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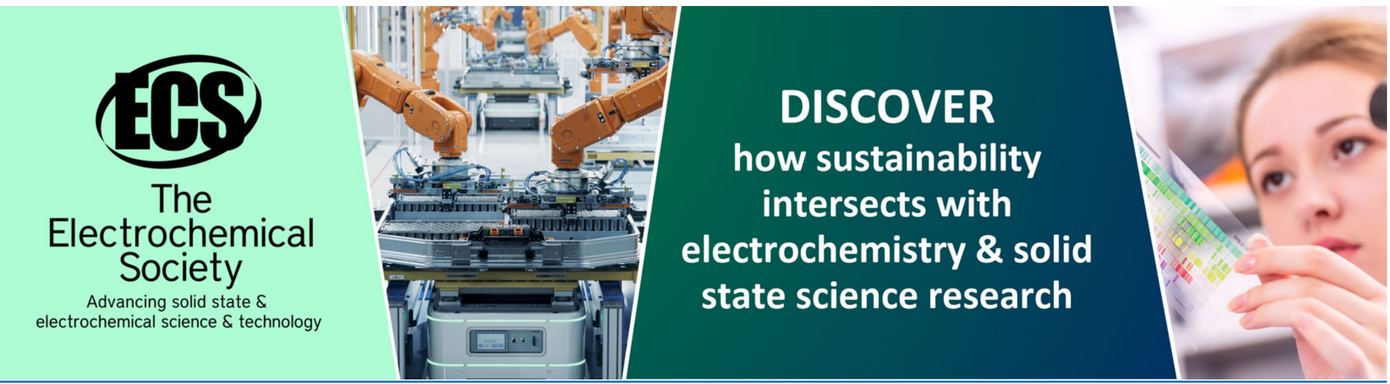

Frequency comparison of lattice clocks toward the redefinition of the second

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Abstract. Strontium is the most popular species for optical lattice clocks. Recent reports of the accuracies from Boulder, U.S. and Tokyo reach 10^{-18} level, which is better than state-of-the-art caesium clocks more than one order of magnitude. While this achievement accelerates the discussion to redefine the second, the agreement of frequencies in separate laboratories is of critical importance. For this context, intercontinental comparison of Sr lattice clocks were demonstrated between Japan and Germany using a satellite-based technique. The frequency difference was consistent with zero with an uncertainty of 1.6×10^{-15}.

1. Introduction

Optical frequency standards are one of major applications of laser spectroscopy. When lasers are invented, it was quite natural to consider making highly stable oscillator in optical region instead of microwave region. There has been tremendous effort for this goal in this half century. It is generally said that laser is coherent radiation. But the coherence time is normally much shorter than 1 second, whereas the stable microwave oscillator seldom cause phase jump. Therefore, laser is much more incoherent when it is compared to microwave. In addition, precision spectroscopy in optical region is affected by photon recoils since momentum of photons is much larger than that of microwave. However, the coherence time of laser radiation is lately extended to more than one second using a highly stable optical cavity [1]. The development of the technique to laser-cool and pin-down ions or neutral atoms has allowed us to eliminate Doppler and recoil shifts. These efforts have finally achieved optical clocks that clearly surpass the state-of-the-art microwave-based clocks in accuracy as well as stability [2-4]. This achievement inspires the community of time and frequency standards to seriously discuss the redefinition of the SI second because current realization of the second does not have the least uncertainty to scale time and frequency. The accuracy of 10^{-18} level, on the other hand, has not been fully trusted at this point in the community since the evaluation is based on the total uncertainties of known systematic shifts. There could be unknown systematic effect which may shift the atomic resonance from laboratory to laboratory. Thus, it is required for the redefinition of the second that the optical reference frequencies in various laboratories were confirmed to be identical.

2. ^{87}Sr lattice clock: the most major optical clock

The necessity to confirm the identical frequencies in separate laboratories is receiving attention since optical lattice clocks based on strontium-87 atoms are now operated in seven laboratories [2-8] with

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systematic uncertainties of 10^{-16} level or below. Furthermore, PTB has accurately evaluated sensitivity of the resonance frequency to black body radiation (BBR), which allowed the total accuracy of clocks to be below 10^{-16} [9]. Furthermore, innovations to manage ambient temperature of strontium atoms have recently occurred. One realized at JILA is to equip highly accurate thermometer inside vacuum chamber which accurately characterizes the BBR of room temperature environment [2]. Another one lately achieved in Katori's group at RIKEN is cryogenic lattice clock, where the atoms were transferred into a small ceyo-cooled cavity of 95 Kelvin for the interrogation, drastically reducing the BBR [3]. These claim the accuracies in 10^{-18} level, which are currently the state-of-the-art of optical clocks.

