Fundamental Physics with a State-of-the-Art Optical Clock in Space

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Recent advances in optical atomic clocks and optical time transfer have enabled new possibilities in precision metrology for both tests of fundamental physics and timing applications. Here we describe a space mission concept that would place a state-of-the-art optical atomic clock in an eccentric orbit around Earth. A high stability laser link would connect the relative time on the orbiting spacecraft to earthbound stations. The primary goal for this mission would be to test the gravitational redshift, a classical test of general relativity, with a sensitivity 30,000 times beyond current limits. Additional science objectives include other tests of relativity, enhanced searches for dark matter and drifts in fundamental constants, and establishing a high accuracy international time/geodesic reference.

Mission Background and Overview

Time is an omnipresent concept in modern society and plays a central role in the foundations of physics and our understanding of the cosmos. Atomic clocks keep international time and their quantum measurements are, by orders of magnitude, the most accurate measurements of any physical observable. The last twenty years have seen a rapid improvement in atomic clock performance due to the introduction of clocks at optical frequencies and the development of fs-laser frequency combs in 2000, which enabled the reliable counting of the ticks of the cycles of laser light at 10^{15} cycles per second [1–3]. The most accurate versions of these optical clocks use trapped quantum absorbers (either ions or lattice-confined neutral atoms) and now have fractional frequency uncertainties approaching or exceeding 1 part in 10^{18}. Future clock inaccuracies could reach below 10^{-21} in two decades, at which point gravity waves could be directly observed by measuring length changes directly with the optical clocks.

Due to their unrivaled level of precision, optical clocks are already being used in a variety of applications and improved tests of fundamental physics. Several of these are based on the fact that in general relativity (GR), the tick rate of time is no longer universal, but slows in the presence of massive bodies. With further advances in clock accuracies and stabilities, measurements of time on the surface of the earth will soon be limited by the instability of time itself due to gravitational fluctuations, for example from tides and seismic noise. A straightforward solution would be to locate one or more clocks in orbits around Earth, thereby avoiding Earth's tidal motion/gravitational noise. Moreover, this sensitivity to gravitational potential can be exploited to test the tenets of General Relativity itself (e.g., theoretical predictions of the gravitational redshift).

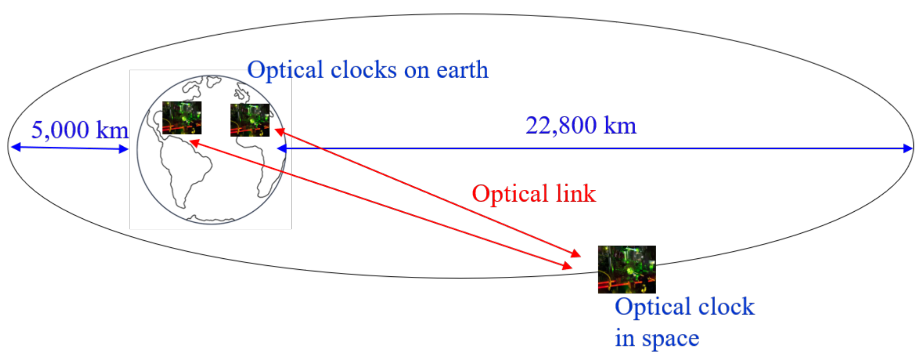

Figure 1. Schematic of the proposed mission. A high-performance optical clock in an elliptical orbit around Earth is connected to ground optical clocks through a high stability optical link. Clock comparisons will enable tests of fundamental physics and provide an international clock reference for timing/geodetic applications.

Here we propose an ambitious mission, which would locate a high stability optical clock in a highly eccentric orbit around Earth. This clock would then be connected to similar clocks on earth through high performance optical links to measure the gravitational redshift with a sensitivity more than 30,000 times beyond those of previous tests as well as to advance other fundamental physics and science goals. In particular, the FOCOS (**F**undamental physics with an **O**ptical **C**lock **O**rbiting in **S**pace) mission will enable tests of local Lorentz invariance and searches for the ultralight fields (this proposed mission is described in detail in Ref [4]). Taken together, these measurements will contribute significantly to our understanding of the basic framework of the universe and will help constrain or support new theories of spacetime/gravity that attempt to explain physical phenomena (dark energy, dark matter, quantum gravity) not presently accounted for in existing theories. Moreover, a space-based clock will provide an ultimate timing/geodetic reference frame that is freed from the noisy gravitational environment of the earth's surface, which will significantly challenge clock operation in the 10^{-19} decade and beyond. We note that this concept is well recognized with proposals dating back to at least 1969 [5] and up to a recent proposal, which employs two optical clocks on separate satellites in offset elliptical orbits to measure the redshift with high precision [6].

Mission Science Goals

The FOCOS system will enable a plethora of scientific investigations, listed in Table 1, many of which will be described in more detail in other White Papers. Of particular relevance here are fundamental tests of General Relativity and the Standard Model at levels orders of magnitude beyond those of current tests (due to the high stability of the clocks, links, and the modulation of gravitational effects). These include tests of the gravitational redshift, Local Lorentz Invariance, combined relativistic effects on the clock time and satellite orbit, and searches for dark matter outside of Earth's shadow. Also listed are potential improvements in international timing/geodesy that could substantially benefit other terrestrial/space activities.

