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

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(NESC-TI-21-01685)

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1.0 Signatures

Delivered to the NESC by:

Original signatures on file.

Dr. John Kitching	Dr. Prem Kumar

2.0 Background

The Subject Matter Experts in the Sensors and Instrumentation Quantum Sensing Community of Practice requested an independent technical assessment of the agency's capabilities in quantum sensing to understand NASA's internal competencies related to quantum sensing and compare agency capabilities with those available externally including in industry, academia, and other government agencies.

3.0 Panel Members

Name	Discipline	Organization
Panel		
Dr. John Kitching, Co-Chair	Atomic quantum sensors	National Institute of Standards and Technology
Prof. Prem Kumar, Co-Chair	Quantum optics	Northwestern University
Dr. Danielle Braje	Atomic quantum sensors	MIT Lincoln Laboratories
Dr. Ronald Walsworth	Atomic quantum sensors	University of Maryland
Prof. Saikat Guha	Quantum optics	University of Arizona
Dr. AJ Metcalf	Optical quantum sensors	U.S. Space Force
Dr. Dana Berkeland		U.S. Government
Dr. John Burke		U.S. Department of Defense

4.0 Summary

Sensors based on quantum mechanical properties of electromagnetic radiation and matter offer unique capabilities and performance sometimes difficult to achieve using classical approaches. This report assesses the suitability of quantum sensing for current and future NASA needs, with a specific focus on NASA's Science Mission Directorate (SMD). Measurement and sensing needs across NASA SMD are reviewed as a driver for the possible incorporation of existing quantum sensors into the NASA portfolio and the development of next-generation quantum sensors. A range of quantum sensing modalities is then described and the current state of the art for each sensor is presented. Current research and development activities on quantum sensing within NASA are compared with the range of activities ongoing throughout the broader scientific community, both within the United States and internationally. In conclusion, there is considerable advantage to be gained by NASA from quantum sensors through the growth of internal programs and collaboration with outside entities.

5.0 Components

This work was carried out beginning in March 2022 and ran through June 2023; and was comprised of three main components.

1. A survey was sent to the Chief Technologists of the NASA Research Centers and select non-NASA centers during the summer of 2022 to gather information about existing programs in quantum sensing at NASA. Reponses were received from the Jet Propulsion Laboratory (JPL), Goddard Space Flight Center (GSFC), Glenn Research Center (GRC), and the Kennedy Space Center. The survey indicated that most, but not all, areas of quantum sensing were under development at some level within NASA. In some areas (for example, the Deep Space Atomic Clock) it was found that internal NASA programs were

on the leading edge of research and development, while in other areas (for example, gravimetry with atom interferometers) NASA was leveraging collaborations with external partners. The results of the survey are compiled within each of the technical areas of the Quantum Sensing Technologies section (Section 8.0).

2. A workshop entitled “NASA Quantum Sensing Workshop” was held on September 27 through 29, 2022, in Newport News, VA. This workshop brought together senior leadership within NASA, technical experts within the quantum sensing community, and external stakeholders from the National Science Foundation, the United States (U.S.) Space Force, etc. The workshop consisted of presentations from leading representatives and discussion sessions during which participants were able to contribute their thoughts and ideas. The first day of the workshop focused on NASA needs and featured representatives from each of the NASA Divisions and Directorates most involved with quantum sensing. The second day focused on specific quantum technologies, with talks being given by technical experts in each area. The third day focused on synergistic activities, workforce development and other peripheral but important elements which could benefit NASA as it develops its quantum sensing program.
3. Finally, limited engagement with international partners was carried out with the goal of understanding the international stage for quantum sensing in space.

Inputs from all these sources have been synthesized in this report.

6.0 Introduction

Quantum mechanics deals with the nature and dynamics of physical systems at the subatomic scale. At such scales, measurements on particles necessarily perturb them in a manner that makes complete information about the particle fundamentally unknowable. Some of the foundational principles of quantum mechanics that are of particular relevance to quantum sensing are:

1. Wave-particle duality: physical systems traditionally viewed as “particles” (electrons, atoms, etc.) have a wavelike nature and systems traditionally viewed as waves (light, mechanical vibrations) have a particle-like nature.
2. Superposition: particles can simultaneously exist in multiple “states” and measurement of a particle results in only one of a well-defined (quantized) set of possible outcomes.
3. Entanglement: many-particle systems can exhibit quantum-mechanical correlations such that a measurement of a particular physical observable on one entangled particle will non-classically affect the probability of a measurement on another particle regardless of their proximity.
4. Correspondence Principle: when the number of particles in a system gets very large ($N \rightarrow \infty$), quantum mechanics approaches classical mechanics, and all noise associated with quantum measurement vanishes.

Among the central tenets of quantum mechanics is the concept of quantized energy levels in systems with a small number of fundamental particles. Electrons in unperturbed atoms, for example, can only exist in well-defined energy states with respect to the nucleus. Similarly, optical fields can only exist in well-defined energy states with respect to a spatial-temporal mode. This quantization has significant implications with regard to sensing. Quantization of energy in atoms is precisely what makes atomic clocks the most stable and accurate instruments for measuring time. Since every atom is nominally identical if subjected to the same external fields, an atomic clock based on one atomic species will tick at exactly the same rate as every other clock based on the same species, regardless of where it is in the universe and when it is measured and therefore provides a universal measure of time. It is for this reason that in 1967, the definition of the second was changed from being based on astronomical effects (the ephemeris year) to the inverse of the frequency corresponding to the 9.2 GHz transition between the quantum-mechanically defined energy levels in the ground state of the cesium (^{133}Cs) atom.

Another central tenet of quantum mechanics is the idea that information one can know about physical systems is fundamentally limited. If, for example, one attempts to measure the position of a particle precisely, the act of measuring it disturbs the momentum of the particle in an unpredictable way making a simultaneous infinitely precise measurement of the complete state of the particle impossible. This limitation is described precisely by the Heisenberg Uncertainly Principle as $\Delta x \Delta p \geq h$, where Δx and Δp are the uncertainties in the measurement of position and momentum, respectively, and h is Planck's constant. This principle fundamentally adds "quantum noise" to the measurement of complementary physical quantities, which limits the resolution of such measurements for small numbers of particles (photons, phonons, atoms, etc.). The Heisenberg limit scales as $1/N$ where N is the number of particles being measured and can be understood intuitively as a counting error: when counting discrete quantized events, the minimum error is unity. In the classical limit or large, macroscopic systems, $N \rightarrow \infty$ and arbitrary measurement precision can in principle be obtained.

For a system containing $N > 1$ particles, the Heisenberg limit is achieved for very specific system states that necessarily involve entanglement (inter-particle quantum-mechanical correlations) between the particles. For uncorrelated particles a second limit applies, usually referred to as the standard quantum limit (SQL), which scales as $1/\sqrt{N}$. This can be understood intuitively as the error resulting from a random distribution of binary outcomes for a series of N measurements. Much of the work in quantum sensing involves the generation of entangled states (of photons, atoms, or phonons) that allow measurement precision beyond the SQL. For example, the Laser Interferometer Gravitational Observatory (LIGO) currently uses quantum-mechanically correlated photon states, namely, squeezed-vacuum states of light, to read out the position of the test masses to better than the SQL allows. So clearly the use of such states can benefit sensing in fundamental ways.

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.

A more stringent definition of "quantum sensing" would include only sensors that specifically include entanglement. For example, photon-number-resolving light detectors are capable of measuring quantum states of light that contain entanglement. And atomic ensembles can be prepared containing entanglement that can overcome the $1/\sqrt{N}$ SQL and hence result in a higher measurement precision than can be achieved with a non-entangled sensor.

Whether or not entanglement is used, a sensor's performance is often determined by a large number of factors, some entirely unrelated to quantum mechanics. Thermal noise resulting from dissipative processes at temperatures above absolute zero is one example. Another is relaxation, caused for example by spontaneous radiative emission of light from an atom in an excited state or collisions between atoms. Such relaxation limits the time over which fully coherent measurements can be made. Finally, fields near an atomic sensor can change the atomic energy level spacings and hence the sensor's output which ultimately results in a measurement error.

6.1.1 Atoms, Photons and Phonons

Quantum sensors can be broadly categorized into three types, loosely focused on the quantum-mechanical particles of atoms, photons, and phonons:

1. Sensors based on quantized energy levels in atoms. Such sensors include microwave and optical atomic clocks, atomic (optical) magnetometers, Rydberg-based radio frequency (RF) field sensors, nitrogen vacancy (NV)-center magnetometers and atom interferometers. These sensors are typically operated at the quantum/classical boundary without interparticle entanglement and operate near or at the standard quantum limit. However, the atoms in these sensors can also be initialized in entangled or "squeezed" states, which can enhance the performance beyond the SQL at the cost of increased complexity as described below.
2. Optical sensors based on the detection of single photons or quantum-mechanically correlated optical fields such as squeezed states. Such sensors include photomultiplier tubes, transition-edge sensors, superconducting nanowire single-photon detectors and systems utilizing squeezed states of light. Such sensors and systems can make measurements with sensitivity beyond the SQL.
3. Resonant mechanical sensors cooled to near their quantum-mechanical ground state. This category includes solid-state micro- and nano-mechanical resonators and trapped particles such as ions, neutral atoms, or nanospheres.

6.1.2 Superposition, Measurement and Entanglement

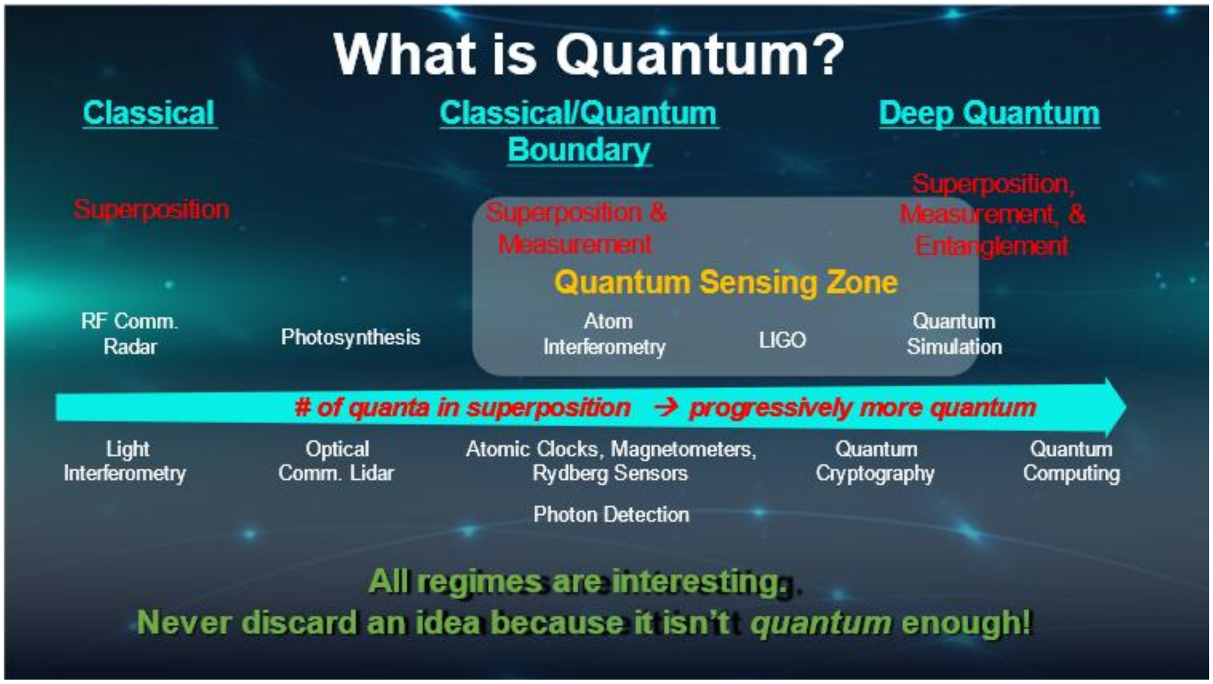
Fundamentally, all physical phenomena in nature are quantum mechanical and must be describable in terms of the quantum principles of superposition, measurement, and entanglement. Superposition is wavelike behavior that is obeyed equally by classical waves such as water waves or the sound waves and by the quantum mechanical amplitudes describing an electron wave packet or the Maxwell field of a photon. Measurement is the quintessential principle that distinguishes quantum behavior from classical. Like the fable of 'Six Blind Men and the Elephant,' the outcome of a measurement depends on how the measurement apparatus is set up (where the blind man is standing) in relation to what is being measured (the elephant). In contrast, in classical physics the measurement apparatus can, in principle, be designed and set up independently of any system quantity it might be used to measure. Systems and applications wherein both superposition and measurement dictate the outcome can be considered to lie on the classical quantum boundary. On the other hand, if the role of measurement turns out to be inconsequential, systems and applications fall solidly in the classical realm in the systems and applications referred to above, superposition and measurement apply to a single quantum particle (electron, photon, neutron, etc.) or quasi-particle/ excitation (phonon, exciton, magnon, etc.). Even though the system might be using many particles to drive the application at hand, the large number of particles is relevant only for the purpose of the usual statistical improvement of the signal-to-noise (SNR) ratio, which grows only as a square root of the number of particles used. Technologies that use the principles of superposition and measurement are often referred to as

Quantum 1.0, and those that incorporate squeezing and entanglement are often referred to as Quantum 2.0.

Entanglement takes systems and applications into a deeper quantum realm. Entanglement refers to the intertwining that occurs when superposition and measurement apply to more than one quantum particle simultaneously. The two or more particles need not be co-located and can in principle be on far corners of the universe. All the entangled particles evolve as a single quantum-wave amplitude obeying superposition and responding to interactions that might be occurring among the particles, with their external environments, or with measurements purposely set up to drive an intended application. Systems based on entanglement can provide an inherent quantum advantage in terms of the achievable SNR in an application. For example, as described above, the SNR can grow as the number of particles used instead of the square root, which can be a tremendous advantage when the number is large (ten times, for example, in an application utilizing 100 entangled particles).

The larger the entangled quantum system, the more sensitive it is to influencing factors not under the system's control. These uncontrolled perturbations independently jiggle the quantum wave amplitudes of the various particles in the multi-particle quantum superposition and wash out the delicately balanced quantum features and the accompanying quantum advantage. Such uncontrolled perturbation is referred to as decoherence and larger quantum systems are progressively more susceptible to decoherence. Phenomenon and systems in day-to-day experience behave classically, obeying the laws of classical physics. This is precisely because of environmental decoherence, which robs the macroscopically large quantum systems of their delicate superpositions and renders them essentially classical. Controlling decoherence, for example by engineering the entangled system to protect it from the environment, is therefore essential in order to extract the available quantum advantage.

Technologies, whether nascent or already fielded, can be classified by their "quantumness" based on how essential the principles of superposition, measurement, and entanglement are at their core. Figure 6.1-1 places many important technologies on such a notional scale where quantumness increases to the right. As shown, mature technologies such as radar and RF communications (wireless telephony) lie in the classical domain because the quantum nature of measurement is inconsequential in such systems. Other technologies such atom interferometry or light interferometry with photon detection fall at the classical/quantum boundary because both superposition and measurement play an essential role. In contrast, technologies such as quantum simulation or quantum computing lie solidly in the deep quantum regime because entanglement is essential for the quantum advantage they promise.



What is Quantum?

Classical

Classical/Quantum Boundary

Deep Quantum

Superposition

Superposition & Measurement

Superposition, Measurement, & Entanglement

Quantum Sensing Zone

RF Comm. Radar

Photosynthesis

Atom Interferometry

LIGO

Quantum Simulation

# of quanta in superposition → progressively more quantum

Light Interferometry

Optical Comm. Lidar

Atomic Clocks, Magnetometers, Rydberg Sensors

Photon Detection

Quantum Cryptography

Quantum Computing

All regimes are interesting.

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

Figure 6.1-1. "Quantumness" Assessment of Key Quantum-Sensing Technologies "Quantum 1.0" technologies take advantage of superposition and measurement and are therefore located in the middle of the continuum. "Quantum 2.0" technologies are located toward the right.

Harnessing the quantum advantage requires engineering quantum systems to protect them from the deleterious effects of environmental decoherence. Such quantum engineering is not trivial even though engineered systems (mechanical, electrical, structural, biomedical, chemical, etc.) have been around for hundreds of years and there are well established industries and academic disciplines continually advancing them.

The example of quantum computing, which lies in the deep quantum regime in Figure 6.1-1, relies on the qubits—quantum bits which form the computing substrate akin to the classical bits of an ordinary computer. Unlike classical bits, which can only be states 0 or 1, quantum bits can additionally be in superpositions of states of 0 and 1. In order to realize the faster processing times of a quantum computing machine, such superpositions must allow simultaneous operations on almost all strings of bits, which when combined with an appropriate algorithm leads to the quantum speedup. The qubits must be isolated from the environment to prevent decoherence but must also interact with the outside world in just the right way to accept the instructions of a quantum algorithm for a given task and to produce the result when the task is completed. This delicate balance between isolation and interaction makes control of quantum computing systems extremely difficult to engineer. Physicists have devised techniques such as quantum error correction which allow control of decoherence in just the right way for the computation to proceed. Much of this progress has been motivated by the invention of the Shor factoring algorithm in 1994 [ref. 1], which threatened the public-key infrastructure on which all of e-commerce is based but required a quantum computer to run on. While tremendous progress has been made over the last two decades, the realization of a quantum computer that implements Shor's factoring algorithm is still decades away.

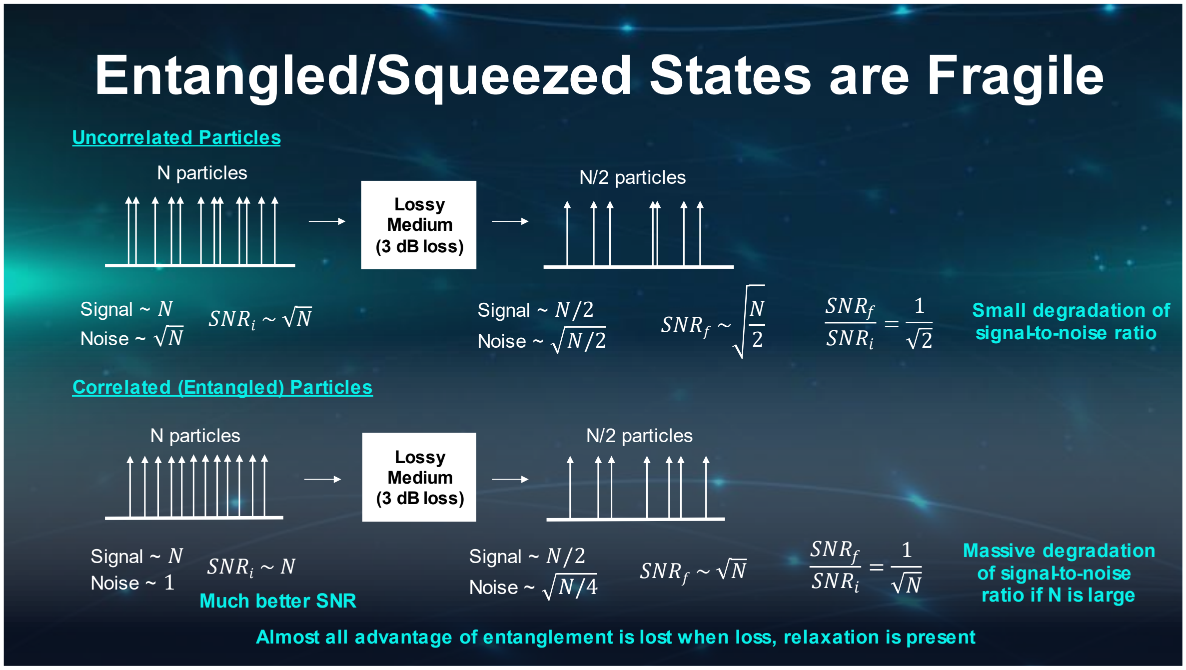
The engineering challenges in building a quantum computer, irrespective of the underlying qubit physics and technology, are multifold. As argued above, the decoherence must be controlled in just the right way for the quantum superpositions of a large entangled system to run coherently and for the external controls to be applied appropriately in order to run the quantum algorithm. This means that the collection of qubits, the computing core, must be surrounded by, or embedded in, technologies that lie themselves on the quantum/classical interface, i.e., technologies that have been perfectly engineered and whose performance is only limited by the quantum principles of superposition and measurement in the “quantumness” hierarchy presented above. Similarly, the whole system that needs to work in the classical world must be surrounded by perfectly engineered classical technology. What is clear from this discussion is that the quest for quantum computing will take considerable time and along the way many fruitful technologies that lie on the quantum/classical interface are likely to be engineered and spun off with concomitant societal benefits.

6.2 Caveats with Respect to Use of Quantum Sensors

The use of quantum mechanics in a sensor does not normally in-and-of-itself imbue any inherent advantage compared to classical sensing modalities. The benefit gained by the use of entanglement and squeezing is closely associated with constraints imposed on the system. If, for example, the number of particles in a system is limited to N (for example because increasing the density of particles causes stronger interparticle interactions and therefore relaxation), entanglement can in principle improve the sensor performance by a factor of $\sqrt{N}$. However, if the number of particles is unconstrained, a quantum-mechanically correlated (entangled) ensemble of N_1 particles would be less sensitive than a non-entangled sensor with a larger number, N_2, of particles if $\sqrt{N_2} > N_1$.

Furthermore, quantum inertial sensors may be far less useful than their classical counterparts if they are excessively complex or do not meet reliability requirements. What matters for sensing in the end is the performance of the instrument, and not whether it incorporates quantum phenomena. When assessing the suitability of any quantum sensor for a proposed mission, a quantum-based approach should be compared with classical alternatives across the range of performance and development requirements, including aspects such as size, weight, power consumption, complexity and development time and cost.

A particularly important aspect of squeezing- and entanglement-based quantum technology is the sensitivity to loss and relaxation. In the presence of such effects, the advantage gained by these deep quantum approaches can be degraded almost completely. Consider, as an example, the case of an optical field passing through a lossy medium, as shown in Figure 6.2-1. In the case of an optical field of uncorrelated particles with no squeezing, a loss of 3 dB reduces the SNR by a factor of $\sqrt{2}$ from $\sqrt{N}$ to $\sqrt{N/2}$ where N is the number of particles (photons) being detected. For a perfectly correlated particles in an amplitude squeezed state, the SNR before the lossy medium is much higher than for the unsqueezed state and equal to N. After the lossy medium, the SNR has degraded to $\sqrt{N}$, which is only a factor of $\sqrt{2}$ better that the uncorrelated state. A similar argument applies for atomic systems where relaxation is the cause of the degradation of quantum correlations.



Entangled/Squeezed States are Fragile

Uncorrelated Particles

N particles

Lossy Medium (3 dB loss)

N/2 particles

Signal ~ N

Noise ~ $\sqrt{N}$

$SNR_i \sim \sqrt{N}$

Signal ~ $N/2$

Noise ~ $\sqrt{N/2}$

$SNR_f \sim \sqrt{\frac{N}{2}}$

$\frac{SNR_f}{SNR_i} = \frac{1}{\sqrt{2}}$

Small degradation of signal-to-noise ratio

Correlated (Entangled) Particles

N particles

Lossy Medium (3 dB loss)

N/2 particles

Signal ~ N

Noise ~ 1

$SNR_i \sim N$

Much better SNR

Signal ~ $N/2$

Noise ~ $\sqrt{N/4}$

$SNR_f \sim \sqrt{N}$

$\frac{SNR_f}{SNR_i} = \frac{1}{\sqrt{N}}$

Massive degradation of signal-to-noise ratio if N is large

Almost all advantage of entanglement is lost when loss, relaxation is present

Figure 6.2-1. Effects of Loss on Quantum-mechanically Correlated Systems

When quantum-mechanically uncorrelated particles pass through a medium with 3 dB of loss, the SNR is reduced by a factor of $\sqrt{2}$***. When perfectly correlated particles pass through the same medium, the SNR is reduced by a factor of*** $\sqrt{N} \gg \sqrt{2}$***. The presence of loss therefore affects the quantum-mechanically correlated state much more than the uncorrelated state.***

This sensitivity to loss poses a serious challenge to the use of quantum-mechanically correlated states for real-world measurements, where loss and relaxation are often present. In many cases, compromises must be made to avoid loss such as using smaller numbers of particles or reducing the measurement time. While as much as 20 dB of spin squeezing has been obtained in atomic systems [refs. 2 and 3], atomic clocks based on entanglement [refs. 2 and 4] still fall short of the stabilities obtained in un-entangled systems [refs. 5 and 6].

A key challenge in the coming years will be to implement protocols involving entangled or squeezed quantum states in instruments already performing at the highest measurement resolution (e.g., in the most accurate atomic clocks) and show that the use of quantum-mechanically correlated states can result in meaningful enhancement of sensitivity without compromising performance in other ways.

6.3 Examples of Successful Quantum Sensing Technologies

Quantum sensing technology has already made considerable impact in both the terrestrial and space-based arenas. Some examples follow in this section and include applications in both basic science and in broadly used infrastructure.

