Local Distribution and Calibration of Timing Signals at NIST

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BIOGRAPHIES

Joshua Savory is a physicist at the National Institute of Standards and Technology. He works in the Atomic Standards group on the NIST timescale and is currently constructing NIST-F3, a continuously running cesium fountain. Previously, he was a postdoctoral researcher at the National High Magnetic Field Laboratory, where he worked on the development of a 21-Tesla FT-ICR (Fourier Transform – Ion Cyclotron Resonance) mass spectrometer. He earned a Ph.D. in nuclear physics from Michigan State University in 2009. His thesis work was completed at the National Superconducting Cyclotron Laboratory, where he performed high-precision mass measurement of radioactive nuclei to better understand astronomical events.

Stefania Römisch is originally from Torino, Italy. She received her Ph.D. in Electronic Instrumentation in 1998, from Politecnico di Torino, Italy. She was a Guest Researcher at NIST (National Institute for Standards and Technology) in Boulder, CO and then joined the Department of Electrical and Computer Engineering of University of Colorado at Boulder. After a few years of work as an independent contractor at Spectral Research, LLC, she joined the Time and Frequency Division of NIST in Boulder, CO. She now leads the Atomic Standards Group whose activities include the generation of UTC(NIST), and the use of GPS and TWSTFT to contribute to Universal Coordinated Time. Her research interests span from time scale generation to the calibration of time transfer links and the application of time synchronization to fundamental physics experiments.

Liz Catherine Hernández Forero is originally from Bogotá, Colombia. She received her Magister in Electronic Engineering and Computers in 2013, from Universidad de los Andes, Colombia. She has been working in Metrology of Time and Frequency since 2008 and from 2012 to 2013 she was involved in Electric Variables Metrology. Since 2014 has worked as a head of the Time and Frequency Laboratory of the National Metrology Institute of Colombia (Instituto Nacional de Metrología de Colombia - INM). In 2015 she was a Guest Researcher at NIST (National Institute for Standards and Technology) in Boulder, CO, and her tasks were related to the Atomic Standards Group. Her activities at INM include the time scale generation of Colombia, the calibration of time and frequency standards from customers, technical assistance in evaluating the external metrology laboratories which are part of the quality system in Colombia and activities of time synchronization projects. Her research interests are related to the generation of UTC(INM).

K. Bradley Maurer is a mechanical engineering student at Colorado State University, with graduation expected in 2019. His main interests are in designing vehicles. He enjoys working on mechanical projects such as bicycles and airplanes, has restored a 1973 Volkswagen Super Beetle, and is a licensed pilot. Working at NIST to design and build the clock cart was his first experience as a paid engineer, and he sees it as one of his greatest achievements. He had previously volunteered for two years at the Colorado Railroad Museum rebuilding historic railway cars, and since has worked as a bicycle mechanic for Performance Bicycle. He lives in Arvada, Colorado, and attends school in Fort Collins.

ABSTRACT

The National Institute of Standards and Technology (NIST) timescale produces a real-time realization of UTC(NIST) in the form of a pulse-per-second (PPS) time signal and a 5 MHz frequency reference. UTC(NIST) contributes to UTC (Coordinate Universal Time) using TWSTFT (Two-Way Satellite Time and Frequency Transfer) and common-view GPS (Global Positioning System) techniques. The NIST timing signal is also disseminated to the international and domestic communities using various other techniques: NIST Automated Computer Time Service (ACTS), Internet Time Service (ITS) and NIST Time Measurement and Analysis Service (TMAS). The accuracy of NIST contribution to UTC and of the dissemination of the NIST PPS time signal

depends upon the quality of the calibration of the time delay between each user and the UTC(NIST) reference point. Hardware constraints, spatial constraints, and in some cases simple convenience, require that the physical input to the transfer and dissemination equipment be distributed throughout the NIST campus. A robust on-campus timing distribution and calibration system is required to ensure the accuracy and stability of these signals: for example, the current error budget for a typical time transfer calibration requires local delays to be known to an uncertainty of less than 200 ps. We utilize a clock trip calibration protocol to measure the delays introduced by the local time distribution system at NIST: a clock trip involves measuring the time difference between the UTC(NIST) reference point and a travelling clock, then transporting the travelling clock to a secondary reference point where another measurement of the time difference is performed. Clock trips are advantageous as they are a nonintrusive measurement of the full system delay. To achieve calibrations with an accuracy on the order 100 ps, we have developed a means to transport a cesium clock between remote locations on site with minimal vibration and an analysis protocol to maximize the information acquired by each clock trip. We will introduce the system used to distribute time signals at NIST, the hardware and protocol we have developed to calibrate secondary timing reference points, and data we have collected based on their implementation.