Table 1. Science goals, both fundamental and applied for the mission concept.

Science	**Expected results**	**Significance**
Relativistic gravitational Redshift (EEP-LPI)	30,000× improvement over existing limit	New limit on the very foundation of GR. A deviation from the GR theory will signal the dawn of new era in modern physics, revealing new physics and helping to understand dark matter.
Dark matter searches	100-1000× higher sensitivity than previous clock-network tests, new mass-environment-dependent unknown force constraints	Direct detection of dark matter could appear as an ultra-light scalar field, which would help understand the *nature* of dark matter.
Combined relativistic effects on the clock time and satellite orbit	Beyond the state-of-the-art relativistic effect analysis and corrections are required, including parameterized post-Newtonian gravity	Test current relativistic-consistent treatments of reference frames (Geocentric and Barycentric), Earth, solar and lunar tidal effects, as well as non-gravitational perturbations to the orbit. Search for deviation from General Relativity and tests for alternative gravity metric theories.
International clock network for fundamental science	1000x improvement in intercontinental clock comparisons than currently possible with GPS	Enable combined utilization of worldwide clocks for fundamental physics experiments such as time-dependence of fundamental constants and dark matter wave detection.
Worldwide Time synchronization	1000x improvement in intercontinental clock comparisons than currently possible with GPS	Lay basis for future space-based time standards, free from local gravity perturbations. Connecting clocks world-wide, with a spatial reference frame enables a new network for Time (epoch) and establishes the foundation for future GNSS.
Local Lorentz Invariance	100× improvement over existing limit	Search for a preferred frame, perhaps the isotropic 3K microwave background radiation; search for the Lorentz violating coupling of Standard Model Extension.

Relativistic leveling	Determine Earth's gravitational potential at mm-level	Continental scale leveling, and potential difference measurements. New method for earth gravity field measurements.
Reference frame for Position, Navigation and Time (PNT)	Demonstrate range determination 100x improvement over GNSS	Improve and validate: geodetic referencing and Terrestrial Reference Frames, Earth center of mass, sea-level rise etc.

Mission Design

The basic idea for the FOCOS mission is to compare the frequency and time of a stable and accurate clock in space with those of earthbound clocks via an accurate earth-to-space time/frequency link. In this mission the onboard clock will experience a continually varying gravitational potential as the spacecraft moves through its eccentric orbit (see Figure 1), continually shifting its frequency relative to that of clocks at earth ground stations. The modulation of the gravitational potential in turn modulates the frequency of the space clock with an accurately known period. This modulation offers two principal metrology benefits: (i) it takes advantage of the stability of the clocks to evaluate gravitational effects at levels beyond the clock accuracies, and (ii) it helps to separate gravitational effects from possible drifts in the clocks and link hardware.

The measured difference of the gravitational redshift is the difference between the minimum clock frequency, at perigee, and the maximum, at apogee. Repeated measurements over many orbits give an accurate difference of the space clock's redshifts, after correcting for perturbations such as the Sagnac effect, special relativistic shifts, non-reciprocal corrections related to asynchronous sampling and point-ahead angle across the two-way link and dispersion effects [7,8]. Comparing the measured and predicted frequency differences will precisely test general relativity. In practice, the measurement would compare the elapsed time (or phases) between the two clocks over some time interval, both to improve sensitivity and to circumvent dropouts of the link due to turbulence or satellite visibility.

Long-term phase or time comparisons between the spaceborne clock and multiple ground stations, over multiple orbits, will effectively create a global clock network with unprecedented timing precision, which has multiple applications. When the spacecraft is far from Earth, it will be visible to a larger number of locations on Earth and its clock frequency will vary slowly. Moreover, because the clock spends most of the orbital period far from Earth, there will be adequate averaging times to reach the low 10^{-18} range after a small number of orbits. The clock in this way can serve as an accurate space-time reference [9], assuming that its orbit is precisely known and that corrections are applied for both non-gravitational accelerations and higher-order relativistic perturbations. Time transfer links can be established globally to connect clocks worldwide for intercontinental comparisons in support of fundamental physics tests, the redefinition of international time, and geodesy-based earth science studies.

One of the distinguishing features of the FOCOS mission is its leveraging of state-of-the-art clock performance and timing links. For example, with a planned fractional frequency instability of $1 \times 10^{-16}\tau^{-1/2}$ and fractional inaccuracy of 1×10^{-18}, the FOCOS apparatus could measure the gravitational redshift with a sensitivity 30,000 times higher than previously achieved. These goals could be reached with existing (Sr or Yb) optical lattice clock technology, supported by a high performance two-way optical time transfer link connected to Earth stations. While conventional long-distance time transfer link performance has lagged behind optical atomic clock advances, recent demonstrations of optical time transfer over 30-km of turbulent air have achieved instability levels below those of the clocks[10] and are scalable to longer distances. Ideally there would be two time-transfer antennas on the spacecraft, thereby enabling simultaneous links to multiple Earth stations, which would increase visibility and averaging times, as well as enhancing clock comparisons.