6.3.1 Global Navigation Satellite Systems (GNSS)

The global positioning system (GPS) is a satellite-based navigation and timing system operated by the U.S. Space Force. The GPS network consists of 32 satellites, one of which is illustrated in Figure 6.3.1, orbiting the Earth at an altitude of 20,200 km in six orbital planes with 55° inclination. The satellites broadcast RF signals directed toward the Earth that can be detected using receivers. These signals contain the time at which the signal was sent, as well as other information such as the precise position of the satellite in the sky. By measuring the time taken for the signal to travel from the satellite to the receiver, the distance between the satellite and receiver can be established. If this distance is established with respect to at least three satellites distributed in space (four satellites are needed if the receiver time is also unknown), trilateration allows the determination of the receiver position with respect to the satellites. The precision of the positioning solution ultimately relies on the timing uncertainty. Since the speed of light is roughly 0.3 m/ns, nanosecond-level timing is required for meter-level positioning precision. The clocks can be resynchronized periodically through links to ground stations but must maintain nanosecond-level timing over several hours between resynchronizations. At present, atomic clocks are the only clocks capable of maintaining such time and hence each GPS satellite contains two vapor cell rubidium (Rb) atomic clocks and one cesium (Cs) atomic beam clock.

Figure 6.3-1. GPS Satellites Orbiting Earth Containing Atomic Clocks [Credit: Wikipedia]

Development of the GPS system began shortly after the launch of Sputnik 1 by the USSR in 1957 and was formally initiated by the U.S. DoD in 1973. The first satellite was launched in 1978 and the system was fully operational by 1993. Contemporaneously to GPS, the USSR developed the very similar GLONASS system, and several other countries are now deploying their own satellite-based navigation systems: Galileo (Europe), Beidou (China), NavIC (India) and Quazi-Zenith Satellite System (Japan). GPS supports a vast array of modern technological infrastructure with the estimated economic impact exceeding $1T.

6.3.2 Gravity Probe A

The use of atomic clocks in space to probe fundamental physics dates back to the early 1970s. The Einstein equivalence principle states that the laws of physics in a gravitational field are indistinguishable from those in a uniformly accelerating platform. Because of this, time flows more slowly on the surface of the Earth than it does in orbit around the Earth, where the gravitational potential is smaller. In 1976, a sounding rocket containing a hydrogen maser (a type of atomic clock) was launched from the NASA Wallops Flight Research Center (WFRC), attaining an altitude of 10,000 km over a roughly 2-hour flight. Microwave signals connected the satellite maser to a second maser on the ground and the relative frequency between the two clocks was measured throughout the flight. The observed (fractional) frequency shifts $\Delta f/f$ agreed with those predicted by general relativity to within 7 x 10^{-5} and this measurement remains to this day one of the most precise tests of the gravitational redshift. The precision of this experiment relied on two key elements: the high precision of the quantum atomic clock and the significant change in the gravitational potential enabled by space flight.

6.3.3 LIGO

Einstein's theory of general relativity predicts the existence of gravitational waves (GWs), which can be caused by cataclysmic cosmic events undergone by massive objects in the universe. Such events include binary black holes and neutron star mergers and inspirals and supernovae. Such waves cause an expansion and contraction of space as they propagate, and these spatial perturbations can be detected using optical interferometers probed with highly stable lasers. The LIGO operates two such Michelson interferometers with 4-km arms located in Hanford, WA and Livingstone, LA. The first direct detection of GWs was made using these detectors on February 11, 2016, and observations of new events continue to this day.

GW interferometers are not inherently quantum sensors: they typically use classical optical fields generated by lasers, large test masses and conventional interferometric detection systems. However, because the length changes induced by GWs are so small (spacetime fractional strain $\Delta L/L \sim 10^{-21}$ these instruments must operate at the stringent limits of detection sensitivity. At higher signal frequencies (f > ~100 Hz), the interferometer strain detection sensitivity is limited by photon shot noise: the random nature of the photon arrival times at the photodetector inherent to classical optical fields imposes a SQL to the detection sensitivity.

Squeezed states of light are optical fields that exhibit noise lower than the SQL along one wave quadrature component at the expense of increased noise along the other. For example, squeezed states of optical fields exist with intensity noise below photon shot noise, but where the phase noise is necessarily higher. In 2013, squeezed states of light were used to enhance the strain sensitivity of the LIGO-Hanford detector by 2.15 dB in the frequency band above 300 Hz. Increased strain sensitivity in this band allows for the detection of higher-frequency GW signals and expands the reach of the detector to sources further away from the Earth. The number of new detectable sources scales as the cube of the maximum distance at which sources can be detected, so even modest improvements in sensitivity can have a substantial impact on the scientific outcomes of the sensor system. The detection of GWs is one of the few measurements significantly aided at a practical level by nonclassical states. Figure 6.3-2 shows the improvement in sensitivity of the LIGO instrumentation resulting from the use of squeezed light.

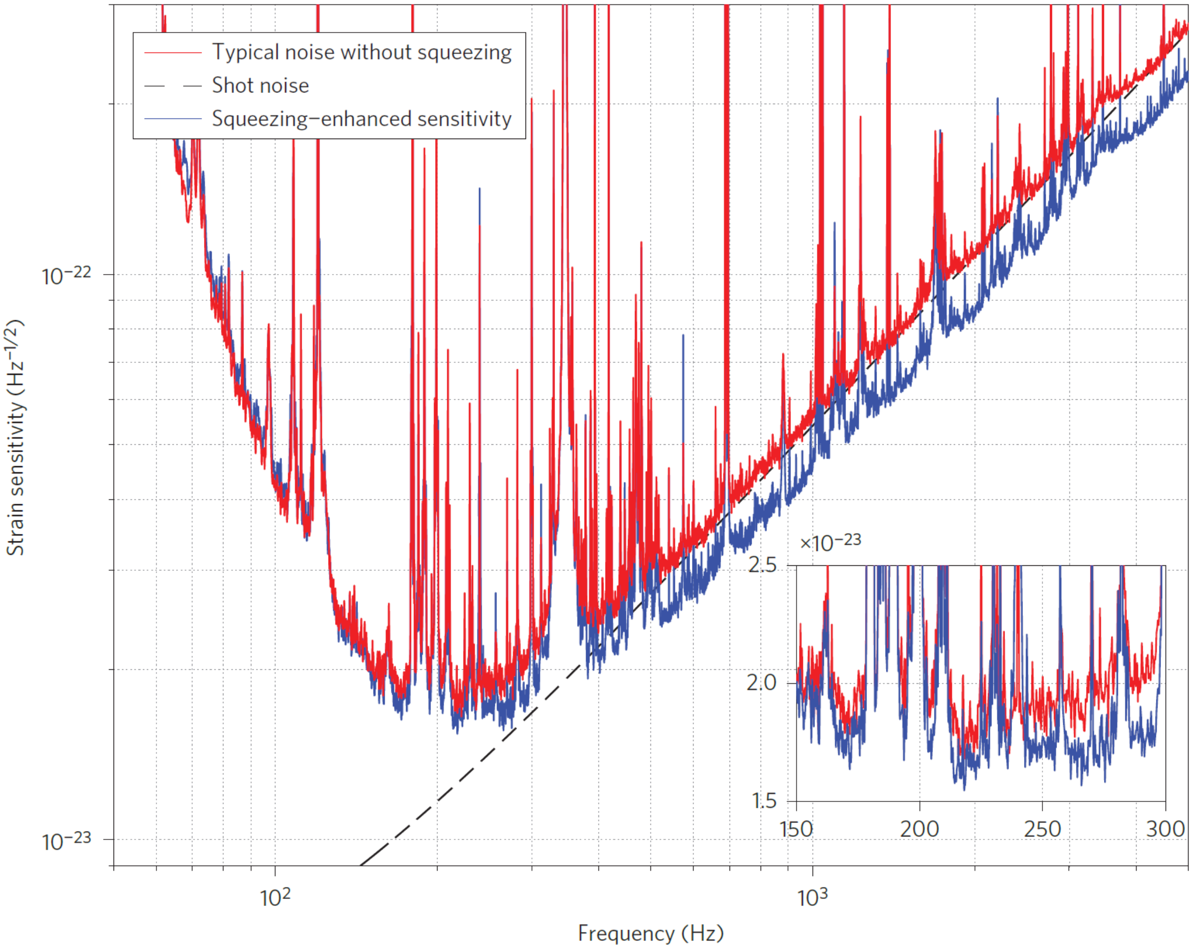


Figure 6.3-2. Improvement in LIGO Sensitivity from Using Squeezed Light (blue trace)The inset shows the portion of the data with the best sensitivity on a linear scale. [ref. 7]

7.0 NASA Mission Goals

This section describes the goals of NASA Science Mission Directorate with a specific focus on sensing. The most common sensing modalities currently in use for each NASA SMD organization unit are reviewed and opportunities where quantum sensors are playing a role, or may play a role in the future, are identified.

7.1 SMD

The mission of NASA's SMD includes searching for life elsewhere in the universe, protecting and improving life on Earth, and discovering the secrets of the universe. Consistent with that, its divisions include the Biological and Physical Sciences (BPS) Division, the Earth Science Division, the Planetary Science Division, the Heliophysics Division, the APD, and a division to plan and execute cross-agency satellite programs named the Joint Agency Satellite Division. The subsections within this section have been similarly organized.

7.1.1 BPS

BPS is the newest division in the NASA SMD which is responsible for all major science missions. The BPS mission is to "enable exploration by expanding the frontiers of knowledge, capability, and opportunity in space, and pioneer scientific discovery in and beyond LEO to drive advances in science, technology, and space exploration to enhance knowledge, education, innovation, and economic vitality.” The main focus is to use space platforms as laboratories for advancing knowledge and science through experimentation. Fundamental physics is a key part of the BPS Division activities as they relate to quantum sensing and emphasizes the utilization of space and microgravity environments to advance the understanding of fundamental laws of physics.

Space and microgravity provide conditions that are not available in ground laboratories and allow investigation of new physical (especially quantum) regimes. One example is the NASA Cold Atom Lab (CAL), currently installed on the International Space Station (ISS). In this facility, gases of alkali atoms are cooled by lasers to sub-microKelvin temperatures producing quantum gases such as Bose-Einstein condensates (BECs) [ref. 8]. On the ground, gravity limits the time over which such atomic ensembles can be interrogated without perturbing forces to about one second. In a microgravity environment, longer interaction times are possible and used to explore unique quantum regimes that are not easily achieved in ground laboratories. This facility is also being used to develop and validate quantum sensors based on cold atoms and BECs (see Figure 7.1-1). Eventually, these quantum sensors may lead to new tests of fundamental physics, helping to further advance the understanding of natural fundamental forces and symmetries, the laws governing the small particles in the quantum regime, and aspects of the cosmological universe [ref. 9].

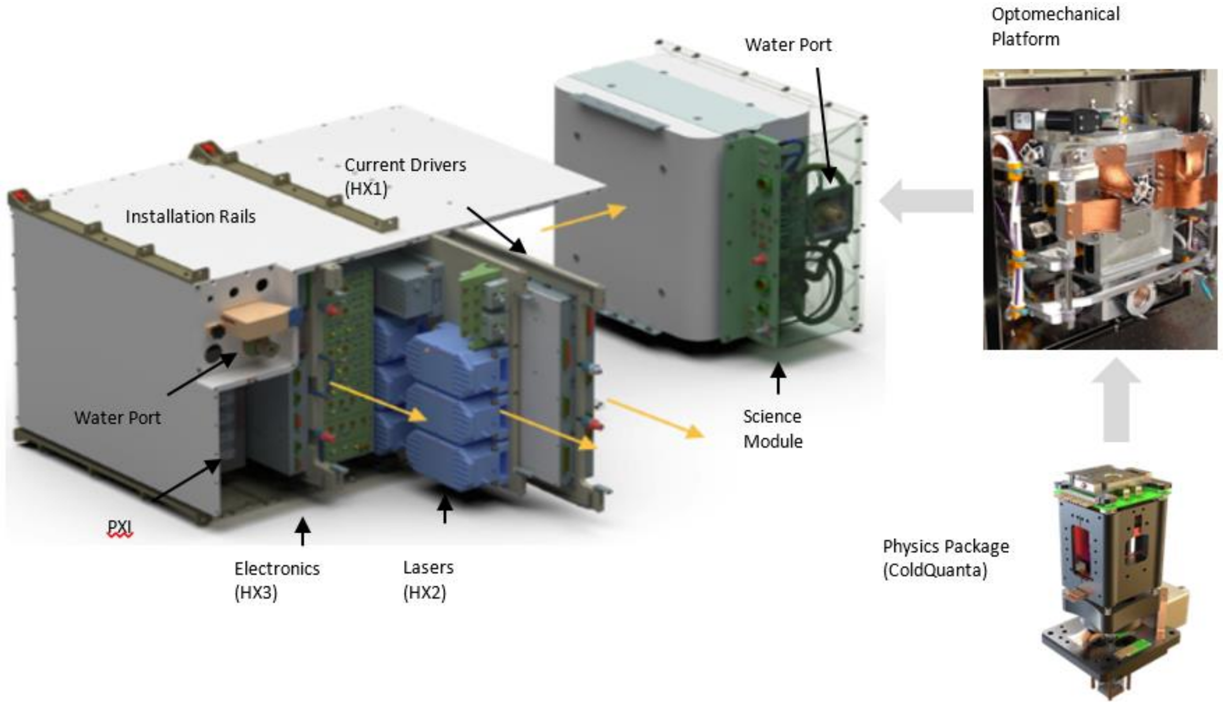


Figure 7.1-1. Exploded View of CAL [Credit: Jet Propulsion Laboratory]

The fundamental physical laws of nature are currently described by the Standard Model (based on quantum mechanics) and Einstein’s general theory of relativity including cosmic dark matter (CDM) at the cosmological scale. However, there are important reasons to question the completeness of these descriptions. In particular, if gravity is to be quantized, general relativity will have to be modified; however, the search for a realistic theory of quantum gravity remains an outstanding problem in theoretical physics. This continued inability to merge gravity with quantum mechanics, together with the challenges posed by the discovery of dark energy, indicates that the pure tensor gravity of general relativity needs modification or augmentation. It is believed that new forces and physics are needed to resolve these inconsistencies.

Theoretical models of the kinds of new physics that can solve the problems above typically involve new physical interactions, some of which could manifest themselves as violations of well-established laws of physics—the Equivalence Principle, the stability of fundamental constants, the inverse square law of gravity, Lorentz-symmetry, and large-scale gravitational phenomena. Each of these manifestations offers an opportunity for experiments based on precision measurements and could lead to major discoveries of new physics.

Fundamental physics has been extensively studied in high-energy (HE) physics accelerator experiments and in astronomical phenomena observed through space telescopes. The former is understood through the Standard Model and quantum mechanics, and the latter through Einstein’s theory of gravity. These investigations are increasingly connected through the study of the early universe and extreme objects like black holes. Together with HE physics and astronomical observations, precision experiments using quantum sensors form three important pillars for science discoveries beyond current models of nature including the nature of dark matter and dark energy.

Space is one of the most likely places where manifestations of new physics might be found. While a microgravity environment can allow for improved performance of sensors capable of measuring new phenomena, many potential signals are amplified in space due to access to greater variation of gravitational potentials, greater velocities, and full orientation coverage.

Progress in ground-based quantum sensors has led to new instruments and technologies including accurate atomic clocks, atom-wave interferometers for inertial motion sensing, and quantum magnetometers. The performance of this new generation of high-performance atomic quantum sensors in some cases surpasses previous state-of-the-art measurement approaches. Combined with access to space platforms, these new tools enable more precise experiments in a search for physics beyond the Standard Model and in tests of the general theory of relativity.

Atomic clocks have been used for decades for various tests of fundamental physics and continue to play an important role, mainly in looking for violations of Einstein’s theory of general relativity:

1. Precision measurements of the gravitational redshift: the theory of general relativity predicts that clocks located in different gravitational potentials tick at different rates. By comparing atomic clocks in orbit around the Earth or Sun, where the gravitational potential is very different than on Earth, with those on the Earth, precision tests of this theory can be made.
2. Tests of the equivalence principle (EP): the EP predicts that non-gravitational physical laws are independent of a system’s location in time and space, and also independent of its velocity and orientation. Atomic clocks in LEO undergo rapid changes in orientation that allow for improved sensitivity to violations of local Lorentz invariance.
3. Searches for spatially or temporally varying dark matter: A propagating dark matter “boundary” may cause clocks (or magnetometers) at different positions in space to undergo a change in frequency (or field reading) at different times. Comparisons of

clocks in space would show relative timing differences caused by dark matter over a long baseline, thereby improving sensitivity.

7.1.2 Earth and Planetary Sciences

Earth and planetary science comprise the study of planets, including the Earth; celestial bodies such as moons, asteroids, comets; and planetary systems, especially those of the Solar System. Earth and planetary science studies objects ranging in size from micrometeoroids to gas giants, aiming to determine their composition, dynamics, the processes of their formation, interrelations, and history. It is a strongly interdisciplinary field, including planetary geology, cosmochemistry, atmospheric science, physics, oceanography, hydrology, theoretical planetary science, glaciology, and exo-planet studies. Related disciplines include space physics, heliophysics, and astrobiology. In academia, Earth and planetary science is usually incorporated into a single department—sometimes together with atmospheric science—and considered part of one larger discipline, with common scientific themes and approaches. Within NASA, Earth and planetary science is broken out into two divisions within the SMD: the Earth Science Division and the Planetary Science Division.

The most recent National Academies decadal survey relevant to NASA's Earth Science Division was produced in 2018: *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space* [ref. 11]. This decadal survey identified the following key research priorities, with a focus on remote sensing of the Earth: aerosol properties, atmospheric winds, greenhouse gases, surface biology and geology, terrestrial ecosystem structure, ocean ecosystem structure, aquatic-coastal biogeochemistry, soil moisture, ocean surface winds and currents, vegetation-snow-surface energy balance, and surface topography and vegetation. Future NASA missions that were prioritized, include:

- Plankton, Aerosol, Cloud, ocean Ecosystem (PACE), an Earth-observing satellite that will advance observations of global ocean color, biogeochemistry, and ecology, as well as the carbon cycle, aerosols, and clouds. Key sensor technology being developed include a high-performance optical spectrometer and both multi-angle and wide-field-imaging polarimeters.
- A surface biology and geology mission to improve measurements of the Earth's surface for natural resources management, food security, and water security. Planned measurement instruments will provide a combination of hyperspectral and multispectral coverage, with tens of meters spatial resolution.
- Completion of, and then a successor to, the GRACE Mission. Gravity Recovery and Climate Experiment (GRACE) was a successful Earth Science mission that flew from 2002 to 2017. GRACE-FO (GRACE Follow-On) was launched in 2018 and is currently towards the end of its nominally 5-year mission (possibly lasting much longer). Using similar technology involving telemetry (two-way microwave-ranging link) to track two Earth-orbiting satellites, GRACE and GRACE-FO perform gravity gradiometry to determine how mass is distributed around the Earth and how it varies over time. The resulting long-term data are an important tool for studying changes in the Earth's oceans, geology, and climate. The Gravity Recovery and Interior Laboratory (GRAIL) Mission performed similar measurements for the moon. Data from the GRAIL Mission is shown in Figure 7.1-2

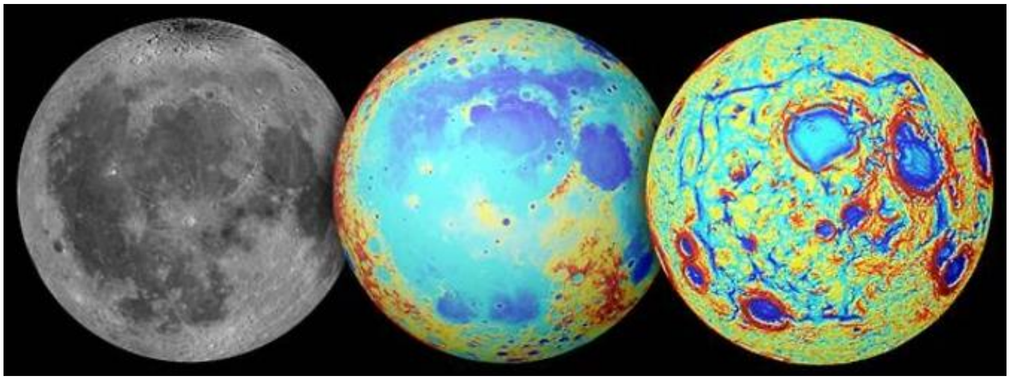


Figure 7.1-2. Visual, Topographic, and Gravity Maps of the Moon Produced by NASA's GRAIL Mission [Credit: NASA]

- Completion of, and then a successor to, the NASA-ISRO (Indian Space Research Organization) Synthetic Aperture Radar (NISAR) Mission. NISAR, which is planned for a 2024 launch and a nominal 3-year mission, will be the first dual-frequency synthetic aperture Earth-observing satellite. NISAR will map the elevation of Earth's land and ice masses 4 to 6 times a month at resolutions of 5 to 10 m. Data collected from NISAR will reveal information about the evolution and state of Earth's crust, helping scientists better understand the Earth's natural processes and changing climate, and aid future resource and hazard management.

The most recent National Academies decadal survey relevant to NASA's Planetary Science Division was produced in 2022: *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032* [ref. 10]. This decadal survey identifies key scientific questions facing planetary science and outlines recommendations for the next 10 years in space and ground-based exploration, as well as supporting technology development. The recommended Flagship (i.e., large-scale) missions are the following:

- Uranus Orbiter and Probe. An orbiter paired with an atmospheric probe will address a range of scientific questions about the ice-giant Uranus and its moons, including the planet's origin, interior, and atmosphere; magnetosphere; and the structure and composition of the moons and rings. A diverse set of measurement instruments are planned for this mission, including magnetometers, optical spectrometers and cameras, a thermal infrared camera, and charged particle detectors.
- Complete the Mars Sample Return Program: i.e., take samples currently being collected on Mars by the Perseverance rover, launch them into orbit around Mars and return them to Earth in the early 2030s. Then, as additional funding opportunities open up over the next several years with the Mars Sample Return Program winding down, begin work on a lander mission called Mars Life Explorer that would look for evidence of current or previous life on Mars by drilling into ice deposits to search for biosignatures.
- Enceladus Orbilander. This probe would spend a year and a half orbiting Saturn's moon, Enceladus, sampling the emitted water plumes from the subsurface ocean that burst through the icy crust into space; and would then land on the moon's surface for a 2-year mission to search for evidence of organic materials and life. This mission would incorporate a wide range of measurement capabilities, including for navigation, environment remote sensing from orbit, on-surface sensing, and organic material and life detection.

The decadal survey also recommended a series of high-scientific-value opportunities as possible New Frontiers (i.e., medium-scale) missions to be selected late in this decade and early/mid next decade: sending an orbiter and lander to a Centaur, a family of icy bodies orbiting between Jupiter and Neptune; a sample return mission from Ceres, the largest body in the main asteroid belt; a comet sample return mission; a spacecraft to perform multiple flybys of Enceladus; a network of lunar landers to collect geophysical data; a Saturn probe; a Titan orbiter; a mission to perform in situ studies of the atmosphere of Venus; and a mission to Neptune's largest moon, Triton. In addition, the decadal survey supported efforts by NASA in planetary defense, including launch of the NEO (Near-Earth Object) Surveyor Mission, followed by a "rapid-response" mission to fly by NEO between 50 and 100 meters across.

Regarding lunar exploration, the decadal survey recommended an interplay of robotic and human exploration. In particular, a mission concept called Endurance-A would send a robotic rover to the Moon's South Pole Aiken Basin on a commercial lander. The rover would travel 2,000 km across the basin and collect 100 kg of scientifically interesting samples, which would then be returned to Earth on a human-crewed Artemis mission, providing a greater quantity of return samples at much lower cost than either a fully robotic or human mission. These New Frontiers, lunar, and planetary defense missions will require advanced techniques for spacecraft navigation, remote sensing (including optical spectroscopy and imaging, lidar, radar tomography, gravity gradiometry, magnetometry etc.), and collected sample analysis of physical, chemical, and biological properties; with these capabilities increasingly being performed autonomously and in very challenging environments (in the outer solar system; under extreme temperature, pressure, radiation, dust conditions).

Several classes of quantum sensors may play important roles over the next decade and beyond in NASA missions in Earth and planetary science, as well as in supporting ground-based research. Applications of quantum sensors can be expected to fall into three general categories:

- Improved remote sensing by spacecraft, as well as local environment probes by landers and rovers. Examples include atom interferometry for improved gravity gradiometry compared to conventional telemetry techniques; quantum (atom and/or solid-state-defect) magnetometers, which may provide better long-term stability and vector magnetic sensing than conventional technology; lower-size, weight, and power (SWaP) optical spectrometers based on quantum dots; light detection and ranging (LIDAR) employing squeezed light; transition edge sensors (TES) to provide better energy resolution of X-rays; and Rydberg atom RF sensors.
- Enhanced space vehicle navigation using space-based optical clocks, which have the potential for orders of magnitude better stability than microwave clocks, together with high-performance optical links.
- Ground-based studies, e.g., of meteorites, ancient Earth rocks, and samples returned from space. An important example is the implementation of quantum diamond microscope (QDM), which in recent years has successfully transitioned from quantum physics research to become a widely used tool for Earth and planetary science [ref. 11]. The QDM provides a unique combination of spatial resolution, wide field-of-view, magnetic field sensitivity, and minimal perturbation to rock samples [ref. 12]. QDMs have already been used in a series of high-impact studies in Earth and planetary science, e.g., helping to understand the role of magnetic fields in planetary formation in the first few million years of the solar system's formation, via studies of the paleomagnetization in primordial

grains found in certain meteorites [ref. 13]; and providing quantitative evidence of plate tectonics on the early Earth (at least 3.25 billion years ago) by paleomagnetic studies of ancient Earth rocks [ref. 14].

