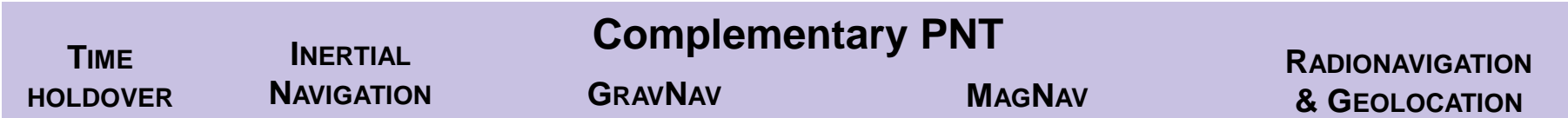
and/or

Smaller SWaP

Types of quantum sensors

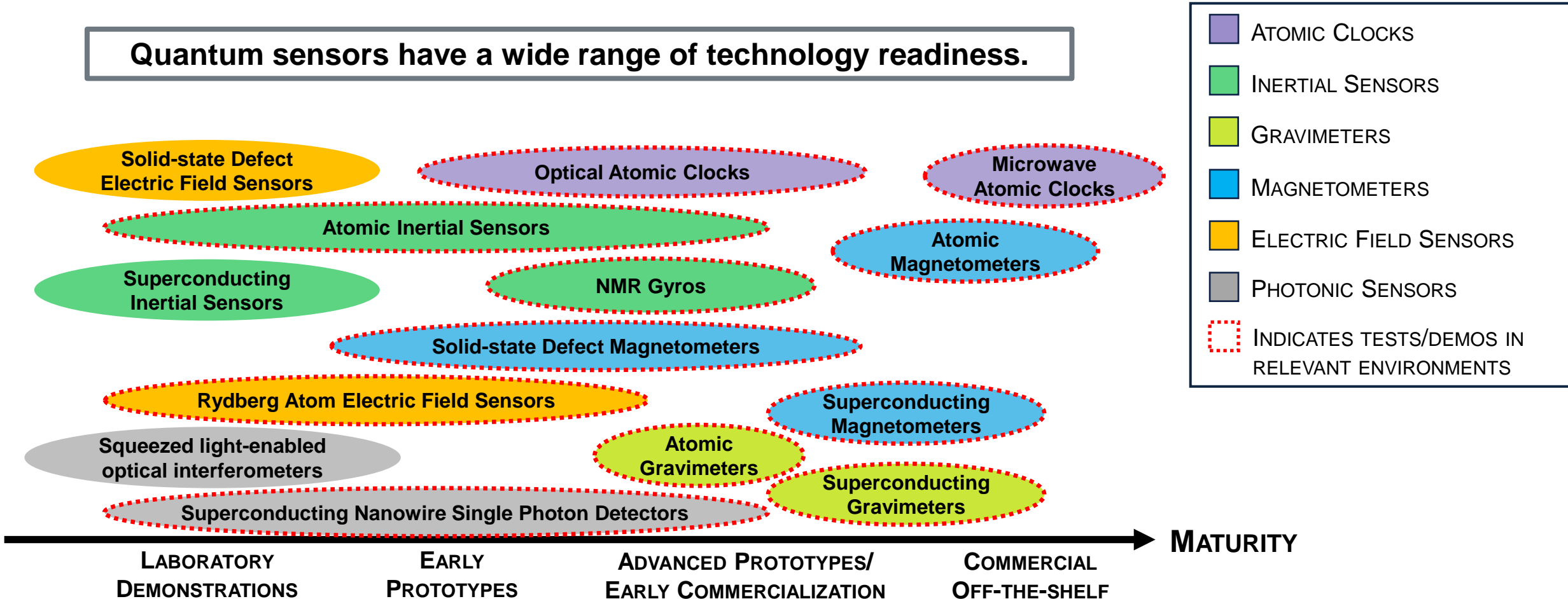


Select potential applications



Maturity of Quantum Sensors

Quantum sensors have a wide range of technology readiness.



Outline

Focus areas for today:

Part I:

Quantum Sensors for
Complementary PNT

Part II:

Quantum Sensors for
Resilient Communications

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What is Quantum PNT?

Complementary PNT

PNT techniques & technologies that are complementary or alternative to GPS

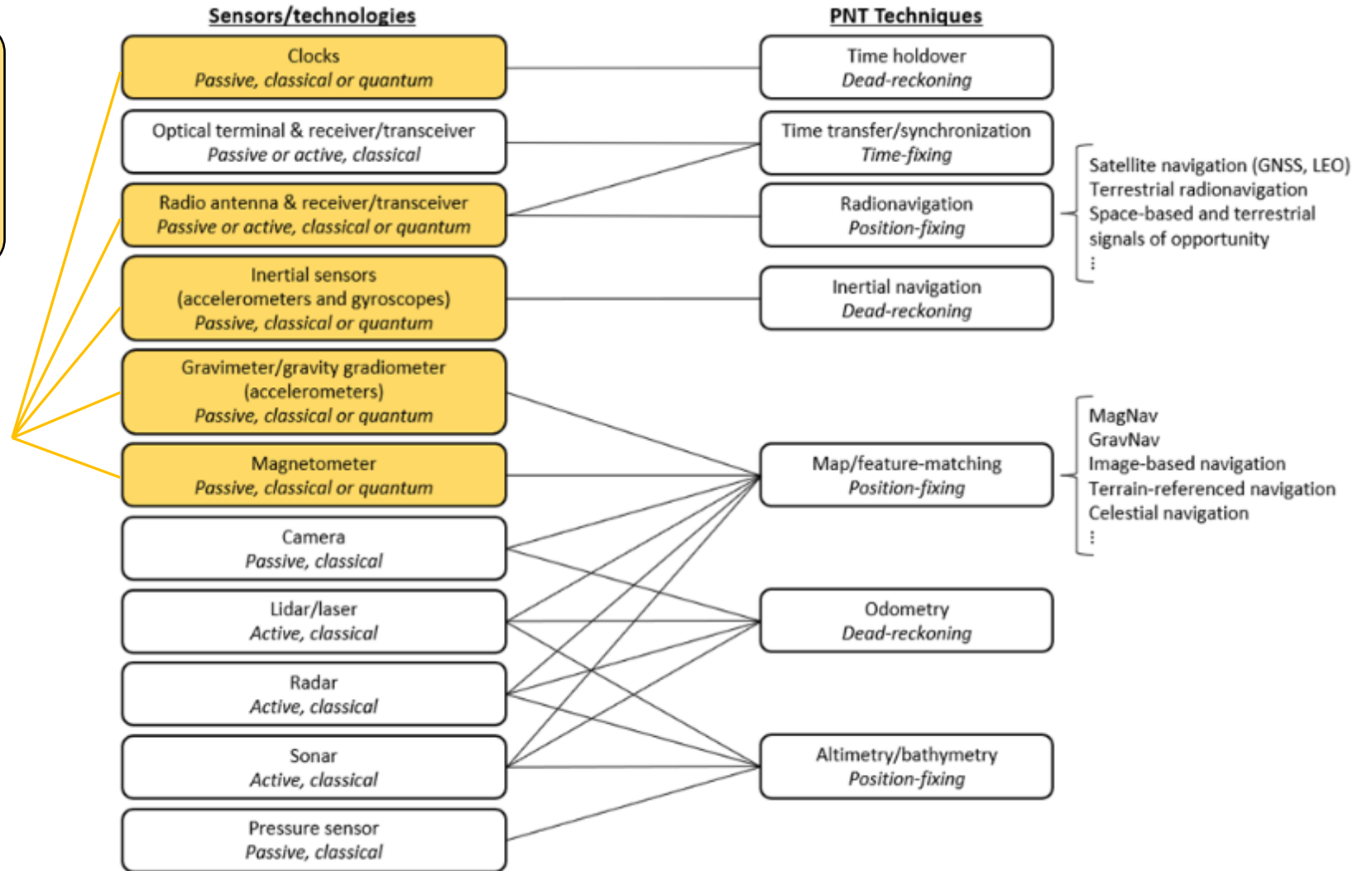
Quantum PNT

is a subset of Complementary PNT in which quantum clocks or sensors are utilized to support or enable time holdover, inertial navigation, or position-fixing.