Figure 1 summarizes the results of absolute frequency measurements of ^{87}Sr clock transition in various laboratories. You may find there is still discrepancy of frequencies in 10^{-15} level, which clearly shows that the SI second is not a good scale any more, and only direct frequency comparison can evaluate the frequency reproducibility of Sr lattice clocks among laboratories. Note that recent frequencies measured at SYRTE (Systèmes de Référence Temps-Espace, Observatoire de Paris) [5] and PTB (Physikalisch-Technische Bundesanstalt, Germany) [6] are in good agreement in 10^{-16} level. This is because both laboratories operate caesium fountain clocks which realized the SI second at the 10^{-16} level. Such accurate SI second is only available in limited number of laboratories. Rather large uncertainties of Japanese clocks are due to the lack of the good realization of the SI second.

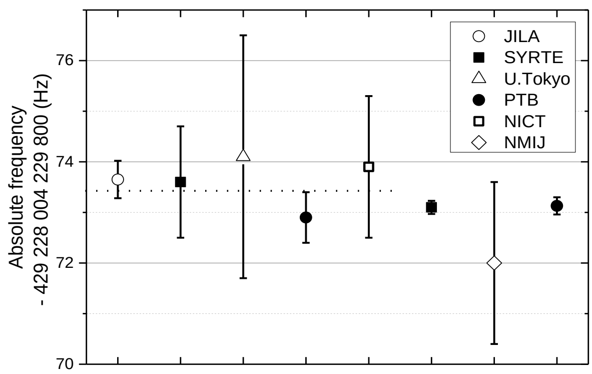

Figure 1. Results of absolute frequency measurements in various laboratories.

3. Two methods of direct comparison: fiber link and satellite link

Direct comparison of optical clocks is straightforward solution to confirm the identical frequency, where we don't express the frequency as numerical number based on the SI second. Thus, fractional frequency difference of two locally available clocks were evaluated in Ref. [1-3], resulting in 10^{-17} level of frequency agreement. For the comparison between physically separated clocks, on the other hand, we need a method to transfer the highly stable frequency to other places. For this purpose, optical fiber is probably the ultimate as the transfer media. For global comparisons, however, satellite-based techniques are the only way at this point since fiber transfer normally extends up to 200km.

3.1 Fiber links

In the case that two clocks are on the same continent and not far separated, an optical fiber link is a strong tool. So far two fiber-based direct comparisons of optical clocks were demonstrated, one is between a Sr clock at JILA and neutral Ca clock at National Institute of Standards and Technology (NIST) with a 4-km-long optical fiber link [11], and the other is between two ^{87}Sr lattice clocks at National Institute of Information and Communications Technology (NICT) and the University of Tokyo (UT) using a 60- km long optical fiber [12]. Optical fiber links are promising at large distances, as demonstrated up to 1840 km [10]. These demonstrations also claim the capability to disseminate standard frequency. However, it is unrealistic that optical fiber network is dedicated only for the delivery of standard frequency. The conventional method of transfer adopted in these work requires dark fiber. In addition, note that 1840km transmission [13] was demonstrated using fiber cables that are calmly buried in the ground. On the other hand, some countries, for instance Japan, hang the optical fiber cables in the air. Such cable suffers considerable vibration noise, which prevents the accurate transfer of reference frequency. Indeed, the NICT-UT comparison [12] often did not work on windy days.

3.2 Satellite –based link

The global positioning system (GPS) is a strong tool of clock synchronization. While modulation code of ~Mbps is utilized for the synchronization of commercial GPS clocks, the use of carrier-phase (GPSCP) improves the accuracy of time transfer for orders of magnitude. However, an averaging time of more than a day is still required to reach the 10^{-16} instability [10]. Another satellite-based technique is two way satellite time and frequency transfer (TWSTFT), which also has the code transfer as well as carrier phase transfer. Using the carrier-phase in TWSTFT might be a quicker route to 10^{-16} instability. Two-way carrier-phase technique (TWCP) was first demonstrated by USNO [14] and characterized for various ranges of the baselines up to 1 000 km [15]. The characterization has been extended to 9 000 km baseline between NICT and PTB [16].

