Development of Atomic, Molecular, Optical Physics-Based Technologies for Reaching Ultimate Limits in the Fundamental Physics Experiments in Space

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Nicholas P. Bigelow[1], Grant Biedermann[2], Scott A. Diddams[3], Kurt Gibble[4], Subhadeep Gupta[5], Ulf E. Israelsson[6], Wolfgang Ketterle[7], John Kitching[3], Gour S. Pati[8], Robert L. Tjoelker[6], Slava G. Turyshev[6], Jun Ye[3,9], and Nan Yu[6]

[1]*Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627*
[2]*Department of Physics and Astronomy, University of Oklahoma, Norman, OK 73019*
[3]*Time and Frequency Division, National Institute of Standards and Technology, Boulder, CO 80305*
[4]*Department of Physics, Pennsylvania State University, University Park, PA 16802*
[5]*Department of Physics, University of Washington, Seattle, WA 98195*
[6]*Jet Propulsion Laboratory, California Institute of Technology,*
4800 Oak Grove Drive, Pasadena, CA 91109
[7]*Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139*
[8]*Physics and Engineering Program, Delaware State University, Dover, DE 19901*
[9]*JILA, Department of Physics, University of Colorado, Boulder, CO 80309*

Primary Author Contact Information:
Dr. Nan Yu
Jet Propulsion Laboratory, MS 298
4800 Oak Grove Drive, Pasadena, CA 91109
Phone: (818) 354-4093, Email: nan.yu@jpl.nasa.gov

Today physics stands at the threshold of major discoveries. Growing observational evidence points to the need for new physics. Efforts to discover new fundamental symmetries, investigations of the limits of established symmetries, tests of the general theory of relativity, detection of gravitational waves, and attempts to understand the nature of dark matter were among the topics at the focus of scientific research at the end of the last century (NRC 2003). These efforts intensified with the unexpected discovery of the accelerated expansion of the universe (i.e., "dark energy") made in the late 1990s, triggering many new activities aimed at answering important questions related to the most fundamental laws of Nature (Turyshev 2009).

The fundamental physical laws of Nature are currently described by the Standard Model and Einstein's general theory of relativity including the ΛCDM model at the cosmological scale. However, there are important reasons to question the validity of this description. 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 a challenge. 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 physics is needed to resolve this issue.

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 the Equivalence Principle, variation of fundamental constants, modification of the inverse square law of gravity at various distances, Lorentz-symmetry breaking, large-scale gravitational phenomena, and introduce corrections to the current model of spacetime around massive bodies. Each of these manifestations offers an opportunity for experiments of precision measurements and could lead to a major discovery.

Space is one of the most likely places where these manifestations may be investigated. While providing microgravity for experiment and technology gains (Aveline 2021, van Zoest 2010), access to greater variation of gravitational potentials, greater velocities, and full orientation coverage, space also extends the well-understood and controlled laboratory environments.

At the same time, ground-based laboratories have seen spectacular developments in Atomic, Molecular and Optical Physics (AMOP), leading to quantum technologies to access measurement regimes with unprecedented sensitivity and accuracy. Progress has led to new instruments and technologies including more accurate atomic clocks, atom-wave interferometers, and femtosecond laser combs. Today's new generation of high performance atomic quantum sensors (accelerometers, gyroscopes, gravimeters, gravity gradiometers) is surpassing previous state-of-the-art instruments. 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. The questions that can be addressed by space experiments with these technologies are: "Does gravity behave as Einstein predicted?"; "What will be the nature of a theory of quantum gravity?"; "Where and how will the Standard Model fail?"; "Are the fundamental constants of nature truly constant?"; "What is the nature of dark matter and dark energy?".

Below we discuss some of these new AMOP-based technologies, including their current status, anticipated performance, challenges of space deployment, and science benefits from their use in space-based research. We also argue for dedicated programs for their development, miniaturization, and space qualification efforts in the next decade in support of future fundamental physics measurement endeavors in space.