Complementary PNT Ecosystem

Quantum Sensors:
Devices that leverage the quantum properties of a system to measure fields, forces, or time

Quantum
 sensors/technologies could be used to support some, but not all, PNT techniques

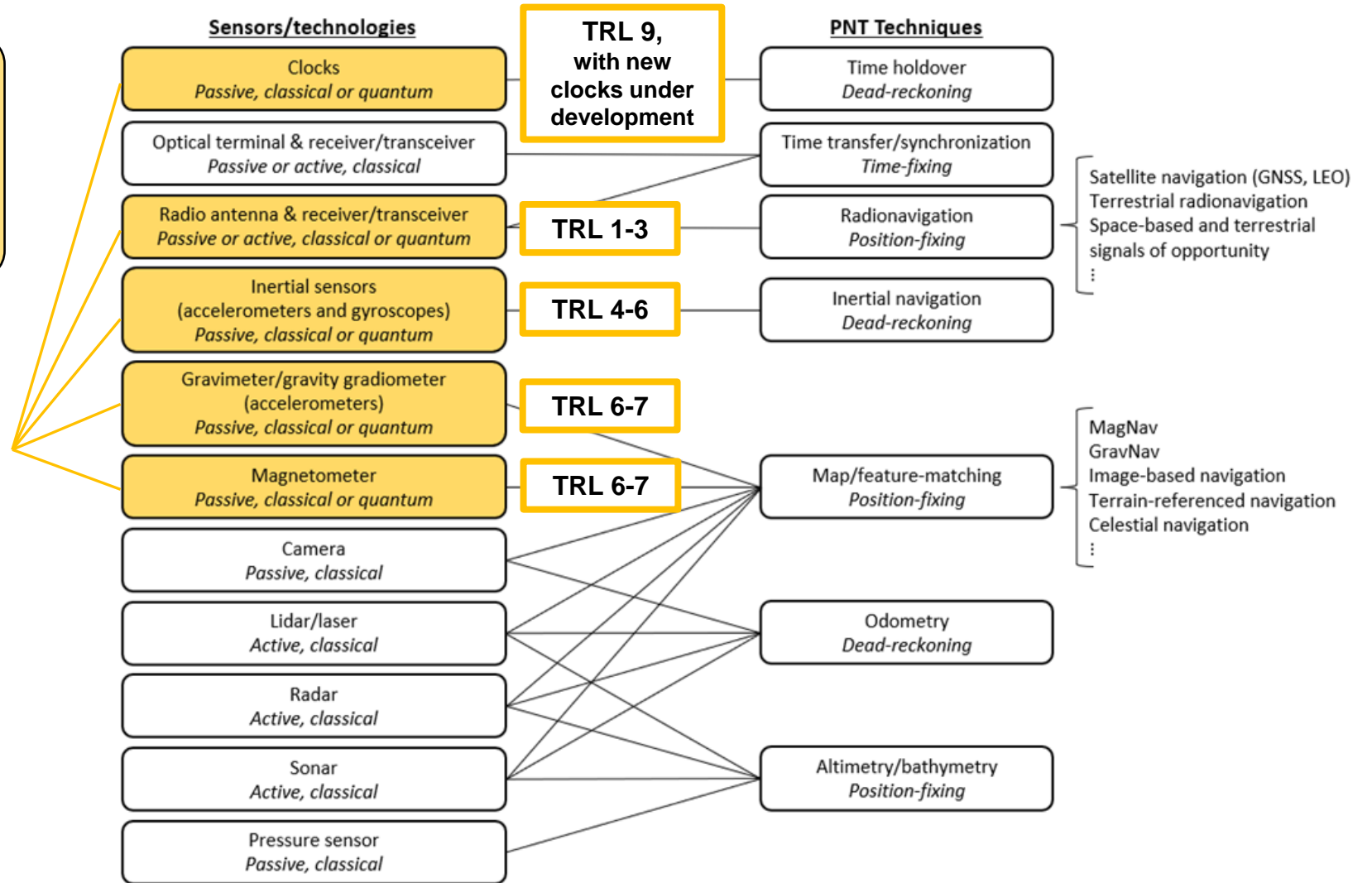


LEO = low-earth orbit
 MagNav = magnetic anomaly-aided navigation
 GravNav = gravitational anomaly-aided navigation

Complementary PNT Ecosystem

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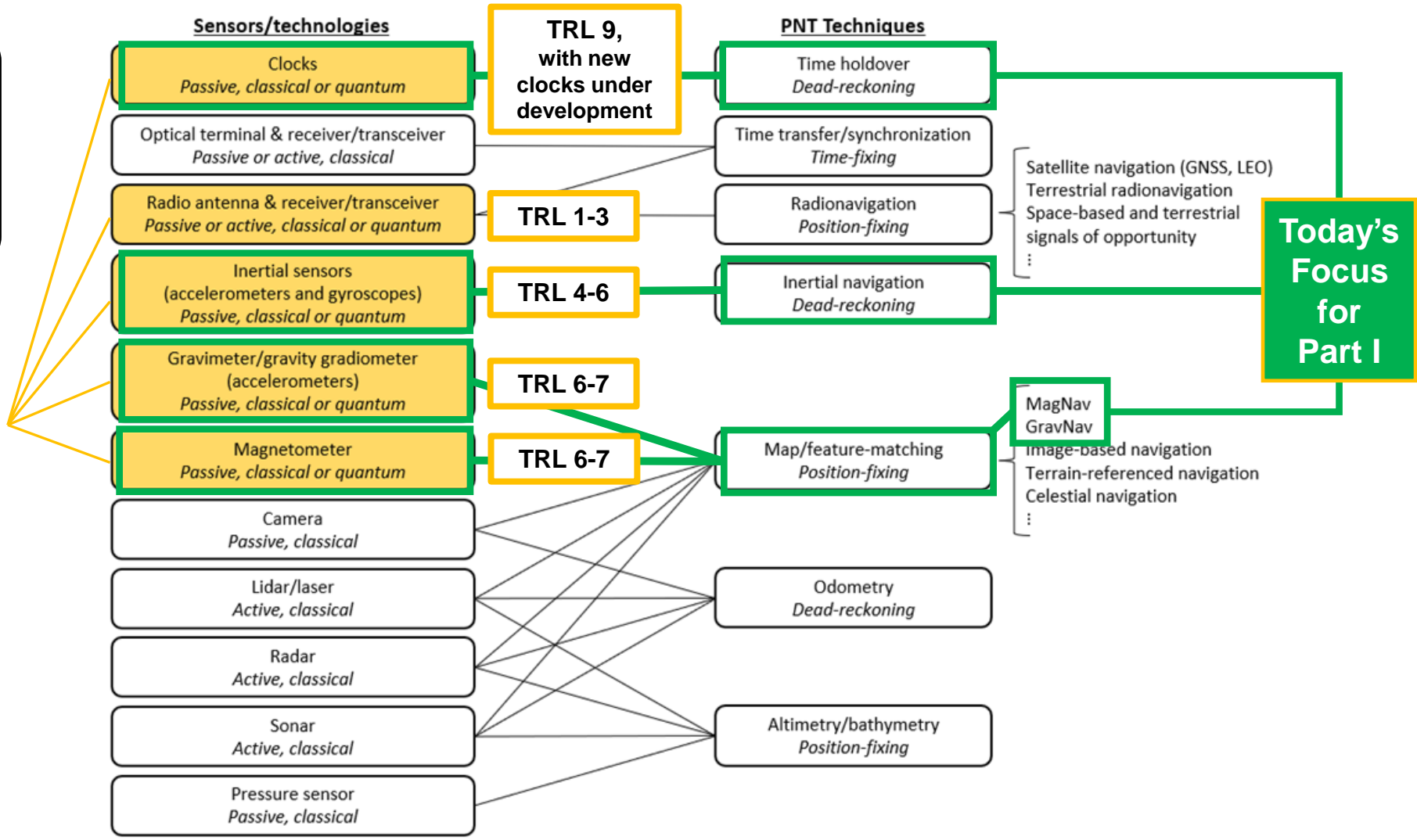