7.1.3 Heliophysics

Heliophysics focuses on the physics of the Sun, the solar wind and the way in which the solar wind interacts with the Earth and other planets. Some of the key questions in this area that potentially relate to quantum sensing are: what are the causes and effects of space weather to help better predict these events and to take precautions to minimize their impact; how does the Sun's magnetic field shape the dynamics of the heliosphere; what are the interactions and feedbacks that connect the magnetosphere, solar wind and ionosphere; and how does the Earth's atmosphere couple to its space environment? Key measurement technologies employed at present by NASA's Heliophysics Division include electromagnetic field sensors from RFs to gamma rays, sensors of low-frequency electric and magnetic fields, and particle sensors to detect electrons, protons, ions and neutral particles. An X-ray image of hot plasmas in the solar corona is shown in Figure 7.1-3.

Traditional field measurements for heliophysics largely use classical sensors: fluxgate and search coil magnetometers, charge coupled device (CCD) imagers, Langmuir probes, mass spectrometers and particle detectors. Measurements include vector magnetic fields with an accuracy of 0.1 nT at 100 Hz, vector low-freqeuncy electric fields with an accuracy better than 1 mV/m at 1 kHz. The Solar Dynamics Observatory (SDO) was launched in 2010 to study how the Sun's magnetic field is generated and how this stored magnetic energy is converted and released into the heliosphere. This satellite primarily contains imagers based on CCDs, which image the Sun's surface at a variety of wavelengths with high spatial and spectral resolution. The Magnetospheric Multiscale Mission was launched in 2015 to study magnetic reconnection and space weather. The FIELDS instrument on this mission included a fluxgate magnetometer and a search coil magnetometer, several double-probe instruments to measure electric fields with an accuracy of 0.5 mV/m [ref. 15] and an electron drift instrument. These instruments measured electric and magnetic fields with <1-ms timing resolution and up to 100 kHz frequency. The Geospace Dynamics Constellations (GDC) is a six-spacecraft mission to understand the high-latitude ionosphere and thermosphere. The sensors on these satellites will include a Langmuir probe, a quadrupole mass spectrometer, an electrostatic charged particle analyzer and a magnetometer to be determined. NASA's Electrojet Zeeman Imaging Explorer (EZIE) mission planned for launch in 2024 is a three-satellite constellation with instrumentation designed to measure Zeeman splitting of molecular oxygen thermal emissions that contain information on the magnetic field perturbations caused by auroral currents flowing the Earth's ionosphere (ref. 16, 17, and 18).

Strategic missions over the next decade will likely require large constellations with many satellites working together and large increases in remote sensing capabilities. As many as 60 satellites are being considered for the Magnetic Constellation Mission in the magnetosphere. To enable such capability, significant decreases in sensor size, weight, power, and cost will be needed, as well as orders of magnitude increases in sensor spectral resolution, sensitivity and angular resolution.

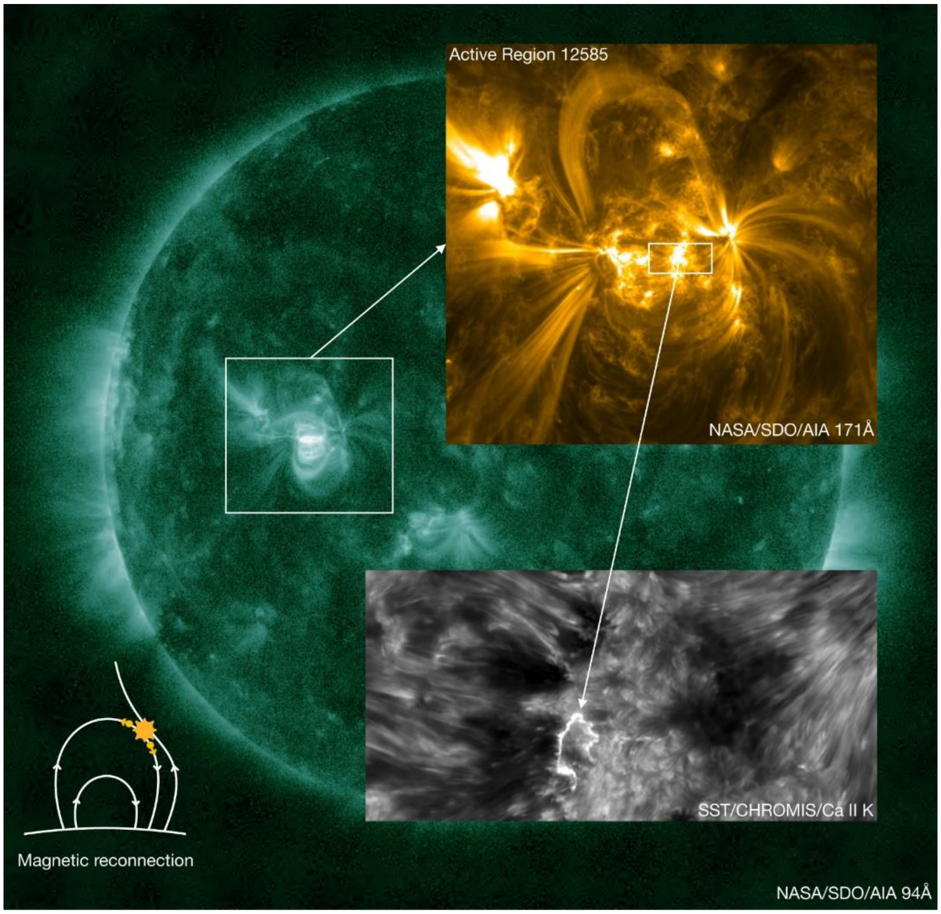


Figure 7.1-3. Hot Plasmas in Solar Corona Emit X-rays Near 1.15 keV [Credit: NASA]

There are several examples of quantum technologies that could impact future NASA missions in heliophysics. One example is TESs for solar science. TESs are a type of superconducting quantum microcalorimeter sensitive to individual photons across a broad spectral range. Arrays of such sensors are possible enabling imaging with broad spectral coverage and single-photon sensitivity. Such sensors can be used to understand the dynamics of hot plasmas in the solar corona, which is key to solving the solar corona problem and the origin of super-heated plasmas from the Sun. TESs provide 100x better energy resolution than traditional X-ray detectors and can resolve key emission lines in soft X-rays.

A second example is spectrometers for auroral emission sensing. Traditional spectrometers involve optical elements such as mirrors, diffraction gratings and prisms, and require a long optical pathlengths to achieve high spectral resolution. However, spectrometers based on quantum dots [ref. 19] are emerging as a potential alternative. Colloidal quantum dots (CQD) are nanoscale particles whose size and composition result in absorption at specific optical wavelengths. By creating an array of such absorptive filters, a single CCD imager can simultaneously resolve many spectral wavelengths and efficiently characterize an input spectrum as shown in Figure 7.1-4.

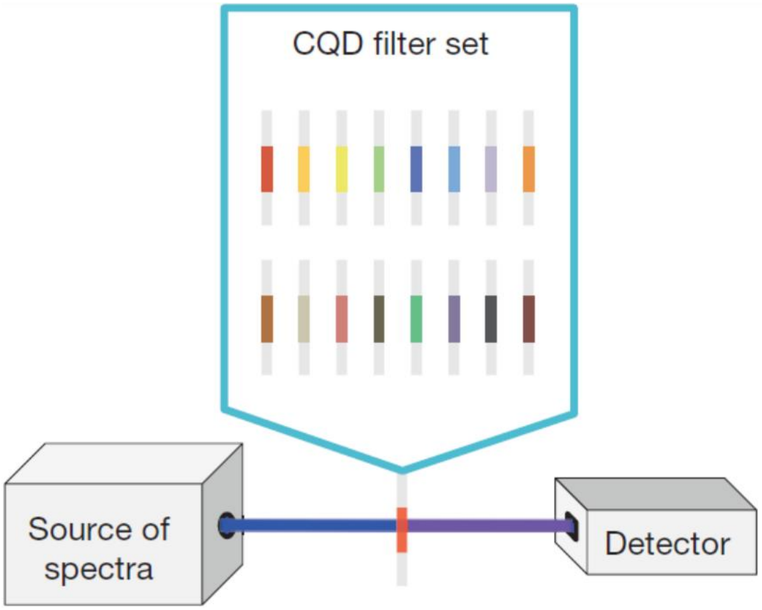


Figure 7.1-4. Colloidal Quantum Dot Spectrometer [ref. 19]

A third example is the use of quantum (solid-state defect or atomic) magnetometers to compliment or replace fluxgate magnetometers. Fluxgate magnetometers suffer from drifting scale factors and voltage offsets that vary with time and temperature and require periodic recalibration. Recalibration is done using comparisons between analog and digital fluxgate sensors and an electron drift instrument. Emerging quantum sensors can offer higher sensitivity, higher accuracy, and lower drift, generally at the cost of increased size, weight, power, and complexity. NV-diamond magnetometers have particular strengths at high spatial resolution and for vector measurements while atomic vapor cell magnetometers have high accuracy and sensitivity. The diamond host material for NV sensors can also be particularly resistant to harsh environmental conditions, such as those relevant for space operation. A plot showing present magnetometer sensitivities as a function of sensor size is shown in Figure 7.1-5.

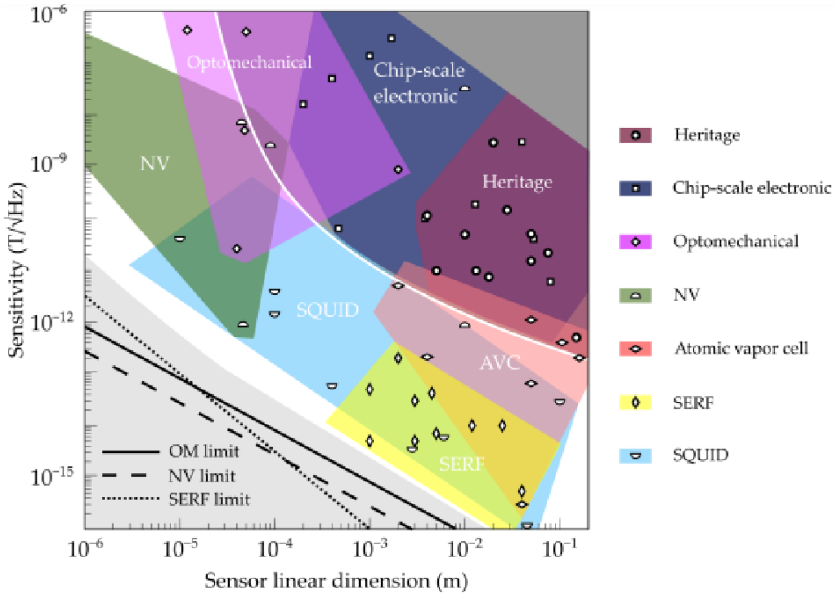


Figure 7.1-5. Quantum Magnetic Sensors [ref. 20]

7.1.4 Astrophysics

7.1.4.1 Goals and Overview

The NASA APD science goals are to “discover how the universe works, explore how it began and evolved, and search for life on planets around other stars.” APD formulates, develops, and operates spaceflight missions that explore the nature of the universe at its largest scales, its earliest moments, and its most extreme conditions. Specifically, the science that these goals encompass includes everything from elucidating the origin and character of dark matter and dark energy, to determining the role of black holes in their host galaxies and mapping their evolution across cosmic time and discovering multiple Earth-like extrasolar planets and ultimately imaging these potentially habitable worlds. These lofty goals can only be met through the discovery and intentional science enabled by a fleet of missions.

7.1.4.1.1 Existing Fleet and Funded Missions

This NASA APD fleet (Figure 7.1-6) consists of various-sized payloads, from single instruments to the Great Observatories that operate across multiple wavelengths and messengers—particles and GWs [ref. 21]. These missions fly on suborbital platforms (high-altitude aircraft, sounding rockets, and balloons) as hosted payloads on the ISS and non-U.S. partner observatories, and as stand-alone free flyers [ref. 21].

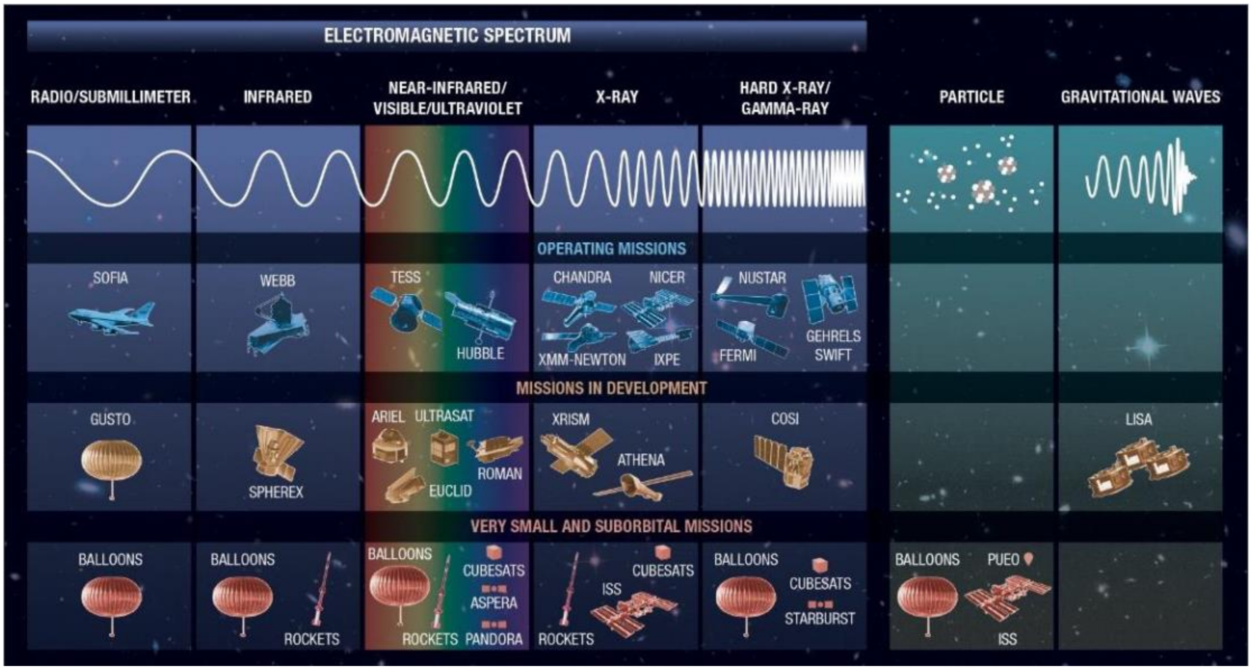


Figure 7.1-6. NASA’s APD fleet of Missions
The fleet spans multiple wavelengths and messengers and includes large Great Observatory missions, such as Hubble Space Telescope, Chandra X-ray Observatory, and the James Webb Space Telescope, as well as many medium and smaller missions. [Credit: NASA, 2022]

Each of these missions require years of technology development and mission design prior to flight. Typically, the larger and more ambitious the mission, the more technology development and advanced planning are required. The types of astrophysics missions that NASA funds are driven by high-priority science topics that the astronomy and astrophysics communities determine are the most critical to address. These science topics are considered every decade and are presented by the National Academies in the Astronomy and Astrophysics Decadal Survey. The Decadal Surveys recommend priority investment areas for NASA (as well as the National Science Foundation (NSF) and the Department of Energy (DOE)/Office of Science).

7.1.4.1.2 Decadal Survey on Astronomy and Astrophysics 2020 (Astro2020)

Astro2020, Pathways to Discovery in Astronomy and Astrophysics for the 2020s, details an ambitious plan for this decade and beyond [ref. 22]. Three broad science themes are defined: Worlds and Suns in Context, New Messengers and New Physics, and Cosmic Ecosystems. Within each of these scientific themes, three priority areas motivate recommended investments over the coming decades. The first priority area is Pathways to Habitable Worlds, which is geared towards finding and characterizing extrasolar Earth-like planets and searching for signatures of life. The recommendation is to develop a large (New Great Observatory (NGO)) space-based infrared/visible/ultraviolet (IR/O/UV) telescope with high-contrast imaging and spectroscopy (recently renamed as the Habitable Worlds Observatory (HWO)). This observatory must be capable of observing planets 10 billion times fainter than their host star. Astro2020 also recommends the use of high spatial and spectral resolution X-ray observations to probe stellar activity across the entire range of stellar types, to understand the stellar ecosystem and how it leads to planet formation.

The second priority area is New Windows on the Dynamic Universe. This area focuses on multi-wavelength and multi-messenger studies to determine the origin and evolution of some of the most energetic events in our universe related to cosmic explosions and mergers of compact objects (such as black holes and neutron stars). Recommended investments are in facilities and observatories that can detect and characterize transient sources, Cosmic Microwave Background (CMB) telescopes, and gravitation wave detectors.

The third science priority is Unveiling the Drivers of Galaxy Growth. Understanding processes that drive galactic evolution, such as black holes and the cosmic web, requires the development of the next-generation IR/O/UV space telescopes, as well as X-ray and Far Infrared (far-IR) telescopes.

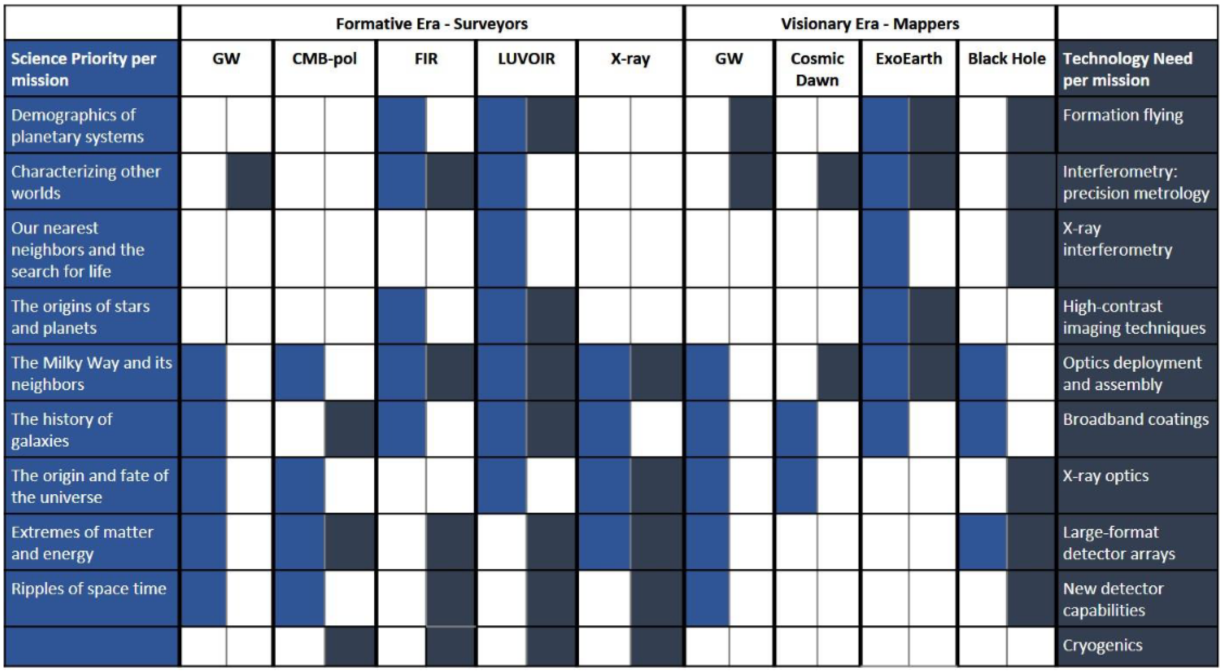
The Astro2020 NASA investment recommendations span a range of mission types, of all sizes. Emphasis is on Time Domain and Multi-Messenger missions (TDAMM), astrophysics probe-class missions, and a NGO Program. The NGO Program prioritizes early technology development and maturation, as it is likely that technologies that are more capable than the state-of-the-art will be required to meet the science priority areas outlined in the report.

7.1.4.1.3 Future of APD

While the Astro2020 report considers NASA investment beyond the 2020s, the Astrophysics Roadmap, Enduring Quests – Daring Visions, provides a science vision through the 2040s [ref. 23] with the goal of answering some of the fundamental science questions such as: are we alone; how did we get here; and how does the universe work?

7.1.4.2 Future Mission Needs & Desired Capabilities

The Astrophysics Roadmap notional missions for the near term (Formative Era) and far term (Visionary Era) as a function of science goals and example technology needs are provided in Figure 7.1-7. Technology needs for these notional missions span both the spacecraft and the payload and many would benefit from the development and application of quantum sensors. Interferometry, for example, is needed to meet many of the notional mission goals, across multiple wavelengths, requiring significant advances in areas such as precision metrology, formation flying, beam combination, aperture synthesis techniques, and data analysis techniques [ref. 23].



	Formative Era - Surveyors										Visionary Era - Mappers								
Science Priority per mission	**GW**		**CMB-pol**		**FIR**		**LUVOIR**		**X-ray**		**GW**		**Cosmic Dawn**		**ExoEarth**		**Black Hole**		**Technology Need per mission**
Demographics of planetary systems					🟦		🟦	⬛				⬛			🟦	⬛		⬛	Formation flying
Characterizing other worlds		⬛			🟦	⬛	🟦					⬛		⬛	🟦	⬛		⬛	Interferometry: precision metrology
Our nearest neighbors and the search for life							🟦								🟦			⬛	X-ray interferometry
The origins of stars and planets					🟦		🟦	⬛							🟦	⬛			High-contrast imaging techniques
The Milky Way and its neighbors	🟦		🟦		🟦	⬛	🟦	⬛	🟦	⬛	🟦			⬛	🟦	⬛	🟦		Optics deployment and assembly
The history of galaxies	🟦			⬛	🟦		🟦	⬛	🟦		🟦		🟦		🟦		🟦		Broadband coatings
The origin and fate of the universe	🟦		🟦				🟦		🟦	⬛	🟦		🟦					⬛	X-ray optics
Extremes of matter and energy	🟦		🟦	⬛		⬛		⬛	🟦	⬛	🟦						🟦	⬛	Large-format detector arrays
Ripples of space time	🟦		🟦			⬛		⬛		⬛	🟦							⬛	New detector capabilities
				⬛		⬛		⬛		⬛									Cryogenics

Figure 7.1-7. Astrophysics Roadmap Notional Missions for Formative and Visionary Eras Science Summary in the left column and required technology developments in the right column. GW = Gravitational Wave, CMB = Cosmic Microwave Background, FIR = Far-Infrared, LUVOIR = Large Ultra-Violet/Optical/Infra-Red. (Modified from Tables in Section 6.4 and 6.5 of reference 23).

7.1.4.2.1 Formative Era (next 10-20 years)

The Astrophysics Roadmap suggests notional missions, such as a GW Surveyor, CMB Polarization Surveyor, Large Ultra-Violet/Optical/Infra-Red (LUVOIR) Surveyor, X-ray Surveyor, and far-IR Surveyor. LUVOIR, X-ray, and far-IR Surveyors are the foundation for the NGOs discussed in Astro2020, and a high priority for NASA for this decade and the next [ref. 22]. Specific technology needs for these mission concepts are highlighted in the Roadmap, Astro2020, in the concept study reports for LUVOIR, HabEx, Origins, and Lynx, and in the SMD “Large Mission Study Report” [ref. 24]. Some of the critical technologies are summarized here:

GW Surveyor: Akin to the Laser Interferometer Space Antenna (LISA) pathfinder mission that flew from 2015 to mid-2017. Paving the way for the LISA mission, critical performance requirements that were tested included displacement sensitivity and measured acceleration noise between two test masses [ref. 25]. The GW Surveyor concept in the Astrophysics Roadmap assumes three spacecraft flying in a triangular formation and would require technology advancements in precision micro-thrusters, frequency-stabilized lasers, robust telescope assemblies and optical benches, precision gravitational reference sensors, and phasemeters capable of high-cadence operation [ref. 23].

CMB Polarization Surveyor: This mission concept would be a successor to the Planck mission, which was designed to map temperature anisotropies of the CMB with very high sensitivity [refs. 26 and 27], and was recommended in Astro2020 under the science priority area "New Windows on the Dynamic Universe" [ref. 22]. A next-generation CMB mission to perform large-angle, high-sensitivity CMB polarization measurements would require improved-sensitivity millimeter-wavelength detectors, larger arrays of superconducting detectors (e.g., TES, or Kinetic Inductance Detectors – KID) and multiplexed electronic readout systems, and large cryogenic optics and optical filters [ref. 23].

LUVOIR Surveyor: A broadband telescope to characterize potentially habitable worlds and explore the universe in the UV, visible, and IR requires a large-aperture mirror assembly with precision wavefront accuracy and high stability, high-reflectivity coatings from UV to near-IR, advanced detector technologies with large format focal plane assemblies that are low-noise and photon counting, energy-resolving detectors (e.g., KIDs), and starlight suppression systems (e.g., coronagraphs and star shades). A mission concept is being formulated in response to Astro2020, which lists the HWO as its highest priority and the first of the NGOs. This concept considers lessons learned from the last two astrophysics flagships, James Webb Space Telescope (JWST) and Roman Space Telescope and makes use of the foundational work done by the LUVOIR and HabEx Teams, who formulated detailed mission concept study reports [refs. 28 and 29] and summarized technology gaps, that have been collectively captured in the "Astrophysics Biennial Technology Report, 2022" [refs. 28 and 30].