1. Highly-accurate optical clocks

1.1. Technology innovation and the state of art

For many years microwave transitions have served as the basis for accurate and ultra-stable atomic clock systems. More recently, a new type of atomic clocks based on optical transitions demonstrated breakthrough improvements. Highly stabilized lasers as optical oscillators have already routinely achieved the $10^{-15}\ \tau^{-1/2}$ level (vs quartz oscillators at 10^{-13},) limited by the thermal noise of the reference cavity (Ludlow 2007 and 2008). When referenced to suitable optical transitions of atoms in ion traps or optical lattices, optical clocks are reaching and going beyond fractional frequency stability of 10^{-18} (e.g. Brewer 2019 and McGrew 2018), limited at this time by blackbody radiation induced uncertainty. Accuracies at 10^{-19} or better are expected in the near future. For comparison, the best clock flown in space to date is at the frequency stability of 10^{-15} level, as recently demonstrated by NASA DSAC technology demonstration mission (Burt 2021).

1.2. Scientific benefits of new technology

Clock comparison is a major method for tests of general relativity, the special theory of relativity and Lorentz invariance. Access to space enables better clock performance and allows us to fully benefit from the larger variations of the gravitational environment for tests of general relativity (gravitational redshift). Atomic clocks made with different atoms or different kinds of transitions (electronic, hyperfine, vibrational for molecules), when operated together can search for violations of the Equivalence Principle (EP). Monitored over time, they are sensitive to variations of the fundamental constants. Identical clocks moved relative to each other can be used to perform tests of special and general relativity tests.

As a direct consequence of the EP, general relativity and other metric theories of gravitation forbid any time variation of non-gravitational constants. Today, optical clocks offer the possibility to test time variations of fundamental constants at a high accuracy level. Such measurements complement the tests of the local Lorentz invariance and of the universality of free fall to experimentally establish the validity of the EP. Furthermore, a global space clock network is ideal for such measurements. Similar networks with various clock combinations can also be used to seek a direct detection of dark matter ultra-light field candidates.

Furthermore, clocks of 10^{-16} or better accuracy and associated ability of time transfer can be used for geodesy through gravitational redshift. Ancillary Earth sciences will greatly benefit from the use of these improved clocks including studies of Earth rotation, climate research, ocean research, earthquakes, tsunamis, etc. Similarly, as clock frequencies are ultimately impacted by the gravity variations on earth, it is possible that the future primary standard and clocks will have to be located in space (Kleppner 2006).

1.3. Benefits and challenges of space deployment

In space, where weightlessness and extremely quiet environments ensure the ideal conditions for laboratory experiments, the clock performances can be improved even further. Clocks in space represent unique tools to test fundamental laws of physics at an unprecedented level of accuracy and to develop applications in time and frequency metrology, universal time scales, global positioning and navigation, and geodesy.

In terms of tests of gravity theories and fundamental physics, space presents an unique platform as these tests often require large gravitational potential differences and large velocity changes which can only be obtained through space based systems. For example, ground redshift tests limited to the laboratory scale and building height (Takamoto 2020). Space can offer the full gravity difference from earth or even the Sun. A space based clock will also enable intercontinental clock networks for some of the physics tests.

Space deployment puts stringent requirements on size, mass, power, and autonomy of an instrument. A compact trapped Hg+ clock has been demonstrated in the NASA Deep Space Atomic Clock (DSAC) mission. While DSAC uses no lasers, optical clocks extensively rely on stabilized lasers. This is one of the major challenges in developing space optical clocks and metrology. For a space-qualified optical clock, lasers must be small and reliable with long lifetimes while working under harsh space radiation environments. High-power lasers are required for neutral atom cooling and trapping techniques, ultra-stabilized lasers for clock transitions, and femtosecond lasers (one octave frequency span) for optical frequency comb generation and self-referencing.