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Complementary PNT Ecosystem

Quantum Sensors:
Devices that leverage the quantum properties of a system to measure fields, forces, or time

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LEO = low-earth orbit
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 GravNav = gravitational anomaly-aided navigation



Quantum PNT Techniques

TIME HOLDOVER

→ Maintaining precision timing and synchronization in the absence of external timing signals



Image credit: Unictron

Applicable quantum technologies: Atomic clocks

Alternative classical technologies: OCXOs, TCXOs, MEMS

INERTIAL NAVIGATION

→ Using an inertial navigation system to estimate a platform's position, orientation, and speed



Image credit: everything RF

Applicable quantum technologies: Atom interferometer-based accelerometers and gyroscopes, NMR gyroscopes

Alternative classical technologies: FOGs, RLGs, MEMS

MAGNETIC ANOMALY-AIDED NAVIGATION (MAGNAV)

→ Position-fixing via matching locally measured magnetic fields to a magnetic map of the region

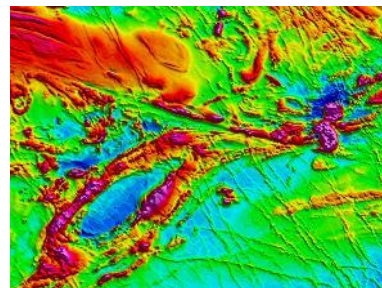


Image credit: Eos

Applicable quantum technologies: Atomic magnetometers, NV diamond magnetometers

Alternative classical technologies: Fluxgate magnetometers

GRAVITATIONAL ANOMALY-AIDED NAVIGATION (GRAVNAV)

→ Position-fixing via matching locally measured gravitational signals (i.e., mass distributions) to a gravitational map of the region

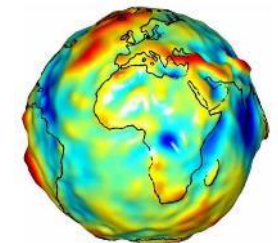


Image credit: NASA

Applicable quantum technologies: Atom interferometer-based gravimeters

Alternative classical technologies: Falling corner cube gravimeters, Spring suspension gravimeters

Quantum PNT Techniques

TIME HOLDOVER

→ Maintaining precision timing and synchronization in the absence of external timing signals



Applicable quantum technologies:
Alternative classical technologies:

INERTIAL NAVIGATION

→ Using an inertial navigation system



Image credit: everything RF

Atom interferometer-based

MEMS

BLUF: Key Takeaways

- I. Quantum clocks and sensors offer enhanced long-term stability and accuracy compared to their classical counterparts.
- II. MagNav & GravNav are not suitable for every platform, but they are passive techniques that can operate in all-weather conditions and any time of day. If you need to use MagNav/GravNav, you will most likely want to use a quantum magnetometer/gravimeter.

MAGNETIC NAVIGATION (MAGNAV)

→ Position-finding by correlating locally measured magnetic fields to a magnetic map of the region

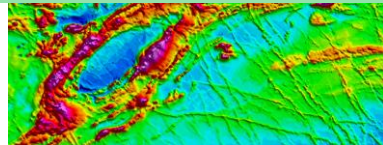


Image credit: Eos

Applicable quantum technologies: Atomic magnetometers, NV diamond magnetometers

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GRAVIMETRIC NAVIGATION (GRAVNAV)

→ Position-finding by correlating locally measured signals (i.e., mass distributions) to a gravitational map of the region

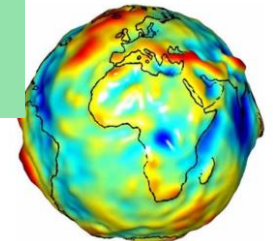


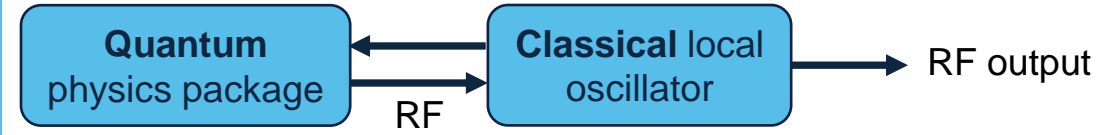
Image credit: NASA

Applicable quantum technologies: Atom interferometer-based gravimeters

Alternative classical technologies: Falling corner cube gravimeters, Spring suspension gravimeters

Atomic Clocks

SIMPLIFIED ATOMIC CLOCK ARCHITECTURE



Standard Microwave Atomic Clocks

Today's commercial microwave atomic clocks underpin many aspects of everyday life, including GPS, communications, and financial transactions.



Image credit: Teledyne

Laser-based chip-scale atomic clocks (CSACs)



Image credit: SRS

Lamp-pumped rubidium clocks



Image credit: Microchip

Cesium beam tube clocks



Image credit: Spectradynamics

(Emerging) Cold atom rubidium clocks



Image credit: Microchip

Hydrogen masers

Emerging Optical Atomic Clocks

Why build optical versions of atomic clocks?

→ They offer intrinsically better stability than microwave atomic clocks.