X-ray Surveyor: This observatory, which is similar to the Lynx NGO mission concept [refs. 31 and 32], would explore some of the most extreme environments in our universe, from the seeds of the first supermassive black holes in the first galaxies, to the large-scale structures associated with clusters of galaxies, and the environments and character of stars that may give light to habitable worlds. Such an observatory would require advances in fine-angular resolution, thin, large effective area X-ray optics; low-stress mirror coatings; high-precision mounting and alignment; precision metrology systems and techniques; large-format microcalorimeter arrays; high-speed, low-noise, large area, radiation tolerant CCD or complimentary metal-oxide semiconductor (CMOS)-based imaging sensors; and high-efficiency, high-dispersion large area X-ray gratings [refs. 32 and 30].

Far-IR Surveyor: The foundation for the Origins Space Telescope mission concept [ref. 33], this observatory would answer pressing questions related to the interplay between galaxies and star formation and evolution, the conditions needed to form habitable planets, and the capacity of planets orbiting M-dwarf stars to support life. The realization of such an observatory requires technological advances in ultralow-noise far-IR direct detectors, broadband (25 to 588 μm) high-resolving power spectrometers, wide-field far-IR polarimeters with diffraction-limited imaging capability, and mid-IR imaging spectrometers with high stability and precision. This concept would also benefit from technology advancements in the area of space-based heterodyne interferometry that would enable sparse-aperture interferometers and a large-area cryogenically cooled mirror assembly. The detectors, ancillary detection system components, and cryocoolers are the primary challenges [refs. 33 and 30].

7.1.4.2.2 Visionary Era (beyond 20 years)

Looking beyond the Formative Era to the Visionary Era, ever more ambitious observatories like the GW, Cosmic Dawn, Exo-Earth, and Black Hole Mappers are envisioned. Innovative technology solutions are critical for these missions, and it is important to note that these notional missions would benefit from significant advances in interferometry.

GW Mapper: This concept is similar to the European Space Agency's (ESA) LISA mission to detect GWs [ref. 34], of which NASA is a contributing partner. Imaging GWs to the point that sources can be associated with individual galaxies will require orders of magnitude increased sensitivity with multi-element arrays of interferometers and associated technologies. This includes improved data analysis techniques, high-stability, high-precision formation flying [ref. 35], more powerful lasers, larger telescopes, and improved gravitational reference sensors [ref. 23]. Further insight into future technology needs is found in reference 25.

Cosmic Dawn Mapper: This notional mission would map out a three-dimensional view of the neutral gas from the epoch of reionization, from now to the dark ages – when the universe started forming neutral hydrogen and helium atoms moments (~400,000 years) following the Big Bang. This mapper requires increased sensitivity in radio telescopes (perhaps on the far side of the Moon – [ref. 36]) which would require significant improvements in antenna and radio receiver design and deployment.

Exo-Earth Mapper: This concept is essentially a follow-on to the HWO and would require multiple ~6-m-diameter optical/near-IR telescopes assembled into a space-based interferometer that would resolve nearby habitable worlds and characterize their atmospheres. While not the architecture of the HWO, the Exo-Earth mapper would be a space-based interferometer with multiple telescopes. In addition to the need for improved interferometry elements, large-aperture optical/near-IR telescopes or interferometers and related technologies are also needed [ref. 23]. Further details on similar concepts and technology needs are found in reference 37.

Black Hole Mapper: This notional X-ray interferometer-based mission would permit direct imaging of the event horizon of a supermassive black hole, complementing observations made by the ground-based Event Horizon Telescope [refs. 38 and 39], and would also be capable of creating detailed velocity-resolved maps of the innermost structure of active galactic nuclei [ref. 23]. Leaps in throughput, energy resolution, and angular resolution (sub-microarcsecond) and high-stability X-ray interferometry are required. Science benefits and technology needs for an X-ray interferometer mission concept are further detailed in reference 40.

7.1.4.2.3 Additional Technology Considerations

In addition to the aforementioned, mission-specific technologies, saving on SWaP for instruments and spacecraft systems is desired. This is especially true in cases that provide a science opportunity or provide cost savings. Instrument and observatory-related technology gaps from the astronomy and astrophysics community are collected on a regular basis and are captured on the NASA Astrophysics website https://apd440.gsfc.nasa.gov/technology.html.

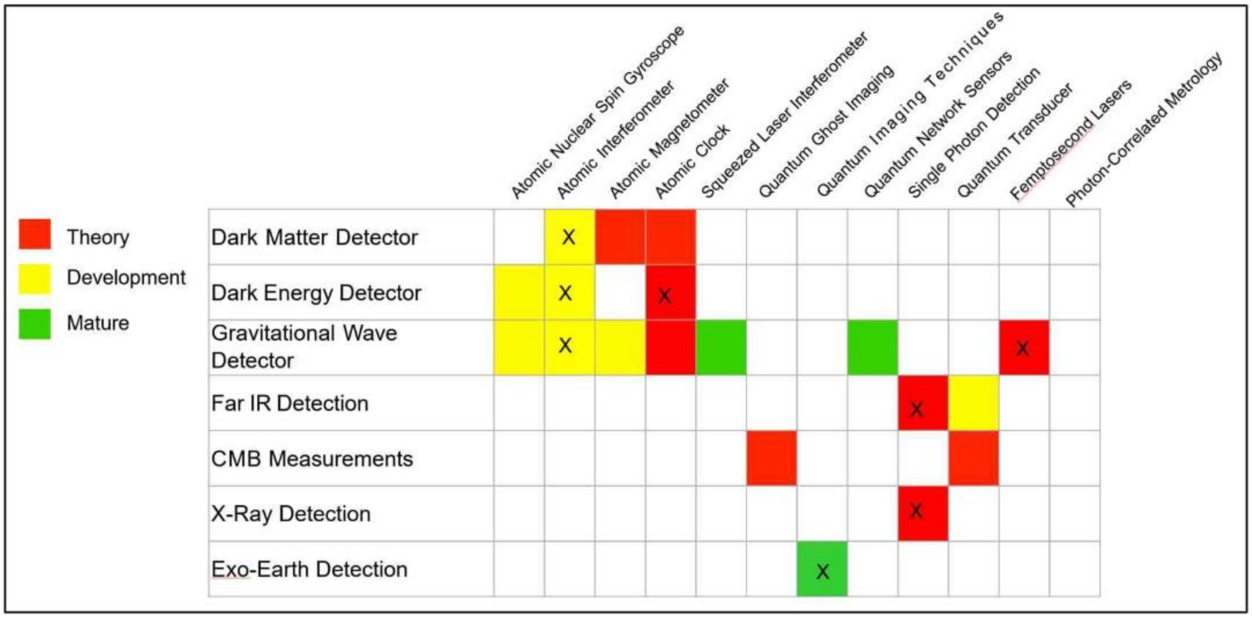
Spacecraft systems with vastly improved timing, onboard computing, and space (secure) communications and navigation are a few areas that are crucial to enabling future astrophysics missions. Other areas include new techniques in data analysis and accommodation of big data. APD has instituted a comprehensive and rigorous technology management program to manage technology awards. Some of the information on technologies funded by APD are also archived and the current portfolio of technology development activities is public http://www.astrostrategictech.us/.

7.1.4.3 Quantum Technologies for Astrophysics

Multiple areas in astrophysics would benefit from the advantages afforded by quantum technologies (see Table 7.1-1). Astro2020 states that "… there is clear synergy between the astrophysical community's needs and expertise, and those of broader society. To seek life on other worlds, astronomers require essentially noiseless, nearly quantum-limited detectors in the UV, visible, and IR. Many of these same properties are needed for quantum computing and information science."

Quantum sensing is a technology domain naturally suited for utilization in astrophysical instruments since for most observations, especially of distant sources, primordial universe and backgrounds, the signals of interest are in an 'information-starved' regime (e.g., single photons). This necessitates the exploitation of quantum effects to obtain the highest sensitivity observations allowed by nature. Most NASA astrophysics investments to date have focused on quantum technologies related to single-photon detectors or ultrasensitive bolometers, which can achieve high sensitivity and optimal performance by using quantum effects such as superconductivity, quantum interference, quantum capacitance, quantum tunneling and quasi-particle trapping. Some of these include superconducting nanowire single photon counting detectors (SNSPDs), KID, TES, Superconducting Quantum Interference Devices (SQUIDs), and various types of superconducting bolometers. Many of these technologies are critical for future X-ray and far-IR missions, including the NGOs [refs. 32 and 33].

Table 7.1-1. Critical Science Areas that would Benefit from Quantum Sensing Advances [Modified from NASA JPL Quantum Sensors Workshop, JPL, September 2019. "X" indicates technologies added post workshop]



🟥 Theory
🟨 Development
🟩 Mature

	Atomic Nuclear Spin Gyroscope	Atomic Interferometer	Atomic Magnetometer	Atomic Clock	Squeezed Laser Interferometer	Quantum Ghost Imaging	Quantum Imaging Techniques	Quantum Network Sensors	Single Photon Detection	Quantum Transducer	Femptosecond Lasers	Photon-Correlated Metrology
Dark Matter Detector		🟨 X	🟥	🟥								
Dark Energy Detector	🟨	🟨 X		🟥 X								
Gravitational Wave Detector	🟨	🟨 X	🟨	🟥	🟩			🟩			🟥 X	
Far IR Detection									🟥 X	🟨		
CMB Measurements						🟥				🟥		
X-Ray Detection									🟥 X			
Exo-Earth Detection							🟩 X					

Multiple documents and previous quantum-focused workshops highlight key technologies (including spacecraft and communications quantum-based technologies) and techniques that would enable future missions that include topics such as the detection of GWs, dark matter and energy, CMB, exoplanet imaging, and X-ray and far-IR emission from weak sources, photon starved regions, or from sources that require very high angular and or spectral resolution. See references 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, and 54 for example uses of quantum technologies for astrophysics.

As an example, one application of quantum sensing to astrophysics is the achievement of spatial super- resolution without an increase in the telescope aperture size. This could be achieved by breaking the diffraction limit (~λ/D) through the use of novel quantum spatial mode demultiplexing filters (see references 55 and 56 for details). The detection of exoplanets could be enhanced by taking advantage of quantum state discrimination and quantum imaging techniques to reduce the probability of error for detecting planets that are at small angular separations [ref. 57]. GW detection is also a high priority at NASA, as evidenced by involvement in the ESA's LISA Program, and the utilization of space missions such as Fermi, Swift, Hubble and now JWST to identify electromagnetic counterparts of LIGO detections. Looking beyond LISA, future programs would benefit from atom interferometry and very precise clocks [refs. 44, 46, and 52]. A femtosecond laser comb could be used to generate a clock signal from the transmitter, effectively suppressing laser frequency noise and clock noise for time-delay interferometry [ref. 54]. Dark energy and dark matter detection would also benefit from atom interferometry and precision clocks [refs. 51 and 53]. Quantum technologies also support future instrument development. One example is high-precision quantum-based correlated photon metrology systems that perform absolute calibrations on photon detectors [ref. 58]. A very high-level summary of quantum technologies as a function of science topic is provided in Table 7.1-1.

8.0 Quantum Sensing Technologies

This section describes what the panel views as the main quantum technologies relevant to current and future NASA missions. For each technology, a basic description of the technology is presented, and the state-of-the art performance across a variety of relevant metrics is described. The results of the NASA Center survey are presented toward the end of each section.

8.1 Atomic Clocks

Isolated atoms are simple quantum systems with discrete energy levels determined by quantum mechanics and fundamental constants of nature. Because of this, their energy level differences are intrinsically stable and do not vary from atom to atom, or in time or space. In its most common form, an atomic clock consists of an initially unstable oscillator (e.g., quartz crystal, microelectromechanical sensor (MEMS) oscillator or laser) locked to a transition between two suitable energy levels in an ensemble of atoms through feedback. The atoms stabilize the frequency of the oscillator over long periods where environmental and ageing effects dominate the free-running oscillator. The primary metric characterizing the performance of atomic clocks is the fractional frequency stability, usually presented as a function of the averaging time as an Allen deviation.

The earliest atomic clocks used microwave transitions in atoms with oscillators based on quartz crystals. The best such clocks today can provide a fractional stability $\Delta f/f$ at 10^{-13} to 10^{-16} level, over days and fractional accuracies near 10^{-16} [ref. 59]. With the advent of the optical frequency comb in the late 1990s, optical clocks based on highly stable laser oscillators locked to optical transitions in atoms became possible. Such clocks now exceed the accuracy of microwave clocks by two orders of magnitude, recently surpassing one part in 10^{18} [ref. 5], as shown in Figure 8.1-1.

There are two main ways in which atomic clocks are relevant to the NASA mission: as enabling technologies enhancing positioning and communications; and as primary sensors for carrying out tests of fundamental physics.

Atomic clocks as enabling technology

NASA has been a primary user of atomic clocks throughout its history. The Deep Space Network deploys a large number of hydrogen masers to support communication with, and tracking of, spacecraft throughout the solar system. In this role, hydrogen masers have a role similar to the atomic clocks on the GPS satellites. More recently, space qualified hydrogen masers have been developed in the European Galileo GNSS system, with performance somewhat better than the Rb clocks on the U.S. GPS satellites.

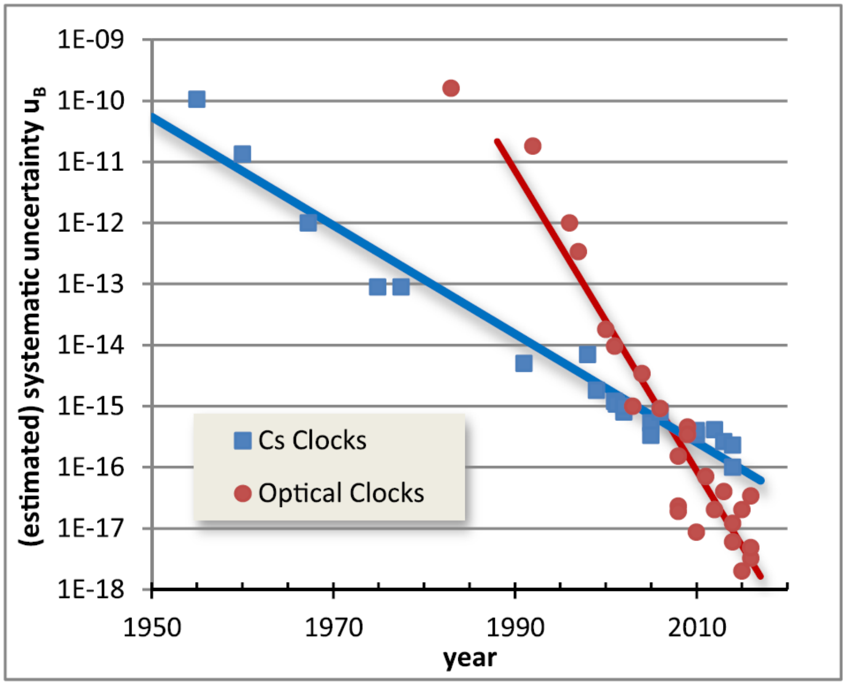


Figure 8.1-1. Optical Clock Uncertainties Compared to Microwave Clocks Uncertainties [ref. 60]

Driven by the need for on-board atomic clocks in deep space for one-way navigation and gravity sciences, NASA has invested in the development of the Deep Space Atomic Clock (DSAC) [ref. 61]. DSAC, demonstrated by JPL, is an atomic clock that uses electrostatically trapped mercury ions in a sealed trap tube. A mercury discharge lamp is used as the light source, as opposed to lasers that are used in most other modern high-performance atomic clocks. This makes the clock simpler to design and increases reliability. With a fractional frequency stability of 10^{-15} at one day in a package of volume 17 L that consumes 60 W of power, it represents the state of the art in atomic clocks in space, capable of providing an order of magnitude better long-term stability than that of current space rubidium clocks used in GPS.

Another type of compact atomic clock is the chip-scale atomic clock [ref. 62]. Developed during the 2000s with Defense Advanced Research Projects Agency (DARPA) funding, this clock achieves atomically precise timing while consuming only 120 mW of power. At the heart of the clock is a silicon/glass vapor cell fabricated using silicon micromachining processes. The clock is interrogated by a low-power vertical-cavity surface emitting laser. These clocks have been space-qualified [ref. 63] and have been deployed on the ISS to test operation in a space environment.

High performance optical clocks can be implemented using either trapped and laser cooled atomic ions or neutral atoms confined in optical lattices [ref. 5]. Both technical implementations have shown competitive state of the art accuracies near 10^{-18} [refs. 64, 65, and 66]. However, because neutral atom lattice clocks typically confine thousands of atoms, whereas trapped ion clocks confine a single (or at most a few) atoms, the overall stability of lattice clocks is typically superior to optical ion clocks. On the other hand, ion clocks have the advantages of easier control of systematic effects that perturb the frequency and more straightforward implementation for low size and power consumption.

Both types of clocks have been developed primarily at major frequency metrology laboratories in experimental implementations that often take up an entire room. Recently, transportable optical clocks have been demonstrated with some compromise in accuracy compared to their laboratory-scale counterparts. These clocks are currently the size of a small refrigerator [ref. 67], and much work remains to make them qualified for missions in space, especially for environments harsher than the ISS. Nevertheless, some progress has been made toward maturing the laser and component technologies for use in space. Most of such developments for space have been in Europe, both in ESA programs and European national space agencies, and in Japan.

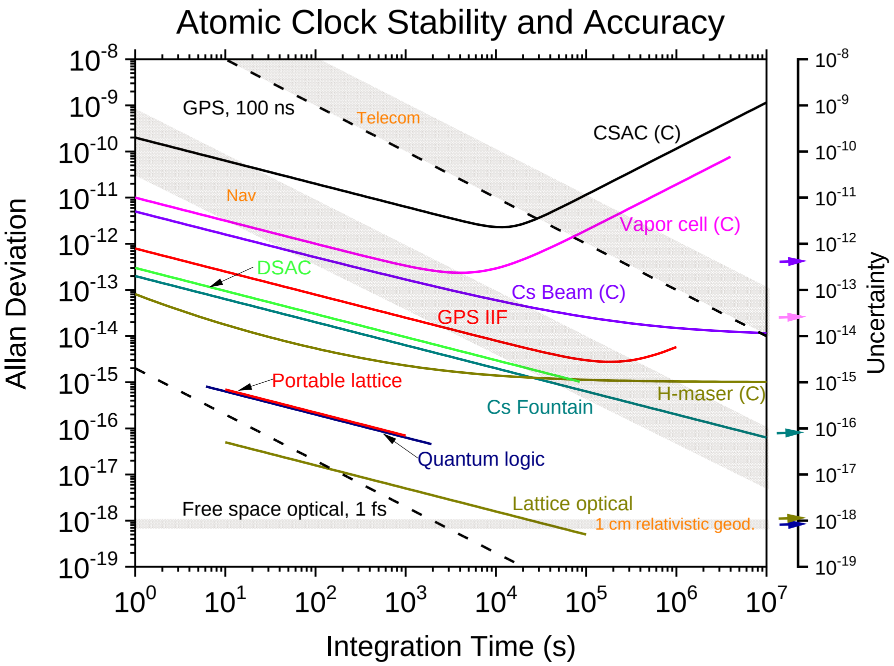


Figure 8.1-2. Allen Deviation of Atomic Clocks for Different Integration/Measurement Times Chip-scale atomic clock (black), commercial Rb vapor cell atomic clock (pink), commercial Cs beam atomic clock (purple), GPS Rb vapor cell atomic clock (red), commercial hydrogen maser (gray), laboratory fountain microwave clock (green), optical lattice clock (gray), portable optical lattice clock (red) and quantum logic ion optical clock (blue). Also shown are stability ranges corresponding to telecommunications (100 ns – 1 µs) and satellite-based navigation (100 ps – 1 ns). [Credit: NIST]

Optical clock technology is likely to impact many areas of NASA, from the Deep Space Network to support of planetary and astrophysics missions. For these applications, SWaP is more critical than clock stability and accuracy. Low-SWaP optical clocks may not achieve the state-of-the-art performance of their larger counterparts but can be useful if they outperform current low-SWaP microwave clocks by a factor of 10 or more. These new capabilities in a smaller package can potentially be deployed on deep-space spacecraft, enhancing the autonomy of the interplanetary network system and increasing ground asset utilization efficiency. At the same time, they will also enable and enhance science measurement capabilities from the traditional radio science (and similar optical science) to clock-based missions for gravity probes and detection of dark matter scalar fields deeper in space and closer to the Sun. The broad range of atomic clock performance is shown in Figure 8.1-2.

Atomic clocks for tests of fundamental physics

On the other hand, time and space are interconnected via gravity. Atomic clocks are therefore a primary tool to explore Einstein's theories of relativity and search for their possible violations. In addition, new fundamental interactions often necessarily depend on the atomic particle constituents of elementary quantum systems and resulting alterations in atomic properties, which can be detected by comparing atomic clocks of different types. Atomic clocks are therefore one of the most useful sensors for probing physics and detecting new phenomena.

An optical clock with a fractional uncertainty of 10^{-18} is capable of detecting a height difference of 1 cm through the gravitational redshift and applications to geodesy are already emerging (see Figure 8.1-1). Such a clock orbiting the Earth in satellite and compared with a clock on the ground would enable vastly improved tests of general relativity. Indeed, multiple optical missions have been proposed over the years. Within NASA BPS, a science definition team has put forward a mission concept to use dual optical clocks on Earth and in an elliptical orbit, promising 30,000 times improvements over the precision of the gravitational redshift measurements [ref. 68].

Many experiments in fundamental physics involve the comparison of high-performance clocks at two or more physical locations (in orbit and on Earth, for example). These comparisons require high-performance timing links to enable the precise comparisons needed to make meaningful scientific advances. The cold atom clock put into orbit by the Chinese Space Agency in 2016 but not precision timing links were reported [ref. 69] and the science it accomplished was correspondingly limited. Both microwave and optical fields can be used for precise time transfer. Optical links over either free-space or optical fiber currently provide the best time transfer precision of around 1 fs. Such links allow comparison of clocks at the 10^{-18} level in only a few hundred seconds of measurement on stationary platforms. Although not quantum in-and-of-itself, the development and demonstration of such links from space to ground is an important aspect enabling the use of quantum technology for fundamental physics.

Figure 8.1-2 shows the Allen deviations (fractional frequency stabilities) of a broad range of atomic clocks as a function of measurement (integration) time. The instabilities span many orders of magnitude, and yet all these clock technologies find relevance due to the equally broad range of size, weight, power consumption and cost. Technologies labelled (C) are commercially available and the stability reference is the product data sheet. References for the non-commercial technologies are GPS IIF [ref. 70]; DSAC [ref. 71]; Cs Fountain [ref. 6]; Portable lattice [ref. 72]; Quantum Logic [ref. 64]; Lattice optical [ref. 66].

Table 8.1-1 shows the current NASA activities focused on the development of atomic clocks, as reflected by the survey.

Table 8.1-1. NASA Activities Focused on Development of Atomic Clocks

Brief Description	NASA Center	Tech. POC	Website	NASA Use Case	ROM Funding ($M/year)	Effort Level (FTE)	Approx. TRL (1 -- 9)
Ion Clocks	JPL	Nan Yu nan.yu@jpl.nasa.gov	https://scienceandtechnology.jpl.nasa.gov/people/n_yu	Deep space clock, other microwave and optical clocks		5	TRL 1-9
DSAC	JPL	Todd Ely todd.a.ely@jpl.nasa.gov	https://www.nasa.gov/mission_pages/tdm/clock/index.html	Deep space navigation			TRL 7-8
Neutral lattice clocks	JPL	Nan Yu nan.yu@jpl.nasa.gov	https://scienceandtechnology.jpl.nasa.gov/people/n_yu	Fundamental Physics			TRL 2-3
Quantum Optics	JPL	Makan Mohageg Makan.Mohageg@jpl.nasa.gov		Fundamental Physics			TRL 3
Hg ion microwave clock	GSFC	cheryl.j.gramling@nasa.gov		Space clock networks, lunar communication, deep space, very long baseline interferometry (VLBI)	varies	1	TRL 1-9
Frequency combs	GSFC	kenji.numata-1@nasa.gov		Precise time in distributed systems, two-way time frequency transfer	varies	1	TRL 1-9

8.2 Quantum Magnetometers

Magnetic fields are ubiquitous in space. From space weather that impacts communications and the electrical grid to interactions between gas giants and their moons and the dynamics of terrestrial planets, quantitative understanding of these systems can be gained by measuring magnetic fields. Near the surface of the Earth the strength of the magnetic field is roughly 50,000 nT. However, in geosynchronous orbit the field falls to around 100 nT which is similar to typical field strengths in orbit around the Martian surface [ref. 73]. This large range of magnetic fields places stringent requirements on the dynamic range of magnetometers or requires magnetometers optimized for specific missions.

Arguably, quantum magnetometers are the first quantum sensors to make an impact in space, being incorporated into missions as early as 1961, when a rocket borne Rb magnetometer was flown [ref. 74]. Over the past 60 years, nearly 200 spacecraft have carried magnetometers throughout the solar system to achieve science goals from observing space weather to studying the habitability of the icy moons of gas giants.

Magnetometers have been developed using a diverse set of physical principles, with a variety of highly competitive classical sensors available commercially. Cell phone magnetometers are highly reliable, extremely small, and cost about a dollar. By contrast SQUID (superconducting quantum interference devices) magnetometers reach sensitivities at the femtoTesla (fT) level at the cost of bulky and cumbersome cryogenic operation. There are a host of applications in between which are not satisfied by the performance of low-end sensors but cannot afford the overhead of SQUIDs. In addition, quantum engineers are actively studying a plethora of quantum magnetometers, each with its own attributes and drawbacks. The magnetometer requirements should use system analysis to match sensor specifications to the mission requirements.

