Incorporating an Optical Clock Into a Time Scale

Jian Yao, Thomas E. Parker, *Life Fellow, IEEE*, Neil Ashby, and Judah Levine, *Member, IEEE*

***Abstract*— This paper discusses the results of a simulation of a time scale based on continuously operating commercial hydrogen masers and an optical frequency standard that does not operate continuously as a clock. The simulation compares the performance of this time scale with one that is based on the same commercial devices but incorporates a continuously operating cesium fountain instead of the optical standard. The results are independent of the detailed characteristics of the optical frequency standard; the only requirement is that the optical device be much more stable than the masers in the ensemble. We discuss two methods for realizing the results of this simulation in an operational time scale.**

***Index Terms*— Cs fountain, hydrogen maser, Kalman filter, optical clock, time scale.**

I. Introduction

THE Al^+ [1] and the Sr/Yb [2], [3] frequency standards show a stability of better than 1×10^{-16} at an averaging time of 1 h, and even more stable devices are being developed. However, it is challenging to run an optical frequency standard continuously as a clock for any length of time, so that it is difficult to incorporate such a device into a conventional time scale, which is based on time differences. In this paper, we present the results of a simulation of a time scale that can accept a device that provides only occasional frequency data in addition to the more traditional time differences. We also discuss two methods for incorporating this type of data into the time scale that is used to realize UTC(NIST).

Section II presents the details of the simulation. Also, we describe a time scale using the Kalman filter that can realize the combination of devices we have simulated. Sections III and IV present the simulation results of a time scale that incorporates a cesium fountain and an optical clock, respectively. In particular, we show how long and how often an optical frequency standard must be run in order to make the time scale comparable to the Cs-fountain time scale. Both simulated scales are based on free-running continuously operating hydrogen masers whose characteristics are derived from the real masers in the NIST clock ensemble. Some practical issues in an optical-clock time scale are also discussed in Section IV, and possible realizations of an optical-clock time scale are discussed in Section V. Section VI concludes this paper.

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J. Yao and J. Levine are with the Time and Frequency Division, National Institute of Standards and Technology, Boulder, CO 80305 USA, and also with the Department of Physics, University of Colorado, Boulder, CO 80309 USA (e-mail: jian.yao@nist.gov; judah.levine@nist.gov).

T. E. Parker and N. Ashby are with the Time and Frequency Division, National Institute of Standards and Technology, Boulder, CO 80305 USA.

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II. Simulation Procedures

There are three steps in the simulation. First, we simulate a free-running time scale, a Cs fountain, and an optical frequency standard. The time scale algorithm is based on a measurement of the time differences every 720 s, which is the measurement interval that is used in the NIST ensemble. A conventional Kalman filter algorithm is used to estimate the frequency and frequency drift of the free-running time scale by using data from either the optical device or the cesium fountain. The frequency stability of the steered time scale is computed.

A. Clock Simulation

We model the characteristics of a "typical" hydrogen maser by using the data from our clock ensemble. The blue curve in Fig. 1 shows the modified Allan deviation of the measured time differences between two such masers. We assume that both masers have the same characteristics, so that the red curve in Fig. 1, which is scaled by $1/\sqrt{2}$ relative to the blue curve, is our estimate of the stability of a single maser. The dotted lines in Fig. 1 show our model of the observed stability.

We generate a time series containing the sum of white frequency noise, flicker frequency noise, and random-walk frequency noise with noise parameters chosen so that the time scale, which consists of N identical masers, is more stable than a single H-maser by a factor of $1/\sqrt{N}$. (This improvement is rigorously true for white noise processes, where there is no correlation between the noise contributions of each of the masers. Our experience is that it is also true for any noise process in an ensemble with no correlations.) Second, we apply the phenomenologically determined moving average algorithm in (1). This algorithm is chosen so as to make the frequency-stability curve flat for averaging times less than or equal to 20 000 s so that the simulation is close to the statistics of our masers. (The white phase noise for averaging times less than 2000 s in Fig. 1 is included in the model for the time-difference measurements.) In (1), $x(n)$ denotes the generated data value at epoch n and $y(n)$ denotes the output of the averaging process at the same epoch. The modified Allan deviation of the simulated maser is shown in Fig. 2. An ensemble of N masers would have modified Allan deviation that was smaller by a factor of $1/\sqrt{N}$

$$y(n) = \frac{1}{3}x(n) + \frac{2}{3}\cdot\frac{1}{3}x(n-1) + \left(\frac{2}{3}\right)^2\cdot\frac{1}{3}x(n-2) + \left(\frac{2}{3}\right)^3\cdot\frac{1}{3}x(n-3) + \cdots \quad (1)$$