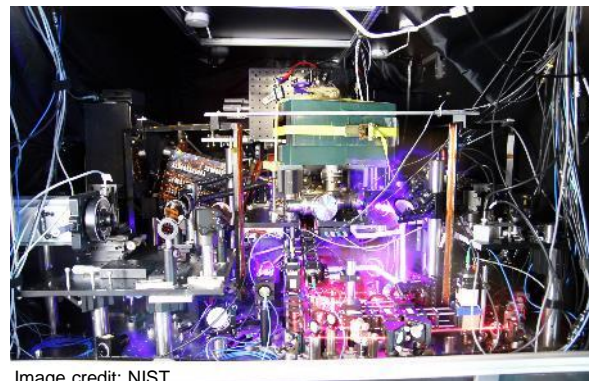


Image credit: NIST

Strontium optical lattice clock

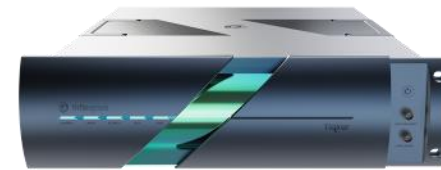
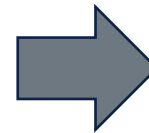


Image credit: Infleqion

Rubidium optical clock (3U)



Image credit: Vector Atomic

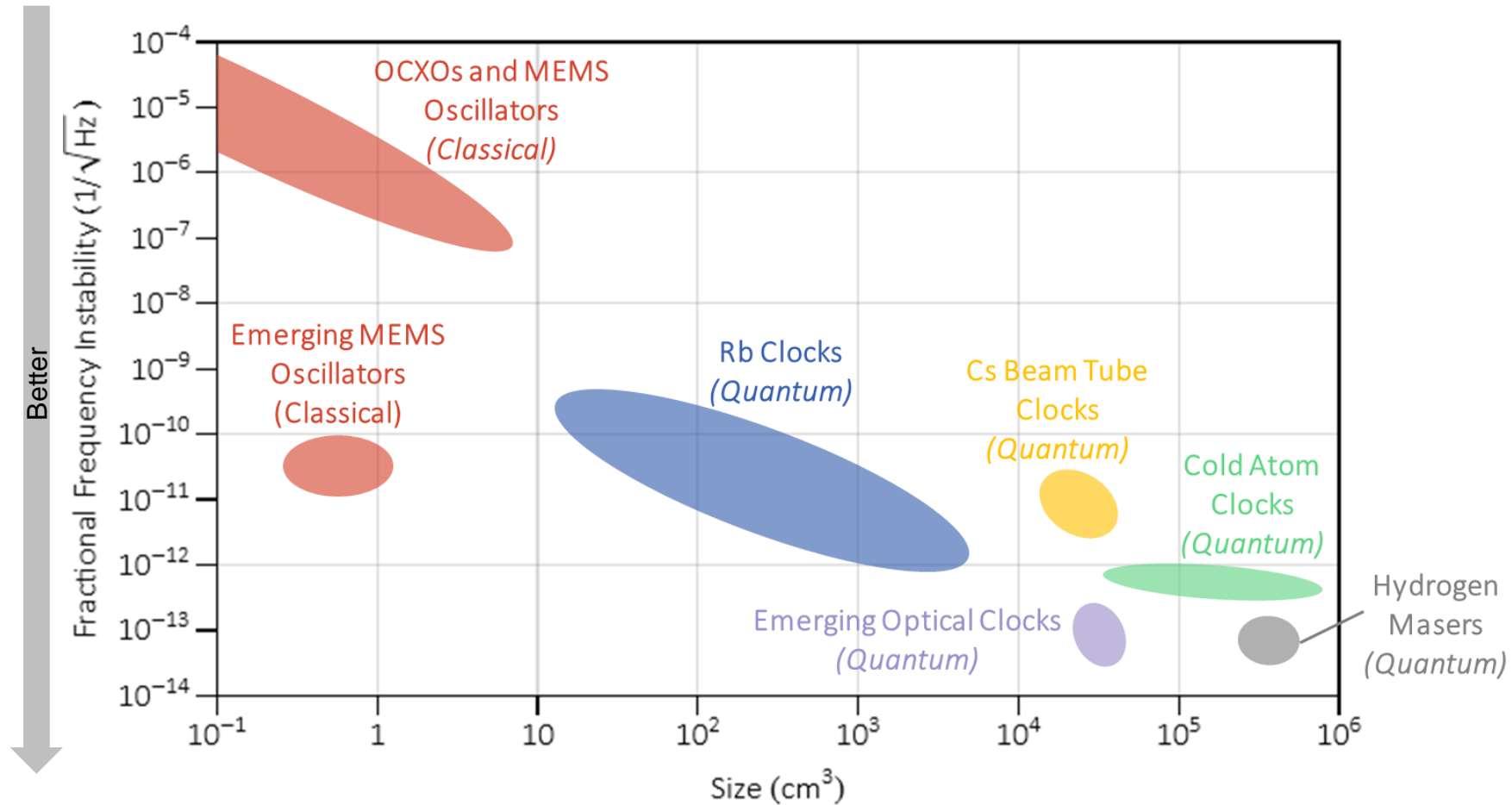
Iodine optical clock (3U)

Outlook for Atomic Clock Technologies

The short-term stability of various clocks/oscillators is shown to the right.

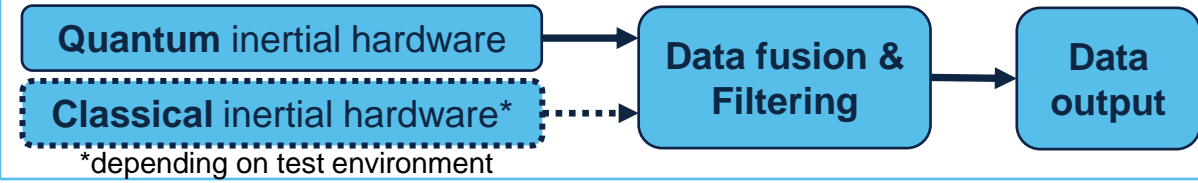
Key takeaways

- Emerging (classical) MEMS oscillators may start to compete with chip-scale atomic clocks (CSACs) for some applications.
- Emerging optical clocks promise high performance with a smaller form factor.



Quantum Inertial Sensors

SIMPLIFIED QUANTUM INERTIAL MEASUREMENT UNIT ARCHITECTURE



Technology

Two primary quantum inertial sensors:

