

# Research Campaign: Space Networks of Trapped-Ion Optical Clocks for Fundamental Physics

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Optical clocks have recently achieved inaccuracies below 1 part in  $10^{18}$  [1], greatly surpassing the performance of previous-generation microwave clocks. State-of-the-art for miniaturization of these clocks is represented by so-called transportable optical clocks [2, 3], where the clock components comprise  $\sim 1 \text{ m}^3$ , allowing for such clocks to be transported from place to place for clock comparisons, redshift measurements, and other operations. To date, high-performance optical clocks compatible with space operation have not been developed.

Numerous tests of fundamental physics could benefit from launching high-performance optical clocks into space. Several of these tests require networks or constellations of such clocks, which would also improve the signal-to-noise ratio and reliability of any experiments performed with space clocks. Space-based optical clock constellations will likely require further miniaturization of current optical clock technology to the tens-of-liters scale or below to avoid prohibitive launch costs.

In this white paper, we propose a Research Campaign targeted at aggressive development of compact and high-performance optical clocks based on trapped ions. The goal of this campaign is to develop an optical clock of mass no more than 30 kg with stability at the  $10^{-14} / \sqrt{\tau}$  level, to space-qualify it, and to prepare for a clock launch by 2032. We describe the fundamental physics experiments that will be enabled by a constellation of such clocks, the specifications that will be required, and technologies we propose NASA develop in order to enable these optical clock constellations. We also propose further development of the integrated technologies that will enable next-generation optical clocks at the few-liter scale, allowing for many-clock networks to be deployed at even less cost in the future.

*Fundamental physics tests with space optical clock networks* — The nature of dark matter (DM) is one of the biggest open questions in fundamental physics. Atomic clocks are sensitive to ultralight scalar dark matter that can lead to either oscillatory or transient signals. If self-interaction between dark matter particles causes clumping, a network of precision clocks in Earth orbit could be one of the most straightforward methods for direct detection of dark matter. The passage of such “transient” DM may be detected in a constellation of clocks via desynchronization as the DM passes through the ensemble, followed by resynchronization afterward. Multiple ion clocks in various orbits could be utilized to detect, or at least further constrain the properties of, such topological dark matter [4]. Similar studies have been performed using GPS atomic clocks [5] and earth networks [6]. However, Earth’s presence can partially screen topological dark matter fields passing by [7], making a space-deployed clock network far more sensitive to such effects than an Earth-based network of the same accuracy. A network of ion clocks in geostationary orbit with reasonable frequency instabilities near a part in  $10^{14}$  at one second could detect frequency fluctuations at a part in  $10^{16}$ , a two-order-of-magnitude improvement upon existing studies. The search for oscillatory dark matter (DM) signals can also be improved with a space-based clock network [8].

Networks of optical clocks in space may also serve as sensitive detectors for exotic low mass fields (ELFs) that may be emitted by high-energy astrophysical events, such as black-hole or neutron-star mergers. Such fields will arrive with some delay with respect to the gravitational wave (GW) signal. GW detectors could thus provide a trigger for observation of ELFs as part of a multi-messenger-astronomy approach to such events. As ELFs are hypothesized to couple to the standard model in ways that would mimic changes in the fundamental constants, atomic clocks will incur oscillating signals over the ELF passage duration, and hence may be used as ELF telescopes [9]. Though ELF signals are delayed from GWs, they are likely still extremely relativistic. Therefore, the signal seen by clocks on Earth

would not provide information for localizing events, as laboratory optical clock updates are typically relatively slow ( $\sim 1$  s), and the transit time across the earth is approximately 40 ms. However, an orbital constellation of optical clocks, with comparable stability to lab clocks, may allow for the required time resolution to track propagation and perform triangulation of ELF signals. The expected transit time is  $\sim 200$  ms across a GPS-like constellation, and the baseline set by orbital distances suggested for future space-based GW detectors ( $\sim 2.0 \times 10^9$  m for LISA/SAGE [10]) would lead to an approximately 7 s transit time. This application suggests several clocks in space, each a lower-interrogation-time clock with many ions to utilize root-N scaling to allow fast response. For example, 10 ms interrogation of a transition in a  $N = 10^2$  ion clock can potentially achieve an instability of  $10^{-16}/\sqrt{\tau}$ . Such a composite array clock may be able to respond on the ten-millisecond timescale with  $1 \times 10^{-15}$  level instability, and address significant unexplored regions of ELF-energy phase space.

