



Quantum Sensors (QS) for Space Science: An NESC Perspective

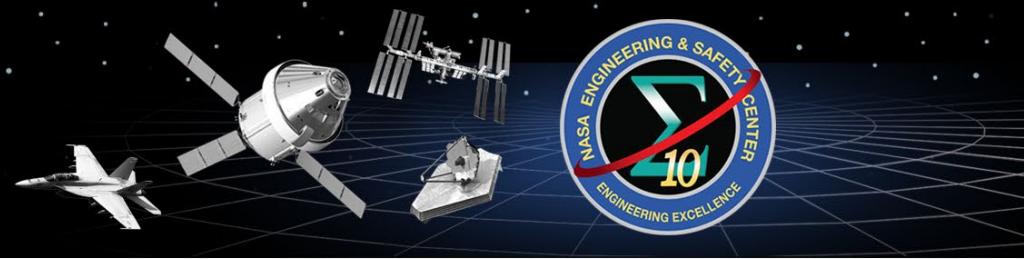
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NASA's NESC S&I Purview: The development and implementation of technologies for remote sensing, observatories, in-situ and proximity, and cross-cutting.



NASA Quantum Sensing Landscape



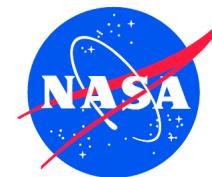
6.1 Quantum Sensing Definition

The term “quantum sensor” is interpreted in a number of ways throughout the quantum research community. The broadest definition includes all instruments in which quantum mechanics plays a fundamental beneficial role in the instrument performance. Atomic clocks and magnetometers are examples of quantum sensors according to this definition. These sensors gain their advantages of good long-term stability and accuracy through energy-level quantization, but usually do not contain entangled particles and perform at levels at or above the SQL.

What is a “quantum sensor”:

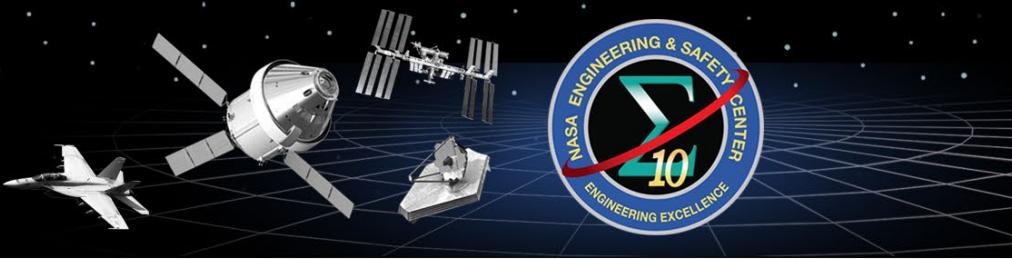
- **Quantum mechanical nature directly benefits performance**
- **Stability, accuracy, SWaP**
- **Entanglement?**

NASA/TM-20230018123



Independent Panel Report for
Technical Assessment of NASA and External
Quantum Sensing Capabilities

NESC Independent Review



Background

- SMEs from the NESC S&I QS CoP requested an independent Technical Assessment of NASA's capabilities and needs.
- Representatives across DoD, NIST, FFRDCs, Industry, & academia
- Assessment spanned 10/2021-10/2023

Assessment Goals

- Broadly define the term 'quantum sensing'
- Establish appropriate NASA strategies and investments to develop and maintain the QS competence and capabilities required to meet the agency's future needs.
- Provide findings, observations and recommendations to NASA and partners

Offered an initial handshake between QS SMEs and Potential End-Users!

NASA/TM-20230018123



Independent Panel Report for Technical Assessment of NASA and External Quantum Sensing Capabilities

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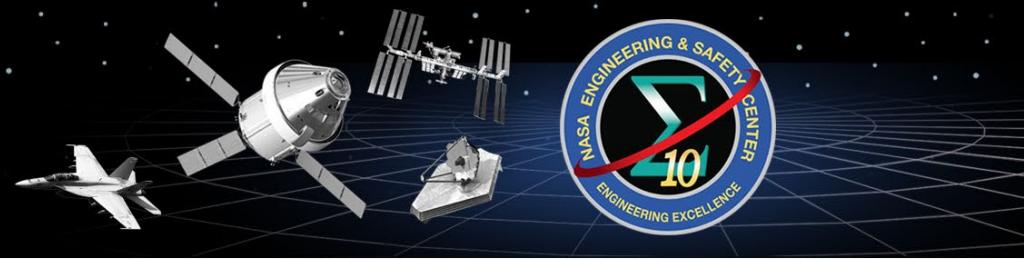


Assessment Approach



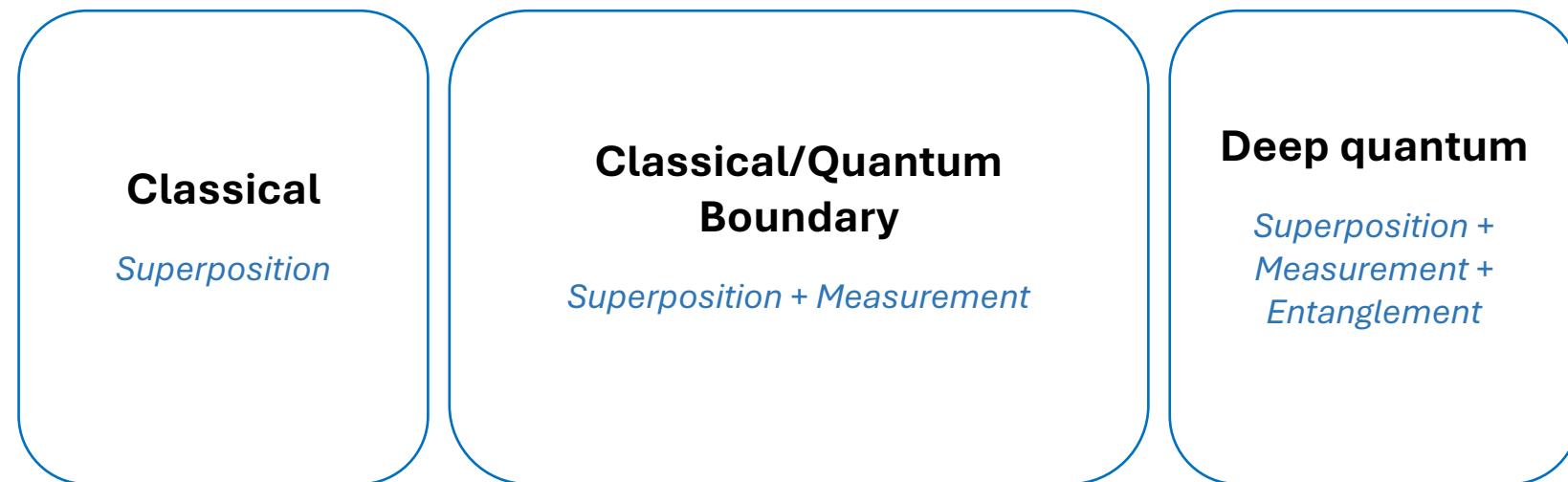
- **Main approaches used**
 - Survey to NASA technical centers: responses received from JPL, GSFC, GRC, and KSC
 - NASA Quantum Sensing Workshop, Newport News, VA, September 27 through 29, 2022
 - 180 attendees from industry, academia, Govt Agencies, FFRDC)
 - Meetings and inputs with national stakeholders (NASA, NRO, DoD, DARPA, USSF, NSF, etc.,)
- **Focus on Science Mission Directorate**
 - The Panel focused mainly on SMD since this appeared to be the NASA Directorate for which quantum sensors would be most impactful
 - Quantum sensing may also have considerable relevance to other Divisions/Directorates within NASA
- **Panel Findings, Observations, and Recommendations**
 - The Panel established 35 Findings, 3 Observations and 23 Recommendations