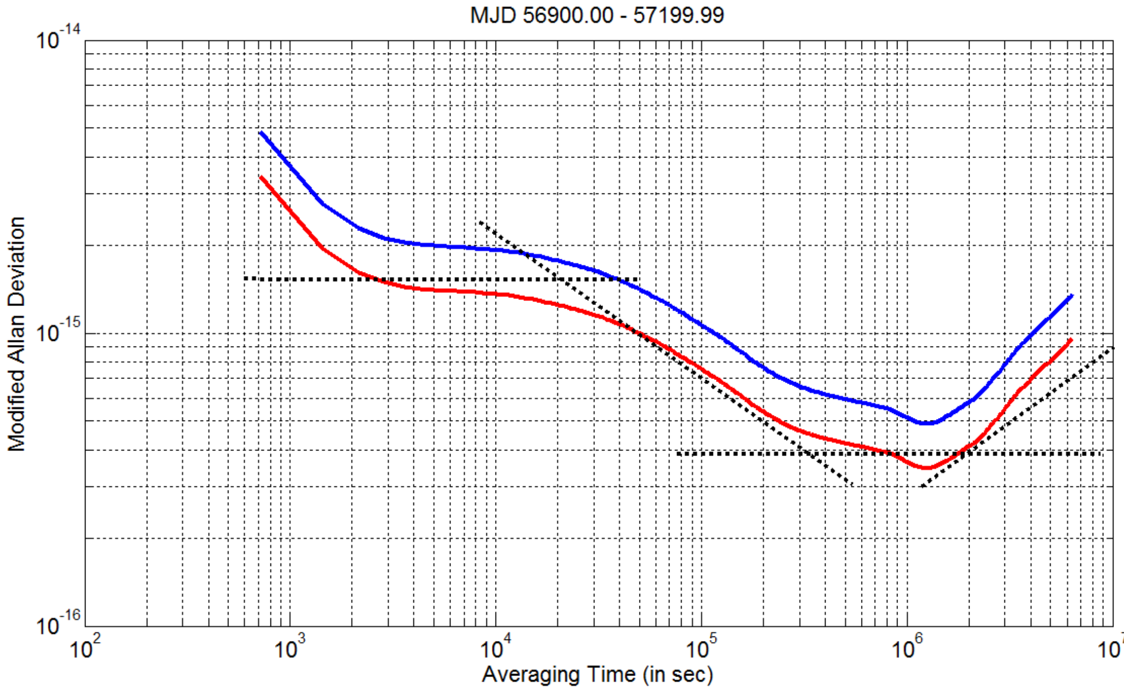

Fig. 1. The blue curve shows the frequency stability of the time difference between two NIST H-masers. The red curve shows the estimated frequency stability of a single H-maser, assuming that the two masers have the same statistical characteristics. We model the stability as shown by the black dotted lines.

The continuously operating cesium fountain is simulated by white frequency noise with a fractional frequency stability of 1.4×10^{-15} at one day, which is typical Cs-fountain performance at low atom density [4]–[6]. We simulate an optical clock as having white frequency noise with the fractional frequency stability of 3.4×10^{-16} at 1 s, which is typical for the Sr/Yb optical-lattice clock [2], [3]. The simulated optical-clock data are truncated to match various operational schedules as discussed in the following.

B. Steering Algorithm

The Kalman filter is used to estimate the frequency and frequency drift of the free-running time scale with respect to the Cs fountain or the optical clock, and the frequency and frequency drift of the time scale are steered based on this estimate.

There are two basic equations in the Kalman filter [7]. Equation (2) is the system model, which predicts the state of the system at epoch $k+1$ based on its state at epoch k. Here, $X(k)$ is the estimate state vector of the system at epoch k, and $X(k+1|k)$ is the predicted state vector of the system at epoch $k+1$. Φ is the transition matrix, which links $X(k)$ and $X(k+1|k)$; it is determined by the physical properties of the system. u is the process noise, which is characterized by the Q matrix. Equation (3) is the measurement model. The H matrix gives the relation between the state vector X and the measurement vector Z. υ is the measurement noise, which is characterized by the R matrix. The R matrix is determined by the details of the measurement process, and its detailed specification is outside of the scope of this simulation. We assume that the white frequency noise of the maser will make a significant contribution to the R matrix, and that other contributions will be much smaller

$$X(k+1 \mid k) = \Phi \cdot X(k) + u, \quad u \sim N(0, Q) \tag{2}$$

$$Z(k+1) = H \cdot X(k+1|k) + \upsilon, \quad \upsilon \sim N(0, R). \tag{3}$$

The estimated state vector at epoch $k+1$ is

$$X(k+1) = X(k+1 \mid k) + K \cdot (Z(k+1) - H \cdot X(k+1 \mid k)) \tag{4}$$

where K is the Kalman gain matrix, which is given by [7, Ch. 4]

$$K = P(k+1 \mid k) \cdot H^T \cdot [H \cdot P(k+1 \mid k) \cdot H^T + R]^{-1} \tag{5}$$

where $P(k+1 \mid k) = \Phi \cdot P(k) \cdot \Phi^T + Q$, and $P(k+1) = [I - K \cdot H] \cdot P(k+1|k)$.

For our clock system, (2) becomes

$$\begin{pmatrix} f_{\text{diff}}(k+1|k) \\ d_{\text{diff}}(k+1|k) \end{pmatrix} = \begin{pmatrix} 1 & \Delta t \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} f_{\text{diff}}(k) \\ d_{\text{diff}}(k) \end{pmatrix} + \begin{pmatrix} \eta \\ \zeta \end{pmatrix} \tag{6}$$

where f_{diff} is the fractional frequency difference between the time scale and the external frequency standard, d_{diff} is the fractional frequency-drift difference, and Δt is the time interval between epoch k and epoch $k+1$. The constant time interval is 720 s. The parameters η and ζ are the noise terms in frequency and frequency drift, respectively [8], [9]. Since the frequency noise of the external frequency standard is assumed to be negligible, η mainly comes from the frequency noise of the free-running time scale. ζ is typically too small to be observed for a measurement time interval of 720 s. Thus, we set the variance of ζ to a small value. In other words, the