There are a variety of commercially available classical sensors, which can be used if they meet mission needs. The fluxgate has been the workhorse for vector magnetic missions. Classical fluxgate magnetometers rely on saturating a ferromagnetic core and measuring the nonlinear response using a pickup loop. Such fluxgate magnetometers require careful calibration both to account for the magnetic susceptibility of the core and the digitization process to produce a signal as well as to compensate for the three axes of a vector magnetometer being not exactly perpendicular to one another. Despite such challenges, fluxgate magnetometers have been a workhorse of spacecraft. They reach accuracies of 1 nT and sensitivities better than $0.015\ \mathrm{nT}/\sqrt{\mathrm{Hz}}$ in one second [ref. 82]. They have flown as part of Geostationary Operation Environmental Satellite (GOES), Voyager, Mars Global Surveyor, soon to launch Psyche, and many other missions.

In recent decades, a series of quantum magnetometers have been developed using technologies including optically pumped atomic gases, solid-state quantum defects, and SQUIDs. These sensors measure either the magnitude of the total magnetic field (scalar magnetometry) or the field magnitude and direction (vector magnetometry) and they have the potential to provide reduced SWaP along with calibration-free sensing and sensitivity significantly better than the classical fluxgate magnetometer.

Aside from frequency, magnetic field is often the most straightforward thing for a quantum system to measure. Elementary particles have spin, resulting a magnetic dipole moment. This manifests itself in variety of fundamental B-field-dependent effects. For example, the Zeeman effect causes energy level splitting proportional to the applied field, which can be directly measured to extract the B-field. Missions using this technology include ESA’s upcoming Vigil space weather mission to the Sun-Earth L5 point, which will include a Photospheric Magnetic Field Imager instrument [ref. 75]. This instrument will utilize the Zeeman technique to obtain maps of the strength, azimuth, and inclination of the magnetic field on the surface of the Sun.

Optically pumped helium magnetometers are an example of a quantum magnetometer that have a long heritage in space flight dating back to Pioneer 10 and 11, and more recently including ESA’s Swarm mission [ref. 76], and CubeSat for Solar Particles (CuSP), a CubeSat intended to study space weather. These magnetometers rely on measuring the spin precession frequency of helium atoms, which depends upon the magnetic field in which they are embedded. They can operate in both scalar and vector mode and commercial optically pumped helium (He) magnetometers reach well below 1-nT accuracy, even in the Earth’s field of 50,000 nT, and have sensitivities competitive with those of fluxgate magnetometers at frequencies above 1 Hz but are more sensitive below 1 Hz.

Overhauser magnetometers are based on the spin precession frequency of protons in hydrogen atoms and operate using techniques akin to nuclear magnetic resonance. These instruments attain 0.1-nT accuracy and $0.01\text{-}\mathrm{nT}/\sqrt{\mathrm{Hz}}$ sensitivity at 1 second in commercial instruments [ref. 77]. They have been flown on ESA’s Challenging Minisatellite Payload (CHAMP) spacecraft [ref. 78].

Optically pumped alkali atom magnetometers, utilizing atoms such as Rb, Cs, and potassium, have been around since the 1960s and are currently being further developed with efforts in academia, government, and industry. Accuracy and stability meet many mission requirements. As an example, with National Institute of Standards and Technology (NIST) demonstrating a Rb scalar magnetometer with a sensitivity below 0.015 $\mathrm{nT}/\sqrt{\mathrm{Hz}}$ at one second and an absolute accuracy <0.5 nT [ref. 79]. This magnetometer has been designed with space missions in mind.

Solid-state quantum magnetometers utilize a quantum defect in crystals, such as the NV color center, which acts like an atom fixed in the crystal lattice. As with the optically pumped atomic magnetometers, a laser excites the system and the amount of light read out can be used to infer the frequency of the transition in the quantum defect and thus the magnetic field. These "diamond" magnetometers are intrinsically vector systems measuring the projections of the magnetic field along the different crystal axes of the diamond. Due to the rigidity of the diamond lattice, the axes are fixed and do not need to be calibrated. Diamond magnetometers have attained <0.001-$\mathrm{nT}/\sqrt{\mathrm{Hz}}$ [ref. 80] sensitivity at a frequency of 20 kHz over 1 second of averaging with work continuing to improve sensitivity and assess the accuracy limits.

New technologies being developed enable laser-free solid-state quantum magnetometers. These include the silicon carbide (SiC) sensor based on the recombination of electron-hole pairs, which has realized a relatively modest 10-$\mathrm{nT}/\sqrt{\mathrm{Hz}}$ sensitivity at 1 second but is extremely low SWaP and remains under development. Within NASA, JPL has small efforts in these deployable magnetometers.

SQUID magnetometers, based on superconducting Josephson junctions measure the magnetic flux passing through a small area surrounded by a superconducting loop. The voltage across the SQUID depends upon the magnetic flux through it and allows very sensitive determination of the magnetic field routinely reaching sensitivities approaching 10^{-6} $\mathrm{nT}/\sqrt{\mathrm{Hz}}$ (1 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$) and accuracies below 1 nT. SQUIDs must be cooled to cryogenic temperatures and are extremely sensitive to vibrations and electromagnetic noise. SQUIDs are routinely flown on aircraft for geophysical surveying [ref. 81].

In Figure 8.2-2, the sensitivity of various solid-state quantum and atomic magnetometers is shown as a function of signal frequency. The most sensitive magnetometers at present are atomic vector sensors (atomic spin-exchange, relaxation-free (SERF)) and superconducting quantum interference devices. NV-diamond magnetometers are competitive with compact atomic magnetometers, especially at higher frequencies and can achieve nm-scale spatial resolution under the right conditions. Note that while sensitivity and stability are valuable tools for comparison, the SWaP, and robustness can be equally if not more important metrics for space missions. Many magnetometers surpass the sensitivities and accuracies of the classical fluxgate sensors and can operate without a need for calibration due to their intrinsic quantum nature, relating the magnetic field to the frequency of an atomic or nuclear transition. Depending upon the modality desired of field magnitude (scalar) or field magnitude and direction (vector) along with a range of readout bandwidths. Additionally, the SWaP of each of these magnetometers is determined in large part by their method of operation and as such can impact the selection of the appropriate magnetometer for a given mission. With respect to space environments, radiation hardening, and robustness are also significant. Robust, low SWaP quantum sensors will enable sub-0.001-$\mathrm{nT}/\sqrt{\mathrm{Hz}}$ sensitivity and sub-nT accuracy vector sensing on space missions in the coming years. The references for Figure 8.2-1 are as follows: Messenger Flux Gate [ref. 82]; NV Center [ref. 83, 84, and 85]; Search Coil [ref. 86]; ^{4}He [ref. 87]; Atomic Scalar [ref. 88]; Flux Gate [ref. 89]; Atomic MEMS Scalar [ref. 90]; Ferrimagnetic [ref. 91]; Atomic MEMS SERF [ref. 92]; High Tc SQUID [ref. 93]; ^{3}He NMR [ref. 94]; Atomic SERF [ref. 95]; Atomic Scalar Pulsed [ref. 96]; SQUID [ref. 97].

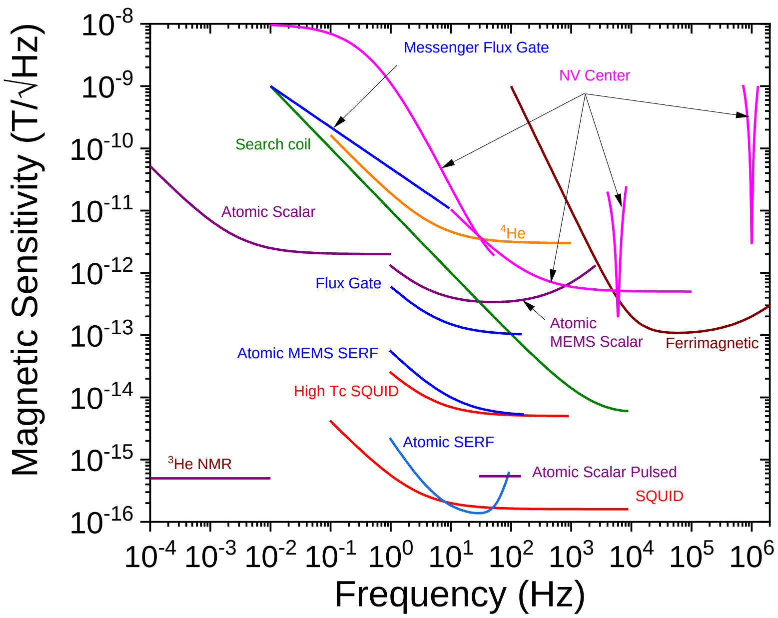


Figure 8.2-1. Sensitivity of Quantum Magnetometers as Function of Signal Frequency
Atomic magnetometers tend to outperform classical sensors (fluxgate magnetometers and search coils) at low frequencies. References are listed in the main text. [Credit: NIST]

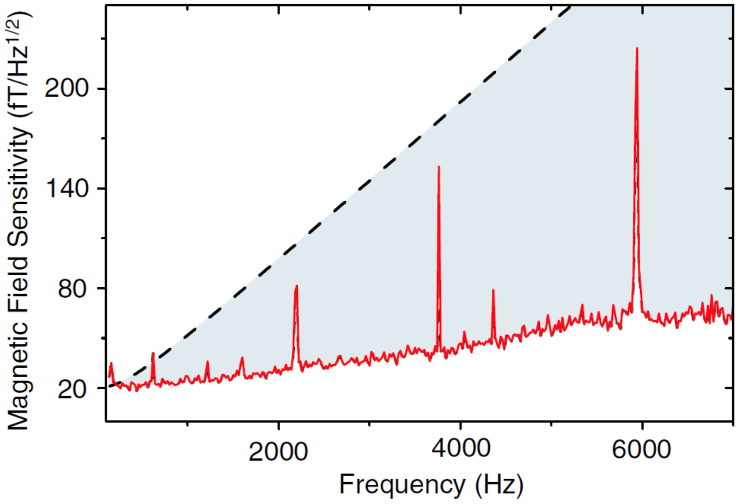


Figure 8.2-2. Magnetometer Performance Improvements through Continuous QND Measurements
The black dashed line shows the sensitivity limited by the relaxation time of the atoms. The red curve shows the sensitivity using QND. [ref. 98]

Quantum non-demolition (QND) measurements of spin states of atoms in thermal vapors have been shown to enhance the bandwidth of atomic magnetometers (see Figure 8.2-2). A QND measurement is one that does not introduce quantum back-action noise on the variable being measured (e.g., the z-component of an atomic spin) but instead puts this noise into a different variable (e.g., the x- or y-component). Measurements of the primary variable can therefore be made semi-continuously, resulting in an enhancement in the rate at which data can be extracted from the sensor. This type of measurement is particularly important in high-Q systems such as atomic clocks [ref. 99] and magnetometers [ref. 98], where the coherence time can be very long, limiting the bandwidth of the sensor or clock stabilization feedback loop.

Table 8.2-1 shows the current NASA activities focused on the development of quantum magnetometers, as reflected by the survey.

Table 8.2-1. NASA Activities Focused on Development of Atomic or Quantum Magnetometers

Brief Description	NASA Center	Tech. POC	Website	NASA Use Case	ROM Funding ($M/year)	Effort Level (FTE)	Approx. TRL (1 -- 9)
Optically Pumped Solid-State	JPL	Hannes Kraus hannes.kraus@jpl.nasa.gov		Planetary science			TRL 1
Helium vector magnetometer	JPL	Carol Raymond, carol.a.raymond@jpl.nasa.gov		Planetary science			TRL 6+
SQUID magnetometer receiver (77K)	GRC	Brian Vyhnalek brian.e.vyhnalek@nasa.gov		Magneto-inductive communications	0.2	0.5	TRL 2-6
SQIF receiver (4K)	GRC	Brian Vyhnalek brian.e.vyhnalek@nasa.gov		RF communications (X-band, Ka-band, etc.), magneto-inductive communications	0.02	0.1	TRL 2-5
Cavity optomechanical magnetometer	GRC	Brian Vyhnalek brian.e.vyhnalek@nasa.gov		Field sensing, navigation, communications	0.02	0.1	TRL 2-4
SiV centers in SiC	GRC	Dan Hart daniel.r.hart@nasa.gov		Magnetometry, electronic spin-control, single-photon source	0.05	0.25	TRL 2

8.3 Atom Interferometers

Atom interferometers [refs. 100 and 101] use the interference of matter waves to sense gradients in potential that exist between the different paths taken by matter in a superposition of spatial states. As such, they resemble classical optical interferometers based on light, but with a sensitivity set by the de Broglie wavelength of the particle rather than the wavelength of radiation. For massive particles such as atoms, this wavelength can be orders of magnitude smaller than that of visible light, resulting in potentially better sensing performance. This improvement is offset by the fact that the photon number in optical interferometers is typically much larger than the atom number in atom interferometers. Nevertheless, for some applications, particularly those requiring high accuracy and scale factor stability, atom interferometers offer compelling advantages. Atomic wavepackets can be diffracted by both physical nanofabricated gratings [refs. 102 and 103], or by light fields [refs. 104 and 105]. Physical gratings offer high stability and low SWaP, while light-pulse interferometers offer reconfigurability and flexibility. Most atom interferometers developed for acceleration/gravity and rotation sensing have been light-pulse designs.

In a typical light-pulse atom interferometer, shown in Figure 8.3-1, an ensemble of atoms is first prepared in a well-defined internal spin state. A light pulse is then used to drive the atom into a quantum superposition of two states, one of which has absorbed a photon from the light field and hence has gained momentum along the direction of the optical field, and the other of which has not. This pulse is equivalent to the first beam splitter in a classical optical interferometer. The additional momentum causes that part of the atomic wavepacket to spatially separate from the other part such that the two components follow a different physical trajectory. The second light pulse acts as a mirror, adding a momentum kick to the wavepacket component that did not originally receive one while not affecting the component that did. A third light pulse recombines the wavepackets such that they interfere, producing fringes that depend on the relative phase shift experienced by each part of the atom wavepacket. This relative phase shift can be created by a potential gradient (acceleration due to gravity, for example) or a Sagnac effect arising from rotation if the atoms are given some initial velocity. Atom interferometers can therefore measure both the acceleration and rotation of some test mass with respect to an ensemble of freely falling atoms.

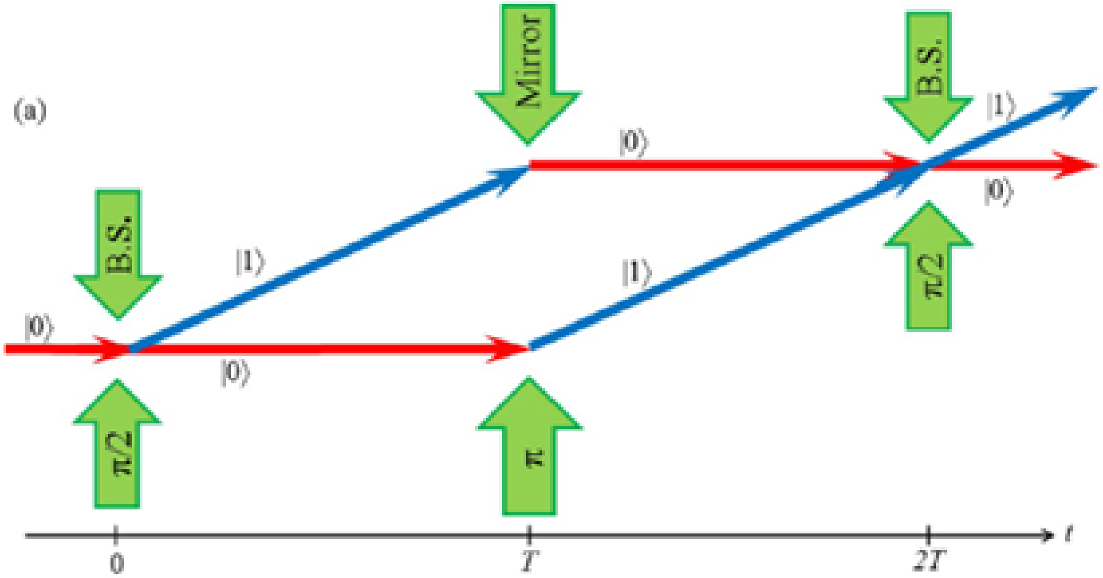


Figure 8.3-1. Atom Trajectories in Light-pulse Atom Interferometer [ref. 106].

Light pulse atom interferometers are typically implemented in one of three categories: atomic beams, freely falling laser-cooled atoms and guided atoms. Atomic beam interferometers are based on a thermal beam of atoms emitted from an oven through collimating tubes. The atoms in these interferometers move at thermal velocities (~300 m/s) resulting in short interrogation times, but the beam flux is high, resulting in high SNRs. Such interferometers tend to perform well as rotation sensors and have demonstrated the best short-term rotation sensitivity of any atom interferometer gyroscopes. The laser cooling of atoms down to sub-microKelvin temperatures allows for substantially longer interrogation times (seconds as opposed to milliseconds) at the cost of fewer atoms (~ 10^7/s instead of 10^{12}/s). Such instruments have the best performance for acceleration/gravity measurements and absolute accuracy.

The first atom interferometers were demonstrated in in the laboratory in the early 1990s [refs. 74, 76, 77, and 107] and development and improvement continues to this day. The most sensitive interferometers are based on freely falling clouds of laser-cooled atoms and achieve an acceleration sensitivity below 10^{-11} g (1 g = 9.81 m/s^2)for measurement times of several seconds, which atom interferometer gyroscopes can measure rotations at the level of 10^{-9} rad/s on similar time scales. Such instruments have been used for absolute measurement of geodetic rotation [ref. 108], the gravitational constant [refs. 109 and 110] gravity gradients [ref. 111] and curvature [ref. 112], and searches for new forces [ref. 80] among others.

Portable versions of these instruments have been developed and are now being deployed in the field for gravitational measurements onboard ships [ref. 113] and aircraft [ref. 114]. Two companies sell commercial atom interferometer gravity gradiometers at present. Figure 8.3-2 shows a portable atom interferometer inertial sensor installed on a gimbled mount to maintain verticality during platform motion.

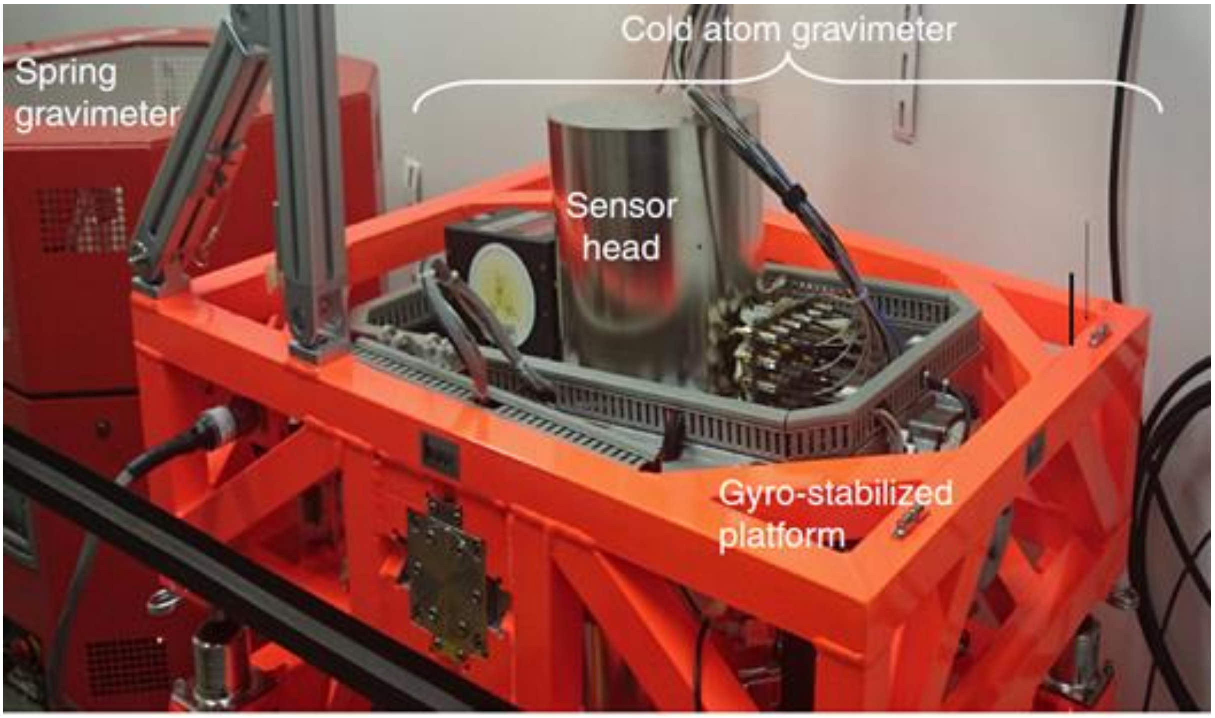


Figure 8.3-2. Portable Atom Interferometer Inertial Sensor [refs. 106 and 113]

In addition, some work at present is focused on developing guided-wave atom interferometers, in which atoms are confined in some (optical or electromagnetic) potential on, for example, an atom chip [ref. 115]. While such interferometers can suffer from the perturbative effects of the guiding potentials, larger loop areas can be achieved potentially resulting in a larger Sagnac signal and higher sensitivity. Work in this area is still developing [ref. 116] but may offer advantages with respect to SWaP for atom interferometers deployed in space. Atom interferometers using shaken lattices are also under development [ref. 117].

A potential application of atom interferometers in space is for inertial navigation. Existing (non-quantum) technologies for acceleration and rotation include silicon micromachined accelerometers, electrostatic accelerometers, mechanical spinning ball gyroscopes [ref. 118] and fiber-optic and ring-laser gyroscopes [ref. 119].

In response to the need for new gravity recovery technologies for Earth science and geodesy called out in the 2018 Earth Science decadal survey, high precision gravity gradiometers based on atom interferometers have been under development by NASA, ESA and private industry. For example, NASA GSFC has partnered with AOSense, Inc to build an experimental Cs cold atom gravity gradiometer testbed that combines advanced laser cooling, optical transport and large momentum transfer. Cold atom gradiometers can theoretically achieve gravity gradient sensitivities of less than 100 μE (1 E = 10-9 g/m) would enable an order of magnitude better time variable gravity measurements over the state of the art in a single satellite rather than constellations of many satellites. Time variable gravity data at this resolution in nearly real time would enable predicting and tracking aquifer depletion, seismic activity and unprecedented sensitivity in climate models.

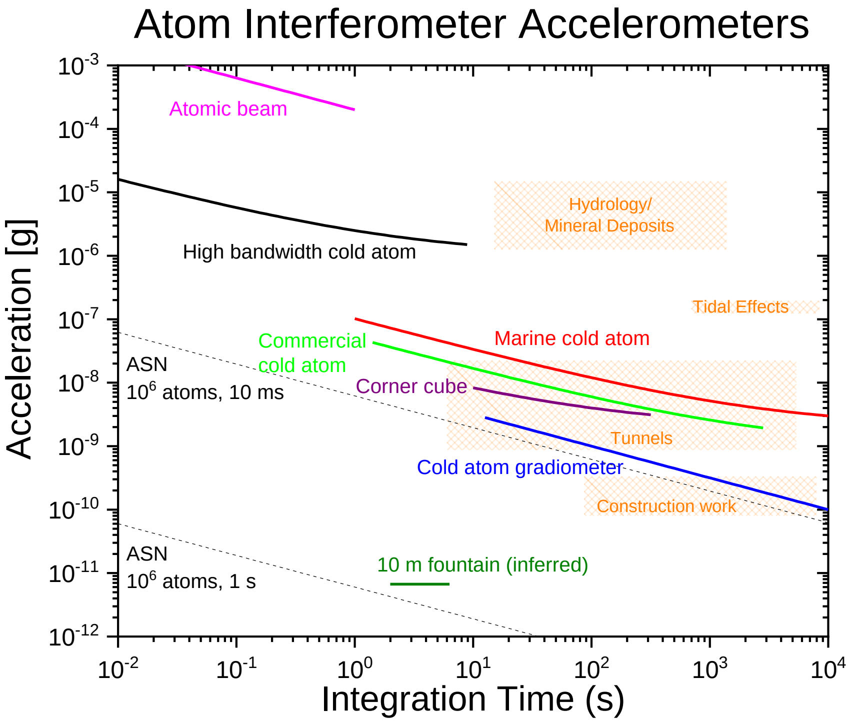
A comparison of various experimentally demonstrated atom interferometer accelerometers/gravimeters and gyroscopes with other types of inertial sensors is show in

Figure 8.3-3. Several features are evident from this plot. First, atomic beams work well for gyroscopes, but accelerometer/gravimeters are best implemented with cold atom ensembles. It can also be seen that the highest-performing laboratory-scale atom interferometer sensors are orders of magnitude better that existing classical sensor approaches, particularly at long integration times. The references for the data in these plot are: (a) Atomic beam [ref. 128; High-bandwidth cold atom [refs. 120 and 121]; Marine cold atom [ref. 122]; Commercial cold atom [ref. 123]; Corner cube [ref. 124]; Cold atom gradiometer [ref. 109]; and 10 m Fountain [ref. 125]. Also shown are the stability limits assuming atom shot noise with 10^6 atoms and measurement times of 10 ms and 1 s (dashed lines). (b) Stability of atom interferometer gyroscopes, compared to optical gyroscopes and ring laser gyroscopes (RLG), fiber-optic gyroscopes (FOG) and hemispherical resonator gyroscopes (HRG). Compact nuclear magnetic resonance (NMR) [ref. 126]; Interleaved cold atoms [ref. 127]; Atomic beam 2 m [ref. 128]; precision inertial navigation systems (PINS) Cold Atoms [ref. 129].

