Rapid evaluation of time scale using an optical clock

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Abstract. Feasibility of steering a time scale using an optical clock is investigated. Since the high stability of optical frequency standards enables rapid evaluation of the scale interval, the requirement for the continuous operation is mitigated. Numerical simulations with the input of real calibration data by a $^{87}$Sr lattice clock indicated that the calibrations once in two weeks maintain the time scale within 5 ns level using a currently available hydrogen maser at NICT. “Optical” steering of a time scale by the intermittent calibrations frees an optical frequency standard from being dedicated to the steering, enabling other applications using the same apparatus.

1. Introduction
The recent progress of optical clocks is so rapid that some atomic clocks based on optical clock transitions have clearly surpassed microwave clocks in terms of the accuracy and stability. Following the advancement of optical clocks, the community of time and frequency standards has begun seeking unprecedented applications such as sensors for geodetic science. While these are still a long way from practical use, maintaining a time scale using an optical clock might be a reasonable choice. Time scales have been so far maintained by microwave clocks, such as commercially available Cs beam clocks or hydrogen masers (H-masers). Cs fountain frequency standards are referenced to realize the ultimate accuracy of the International Atomic Time (TAI). The fountains have become mature technology these days, and some laboratories almost always operate fountains and adjust their time scale in real time according to the error that fountains detect [1,2]. For laboratories without Cs fountains, on the other hand, it is not easy to begin the development of a Cs fountain from scratch only for the purpose of time scale maintenance. Thus, in the near future, an optical clock might be required to play a role in maintaining a time scale. From this viewpoint, we studied the feasibility of the “optical” steering of time scale. Assuming that the performance of currently available H-maser at NICT remains as demonstrated in the past, our numerical simulation employing real data gathered from a Sr lattice clock has revealed that the operation of optical clocks twice in a month will keep the time scale within the $\pm 5$ ns level.

2. UTC: reference time scale that local time scales synchronize
Universal Coordinated Time (UTC) is a time scale with the same scale interval as the TAI. TAI is based on the average of more than 400 commercial atomic clocks operated in various metrological or astronomical institutes worldwide. The interval obtained by the average of the 400 clocks is adjusted to the SI second by referring to the calibrations provided mainly by caesium fountain standards operated in national metrological institutes. The averaging and adjustment are virtually performed by a
numerical process. There is no real signal of UTC. On the other hand, participating institutes normally maintain their own real time scale as close as possible to UTC. This local realization of the UTC is called UTC(k), where k denotes the name of the institute. Bureau International des Poids et Mesures (BIPM) is in charge of the numerical process of calculating the TAI. The “tick” of the TAI is once in five days since this numerical process is performed for the moments at 0:00 UTC on every five days. BIPM notifies participating institutes of the time difference of UTC and their local realization, UTC(k). The notification is performed in a monthly published report, the so-called Circular T. The institutes steer the scale interval according to this notification. Note that BIPM also publishes rapid UTC (UTCr), where the time differences are reported daily. However, the shorter average of a single day suffers from rather large link uncertainty.

The difficulties of this steering are partly due to the latency of the Circular T. The time-keeping institutes are unable to obtain the time difference UTC − UTC(k) in real time. In other words, for the duration of one month, the scale interval of UTC(k) is basically determined by their local frequency standards. Hence, locally available atomic frequency standards are important for the time scale. Caesium fountain frequency standards were first developed in the 1990s, and now the operation of some standards in advanced laboratories is so stable that an up-time ratio of more than 90% has recently been maintained [1]. Thus, some institutes can maintain accurate scale interval of the time scale in real time [1, 2]. This improvement was clearly witnessed in the record of UTC − UTC(k) in the past ten years, which is shown as figure 1. The reductions of the fluctuation in UTC − UTC(PTB) and UTC − UTC(OP) are found at around MJD 55500 and MJD 56200, respectively, where the two institutes initiated the steering of UTC(k) by referring to real-time evaluation using a reliably operated Cs fountain.