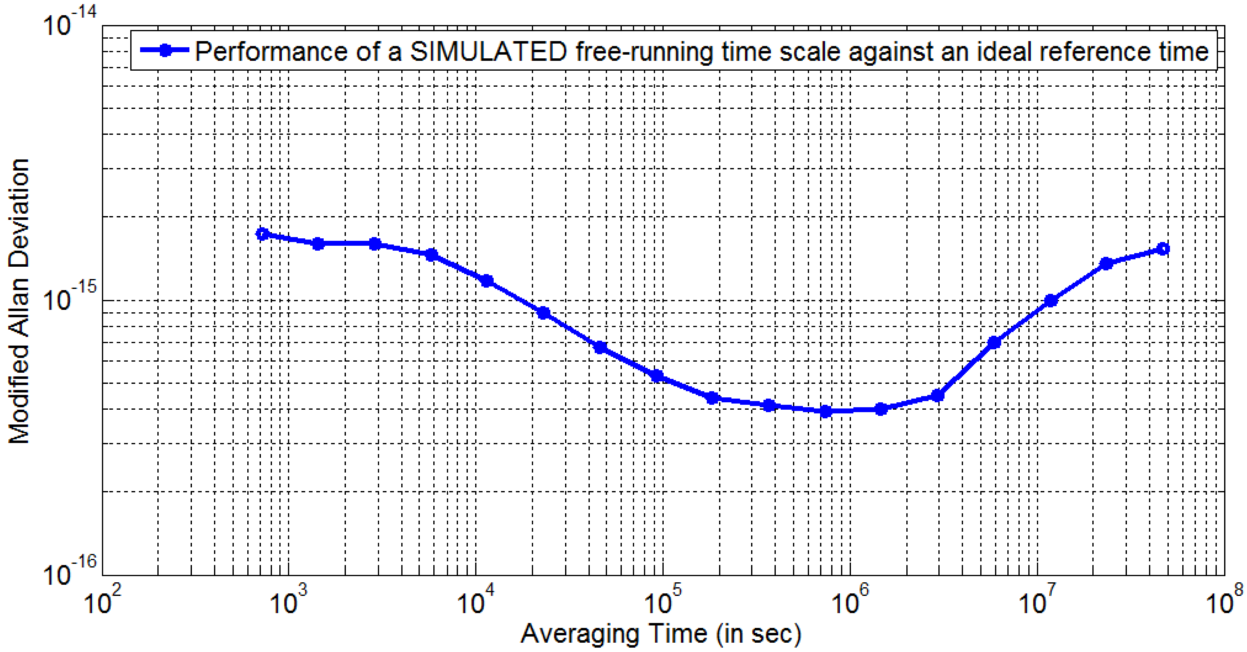

Fig. 2. Frequency stability of a simulated free-running time scale with one maser against an ideal reference time.

model assumes that the frequency drift is essentially constant over the measurement interval of 720 s.

If the Cs fountain is used as the reference, the measurement vector Z is the scalar frequency difference between the time scale and the Cs fountain measured every 720 s. If the optical clock is used as the reference, we do the preprocessing to get the average frequency difference between the time scale and the optical clock during the operation period of the optical clock. (As we discussed in the previous paragraph, this assumes that the frequency drift of the maser is constant during this interval.) Then we use the average frequency difference as the measurement vector Z.

The measurement process provides an estimate of frequency, so that the H matrix of the measurement system is

$$H = \begin{pmatrix} 1 & 0 \end{pmatrix}. \tag{7}$$

The frequency and frequency drift at epoch $k+1$ are given by (4)

$$\begin{pmatrix} f_{\text{diff}}(k+1) \\ d_{\text{diff}}(k+1) \end{pmatrix} = \begin{pmatrix} f_{\text{diff}}(k+1|k) \\ d_{\text{diff}}(k+1|k) \end{pmatrix} + K \cdot \left(Z(k+1) - H \cdot \begin{pmatrix} f_{\text{diff}}(k+1|k) \\ d_{\text{diff}}(k+1|k) \end{pmatrix} \right) \tag{8}$$

where K is the Kalman gain matrix, which can be calculated using (5).

Finally, we use the updated estimates to steer the time scale by adjusting its frequency and frequency drift.

III. Simulated Performance of a Cs-Fountain Time Scale

In this section, we show the simulated performance of a time scale steered to a continuously operating cesium fountain. The results of the simulation are shown in Fig. 3. The green dashed line is the estimate of the stability of a typical cesium fountain operating at low atom density. The solid curves show the stability of a steered time scale containing one or four masers. The stability of an ensemble of N masers would be scaled by a factor of $1/\sqrt{N}$ relative to the one-maser values.

All of the ensembles are more stable than the cesium fountain standard for averaging times less than about ten days. Fig. 3 illustrates the statistical advantage of steering an ensemble of multiple masers rather than a single device. This point is discussed in more detail in Section V. This advantage is in addition to the ability of an ensemble algorithm to minimize the impact of the failure of any one of the masers and to provide a flywheel should the link to the cesium fountain fail for any reason.

A real-world Cs-fountain time scale, such as UTC(OP) which is generated at Paris Observatory (OP) in France [6] and UTC(PTB) which is generated at Physikalisch-Technische Bundesanstalt (PTB) in Germany [5], has a quite similar performance to the red curve in Fig. 3. For example, analyzing the UTC(OP) data during modified Julian date 56649–57514 indicates that the frequency stabilities of UTC(OP) are about 4.8×10^{-16} at ten days and 2.4×10^{-16} at 60 days. The small difference between UTC(OP) and our simulation may come from the time-transfer noise and the fact that the Cs fountain does not run exactly 100% of the time.

IV. Simulated Performance of a Time Scale With an Intermittently Operating Optical Clock

In Figs. 4–7, the orange dotted line is the modeled stability of a Sr/Yb optical clock, with a stability dominated by white frequency noise with an amplitude of 3.4×10^{-16} at 1 s. The green dotted line is the estimate of the stability of a continuously operating cesium fountain as in Fig. 3. The solid curves show the stability of a time scale ensemble of one maser

