Ultra-stable light sources for optical atomic clocks in space

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Time and frequency are the quantities that humans can measure with the greatest accuracy and precision. This makes time and frequency measurements key to many areas of fundamental science, engineering, and technology. Examples include positioning and navigation, geodesy, synchronization across spatially distributed networks, etc.

Key to the technological advantages of high accuracy clocks is their stability; i.e., their ability to keep the same frequency over time. The stability of clocks has improved following an exponential pattern over the last 60 years with clock stability improving by approximately a factor of ten every decade. However, during the last decade a new technology has emerged that leads to clocks improving at an even faster pace: optical atomic clocks. These clocks, enabled by octave-spanning laser frequency combs, use ultra-narrow atomic transitions with optical frequencies as their frequency standard. Optical atomic clocks are now the most stable clocks with clocks in several laboratories approaching a total clock stability of 1 part in $10^{18}$ [1].

Space borne clocks with such a high level of stability enable new applications relevant to the National Reconnaissance Organization. For example, satellites equipped with such clocks could be used to detect underground structures like tunnels, bunkers, or caves by means of measuring variations in the earth’s gravitational potential. An advantage of this approach is that it is impossible to shield the gravitational potential and hence it is very difficult to defeat this detection mechanism. Another avenue opened up by optical atomic clocks in space are quantum networks of clocks [2]. A satellite based quantum network of clocks would yield real time access to a globally synchronized clock. By exploiting quantum measurement protocols it is possible to optimally use all resources in the network. The precision of the clock network would be limited only by fundamental quantum mechanical effects and in particular it would surpass classical stability limits by a significant margin. Furthermore, the network could be made secure against sabotage and eavesdropping by means of quantum encryption protocols.

One of key technological challenges with optical atomic clocks in space is phase noise in the local oscillator. This phase noise is caused by thermal vibrations in the mirror substrates of the reference cavities used for stabilizing the laser that serves as the local oscillator. These reference cavities have been refined through decades of optical engineering and further enhancements are very difficult and costly. Furthermore, reference cavities are difficult to deploy in non-laboratory environments. A design without a reference cavity would be much easier to put on a satellite or aircraft.

We have recently proposed a disruptive approach that addresses these issues [3]. The basic idea is to use the ultra-narrow atomic transition upon which an optical atomic clock is based in an active, laser-like light source. This is rather similar to how hydrogen masers work except that hydrogen masers operate in the microwave domain. With currently available experimental technology laser linewidths in the milli Hertz
range have been predicted corresponding to a $Q$-factor of the oscillator in the $10^{18}$ range. This corresponds to an improvement by about an order of magnitude over the state-of-the-art. The fundamental limits of this new approach are orders of magnitude beyond that.

The basic working principles of this ultra-stable light source have been explored extensively theoretically [3, 4, 5]. Proof of principle experiments have demonstrated that these theoretical ideas are sound [6]. Several experimental research groups are now ramping up efforts to use this idea for the construction of optical atomic clocks.

Detailed quantitative simulations will be invaluable in the transition of this laser technology from proof of principle experiments to actual clock technology. For example we need accurate calculations of the atomic level shifts due to the various optical fields present in the ultra-stable laser proposal. So far most theoretical models have been limited to simple few-level models with rough estimates for multi-level effects. We need to incorporate spatial inhomogeneities of the pumping lasers and the laser mode. Modeling will help with optimizing the design of the laser cavity and field geometry. Another major area where simulations will be helpful is in mitigating atom losses.

We are uniquely qualified to carry out this simulation and modeling work. We made the initial theoretical proposal underlying the ultra-stable laser and we have expanded on that with several key theoretical contributions. We have collaborated with several experimental researchers and we were involved in the first successful experimental demonstration of the feasibility of this light source. At Tech-X, this expertise in atomic physics, laser physics, and quantum optics is complimented by expertise in computational methods, scientific computing, and simulation development.

Of course, advanced simulations require careful validation and experimental partners to translate the innovations into working hardware. Close collaboration with Prof. Jun Ye, Prof. Murray Holland, and Prof. James K. Thompson (all three at JILA, NIST, and University of Colorado) and Andrew Ludlow (NIST, Boulder) would be done. These researchers are at the forefront of optical atomic clock development, frequency standards, and precision metrology, in addition to being co-located in Boulder.

The development of ultra-stable lasers would provide a disruptive technology by enabling optical atomic clocks in space. These clocks, when combined into quantum networks, could be sufficiently powerful to detect man-made underground structures such as tunnels and bunkers. Furthermore, the network could be made resilient against eavesdropping and sabotage using quantum encryption technology.

References


