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Feasibility of Optical Atomic Clocks implementing on Global Navigation Satellite System (GNSS) in the Near Future

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Abstract. This paper evaluates the feasibility and advantages of implementing optical atomic clocks in Global Navigation Satellite System (GNSS). Traditional GNSS relies on atomic clocks that works on microwave frequencies, which, while reliable, have limitations in precision and stability. Optical atomic clocks, operating at higher frequencies and narrower linewidths, promise significantly enhanced precision and stability due to their utilization of highly stable lasers, atomic references, and optical cavities. These improvements could address current shortcomings in GNSS accuracy and reliability. The operation principles of optical atomic clocks are explored, detailing the mechanisms that afford them superior timekeeping capabilities. Additionally, the paper discusses the challenges of integrating these clocks into GNSS, including the need for environmental resilience and compactness, and outlines technological advancements that might overcome these obstacles. The findings suggest that optical atomic clocks could substantially enhance the performance of GNSS, paving the way for more precise global navigation and timing solutions.

Keywords: Atomic Clocks; Optical Atomic Clocks; Single-ion Optical Atomic Clock; Global Navigation Satellite System.

1. Introduction

Global Navigation Satellite Systems generally rely on highly precise atomic clocks to deliver accurate position, navigation, and timing (PNT) services. These clocks, mounted on satellites, generate precise time signals that are broadcast to receivers on Earth. The travel time of these signals is used to calculate distances, allowing for the triangulation of the receiver's exact location.

The basic operation of an atomic clock involves three main components: an oscillator, an atomic reference, and a feedback control system. The oscillator provides an initial frequency signal, which is used to probe the atomic reference—typically atoms like cesium-133 or rubidium-87 in a controlled environment. These atoms undergo a transition between energy states when exposed to radiation at a frequency matching their hyperfine transition. The feedback control system continuously adjusts the oscillator's frequency to match this atomic resonance, ensuring high stability and precision.

The precision of atomic clocks is crucial for Global Navigation Satellite System (GNSS) functionality. Even minor inaccuracies can lead to significant errors in positioning, impacting numerous applications from navigation to scientific research. Current GNSS satellites utilize microwave-based atomic clocks, such as cesium and rubidium clocks, which have reliably served for decades. However, the next generation of GNSS aims to achieve even higher accuracy by incorporating optical atomic clocks [1].

Optical atomic clocks operate at higher frequencies, offering significantly improved precision and stability compared to microwave clocks. These clocks use light frequencies to measure atomic vibrations, providing finer resolution and greater accuracy. The improved stability of optical clocks reduces timing errors to mere millimeters, dramatically enhancing GNSS accuracy for various applications [2].

2. Current Atomic Clocks on GNS

To comprehend the potential enhancements optical atomic clocks might bring to GNSS accuracy, it's crucial to compare them with the atomic clocks currently employed in major Global Navigation Satellite Systems. The US Global Positioning System (GPS) and Russia's GLONASS mainly use Cesium and Rubidium atomic clocks. Meanwhile, the European Union’s Galileo and China’s BeiDou systems also incorporate Passive Hydrogen Maser (PHM) clocks [2].

Cesium Beam Clocks and Rubidium Atomic Clocks share similar operational principles where atomic transitions are induced by microwave radiation. While these systems have provided reliable timekeeping and feature inherent long-term stability, they are susceptible to environmental variations like magnetic field asymmetries and gravitational effects that can induce frequency instability [3]. In particular, Rubidium clocks, despite their lower weight and power consumption, exhibit frequency instabilities of about 10^{-12} under conditions experienced by navigation satellites [4].

PHM clocks, used by some systems, harness natural microwave emissions from hyperfine transitions of hydrogen atoms. These clocks provide stable outputs in the short to intermediate term but are vulnerable to thermal, wall noise, and internal molecular collisions that can shift frequencies over longer periods [5].

These characteristics highlight the necessity for optical atomic clocks in GNSS. Optical clocks operate at higher frequencies, offering improved precision and stability. They are less affected by external environmental factors and provide advantages in compactness and energy efficiency. This section leads into the need to explore how performance is measured in atomic clocks to fully grasp the superiority of optical technology over traditional microwave-based clocks.

3. Measurement of performance of Atomic Clocks: Allan Variance and Deviation

One of the most common ways to quantify the performance of atomic clocks is Allan Variance, $\sigma_y(\tau)^2$. It is a statistical measure used to evaluate the stability and performance of precision oscillators and clocks.

Actually, it is Allan Deviation $\sigma_y(\tau)$, the square root of Allan Variance, which provides a clearer understanding of frequency stability because Allan Deviation can differentiate different frequency noise exhibited in atomic clocks in different time scales.