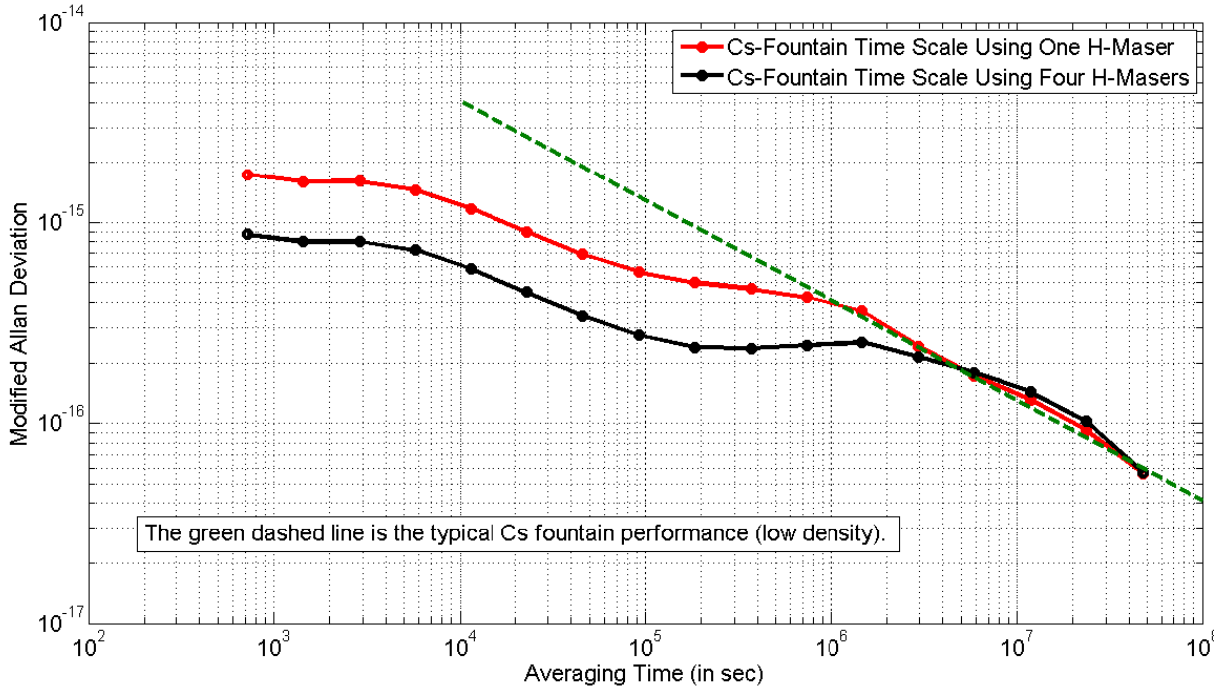

Fig. 3. Performance of a time scale steered to a continuously operating cesium fountain. The green dashed line shows the performance of the cesium fountain. The solid curves show the stability of a steered time scale that contains one or four masers.

when its frequency and frequency drift are estimated from the optical clock data.

In Fig. 4, the optical clock runs every half a day for either 12 or 24 min. In both of these cases, we can achieve the same performance as that of a continuously operating Cs-fountain time scale. The operation time of the optical clock is only 1.66%, for the blue curve. We can also see that there is little improvement if we double the running time to 24 min every 12 h. This is due to the maser's flat noise characteristics at times on the order of 1000 s (see Fig. 2).

Fig. 5 shows the simulated performance of the same time scale with an optical clock running for various time intervals once a day. If we run an optical clock 12 h per day (gray curve), the frequency stability of the time scale will be improved to 3 times better than the Cs-fountain time scale for an averaging time of greater than ten days. Even with a 50% duty cycle, the stability of the steered time scale is significantly worse than that of the optical clock itself.

Fig. 6 shows the simulated performance of the same time scale with an optical clock running 3 times every week. To achieve performance similar to that of a Cs-fountain time scale, we need to run an optical clock for at least 4 h, 3 times a week.

Fig. 7 shows the simulated performance of the steered time scale with an optical clock running once a week. The optical clock must operate for 12 h each week to make the optical-clock time scale comparable to a Cs-fountain time scale. Practically, a free-running time scale can be significantly pulled by an abnormal hydrogen maser, and the error becomes larger over time. Thus, a frequent evaluation of the free-running time scale using the optical clock is necessary to avoid a large timing error. From this perspective, the actual performance of a time scale steered once a week is unlikely to be as good as the simulation indicated in Fig. 7.

Fig. 8 shows the improvement that can be realized by steering an ensemble of N masers rather than just a single device as in Figs. 4–7. The optical clock runs for 1 h per day in these simulations. The stability has an improvement of $\sqrt{N}$, for all averaging times. Comparing Fig. 8 with Fig. 3, for an averaging time of greater than ten days, using an ensemble of masers, instead of a single maser, does not reduce the instability of a Cs-fountain time scale, while there is an improvement of $\sqrt{N}$ for an optical-clock time scale by using an ensemble of masers. Comparing the black curve in Fig. 8 with the orange curve in Fig. 5, the time scale composed of four masers and one optical clock running 1 h per day is better than the time scale composed of one maser and one optical clock running 2 h per day.

In summary, to achieve the same performance as a Cs-fountain time scale, it is necessary to run an optical clock according to one of the following options: 12 min per half a day, 1 h per day, 4 h per 2.33 day, or 12 h per week. The results are not sensitive to the assumed stability of the optical clock, provided only that it is much more stable than the free-running time scale.

V. Practical Realizations

The time differences between the clocks in the NIST time scale ensemble and UTC(NIST) are reported to the BIPM periodically as part of the NIST contribution to the calculation of the BIPM time scales EAL, TAI, and UTC. Therefore none of these clocks can be steered, since only data from free-running

