



NASA SBIR 2021 Phase I Solicitation

S1.10 Atomic Quantum Sensor and Clocks

Lead Center: JPL

Participating Center(s): GSFC

Scope Title:

Atomic Quantum Sensor and Clocks

Scope Description:

Space exploration relies on sensors for science measurements as well as spacecraft operation. As sensing precisions push their limits, quantum phenomena inevitably must be exploited. It is expected that sensors utilizing quantum properties will offer new and significantly improved capabilities. NASA is interested in advancing quantum sensing technologies and infusing them into space science missions. In particular, this call seeks the development and maturation towards space application and qualification of atomic systems that leverage their quantum properties (e.g., optical atomic clocks, atom interferometers, Rydberg atom sensors, and artificial-atom-based sensors such as nitrogen-vacancy (NV) center point-defect sensors, etc.).

Recent developments of laser control and manipulation of atoms have led to new types of quantum sensors and clocks. Atomic particles, being intrinsically quantum mechanical, have demonstrated their unique advantages in metrology and sensing. Perhaps the most celebrated atomic metrology tool is the atomic clock. Atomic clocks in the optical frequency domain (i.e., optical primary frequency standards) have approached, and are expected to exceed, a frequency uncertainty beyond 1 part in 10^{18} . These optical clocks can be used, in turn, as precision sensors; for example, sensitivity to the fundamental physics constants have been explored for detection of dark matter and time variations in those fundamental constants. These approaches, when made Doppler sensitive, become exquisite inertial sensors, mostly in the form of atom interferometers. Because the center-of-mass motion is involved, atom interferometers use atomic particles as test masses and quantum matter-wave interferometry for motional measurements. Indeed, clocks and sensors are two sides of the same coin, sharing many common physical processes, technology approaches, and salient performance features. Therefore, this subtopic combines the two subject areas for leveraged and coordinated technology advancement.

The gaps to be filled and technologies to be matured include, but are not limited to, the following:

(1) Optical atomic clocks

- Subsystem and components for high-performance and high-accuracy optical clocks, mostly notably Sr and Yb lattice clocks as well as Sr⁺ and Yb⁺ singly trapped ion clocks. They comprise atomic physics packages, which are necessarily laser systems, and include clock lasers, optical frequency combs, as well as advanced electronics and controllers based on microprocessors or field-programmable gate arrays (FPGAs). They should have a path to a flight system.
- Space-qualifiable small-size low-power clock lasers at, or subsystems that can lead to, better than 3×10^{-15} Hz/?? near 0.1 to 10 s (wavelengths for Yb⁺, Yb, and Sr clock transitions are of special interest).
- Technical approaches and methods for beyond state-of-the-art compact and miniature clocks for space with emphasis on the performance per size, power, and mass.

(2) Atom interferometers

- Space-qualifiable high-flux ultra-cold atom sources, related components, and methods: e.g., $>1 \times 10^6$ total atoms near the point at <1 nK: Rb, K, Cs, Yb, and Sr.
- Ultra-high vacuum technologies and approaches for atom interferometer applications that allow small-size and low-power, completely sealed, nonmagnetic enclosures with high-quality optical access and are capable of maintaining $<1 \times 10^{-9}$ torr residual gas pressure. Consideration should be given to the inclusion of cold atom sources of interest, such as switchable and/or regulated atom vapor pressure or flux.
- Beyond the state-of-the-art photonic components at wavelengths for atomic species of interest, particularly visible and ultraviolet (UV):
 - Efficient acousto-optic modulators: e.g., low radio-frequency (RF) power ~ 200 mW, low thermal distortion, $\sim 80\%$ or greater diffraction efficiency.
 - Efficient electro-optic modulators: e.g., low bias drift, residual AM, and return loss; fiber-coupled preferred.
 - Miniature optical isolators: e.g., ~ 30 dB isolation or greater, ~ -2 dB loss or less.
 - Robust high-speed high-extinction shutters: e.g., switching time <1 ms and extinction >60 dB are highly desired.
- Flight qualifiable: i.e., rugged and long-life lasers or laser systems of narrow linewidth, high tunability, and/or higher power for clock and cooling transitions of atomic species of interest;
Also, cooling and trapping lasers of 10 kHz linewidth and ~ 1 W or greater total optical power are generally needed, but offerors may define and justify their own performance specifications.
- Analysis and simulation tool of a cold atom system in trapped and freefall states

relevant to atom interferometer and clock measurements in space.