Space-based optical clock networks may enable several other fundamental physics studies. These include improved resolution very-long-baseline interferometry (VLBI) systems able to image nested black hole photon rings [11], observation of which can provide information about a black hole’s angular momentum and provide a universal signature of general relativity. Space-based ion traps may also be useful for confirming or rejecting signals for exotic dark matter candidates, such as millicharged dark matter [12]. Furthermore, multiple clocks in heliocentric orbits may be used as a gravitational wave detector [13], although clock stability at the  $10^{-20}/\sqrt{\tau}$  level is required to achieve performance beyond that expected for the Laser Interferometer Space Antenna (LISA). The range of applications for space-based clock networks speaks to the versatility of this sensor platform for fundamental physics studies, and it is expected that improvements to clocks over time will yield improved stability.

Finally, we note that the proposals on how to detect ultralight dark matter with atomic clocks are extremely recent. We expect many more ideas on using space clocks for fundamental physics searches to bloom in the next decade, as significant particle physics theory efforts shift towards using quantum sensors.

*Optical clock requirements* — The aforementioned experiments require clocks with high stability and accuracy that can operate in space. To achieve sensitive detection of transient dark matter or exotic low-mass fields at levels beyond what can be achieved via other methods, clock stabilities at or exceeding  $10^{-14}/\sqrt{\tau}$  are required, allowing the clock to detect the signal in a limited time window. These levels of stability are achievable via optical clocks based on narrow-linewidth transitions in ions or atoms, but exceed what has been achieved so far in space-based microwave clocks [14]. Clock uncertainties at the  $10^{-16}$  level or better allow for measurements of the gravitational redshift exceeding previous efforts [15–17]. These accuracy levels are likewise achieved only by a few clocks, including optical clocks [1–3].

To launch a space-based network of optical clocks for dark matter or ELF detection, the size, weight, and power (SWaP) of each clock must be compatible with launching the network’s many clocks into orbit without prohibitive costs. Geostationary orbits are required for GPS-like clock constellations, while some applications may benefit from even larger orbits. The current  $\sim 1$  m<sup>3</sup> sizes of optical clocks are not compatible with launching a constellation of many clocks into space. We anticipate that many-clock networks will not become realistic until optical clock weight and power draw approach the tens-of-kg and 100 W scale. Furthermore, the clocks must be compatible with space qualification, as described later.

Trapped ions have several advantages over other optical clock technologies for space applications, particularly for many-clock constellations. Ion-based optical clocks have very

small and well-known systematic frequency shifts due to environmental perturbations, allowing for extremely high accuracy. Traps based on RF electric fields provide high motional frequencies and ion lifetimes of days, potentially leading to a technology better-suited to remote operation in harsh environments. Long lifetimes mean less frequent trap reloading, and therefore more straightforwardly attainable specifications for ion source material and loading apparatus. Similarly, the high motional frequencies provide vibration resilience, a necessity in a spacecraft environment. Due in part to the use of RF trapping, the number of lasers and required optical powers are quite low. For comparison, neutral-atom based optical lattice clocks use high intensity lasers to confine atoms with sufficient trap depth for long interrogation times, leading to substantial SWaP of the laser system. In contrast, ion clocks require only sub-milliwatt-level optical powers at all required wavelengths, greatly simplifying laser beam production in a compact platform. For several ion species, all wavelengths can be produced with low SWaP laser diodes. Moreover, the use of integrated photonics technologies [18, 19] for delivering light to ion arrays can produce near-diffraction-limited beams at each ion’s location, potentially further reducing overall optical power requirements if optical losses in waveguides can be made low.

Optical clocks based on trapped ions have seen rapid development in the past decade, but scientific and technical obstacles remain before reliable clocks achieving the required uncertainty can be flown in space. Here we describe key technologies that can enable such operation, both in terms of the status of the field and the new research and development needed to realize systems which can achieve the fundamental physics goals laid out above.