![Figure 1](image_url)

**Figure 1.** (colour online) Time difference of UTC and its various local realization UTC(k).

### 3. Real-time estimation of UTC(k)-UTC using a Sr lattice clock

The detail of the $^{87}$Sr lattice clock at NICT is described in [3]. The configuration of the lattice is a vertically oriented one-dimensional lattice. Thanks to the vacuum chamber made of >20 cm-thick aluminium alloy, rather homogeneous distribution of the temperature was observed over the chamber. The total systematic uncertainty as an optical standard amounts to $8.6 \times 10^{-17}$, which is sufficient to steer time scale. On the other hand, the source oscillator of UTC(NICT) is one of commercial H-masers contained in the NICT maser array. The H-maser frequency is steered with reference to the weighted average of eighteen commercial caesium clocks. The long term stability of this averaged Cs frequency is low $10^{-15}$ level around 30 days. This stability is not sufficient to maintain the $|\text{UTC} − \text{UTC(NICT)}|$ below 10 ns during one month.
Absolute frequency measurements of an optical clock transition are normally performed when one builds an optical frequency standard. Particularly, in the case of $^{87}$Sr lattice clocks, more than ten frequency measurements were already reported. On the basis of these data, we are able to calculate the weighted mean frequency with an uncertainty of less than $1 \times 10^{-15}$. In addition, optical clocks have better short-term stability than microwave standards. Thus, a lattice clock has the ability of the real-time evaluation of the scale interval of UTC(k). We investigated this potential capability using the data of five consecutive days of measurement (MJD 57079-57083), which we obtained for the latest absolute frequency measurement [3].

The uncertainty of the absolute frequency of $^{87}$Sr lattice clock transition has recently been reduced in some laboratories, where the state-of-the-art Cs fountain standards serve as a reference of the SI second. Two measurements [4, 5] have an uncertainty of $< 5 \times 10^{-16}$, and the fractional difference is less than $1 \times 10^{-16}$. Thus, it is reasonable to assume the weighted average of the two measurements as the absolute frequency of the Sr lattice clock transition. Because of the lack of a state-of-the-art Cs fountain, our frequency measurement first leads the frequency of the $^{87}$Sr lattice clock transition with reference to UTC(NICT). Conversely, this measurement allows us to evaluate the frequency of UTC(NICT) on the basis of the Sr lattice clock. We measured frequency for 10000-20000 s per day for five consecutive days. The instability of the 10000-20000 s measurement deviates from high $10^{-16}$ to low $10^{-15}$, depending on which H-maser is used in the maser array. Assuming that the offset of the UTC(NICT) frequency from that of UTC is constant until the following day’s update, it is possible to estimate the gain or loss of UTC(NICT) during the five days.

The result is summarized in figure 2. The data, from which the scale interval of UTC(NICT) is deduced, was originally taken from the latest absolute frequency measurements [3]. By integrating the fractional offset frequency of UTC(NICT), the gain of UTC(NICT) since 0:00 UTC on MJD57079 is estimated as drawn in red, where the slope to the first point is assumed to be same as that between first and second frequencies. Large dots indicate the update of the scale interval by the operation of the optical clock, and red lines are the resultant estimation, indicating the real time estimation of UTC(NICT) – UTC. UTC(NICT) has an instability of $1 \times 10^{-15}$ at one day. There are five estimations in figure 2, which lead to the error of $5^{1/2} \times (10^{15} \times 86400$ s) = 0.19 ns at the end of fifth day. Besides that, the evaluation of the UTC(NICT) frequency has an uncertainty due to the uncertainty of the $^{87}$Sr clock transition frequency ($5 \times 10^{-16}$) as well as the type-A uncertainty of HM4-UTC(NICT) link which was measured to be $2 \times 10^{-16}$ in 10000 s average. In total, we evaluate the uncertainty of the time difference on MJD 57084 to be 0.29 ns.