4. NICT-PTB direct comparison using a TWCP technique

NICT and PTB have an ^{87}Sr lattice clock in operation for each. Thus, the two-way carrier phase technique (TWCP) was applied to perform real-time frequency comparison of lattice clocks in intercontinental scale. The experimental scheme is depicted in Fig. 2. The geostationary satellite (AM2) locates at the longitude of 80 degrees east. The elevation angles of the satellite from the earth station at NICT and PTB are 16.0 degree and 3.7 degree, respectively. The transponder is available for approximately 13 hours (from 10:05 to 22:59 in UTC) per a day. The correction due to the dispersion of up-down link was included referring a VTEC map provided by NICT [17] and Royal Observatory of Belgium [18]. Figure 2(b) shows schematic diagram of the comparison. During the measurement campaign, the clock frequencies were measured referring to respective local hydrogen masers (H-masers). The frequency difference of the two H-masers was simultaneously evaluated by the TWCP technique. An Yb^+ clock is also operated in PTB to bridge offline-times of the Sr clock at PTB, and thus reduced the statistical uncertainty of the measurement. We performed the comparison for four days in late June 2013. The direct Sr lattice clock comparison worked for ~70 000 s, extended to 84 000 s by the Yb^+ ion clock. The total measurement time leads to a statistical uncertainty of 1.2×10^{-15}. Systematic uncertainty of the fractional frequency difference is summarized in Table 1. Frequency link is currently the source of the dominant uncertainty. This uncertainty is the experimental result of TWCP-GPSCP comparison reported in [16]. The uncertainty of ionospheric delay could be a dominant source of this uncertainty. Progress of the evaluation of ionospheric effect may reduce systematic as well as statistical uncertainty. Considering the systematic uncertainties, the total uncertainty was determined to be 1.6×10^{-15}, whereas the overall average of the fractional frequency difference was 1.1×10^{-15}, indicating the agreement of clock frequencies.

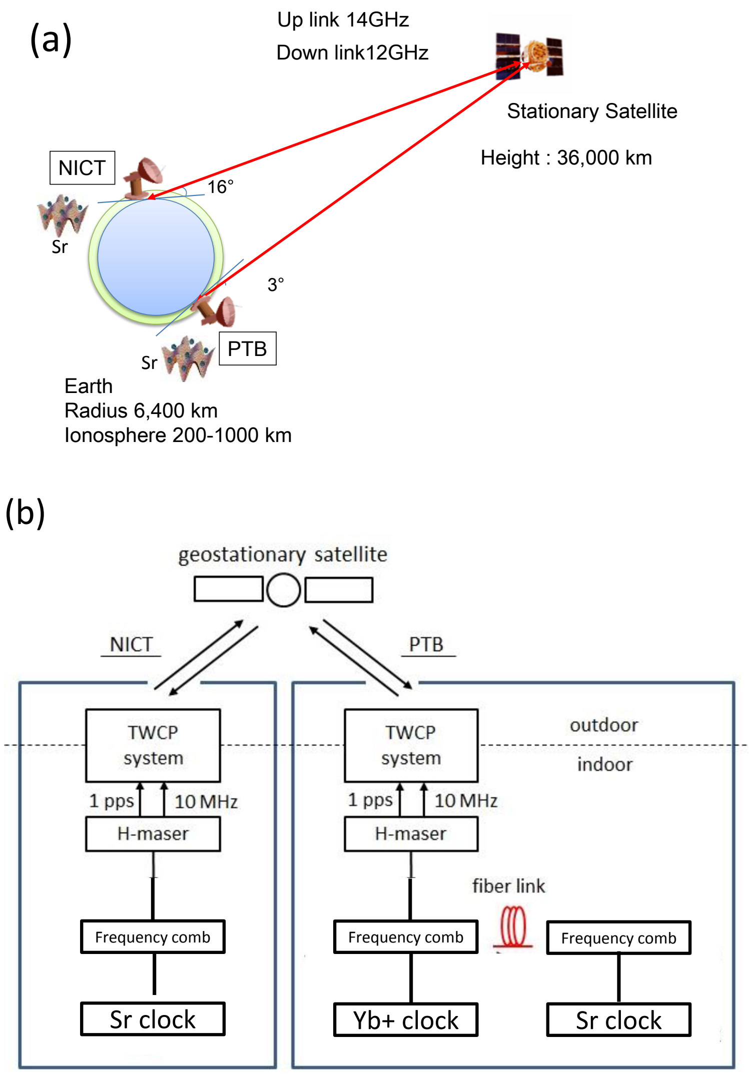

Figure 2. (a) Elevation angle and distance from two earth stations to the satellite (b) Schematic diagram of the experiment

Table 1. Uncertainty budget of the frequency comparison

Contributor	uncertainty ($\times 10^{-16}$)
Statistical	12
Systematics	
TWCP link[a]	10
Sr clock @ PTB[b]	0.4
Sr clock @ NICT	2
Gravitational red shift	1
Total	16

[a] Ref. [16]
[b] Ref. [6]

5. Conclusion

Following the fiber link experiment of two Sr lattice clocks in Tokyo area, the frequency agreement was also confirmed on intercontinental scale between Japan and Germany by using the satellite-based TWCP technique. The frequencies agreed with uncertainty of 1.6×10^{-15}, which is dominated by the uncertainty contribution of the link.

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