Bottom Line Upfront



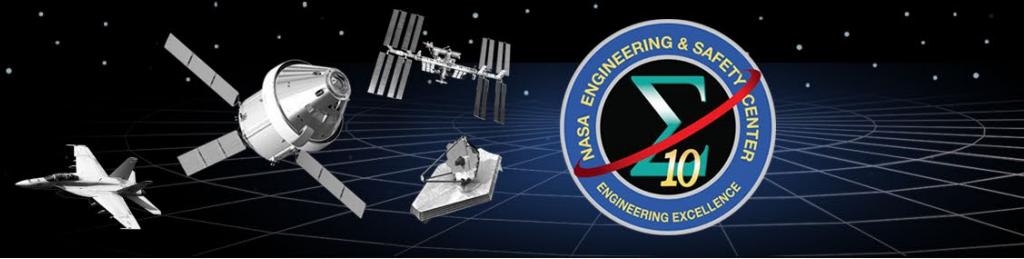
Overarching Assessment Findings

- F-1. Quantum sensors offer considerable benefits compared to classical sensors across a broad range of NASA missions and programmatic goals.
- F-2. Not all quantum sensors are better than classical sensor approaches. Many quantum sensors involve higher complexity and lower reliability than their classical counterparts.



Progressively more “quantum”

Key Findings: Near-Term Sensors



**Optical
interferometry**

Radar

RF Comms

Atomic and optical clocks

Atom interferometry

Rydberg sensors

Atom/Defect Magnetometers

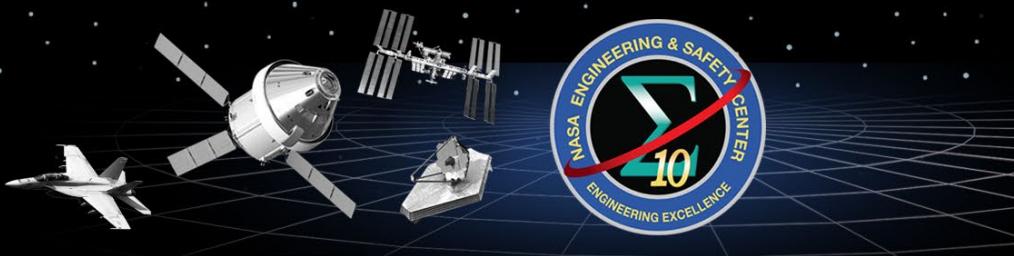
Non-classical light

Entangled photons

Progressively more “quantum”

1. Optical clocks (fundamental physics, GW detection beyond LISA, PNT)
2. Atom interferometry (gravity gravimetry/gradiometry, PNT, Earth/planetary science)
3. Compact quantum magnetometers (atomic, solid-state)
4. Rydberg rf/microwave sensing, colloidal QDs (spectrometry), passive quantum imaging
5. Superconducting photon detectors (TES, SNSPD)

Atomic Clocks



Quantum-mechanically defined energy levels in atoms

Microwave clocks: $\frac{\delta f}{f} \sim 10^{-11} - 10^{-16} \Rightarrow$ ns over hours, μs over days

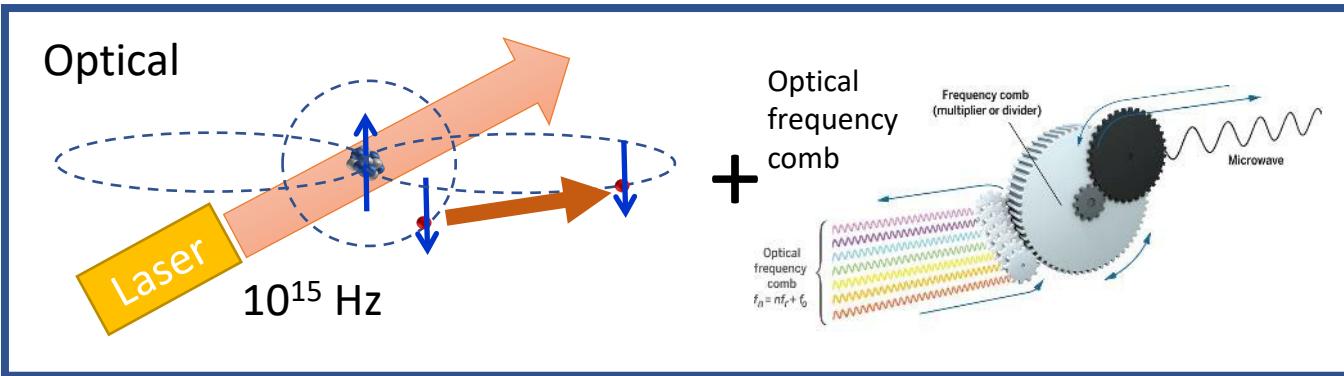
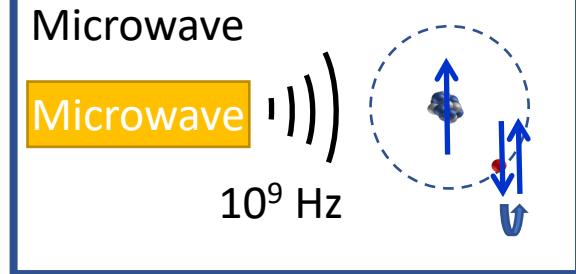
Optical clocks: $\frac{\delta f}{f} \sim 10^{-14} - 10^{-18} \Rightarrow$ ns over days, μs over years

Potential NASA uses

Fundamental physics

Deep space navigation

Deep space communications



Vapor cell microwave



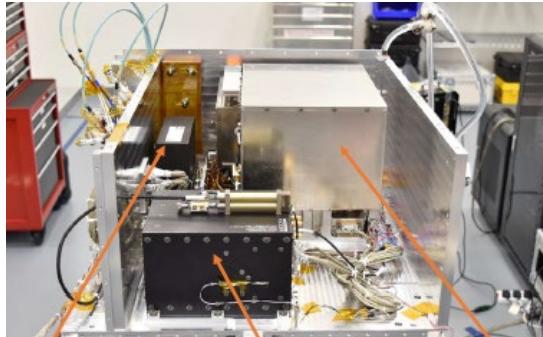
GPS Clocks, Rockwell/Efratom

Cold atom microwave



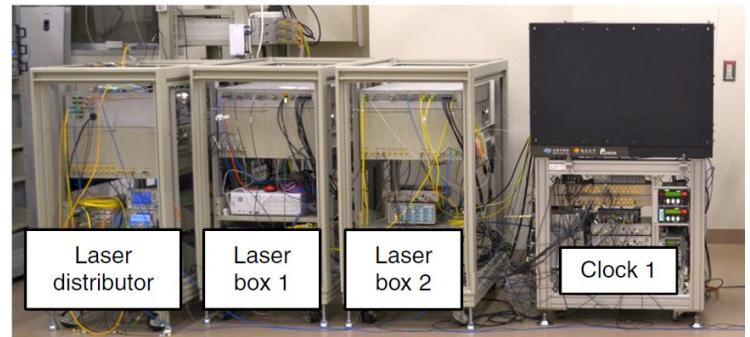
ESA ACES

Ion microwave



NASA DSAC

Neutral atom optical

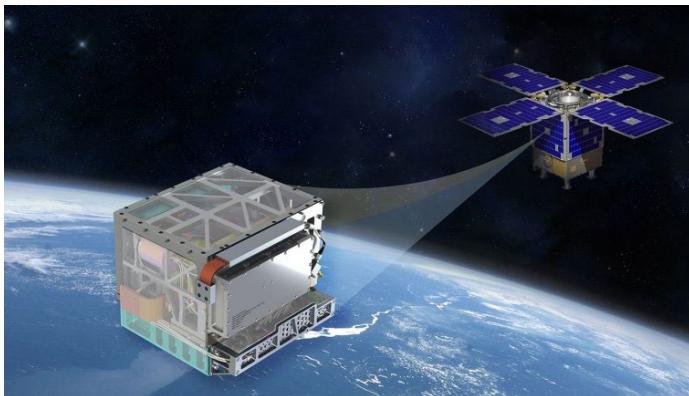


Riken (Japan)