Atom Interferometer-based Accelerometers & Gyroscopes



Image credit: DIU

Recently developed space-qualified atomic gyro

NMR Gyroscopes

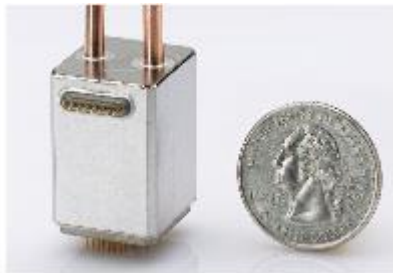
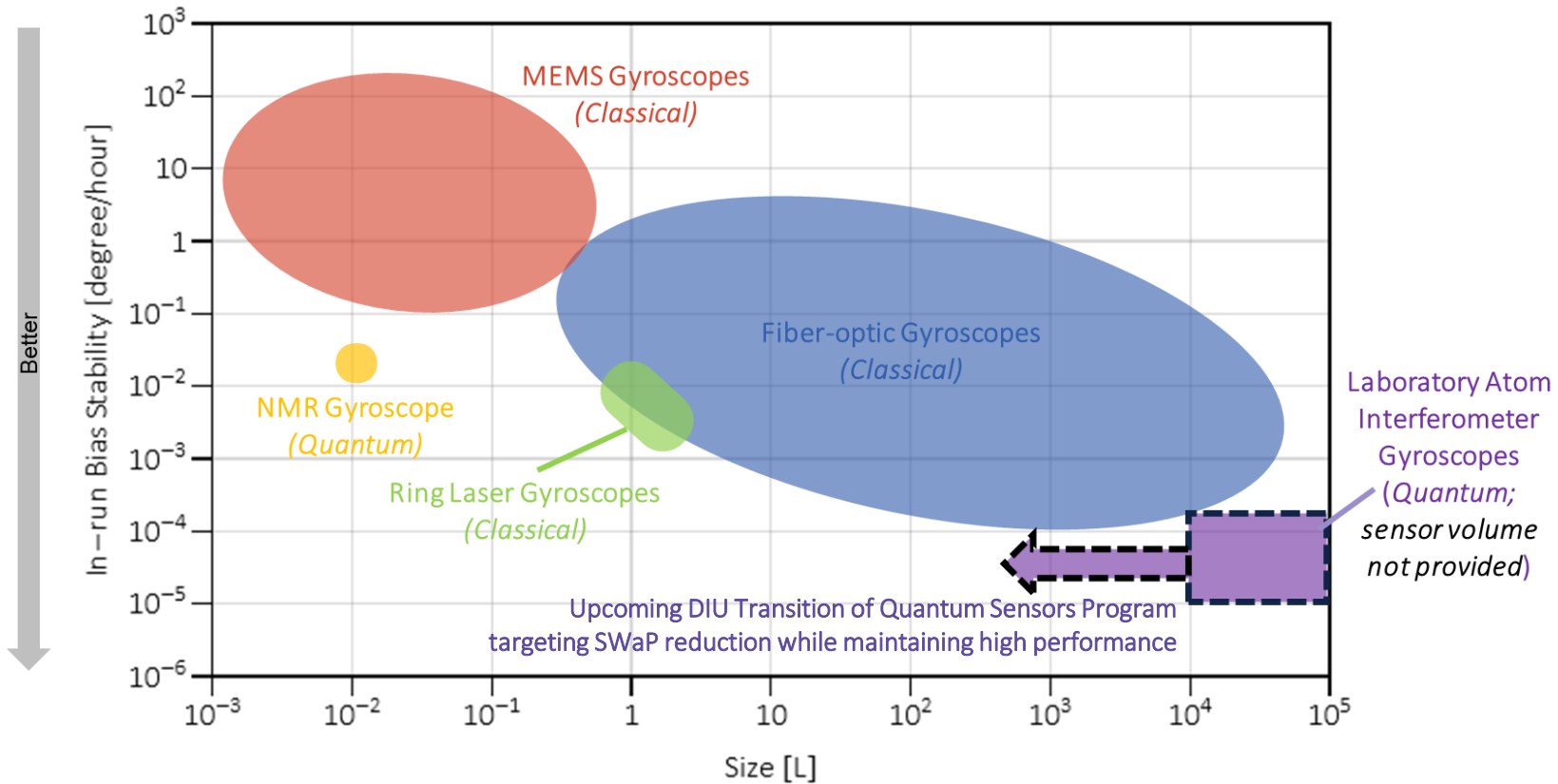


Image credit: Northrop Grumman

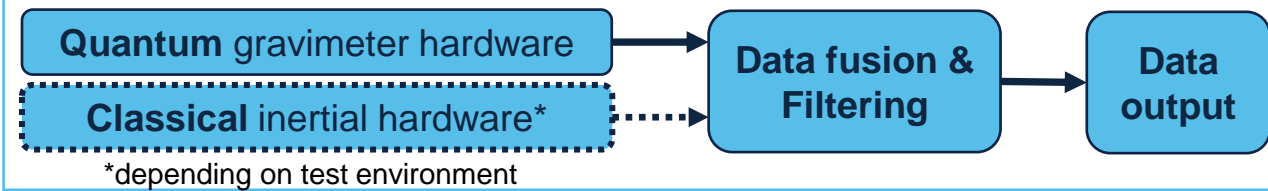
Status and Outlook



Quantum inertial sensors offer the potential for high performance with smaller SWaP than traditional (classical) inertial sensors.

Quantum Gravimeters

SIMPLIFIED QUANTUM GRAVIMETER ARCHITECTURE



Technology

There are two primary quantum gravitational sensors:

Atom Interferometer-based Gravimeters and Gravity Gradiometers

Superconducting Gravimeters and Gravity Gradiometers



Key advantages

(compared to classical gravitational sensors):
Improved long-term stability and accuracy

Recent Developments and Trends



B. Stray et al., Nature 602, 590 (2022)

Univ. of Birmingham's atomic gravity gradiometer measured the center of an underground tunnel to within 20 cm



Image credit: Muquans

Muquans atomic gravimeter deployed on Mt. Etna for monitoring volcanic activity



Image credit: Vector Atomic

Vector Atomic's atomic gravimeter tested at RIMPAC 2022 (Hawaii exercise) for maritime gravitational anomaly mapping

Projected Use Cases:

- Gravitational map-making and gravitational anomaly-aided navigation (GravNav) for position-fixing
- Subsurface mapping
- Mineral exploration

Quantum Magnetometers for MagNav

Technology

Atomic vapor magnetometers



Image credit: Geometrics

Solid state defect magnetometers

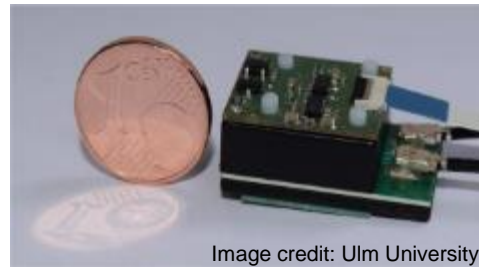


Image credit: Ulm University

Key advantages of quantum magnetometers (compared to other magnetic sensors)

- Comparable or smaller size with sensitivities better than that required for MagNav
- Good long-term stability and accuracy

Recent Advances & Trends

Wider commercial availability of atomic magnetometers from numerous vendors (Geometrics, QuSpin, Twinleaf, Fieldline)

Magnetic navigation using atomic magnetometer achieved < 20 m position accuracy @ 1 hour under optimal conditions

Magnetic navigation test on C-17A Globemaster III during Golden Phoenix exercise (May 2023)