The Allan deviation is approximated as the atomic hyperfine transition interrogation

$$\sigma_y(\tau) \approx \frac{\alpha\,\Delta\nu}{\nu_0 \times SNR}\sqrt{\frac{1}{\tau}} \tag{1}$$

Here, ν_0 is the center frequency, $\Delta\nu$ is a measure of linewidth, particularly the width at half maximum, α is a constant that is determined by the interrogation technique of an atomic clock, and SNR is detection signal-to-noise ratio. This formula provides detailer inspection on how to lower the noise frequency in an atomic clock. First, increasing the center frequency ν_0, and decreasing width at half maximum $\Delta\nu$, which is inversely proportional to the interrogation time. Therefore, longer interrogation time will make the atomic clock more stable. Also, improving SNR by isolating atoms from its environment that will affect atomic hyperfine state transitions [1, 3]. Therefore, these qualities largely affect the stability and precision of an atomic clocks.

The optical atomic clock is coming up with the idea of harnessing higher center frequency ν_0 and usually transitions at this range have narrower linewidths [6]. However, their integration into Global Navigation Satellite Systems (GNSS) presents challenges. The subsequent section explores the issues, focusing on the need for frequency stability and resilience against environmental factors in space, alongside compliance with the stringent constraints of satellite payloads. Then, with the working principles of Optical Atomic Clocks introduced, their advantages will also be discussed.

4. Optical Atomic Clocks for GNSS

4.1. Challenges for Atomic Clocks to be implemented on GNSS

4.1.1. Long- and Short-Term Frequency Stability during Movements: Low Allan Deviation.

Optical atomic clocks must demonstrate exceptionally high frequency stability during movements to be effectively used in GNSS. This stability is crucial for maintaining a consistent and accurate frequency over time, which directly impacts the precision of timing and positioning data. The frequency stability of optical atomic clocks is typically quantified by a low Allan deviation over various timescales, ensuring the clock's frequency remains constant and accurate over extended periods. This high degree of stability is essential for the precise timing needed in GNSS, where even minor deviations can lead to significant errors in positioning [2].

4.1.2. Environmental Resilience.

Atomic clocks, especially those used in space applications such as GNSS, must be highly resilient to environmental factors to maintain their precision and reliability. The space environment presents numerous challenges including temperature fluctuations, radiation exposure, and mechanical stresses from launch and operation.

In space, temperatures can vary dramatically between sunlight and shadow, potentially causing expansion or contraction of materials within the clock [7]. This can affect the alignment of critical components, leading to frequency instability. Effective thermal management systems and materials with low thermal expansion coefficients are essential to mitigate these effects and ensure consistent performance.

High levels of cosmic radiation can degrade the materials and electronic components of atomic clocks, leading to shifts in frequency and reduced lifespan. Radiation-hardened materials and components are crucial to withstand this environment and maintain the clock's long-term stability and accuracy [8].

The vibrations and shocks experienced during launch can cause misalignment or damage to the inner delicate components [9]. Designing robust structures that can absorb and dissipate these mechanical stresses without affecting the clock's performance is essential.

4.1.3. Compactness.

Satellites have strict size, weight, and power (SWAP) constraints due to the high costs and technical challenges associated with launching and operating them in space. Therefore, optical atomic clocks must be miniaturized to fit within the allocated space without compromising their performance. Compact and lightweight designs help maximize the use of available space for other essential satellite components and instruments, thereby enhancing the overall efficiency and functionality of the satellite system [1].

Having outlined the challenges of implementing atomic clocks in GNSS, it is essential to understand the fundamental mechanisms that enable these clocks to meet such demanding specifications. The next section details the operational principles of optical atomic clocks, including the crucial roles of stable lasers, atomic references, and optical cavities in achieving unparalleled timekeeping precision as well as the shortcomings to be addressed.

4.2. Working Principle of Optical Atomic Clocks: Their Advantages and Disadvantages

The fundamental components of an optical atomic clock include a highly stable laser, an atomic reference, and an optical cavity. The laser provides the coherent light necessary to probe the atomic transitions, and the atomic reference is typically a group of cold atoms or ions that undergo specific transitions between energy levels. Finally, the cavity is utilized to further enhance the interaction between the laser light and the atoms, thereby improving the precision of the frequency measurement [10].

The atoms are first cooled using laser cooling techniques, where laser light is tuned slightly below the atomic transition frequency. This causes the atoms to absorb and re-emit photons, gradually reducing their kinetic energy and cooling them to microkelvin temperatures. The cooled atoms are then trapped in an optical lattice or ion trap, where they are held in place by the light field of the laser [9]. Furthermore, the optical atomic clocks frequencies have demonstrated an advantage over the Rubidium, Cesium Atomic clocks, and PHM, that Optical atomic clock ν_0, the center frequency, is in the range of visible range. It is higher than the microwave frequencies used in the current GNSS. Therefore, it demonstrates the potential for optical atomic clocks to outperform current atomic clocks used on GNSS. Also, this range of atomic transition has a very low linewidth $\Delta\nu$ [6].