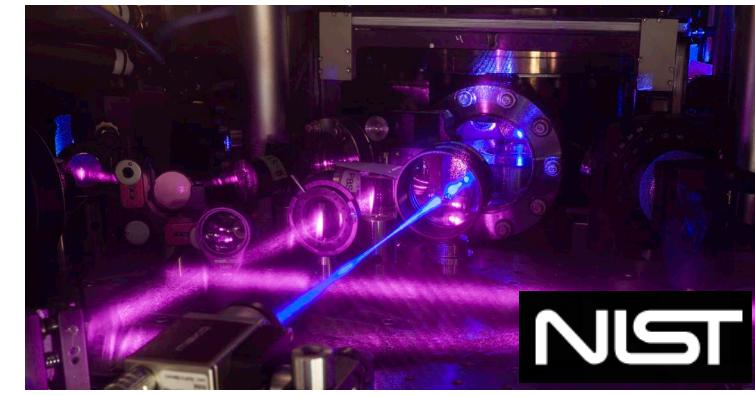
Optical Atomic Clocks



GPS
 $1 \text{ ms/day} = 300 \text{ km/day}$



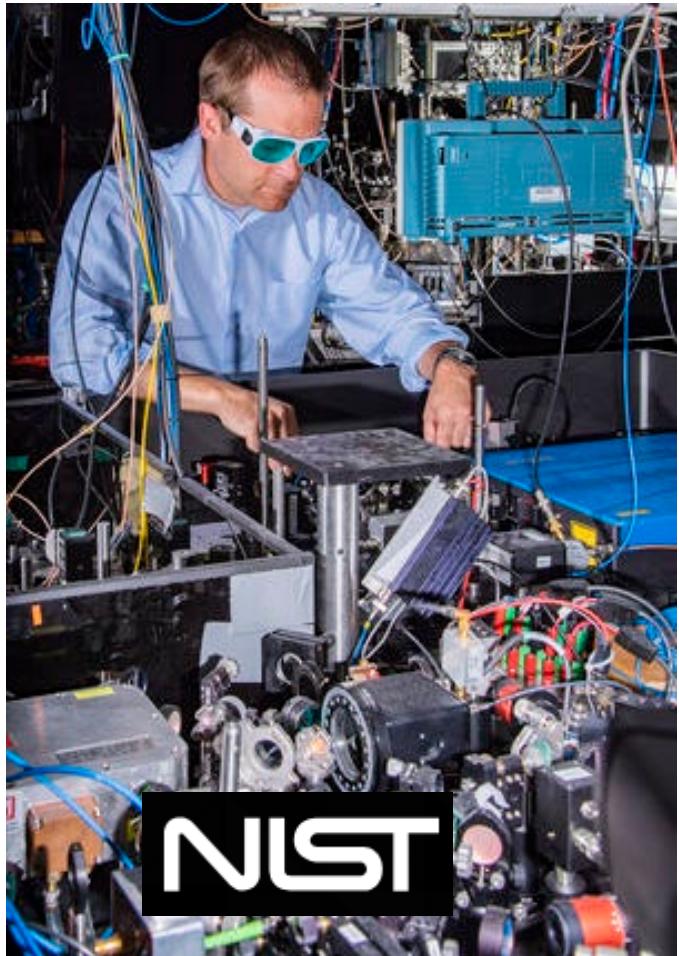
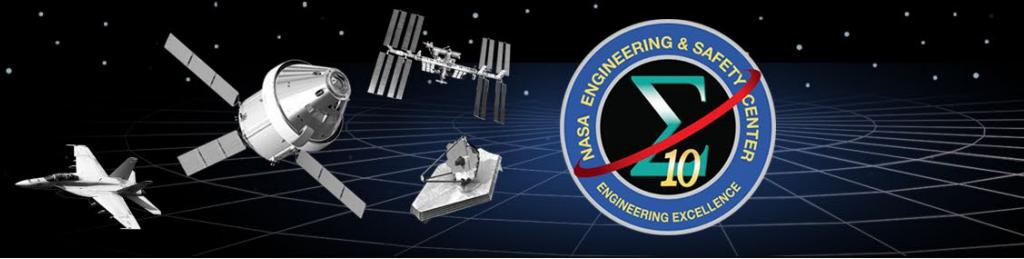
Deep Space Atomic Clock
(DSAC)
 $1 \text{ } \mu\text{s/day} = 1 \text{ km/day}$



Lab scale optical lattice
clocks
 $<1 \text{ ns/day} = <30 \text{ cm/day}$

Longer time stability = better positional accuracy

NASA Optical Atomic Clock Investment



Laboratory-scale performance

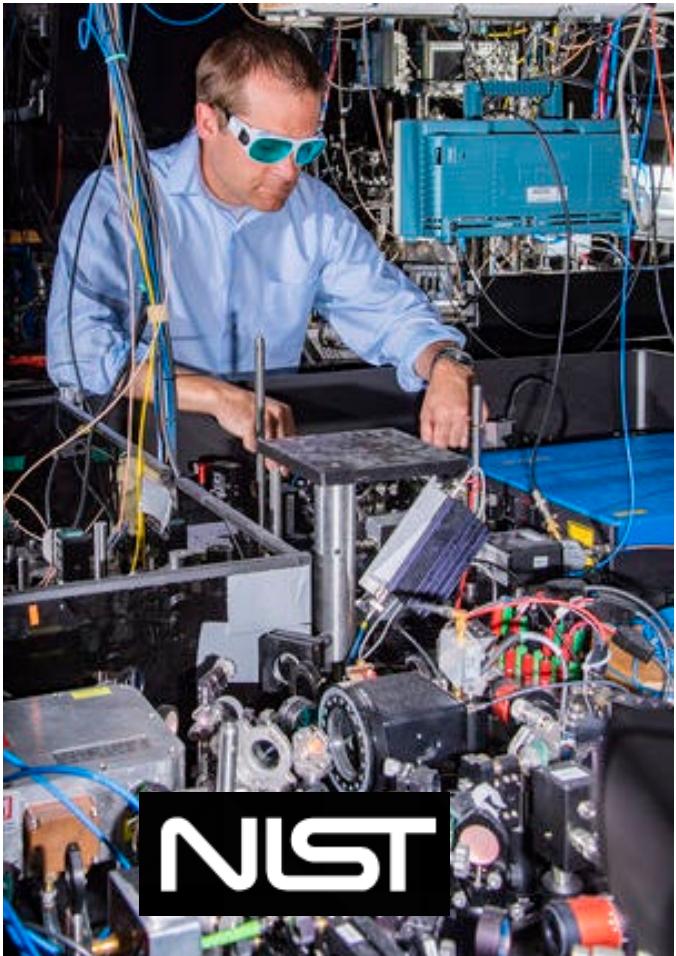


 **GENERAL ATOMICS**
ELECTROMAGNETICS

Space-qualified
form factor



NASA Optical Atomic Clock Investment

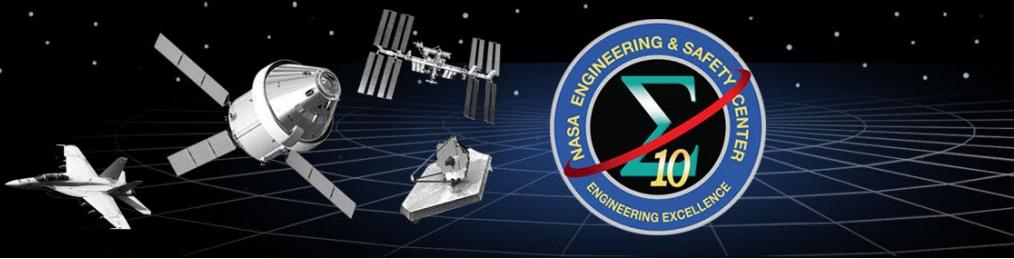


Technology Maturation

- DSAC Microwave Ion Clock
- SBIR investments
- Optical frequency combs
- Photonic integrated circuits



