Invited Review Article: The uncertainty in the realization and dissemination of the SI second from a systems point of view

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The uncertainty (accuracy) in the realization and dissemination of the SI second is determined by the characteristics of three major components: (1) primary frequency standards, (2) time scale flywheels that provide a continuously present frequency reference, and (3) frequency transfer systems. Currently these three systems contribute at approximately equal levels in the mid 10^{-16} range over 20 to 30 days of averaging time to the practical delivery of the SI second to the most demanding users. Any significant improvement in one system requires similar improvements in the other two systems in order for most users to see the full benefits. [http://dx.doi.org/10.1063/1.3682002]

I. INTRODUCTION

In the international system of units (SI) the second is defined as "the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom," with the additional requirement that "this definition refers to a caesium atom at rest at a temperature of 0 K." [1] With the acceptance of this definition in 1967, it became necessary for at least some National Metrology Institutes (NMIs) to maintain primary frequency standards (PFSs) based on the caesium atom. The SI second is now realized at seven NMIs around the world through the construction and operation of caesium PFSs. These are laboratory devices that generally do not operate all of the time. At any given time there are a relatively small number of PFSs actually operating, ranging from as few as 2 to as many as 11. Therefore, it is also necessary to maintain a system of several hundred commercial atomic frequency standards, calibrated by the PFSs, which provide reliability and continuity through the operation of a clock ensemble. A clock ensemble is a sophisticated way of combining and averaging time information from many clocks. An integrated time scale can then be generated from this always present system of frequency standards. For increased reliability, it is highly desirable that this group of standards not be located in one location, so it is also necessary to have a system for comparing remote standards (clocks) over long distances. Once the time scale is generated, it also needs to be disseminated to the world's users. Thus, the generation and dissemination of the world's time is a complex system that involves three major components: (1) a small number of primary frequency standards, (2) an ensemble of a large number of commercial atomic frequency standards to form a time scale, and (3) a means to transfer time and frequency over large distances. The characteristics of all three systems determine with what uncertainty time and frequency can be delivered to the user. These three systems have all been individually addressed extensively in the literature and it is not the intention of this paper to repeat what is already available. Here, we would like to look at how each of these systems contributes to the overall accuracy and stability of delivered time and frequency signals. The total uncertainty is obtained by adding the individual contributions in quadrature.

In Sec. II, a brief overview of the world's primary frequency standards will be presented along with a discussion of the current level of performance. Section III provides a short discussion of time scales and reviews the accuracy and stability that can be obtained with current commercial clock technology. In particular, the concept and impact of "dead time" will be examined. In Sec. IV, the current techniques for time and frequency transfer will be reviewed and a discussion will be presented on the impact of instabilities in these techniques on time- and frequency-transfer uncertainty. New optical frequency standards are now being developed that will provide an order of magnitude, or more, improvement over the current caesium-based standards. In Sec. V, we will examine what performance levels will be required in time scales and transfer systems in order to realize the full potential of the new optical frequency standards. Section VI is a summary.

II. PRIMARY FREQUENCY STANDARDS

In 1967, when the definition of the second was changed from a system based on astronomical observations to caesium atomic frequency standards, the technology for a PFS was a thermal beam caesium standard. Even today there are a few thermal-beam PFSs still operating. The best thermal beam PFS today has a fractional frequency uncertainty (accuracy), u, of about 6×10^{-15} when averaged over an interval of 30 days. In 1995, a new PFS technology was introduced based on laser-cooled caesium atoms.[2] These new PFSs are commonly referred to as caesium fountains. The term fountain arises because the cold caesium atoms are manipulated by laser beams to follow a path similar to water in a fountain. By the year 2000, caesium fountain PFSs were operating on a regular basis and the frequency uncertainties of the best fountain PFSs are now about 4×10^{-16}, more than an order of magnitude better than the thermal beam standards. There are currently 12 PFSs from 7 NMIs operating on a fairly regular basis. The publications of the International Bureau of Weights and Measures, BIPM,

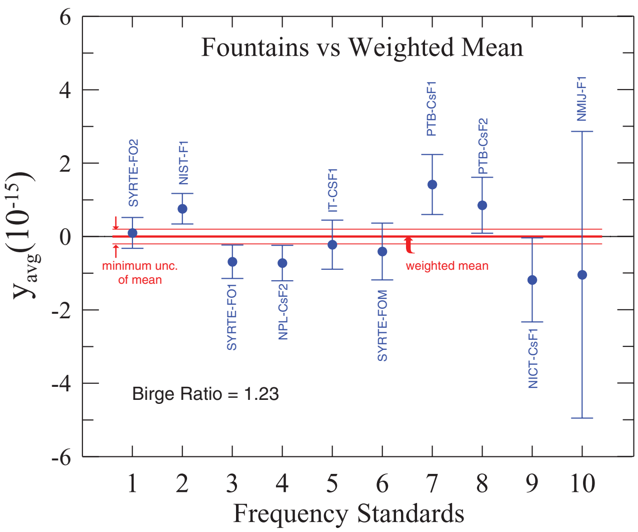

FIG. 1. (Color online) Average frequency offsets versus the weighted mean for ten different caesium fountain primary frequency standards over a recent three year interval. The Birge ratio is a measure of the consistency of the scatter in the data relative to the stated uncertainties and should nominally be 1.