Image credit: Geometrics

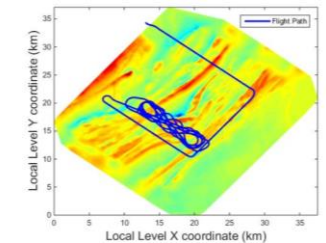


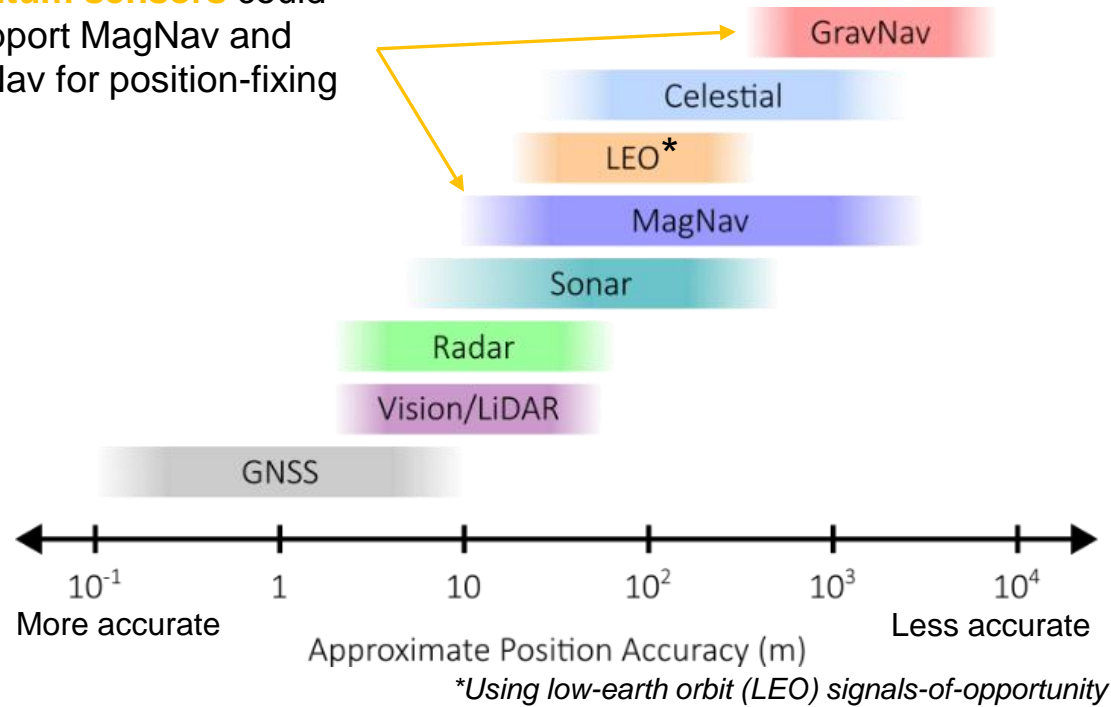
Image credit: A. Canciani dissertation: AFIT-ENG-DS-16-S-074, 2016.



Image credit: <https://www.af.mil/News/Article-Display/Article/3408951/magnav-project-successfully-demonstrates-real-time-magnetic-navigation/>

Outlook for Position Fixing with Quantum Sensors

Quantum sensors could support MagNav and GravNav for position-fixing



Many position-fixing techniques supported by classical sensors can provide comparable or better positioning accuracy than MagNav and GravNav.

However, **MagNav and GravNav have 3 key advantages:**

- They are **passive** techniques (unlike lidar, radar, and sonar),
- They are **difficult to jam or spoof** (unlike radionavigation techniques), and
- They can **operate in all-weather conditions and at all times of day** (unlike certain image-based and/or celestial navigation techniques)

Value of Quantum Sensors for MagNav and GravNav

- Quantum magnetometers and gravimeters are likely to be better than their classical counterparts for generating high-accuracy maps.
- Once maps are generated, quantum sensors may be used for MagNav and GravNav due to their long-term accuracy and stability.

Outline

Focus areas for today:

Part I:

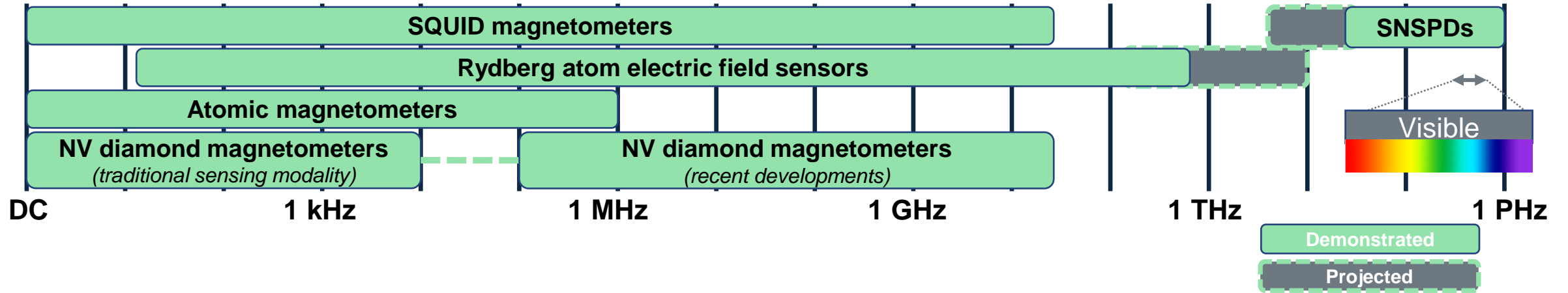
Quantum Sensors for
Complementary PNT

Part II:

Quantum Sensors for
Resilient Communications

Quantum Sensors for Resilient RF and Optical Comms

Spectrum Coverage of Quantum Electromagnetic and Photonic Sensors



Today's Focus Areas for Part II

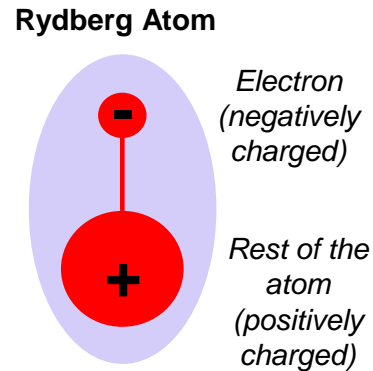
- I. Overviews of
 - Rydberg atom electric field sensors
 - SQUID magnetometers and SQUID arrays (SQAs)
 - Superconducting nanowire single photon detectors (SNSPDs)

- II. Highlights from MITRE R&D in Rydberg atom electric field sensors for wideband spectrum sensing and NV diamond magnetometers for near-field magnetic imaging of microelectronics

Rydberg Atom Electric Field Sensors

Technology

Rydberg atom electric field sensors are based on highly excited “Rydberg atoms,” which behave as sensitive electric dipoles.

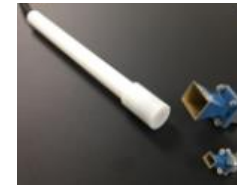


Use cases: Resilient communications and sensing (e.g., broadband noise rejection), high-accuracy precision metrology (e.g., precision antenna characterization), terahertz sensing

These sensors can be thought of as a device that can replace the antenna and front-end electronics of a traditional receiver.

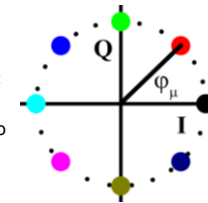
Recent Developments and Trends

Image credit:
Rydberg
Technologies
[Anderson]



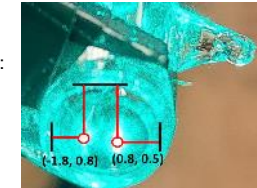
Miniaturization of the
sensor head

Image credit:
Army
Research Lab
[Meyer 18]



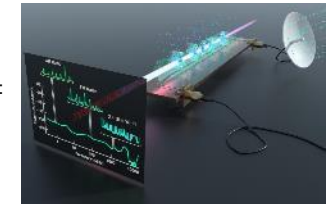
Standard waveform detection
(e.g., AM/FM, 8-state PSK)

Image credit:
NIST
[Robinson]



First angle-of-arrival
measurement

Image credit:
U.S. Army
[Meyer 21]



