# Topical: Testing General Relativity and Measuring Geopotential Beyond the State-of-the-Art with Optical Clocks

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Abstract:

*General relativity prescribes that clocks in different gravitational reference frames tick at different rates, i.e. the gravitational redshift. In recent years, the performance of optical clocks, and optical time transfer techniques for linking clocks, have advanced to an exciting level [1,4]. In tandem with the ability to operate these systems outside the laboratory [2,3], they can now be used to carry out the most stringent tests to-date of the gravitational redshift, and in so doing search for new physics as predicted by unification models. Furthermore, through the redshift, they can measure differences in the gravitational potential at discrete locations at a level beyond state-of-the-art geodetic techniques. Here we will carry out beyond-state-of-the-art redshift tests and relativistic geodesy using a portable optical lattice clock and comb-based optical two-way time-frequency transfer [4]. While these terrestrial measurements are deeply valuable in their own right, they will also serve as a critical R&D precursor to a more precise space-based optical clock redshift measurement, like the FOCOS mission [5].*

Optical lattice clocks have demonstrated uncertainty and reproducibility at the $1\text{x}10^{-18}$ fractional frequency level, corresponding a gravitational redshift of 1 cm elevation change on Earth's surface. What's more, their stability supports reaching this level of precision in $10^{4}$ seconds or less, and they have reached absolute levels of stability of $4\text{x}10^{-19}$ [1]. Indeed, it is anticipated that these systems will offer $1\text{x}10^{-19}$ accuracy levels or beyond in the coming future, enabling mm level geodetic measurement capability.

In order to leverage this measurement power for new tests of the gravitational redshift, two or more lattice clocks must be operated in disparate locations and geopotential, with a high precision link connecting them. At the National Institute of Standards and Technology, we have been developing a portable optical lattice clock that targets an accuracy in the low $10^{-18}$ range, at the level of state-of-the-art laboratory standards. This system will soon be operational, and after being vetted with a combination of NIST-in-house optical clock measurements and operation at offsite facilities, it will be ready for future deployment in the field. The portable lattice clock system employs ultracold ytterbium that, because of atomic structure considerations, affords arguably the simplest lattice clock operation, while also delivering state-of-the-art performance. For example, ytterbium lattice clocks typically employ fewer laser systems, many of which have already been space-qualified as part of the ESA Space Optical Clock program [6].

We have also developed a coherent two-way time and frequency transfer system that utilizes the exchange of pulses from frequency combs, which are self-referenced to the local optical clock [4]. This system has already been deployed in field measurements using link baselines of tens of kms or more. Even with turbulence, these single-mode free-space links have proven highly reciprocal and Allan deviations to below $10^{-18}$ with femtosecond Time Deviations have been demonstrated over long, strongly turbulent links on the ground.

We have identified two high-altitude locations of interest, both of which would afford operation of the portable Yb clock and comb-based time transfer terminal linking back to laboratory clocks at NIST in Boulder, Colorado. One location is the summit of Pikes Peak (Colorado Springs, Colorado) and the other the summit of Mt. Evans (Clear Creek County, Colorado). Both offer road access to (or very nearly to) the summit, as well as line of sight to the plains of Colorado, where optical time transfer links back to NIST can be established. Both have the distinction of being a ‘Colorado 14er’, indicating that the summit exceeds 14,000 feet in elevation above sea level. With NIST in Boulder sitting near 5,300 feet above sea level, a differential elevation of more than 2.6 km is realized. This corresponds to a gravitational redshift of nearly $3x10^{-13}$ fractional frequency. The lattice clocks could therefore measure the gravitational redshift near the 10 ppm (parts per million) level.

To put this in perspective, the most accurate redshift measurement to date is based on Galileo satellites in an eccentric orbit, achieving an accuracy of 25-30 ppm [7]. On the other hand, the best terrestrial-based redshift measurement was recently realized using a pair of lattice clocks in the Tokyo Skytree Tower, achieving an accuracy of 90 ppm [3]. Terrestrial and space-based redshift measurements naturally complement each other, as a test of local position invariance. The measurement proposed here would serve as a pathfinder effort towards a more precise GR measurement utilizing a lattice clock in orbit. In this case, redshift tests could approach the ppb level [5].

In order to compare the measured gravitational redshift with the GR prediction, the geopotential difference between the high altitude summit and NIST in Boulder must be known. A team from the National Geodetic Survey will carry out GPS-based position and local gravimetry measurements. In tandem with high accuracy geodetic models for the Colorado mountain region, this will facilitate determination of the geopotential difference at the level of 5 cm equivalent elevation. While this could limit the redshift test closer to the 20 ppm level, it will mark an important milestone: using clocks for geodetic measurements beyond what can be achieved with state-of-the-art conventional techniques. While this capability has been anticipated for decades, here we would achieve this milestone for the first time, benefiting from the combination of high-accuracy optical clocks and optical time transfer link, and heralding in the era of relativistic geodesy on Earth.

Benefiting from a second portable Yb clock under development, clock-based geodesy could further be deployed in other locations of geodetic interest. Over long clock baselines, tidal variations could also be studied. Operation of the optical clock and time transfer system at remote locations, like the high altitude summit, will provide a natural testing ground for these technologies, accelerating their maturation and technology readiness for subsequent space-based missions and deployment. The clock systems could also be easily deployed at VLBI stations for exploring enhanced VLBI capabilities.

In parallel with the GR measurements outlined above, we aim to simplify the experimental apparatus, reducing its size, weight, and power (SWaP) towards future space mission requirements. For the portable Yb lattice clock, significant SWaP reductions can be realized through custom electronics and by employing miniaturized wavelength-stabilized lasers. We currently use one such compact laser in the existing apparatus, and with additional efforts, we see a path for implementing these at all required laser wavelengths. Furthermore, we have recently demonstrated techniques that reduce the required number of lasers to four, without any clock performance degradation.

SWaP reductions in the atomic physics package can be realized by pivoting from the current implementation of a six beam magneto-optical trap, to a one-beam design based on 2-D planar gratings [8]. Grating-MOTs have now been realized in rubidium, lithium, and strontium, and we have also used them in laser cooling of ytterbium. To be fully useful, our efforts will focus on implementing a two-color grating-MOT, accommodating both laser cooling transitions required for lattice clock operation. Together with miniaturized atom sources and vacuum pumping, we anticipate complete atomic physics packages that occupy a few liters, while still supporting control of systematic effects at the $10^{-18}$ fractional frequency level or beyond. Benefiting from these SWaP enhancements, we can straightforwardly merge two compact atomic physics packages in a zero-dead-time clock configuration. As previously demonstrated in the laboratory, this will accommodate improved clock stability, while also relaxing the performance requirements of the cavity-stabilized optical local oscillator [9]. This architecture can support frequency stability $<1\text{x}10^{-16}$/sqrt[tau] (for averaging time, tau) for the portable clock system.

We anticipate that all the efforts summarized here could be carried out over a duration of three to five years.

## References

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