*Ion trap arrays* — While ion clocks naturally have very high accuracy compared to other systems due to a high degree of isolation and to well-understood systematic effects, they often suffer from higher absolute uncertainty in a fixed measurement time. This is because ion-based optical frequency standards to date are almost exclusively based on a single trapped ion. A route to faster averaging to a low uncertainty is to use multiple ions, but quadrupole and second-order Doppler shifts can become larger when multiple ions are trapped in a single potential well. Using an array of individually trapped ions is a potential solution to this challenge; more ions are available for simultaneous interrogation, improving the signal-to-noise ratio, and control over systematics can be maintained in each trapping site without significant additional shifts due to the other ions. An additional benefit of a clock built up from an array of individual ions is that subarrays may be used for staggered interrogation to eliminate the Dick effect [20] caused by finite clock dead time; to perform simultaneous subarray processing to cancel out systematic errors due to e.g. magnetic-field variations [21]; and to extend the spectroscopic probe times beyond the laser coherence time [22].

*Integrated electronics, photonics, and detectors* — The table-size optical systems used for delivery of the many wavelengths required for clock ion control and state detection pose one obstacle to the miniaturization of high-performance optical clocks. These optical systems can also be subject to vibrations that degrade ion coherence and thus limit clock performance. Recently, several proof-of-principle demonstrations highlight the possibility of integrating optical control and detection systems into a microfabricated surface-electrode ion trap, which could drastically reduce the system overhead required for light delivery. Low-loss photonics platforms have been developed for multiple ion species of interest for optical clocks [18, 19, 23]. Similarly, recent experimental results have shown that free-space photon collection systems for ion detection may be replaced by high-efficiency on-chip detectors [24, 25]. Further development of these technologies may allow for ion traps which do not

require any free-space optical components for light delivery or collection, greatly simplifying miniaturization. The focus should be on technology development that allows for combining all of these elements in a way that is compatible with high-performance clock operation.

Along with integrated photonic elements, integrating control electronics into an ion-trap chip substrate can reduce the size and complexity of control hardware required to operate the clock. Initial experiments have demonstrated control of ion-trap electrode voltages with integrated digital-to-analog converters (DACs) [26]. Several other operations, such as readout circuits for integrated detectors, may also be integrated into the chip. Chip-integrated electronics must be designed to minimize voltage noise and power required, and must mitigate voltage drifts caused by transistor leakage. All electronics need to be radiation tolerant and designed to mitigate Single Event Effects (SEE) from incident radiation.

*Chip-based lasers and frequency combs* — High-performance portable optical clocks require compact and vibration-tolerant clock lasers with linewidths below 100 Hz for ion interrogation. Multiple pathways to achieve the necessary specifications are being investigated. One approach is to miniaturize the ultra-low-expansion (ULE) glass cavities that have traditionally served to stabilize the clock oscillator. Recent work has demonstrated compact optical cavities with sub-liter volumes and with low vibration sensitivity [27, 28], although operation in vacuum is still required. An alternative approach, which may ultimately lead to smaller sizes and improved vibration tolerance, is to use on-chip solutions for the clock laser, such as stimulated-Brillouin-scattering lasers [29] or self-injection locking to an integrated resonator [30]. Locking of a fiber Brillouin laser to a trapped clock ion has been demonstrated [31], but translating this performance to a chip-based laser has yet to be achieved.

For applications such as space-based VLBI astronomy, an octave-spanning frequency comb is required to translate the clock oscillator’s stability from the optical regime to the microwave domain—at frequencies from hundreds of MHz to GHz—such that the timing signal can be disseminated and directly read out [32]. Fiber frequency combs at the 10-kg scale have been operated on suborbital sounding rocket flights [33], but recent developments towards fully integrated on-chip combs [34, 35] may lead to significantly smaller, lower-power devices.

*Compact vacuum hardware* — Compact, robust ion trap packaging is important for existing and future applications of quantum-enabled technology and fundamental research. Currently, laboratories construct one-off vacuum systems that tend to be large and are unsuitable for deployed environments such as space flight. A non-trivial effort will have to be made to improve the robustness of the atomic clock vacuum hardware including vacuum performance improvements to enable long ion trapping lifetimes, new feedback mechanisms for active control of the clock module temperature in the space environment, and upgrades for compatibility with an integrated photonics platform.

*Autonomous operation* — Harsh and remote environments result in a variety of challenges for atomic clock soft- and hardware including SEE, broadened data point distributions, and environmentally induced frequency drifts. Both the clock and the electronics control system will be required to withstand the shock, vibration, and radiation environments of space.

In all cases, the clock must be able to operate independently of human intervention from a cold start. Methods must be adopted to trouble-shoot clock operations and all subsystems autonomously. The laser system must be able to turn itself on and find the desired spectral features of the clock ion unsupervised. Additional clock-shift-mitigation techniques may also be required for autonomous operation, similar to some currently being researched [36].