Rydberg spectrum analyzer
tunable from 0 Hz-20 GHz

Key advantages cf. traditional antenna-based receivers

**Small-size
sensor head**

+

**Broad tunability
(DC-THz)**

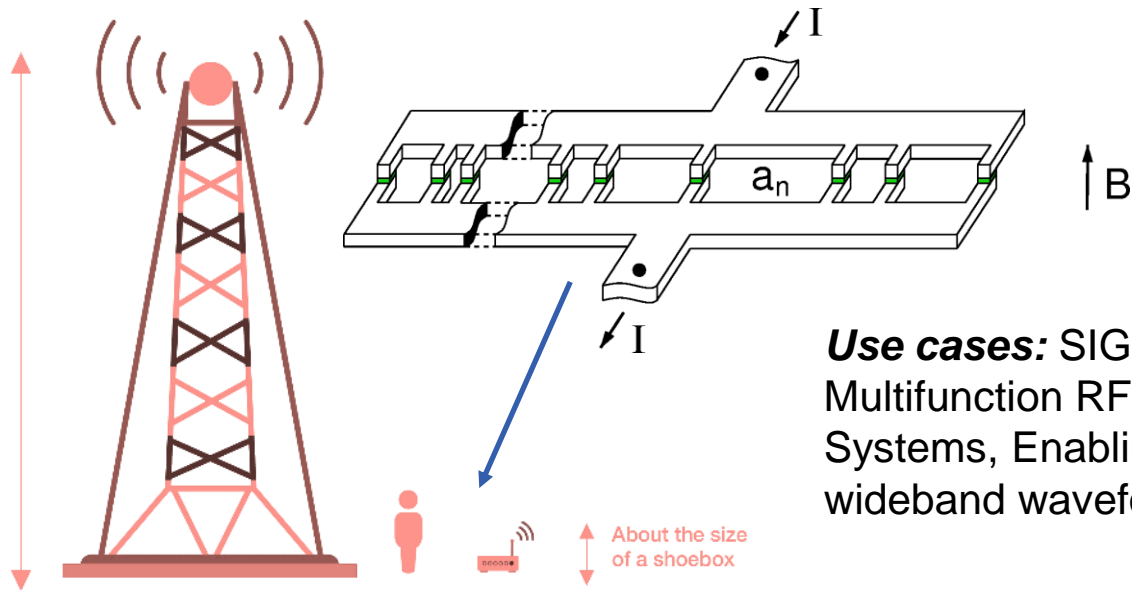
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**Enhanced spectrum
situational
awareness**

SQUID Magnetometers and SQUID Arrays

Technology

Leveraging exquisite sensitivity of SQUIDs to magnetic fields to sense of RF signals



Classical Long Wavelength RF Sensor

Potential SQUID Sensor

Use cases: SIGINT, Multifunction RF Systems, Enabling of wideband waveforms

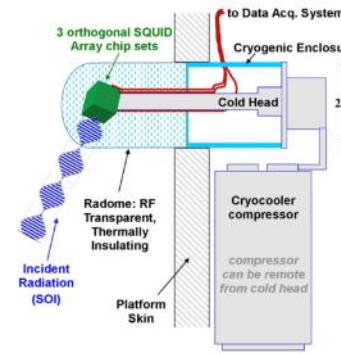
These sensors can be thought of as a device that can replace the front end antenna and is compatible with traditional electronics and software



Recent Developments and Trends

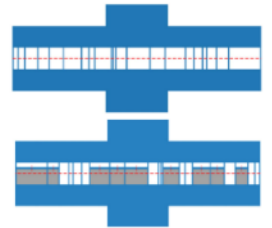
SWAP Reduction

Image credit: NIWC Pac, Dist. A



Circuit Design for Improved Performance

Image Credit: DOI: 10.1109/TASC.2023.3247988



RF Measurements

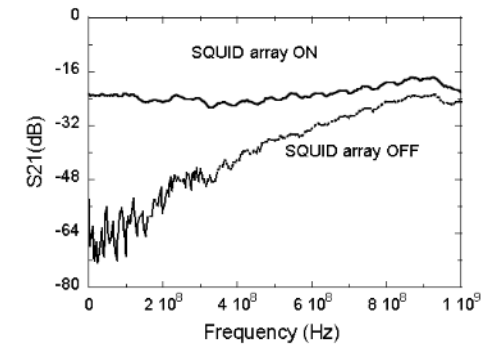


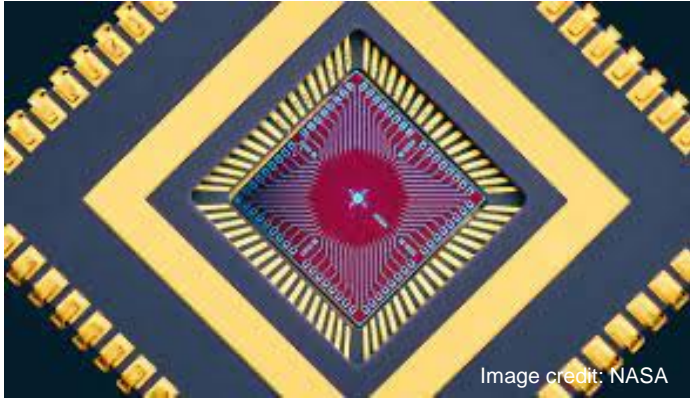
Image Credit DOI: 10.1109/TASC.2015.2470677

Key Characteristics

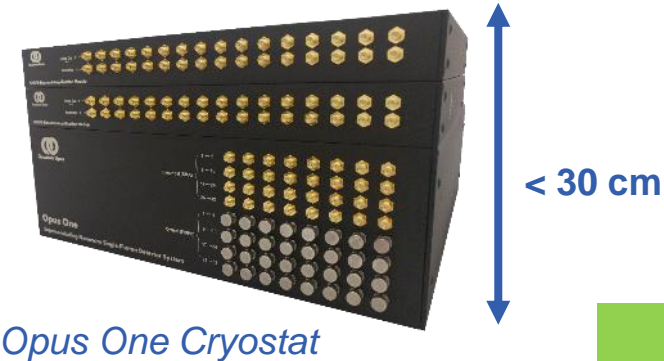


Superconducting Nanowire Single Photon Detectors (SNSPDs)

SNSPD Technology



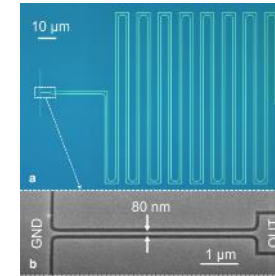
- Can detect single photons with high efficiency
- Can be fabricated to sense wavelengths from near-to-far infrared



Requires cryogenic cooling to operate, but there now exist cryostats that are relatively compact.

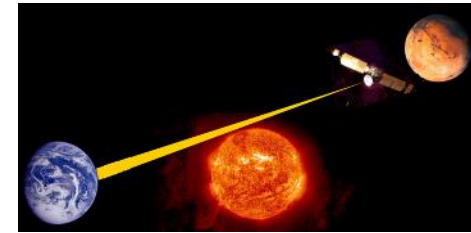
May enable novel chemical sensing applications

Recent R&D Highlights



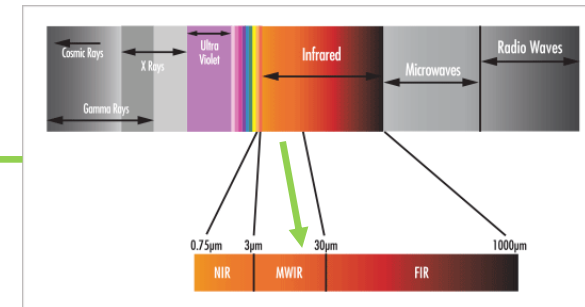
Demonstration of temporal resolution below 3 picoseconds for higher communication rates, improved ranging for LiDAR

[Korz et al., Nat. Photon. 14, 250-255 2020]