including *Circular T* provide information on the various reporting standards.[3] Two of these standards are thermal beams and the remaining ten are caesium fountain standards, ranging in frequency accuracy (uncertainty) from about 4×10^{-16} to 4×10^{-15}.[4–16] In most cases, for formal reports to the BIPM, a fountain PFS must operate in a nearly continuous fashion over 20 to 30 days to achieve accuracies at the $\sim 4 \times 10^{-16}$ level. (In some circumstances, accuracies at the 4×10^{-16} level can be obtained in just a few days of operation for local applications.) These primary standards are used for fundamental research and to calibrate time scales and commercial atomic frequency standards around the world (commercial standards include caesium thermal beams standards, hydrogen masers, and rubidium gas cell standards). However, most of these PFSs do not operate all of the time. They are sophisticated laboratory devices for which all of the known frequency biases (atom density, temperature, gravitational red shift, magnetic field, etc.) must be correctly accounted for and with uncertainties assigned. This is generally inconsistent with continuous operation. Typically a caesium fountain PFS is operated for only 10 to 30 days of nearly continuous operation, but over a year may operate only 10% to 80% of the time.

Figure 1 shows a comparison of the ten currently active caesium fountain PFSs relative to a weighted mean of these fountains based on data published in *Circular T* over the interval March 2008–May 2011.[17,18] Individual fountain uncertainties (1 sigma) are shown by the error bars that also include dead time and frequency transfer contributions as discussed below. SYRTE-FO2, SYRTE-FO1, and SYRTE-FOM are operated by Laboratoire National de Métrologie et d'Essais, Systèmes de Référence Temps Espace (LNE-SYRTE) in France, NIST-F1 by the National Institute of Standards and Technology (NIST) in the USA, NPL-CsF2 by the National Physical Laboratory (NPL) in the United Kingdom, IT-CSF1 by the Istituto Nazionale di Ricerca Metrologica, (INRIM) in Italy, PTB-CsF1 and PTB-CsF2 by the Physikalisch-Technische Bundesanstalt (PTB) in Germany, NICT-CsF1 by the National Institute of Information and Communication Technology (NICT) in Japan, and NMIJ-F1 by the National Metrology Institute of Japan (NMIJ). The Birge ratio shown in Fig. 1 is a measure of the consistency of the actual scatter in the data from the 10 fountains with the stated uncertainties and ideally would be near 1.[17] At 1.23, it is just about one standard deviation (for 10 data points) of the Birge ratio above 1.[18] Overall, the distribution is reasonable.

A clock consists of a frequency reference and a means to count the "ticks" of the reference. Clearly, a frequency reference that does not operate all of the time makes a poor clock. Therefore, a PFS is generally not operated as a clock and cannot supply time. It supplies only the SI second (frequency). A more reliable frequency reference is needed to provide time as a continuous series of "ticks." This reference need not be inherently accurate, but it must be stable and very reliable. Accuracy can come from periodic calibrations with a PFS. The role of these "flywheel" frequency references is usually filled by commercial atomic clocks. High stability requirements are usually satisfied with high performance commercial atomic clocks such as atomic hydrogen masers and/or high end thermal beam caesium standards. NMIs, the military, and some telecommunication companies use these types of standards. Other applications can be satisfied with lower cost caesium or rubidium standards. In any case, commercial atomic frequency standards provide the necessary "flywheel" component for the generation and dissemination of time and the SI second.

For the world's official time, the BIPM generates an ensemble-based time scale with data from a large number of commercial atomic clocks located at laboratories around the world. A major function of the world's PFSs is to calibrate the frequency (rate) of this time scale generated by the BIPM. With periodic inputs from the world's PFSs, the BIPM time scale can be calibrated with a frequency uncertainty at the 4×10^{-16}–5×10^{-16} level over a 30 day interval.[3] Time scales are discussed below in Sec. III.