In addition, ultra-high vacuum systems with good optical access without magnetic materials are required for housing trapped atoms. The vacuum chambers should ideally be completely sealed enclosures without the active pumps typically used in laboratories. All corresponding precision microwave and laser control electronics need to be specifically developed for the space instrument. All systematic effects must be extremely well controlled.

1.4. Program objectives

High-performance microwave space clock experiments have been planned and demonstrated on space station platforms in the ESA's ACES mission (Savalle 2019) and in the Chinese Cold Rubidium clock payload (Liu 2018). As optical clocks have shown potential for greater precision than microwave clocks, missions using optical clocks have already been proposed under the European Space Agency (ESA) Cosmic Vision program and other national space agencies. An optical clock mission concept is also being studied by NASA BPS. Before implementation of an optical clock mission, technologies not previously demonstrated in space must be matured to a TRL 6 level. We argue that it would be beneficial to NASA to establish such a program. The program could support an initial development of several advanced clock technologies and common component technologies and later focus on one approach for a specific science experiment concept.

2. Atomic quantum inertia sensors

2.1. The nature of innovation

Atomic quantum inertial sensors exploit the particle-wave duality of atomic particles for ultra-sensitive interferometric measurements similar to laser interferometers. Because the rest energy of the atomic particles is on the order of 10^{11} higher than the energy of a laser photon, atom interferometers can be intrinsically much more sensitive to inertial forces. Laboratory atom interferometers have achieved $\delta a \sim 10^{-10}$ m/s^2/Hz$^{1/2}$ (Asenbaum 2020) as accelerometers and $\delta\omega \sim 6\times10^{-10}$ rad/s/Hz$^{1/2}$ (Gustavson 2000) as gyroscopes, already surpassing the state of the art in traditional sensors. Significant advances have been made more recently in the sensor performances and the technology maturity. Various transportable systems are being developed around the world including gravimeters, gradiometers, and gyroscopes.

Major fundamental advances are still being made today in laboratories. For example, a large momentum-transfer for atom-wave splitting has been demonstrated with a high fringe contrast (Müller 2008). In addition, the use of coherent quantum matter waves offers potential of further improvement to overcome standard atom projection noise by exploiting quantum entanglement and non-classical states.

2.2. Scientific benefits of new technology

Atomic quantum inertia sensors are becoming a key-technology for ultra-precise measurements of gravity, accelerations and rotations. Their space deployment can be used to support new classes of experiments such as tests of the gravitational inverse-square law at distances of a few microns or at solar system scales (Yu 2018), the universality of freefall, and tests of the EP using quantum wave packets, as well as measurements of the relativistic frame-dragging precession (Jentsch 2004). It also provides new experiment possibilities for direct detection of dark energy (Hamilton 2015 and Chiow 2018) and gravitational wave detections (Dimopoulos 2008).

When used as sensitive accelerometers, cold atoms in space as ideal test masses in a drag-free environment provide excellent candidates for tests of the universality of free fall. By measuring the differential acceleration of two co-located matter-wave interferometers with different atomic species, atom interferometers in space can be used to perform highly accurate searches for a violation of the EP which is at the foundation of the general theory of relativity and other metric theories of gravity. Such a fundamental principle should be tested to its utmost precision. Many modern theories of physics beyond the Standard Model predict a violation of the EP at different levels. The ground measurement limits of 1×10^{-13} on the EP violations (Turyshev 2007) were only surpassed by the recent CNES Microscope mission (Touboul 2017). Atom interferometers in space could be used to reach accuracies beyond these current limits. The use of atomic test masses as quantum wave packets in gravity free fall can also provide new science interpretations, Thus, the objective of the Quantum Test of Equivalence and Space Time (QTEST) experiment was to achieve $<1\times10^{-15}$ (Williams 2016). More ambitious mission concepts to reach $<1\times10^{-17}$ are being discussed.

