

## **Topical: Optical Frequency Combs for Space Applications**

A White Paper for the Decadal Survey on Biological and Physical Sciences (BPS) Research in Space 2023-2032

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### **Abstract**

*Many of the science goals in the new Decadal Survey on Biological and Physical Sciences Research in Space will require precision timekeeping and metrology, as was the case in the 2011 report, Recapturing a Future for Space Exploration: Life and Physical Sciences Research for a New Era.” The optical frequency comb is a core technology needed for the next generation of highly precise, stable clocks and time distribution systems. The implementation of these technologies in space presents the opportunity to answer some of the most pressing questions in fundamental physics, and even to discover new physics. And while many advances have been made in frequency comb technology in recent years, self-referenced, fully stabilized combs have yet to be made available in a low power, small form factor, space flight qualified package. As such, the flight qualification of optical frequency combs suitable for SmallSats should be a high priority in the early part of this decade.*

### **Introduction**

The Decadal Survey on Biological and Physical Sciences Research in Space 2023-2032 call for research campaign white papers will see advocacy for many programs that rely on precision timekeeping and metrology capability to achieve their science goals. This was also the case in the last Decadal Survey released in 2011 entitled, “Recapturing a Future for Space Exploration: Life and Physical Sciences Research for a New Era”. In that report under the topic of Fundamental Physical Sciences in Space, Recommended Program Element 2 was “Research That Tests and Expands Understanding of the Fundamental Forces and Symmetries of Nature.” The report went on to recommend atomic clocks in space that “... are useful in the study of time variation of the

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fundamental constants and have many more applications” [1]. Since the last Decadal Survey, many achievements have been made in atomic clock research and development [e.g. 2-4], but the ability to achieve the challenging, still unmet goals set forth in 2011 and those likely to appear in the new survey rely heavily on further developments in precision timekeeping.

Critical to the realization and comparison of state-of-the-art atomic clocks is the optical frequency comb. Optical frequency combs, the Nobel prize-winning technology recognized in 2005 [5,6], have revolutionized time and frequency metrology by enabling the straightforward distribution and comparison of advanced optical clock signals at the  $10^{-18}$  level [7], two orders of magnitude better than the cesium fountain clock technology that is the basis of the *Système International* definition of the second. Thus, they are now central to a new generation of optical clocks, as well as allowing radically new capabilities in communication, navigation, spectroscopy, and advancement of fundamental science.

An Optical Frequency Comb (OFC) is an optical spectrum consisting of an array of modes with perfectly uniform spacing. If spectrally broadened to encompass an octave of bandwidth, then the comb can be “self-referenced”, endowing it with absolute frequency stability at and below the Hertz level. It is accordingly a very precise spectroscopic tool for measuring different frequencies of light - a “spectral ruler”. OFCs are also sometimes referred to as optical clockworks because they can relate an optical frequency standard to an electronic one, enabling signal processing with fast electronics, yet with the precision afforded by optical frequencies.

Optical frequency combs are now being supplied by an increasing number of commercial sources for ground-based applications. However, although there have been three sounding rocket flights of OFCs made by the German company, Menlo Systems [8], this technology has yet to be made available as a space-based tool. A prior effort to fly an OFC-based optical clock in the Optical Rubidium Atomic Frequency Standard (ORAFS) payload of the Airforce’s NTS-3 [9] satellite was abandoned due to inability to meet the size, weight, and power (SWaP) requirements of that mission. Yet a long-duration (1 year) flight of a mode-locked laser by South Korea in 2013 [10] demonstrated the feasibility of the core comb generating element of a flight system. Furthermore, recent advances in nonlinear spectral broadening techniques [11] have significantly reduced the optical power required to generate octave-spanning frequency combs [12]. However, a fully stabilized, low SWaP optical frequency comb *subsystem* that includes not only the comb, but also the locking electronics, detectors, and pump lasers, has yet to be configured for and operated in sustained orbital spaceflight.

Flying an optical frequency comb by itself does not constitute a complete instrument payload – it is a component. Yet mission proposals that rely on frequency combs as part of their instrument systems are disadvantaged in that there is no flight heritage of the combs at the subsystem level. Thus, what is needed is an orbital flight demonstration of a low SWaP frequency comb that validates its functionality, performance, and reliability without compounded science and technology requirements, and yet returns compelling data.

### ***Science Cases***

Frequency comb based clocks form the backbone for meeting the objectives of the Fundamental physics with Optical Clock Orbiting in Space (FOCOS) mission concept, which targets performing high-resolution tests of fundamental physics with  $10^{-18}$  accuracy optical clocks in space to measure red-shift and local position invariance of general relativity with an improvement by  $\sim 3$  orders of magnitude, search for time variations in the fine structure constant, and search for ultra-light ( $<1$  eV) dark matter candidate particles [13].

Science investigations like these and others dependent on high precision, high stability clock technology were summarized at the 2015 and 2016 Keck Institute for Space Studies workshops on Optical Frequency Combs for Space Applications [14]. Some of the science cases relevant to the Decadal Survey on Biological and Physical Sciences identified at the workshops included the use of comb-based clocks for relativistic geodesy, gravitational wave detection, Dark Matter experiments, opportunities to search for violations of general relativity, the standard model, and the Einstein equivalence principle, and to provide the potential to discover new physics. Workshop participants envisioned a frequency comb-based Space-Time Observatory designed around a distributed network of high accuracy atomic clocks, highly stable timing links to GNSS constellations, and the ability to establish a timing link to any GNSS satellite at any given moment.