(3) Other atomic and artificial atomic sensors

- Rydberg sensors or their subsystems/components for electric field or microwave measurements.
- Space qualifiable NV diamond or chip-scale atomic magnetometers.
- High-performance, miniaturized or chip-scale optical frequency combs.
- Other innovative atomic quantum sensors for high-fidelity field measurements that have space applications and can be developed into a space-quantifiable instrument.
- Because of the breadth and diversity of the portfolio, performers are expected to be aware of specific gaps for specific application scenarios. All proposed system performances may be defined by offeror with clear justifications. Subsystem technology development proposals should clearly state the relevance to the anticipated system-level implementation and performance; define requirements, relevant atomic species, and working laser wavelengths; and indicate its path to a space-borne instrument. Finally, for proposals interested in quantum sensing methodologies for achieving the optimal collection of light for photon-starved astronomical observations, it is suggested to consider the STTR subtopic T8.06.

Expected TRL or TRL Range at completion of the Project: 3 to 5

Primary Technology Taxonomy:

Level 1: TX 08 Sensors and Instruments

Level 2: TX 08.3 In-Situ Instruments/Sensor

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Research
- Analysis
- Software

Desired Deliverables Description:

Phase I deliverables: results of a feasibility study, analysis, and preliminary laboratory demonstration, as described in a final report.

Phase II deliverables: prototype or demonstration hardware; summary of performance analysis; and applicable supporting documentation, data, and/or test reports.

State of the Art and Critical Gaps:

Many technology gaps exist in the development state of atomic sensors and clocks intended for NASA space applications. These gaps are mainly in the areas of reducing size, mass, and power, while increasing their performance and advancing them towards

space qualification. These gaps may pertain to components, subsystems, instruments/devices, novel approaches and/or theoretical analysis tools. Most of the needed improvements are elements which are beyond current state-of-the art. These needed improvements include high-flux ultra-cold atom sources, atomic physics packages and atomic vacuum cell technology specific for clock and atom interferometer applications, miniature optical isolators, efficient modulators, active wave front and polarization devices, fast high-extension-ratio switches, efficient detectors, and novel frequency conversion methods/devices. Also needed are lasers and laser-optics system approaches with a high degree of integration and robustness, and suitable for atomic devices; small ultra-stabilized laser systems, and miniature self-referenced optical frequency combs. These are examples and not an exhaustive list.

Relevance / Science Traceability:

Currently, no technology exists that can compete with the (potential) sensitivity, (potential) compactness, and robustness of atom optical-based gravity and time measurement devices. Earth science, planetary science, and astrophysics all benefit from unprecedented improvements in gravity and time measurement. Specific roadmap items supporting science instrumentation include, but are not limited to:

- TX07.1.1: Destination Reconnaissance, Prospecting, and Mapping (gravimetry)
- TX08.1.2: Electronics (reliable control electronics for laser systems)
- TX08.1.3: Optical Components (reliable laser systems)
- TX08.1.4: Microwave, Millimeter, and Submillimeter-Waves (ultra-low noise microwave output when coupled w/ optical frequency comb)
- TX08.1.5: Lasers (reliable laser system w/ long lifetime)

References:

- 2020 NASA Technology Taxonomy: <https://go.nasa.gov/3hGhFJf>
- 2017 NASA Strategic Technology Investment Plan: <https://go.usa.gov/xU7sE>