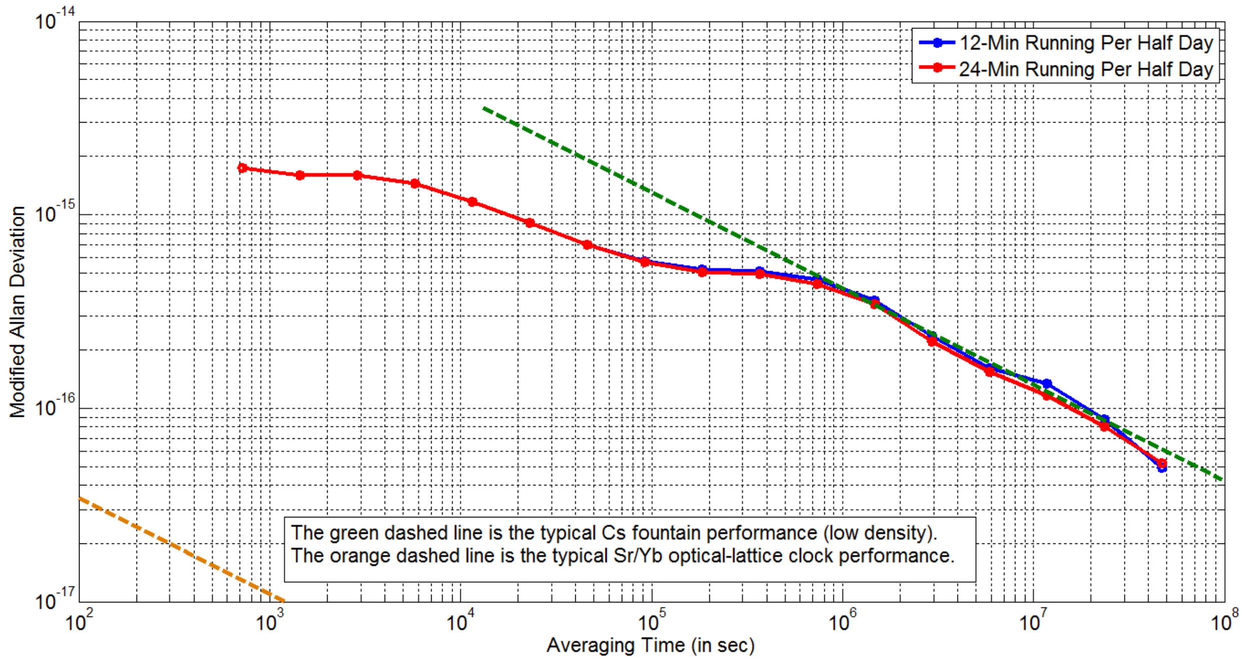

Fig. 4. Running an optical clock every half a day.

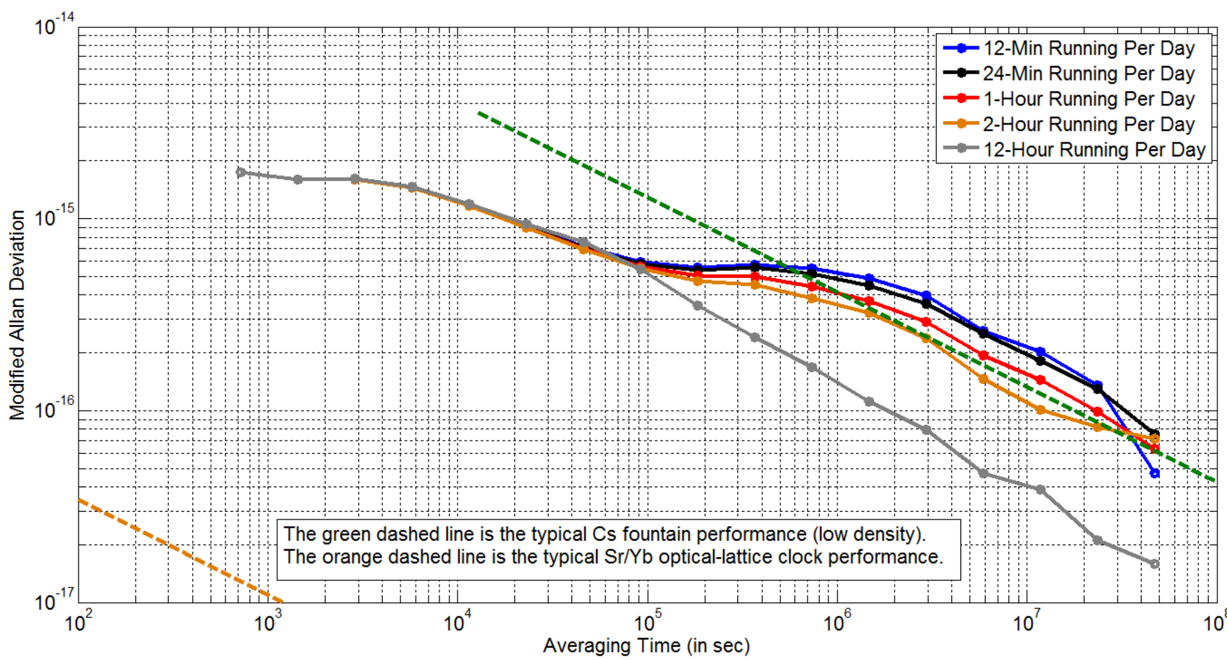

Fig. 5. Running an optical clock once a day.

clocks can be submitted to the BIPM. Because of this consideration, the steering that we have described must be realized without actually modifying the output signal of any clock. There are two methods for realizing this consideration.

In the first method, the steering would be applied to a phase stepper, which uses the free-running output of the maser linked to the optical clock as a reference signal, and the output of the phase stepper would be UTC(NIST). The algorithm that controlled the phase stepper would revert to a hold-over mode when the data from the optical clock was not available. The stability and accuracy of UTC(NIST) in this configuration would be determined by the free-running stability of the maser whose frequency was the reference for the phase stepper. (The phase stepper would make an additional contribution to this noise, but this contribution is very small compared to the noise of the reference maser.) The advantage of this method is its relative simplicity; the primary disadvantage is that this simple configuration has several single points of failure, so that some