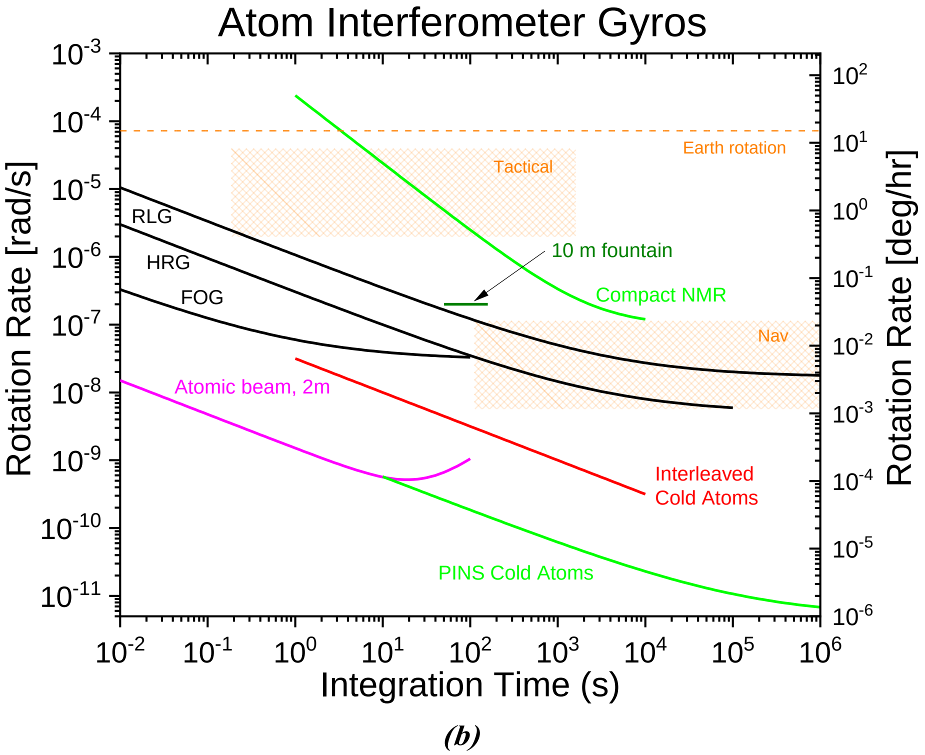
Table 8.3-1 shows the current NASA activities in atom interferometry, as reflected by the survey.

Table 8.3-1. NASA Activities Focused on Development of Atom Interferometers

Brief Description	NASA Center	Tech. POC	Website	NASA Use Case	ROM Funding ($M/year)	Effort Level (FTE)	Approx. TRL (1 -- 9)
Cold atom interferometer inertial/gravity measurement devices	JPL	Nan Yu Sheng-wey Chiow		Earth and planetary gravity and atmospheric drag measurements, precise orbit determination, and in-situ gravity and seismic measurements			TRL 3-5
AIGG (Atom Interferometer Gravity Gradiometer) - Cs cold atom gravity gradiometer	GSFC	peter.g.brereton@nasa.gov; holly.f.leopardi@nasa.gov		Time-variable gravity	varies	3	TRL 1-5



(a)



(b)

Figure 8.3-3. Stability of Atom Interferometer Accelerometers (a) and Gravimeters (b) Compared to a falling corner cube gravimeter. References are listed in the main text. [Credit: NIST]

8.4 Imaging and Remote Sensing

Optical imaging and sensing applications relevant to the NASA mission, including, but not limited to, astronomical imaging that could benefit from quantum technology are discussed in this section. Some of these applications benefit from the incorporation of quantum light sources such as squeezed light and entangled photons, whereas some benefit from high-precision single-photon-sensitive detectors. Then there are others that benefit from quantum phenomena through a powerful mathematical framework of quantum information theory, within which the fundamental performance limits of sensor systems can be analyzed, often leading to system designs whose resolution and precision are unattainable with conventional means.

(a) Photonic sensors augmented by squeezed light: Injecting squeezed light into an interferometric phase measurement can improve the measurement sensitivity beyond that attainable with classical (laser) light, for the same total probe energy. The best-known modality of such quantum enhancement occurs for the LIGO interferometer [ref. 130]: a giant GW detector that detects a tiny optical path-length difference caused by a GW. When a continuous-wave (cw) squeezed-light source is split by a fiber splitter, the outputs of that splitter are in an entangled state. This is a distinct deviation from splitting cw classical laser light by a fiber splitter, which results in statistically independent uncorrelated cw laser-light signals at the output of the splitter. The entanglement produced by splitting squeezed light in a linear-optical interferometer can be used to boost the collective sensitivity of an array of M interferometric phase sensors, especially when that sensor array is engaged in estimating a function of their locally sensed phases. The root-mean-squared (RMS) estimation error scales as 1/M (as opposed to the classical scaling of $1/\sqrt{\mathrm{M}}$). An example application of this form of a quantum-enhanced sensor network is when a RF photonic sensor array is read out using a squeezing-augmented laser light probe, enhancing its sensitivity in gleaning information embedded in the incoming RF signal [ref. 131]. The same principle underlies squeezing-enhanced fiber-optical gyroscopes for better-than-classical position and navigation [ref. 132], high-precision beam pointing and tracking [refs. 133 and 134] and squeezing-enhanced quantum machine learning for sensor data classification [ref. 135], and entanglement-enhanced opto-mechanical sensor networks [ref. 136].

(b) Fundamental science discovery assisted by quantum-enhanced measurement sensitivity: non-classical light sources can be used for ultra-sensitive detectors of dark energy and dark matter [ref. 136], as well as tabletop tests of quantum gravity. Multimode squeezed light impinging on arrays of nano-trampolines can enable ultrasensitive measurements of force, acceleration, and magnetic fields [refs. 45 and 137].

(c) Astronomical imaging of traditionally unresolved scenes: For spatial or spectral resolution, tools from quantum detection and estimation theory have revealed receiver designs to achieve the best resolution [refs. 138, 139, and 140]. In hindsight, the inner workings of these receiver designs can be described using the semiclassical (shot-noise) theory. But these designs would not be discovered if not for quantum estimation theory. Quantum-inspired receivers for sub-Rayleigh imaging using pre-detection spatial and spectral mode transformations can resolve four to five stars within a 0.25 Rayleigh field of view, with 100,000 collected photons. A conventional telescope equipped with the state-of-the-art focal plane array, cannot resolve more than one star in that regime [ref. 141]. This technology could lead to advanced telescopes to discover exoplanets that are currently inaccessible using conventional coronagraphic methods, attain

spectral resolution to assess life-sustaining elements [refs. 142, 139], and for quicker detection of minute changes in the universe far better than conventional telescopes.

(d) Long baseline telescopes: The European Southern Observatory's Very Large Telescope array reported the first direct detection of an exoplanet by optical interferometry, separating light from the exoplanet from that of its central star for spectroscopic analysis. Pre-shared entanglement among distant telescope sites across the Earth (and possibly in space) will enable stringing together very long baselines that will enable unprecedented high imaging resolution [refs. 143, 144]. Single photon detectors, spontaneous parametric down-conversion (SPDC) sources, and quantum memories will all play key roles in its development; in building quantum repeaters and/or space-assisted long-distance entanglement distribution networks, and the transduction process of loading the starlight into banks of quantum memories at each telescope site.

(e) Space-based quantum sensor networks: In general, when multiple sensors modulated by a correlated field work to serve a common goal, pre-distributed entanglement can help to attain far-higher resolution versus a classical collaboration. At one extreme of the distance scale are long-baseline telescopes and entanglement-assisted clock synchronization using a network of distant atomic clocks [ref. 143] whose realizations will need significant developments in enabling-technology. At the other extreme are entanglement-enhanced RF photonic sensors [ref. 145] and squeezing-enhanced fiber-optic gyroscopes using networks of fiber loops [ref. 132] discussed above, where the multiple "sensors" working together towards the common sensing task are co-located within one sensor device. Space-based quantum sensor networks with distributed entanglement shared among them can not only lead to unprecedented Earth imaging capability but could also lead to revolutionary advances in GW detection, and ultra-high-resolution imaging of the universe.

(f) Quantum sensors for biological imaging applications: Near-field imaging and sensing applications in low-loss environments, where the probe light's interaction with the scene involves a highly multimode linear optical scattering transformation, an optical probe that is entangled across those modal degrees of freedom can yield a far higher sensing resolution than that is possible with a classical-optical probe of the same photon energy and occupying the same (spatio-temporal-polarization) degrees of freedom as the quantum probe. Applications range several diagnostic imaging paradigms, such as: fluorescence microscopy with single-photon-emission photo-activable fluorophores, two-photon microscopy enhanced by entanglement, multimode optical fiber-based endoscopic imaging via multi-spatial-mode entangled probe, and quantum enhanced optical coherence tomography (OCT). These technologies will all translate to lower SWaP compared to their conventional classical sensor counterparts, which will be an important enabler for applications during long human-driven space missions.

(g) Deep space classical communications: One of the key benefits of optical-frequency modulation for deep space communications, is the far higher data rates possible (compared to RF communications) due to the much higher optical bandwidths, and the far narrower beam spread. Conventional deep-space lasercom, e.g., the kind employed for the Lunar Lasercom Demonstration program, already uses quantum limited Single photon detectors (SPDs) since it uses pulse-position modulation (PPM) and superconducting nanowire SNSPDs [ref. 146]. Using quantum processing within the receiver, e.g., using all-optical pre-detection transformations of the received modulated codeword using squeezing, linear optics and photon number resolving (PNR) detection [ref. 147] (or alternatively transduction of the received modulated optical frequency light into atomic qubits followed by quantum processing and detection on those qubits

[ref. 148]) can further enhance the data rates achievable, over and above the highest-possible data rates permissible with PPM and SNSPDs. Finally, a receiver that uses pre-detection linear temporal modal processing on the received modulated codewords followed by SPDs, can lower the transmitter laser's peak power requirements by several orders of magnitude, e.g., for the Mars-to-Earth lasercom link [ref. 149].

(h) Quantum radar and stand-off imaging and sensing: A rigorous analysis of an entanglement-based target-detection radar [refs. 150, 151] revealed that under the rather restrictive operational regime of (i) low transmitter brightness, (ii) high thermal noise (e.g., for a microwave center wavelength probe), and (iii) over a high-loss return path, an entanglement based quantum radar can provide a moderate (6 dB) SNR improvement over a classical coherent radar using the same transmit power and optical bandwidth. The optical parametric amplifier receiver [ref. 151] achieves 3 dB of that full quantum-promised 6-dB improvement over classical radars for the aforesaid operational regime, which was realized experimentally [ref. 152] and proved that entanglement can be a valuable resource, even when it dies during target interrogation. More recently, a Bayesian continuous-wave analysis for a target-detection radar revealed [ref. 153] that there can be a 10- to 20-dB improvement in the radar's SNR performance in the "mid-SNR" regime over a classical radar. But again, this purported improvement occurs in the regime of very-low transmitter brightness, high thermal noise, and high return-path loss environments. Quantum radar may not be a viable technology for the NASA mission due to the restrictive regime where quantum improvement prevails, the difficulty in preparing and storing microwave entanglement, and the moderate gains (that could vanish with small system imperfections). In limited scenarios however, such as for a Laser Detection and Ranging system with an inefficient heterodyne receiver, one can get a performance boost (for a classical coherent detection radar) by preceding the receiver with a quantum-noise-limited phase-sensitive amplifier [ref. 154].

(i) Space-based quantum communications: For realizing a global scale quantum internet, satellite-assisted distribution of entanglement across continental scales must support a ground-based (quantum repeater) fiber infrastructure, especially for transcontinental links [refs. 155, 156, 157, and 158]. Space Communication and Navigations's quantum communication ground terminal at the Optical Communications Test Laboratory (OCTL) is one such step in the direction of space-assisted quantum communications. SPD and SPDC sources will play a key role in realizing high-rate photonic entanglement sources, e.g., to be deployed on a satellite [refs. 159 and 160]. In addition, one would need to mature efficient light-matter interfaces necessary for heralded loading of photonic entanglement from a satellite-mounted entanglement source into quantum memory banks (e.g., built with trapped ion or color center qubits) at ground terminals [ref. 161], and finally, realizing photonically heralded entanglement locally among the matter qubits [ref. 162], which in turn will be used to perform entanglement distillation.

In conclusion, many optical imaging and sensing technologies, with applications to astronomical imaging, Earth observation, position, navigation and timing, clock distribution, fundamental physics discovery in quantum gravity aided by long-range entanglement, deep-space laser communications, and various high-precision photonic sensors for manned space missions, will benefit from quantum-technology augmentation. Such augmentation will require the maturation of integrated photonic nonlinear-optics-based sources of squeezed light and entangled photon pairs, ultra-low noise and high-efficiency single-photon and photon-number-resolving detectors, low SWaP cryocooling capacities, and system integration.

Table 8.4-1 shows the current NASA activities focused on quantum imaging and remote sensing, as reflected by the survey.

Table 8.4-1. NASA Activities Focused on Development of Quantum Imaging and Remote Sensing

Brief Description	NASA Center	Tech. POC	Website	NASA Use Case	ROM Funding ($M/year)	Effort Level (FTE)	Approx. TRL (1 -- 9)
Quantum Rydberg Radar	JPL	Darmindra Arumugam darmindra.d.arumugam@jpl.nasa.gov		Surface Topography, and Vegetation, Cryospheric science, pulsar-based navigation			TRL 1-2
VLBI	GRC	Evan Katz, evan.j.katz@nasa.gov	https://www1.grc.nasa.gov/research-and-engineering/optical-instrumentation/#quantum-communications	Observational astronomy	0.1	0.3	TRL 1

8.5 Single-Photon Detectors

Single-photon sensitive and photon-counting detectors with quantum-limited sensitivity-spanning visible to long-wave IR wavelengths are a key enabling technology for multiple quantum-enhanced and quantum-inspired applications critical to NASA’s mission. Some specific applications of such detectors are exoplanet detection and low-light star tracking. The state-of-the-art SPD and PNR detector technology being developed within the U.S. Government, spearheaded to a large extent by the groups led by Dr. Sae Woo Nam (NIST Boulder) and Dr. Matthew Shaw (JPL), are discussed in this section. Prof. Karl Berggren (Massachusetts Institute of Technology (MIT)) and Prof. Hong Tang (Yale University) are among the key U.S. academic groups leading SPD research. Much of the work on the development of applications that would benefit from quantum-noise-limited SPDs and PNR detectors has happened outside of NASA, in the U.S. (and foreign) academia, several of which were represented at the NASA workshop, and will be discussed in the next section. The applications of quantum-noise-limited SPDs include: photonic sensors augmented with squeezed light with applications to RF-photonic antennas, quantum-enhanced navigation and precision beam pointing; fundamental science discovery with applications to dark matter search, explorations of the theory of quantum gravity, and quantum-squeezing-enhanced LIGO and entanglement-enhanced global GW observatory network; quantum computing for important search and optimization problems; astronomical imaging of traditionally unresolved scenes with applications to exoplanet search and more; entanglement-assisted very long-baseline ground and space-based telescopes; quantum enhanced low SWaP optical sensors for biological imaging applications for long manned missions; and deep-space high-data-rate laser communications.

The key SPD technology being pursued within NASA (by Dr. Matt Shaw, JPL) is SNSPDs. The impinging photon creates a *hot spot* within a meandering nanowire built with a material such as tungsten silicide (WSi) or niobium nitride (NbN), through electron-hole pairs created by the photon energy and a 100-fs-scale electron-electron scattering process that ensues. The resulting thermalization creates a detectable voltage spike (and a corresponding dip) at the two endpoints of the nanowire. The key features of the state-of-the-art SNSPDs are as follows [ref. 163]:

(1) They are time-resolved single photon counting detectors that have high system efficiencies all the way from UV to mid-IR, i.e., active up to ~18 μm, making them a very versatile choice.

(2) They have very high system detection efficiency (e.g., 98% measured by NIST at 1550 nm) [ref. 164].

(3) These detectors have extremely low dark count rates (e.g., 6 x 10^{-6} counts per second measured with the MIT/NIST WSi SNSPD), thereby excellent for low-photon-flux applications [ref. 165].

(4) Their operating temperatures usually range from 1 to 4 K easily accessible with compact cryostats.

(5) They have ultrafast time-stamping accuracy (~2.6 picoseconds (ps) full width at half maximum (FWHM) rise time measured by NIST, MIT, and JPL) [ref. 166].

(6) FWHM timing jitter of 12 ps was measured on these detectors, which enables communications on 10 GHz clock.

(7) Current work is studying further improving jitter at high count rates. JPL plans to build a 4-detector system in FY23 to support SCaN's quantum communication ground terminal at OCTL.

(8) They are realizable in a compact 2D array to support high-sensitivity imaging applications. A 32x32 array (shown in Figure 8.5-1) was built (NIST/JPL) over a 30x30 µm active area on 50-µm pitch with a total area of 0.92 mm^2, with only 64 readout lines (as opposed to 1024) [ref. 167], using a row-column readout technique, wherein the appearance of a voltage spike/dip across a pair of vertical and horizontal nanowires, arranged in a crossbar geometry, pinpoints the spatial location of the impinging photon. A 400,000 pixel array [ref. 168] optimized for UV radiation has also recently been demonstrated.

(9) These are high-event-rate capable, e.g., JPL demonstrated 1.4 Gcps in a 32-element array, which is readily scalable to 6 Gcps by time-multiplexing four detectors in one cryostat.

(10) These detectors can be accessed by free-space photons coupled into a 1-K cryostat, through a window assisted by a system of cryogenic filters and lenses, which is important for lasercom and other inherently free-space applications.

(11) Through a process termed differential readout, PNR is possible using SNSPDs, to resolve 0 photons from 1 from *more* photons, which is a huge enabler (beyond just SPD operation, i.e., 0 versus *more* photons) especially for high Fidelity photonic Bell state measurement (BSM) and single photon boosted BSMs that is not possible with SPDs alone.

TES are bolometric detectors sensitive to the heat generated from the energy of the impinging photons. TES detectors are more inherently PNR-capable (compared with SNSPDs) as the photocurrent temporal waveforms corresponding to the impinging optical pulse having 1, 2, 3, …, etc. photons are sufficiently distinguishable. NIST demonstrated detectors capable of resolving up to 8 photons at 93% system efficiency and negligible dark counts, which can be scaled to 15-photon resolution. But these detectors are much slower than SNSPD as their reset times are typically in 10 s of ns, and they need <100 mK, necessitating a dilution fridge. Currently, the biggest commercial users of TES detectors are the photonic quantum computing industry, especially Toronto-based *Xanadu*, which needs PNR detection along with squeezed-light sources (built with nonlinear optical waveguides) to generate photonic qubits encoded in the Gottesman-Kitaev-Preskill format, the most loss-resilient embedding of the qubit in the photon.

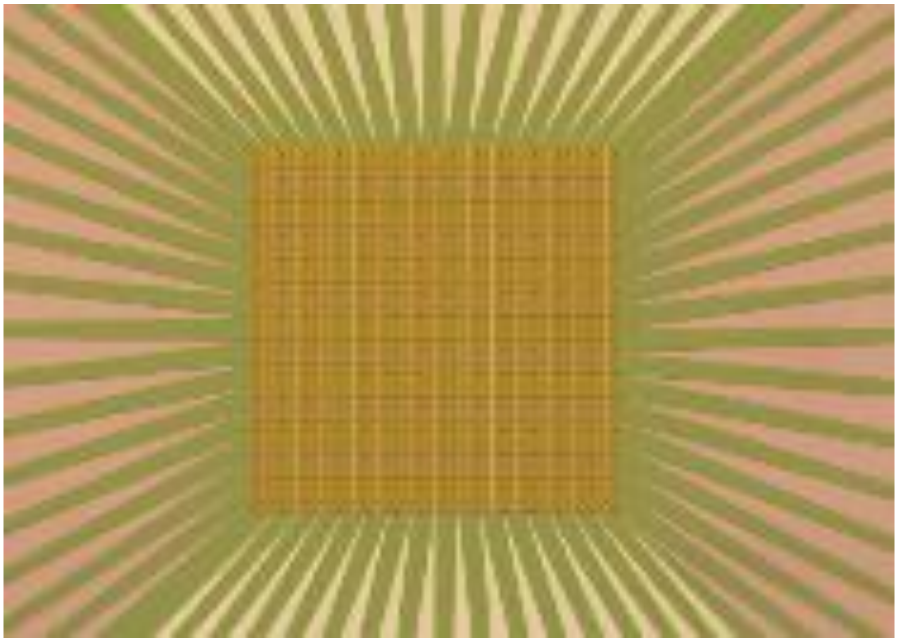


Figure 8.5-1. A kilopixel Array of SNSPDs (See reference 169 for details.)

SNSPDs emerged from research at NIST, MIT and JPL, but are now readily available commercially through companies such as PhotonSpot and IDQuantique, fully packaged and fiber (or custom free space) coupled in compact form factor, including the cryostat. There remain several research questions surrounding SNSPDs—being pursued both at NASA/JPL as well as in academia—whose success could lead to disruptive progress in some of the key applications of SPDs we mention above. A couple of examples of such important research and development (R&D) pursuits include:

(1) *Scalable multiplexed readout* of single photon encoded signals in a multi-channel photonic integrated circuit (PIC), where time-of-flight measurements of hotspot-induced voltage pulses across a single nanowire crisscrossing many waveguides can accurately register both the spatial (which waveguide did the photon arrive in) and the temporal (what time did the photon arrive) arrival windows. A related technique is the *thermally coupled imager*, which exploits thermal coupling to fan out multiple nanowire sensors on a single readout bus [ref. 170]. This readout capability could tremendously reduce the RF readout lines and enable scalable PIC-based quantum photonics ranging from photonic quantum computing to circuits that prepare tailored continuous-variable entangled states by splitting continuous-wave squeezed light into a many-mode entangled probe state and designing receivers for photonic quantum sensors and quantum enhanced receivers for laser communications.

(2) *Cryo-electronic Boolean logic and feedforward* on click/no-click patterns across multiple photon-bearing waveguides is critical in eliminating individually reading out each SNSPD pixel (followed by electronic post-processing in a field-programmable gate-array processor or on the computer). This capability would be critical to processing complex click patterns involved in fusion-gate patterns of photonic quantum computing, in enabling entanglement distillation logic within arrays of solid-state qubits at quantum

repeater stations, and in image data synthesis using 2D SNSPD arrays. Electro-optic feedforward from SPD output (e.g., into an optical modulator in a subsequent processing stage) is often an important enabler in quantum optical sensing and communications systems that leverage adaptive signal processing.

In summary, the need for quantum noise-limited single-photon, time-resolving, number-resolving, low-jitter, low-noise optically broadband detectors is ubiquitous across many ground-based and space-based sensor and communications applications. SNSPD and TES are two SPD technologies that have matured significantly over the past decade. Despite SNSPD technology itself being TRL 6 or higher, there remain several open research questions (e.g., to enable scalable multiplexed multi-channel arrayed readout) as well as significant system-integration challenges (including operating within a radiation-hardened system, and under wall-plug power constraints) that need addressed.

Table 8.5-1 shows the current NASA activities focused on the development of single photon detectors, as reflected by the survey.

Table 8.5-1. NASA Activities Focused on Development of Single Photon Detectors

Brief Description	NASA Center	Tech. POC	Website	NASA Use Case	ROM Funding ($M/year)	Effort Level (FTE)	Approx. TRL (1 -- 9)
SNSPD	JPL	Matt Shaw matthew.d.shaw@jpl.nasa.gov		Quantum Communication, Quantum Computing, Deep Space Optical Communication, infrared astronomy (15 to 30 µm), remote sensing (photon counting lidar and remote chemical sensing)			TRL 1-5
MKID (microwave kinetic inductance detector)	JPL	Peter Day peter.k.day@jpl.nasa.gov		Far-infrared astronomy, dark matter detection			TRL 1-5
Quantum Capacitance Detector	JPL	Pierre Echternach pierre.m.echternach@jpl.nasa.gov		Far-IR astronomy, dark matter detection			TRL 3
Quantum dot spectrometer	GSFC	mahmooda.sultana@nasa.gov		Ultra-low SWAP spectrometry	0.2	0.6	TRL 4
TES	GSFC	john.e.sadleir@nasa.gov		Ultra-high efficiency noiseless single photon detection	0.05	2	TRL 1-5
SQUID detector amplifier	GSFC	Karwan.rostem@nasa.gov		Readout of TES arrays	1	1	TRL 4

8.6 Rydberg Receivers

The canonical classical alternating current (AC) electric field sensor is an antenna, which is a reciprocal device (equal properties in transmit and receive) and transduces free space field to alternating current or vice-versa. In contrast to their classical counterparts, quantum systems are non-reciprocal—they have different receive and transmit properties. In the case of Rydberg systems, they function primarily as receivers. In order to have a reasonable comparison of the two, applications and systems which operate as electric field receive only are considered.