III. TIME SCALES

Time scales and clock ensembles are discussed in great detail in the companion paper "The statistical modeling of atomic clocks and the design of time scales" by J. Levine.[19] Therefore, only a brief overview will be presented here. The function of a clock ensemble is to provide a continuous frequency reference from which the "ticks" can be counted to produce a time scale. As mentioned above, the BIPM is responsible for producing the world's official time. Once a month, the BIPM collects data from about 400 commercial atomic frequency standards located at NMIs and other institutions scattered around the world. (How these data are collected will be discussed in Sec. IV.) These data are used to form a clock ensemble and once a month a calculation is performed to generate a time scale called EAL. EAL is the acronym for Echelle Atomique Libre, or free atomic timescale in English. Inputs from the PFSs operating during this interval are used to determine the rate (frequency) of EAL and to produce a frequency-corrected scale called international atomic time (TAI), which is a representation of the SI second. Leap seconds are added as needed to TAI to generate coordinated universal time (UTC). UTC is the world's official time. The BIPM does not actually operate atomic clocks, so UTC and TAI are "paper" time scales. These scales are calculated only once a month on a five-day grid, so they do not exist in real time. See Ref. 3 for more details on EAL, TAI, and UTC.

A frame of reference must be defined for a time scale, and for TAI and UTC it is the rotating geoid – essentially sea level for a fixed point on the surface of the Earth. Thus, the SI second from a PFS must be corrected for the relativistic frequency shift due to gravitational potential (effectively altitude). In the case of the PFS operated by the NIST in Boulder, Colorado, USA, the fractional frequency correction is -1.8×10^{-13}. Although this is a large correction, the uncertainty of the correction is only 3×10^{-17}.[8]

Since UTC and TAI do not physically exist and are not available in real time, there is the practical problem of how to obtain time and frequency when and where they are needed. To solve this problem, many NMIs, or other laboratories, operate physical time scales in real time. Two such institutions are NIST and the U.S. Naval Observatory in Washington DC. Local time scales consist of anywhere from one clock to more than 100 clocks and some laboratories operate a clock ensemble. Clock ensembles are particularly useful since individual clocks can come and go without the loss of continuity. In all cases, the laboratory provides a hardware clock or time scale that has a physical output available in real time. All of these time scales are steered to UTC when information on UTC is made available by the BIPM. NMIs that have a PFS can use it to calibrate the frequencies of the local clocks. This has the advantage of eliminating the increased uncertainty introduced by long distance time and frequency transfer (see Sec. IV)

Two important characteristics of a local time scale are how accurately it represents the UTC and how stable its frequency is. Most local time scales are always within 100 ns of UTC, and some of the best can stay within 10 ns most, if not all, of the time. The frequency stability depends on the type of clocks used, but if hydrogen masers make up a significant fraction of a local clock ensemble, a fractional frequency stability of 4×10^{-16}–5×10^{-16} at a few days can be achieved. Note that this stability is comparable to the uncertainty of a caesium fountain PFS. TAI has a similar stability.

A common application of TAI, or a local time scale, is as a frequency reference to be used to relate the frequency of a general frequency source, or a so-called secondary standard, to a primary standard. In such a situation, the frequency of the standard to be calibrated might be physically compared to the local time scale with a frequency counter or with other more sophisticated phase comparison equipment. However, the time interval over which the standard to be calibrated is operated may not correspond to the same time interval over which the time scale was calibrated by a PFS (or comparison to TAI if no PFS is available locally). This lack of simultaneity brings up the issue of dead time in determining the uncertainty of the calibration. In situations where a flywheel standard is used to transfer a frequency calibration from one standard to another, the presence of dead time and the frequency stability of the flywheel play an important role in determining the uncertainty of the calibration.[20,21]

The overall fractional frequency stability of a time scale can be approximated as the quadratic sum of three noise components expressed in terms of the Allan deviation, $\sigma_y(\tau)$.[22] The definition of the Allan deviation is shown in Eq. (1), where $\overline{y}_k$ is the average fractional frequency difference over the time interval τ,

$$\sigma_y(\tau) = \sqrt{\tfrac{1}{2}\langle(\bar{y}_{k+1} - \bar{y}_k)^2\rangle}. \tag{1}$$

The three noise components are white frequency noise, flicker frequency noise, and random walk frequency noise. For TAI, the values are:

White frequency	$\sigma_y(\tau) = 20 \times 10^{-16}\,\tau^{-1/2}$
Flicker frequency	$\sigma_y(\tau) = 4 \times 10^{-16}$
Random walk frequency	$\sigma_y(\tau) = 1 \times 10^{-16}\,\tau^{-1/2}$,

where τ is the averaging time in days (see *Circular T* (Ref. 3)). For AT1E, a local post-processed time scale at NIST made up of five masers and eight thermal beam caesium standards,[23] the typical values are:

White frequency	$\sigma_y(\tau) = 8 \times 10^{-16}\,\tau^{-1/2}$
Flicker frequency	$\sigma_y(\tau) = 5 \times 10^{-16}$
Random walk frequency	$\sigma_y(\tau) = 1.5 \times 10^{-16}\,\tau^{-1/2}$.