Atomic Magnetometers



Precession of electron spins in a magnetic field

- Good sensitivity
 - Earth's field \sim pT
 - Low field: sub-fT
- High accuracy \sim nT
- Good long-term stability

Potential NASA uses

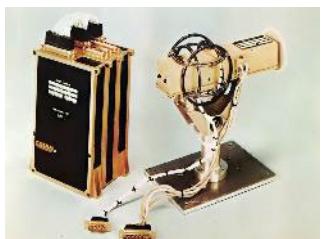
- Magnetic mapping of Earth and planets (dynamo)
- Measurements of solar wind, magnetosphere



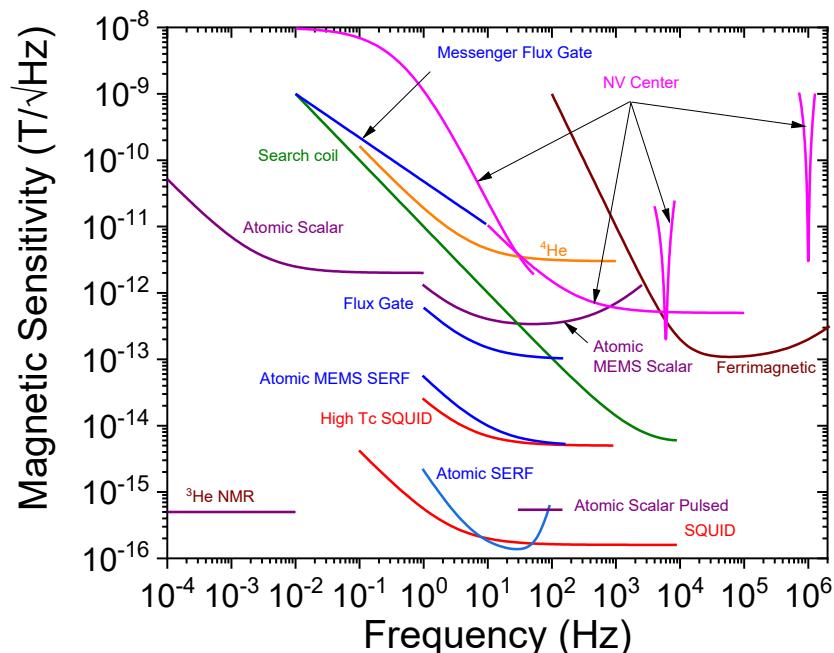
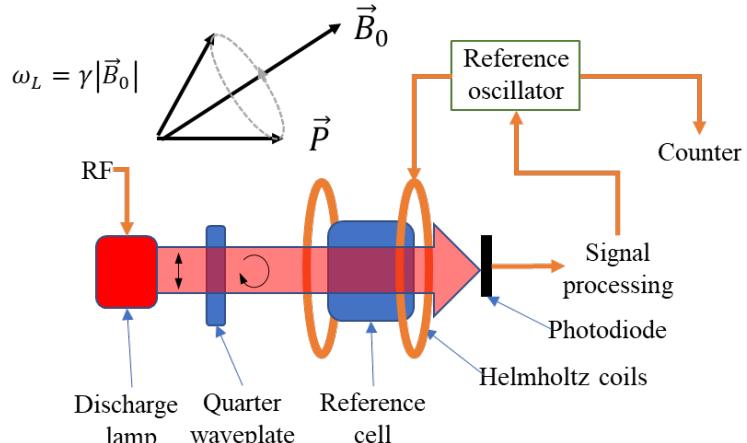
QuSpin



Geometrics



Pioneer 10, 11



Atom Interferometers



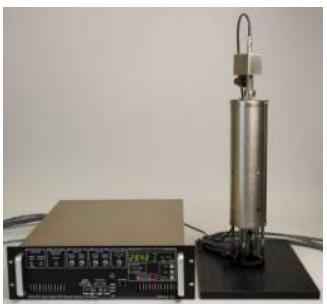
Interference of atomic wave packets: $\lambda_{db} \sim 10^{-11} \lambda_{opt}$

- Light pulse create beamsplitters and mirrors
- Phase shift determined by wavelength of light
- Accelerometers, gravity $\sim ng$
- Gyroscopes nrad/s
- Gravity gradients: $\sim ng$ over 1-m baseline

Potential NASA uses

- Inertial navigation
- Gravity mapping of Earth, planets

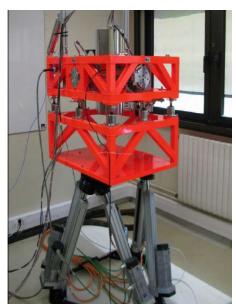
Commercial systems



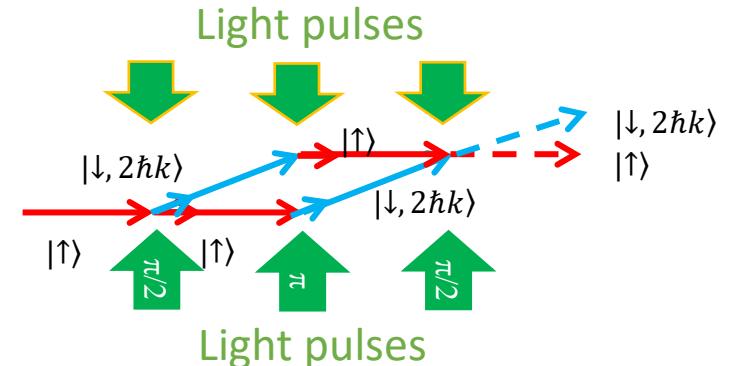
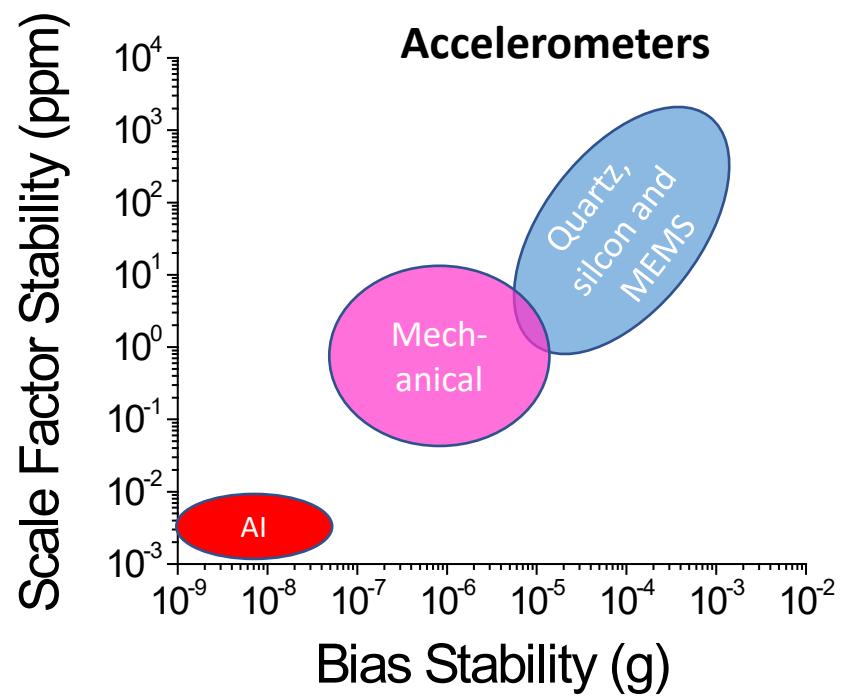
AOSense