Figure 1 shows our proposed schedule for this Research Campaign. Development of key

enabling technologies for a 30-kg scale clock will be followed by a laboratory demonstration, space qualification, and a single clock launch in 2032. A successful launch will allow multi-clock networks to follow in short order. Development of compact clock technologies will continue in the second half of the decade to enable future-generation clock networks.

We estimate a total budget of around \$135M for this Research Campaign. Technology development will require around \$10M/year for the first three years to accelerate the core capabilities in the early stages of the program, and an additional \$5M/year for the next five years, totaling \$55M. Construction of the prototype 30-kg laboratory ion clock and an initial space qualification design is expected to cost \$20M over 2 years, with a sounding rocket test costing \$10M. Space qualifications to enable space-deployability is expected to require another \$20M. Space qualifications will include the development of autonomous control, compact laser systems, and space-ready hardware upgrades. The development of deployable sub-system and a successful sounding rocket test will culminate in a zero-gravity performance verification costing \$5M. The campaign will end with construction of a single space-ready clock costing \$5M and a subsequent launch, expected to cost \$20M.

The development of compact optical clocks can have an outsized impact on the pace of new scientific discoveries due to the achievable precision and the possibility of placing constellations of these clocks in Earth and Sun orbits. In particular, orbiting clocks may aid in detection of dark matter candidates, improve bounds on the existence of various exotic beyond-standard-model fields, and revolutionize radio astronomy via enhanced-resolution VLBI. Trapped ions are a very promising technology for such clocks, as they have high intrinsic accuracy and their control systems can likely operate with lower SWaP requirements than competing clock technologies. Moreover, their higher motional frequencies make them more suitable for operation on accelerating platforms. Recent developments in integrated control and vacuum technologies should allow the realization of high-precision space-based sensor networks based on robust, reproducible integrated ion systems. Such a campaign could reach launch readiness within a decade for comparably low cost, providing many useful avenues for new science in the near term, while establishing a formidable distributed frequency-measurement infrastructure for the pursuit of as-yet unforeseen future endeavors.

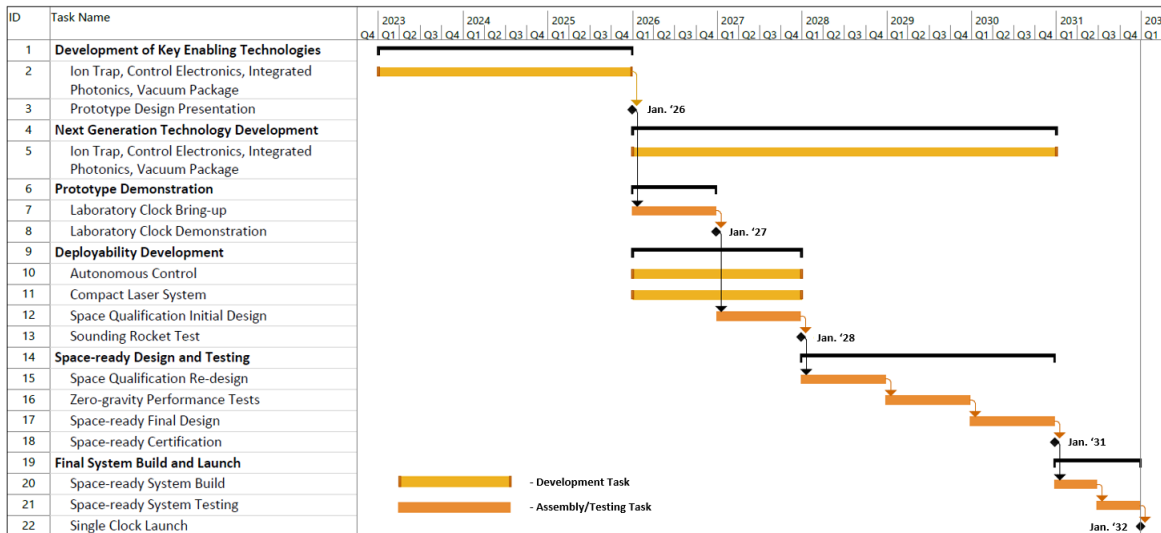


FIG. 1. Performance schedule for the development and launch of the first space optical clock.

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