Even though AT1E has a much smaller number of commercial clocks, the white frequency noise in AT1E is lower than that of TAI, because there is no long distance time transfer noise (all the clocks are local).

To illustrate how the stability of a time scale (or any frequency reference) influences the uncertainty of a comparison, consider the example of comparing two PFSs using TAI as a reference. Assume that one PFS operates for ten days continuously and determines the frequency of TAI with an uncertainty, u, of 5×10^{-16}. Now assume that a second PFS operates continuously for the next ten days and also measures the frequency of TAI with an uncertainty of 5×10^{-16}. Both have operated for ten days, but there is no overlap. Now if we want to compare the frequency of PFS1 to PFS2, we can calculate

$$y(\mathrm{PFS1} - \mathrm{PFS2}) = y(\mathrm{PFS1} - \mathrm{TAI}) - y(\mathrm{PFS2} - \mathrm{TAI}), \tag{2}$$

where $y(x)$ is the fractional frequency difference. However, the frequency of TAI in the first measurement is not exactly the same as the frequency of TAI in the second measurement due to the noise in TAI. Based on the noise characteristics of the TAI shown above, the additional uncertainty introduced by instabilities in TAI can be calculated from the expressions in Ref. 20 and is found to be 1.15×10^{-15}. For the same situation using AT1E as the flywheel reference, the additional uncertainty is 1.04×10^{-15}. If both PFSs had been operated over the exact same ten days (perfect overlap), the stability of the reference time scale would be irrelevant and no additional uncertainty would be added. With perfect overlap, the total comparison uncertainty, u_c, for y(PFS1-PFS2) would be

$$u_c = 7.07 \times 10^{-16} = ((5 \times 10^{-16})^2 + (5 \times 10^{-16})^2)^{1/2}. \tag{3}$$

With the ten day offset and using TAI as the reference, it would be

$$u_c = 13.5 \times 10^{-16} = ((11.5 \times 10^{-16})^2 + (5 \times 10^{-16})^2 + (5 \times 10^{-16})^2)^{1/2}. \quad (4)$$

Thus, the presence of the offset nearly doubles the uncertainty of the comparisons of the two PFSs. With smaller amounts of dead time, the uncertainty introduced by the time scale will become smaller. It should also be noted that distributed dead time (not all missing data occurs in the same time interval) is generally less detrimental than the equivalent amount of lumped dead time.[21]

In addition to the three noise types discussed above, there may also be frequency drift present. This is not usually a problem with a high-quality time scale, if the measurement interval offset is not too large, but if an individual clock is used as a frequency reference (particular a hydrogen maser), the drift may also have to be taken into consideration. Dead time is generally not an issue in situations where a time scale is being used to calibrate a commercial atomic frequency standard at perhaps the 10^{-14} or 10^{-13} level.

So far, we have discussed the PFSs that provide the SI second at an accuracy of about 4×10^{-16}, and clock ensembles (calibrated by the PFSs) that provide reliability and continuity for the generation of time. The frequency stability of the ensemble time scales is reasonably consistent with the uncertainties of the PFSs so that the impact of dead time is usually not too large. The next component to be considered is the process of disseminating time and frequency.

IV. TIME/FREQUENCY TRANSFER

The SI second is the only fundamental SI unit of measure that can be disseminated remotely in real time, and this is usually accomplished through the propagation of electromagnetic waves. There are a number of techniques to accomplish this and the accuracy of the obtained time can range from a few tenths of a second to better than 1 ns. For the high end user, the two most common techniques make use of earth orbiting satellites. The global positioning system (GPS) is not only a navigation system, but also a time dissemination system. One can obtain time and frequency directly from GPS satellites or with a method known as "common view."[24] A GPS receiver designed to obtain time directly from GPS can easily deliver UTC to within 1 μs and with careful calibration can achieve an instantaneous (a quick measurement with little or no time to average down transfer noise) accuracy better than 40 ns.[25] These receivers are designed to use the information broadcast by GPS to account for the propagation delay (roughly 3.3 ns/m). To compare two remote clocks on the ground, the GPS common view method can be used.[24] Here the two ground stations receive timing signals from the same GPS satellite at the same time and then must exchange data. The time of the clock on the satellite drops out when calculating the time difference of the two ground stations. With GPS, common view time comparison accuracy better than 2 ns can be achieved if the local clocks are stable enough to average for 1 day and if receiver delays are well calibrated.[25] Instantaneous accuracy is more on the order of 15 ns. A variation on common view which is useful over very long distances is the "all in view" technique.[26] For intercontinental distances, there may be only a few satellites that two stations can see at the same time. In this case, GPS system time (available on all the satellites but with some small errors) is used as the common clock. Now the GPS receivers can use all visible satellites, but with some instability introduced by using GPS system time as the common clock. For long distances, the "all in view" technique works about as well as strict common-view over short baselines.[26] Another variation on the common view approach is to use the phase of the GPS carrier in addition to the modulated signal.[27] This GPS carrier phase technique greatly improves the short term stability (time intervals less than 1 day) of the timing signal,[27] but the signal processing is considerably more complicated and more prone to unexplained time steps. Also, for all practical purposes, it cannot be done in true real time.