The ultra-stable laser is then used to interrogate the atomic transitions. The laser frequency is meticulously tuned to match the natural frequency of the atomic transition. When the laser frequency aligns with the transition frequency, the atoms absorb the light and undergo a transition between energy levels. This interaction is detected and used to measure the frequency of the transition. However, the laser systems can consume several hundred kilowatts, so maintaining low power consumption is a significant challenge due to the need for continuous cooling, laser systems, and other components [11].

Next, the feedback control system receives the signal resulting from atomic transitions and uses it to regulate the laser's frequency. It consistently modifies the frequency of the laser to align with the transition frequency and therefore guarantees that the frequency of the laser matches that of the atomic transition, thus sustaining the precision of the clock over extended periods.

The stabilized laser frequency serves as the timekeeping signal and this frequency is counted and used to generate an accurate time signal [6].

Another issue to be addressed is the size of the setup. Despite their superior precision and stability, the complexity of the required components, such as high-stability lasers, extensive cooling systems, and intricate optical cavities. This setup results in a larger and heavier setup compared to traditional atomic clocks, so miniaturizing optical clocks is a necessary effort to implement them on GNSS [11].

In conclusion, Optical atomic clocks might offer superior precision and stability due to their use of highly stable lasers, atomic references, and optical cavities. These clocks operate at higher frequencies in the visible range, providing finer resolution and greater accuracy compared to traditional microwave atomic clocks like rubidium and cesium clocks. Laser cooling techniques cool atoms to microkelvin temperatures, reducing thermal motion and minimizing frequency shifts. Trapping atoms in an optical lattice or ion trap further reduces atomic interactions, enhancing precision and stability. On the other hand, the high-power consumption of the laser systems and cooling mechanisms, which can reach several hundred kilowatts, is a significant challenge. Additionally, the complexity and size of the required components result in larger and heavier setups compared to traditional atomic clocks. This is problematic given the strict size, weight, and power constraints on satellites. Then, it is necessary to inspect the current efforts that tackle these issues

4.3. Possible Techniques to Address issues based on Single-ion Optical Clocks

Though Single-ion atomic clocks have lower short-term fractional frequency stability because of a decreased signal-to-noise ratio, they present a significant advantage in terms of compactness. This type of atomic clocks typically requires less optical power and feature simpler loading mechanisms, making it feasible to fit them into smaller chambers and shows potential for operations in harsher environments like outer-space [12]. At the recent time, advances in essential technologies, such as low-power ultra-stable lasers and spiral cavitird, have inspired more improvements on single-ion optical clocks. Furthermore, some even tries to combine both single ion clocks and lattice clocks to harness both of their strengths.

4.3.1. Single-Frequency Fiber Laser.

An example of the laser is the single-frequency fiber laser used in Yb^+ ion optical clocks. This laser is a Distributed Bragg Reflector (DBR) fiber laser operating at a frequency for precise measurements required in Yb^+ optical clocks. It achieves this by generating a specific narrow-bandwidth light through second-harmonic generation. The laser uses a neodymium (Nd^{3+})-doped phosphate fiber as the gain medium, delivering a linearly polarized output in a single-longitudinal-mode with excellent stability and power.

The DBR configuration is chosen for its straightforward design, compactness, and reliable operation at a single frequency. Unlike Distributed Feedback (DFB) lasers, DBR lasers feature gratings located in passive sections of the fiber core, which enhances their stability and output power while lessening the dependence on extensive temperature control.

Phosphate glass is preferred over silica for doping with neodymium because of its better solubility for the dopant and its reduced quenching of concentration. This glass is particularly advantageous for lasers that operate below 900 nm due to its emission characteristics. It also supports the use of more cost-effective and efficient laser diodes because of its absorption properties, improving the practicality of the system [13].

This advancement is significant for enhancing the performance and reliability of current Yb^+ optical clocks, which could have substantial implications for improving the accuracy and stability of GNSS.

4.3.2. Integrated Spiral Cavity Laser (ISCL).

Integrated Spiral Cavity Laser (ISCL) is another invention potentially applicable for space-based operation in the near future.

The core of the ISCL is a high-quality spiral resonator, which is meticulously designed to fit within a 26 mm × 32 mm footprint, maximizing the optical path length by coiling the waveguide into a spiral. This design choice enables a total path length over six meters within a compact area, which helps to average out thermal fluctuations over a larger distance, thus reducing noise and enhancing frequency stability.