The validity of the estimation was confirmed by the comparison against two values. One is the UTC(NICT)-UTC(USNO) derived from the GPS P3 all-in-view methods. The data is expressed as small dots in figure 2. One dot is the mean of 15 min. The overall trends fairly agree with the prediction. The other data to be compared is the time difference reported in Circular T. The UTC-UTC(NICT) at 0:00 on MJD 57079 and on 57084 is found in Circular T No. 327. From these two values, we can calculate the change in UTC – UTC(NICT) during these five days, which is shown as blue empty circles in figure 2. The change is 1.9 ns for the five days, whereas the estimation by the Sr lattice clock is 1.7 ns, showing reasonable agreement. Note that the scale unit of the UTC is not identical to the SI second. The mean difference in scale unit of TAI from the SI second for MJD57079-57109 is $2.7 \times 10^{-16}$. Considering the link uncertainty, the uncertainty of UTC-UTC(NICT) is $9.8 \times 10^{-16}$ for five-day average [6]. This frequency uncertainty corresponds to $(9.8 \times 10^{-16} \times 5 \times 86400) = 0.42$ ns of the uncertainty of the variation of the five-day time difference, which is consistent with the 0.2 ns difference.

Figure 2 demonstrates that 10000 s of lattice clock operation each day is sufficient to maintain the time scale within a 1 ns time difference. However, it is not yet practical to dedicate one system of an optical clock to a time scale. The quest for high accuracy is under way in most laboratories, which is not compatible with daily routine operation of the time scale maintenance. This limitation may be resolved by a stable transfer oscillator such as a H-maser. An H-maser with highly predictable
behaviour can be responsible for the down time of optical clocks. To pursue this strategy of intermittent operations of an optical clock, we performed some numerical simulations on the basis of the data of real optical frequency measurements and those of H-masers. The relevant data related to H-masers are available as records of the Japan Standard Time (JST) system.

4. Capability of keeping a time scale using an optical clock and a highly predictable source oscillator

In our recent campaign of absolute frequency measurements [3], measurements based on an H-maser (HM4) were performed in four campaigns which are temporarily separated by 20–30 days. Conversely, this measurement allows us to obtain the scale interval of the HM4 based on the Sr lattice clock. A sample of the evaluation of HM4 frequency by the $^{87}$Sr lattice clock is shown in figure 3. Four campaigns were performed on MJD 57060–57064, 57079–57084, 57108, and 57124–57129. On these days, we obtained the calibration of the HM4 frequency on the assumption that the $^{87}$Sr lattice clock generates an optical frequency of 429 228 004 229 873.11 Hz, which is the weighted average of the results shown in [4, 5]. The calibrations were expressed as four groups of green dots. All points are derived from the calibration of $10^{12}$-$10^{14}$ s. The type-A uncertainty of each point is $<1 \times 10^{-15}$. Whole points may have an offset of $<5 \times 10^{-16}$ due to the error in assuming the $^{87}$Sr clock frequency. Overall points indicate a fairly stable linear frequency drift of HM4. This was also confirmed by the instability against UTC, which is shown as the inset of figure 3. Thus, we can estimate the frequency of HM4 on any instant by interpolating past data by a linear regression. The red thick line indicates such a possible estimation. Using the data taken in the nearest 45 days, the linear drift of the H-maser is estimated, and we interpolate it to estimate the HM4 frequency on that date. Since the data of the first 4 days (MJD 57060-67064) is insufficient to estimate the overall drift rate of the HM4, the red thick line is probably steeper than the real drift rate for the first 30 days. However, the data on MJD 57079, which is a point after 15 days of down time, allows the system to notice that the estimation of the drift rate was higher. Later than that, the estimation of the HM4 frequency becomes fairly good. The blue line is another estimation of HM4 frequency provided by the JST system. JST is a product composed by steering an H-maser frequency in reference to an ensemble time scale of 18 commercial Cs clocks. Since the $^{87}$Sr lattice clock has an accuracy of $<1 \times 10^{-16}$, the discrepancy of green dots and the blue line is predominantly attributed to the Cs ensemble. The maximum discrepancy often amounts to $5 \times 10^{-15}$, which easily causes the time difference of more than 10 ns in 20 days.
The data shown in figure 3 enables the simulation of steering time scale using an optical clock. We assume in the simulation that the HM4 signal is supplied to a phase micro-stepper (PMS), where the frequency error estimated as the red thick line in figure 3 is compensated; thus, the calibrated output of the PMS is steered by an intermittent operation of an optical clock. A simulation by this method is feasible in our environment because the relative time difference of HM4 vs UTC(NICT) is monitored and recorded in the JST system on every second, thus enabling the calculation of the time error of the optically steered time scale against UTC. Note that UTC-UTC(NICT) is only available every five days. We can compare the optical-based time scale to UTC at 0:00 UTC on every five days.