A second technique for the high end user is two-way satellite time and frequency transfer (TWSTFT).[28] Here microwave signals are simultaneously transmitted and received by two stations through a telecommunications satellite in a geostationary orbit. Since both stations transmit and receive timing signals simultaneously through the same satellite, the path delay almost completely drops out of the clock difference. The TWSTFT transmit and receive equipment is relatively expensive compared to a GPS receiver, and the user must pay for satellite time, but the technique can deliver better performance in both accuracy and stability than GPS common view. With TWSTFT, the short-term stability at a few minutes is considerably better than code-based GPS common-view and can provide an instantaneous accuracy on the order of 2 ns.[29] For a 24 h average, an accuracy of marginally better than 1 ns can be achieved with careful equipment calibration.[30] The accuracy and stability of TWSTFT at 1 day are similar to GPS carrier phase, but the signal processing in TWSTFT is much simpler and less prone to errors. However, the equipment is more complex and the satellite time is expensive. In many ways, the two techniques are complimentary and for the most demanding users both techniques are used to provide a means of detecting errors. As an example, Fig. 2 shows the time difference between UTC(NIST) and UTC(PTB) in nanoseconds for a period of 180 days from January 9, 2011 to July 8, 2011. The horizontal axis is the modified Julian date in days. Each measurement is a 2 min average and the measurements are made 12 times per day at 2 h intervals. The short-term fluctuations at less than a day are from transfer noise, whereas the long-term fluctuations, over a few days and longer, originate in the maser-based time scales at both locations. Over a one or two day interval, the standard deviation is typically about 200 ps and originates mostly from transfer noise. The two-way technique can also be used over optical fibers with even better results, but at this time it has been limited to frequency transfer over distances of up to only a few hundred kilometers.[31] TWSTFT, GPS all-in-view, and GPS carrier phase based techniques are all used by the BIPM in the collection of clock data necessary for the calculation of TAI and UTC.

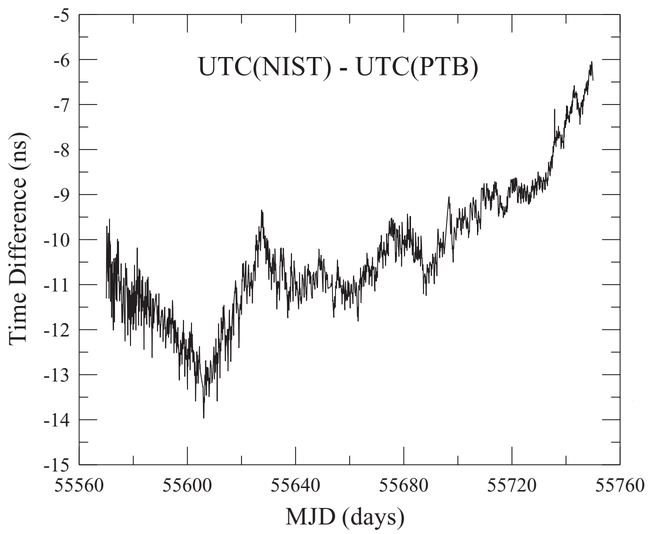

FIG. 2. UTC(NIST)–UTC(PTB) as measured by two-way time and frequency transfer at 2 h intervals. The fluctuations within one or two days are due mostly to transfer noise, while the longer term fluctuations originate in the time scales.

There are a number of other time and frequency transfer techniques available for the less demanding user. For applications requiring timing accuracy on the order of a few tenths of a second, the internet or dial up phone systems can be used. These techniques are very popular and internet timing is free. With care, these techniques can achieve 5–50 ms accuracy and 1–10 ms stability. There are also radio broadcasts that supply time information that can achieve millisecond accuracies if path delays are accounted for. In all of these "low precision" transfer techniques, the time/frequency accuracy and stability are so dominated by the transfer process that the characteristics of the primary time/frequency references are largely irrelevant.

The *stability* of time transfer determines the *uncertainty (accuracy)* of frequency transfer. If x_i is the time difference between two clocks at time t_i, then the frequency (rate) difference between the two clocks is given by

$$y_{AB} = \frac{x_2 - x_1}{T}, \tag{5}$$

where x_1 and x_2 are the time differences measured between clocks A and B at times t_1 and t_2, $T = t_2 - t_1$, and y_{AB} is the average fractional frequency difference between clocks A and B over the time interval T.