Development of large SNSPD arrays for deep-space optical communications

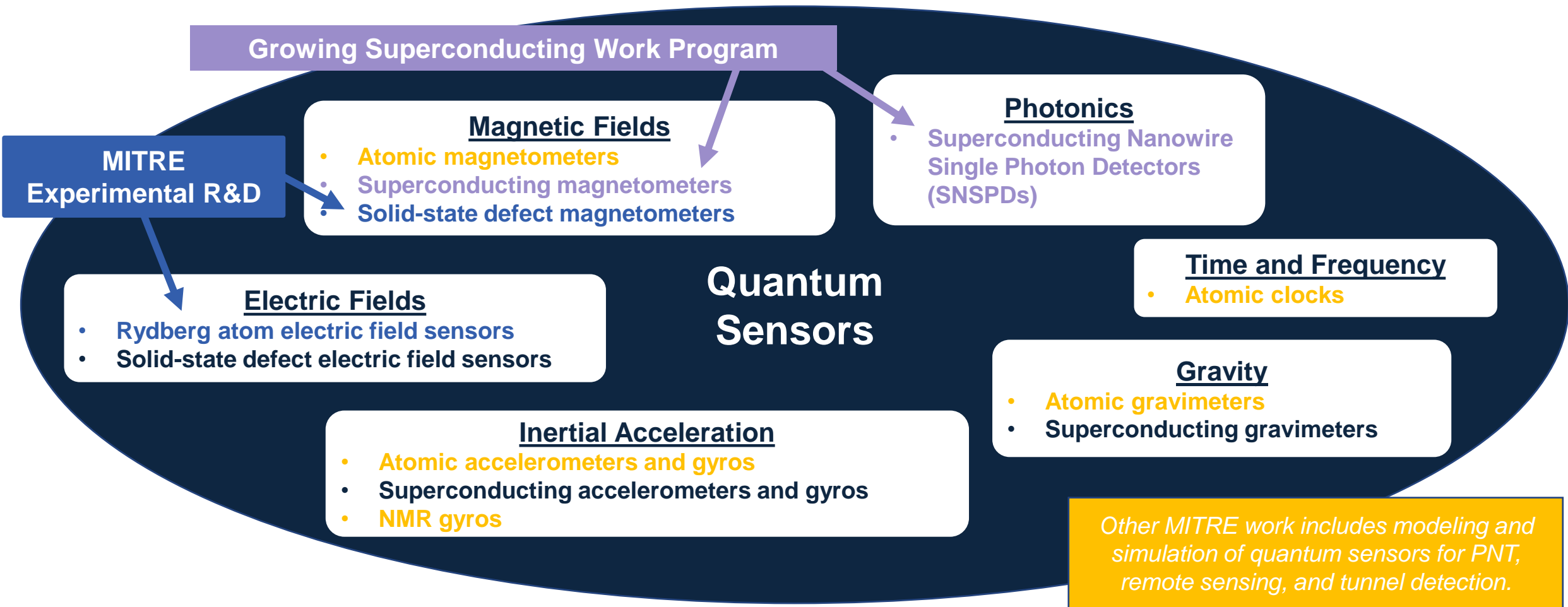
[<https://microdevices.jpl.nasa.gov/news/superconducting-nanowire-single-photon-detectors-for-dsoc/>]



Fabrication of SNSPDs sensitive to mid-infrared (~10 micron) wavelengths

[M. Shaw, Proceedings Volume 11454, X-Ray, Optical, and Infrared Detectors for Astronomy IX; 1145411 (2020)]

MITRE and the Quantum Sensing Ecosystem



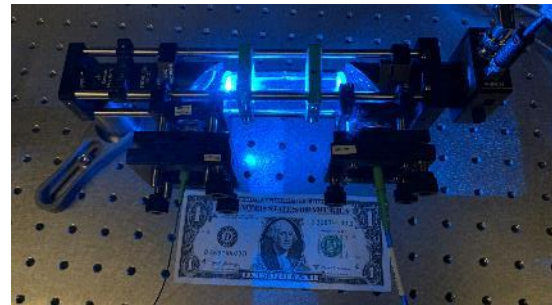
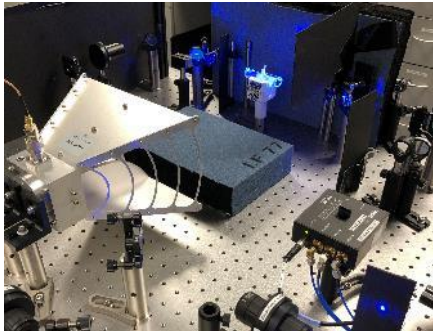
Quantum Sensing Experiments at MITRE

Rydberg Atom Electric Field Sensor

A sensor that can replace the antenna and front-end electronics of a traditional receiver.



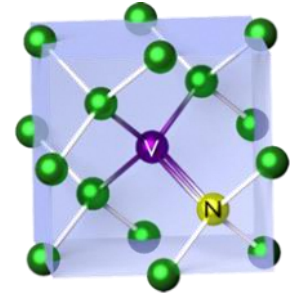
MITRE's Focus Area: Broad spectrum situational awareness for electronic support



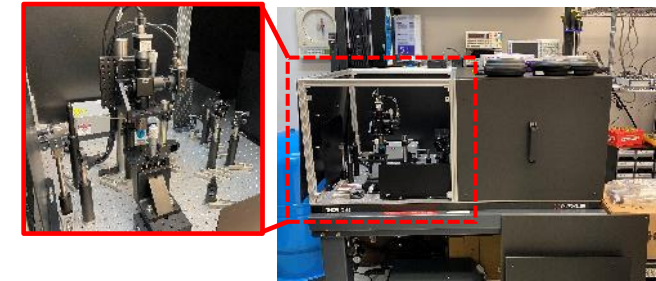
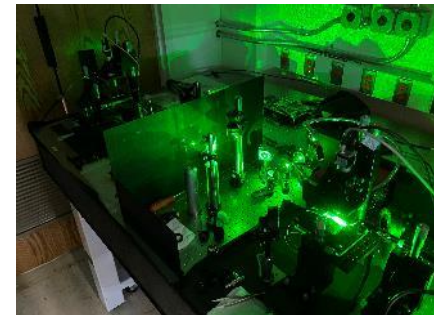
Rydberg atom sensor in the Quantum REALM Lab (McLean)

Quantum Diamond Microscope (QDM)

A magnetometer that uses nitrogen-vacancy (NV) centers in diamond to transduce near-field magnetic fields into optical fluorescence intensity.



MITRE's Focus Area: Microelectronics Assurance



Quantum Diamond Microscopes in the μ E Lab (Bedford, left) and in the Photonics Lab (McLean, right)

Outlook

Challenges for Advancing Quantum Sensor R&D

Key Challenge I: Miniaturization and Ruggedization

- Photonic integration
- Laser miniaturization
- Atomic integration (e.g., waveguides for atoms)
- Fabrication (e.g., nitrogen-vacancy defects in diamond)
- Improved portability of ultra-high vacuum systems and cryogenic/liquid nitrogen cooling systems

Key Challenge II: Connecting End Users with Researchers and Developers to Accelerate the R&D Pipeline

- Facilitating increased communication between end users/other stakeholders and sensor researchers & developers would enable early identification of potential systems integration challenges, ruggedization requirements, and impactful performance metrics