INTRODUCTION

The real-time realization of UTC(NIST) as a 1-pulse-per-second timing signal is defined at its reference point, at a specific location on the NIST campus. While frequency references are easily distributed to users, time references must be distributed with care and require periodic and accurate measurements of the delay between the reference point and the users to preserve the quality of the distributions system. The scope of this paper is limited to the distribution of UTC(NIST) within the NIST campus, hence the use of the term “local”, however local time distribution at NIST has a much broader impact. The quality of a timing laboratory’s local time distribution system directly impacts the overall accuracy of the time transfer between that laboratory and any other member of the timing community, including participation in the generation of UTC.

Starting in the 1960s, the transportation of stable clocks between different points in a timing distribution system was the primary way to accurately measure the time difference between time references in different locations (i.e. “synchronizing” the two locations) [1-4]. Later, the transportation of stable clocks was used to verify gravitational time dilation and special relativity in a series of experiments described in [5,6]. Described in this paper is the first recent sustained effort to achieve and maintain accurate calibration of the time distribution system internal to the NIST campus. There were several motivations leading to this effort: the construction of a new building on the NIST campus, the newly structured global calibration campaigns for both GPS time transfer and TWSTFT promoted by BIPM through the work of the CCTF (Consultative Committee for Time and Frequency) GNSS (Global Navigation Satellite System) and TWSTFT Working Groups [7,8]; and the impending installation of the ground terminal for the microwave link to the International Space Station (ISS) as part of the Atomic Clock Ensemble in Space (ACES) project [9]. All of these require accurate knowledge of the delay between the user and the UTC(NIST) time reference point.

In particular, two secondary reference points have been defined: one in the new building, which will serve the future primary GPS receiver, the future TWSTFT earth station and the Ground terminal for the ACES project; and one in the laboratory designated to host the travelling GPS systems that are used in all calibration campaigns involving NIST [10,11]. The clock trips are designed to calibrate the secondary reference points with respect to the UTC(NIST) time reference point. The delays between the secondary reference points and all the local users are regularly calibrated as well, but are not discussed in this paper. The reader can see a detailed discussion about measuring cable delays in [12].

DESCRIPTION OF A CLOCK TRIP

In a clock trip, a portable clock is moved between two locations (A and B) where the time difference between the travelling clock and the local time reference is measured. Using knowledge of the travelling clock’s frequency offset with respect to time reference A, their accumulated time difference when the travelling clock is measured at location B can be predicted. Using this predicted time difference and the time difference measurement made between the travelling clock and time reference B, the difference between time reference A and B can be calculated. The time references in A and B are considered to be of a quality that their rates are assumed to be essentially the same, while the travelling clock will have a frequency offset with respect to the time references. The frequency offset of the travelling clock can be estimated through an *a priori* or *a posteriori* comparison of the traveling clock and the time reference A, or by interpolating the time measurements of the travelling clock against time reference A made at the beginning and end of the clock trip.

After the measurements at location B, the travelling clock is then returned to its starting location A and a second (final) time difference is measured with respect to that time reference, providing the trip’s closure. In the situation at NIST this is simplified, as the clock at point A and B is essentially the same clock, UTC(NIST), with a time offset (delay). The closure provides a means to evaluate the quality of the clock trip, by verifying the predictability of the travelling clock's behavior. It is calculated by computing the difference between the measured value and predicted value for the time difference between time reference A and the travelling clock at the end of the clock trip.

THE TIME DISTRIBUTION SYSTEM

Figure 1 shows a conceptual diagram illustrating how UTC(NIST) is distributed throughout the NIST campus for the purpose of the clock trips discussed in this paper. The UTC(NIST) time reference point is defined in room 2051. The timing signal at the secondary reference point in room 4016 provides UTC(NIST) to the GPS travelling receivers used in several GNSS calibration campaigns, while the timing signal at the secondary reference point in room 1G124A will supply UTC(NIST) for the ACES project as well as for the new TWSTFT earth station and the future GPS primary receiver. In order to ensure high-quality timing signals to all users on campus, the 5 MHz signal from the NIST timescale is sent to room 4016 through a coaxial cable (FSJ1-50A) and to room 1G124A using a two-way, fiber-based frequency transfer system. Upon arrival in each room, the 5 MHz signal is converted into a PPS, using a PPS generator, which is input into a pulse distribution amplifier to create the 4016 and 1G124A secondary reference points and for dissemination of the PPS signal.