Each value x_i will have a time transfer uncertainty, u, associated with it that is made up of two components. One component is a static uncertainty, u_b, that does not change over time. This may be a fixed calibration uncertainty, for example. The other component, u_a, comes from random noise that fluctuates with time (i.e., instabilities). The static component u_b does not contribute to a frequency error or uncertainty, but the random component does. The uncertainty, u_{yab}, of y_{AB}, is given as

$$u_{yab} = \frac{\sqrt{u_{a2}^2 + u_{a1}^2}}{T}, \tag{6}$$

where u_{a1} and u_{a2} are the random time transfer uncertainties at t_1 and t_2 and T is the same as in Eq. (5). Thus, we see that the instabilities in the time transfer process contribute to the uncertainty (inaccuracy) of a frequency comparison.

The time transfer uncertainty u_{ai} can be made up of several noise types.[32] Over short intervals, it is generally white phase (time) noise. Over longer time intervals, it becomes flicker in nature and eventually there may be a random walk contribution. u_{a2} will equal u_{a1} for white phase noise and u_{yab} will decrease as $1/T$. For flicker and random walk noise types, u_a will tend to increase with time. Thus for flicker phase noise, u_{yab} will decrease approximately as $1/T^{0.8}$ and for random walk phase noise, u_{yab} will decrease as $1/T^{0.5}$. A detailed discussion of the time and frequency transfer uncertainties is presented in Ref. 32. For the data in Fig. 2, the frequency transfer uncertainty for $T = 10$ days is approximately 6×10^{-16}, under the reasonably good assumption that the transfer noise is flicker in nature at 10 days.[32]

Thus, we see that the time/frequency transfer process may also contribute significantly to the uncertainty of a frequency comparison. We have the inherent uncertainty of the frequency standards, plus we may have a dead time uncertainty that comes from the stability of a flywheel standard if the two standards are not operated at exactly the same time. Finally, there is always an uncertainty contribution by the transfer process. If the transfer is made over short distances (say within a laboratory) the transfer uncertainty may be negligible, but over long distances it can be significant. Currently the best long distance comparison techniques, such as TWSTFT and GPS carrier phase, will contribute a frequency comparison uncertainty of about 2×10^{-16} for $T = 30$ days.[32] The noise type in the range of 1 to 30 days for these transfer techniques is generally flicker phase, so the frequency transfer uncertainty does not decrease as fast as $1/T$, but more like $1/T^{0.8}$. Thus, we see that for the current caesium fountain technology the uncertainties of the three major components (PFS, dead time and frequency transfer) are approximately balanced at a level in the mid 10^{-16} range for reasonable comparison times.

Table I summarizes the general performance of various time and frequency transfer techniques in terms of time transfer accuracy, time transfer stability, and frequency transfer uncertainty.[25] The values in the table reflect the performances that the various transfer techniques are capable of delivering, not what is actually obtained by the user's equipment. In many cases, commercial equipment does not demonstrate optimum performance.

V. IMPACT OF OPTICAL FREQUENCY STANDARDS

The new optical atomic frequency standards that operate at optical frequencies will provide at least an order of magnitude improvement in accuracy,[33,34] and it is very likely that the SI second will eventually be redefined in terms of a new optical transition. This will enable the SI second to be realized at the 10^{-17} level, or better. However, as we have seen, there are other major systems involved in the dissemination of time and frequency. Clearly, time and frequency transfer techniques must be improved by about an order of

TABLE I. Approximate characteristics of various time/frequency transfer techniques.

Technique	Time accuracy	Time stability (24 h)	Frequency transfer uncertainty (24 h)
Internet	50 ms–1 s	10 ms	1×10^{-7}
Phone	5 ms–0 .1 s	1 ms	1×10^{-8}
HF radio	1–40 ms	0.1 ms	1×10^{-9}
LF radio	0.1–20 ms	0.5 μs	6×10^{-12}
GPS one-way	10–40 ns	5 ns	6×10^{-14}
GPS CV	1–15 ns	0.5 ns	6×10^{-15}
TWSTFT	0.5–5 ns	0.1 ns	1×10^{-15}
GPS carrier phase	0.5–5 ns	0.1 ns	1×10^{-15}

magnitude in order to support frequency transfers at the 10^{-17} level in a reasonable time interval. With current technology, a long distance frequency transfer at the low 10^{-17} level would take well over a year, and require very little dead time. This is clearly impractical. There are promising technologies for short distances such as two-way over optical fibers,[31] but at this time there are no obvious practical and affordable techniques for intercontinental distances. Very long distance dedicated optical fibers suitable for two-way frequency transfers are not now available. Frequency transfer by laser pulses reflected off of a satellite is capable of approaching the 10^{-17} level, but it requires large laser transmit and receive stations, and of course would not work in cloudy weather.[35] A dedicated wideband microwave two-way system and an optical atomic frequency standard on a satellite could provide the necessary performance, but would be very expensive (an experiment using a cold atom microwave atomic frequency standard is currently planned for launch to the International Space Station in 2014).[36] Clearly, there will have to be a major effort made to improve long distance transfer techniques by at least an order of magnitude. There are several promising technologies on the horizon, but the main impediment right now appears to be cost.