Given the wide spectrum of frequencies and dynamic ranges that are of interest, the technology space related to electric field sensing is large and varied. More mature classical electric field receivers span a broad range of technologies from the workhorse of an antenna coupled with traditional electronic circuits to more specialized devices such as optical sensors (i.e., electro-optic and piezoelectric), plasmonic sensors, and electric field mills. On the "budget" end, integrated circuit antennas are extremely small, reliable and cheap. For specific frequency ranges, "high-performance" devices have been optimized across the spectrum. Therein lies the challenge for the new wave of electrometers; they need to find niches which are not satisfied with the properties of commercial-off-the-shelf cheap classical systems. Notable technologies, which can be considered quantum, include Rydberg atom sensors, superconducting transition edge bolometers, trapped ions, and NV diamond color centers. Rydberg atom devices have gained significant attention in recent years with the benefits of sub-wavelength, resonant, non-destructive, precise measurements. Identifying applications where the Rydberg sensor can provide a significant advantage over traditional technologies is an open question which necessitates end-to-end analysis of gains in relevant scenarios.

A Rydberg-atom approach of electric field detection is based on the interaction of RF fields with alkali atoms in optically excited Rydberg states. The hydrogen-like orbits of Rydberg atoms result from exciting a valance electron into a high quantum number shell, producing a very sensitive detector of a nearly free electron interacting with an external RF field. The technique at the heart of most Rydberg atom-based RF sensing is electromagnetically induced transparency (EIT) in a gas of atoms, typically a room-temperature atomic vapor or laser trapped atoms. This EIT-based quantum interference enables direct optical probing of high-energy Rydberg states, such that the effect of an RF field is mapped onto a laser, which can be read out on a photodetector.

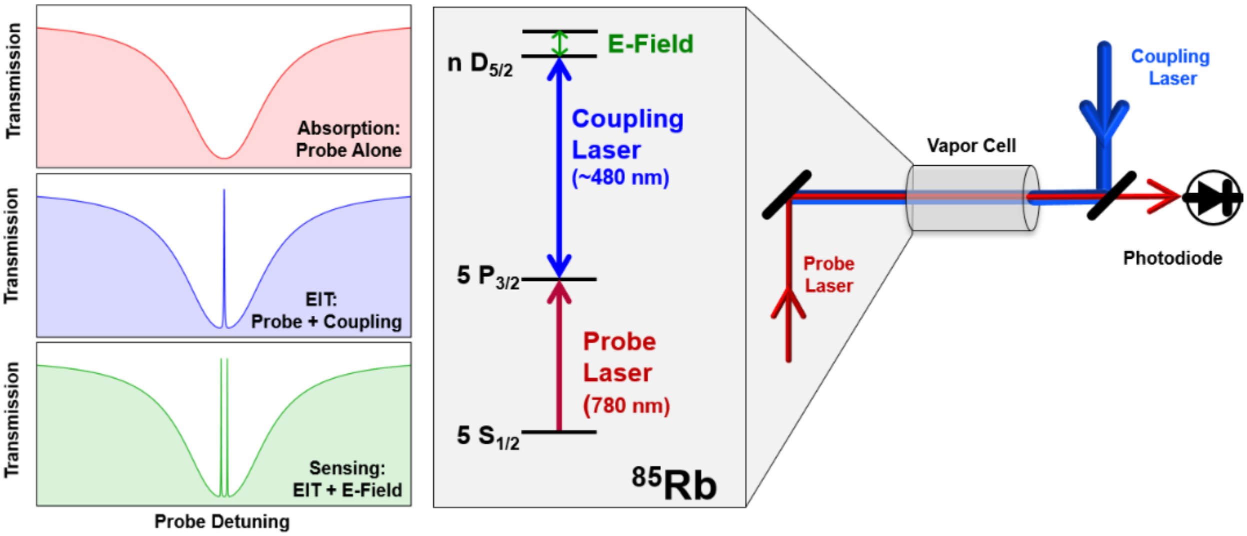


Figure 8.6-1. Simplified Schematic of Rydberg Sensor Operation (Courtesy MIT Lincoln Laboratories.)

Figure 8.6-1 details the basic concept for Rb alkali atoms. As shown in the energy-level diagram, a probe laser is tuned near resonance between the ground and excited state. The addition of a coupling laser creates a quantum interference, called EIT, which provides a narrow peak with unity transmission of the probe laser. Rydberg states with high principal quantum numbers have large electric dipole moments and hence are very sensitive to external electric fields, which perturb the EIT in predictable ways. Fields that are not resonant with a Rydberg transition cause stark shifts, while resonant fields cause a splitting of the EIT peak. These effects can be used to determine the strength of the external field or receive a signal sent by modulating the field.

The rich manifold of Rydberg states enables the atomic system to be tuned to be sensitive to fields from DC to THz. Note that taking advantage of the full Rydberg bandwidth requires a 100-mW scale, single frequency mode laser, tunable over 10 nm or several lasers at distinct frequencies. Different modes of operation, often adding complexity, enable detection of polarization, phase as well as field amplitude.

While it is often straightforward to compare quantum sensors to their classical counterparts, Rydberg electrometers are a bit of a conundrum. RF system development and quantum research lack common metrics to enable understanding of trade space and benefits.

Rydberg systems have intriguing properties that need to be quantified with respect to the application. For example, there are several advantages of quantum receivers relative to classic antenna-based receivers:

(1) Replacing the traditional thermal noise limit with quantum noise, which can be orders of magnitude less.

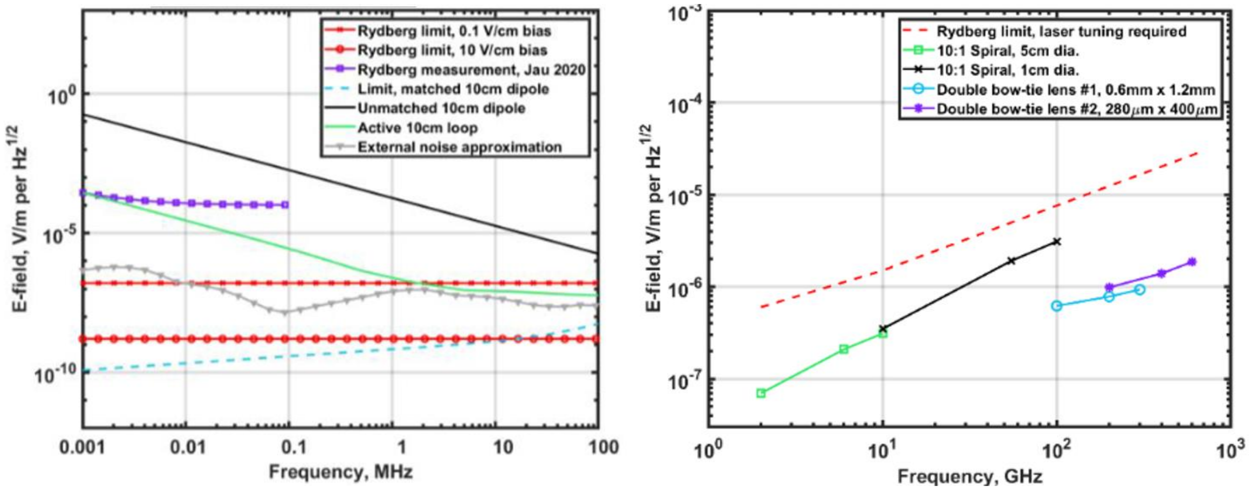
(2) Overcoming classical antenna size and shape limitations whereby effective electrical length is the same order of magnitude as the wavelength of the signal to be detected for best performance with point-like sensor volume (for wavelengths large compared to sensor size). This decoupling of the aperture shape and the RF frequency enables a single Rydberg sensor to operate from MHz to THz.

(3) Elimination of mutual coupling between receiving antennas enables improved direction-of-arrival estimates, scan performance in large arrays, gain in small arrays, etc.

(4) Point-source-like quantum receiver maintains a fixed physical ‘phase center’ over extremely wide bandwidths, enabling unique solutions for wideband dish and lens geometries.

Despite the promising capabilities of quantum systems, end-to-end analysis of gains in relevant scenarios is needed both to prioritize high-impact concepts and to provide insight into technology readiness and future prospects.

Performance metrics include tunable and instantaneous bandwidth, dynamic range, aperture efficiency, ‘antenna’ pattern shape and gain, polarization properties, and tuning speed. For high-performance applications, a key metric is often sensitivity for a given instrument size. Figure 8.6-2 shows a theoretical sensitivity comparison for Rydberg receivers compared to antennas. In Figure 8.6-2a, the Rydberg theoretical derivations assume 100 atoms and static electric field. Antenna derivations use a receiver total noise floor of 10 dB. The limit for the conjugate-matched antenna (blue dotted line) is for reference and is not necessarily realizable in a small form factor; even when possible, the value is reached at a single frequency. Approximate external noise floor uses the lower atmospheric noise limit <10 MHz, man-made noise >10 MHz, from international telecommunications union-radiocommunications (ITU-R) [ref. 171]. In Figure 8.6-2b, the Rydberg derivation (red dotted line) assumes 1000 participating atoms, optimized atomic state by frequency (from ref. 172); like the conjugate matched antenna, this value is reached at a single frequency. Antenna derivations use a receiver total noise floor of 10 dB (Bow-tie lens antennas [ref. 173]).



a) *b)*

Figure 8.6-2. Theoretical Sensitivity of Rydberg Receivers Compared to Antennas (a) Low frequency, (b) Near THz frequency. (Credit: Cara Kataria, MITLL, unpublished)

It is important to note that Rydberg atom sensors are a nascent technology, and systems have yet to reach the fundamental predicted limits. In Figure 8.6-2a is the low frequency regime, where antennas are electrically small compared to the wavelength being sensed. In this frequency regime, “small” antennas have notable shortcomings. Near-field measurements suffer from coupling effects, electrically small antennas are narrowband, inefficient and limited gain, even when matched. Note that common Rydberg literature reviews compare to the more commonly known passive antenna. If an electrical engineer were to build a receiver-only system, an active antenna provides good sensitivity over a wider bandwidth, and as such is the more relevant comparison. This puts Rydberg sensors and antennas in much closer comparison with sensitivity alone. A full system analysis is required to ensure the gain is significant enough to warrant technology development.

In Figure 8.6-2b, the high frequency regime is shown. At higher frequencies, apertures of classical antenna are relatively smaller, so a major Rydberg advantage in size is not realized. Stated simply, traditional antenna sensitivity is likely better for the same size aperture, and Rydberg atoms are competing with a mature technology area. In addition, Rydberg atoms have comparatively less instantaneous absolute bandwidth. Rydberg sensing advantages in this near THz regime are then more versatility than straight sensitivity.

Since the early 2000s, Rydberg-atom research has seen a resurgence in metrology, sensing, quantum optics, and quantum computation/simulation, with a growing academic (Harvard, Michigan), national lab (i.e., Army Research Laboratory (ARL), NIST), and industrial base (i.e., Rydberg Technologies, ColdQuanta) to support.

NASA’s investment in Rydberg sensing technology leverages this emerging Rydberg community and applies the sensor to a unique broadband sensing application requirement, remote (space-based) sensing of soil moisture from canopy to root zone soil moisture, which is critical for modeling of land surface hydrological processes and its applications to water resource management, agriculture yield and flood forecast.

This application takes advantage of a single sensor, which can access a wide spectrum. A key challenge for space radar technologies is aggregating differing types and sizes of antenna apertures to cover the diverse spectrum. As shown in Figure 8.6-3, Rydberg Radar for radio reflectometry needs to operate on several distinct radar bands from VHF-to-Ku bands (covering 137 MHz, 255 MHz, 370 MHz, 1.2-2.2 GHz, 5.4-5.7 GHz, 7-9.6 GHz, and 13.5 GHz). Radio reflectometry techniques for signals of opportunity are used to study/measure bedrock topography (137 MHz), snow water equivalent of snow accumulation (255 and 370 MHz), ice sheet dynamics/flow (1.2 to 2.2 GHz), snow accumulation rates (5.4 to 9.6 GHz), and precipitation (13.5 GHz). Darmindra Arumugam at NASA JPL leads the effort in cryospheric Rydberg radar, which leverages Rydberg atoms' ability to detect a wide band of frequencies in a single instrument.

The Rydberg Radar instrument concept may improve the existing radar capability to study dynamics and transients of the Earth system by enabling a single detector-based measurement covering the entire 'radio window' (0 to 30 GHz) in a small form-factor deployable-free architecture.

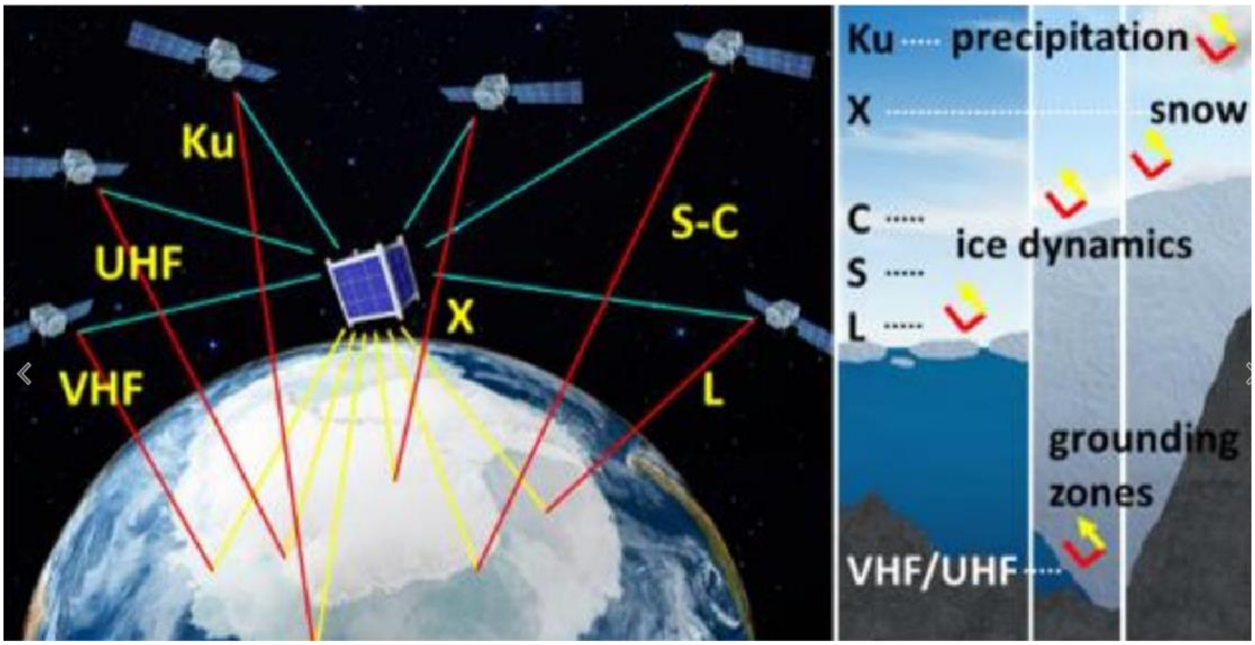


Figure 8.6-3. Cryospheric Rydberg Radar [ref. 174]

Rydberg atom electric field sensors are a newly emerging technology, where limits are being actively explored. As with any new technology, the barrier is high to displace decades worth of classical technology maturation. In many areas—particularly at higher frequencies— traditional antennas are likely to outperform Rydberg sensors in important metrics such as sensitivity, instantaneous bandwidth, simplicity, and SWaP. While Rydberg electric field sensors will not replace traditional receivers in commodity applications for RF signal reception, these sensors could be an enabling technology in specialized application spaces, such as those of interest to NASA, accounting for end-to-end system analysis quantifying advantages.

8.7 Quantum Opto-Mechanics

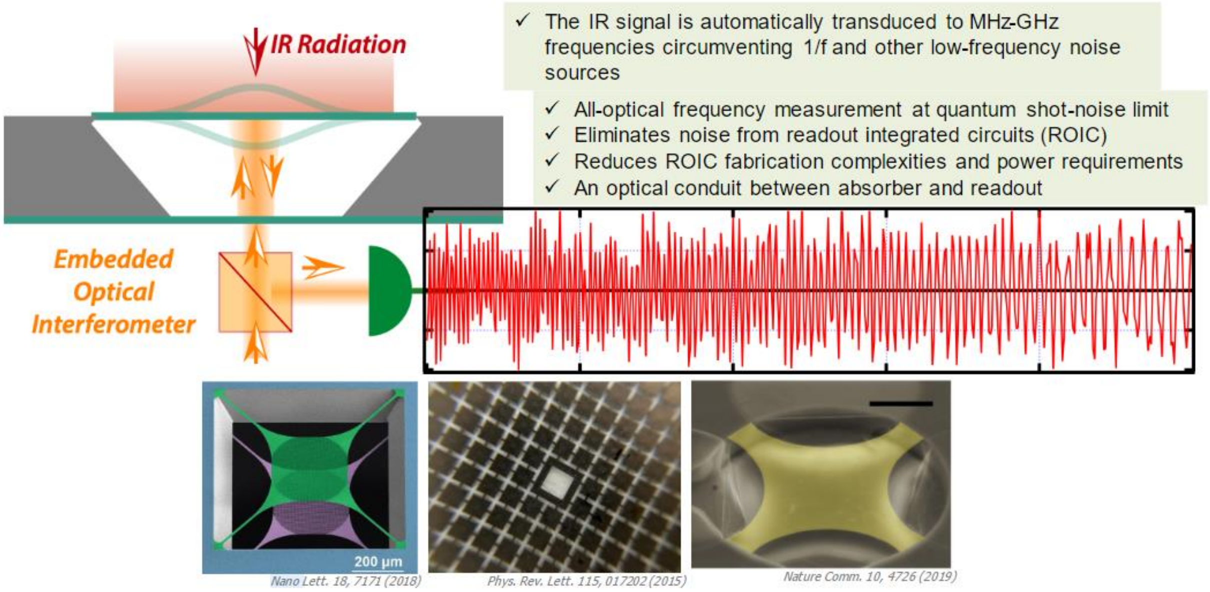
Quantum opto-mechanics is a field based on the quantized interaction of light with matter through the radiation pressure force. The field started in the 1970s during the development of GW detectors, where interferometric measurement techniques sufficiently enhanced the detection of light-matter interaction making the radiation pressure force relevant to achievable measurement sensitivity. Over the last few decades improved micro and nano fabrication techniques combined with the inherent coupling flexibility of mechanical systems led to a rapid expansion of the field. Of particular note has been the development of high-quality mechanical and optical cavities, which can provide enhanced mechanical response and improved readout sensitivity on a small scale. The platform has been used to study and test fundamental principles of quantum mechanics as well as for targeted applications in precision sensing. The quantum nature of these sensors can be defined into two ways. The mechanical sensing is accomplished by leveraging non-classical techniques like superposition or entanglement, or a classical sensing scheme could be enhanced through the use of quantum techniques like squeezing to improve the sensitivity of the measurement. The latter category has been leveraged on the macro-scale for improving the sensitivity of gravity-wave interferometers (GWIs). Large scale GWIs like LIGO are now fundamentally limited by quantum noise and they are employing techniques like squeezed-vacuum light. One of the most promising aspects of opto-mechanics is their low SWaP which opens the possibility of extending techniques like these to space. Other application examples that could be useful in space include quantum-limited transduction or the ability to efficiently couple photons across a broad range of the electromagnetic spectrum (microwave to optical for examples).

The operation of opto-mechanical sensors is based on the radiation pressure induced interaction between photons and the mechanical motion of a cavity. Various flavors of sensors can be made from this basic principle. The radiation pressure from an incident photon will cause a change in the length of the cavity causing the resonant frequency to change. The resonant enhancement of the cavities enables small forces to be read out either electronically or optically, with the latter having the benefit of avoiding higher noise electronics at the cost of photon shot noise. In addition, optical readout can provide greater accuracy without the need for calibration because displacement can be measured very precisely in terms of laser wavelength rather than electrical quantitates.

Opto-mechanical sensors have now been developed to measure force, displacement, acceleration, and magnetic fields among others with impressive results that are on par with other commercialized sensors but have a much smaller footprint advantageous for SWaP constrained space applications. LIGO and LISA for example, require constant monitoring of small external perturbations in order to measure miniscule vibrations in space-time. Monoclinic optomechanical based accelerometers could be ideal for measuring localized perturbations and providing correction to the instrument alignment. Other targeted applications include quantum information processing, the study of fundamental physics, gravity wave detection [ref. 175], electromagnetic sensing, chemical spectroscopy, and navigation. From a space perspective, one of the most intriguing qualities of optomechanical-based sensors is their high degree of thermal and mechanical isolation from the environment. Combined with novel readout techniques optomechanical sensors can provide both stable and noiseless transduction between disparate regions of the electromagnetic spectrum.

DARPA is currently developing optomechanical-based sensors for room-temperature IR detection under their Optomechanical Thermal Imaging (OpTIm) program. In this scheme, the optomechanical sensor is made up of a thin mechanical membrane which forms one end of an optical cavity as shown in Figure 8.7-1. The incident IR radiation is absorbed into the membrane and causes a displacement in the membrane, which in turn causes a resonant shift in the optical cavity that can be read out with high precision.

This simple all-optical readout scheme avoids and added noise from readout integrated circuits (ROICs) by directly transducing the IR signal to the MHz-GHz range to achieve quantum shot-noise limited sensitivity. DARPA is looking to further improve sensitivity by incorporating correlation-enhanced techniques like optical squeezing. Further, they are looking at leveraging developments in IR-sensitive metamaterials which could enable tunable and hyperspectral IR detection for targeted chemical spectroscopy in an overall low-SWaP sensor. This could have applications for NASA Earth remote-sensing missions.



- ✓ The IR signal is automatically transduced to MHz-GHz frequencies circumventing 1/f and other low-frequency noise sources
- ✓ All-optical frequency measurement at quantum shot-noise limit
- ✓ Eliminates noise from readout integrated circuits (ROIC)
- ✓ Reduces ROIC fabrication complexities and power requirements
- ✓ An optical conduit between absorber and readout

Nano Lett. 18, 7171 (2018) Phys. Rev. Lett. 115, 017202 (2015) Nature Comm. 10, 4726 (2019)

Figure 8.7-1. Cavity Optomechanical Transduction of Mechanical Motion into Optical Signal[refs. 176, 177, and 178]

8.8 Other

There are many quantum sensors in addition to those covered so far in this report being developed both within NASA and externally.

Super-radiant lasers are based on quantum-mechanically correlated states of atoms and light within an optical cavity. The collective behavior of the atoms leads to a strongly reduced sensitivity of the laser frequency to the cavity length and can enable lasers with exceedingly narrow spectral width.

NMR gyroscopes use the precession of nuclear spins in a fermionic noble gas about a magnetic field to measure rotation. While not strictly speaking “quantum,” such gyroscopes share many properties with atomic magnetometers and have the potential for achieving moderately precise rotation sensing stability with small size and low power.

Table 8.8-1 describes activities at NASA captured by the survey that did not fit neatly into the sensor categories elsewhere in this section.

Table 8.8-1. NASA Activities Focused on Development of Quantum Sensors Not Previously Discussed

Brief Description	NASA Center	Tech. POC	Website	NASA Use Case	ROM Funding ($M/year)	Effort Level (FTE)	Approx. TRL (1 -- 9)
Original D-Wave Qubit chip	JPL	Alan Kleinsasser Alan.W.Kleinsasser@jpl.nasa.gov					
Quantum-enhanced sensors and measurements	JPL	Nan Yu nan.yu@jpl.nasa.gov	https://scienceandtechnology.jpl.nasa.gov/people/n_yu	Space interferometric and array measurements			TRL 1-3
Cold quantum gas facilities on ISS	JPL	Jason Williams	https://coldatomlab.jpl.nasa.gov/	quantum science experiments and technology demonstration			
Long-coherence time memory	GSFC	john.e.sadleir@nasa.gov		Optical quantum networking	0.05	2	TRL 1-5
Quantum compressive sensing algorithms	GSFC	harry.c.shaw@nasa.gov		Developing quantum algorithms	N/A	N/A	TRL 1-3
Superconducting microwave parametric amplifiers	JPL	Peter Day peter.k.day@jpl.nasa.gov		Radio astronomy, qubit readout, dark matter detection			TRL 1-4
Laser Optical System for Gravity gradient measurement	JPL	Siamak Forouhar siamak.forouhar@jpl.nasa.gov		Mass change			TRL 2-3

8.9 Non-U.S. Activities

The rise in the number of national quantum programs in recent years has accelerated efforts worldwide in quantum computation, quantum communication, and quantum sensor research. Intersecting with the space sector are quantum communications and quantum sensors, to include atomic clocks.

Quantum communication is relevant to quantum sensors research in that a long-term goal of this research is to use a quantum channel to network quantum sensors or to improve the synchronization of atomic clocks [ref. 179]. Space-based quantum communications experiments have demonstrated quantum key distribution from a satellite to ground, satellite-mediated quantum key distribution over continental scales, entanglement distribution between a satellite and ground, and quantum teleportation of a photonic quantum state from ground to satellite. While most of this work has resulted from China’s Micius satellite [ref. 180], launched in 2016 and dedicated to quantum experiments, other countries are also supporting space-based quantum communication experiments. Notably, Canada’s Quantum EncrYption and Science Satellite [ref. 181] program has an anticipated launch date of 2024, and the space segment of the European Union’s (EU’s) European Quantum Communication Infrastructure [ref. 182]. Quantum communications experiments, notably from Singapore, are also advancing the use of small-sats and CubeSats for less expensive development of space-borne experiments.