iXblue



ONERA



Rydberg Sensors

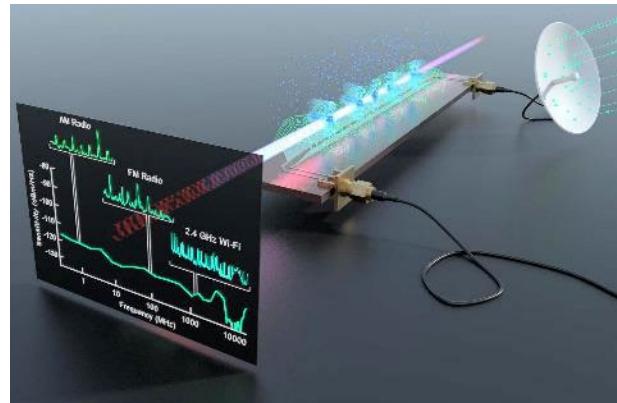


Electrons in large orbitals around atoms nucleus

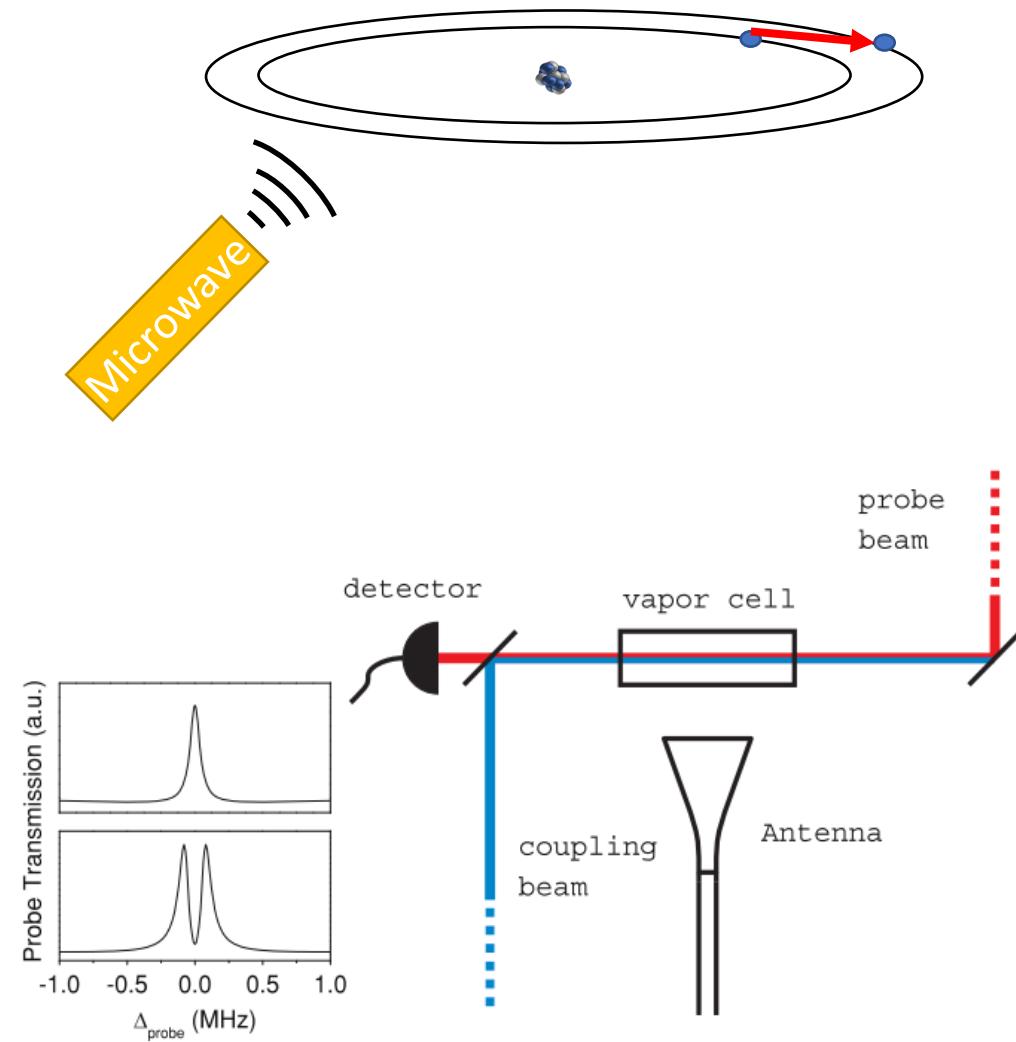
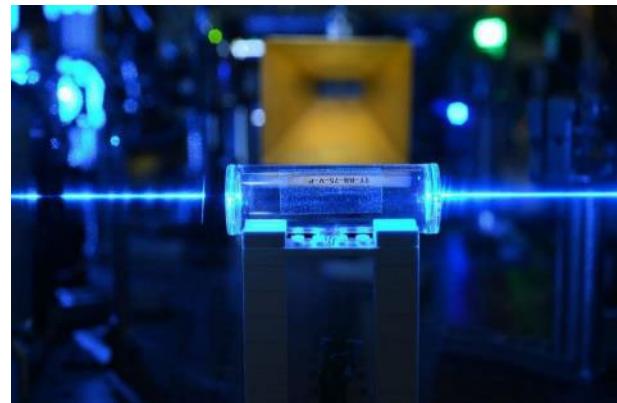
- Large electric dipole moments, very sensitive to electric fields
- RF Fields cause transitions between adjacent Rydberg levels
- Detect using lasers

Potential NASA uses

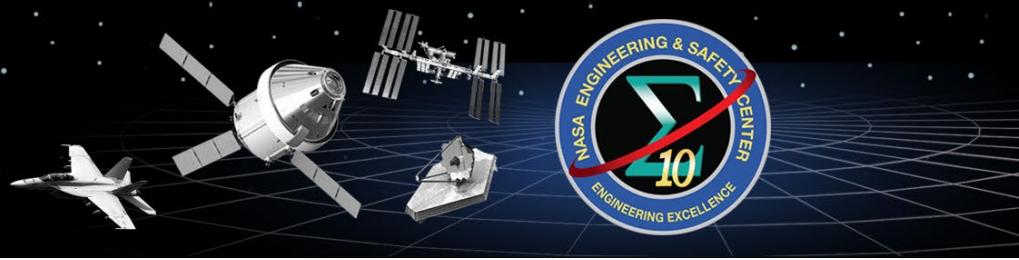
- Microwave receivers: MHz → THz
- DC electrometers