Improved technology for flywheel frequency standards is also needed to handle issues of dead time. As shown in Sec. III, the stability of present day flywheel frequency standards would not come even close to maintaining a calibration from an optical standard at the 1×10^{-17} level. A ten-day calibration by an optical standard will degrade by two orders of magnitude in the next ten days. A misalignment of only half a day (5% dead time) would add an uncertainty of about 1×10^{-16}. In fact, the percentage of dead time would have to be less than 0.3% to reduce the dead time uncertainty to 1×10^{-17}. It is very likely that optical techniques similar to those used for possible new primary frequency standards would have to be used for the flywheel function also, but these standards would need to be engineered as commercial products with very high reliability and reasonable cost. These commercial products would need to have frequency stabilities at a few days that are comparable to the uncertainties of the optical PFS. Well-coordinated comparisons between laboratory standards could minimize the problem of dead time, but for many users this would not be possible.

A very interesting discussion involving long distance frequency comparisons of terrestrial and astrophysical frequency standards is presented in Ref. 37.

VI. SUMMARY

The uncertainty in the realization and dissemination of the SI second is determined by the characteristics of three major components: (1) the primary frequency standards themselves, (2) the time scale flywheels that provide a continuously present frequency reference, and (3) the frequency transfer systems. Currently, these three systems contribute at approximately equal levels in the mid 10^{-16} range over 20 to 30 days of averaging time to the practical delivery of the SI second to the most demanding users. The total uncertainty for the user is obtained by adding each contribution in quadrature. Any significant improvement in one system requires similar improvements in the other two systems in order for the most demanding users to see the full benefits. The new optical frequency standards offer the real possibility for one to two orders of magnitude improvement in frequency accuracy and stability. However, for the full potential of these new standards to be available to a wide range of users, significant improvements must also be made in the standards used as flywheels and in frequency transfer techniques.

[1] See http://www.bipm.org/en/si/si_brochure/chapter2/2-1/second.html for more information on the definition of the second.

[2] A. Clairon, S. Ghezali, G. Santarelli, Ph. Laurent, S. Lea, M. Bahoura, E. Simon, S. Weyers, and K. Szymaniec, in *Proceedings of the 5th Symposium on Frequency Standards and Metrology* (World Scientific, Singapore, 1996), pp. 49–59.

[3] See http://www.bipm.org/jsp/en/TimeFtp.jsp?TypePub=publication for BIPM publications on time and frequency, including Circular T and information on reporting primary frequency standards.

[4] R. Wynands and S. Weyers, Metrologia **42**, S64 (2005).

[5] C. Vian, P. Rosenbusch, H. Marion, S. Bize, L. Cacciapuoti, S. Zhang, M. Abgrall, D. Chambon, I. Maksimovic, P. Laurent, G. Santarelli, A. Clairon, A. Luiten, M. Tobar, and C. Salomon, IEEE Trans. Instrum. Meas. **54**, 833 (2005).

[6] C. Vian, P. Rosenbusch, H. Marion, S. Bize, L. Cacciapuoti, M. Abgrall, D. Chambon, G. Santarelli, Ph. Laurent, A. Clairon, A. Luiten, M. Tobar, and C. Salomon, in *Proceedings of the 19th European Frequency and Time Forum, Besancon, France, 2005*, pp. 52–57.

[7] S. R. Jefferts, J. Shirley, T. E. Parker, T. P. Heavner, D. M. Meekhof, C. Nelson, F. Levi, G. Costanzo, A. De Marchi, R. Drullinger, L. Hollberg, W. D. Lee, and F. L. Walls, Metrologia **39**, 321 (2002).

[8] T. P. Heavner, S. R. Jefferts, E. A. Donley, J. H. Shirley, and T. E. Parker, Metrologia **42**, 411 (2005).

[9] T. E. Parker, S. R. Jefferts, T. P. Heavner, and E. A. Donley, Metrologia **42**, 423 (2005).

[10] S. Weyers, U. Hübner, R. Schröder, Chr. Tamm, and A. Bauch, Metrologia **38**, 343 (2001).