2.3. Benefits and challenges of space deployment

A flight experiment in microgravity will greatly enhance the performance of atomic sensors because of the long interaction times achievable in a freely falling environment. The lack of large gravity bias also minimizes the experiment's spatial extent for better environmental controls (a 10-s free fall time on earth equals to 500 m!). The much better vibration isolation available in space is also a benefit. Thus, if used as accelerometers, atom interferometers in space could potentially reach the level of $\delta a \sim 10^{-12}$ m/s^2/Hz$^{1/2}$ or better (Yu 2006 and Dimopoulos 2008).

Performance testing and relevant technology validation requires a microgravity environment. Microgravity validations may be performed in a drop tower, zero-g plane, sounding rockets, ISS, or technology demonstration satellite mission.

2.4. Program objectives

While most of the atomic sensor system developments to date are for terrestrial use, several efforts developing space-based atomic sensors (e.g. DLR QUANTUS and MAUIS, and NASA CAL) have been undertaken. The NASA Earth Science and Technology Office has also funded atom interferometer gravity gradiometer developments to be used for global gravity mapping in space, now at TRL 4-5. Maturation of these types of measurement systems for space requires further development of laser and optics systems, optically accessible vacuum systems, high flux atom sources, and low noise atom detection techniques. The potential systematics of atomic quantum sensor based measurement systems will also need careful study. In addition, investment should be made to continue basic atom interferometer research activities in ground research laboratories to better understand these inertial sensors, their error sources, and generate new capabilities.

A dedicated program for developing atom interferometer-based technology for space could encompass a multi-year multi-million dollar effort from universities, research laboratories, and industry. Separate funding may be needed to validate it in the space environment, perhaps in conjunction with moderate science measurement objectives in a pathfinder mission.

3. Recommendations

Recent scientific and technological advances have produced new clocks and quantum sensors that have enabled measurements to unprecedented regimes of sensitivity and accuracy at which the foundations of modern physics can be tested. We argue that a well-defined technology program with adequate investments can lead to major scientific advances in fundamental physics by maturing technology for space-based missions within the decade.

Many space missions already studied would benefit from hastened maturity of AMOP technologies. This maturity can be reached via important development of the following crucial elements:

- Suitable laser systems: currently, the lack of efficient space-qualified stable lasers is a major limitation.
- Atom sources: Efficient high-flux ultra-cold atom source for atom interferometer..
- Optical benches and high-quality optical interface with vacuum systems
- Component and system volume / mass reduction
- Self-referenced optical frequency comb as a key part of an optical clock
- High performance frequency and time transfer supporting optical clock performances
- Continued improvement of ground experiments: today, most of quantum technologies and experiments are on the edge of knowledge. Ground experiments will be always needed for the preparation and support of a space mission and for the improvement of scientific knowledge.
- System level development for maturing integration and packaging capabilities

To meet the challenges in fundamental physics ten years from now, technology investments are required today. The most important focus areas are (i) tunable lasers (to cool and manipulate atoms), (ii) stabilized clock lasers and frequency combs (for laser interferometry and optical clocks); (iii) efficient methods for high-flux cold atom production, (iv) atom interferometry systems, and (v) atomic clocks. Challenges of space deployment impose additional requirements on the reliability of the instruments and put pressure to minimize their mass, volume, and power requirements. This brings about the need for dedicated miniaturization and space qualification efforts.

Because of the significant discovery potential offered by the quantum sensor technologies out of AMOP and their application for space-based laboratory research, it will be beneficial to establish a strong and well-funded research program with BPS and across the NASA directorates. This program should be vertically integrated with science mission visions at the top and broad research programs at the bottom to support. While the state of technological readiness to tackle the science opportunities discussed in this white paper has changed markedly in the last few decade, there remains a significant gap to bring many of the technologies into instruments qualified for space operations and infusion into discovery missions in this and next decades. In order to advance our exploration of fundamental physics in space, an integrated and focused research and technology program is critical.

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