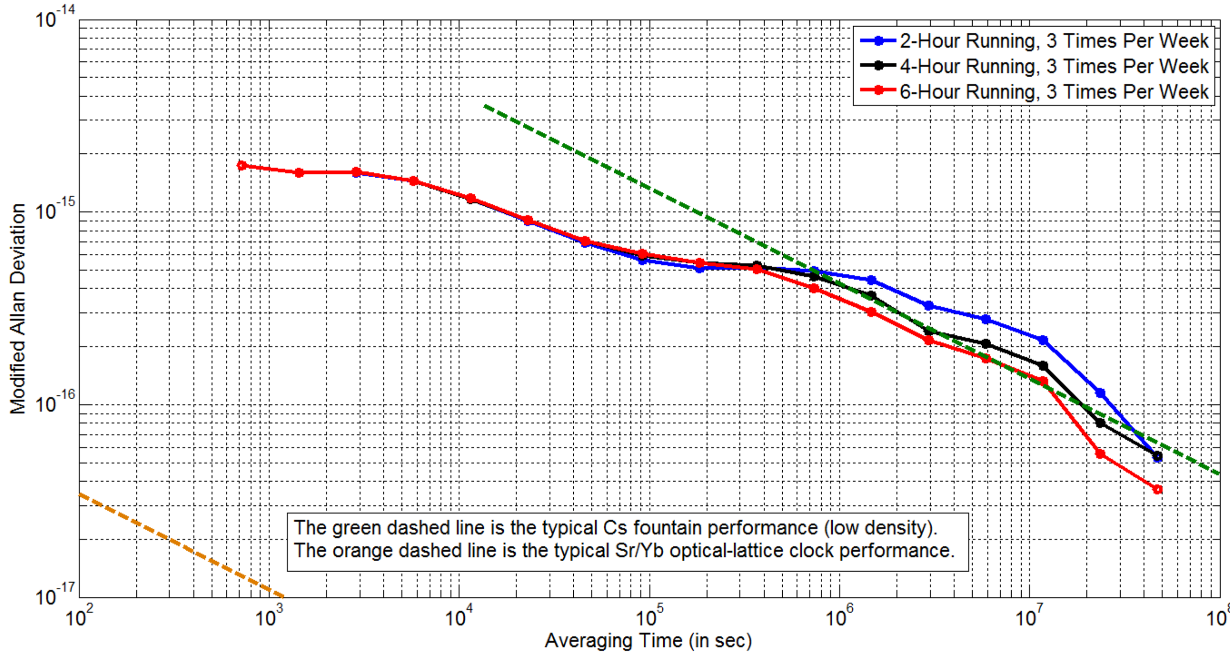

Fig. 6. Running an optical clock 3 times a week.

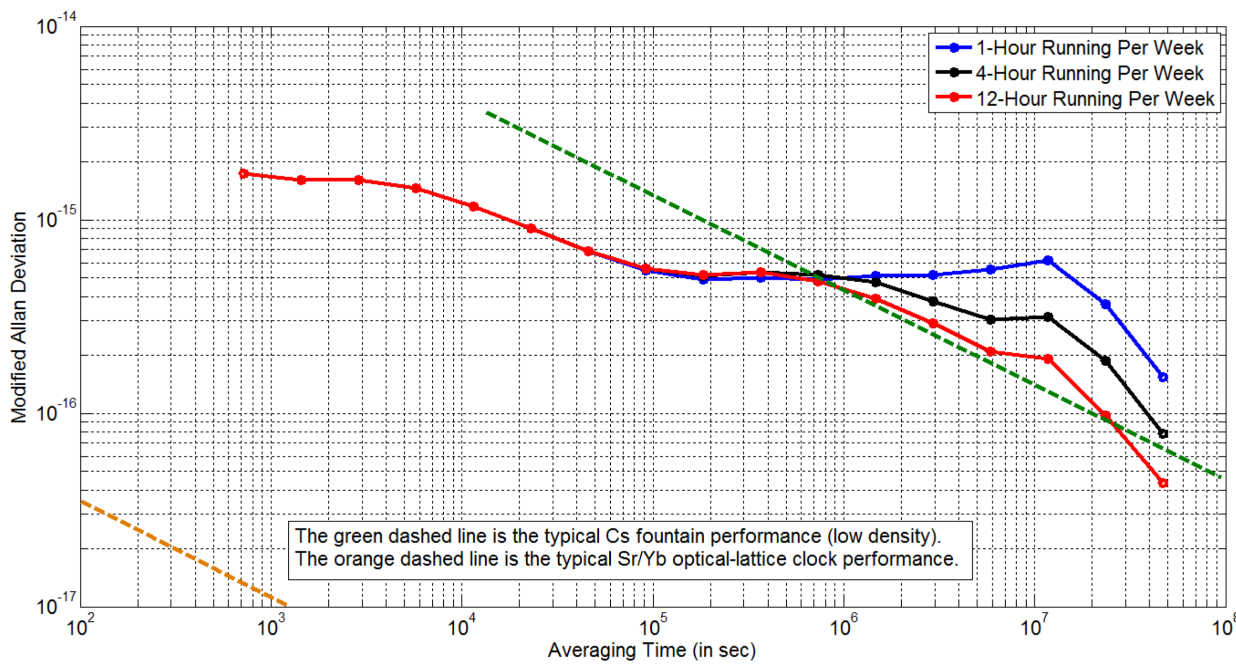

Fig. 7. Running an optical clock once a week.

kind of hardware redundancy would be needed for a real-world implementation. A more sophisticated version of this method would include a system to compare the output of the phase stepper with the input frequency of the reference maser to confirm that the steering algorithm was being realized correctly. This would detect (but not necessarily correct) a failure of the phase stepper.