US Army



Single Photon Detectors: Superconducting Nanowires

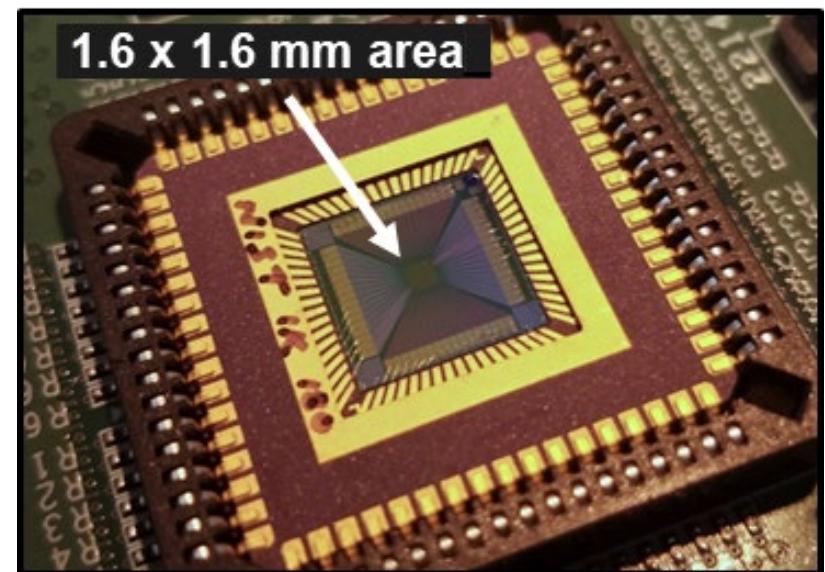
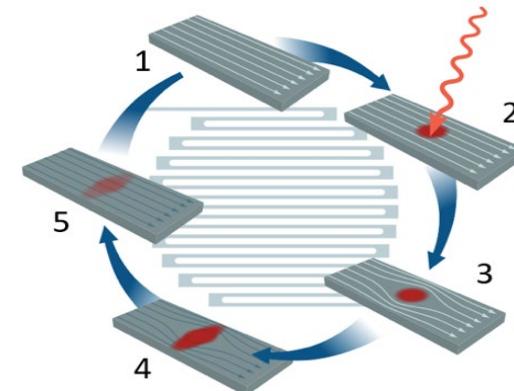


Photon energy causes phase transition in superconductor

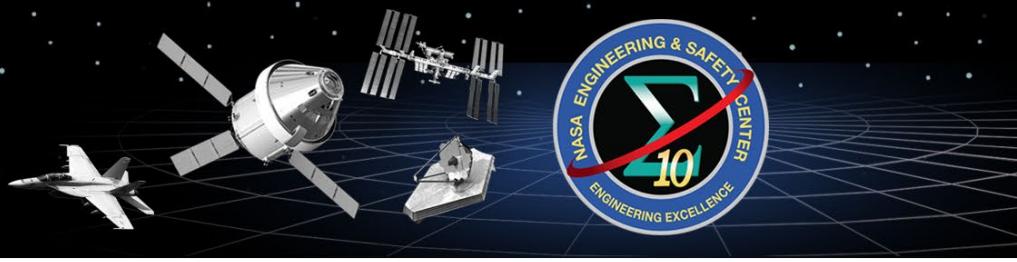
- High Efficiency
- Low Dark Counts
- UV – Mid-IR Operation
- Kilo-pixel Array Formats
- High Time Resolution
- High Event Rate

Potential NASA uses

- Low-light detection for astronomy/astrophysics
- Weak signal detection in communication systems
- Dark matter searches for fundamental physics

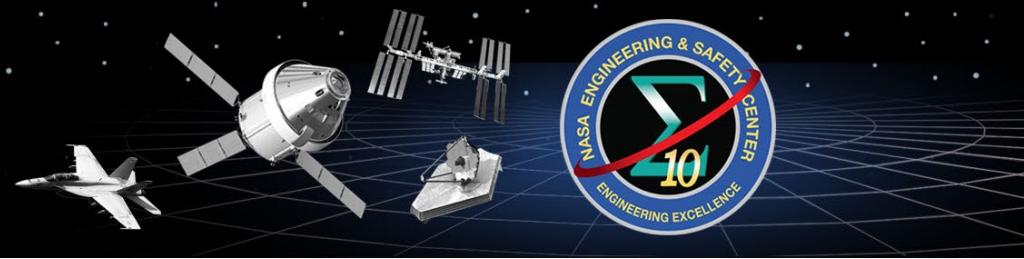


Most Promising Quantum Sensors for Future NASA Missions



1. Optical clocks for tests of fundamental physics, gravitational wave detection, and precise positioning of spacecraft
2. Transition edge sensors for X-ray detection with enhanced energy resolution for Heliophysics
3. Compact magnetometers for multi-satellite Earth and planetary science
4. Rydberg atoms for RF communication
5. Colloidal quantum dots for spectrometry
6. Atom interferometry for Earth science and hydrology
7. Solid-state quantum sensors for magnetic analysis and imaging of extraterrestrial rocks and minerals
8. Passive quantum imaging for low-light star tracking and passive navigation

REFERENCES



Independent Panel Report for Technical Assessment of NASA and External Quantum Sensing Capabilities Report, December 2023.

Dr. John Kitching (NIST), Prof. Prem Kumar (Northwestern University), Dr. Dana Berkeland (U.S. Government,), Dr. Danielle Braje (MIT Lincoln Laboratory), Dr. John Burke (U.S. Department of Defense), Prof. Saikat Guha (University of Arizona), Dr. AJ Metcalf (U.S. Space Force), Prof. Ronald Walsworth (University of Maryland)

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NASA/TM-20230018123, <https://ntrs.nasa.gov/search?q=20230018123>

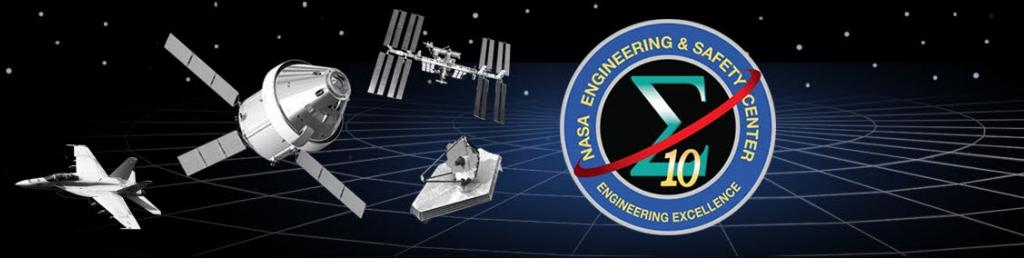
Proceedings of NASA Quantum Sensing Workshop (Newport News, Virginia, Sept 2022)

Editors: Dr. Upendra N. Singh, NESC Technical Fellow (NASA LaRC) and Dr. Jessica Gaskin, Deputy Technical Fellow (NASA MSFC)

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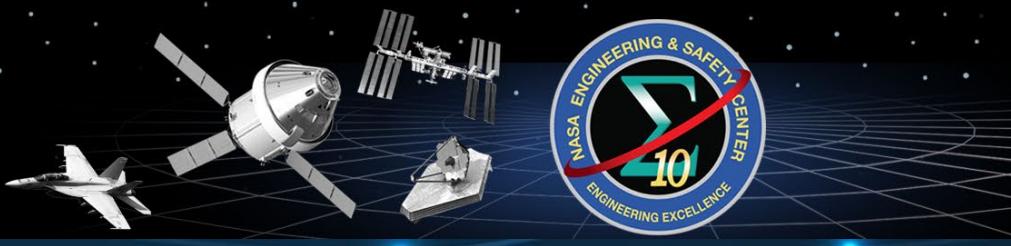
NASA/CP-20240004533, April 2024. <https://ntrs.nasa.gov/search?q=20240004533>

Questions?



BACKUP SLIDES

What is Quantum?