Here, we excerpt the salient findings from the workshop, and put them in the context of the three categories in the Decadal Survey white paper solicitation:

*Part 1: Science that can or must be done in space, with anticipated value to human exploration*

As human exploration of the solar system ventures out beyond Earth orbital and cis-lunar space to Mars, high accuracy clocks will be a central part of future advanced communication and navigation systems; frequency combs would provide the means to seamlessly transfer the exquisite performance of optical clocks across the microwave, millimeter wave or terahertz domains in an environment well beyond the reach of our GPS constellation. Such technology is enabling, as the “7 minutes of terror” famously used to describe the time lag in communication between Earth and Mars during the entry, descent, and landing phase of robotic missions to Mars are far less esoteric with human voyagers. Autonomous operations by crewed vehicles demand stable on-board clocks.

*Part 2: Science that can be done in space, with anticipated value to humans on Earth*

The space environment provides a unique opportunity for the study of fundamental physics with distinct advantages over ground-based laboratories. Microgravity, long baselines, and the absence of seismic and environmental noise [1] enable science investigations that will further human understanding of our universe.

While ground-based optical atomic clocks could provide benefit through the existing GNSS architecture if optical upgrades are made, the atmosphere provides significant challenges. Turbulence will challenge time transfer links from ground to space and changes in the index of refraction will degrade the absolute ranging knowledge. This limits the full capability provided by a space-based implementation of high precision optical clocks.

A Worldwide Time Standard for Fundamental Physics Studies: At present, most state-of-the-art optical clocks are scattered across the northern hemisphere in the United States, Europe and Japan, making international time comparisons between them currently impossible. However, a link between these trans-continental optical clocks would enable a global measurement of variations of fundamental constants which could provide insight into fundamental physics, Dark Matter and astrophysics which require clocks to be separated at large distance scales to resolve the predicted effects. As the fractional uncertainty of these optical clocks is pushing through the  $10^{-18}$  level, local variations in the Earth’s gravitational potential at the centimeter level and below will limit the accuracy of ground based optical clocks. To overcome these limitations, optical clocks will need to be moved into space where temporal variations of Earth’s gravitational potential are reduced to provide a reference timescale for optical clocks on the ground.

*Part 3: Science that can be done in space, because the reduced gravity environment enables cleaner analysis of fundamental research questions*

Because high performance clocks are affected by local gravity, it will be necessary that such clocks become space based. Space based optical clocks will offer opportunities to search for violations of general relativity, the standard model, and the Einstein equivalence principle, and have the potential to discover new physics.

Geodesy: High accuracy clocks are required for relativistic geodesy, where clocks connected by frequency comb-based time transfer would be used to measure gravitational potential. In these types of measurements, comparison of terrestrial clocks at different potentials via a space-borne clock or satellite transponder would enable mapping of the geoid and advance understanding of geophysical dynamics that shape our Earth.

Gravitational Waves: While groundbreaking discoveries continue to emerge from ground-based gravitational wave observatories [15], gravitational waves at very low frequency, with wavelengths larger than Earth, will not be detectable with existing facilities. For a window into this realm, space-based gravitational wave detection is necessary to enable the very long baselines required.

The Laser Interferometer Space Array (LISA) mission is currently in line as a European Space Agency-led endeavor with the goal of formation flying a three-spacecraft laser interferometer to continuously monitor gravitational wave activity by coherently measuring the stretching and squeezing of space-time [16].

The LISA spacecraft ranging system must eliminate the effects of laser frequency noise, which would otherwise couple to the science signal through the sizable armlength difference. Tinto and Yu [17] have shown that using self-referenced optical frequency combs, it is possible to generate a heterodyne microwave signal that is coherently referenced to the onboard laser such that the microwave noise can be canceled directly. This approach avoids the use of modulated laser beams as well as the need for additional ultrastable oscillator clocks (USOs).

An alternative to the LISA mission architecture has been proposed by Loeb and Maoz [18] who suggest using an array of atomic clocks distributed along the Earth's orbit around the Sun to detect the time dilation effect of mHz gravitational waves. Here again, OFCs offer a technology path forward.

Dark Matter: The theory of Dark Matter arises from our failure to explain anomalous behavior of large astrophysical systems, with sizes ranging from galactic to cosmological scales, assuming that there is no deviation from the known laws of gravitation and the theory of general relativity. As such, with current models predicting that Dark Matter – which does not interact with electromagnetic radiation but does interact gravitationally – constitutes 84.5% of all mass in the universe [19], our technological capability to help elucidate the nature of this enigmatic matter is of great importance; optical clocks employing frequency combs may provide one tool for probing the nature of Dark Matter.

Derevianko and Pospelov [20] have hypothesized that the precision clocks on a GPS-like network of spacecraft could be affected by 'topological defect dark matter (TDM)' interacting with our solar system. The time scale over which the clocks exhibit a change could provide a clue to the extent and nature of a TDM. Increasing the precision of the clocks on GNSS spacecraft by ~3

orders of magnitude could correspondingly increase the sensitivity to small deviations resulting from dark matter. Optical clocks with  $10^{-18}$  stability could meet this requirement.

### ***Conclusion***

Pursuing science goals that require revolutionary capability in time and frequency metrology without having demonstrated a flight qualified, low SWaP OFC is putting the proverbial cart before the horse. Flight qualification of optical frequency combs is a critical milestone that must be achieved to enable the recommended high precision optical clock science applications. Placing the flight qualification of OFCs as a high priority in the next Decadal Survey will ultimately enable the science community to procure the tools needed to achieve GPS-like satellite timekeeping in a small form factor and high precision two-way time and frequency transfer, explore relativistic geodesy, gravitational waves, and Dark Matter, search for violations of general relativity, the standard model, and the Einstein equivalence principle, and to provide the potential to discover new physics.

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