The FOCOS orbit has been chosen to offer a large modulation of the gravitational potential while offering good satellite visibility to the ground stations. We note that while this eccentric orbit, and its resulting modulation of the gravitational potential, is required to meet the primary scientific objectives (tests of the gravitational redshift and Lorentz invariance), a circular orbit in medium-earth-orbit might be more natural for other scientific objectives (e.g., an international space-time reference). For the FOCOS mission, to avoid drifts of systematic errors in the clock that would degrade the measurement of the redshift, we favor observing the satellite clock from the same ground location both at apogee and then at perigee with minimal time gap between the two observations, as set by the orbit. We have found that a baseline orbit with a period of about 8 hours, and a perigee altitude of approximately 5,000 km and an apogee of 23,000 km satisfies these requirements and would offer 30 minutes of visibility at perigee and 2-3 hours at apogee. Averaging over ~100 orbits would then yield the desired sensitivity for the redshift measurement.

Figure 2. Proposed timeline for the FOCOS mission, including a ground-based technology program in the early years.

Mission Implementation, Schedule and Cost

FOCOS is an ambitious science measurement mission. In order to achieve the stated science objectives, it plans to deploy a state of the art lattice optical clock with a precision only recently demonstrated in research laboratories. As such, the mission implementation is also challenging in terms of technology maturation, not only for the clock payload, but also for the time and frequency transfer system and precision orbit determination. Currently, NIST is developing a rack-sized portable optical clock, which meets the performance targets of the proposed space clock, but will require further SWaP (Size, Weight, and Power) reduction. To bring the clock system technology to TRL5-6 needed for the implementation of FOCOS in 2027, a focused technology development program needs to be established right after the Decadal report in 2023. Similarly, the high performance time and frequency link system needs to be validated and matured in time. All in all, it is estimated it would cost $30M over three years to mature these key technologies sufficiently in time for mission implementation. This technology development can be led by JPL, in collaboration with NIST and with support from other universities and industry. For the mission development schedule, we envision FOCOS will be the first dedicated free flier mission by BPS. A notional development schedule is illustrated in the chart below.

The estimated cost of the mission is largely driven by the mass and power of the payload and the optical link pointing requirements. To establish a credible cost and schedule for FOCOS, JPL's Advanced Projects Design Team (Team X)[1] developed cost and schedule for standard Phase A-F activities associated with this concept as a Class C mission. For the baseline mission with a lattice optical clock with dual antennas in the described elliptic orbit, the mission lifecycle cost was estimated to be \$452M in 2021 US dollars[2]. This cost includes all the ground support and science PI investigations. A rough cost breakdown is given in Table 2. This evaluation assumed a payload SWaP of 300 kg and 580 W. However, this is a very conservative estimate, largely based on the activities of the NIST portable lattice optical clock development. Through the pre-Phase A technology maturation program as outlined in the schedule above, the mass and power can be significantly reduced. As a demonstration of the mission cost dependence of mass and power, Team X estimated that a similar mission with an optical clock of 40 kg and 100 W would reduce the cost to just over \$200M. While currently available clocks with this smaller SWaP do not yield the same science outcomes, this example illustrates the impact of the payload mass and power on overall cost and the importance of the technology maturation activities before the implementation of the mission.

Table 2. The FOCOS mission cost breakdown by category.[3]

PM	SE	SMA	Sci.Tech.	Payload	s/c+ATLO	MOS	GDS	Reserve	Total
\$19M	\$9M	\$9M	\$28M	\$146M	\$110M	\$18M	\$14M	28%	\$452M

In summary, we have described a mission that we believe would leverage significant recent advances in atomic clocks and optical time transfer to enable a dramatic improvement in tests of General Relativity as well as other tests of fundamental physics (e.g., searches for dark matter). Moreover, this mission would link international clocks at the 1×10^{-18} level, which could enable advances in international timing, precision navigation, and chronometric geodetic leveling. Such a flagship mission would also provide structure for a ground-based space clock research program as well as serving as a critical steppingstone for other ambitious future clock/atom-based missions that could test GR and the Standard Model in other ways via gravitational wave detection, tests of the Weak Equivalence Principle, or novel searches for new physics (e.g., dark matter and energy).

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[1] JPL Team X is a concurrent engineering design environment with representatives from all JPL technical disciplines. JPL line organizations create, maintain, and operate Institutional Cost Models (ICMs) within Team X, and Team X management ensures consistency between the use of ICMs and institutional guidelines.

[2] The cost and schedule information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

[3] PM = Program Management, SE = System Engineering, SMA = Safety & Mission Assurance, s/c + ATLO = spacecraft bus + Assemble, Test, Launch, and Operation, MOS = Mission Operation System, GDS = Ground Station.

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