Classical

Superposition

RF Comm.
Radar

Light
Interferometry

Photosynthesis

Optical
Comm. Lidar

Classical/Quantum Boundary

Superposition &
Measurement

Quantum Sensing Zone

Atom
Interferometry

LIGO

Quantum
Simulation

Deep Quantum

Superposition,
Measurement, &
Entanglement

Quantum
Cryptography

Quantum
Computing

of quanta in superposition → progressively more quantum

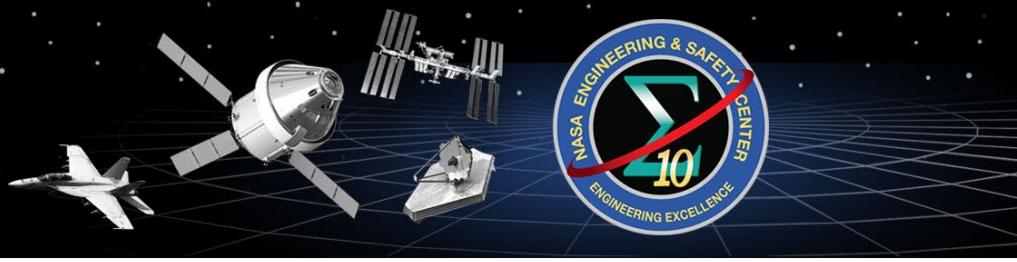
Photon Detection

Atomic Clocks, Magnetometers,
Rydberg Sensors

All regimes are interesting.

Never discard an idea because it isn't quantum enough!

Acknowledgements

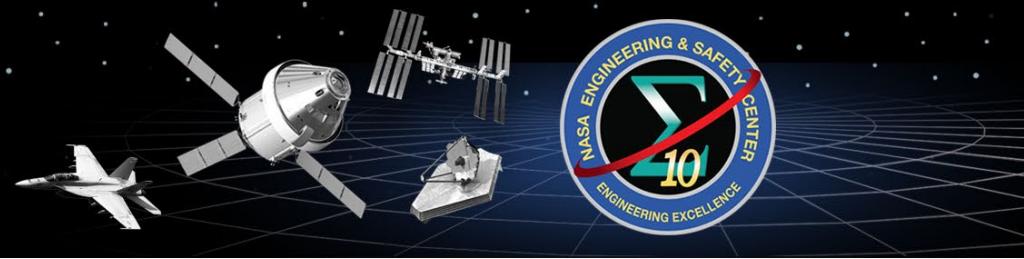


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Prof. Prem Kumar, Co-Chair	Quantum optics	Northwestern University
Dr. Danielle Braje	Atomic quantum sensors	MIT Lincoln Laboratories
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Problem Background



- Task 1: Develop a **methodology** to assess NASA's current QS capabilities
- Task 2: Conduct internally and externally sourced **information review** to establish the assessment knowledge base
- Task 3: The Panel shall **assess** NASA and External QS **capabilities** organizational entities
- Task 5: The Panel shall conduct research on the **industry capability**
- Task 6: The Panel shall develop findings and conclusions that describe **NASA's state of capability** relative to the near-term and far-term mission needs
- Task 7: The Panel shall provide an analysis of the **gaps** between the industry and agency and how these gaps present any risks to near-term, or far-term mission needs and shall recommend a list of possible solutions on how to close the gap(s)
- Task 8: The Panel shall make recommendations, based on their analysis, of the **most enabling QS areas** in short- and long-term for NASA to focus on
- Task 9: The Panel shall make recommendations, based on their analysis, of **how to establish, strengthen and maintain NASA QS capabilities** for the next 3 decades
- Task 10: The Panel shall make recommendations, based on their analysis, **how NASA should work with universities/industry/ other government agencies/federally funded research and development centers** and collaborate internationally

General: Findings/Observations

Findings:

- F-1 Quantum sensors offer considerable benefits compared to classical sensors across a broad range of NASA missions and programmatic goals.**
- F-2 Not all quantum sensors are better than classical sensor approaches. Many quantum sensors involve higher complexity and lower reliability than their classical counterparts.**

Atomic Clocks: Panel Findings/Observations

Findings:

- F-3 Optical atomic clocks now achieve relative uncertainties below 10^{-18} and have been engineered to fit in packages about the size of three filing cabinets.
- F-4 Ion microwave clocks have been flown in deep space with stability levels exceeding those of existing GPS clocks.
- F-5 The Chinese Space Agency has recently deployed a microwave clock based on laser-cooled neutral atoms in space and ESA has a planned launch of a similar clock in the next 5 years.
- F-6 Optical clocks, if deployed in space, would enable tests of fundamental physics with a precision orders of magnitude beyond previous or near-term planned missions based on microwave clocks.
- F-7 Optical clocks are complex systems with many optical components that do not have significant legacy deployment in space.

Observations:

- O-1 Most tests of fundamental physics using clocks in space require a high-performance time-transfer link to a ground-based clock.
- O-2 Optical time transfer links on the ground already exist capable of time comparison at 1 fs, or 10^{-18} over 1 hour. These links require direct line of site or optical fiber connections.

Atomic Clocks: Panel Recommendations

R-1 **NASA Biological and Physical Sciences (BPS) should pursue opportunities for deployment of such optical clocks in space for fundamental physics. Such clocks would be deployed in a small number (1 to 5) of medium-payload satellites. (F-3, F-5)**

NASA BPS should leverage collaborative opportunities with NIST and the U.S. Naval Observatory, as well as companies to advance the development of compact/portable optical lattice clocks with a size scale and laser-cooled ion optical clocks with accuracies below 10-17. This collaboration should focus on adapting current portable clock technologies for space environments and medium-scale (10 kW, 100 kG) satellite platforms. (F-3, F-6, F-30)

R-2 **NASA BPS and Earth Science Division (ESD) should begin/continue testing of “component-level” enabling technologies for optical clocks (lasers, modulators, optical switches, fiber-optics, etc.) in space-like environments to ensure no critical technologies will fail when deployed in space. (F-8)**

R-3 **NASA BPS should develop existing ground-based optical time transfer protocols for ground-space links and space-space links. (O-1)**

Magnetometers: Panel Findings/Observations

- F-8 Atomic magnetometers have been flown for decades in space and in fact were the first “quantum sensor” in orbit.
- F-9 Atomic magnetometers based on alkali atoms (Cs, Rb, potassium) can achieve fT sensitivity at very low SWaP. Such sensors can also have excellent accuracy, long-term stability and vector sensing capability, sometimes simultaneously. Atomic magnetometers outperform conventional approaches (e.g., fluxgate magnetometers) in almost every aspect with the exception of, perhaps, reliability.
- F-10 A new generation of commercial atomic magnetometers has emerged in the last decade based on new atom interrogation techniques (SERF, laser-driven) and new fabrication processes (silicon micromachining). These commercial sensors are now being deployed broadly in real-world environments for where reliability is of high importance.
- F-11 Multi-spacecraft missions and resource-constrained satellites are becoming more prevalent within NASA.
- F-12 Low-SWaP ^4He magnetometers are challenging because of the light sources needed for optical pumping: discharge lamps and distributed feedback lasers at 1083 nm consume considerable power.
- F-13 Solid-state quantum magnetometers offer the unique combination of high spatial resolution, good sensitivity, ability to measure vector fields, and very low drift.
- F-14 Solid-state quantum magnetometers can operate in harsh environments such as at elevated temperature.