The spiral resonator uses silicon nitride (Si_3N_4) for the waveguide core and silicon dioxide (SiO_2) for the cladding. Silicon nitride is selected for its high refractive index contrast and low propagation losses, making it an ideal material for maintaining high-quality factors (Q-factors) and achieving low linewidths. The SiO_2 cladding minimizes scattering and absorption losses at the waveguide sidewalls, contributing to the overall stability and performance of the laser. The structure also includes a 15 µm thermal oxide layer below the nitride waveguide and a 4 µm tetraethyl orthosilicate (TEOS) oxide layer above, which help manage thermal expansion and refractive index changes, thus improving stability. Furthermore, the resonator is housed in a copper enclosure with thermoelectric cooling to maintain a stable temperature to make the clock more robust.

The ISCL achieves a fractional frequency instability of 7.5×10^{-14} at 1348 nm, translating to a linewidth of 16.7 Hz. This performance is critical for locking the laser to the narrow-linewidth transition of a trapped strontium ion (88-Sr^+), which operates at 674 nm after frequency doubling. The spiral resonator's stability is paramount for maintaining the coherence required for optical clock operation [14].

4.3.3. Optical Clock System Made of an Array of Single-Atom Optical Clock.

Additionally, a system has been developed that integrates the advantages of ion clocks and lattice clocks, combining quantum simulation and neutral atom computing technologies. This system aims to utilize the high precision of ion clocks and the large atom count characteristic of lattice clocks.

The clock system uses an optical tweezer array with about eighty positions, each containing one strontium-88 atom. This array is loaded from a cold atom cloud and ensures single atom occupancy through photo-assisted collisions. The atoms are cooled using the narrow-line Sisyphus cooling technique, achieving an average transverse occupancy number of about 0.66. The atoms are then interrogated on the clock transition, using a repeated imaging method to stabilize the local oscillator, with dead time about one hundred milliseconds between clock interrogation blocks.

The system uses an interleaved self-comparison technique to evaluate system frequency shifts by varying external parameters such as trap depth and wavelength. From these parameters, a magic condition is determined to make the system more robust to fluctuations in trap depth. The system also addresses specific system frequency shifts, indicating high precision potential for space applications.

The system displays a line shape close to the Fourier limit, with a maximum half-width of about 7 Hz. Experimental results align very well with the researchers' soecifically tuned Monte Carlo simulations, indicating that the noise processes are well-understood and predicted at the achieved stability level. Furthermore, the short-term instability of the clock was evaluated, and predictions based on the researchers' Monte Carlo model suggest improved stability with single clock operation [15].

In conclusion, several advanced technologies have been developed to make optical atomic clocks more compact and robust for potential space-based operations, each utilizing distinct approaches to enhance their performance. The trapped-ion optical clocks can be a suitable candidate for optical clocks on GNSS, because this design is more compact, consumes less power through lower optical powers, and has simpler loading schemes, allowing it to fit into smaller vacuum chambers. Several inventions focus on improving the compactness, robustness, and energy economy of single-ion or -atom atomic clocks are also introduced. The single-frequency fiber laser for Yb+ ion optical clocks utilize a distributed Bragg reflector (DBR) configuration and neodymium-doped phosphate fiber to achieve a compact, stable, and high-performance laser source. Meanwhile, the Integrated Spiral Cavity Laser (ISCL) employs a high-quality spiral resonator design with silicon nitride waveguides to maximize optical path length within a small footprint, providing high frequency stability and low noise. Lastly, the optical clock system made of an array of single-atom optical clocks combines the high precision of ion clocks with the high atom number benefits of lattice clocks, using an optical tweezer array for individual atom trapping and a narrow-line Sisyphus cooling scheme for enhanced precision. These technological innovations collectively address the challenges of miniaturization, power efficiency, and environmental resilience, paving the way for the deployment of optical atomic clocks in GNSS and other space-based applications.

5. Conclusion

This paper has examined the feasibility and potential benefits of implementing optical atomic clocks in Global Navigation Satellite Systems (GNSS). Current GNSS relies on cesium, rubidium, and passive hydrogen maser clocks, each with its own strengths and limitations. Optical atomic clocks, utilizing higher frequencies and narrower linewidths, offer superior precision and stability, addressing many of the shortcomings of existing clock technologies.

The operation principles of optical atomic clocks have been explored, highlighting their use of highly stable lasers, atomic references, and optical cavities to achieve unparalleled timekeeping accuracy. Various innovations, such as the single-frequency fiber laser and the Integrated Spiral Cavity Laser (ISCL), demonstrate significant advancements in making these clocks more compact and robust for space applications.

Challenges of integrating optical atomic clocks into GNSS include the need for long- and short-term frequency stability, environmental resilience, and compactness. Addressing these challenges through technological innovations is crucial for the successful deployment of optical atomic clocks in satellite systems.

In summary, optical atomic clocks hold great promise for enhancing the accuracy and reliability of GNSS, paving the way for more precise and robust global navigation and timing solutions.

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