Figure 3. (colour online) Estimation of a H-maser (HM4) frequency by intermittent operations of an optical clock. The inset shows the instability of the HM4 against UTC, where the drift is removed by the fitting of 60 days beforehand.

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Figure 4. (colour online) Simulation of a steering of a time scale using an optical clock (circle). Filled squares are the results reported in Circular T. Note that manual adjustment was made on MJD 57074 for UTC(NICT).
The result of the comparison against UTC is shown in figure 4. The squares are the real record of UTC(NICT) which are found in Circular T. On the other hand, the circles are the simulation result. The vertical bands represent the duration in which the UTC(NICT) is calibrated by the Sr. We did not make a real physical signal, but the method described above allows us to simulate the possible result of generating a time scale. The estimation of the HM4 overall drift rate with reference to the first four days was affected by a sporadic short-term frequency fluctuation, which causes the increase in the time difference during MJD 57060–57080. After the 2nd campaign that began on MJD 57079, the overall drift of the HM4 frequency is well estimated, realizing a stable time difference. While the current system of UTC(NICT), which steers the H-maser frequency referring to the Cs ensemble, causes a maximum deviation of 7 ns from UTC during the 65 days of MJD 57074-57139, the steering using an optical clock calibration suppresses the deviation to 3 ns. This improvement is found in the instability as well. The 5-day instabilities of squares and circles after MJD 57079 are $2.7 \times 10^{-15}$ and $1.3 \times 10^{-15}$, respectively.

5. Summary

In summary, we have investigated the feasibility of steering a time scale using an optical clock. We performed three sets of five (or four)-consecutive-day measurements as well as a one-day measurement of $^{87}$Sr lattice clock frequency with reference to an identical H-maser over two and a half months. Since the JST system always monitors the time difference between the H-maser oscillator and UTC(NICT), we succeeded in estimating the scale interval of UTC(NICT) in real time with this data. Dealing with the $^{87}$Sr clock frequency as a reference, we evaluated the frequency as well as the drift rate of the source oscillator. The estimation agreed well with UTC(NICT) – UTC given by Circular T. Furthermore, the numerical simulation of the steering showed the possibility of steering the time scale using the intermittent operation of an optical clock. We simulated the steering of a time scale, which indicated that the calibration of the H-maser frequency twice a month maintains the time scale in ±5 ns. Since optical clocks are nearly one order of magnitude more stable than microwave frequency standards, the operation of optical clocks in several hours is long enough to evaluate the scale interval of the time scale at the $<10^{-15}$ level. Therefore, intermittent operations of optical clocks can maintain the time scale, allowing an optical frequency standard to be utilized for other applications in extra time. The ability to steer the time scale using an optical clock would allow some laboratories to focus on optical atomic standards. This would be the case particularly for some national metrological institutes, where atomic frequency standards are developed for the first time.

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