Magnetometers: Panel Recommendations

- R-4** **NASA ESD and Planetary Science Division (PSD) should pursue compact alkali vapor cell magnetometers for multi-spacecraft missions on resource-constrained platforms with a view toward displacing existing classical magnetic sensing approaches (e.g., fluxgate magnetometers) within 10 years. (F-10)**
- R-5** **NASA ESD and PSD should consider new tethered or tether-free approaches enabled by low-SWaP sensors to allow magnetometers to be located away from magnetically dirty spacecraft. (F-10, F-12)**
- R-6** **NASA ESD and PSD should pursue atomic magnetometers for deployment CubeSat, nanosat, and chipsat platforms. (F-10, F-11)**
- R-7** **NASA ESD and PSD should pursue quantum solid-state magnetometers (e.g., quantum diamond microscope) for magnetic imaging of extraterrestrial rocks and minerals in ground-based labs (i.e., material from meteorites and/or returned by space missions). (F-14)**
- R-8** **NASA ESD and PSD should pursue quantum solid-state magnetometers for use in harsh environments. (F-15)**

Atom Interferometers: Panel Findings, Observations and Recommendations

Findings:

- F-15 Atom interferometers allow for accurate and stable measurements of acceleration/gravity, gravity gradients, and rotation.
- F-16 Atom interferometers have specific strengths for measuring inertial forces over long integration times (days to weeks) and also have excellent scale factor stability.
- F-17 Atom interferometers are moderately complex instruments requiring ultra-high vacuum systems, high-power lasers and an array of optical modulators, switches, and careful optical alignment. Compared to alternative classical inertial navigation technologies (ring laser gyros), atom interferometers appear too complex to be a likely candidate for inertial navigation on space-based platforms in the near term.
- F-18 Several companies have released atom interferometer gravimeter products in the last decade and some atom interferometers have been deployed on mobile platforms such as ships and aircraft.

Recommendations:

- R-9 NASA ESD should focus on the short-term goal of gravity gradiometry in low Earth orbit (LEO) for high-resolution hydrology and Earth science. (F-15, F-16)
- R-10 NASA PS should pursue the longer-term goal of deployment of atom interferometers in deep space for gravity measurements around other planets. (F-15, F-16)
- R-11 For inertial navigation, NASA STMD should consider navigation needs for deep-space missions where GNSS-free navigation may be needed over extended mission durations. (F-16, F-17)
- R-12 NASA ESD should continue its partnership with the private sector in developing atom interferometers to advance engineering for deployment in space. (F-18)

Rydberg Sensors: FORs

Findings:

- F-19 The use of Rydberg atoms as RF receivers has been under development for only about 10 years.
- F-20 Rydberg-based sensors can be quite simple, requiring only a vapor cell and two lasers. However, the lasers must be tuned to very specific wavelengths that are sometimes difficult to manufacture in a low-SWaP package.
- F-21 Existing Rydberg sensors have great promise but currently do not achieve sensitivity levels comparable to existing antenna-based technologies. While there is considerable research activity in this area largely funded by DARPA, the advantages of Rydberg-based receivers compared to conventional antenna-based detection are currently unclear but are likely to be more clearly defined in the coming 5 years.
- F-22 Rydberg-based RF field sensors can potentially enable unique sensing modalities such as very broadband sensing from MHz to THz, reconfigurable directional field sensing

Recommendations:

- R-13 NASA STMD should engage with other agencies (DARPA, NIST) developing such sensors to monitor advances and clarify advantages over conventional antenna-based approaches. (F-19, F-21)
- R-14 NASA STMD should invest in basic research to address basic technology challenges related to Rydberg-based receivers such as cell fabrication, laser development and charge neutralization. (F-19, F-20, F-22)

Single Photon Detectors: FORs

Findings:

F-23 Cryogenically cooled single-photon detectors now achieve quantum efficiencies approaching 100%.

F-24 **Arrays of such sensors are being developed for imaging applications.**

F-25 These sensors are sensitive over a broad wavelength range from the mid-IR to the UV and could form the basis of future electromagnetic imaging systems.

Recommendations:

R-15 NASA Astrophysics Division (APD) should invest to advance arrays of cryogenically cooled, high-efficiency single-photon detectors (transition-edge sensors, superconducting nanowire single-photon detectors, etc.) for imaging. (F-23, F-24)

R-16 NASA APD should consider the broad frequency range in the electromagnetic spectrum over which single photon detectors (SPDs) can operate and match this to specific detection needs. (F-23, F-25)

R-17 NASA APD should develop space-qualified cryogenics to support eventual deployment of SPDs in space. (F-24)

Squeezing and Entanglement: Findings

- F-26 Squeezed or entangled states of atoms (deep quantum) and light have been produced with up to 20 dB of noise suppression below classical limits. These states have potential to significantly improve the performance of atomic clocks, magnetometers and atom interferometers. However, to date none of the best clocks take advantage of this potential resource due to the complexity of implementing it and the fragility of such quantum states once created.
- F-27 Squeezed states of light are currently used to advantage in the LIGO, providing meaningful enhancement of source detection. LIGO is one of the very few applications for which deep quantum has been shown to be metrologically useful.
- F-28 Distributed parameter estimation can benefit from availability of quadrature entangled light with large number of modes.
- F-29 The advantage associated with “deep quantum” depends on the constraints imposed on the system.
- F-30 A primary advantage deep quantum offers for sensing is increased sensor bandwidth. Spin squeezing has already enabled bandwidth enhancement in atomic magnetometry *and* may offer opportunities to enhance the performance of optical clocks by relaxing the requirements on local oscillator performance.
- F-31 Because of the complexity of generating such states and the fragility of these states once created, “deep-quantum” entanglement and squeezing is likely to be most important in highly controlled environments where loss and relaxation can be carefully controlled.

Squeezing and Entanglement: Recommendations

- R-18 NASA APD and BPS should invest in ground-based atomic sensors based on entanglement with the goal of achieving superior performance to non-entangled sensors for those parameters relevant to NASA mission needs. (F-26)**
- R-19 NASA APD and BPS should invest in developing quadrature entangled light sources that entangle a large number of degrees of freedom. (F-27, F-28)**
- R-20 There may be certain niche applications for which such technology would be beneficial. For example, squeezed states of light are currently used in LIGO to enhance performance in a meaningful way. NASA APD and BPS should look out for these and invest as appropriate but should carefully consider the tradeoffs that the implementation of such approaches imply with regard to system complexity and deployment in space. (F-26, F-30, F-31)**

Interagency Collaboration: FORs

Findings:

- F-32** There is already considerable activity in quantum sensing outside of NASA over the entire range of academia, government and industry. Existing quantum sensing within NASA is comparatively limited.
- F-33** Other government laboratories have considerable expertise in quantum sensing (e.g., NIST for clocks, Sandia National Labs for photonics, etc.).
- F-34** Much of this activity predates the National Quantum Initiative, which has considerably enhanced this activity, especially through NSF and DOE, both of which have established a series of centers for focused research on quantum sensing.

Recommendation:

- R-21** NASA should focus its activity on adapting existing research in QS for space in collaboration with outside experts, where that expertise exists. This would advance NASA's mission more effectively than starting new programs from scratch or working in parallel with much larger organizations employing far more people. (*F-32, F-33, F-34*)

Workforce Development: FORs

Finding:

F-35 The rapid expansion of commercial quantum-computing companies over the last decade has drawn many young scientists, depleting the number of quantum-trained scientists available for more traditional career paths in government labs and academia. This is causing a drop in early career scientists available for post-doctoral and entry-level positions across the government.

Recommendations:

R-22 NASA should significantly increase the number of graduate fellowships it allocates to graduate students at universities focused specifically on quantum information science and technology. *(F-35)*

R-23 NASA should consider looking outside the U.S. for talent in quantum sensing within the limits imposed by information security requirements. *(F-35)*