In the second method, the maser would act as a transfer standard between the optical clock and the NIST clock ensemble. The frequency difference between the maser and the optical clock would be used to adjust the parameters of the maser with respect to the time scale. The most important ensemble parameter is the frequency drift of the maser, which is often irregular and difficult to predict by other means. The frequency of the maser with respect to the ensemble is equivalent to the frequency of the ensemble with respect to the maser (but opposite sign), and the link between the maser and the optical clock transfers the frequency stability, and perhaps the frequency accuracy, of the optical clock into the time scale through the maser. The output of the time scale would continue to control a phase stepper as at present, and this output would continue to be UTC(NIST). The reference device

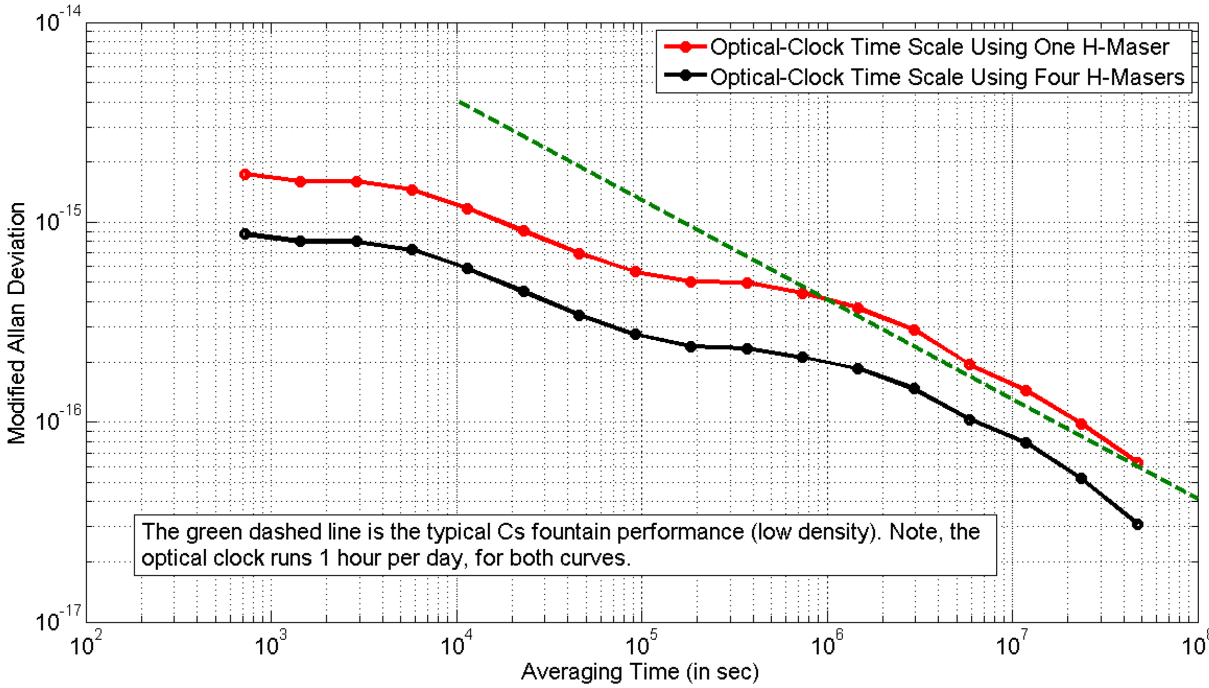

Fig. 8. Simulated results of steering an ensemble of masers to an optical frequency reference that runs 1 h per day. An ensemble of four masers steered to an optical clock running 1 h per day is more stable than a cesium fountain for all averaging times.

for this phase stepper can be any of the clocks in the ensemble, since the ensemble algorithm will characterize all of them with respect to the maser that is linked to the optical clock, with an uncertainty that is determined to a great extent by the measurement noise of the time-difference data that is the input to the ensemble calculation. This noise is well characterized as white phase noise for the time interval between measurements that is currently used (720 s), and its magnitude sets the lower limit to the interval between measurements, which is determined by the consideration that the white phase noise of the measurement process have an impact that is much smaller than the noise processes of the contributing clocks.

If the data from the optical clock are not available, the stability and accuracy of UTC(NIST) would be determined by the free-running stability of the ensemble, which is generally better than the free-running stability of any of its contributing members. In the current realization of this method, the output of the phase stepper is reinserted into the ensemble calculation as a clock with a weight of zero, and the calculated offset of this signal in time and in frequency with respect to the ensemble is a direct validation that the phase stepper is operating correctly to realize the steering commands that have been transmitted to it.

In either method, the practical algorithm that is used to control the phase stepper and generate UTC(NIST) must be a compromise between time accuracy, which would favor an aggressive steering algorithm that would probably include time steps, and frequency stability, which would suggest a longer attack time that maximized the stability of the frequency of UTC(NIST) at the expense of its time accuracy. In addition, the steering algorithm would include data, received from the BIPM, giving the difference between UTC(NIST) and UTC and between UTC(NIST) and UTC, the rapid calculation of UTC. These data would compensate for any systematic frequency offset of the local optical clock with respect to the BIPM estimate of the frequency of TAI. These considerations are unchanged from current practices; the details are outside of the scope of this discussion. We note in passing that the current steering algorithm is implemented by periodic frequency adjustments with no time steps and that the algorithm considers time accuracy to be more important than frequency stability.

VI. Conclusion

This paper studies how to build a time scale with an intermittently operating optical clock, based on simulations. To achieve the same performance of a continuously operating Cs-fountain time scale, we find that it is necessary to run an optical clock 12 min per half a day, 1 h per day, 4 h per 2.33 day, or 12 h per week. These results are independent of the choice of an optical clock, as long as the optical clock's stability is well below that of the free-running time scale. There is a clear advantage to steering an ensemble of several masers rather than just one device.

Acknowledgment

The clock noise in this paper is generated by the method proposed in [10]. The authors would like to thank C. Oates, J. Sherman, J. Savory, V. Zhang, and M. Lombardi for their helpful inputs. Last, the earlier experimental work done by PTB, Braunschweig, Germany [11] and NICT, Japan [12] inspires this work. The simulation work here provides a guideline of optical-clock running schedule for experimentalists.

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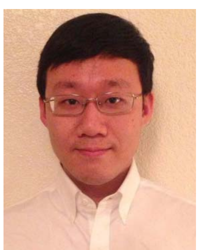


Jian Yao was born in Jiangxi, China, in 1988. He received the B.S. degree in physics with a minor in microelectronics from Nanjing University, Nanjing, China, in 2009, and the M.S. and Ph.D. degrees in physics from the University of Colorado, Boulder, CO, USA, in 2012 and 2014, respectively.