[11] S. Weyers, A. Bauch, R. Schröder, and Chr. Tamm, in *Proceedings of the 6th Symposium on Frequency Standards and Metrology* (World Scientific, Singapore, 2002), pp. 64–71.

[12] H. Marion, F. Pereira Dos Santos, M. Abgrall, S. Zhang, Y. Sortais, S. Bize, I. Maksimovic, D. Calonico, J. Grünert, C. Mandache, P. Lemonde, G. Santarelli, Ph. Laurent, and A. Clairon, Phys. Rev. Lett. **90**, 150801 (2003).

[13] F. Levi, D. Calonico, L. Lorini, and A. Godone, Metrologia **43**, 545 (2006).

[14] K. Szymaniec, W. Chalupczak, P. B. Whibberley, S. N. Lea, and D. Henderson, Metrologia **42**, 49 (2005).

[15] T. Kurosu, Y. Fukuyama, Y. Koga, and K. Abe, IEEE Trans. Instrum. Meas. **53**, 466 (2004).

[16] M. Kumagai, H. Ito, M. Kajita, and M. Hosokawa, Metrologia **45**, 139 (2008).

[17]T. E. Parker, Metrologia **47**, 1 (2010).
[18]T. E. Parker, in *Proceedings of the 2011 Joint Conference of the IEEE International Frequency Control Symposium and the European Frequency and Time Forum, San Francisco, CA, 2011*, pp. 596–599.
[19]J. Levine, Rev. Sci. Instrum. **83**, 021101 (2012).
[20]R. J. Douglas and J. S. Boulanger, in *Proceedings of the 11th European Frequency and Time Forum, Neuchatel, Switzerland, 1997*, pp. 345–349.
[21]D. H. Yu, M. Weiss, and T. E. Parker, Metrologia **44**, 91 (2007).
[22]D. W. Allan, IEEE Trans. Ultrason. Ferroelectr. Freq. Control, **34**(6), 647 (1987).
[23]T. E. Parker, in *Proceedings of the 1999 Joint Meeting of the IEEE International Frequency Control Symposium and the European Frequency and Time Forum, Besancon, France, 1999*, pp. 173–176.
[24]D. W. Allan and M. Weiss, in *Proceedings IEEE Frequency Control Symposium, Philadelphia, PA, 1980*, pp. 334–356.
[25]T. E. Parker and D. Matsakis, GPS World **15**, 32 (2004).
[26]G. Petit and Z. Jiang, Metrologia **45**, 35 (2008).
[27]K. M. Larson, J. Levine, L. M. Nelson, and T. E. Parker, IEEE Trans. Ultrason. Ferroelectr. Freq. Control **47**(2), 484 (2000).
[28]D. Kirchner, *Review of Radio Science 1996–1999* (Oxford University Press, New York, 1999), pp. 27–44.
[29]T. E. Parker and V. Zhang, in *Proceedings of the 2005 Joint IEEE International Frequency Control Symposium and Precise Time and Time Interval Systems and Applications Meeting, Vancouver, Canada, 2005*, pp. 745–751.
[30]D. Piester, A. Bauch, L. Breakiron, D. Matsakis, B. Blanzano, and O. Koudelka, Metrologia **45**, 185 (2008).
[31]A. Amy-Klein, O. Lopez, F. Kéfélian, C. Chardonnet, H. Jiang, and G. Santarelli, in *Proceedings of the Joint European Frequency and Time Forum and 2009 IEEE International Frequency Control Symposium, Besancon, France, 2009*, pp. 813–814.
[32]G. Panfilo and T. E. Parker, Metrologia **47**, 552 (2010).
[33]S. A. Diddams, J. C. Bergquist, S. R. Jefferts, and C. W. Oates, Science **306**, 1318 (2004).
[34]T. Rosenband, D. B. Hume, P. O. Schmidt, C. W. Chou, A. Brusch, L. Lorini, W. H. Oskay, R. E. Drullinger, T. M. Fortier, J. E. Stalnaker, S. A. Diddams, W. C. Swann, N. R. Newbury, W. M. Itano, D. J. Wineland, and J. C. Bergquist, Science **319**, 1808 (2008).
[35]E. Samain, P. Exertier, Ph. Guillemot, F. Pierron, D. Albanese, J. Paris, J.-M. Torre, I. Petitbon, and S. Leon, in *Proceedings of the Joint European Frequency and Time Forum and 2009 IEEE International Frequency Control Symposium, Besancon, France, 2009*, pp. 194–198.
[36]L. Cacciapuoti, R. Much, S. Feltham, R. Nasca, T. Vudali, M. P. Hess, L. Stringhetti, and C. Salomon, in *Proceedings 24th European Frequency and Time Forum, Noordwijk, NL, 2010*.
[37]J. G. Hartnett and A. N. Luiten, Rev. Mod. Phys. **83**, 1 (2011).