Current space-based quantum sensors are dominated by cold atom interferometers (CAIs) used as accelerometers or gravimeters. The driving mission is to use CAI gravimeters for space geodesy, fundamental science experiments such as tests of the weak equivalence principle and detection of GWs, and potentially inertial navigation. These goals have led the EU in particular to support ground-based tests in micro-gravity, airborne testing, and space-based testing of cold atom systems [ref. 46]:

- Several ground-based microgravity facilities (the Bremen drop tower, the Einstein elevator, zero-g simulator at LP2N in Bordeaux) which provide microgravity for one to several seconds. EU projects using these facilities include QUANTUS (DLR) [ref. 183], PRIMUS (DLR/ZARM) [ref. 184], ICE (CNES) [ref. 185], and DESIRE (joint NASA and DLR) [ref. 186]. See also references 187 and 188.
- Longer microgravity experiments have been performed in parabolic airplane flights. In 2016 ICE was able to demonstrate the production of a dual-species BEC and interferometry during 20-second periods of near-zero gravity [ref. 189].
- The German DLR funds the MAIUS mission, which uses sounding rockets to send Rb and K BEC atom interferometers to space, testing e.g., the universality of free fall during several minutes of microgravity [ref. 190]. MAIUS-1 launched in 2017, while MAIUS-2/3 (MAIUS-B) is scheduled to launch in the coming years.
- While NASA and DLR are collaborating in the CAL onboard the ISS and its planned successor BECCAL (BEC and CAL), the UK has funded the Cold Atom Space PAyload (CASPA) project to put a compact CAI accelerometer aboard a 6U CubeSat, which continues under ESA funding as CASPA- Atmospheric Drag Mission (ADM). The experiment would measure the thermospheric mass density [ref. 191].

The EU plans two key missions utilizing CAIs and has initiated a pathfinder study for these:

- The CNES GRICE mission would follow the success of ESA's Gravity field and steady-state Ocean Circulation Explorer (GOCE), and NASA's GRACE, and GRACE-FO geodesy missions. GRICE is in the Phase 0 planning stage. It would use two satellite equipped with one CAI accelerometer each. A laser link measures the distance between the CAIs and correlates their output [ref. 192].
- Space-Time Explorer and Quantum Equivalence Principal Space Test (STE-QUEST) is a proposed mission to test the Einstein equivalence principle using dual isotope Rb BEC CAIs [ref. 193]. Although not selected for the original ESA call in 2014, the concept remains viable. STE-QUEST may also include atomic clocks.
- CARIOQA is a joint Phase 0 study by CNES and DLR to develop a quantum pathfinder mission that would support new missions such as STE-QUEST and GRICE [ref. 194]. The main goal of the quantum pathfinder mission is to operate a CAI accelerometer in space, reaching a goal sensitivity of $1\times10^{-10}\ m/s^2/\sqrt{Hz}$, and maturing the system and its components it to TRL8. The pathfinder would also perform preliminary experiments relevant to space geodesy.

Non-U.S. efforts in clocks in space are led by the EU and China:

- The Chinese CACES (Cold Atom Clock Experiment in Space) [ref. 195] demonstrated a cold atom Rb microwave clock. The clock operated in orbit from 2016 until 2019, demonstrating Ramsey fringes. From the SNR, the fractional short-term stability was estimated to be 3.0×10^{-13} at one second of integration time for a Ramsey time of 2.0 seconds.
- ACES (Atomic Clock Ensemble in Space) is an ESA coordinated mission to operate two atomic clocks on board the ISS: the laser cooled Cs atomic clock PHARAO (CNES) and an active hydrogen MASER developed by SpectraTime (Switzerland). The mission will also

include a precise time and frequency transfer system. ACES is currently expected to launch in 2025.

- COMPASSO is a DLR mission to operate two optical iodine clocks on ground and on board the ISS and perform time and frequency transfer between them using an optical frequency comb. The mission would mature and validate the technology in space. The expected launch date is 2025.
- Various sounding rocket experiments have contributed to the maturation of the required technology for quantum sensors in space. The DLRs 2016 KALEXUS mission developed the lasers required for potassium atomic clocks, while their 2015 FOKUS mission developed optical frequency combs for space. DLRs 2017 JOKARUS mission flew an iodine frequency reference and an optical frequency comb.

9.0 Looking to the Future

9.1 Most Promising Quantum Sensors for Future NASA Missions

In Section 7, NASA needs for current and future missions was surveyed and in Section 8 a range of quantum technologies were described that could enable new capability and sensing modalities. The most promising quantum technologies relevant to NASA are summarized here.

1. Optical clocks for tests of fundamental physics, GW 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

The above list is not prioritized by position in the list and is necessarily incomplete and that many applications of quantum sensing within NASA may grow in importance over time.

9.2 Interagency Cooperation

Considerable expertise in quantum sensing exists outside NASA at present. NIST has an entire Division (~150 people) focused in part on the development of atomic clocks while substantial expertise in photonics is found at Sandia National Labs and the MIT Lincoln Labs. DARPA, as well as other DoD agencies such Air Force Office of Scientific Research (AFOSR) and ARL have invested hundreds of millions of dollars in quantum sensing over the last two decades and active programs continue to this day. Work by other agencies is also often highly relevant to NASA technical goals. For example, many DARPA programs from the Microsystems Technology Office focus on low-SWaP technologies that would lend themselves well to low-resource space platforms.

It therefore appears that there is a lot to be gained by NASA in leveraging these extramural activities for NASA’s benefit. Space-qualification and flight engineering are areas not usually considered by outside agencies and NASA has a unique role to play here. Turnkey operation and remote monitoring and control are also needed for commercial sensors and therefore collaborating with industrial partners may advance this aspect of quantum sensing within NASA.

Quantum technology often has long development times, making it challenging to build world-leading programs from scratch. For example, the development of new primary standard atomic clocks typically takes on the order of one decade. Accuracy is hard to assess and requires extensive testing and metrology.

Below we list some (non-NASA) government and private sector entities engaged in various aspects of quantum sensing. This list was compiled by informally polling the panel members and from the industry representatives present at the Newport News workshop and is not intended to be comprehensive. In the table, agencies funding work in quantum sensing are distinguished from agencies actually carrying out research and development in quantum.

Clocks:

Activities: NIST, U.S. Naval Observatory (USNO), Draper, Sandia National Labs, Aerospace Corporation, Penn State, Joint Institute for Laboratory Astrophysics (JILA), Stanford University, Air Forge Research Laboratory (AFRL)/Kirtland, Vector Atomic, AOSense, Spectra Dynamics, Honeywell Aerospace, MIT, ColdQuanta/Infleqtion, Vescent, OEWaves
Funding: DARPA, AFRL/Kirtland, ONR

Atom Interferometers:

Activities: Stanford, Draper, AOSense, Sandia, University of Oklahoma, NIST, Northwestern University, Los Alamos National Lab, University of Virginia, U.S. Naval Postgraduate School, U.S. Naval Research Laboratory, Honeywell Aerospace, University of California, Berkeley, Stanford Research Institute (SRI)
Funding: DARPA, Office of Naval Research (ONR), National Geospatial-intelligence Agency (NGA)

Magnetometers:

NIST, Sandia National Labs, Draper, University of Colorado, MIT Lincoln Laboratories, MITRE, University of Maryland, Harvard, MIT, QuSpin, Fieldline, Twinleaf, Geometrics, Quantum Diamond Technology, Inc., Element Six, Northrup Grumman, Polatomic, SRI International, Honeywell Aerospace, Sandbox AQ, Lockheed Martin, Boeing, Raytheon BBN, Quantum Catalyzer, QDM.IO
Funding: DARPA, National Institute of Health (NIH), ARL, AFRL, DOE

Rydberg Sensors:

Activities: NIST, University of Michigan, ARL, Rydberg Technologies, Inc., Coldquanta/Infleqtion, Quantum Valley Ideas Lab (Canada), Northrup Grumman, SRI, Honeywell Aerospace
Funding: DARPA

Superconducting quantum sensors:

Activities: Fermilab, NIST

Single photon detectors:

Activities: DOE/Argonne, NIST, AFRL/Rome, MIT Lincoln Labs
Funding: DARPA

In response to the National Quantum Initiative, the DOE has set up several National Quantum Information Science (QIS) Research Centers. The DOE National Quantum Information Science Research Centers are [ref. 57]:

1. Next Generation Quantum Science and Engineering at Argonne National Lab
2. Co-design Center for Quantum Advantage at the Brookhaven National Laboratory
3. Superconducting Quantum Materials and Systems Center at the Fermi National Accelerator Laboratory
4. Quantum Systems Accelerator at Lawrence Berkeley National Laboratory
5. The Quantum Science Center at Oak Ridge National Laboratory

9.3 Technology Transition:

NASA's goal for research and development of quantum sensors is that they be incorporated into its mission by being integrated into a space or ground platform. This internal technology transition—as opposed to other types of technology transition such as intellectual property (IP) transfer to the private sector—needs technology to move from fundamental and applied research (typically in a physics laboratory), to an engineering development cycle (building robust and compact components, reducing power requirements and weight), to demonstrations in relevant environments (drop towers, sounding rockets, small satellites), and ultimately integration into a mission system (space or ground platforms). Especially for novel and complex systems such as quantum sensors, this process can require decades. For example, the research that became JPL's Deep Space Atomic Clock started in the early 1990s and only in the 2019 to 2021 timeframe did an advanced prototype complete a mission in LEO to test its potential for navigation, communication, and radio science [ref. 196].

In general, technology transition is challenging for multiple reasons, and depends on technical, organizational, and cultural factors, and often luck. It depends on how hard it is for an organization to understand and adopt a new technology [refs. 197, 198, and 199], the maturity of the organizational structures that will deal with the new technology [ref. 197], and how the sociology of the organization helps or hinders the flow of novel ideas and technology between sub-organizations or from the outside [refs. 199 and 200]. Finally, it is affected by relatively uncontrollable events such as failure of existing technologies, the discovery of new opportunities or capabilities, changes in administrative and funding priorities, and so on. These events can drive the transition of a project past of the exploration stages towards deployment (often suddenly) [ref. 201].

The long-time scale for the development of quantum sensors can increase the likelihood and severity of many of these challenges. Fortunately, NASA is in a strong position to address these problems, due to a strong technical workforce and having sub-organizations focused on R&D (ARC, JPL). The quantum sensors workshop was an important first step towards tech transition, because it facilitated information exchange between quantum researchers and NASA mission/user groups. Sustaining and growing this relationship will be critical, so that each group better understands the needs and capabilities of the other. Researchers and users should continue to learn each other's languages, towards efficient communication.

Research, engineering development, and mission groups need to work with each other in order to advance quantum sensor technology. Researchers should seek to better understand the limits of their quantum sensors in non-laboratory environments, and gain experience using the counterpart non-quantum sensors to better understand what the mission user is accustomed to using. Engineering development groups can assist researchers in incorporating best device development practices into their setups. Critically, user groups need to conduct trade studies to determine how (or if) quantum sensors could provide an advantage over traditional sensors to ensure that investments of time and funding are directed productively.

Critical input to such trade studies includes the characteristics and availability of enabling technologies for quantum sensors, such as lasers, atomic sources, specialized materials, photonic integrated circuits, RF and microwave electronics, optics, and so on. These components are generally not available as low SWaP-C and space-qualified (robust against shock, vibration, radiation, and extreme temperature swings) versions. While the laboratory performance of quantum sensors is generally not limited by these components and sub-systems, transitioning quantum technology to a mission platform will require a significant investment in developing and manufacturing these technologies [ref. 202]. Typical research-funding organizations do not have the resources or the mandate for this critical step in technology development, but NASA could support a sustained effort along these lines once a mission need is identified (e.g., via the trade studies recommended above) or for components that are useful across a variety of quantum sensors. Traditional and non-traditional approaches such as Small Business Innovative Research projects, Small-business Technology Transfer Research projects, Broad Area Announcement projects, Cooperative Research and Development Agreements, or engagement with one of the several industry and academic quantum consortia could promote research into new supporting technology. NASA can also help identify existing technology within its portfolio that may be adapted to enable quantum sensors.

Better enabling technology will support another critical step towards technology transition: testing the sensors in a relevant, non-laboratory environment. Most quantum sensors have not been taken outside of the laboratory. Researchers are often surprised by the problems that their sensors face when exposed to more extreme temperature swings, vibrations, magnetic field noise, and so on, or that non-physicists struggle to operate the prototype sensors. Researchers need to understand these barriers to deployment relatively early in the development cycle, as finding solutions can be time consuming and sometimes incompatible with the lab-based sensor design. NASA can support projects that aim to do early field testing of quantum sensors, and more basic research projects that seek novel ways to solve the problems encountered while fielding a sensor (e.g., machine learning to improve performance, novel materials, etc.). Subsequent to these tests, NASA can support the engineering of the sensor system as necessary to better withstand the often-harsh environments of launch and space.

Finally, making the long-term investments required to transition quantum sensors to mission use, in the face of uncertainty in the sensor potential (due to the nature of early-stage research) and changes in mission direction, will require organizational agility. As quantum sensor research continues to advance and NASA missions evolve, NASA should actively monitor outside research, keep clear and complete documentation of its internal quantum-sensor work, and develop a diverse portfolio of active, exploratory projects along with resources to test new ideas.

Technology transition can take many paths to success, and NASA has deep experience in bringing R&D to mission. It is critical that, even at this early stage of development for most quantum sensors, a NASA quantum-sensor strategy clearly identifies the steps that quantum researchers, engineers, user groups, and leadership will take towards integrating this technology into the NASA mission.

9.4 Workforce Development

A trained and capable workforce will be critical to the success of any significant activities in quantum sensing at NASA. Most active researchers in quantum sensing in the U.S. are at the post-doctoral level, having received their PhD in atomic, molecular, and optical physics or quantum information science.

Over the last decade the quantum computing industry has seen massive growth as a result of both public and private investments in this field. In 2022 alone, $2.35B was invested worldwide in quantum technology startups according to an analysis by McKinsey Digital in 2023 [ref. 203]. There remains a significant shortage of talent to fill existing and expected open positions in industry, but this talent gap appears to be narrowing, partly because academic institutions are expanding their educational programs in quantum science and technology. The McKinsey Digital report indicated that Master of Science programs in quantum technologies almost doubled from 2021 to 2022. In 2020, the EU led the world in producing graduates in quantum technology and related fields, with India, China, and the U.S. placing second, third and fourth, respectively. An informal survey of scientists at universities and national labs carried out by the panel suggests that over the last few years, it has become increasingly difficult to find qualified post-doctoral research associates to staff research programs. NASA is likely to encounter similar challenges in expanding programs in the quantum realm.

As part of the National Quantum Initiative, the NSF, and the DOE have set up several centers focused on quantum information science and technology that are in part focused on developing the quantum workforce of the future.

The NSF Quantum Leap Challenge Institutes are [ref. 204]:

1. Hybrid Quantum Architectures and Networks at the University of Illinois
2. Quantum Systems through Entangled Science and Engineering at the University of Colorado
3. Challenge Institute for Quantum Computation at the University of California, Berkeley
4. Institute for Robust Quantum Simulation at the University of Maryland
5. Quantum Sensing for Biophysics and Bioengineering at the University of Chicago

Most of these centers have been initiated in the last 3 years and it remains to be seen how their presence will affect the quantum workforce.

10.0 Panel Findings, Observations, and Recommendations

10.1 Panel Findings

General

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

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.

Quantum Magnetometers

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 ^{4}He 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.

Atom Interferometers

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 integrations 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.

Rydberg Atom RF Sensors

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

Single Photon Detectors

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.

Squeezing and Entanglement

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.

Interagency Collaboration

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.

Workforce Development

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.

10.2 Panel 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.

O-3. Dedicated efforts are needed to develop enabling component technologies for quantum sensors such as low-cost lasers, photonics, vacuum technologies, and optical systems.

10.3 Panel Recommendations

Clocks

R-1. NASA 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

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

R-9. NASA ESD should focus on the short-term goal of gravity gradiometry in LEO for high-resolution hydrology and Earth science. ***(F-15, F-16)***

R-10. NASA PSD 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-Based Quantum Sensors

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

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 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

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.

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

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

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)***

11.0 Acronyms and Nomenclature List

2D	Two Dimensional
$M	Millions of Dollars
AC	Alternating Current
ACES	Atomic Clock Ensemble in Space

ADM	Atmospheric Drag Mission
AFOSR	Air Force Office of Scientific Research
AFRL	Air Force Research Laboratory
AIGG	Atom Interferometer Gravity Gradiometer
APD	Astrophysics Division
ARC	Ames Research Center
ARL	Army Research Laboratory
ASN	Atom Shot Noise
BEC	Bose-Einstein Condensates
Beidou	Chinese Global Positioning System
BPS	Biological and Physical Sciences
BSM	Bell State Measurement
CACES	Cold Atom Clock Experiment in Space
CAI	Cold Atom Interferometry
CAL	Cold Atom Lab
CARIOQA	Cold Atom Rubidium Interferometer in Orbit for Quantum Accelerometry
CASES	Cold Atom Clock Experiment in Space
CASPA	Cold Atom Space Payload
CCD	Charge Coupled Device
CDM	Cosmic Dark Matter
CHAMP	Challenging Minisatellite Payload
cm	Centimeter
CMB	Cosmic Microwave Background
CMOS	Complimentary Metal-Oxide Semiconductor
CNES	Centre National D’etudes Spatiales
CQD	Colloidal Quantum Dot
Cs	Cesium
CSAC	Chip-Scale Atomic Clock
CuSP	Cubesat For Solar Particles
cw	Continuous Wave
DARPA	Defense Advanced Research Projects Agency
dB	Decibels
DC	Direct Current
deg	Degrees
dia	Diameter
DLR	German Aerospace Center (Deutsches Zentrum Für Luft- Und Raumfahrt)
DoD	Department of Defense
DOE	Department of Energy
DSAC	Deep Space Atomic Clock
DSN	Deep Space Network
EIT	Electromagnetically Induced Transparency
EP	Equivalence Principle
ESA	European Space Agency
ESD	Earth Science Division
EU	European Union
EZIE	Electrojet Zeeman Imaging Explorer

f	Frequency
FIELDS	Parker Solar Probe Instruments to Measure the Solar Electric and Magnetic Fields
FIR	Far-Infrared
FOG	Fiber-Optic Gyroscopes
fs	Femtosecond
fT	Femtotesla
FTE	Full-Time Equivalent
FWHM	Full Width at Half Maximum
G	Gravitational Constant
Galileo	European Global Positioning System
Gcps	Gigachips Per Second
GDC	Geospace Dynamics Constellations
GHz	Gigahertz
GLONASS	Russian Global Positioning System
GNC	Guidance, Navigation, and Control
GNSS	Global Navigation Satellite System
GOCE	Gravity Field and Steady-State Ocean Circulation Explorer
GOES	Geostationary Operation Environmental Satellite
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
GRACE-FO	GRACE-Follow On
GRAIL	Gravity Recovery and Interior Laboratory
GRC	Glenn Research Center
GRICE	Gradiométrie À Interféromètres Quantiques Corrélés Pour l'Espace (CNES)
GSFC	Goddard Space Flight Center
GW	Gravitational Wave
GWI	Gravity-Wave Interferometer
h	Plank's Constant
HabEx	Habitable Exoplanet Observatory
He	Helium
HE	High Energy
Hg	Mercury
H-maser	Hydrogen-Maser
hr	Hour
HRG	Hemispherical Resonator Gyroscope
HS	Heliophysics
HWO	Habitable Worlds Observatory
HX	Type of Intel Processor
Hz	Hertz
ICE	Cnes' Electric Field Experiment
IEEE	Institute Of Electrical and Electronics Engineers
IP	Intellectual Property
IR	Infrared
IR/O/UV	Infrared/Visible/Ultraviolet
ISRO	Indian Space Research Organization

ISS	International Space Station
ITU-R	International Telecommunications Union-Radiocommunications
JILA	Joint Institute for Laboratory Astrophysics
JOKARUS	Jod Kamm Resonator Unter Schwerelosigkeit
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
K	Kelvin
K	Thousands
KALEXUS	Kalium Laser-Experimente Unter Schwerelosigkeit
keV	Kilo (Electron Volts)
kg	Kilogram
kHz	Kilohertz
KID	Kinetic Inductance Detector
km	Kilometers
LA	Louisiana
LaRC	Langley Research Center
LED	Light Emitting Diode
LEO	Low-Earth Orbit
LIDAR	Light Detection and Ranging
LIGO	Laser Interferometer Gravitational-Wave Observatory
LISA	Laser Interferometer Space Antenna
LP2N	Laboratory of Photonics, Numerical, and Nanosciences
LUVOIR	Large Ultra-Violet/Optical/Infra-Red
m	Meters
M	Integer Number of Sensors
m/ns	Meters Per Nanosecond
m/s	Meters Per Second
MASER	Microwave Amplification by Stimulated Emission of Radiation
MEMS	Microelectromechanical Sensor
MHz	Megahertz
MIT	Massachusetts Institute of Technology
MITLL	Mit Lincoln Laboratories
mK	Millikelvins
MKID	Microwave Kinetic Inductance Detector
mm	Millimeters
MOU	Memorandum of Understanding
ms	Milliseconds
MSFC	Marshall Space Flight Center
MTSO	Management and Technical Support Office
mV	Millivolts
mV/m	Millivolts Per Meter
mW	Milliwatts
N	Number of Particles Measured
N	Number of Measurements
NASA	National Aeronautics and Space Administration
NavIC	Indian Global Positioning System

NbN	Niobium Nitride
NEO	Near-Earth Object
NESC	NASA Engineering and Safety Center
NGA	National Geospatial-Intelligence Agency
NGO	New Great Observatories
NIH	National Institute of Health
NISAR	Nasa-Isro Synthetic Aperture Radar Nmr
NIST	National Institute of Standards and Technology
nm	Nanometer
NMR	Nuclear Magnetic Resonance
NRO	National Reconnaissance Office
NSF	National Science Foundation
nT	Nanotesla
NV	Nitrogen Vacancy
OCT	Optical Coherence Thermography
OCTL	Optical Communications Telescope Laboratory
OM	Optomechanical
ONR	Office of Naval Research
OpTIm	Optomechanical Thermal Imaging
PACE	Plankton, Aerosol, Cloud, Ocean Ecosystem
PCI	Peripheral Control Interconnect
PIC	Photonic Integrated Circuit
PINS	Precision Inertial Navigation Systems
PNR	Photon Number Resolving
PNT	Positioning, Navigation, and Timing
POC	Point of Contact
PPM	Pulse Position Modulation
ps	Picosecond
PSD	Planetary Science Division
PXI	PCI Extensions for Instrumentation
QDM	Quantum Diamond Microscope
QIS	Quantum Information Science
QND	Quantum Non-Demolition
QS	Quantum Sensing
QUANTUS	Quantengase Unter Schwerelosigkeit
Quazi-Zenith Satellite System	Japanese Global Positioning System
R&D	Research and Development
rad/s	Radians Per Second
Rb	Rubidium
RF	Radio Frequency
RLG	Ring Laser Gyroscope
RMS	Root Mean Squared
ROIC	Readout Integrated Circuits
ROM	Rough Order of Magnitude

s, sec, μs, ns, ps, fs	Seconds, Microseconds, Nanoseconds, Picoseconds, Femtoseconds
SCaN	Space Communications and Navigation
SDO	Solar Dynamics Observatory
SERF	Spin-Exchange, Relaxation-Free
SiC	Silicon Carbide
SiV	Silicon Vacancy
SMD	Science Mission Directorate
SNR	Signal-To-Noise Ratio
SNSPD	Superconducting Nanowire Single Photon-Counting Detector
SOA	State-of-the-Art
SPD	Single Photon Detector
SPDC	Spontaneous Parametric Down-Conversion
SQIF	Sublinear-Resource Quantum Integer Factorization
SQL	Standard Quantum Limit
SQUID	Superconducting Quantum Interference Device
SRI	Stanford Research Institute
STAR	Strategic Technology Architecture Roundtable
STE-QUEST	Space-Time Explorer and Quantum Equivalence Principal Space Test
STMD	Space Technology Mission Directorate
STORM	Stochastic Optical Reconstruction Microscopy
SWaP	Size, Weight, and Power Consumption
SWaP-C	Size, Weight, Power Consumption and Cost
T	Time
T	Trillion
T	Tesla as a Measure of Magnetic Field Strength
T_c	Critical Temperature, the Temperature Below Which a Material Is Superconducting
TDAMM	Time Domain and Multi-Messenger
TES	Transition Edge Sensor
THz	Terahertz
TRL	Technology Readiness Level
UHF	Ultra-High Frequency
UK	United Kingdom
US	United States
USNO	Us Naval Observatory
USSR	Union of Soviet Socialist Republics
UV	Ultraviolet
V	Volts
VA	Virginia
VHF	Very High Frequency
VLBI	Very Long Baseline Interferometry
WA	Washington
WFRC	Wallops Flight Research Center
WSi	Tungsten Silicide
x	Linear Distance

y	Linear Distance
ΔE	Change In Atomic Energy State
Δf	Frequency Shift
Δx, Δp	Uncertainties In Position and Momentum, Respectively
$\Delta \phi$	Phase Shift
λ/D	Diffraction Limit
μm	Micrometer
τ	Time Increment

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14. ABSTRACT

Quantum sensing is reviewed in terms of application and relevance to deployment in space and NASA Science Mission Directorate’s scientific interests. Findings, observations and recommendations are made with regard to how NASA should engage with the quantum sensing field in the coming years. It is found that significant advantage may be gained from deploying sensors.

15. SUBJECT TERMS

Quantum Sensing; Quantum Technology; Atom Interferometers; Atomic Clocks; Single-Photon Detectors; Squeezing; Entanglement; Imaging; Quantum Magnetometers; Rydberg Sensors

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