He is currently a Research Associate with the National Institute of Standards and Technology, Boulder, CO, USA, where he focuses on time scale and GPS carrier-phase time transfer.

Dr. Yao received the Best Student Paper Award in the 2012 and 2013 Institute of Navigation Precise Time and Time Interval (PTTI) Conferences. He also served as the Student Representative for the IEEE Ultrasonics, Ferroelectrics, and Frequency Control Society for two years. He has served as the Session Chair for the 2017 PTTI Conference. He has also served on the Technical Program Committees of the Frequency Control Symposium in 2016 and the Symposium on Precision Clock Synchronization for Measurement, Control and Communication in 2016. He is a reviewer for *IOP Measurement Science and Technology*.

Thomas E. Parker (M'79–SM'86–F'94–LF'13) was born in Natrona Heights, PA, USA. He received the B.S. degree in physics from Allegheny College, Meadville, PA, USA, in 1967 and the M.S. and Ph.D. degrees in physics from Purdue University, West Lafayette, IN, USA, in 1973 and 1969, respectively.

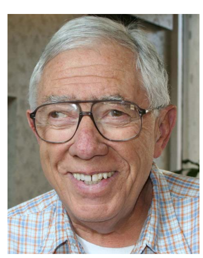
In 1973, he joined the Professional Staff of the Raytheon Research Division, Lexington, MA, USA. Initially, his focus was primarily related to the development of improved temperature stable surface acoustic wave (SAW) materials. In 1977, he contributed to the development of high-performance SAW oscillator technology at the Research Division, including the "All Quartz Package" for SAW devices. In 1994, he joined the Time and Frequency Division, National Institute of Standards and Technology (NIST), Boulder, CO, USA, where he was the Leader of the Atomic Frequency Standards Group until 2007. Since 2007, he has been a contractor for the Time and Frequency Division, NIST. He has been instrumental in incorporating hydrogen masers into the NIST time scale, improving the two-way satellite time and frequency transfer (TWSTFT) system, and in making high accuracy frequency comparisons between primary frequency standards. He has 36 years of experience with precision frequency sources, including 21 years specifically with operating and improving time scale operations, operating and improving time and frequency transfer systems including TWSTFT and GPS-based systems. He also has 22 years of experience processing data from primary frequency standards for transmission to the BIPM and in comparing frequency standards. He has authored or co-authored more than 170 technical publications, including over 100 in the areas of time scales, time and frequency transfer, atomic frequency standards, and primary frequency standards. His research interests included primary frequency standards, time scales, time-transfer technology, frequency stability, with an emphasis on $1/f$ noise, vibration sensitivity, and long-term frequency stability.

Dr. Parker received the 1988 Outstanding Transactions Paper Award from the IEEE Ultrasonics, Ferroelectrics, and Frequency Control Society (UFFC-S) as a co-author of two papers which appeared in the May 1988 and November 1988 issues of the TRANSACTIONS. He was the recipient of the Thomas L. Phillips "Excellence in Technology Award" from Raytheon in 1992. In 1994, he received the W. G. Cady Award presented by the IEEE International Frequency Control Symposium. He was the 1996 Distinguished Lecturer for the IEEE UFFC-S and received the 1999 Achievement Award from the IEEE UFFC-S. In 2003, he received the European Frequency and Time Award from the Societe Chronometrique de France (a sponsor of the European Frequency and Time Forum). In 2007, he received the Department of Commerce Gold Medal award for leadership in the NIST time scale. He has served as an Elected Member of the Administrative Committee of the IEEE UFFC-S from 1988 to 1990 and from 2000 to 2003 and as Chair of the Frequency Control Standing Committee of the UFFC-S from 1989 1997. He has served on the Technical Program Committees of both the Ultrasonics and the Frequency Control Symposia. He was the Technical Program Committee Chair for the Frequency Control Symposium in 1990 and 1991 and the General Chair in 1997 and 1998. He also served as the Associate Editor for Frequency Control—Acoustics of the UFFC-S Transactions from 1993 to 2003.

Neil Ashby was born in Dalhart, TX, USA, in 1934. He received the B.A. degree (*summa cum laude*) in physics from the University of Colorado, Boulder, CO, USA, in 1955, and the M.S. and Ph.D. degrees from Harvard University, Cambridge, MA, USA.

After spending a year in Europe as a post-doctoral fellow, he joined the faculty of the Department of Physics, University of Colorado in 1962, where he has been a Professor of physics since 1970, and was the Department Chair from 1984 to 1988. He is currently an Associate with the Time and Frequency Division, National Institute of Standards and Technology, Boulder, CO, USA, where he focused on relativistic effects on clocks, global time synchronization, and on quantum effects in atomic fountains.

Dr. Ashby was a member of the International Committee on General Relativity and Gravitation from 1989 to 1995. In 2005, he received the University of Colorado Alumni Foundation Norlin Award, and in 2006, the F. K. Richtmyer Award from the American Association of Physics Teachers. He serves on several international working groups on relativistic effects in geodesy and in metrology.



Judah Levine (A'02–M'09) received the Ph.D. degree in physics from New York University, New York City, NY, USA, in 1966.

He is currently a Fellow of the National Institute of Standards and Technology, Boulder, CO, USA, and the leader of the Network Synchronization Project with the Time and Frequency Division, NIST laboratories. He is responsible for the design and implementation of the time scales AT1 and UTC(NIST), which provide the reference signals for all of the NIST time and frequency services. In addition, he designed and built the servers that support the Automated Computer Time Service (ACTS) and the Internet Time Service, which provide time and frequency information to users in a number of different digital formats. The ACTS service is realized using a number of parallel computers that control a 12-line telephone rotary. The Internet Time Service uses 20 computers, which are located at several sites in the U.S. These computers receive about 45 000 million (45 billion) requests per day for time stamps in three different standard formats.

Dr. Levine is a fellow of the American Physical Society.