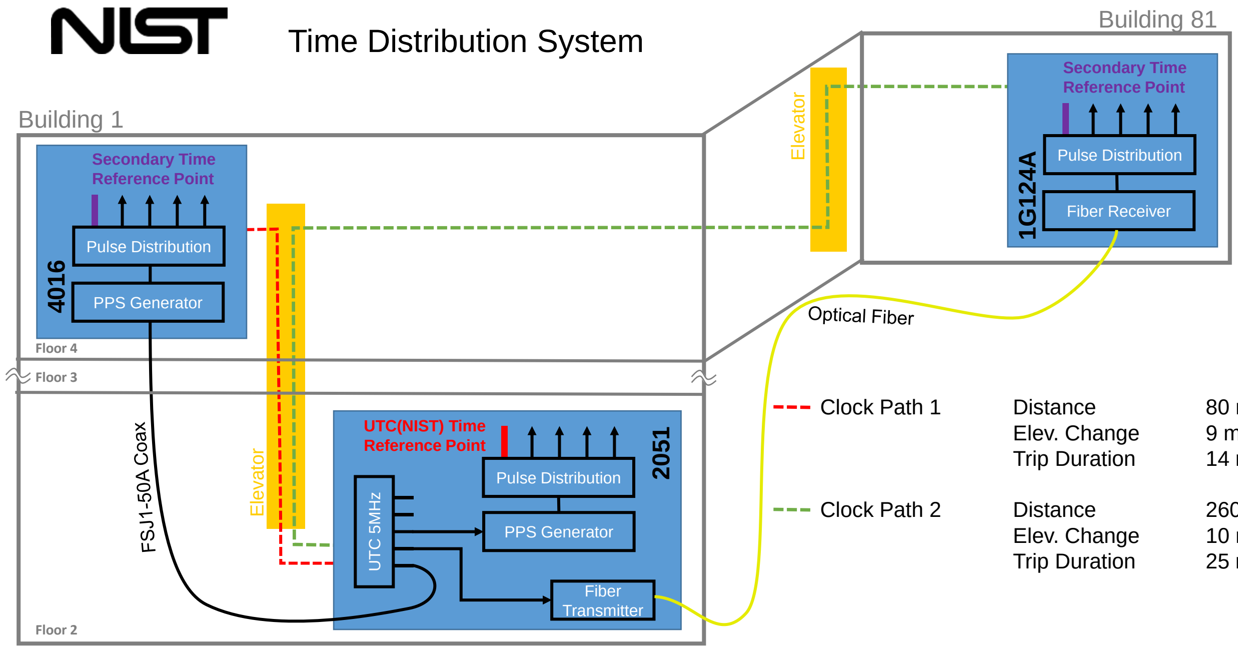

Figure 1. A simplified layout of the current time distribution system on NIST campus, with the clock trip paths from the UTC(NIST) time reference point to both secondary reference points.

THE CLOCK CART

To make the clock trip process easily repeatable and robust, a transport system, called a clock cart, was developed at NIST. The longest clock trip, approximately 260 m, is between 2051 and 1G124A (see Figure 1). This clock trip requires the clock to be transported between two separate buildings and through two elevators. Due to the possibility of vibration induced-clock errors [13] and damage to sensitive equipment, the cart was designed to have a high degree of mobility while simultaneously protecting the payload from any shock or vibration. Shown in Figure 2 is the clock cart designed and built at NIST to transport a 5071A cesium clock and the hardware required for all measurements in a clock trip. The clock cart consists of an outer frame and inner frame made out of 80/20 aluminum hardware. The outer frame is attached to four inflatable casters, and the inner frame is floated on the outer frame by four air springs with an isolation range of 70 lbs to 400 lbs each. The inner frame houses a 5071A cesium clock, a pulse-per-second generator, a time interval counter (HP5370B), and a 2 kVA Uninterruptable Power Supply (UPS).

A 5 MHz signal from the 5071A cesium clock is input into the PPS generator to create the travelling clock's PPS. This PPS is, in turn, connected to the stop channel of the time interval counter (TIC) which is used to measure the time difference between the travelling clock and the time reference at each location. Located on top of the outer frame of the cart is a laptop computer for data collection. The onboard UPS is necessary to keep all systems running during transport. The most important reason for having a UPS is that the cesium clock must be kept running to have phase continuity throughout the trip, but it also reduces the time required to restart the data collection at each location and reduces possible errors due to thermal effects at startup for all the hardware.

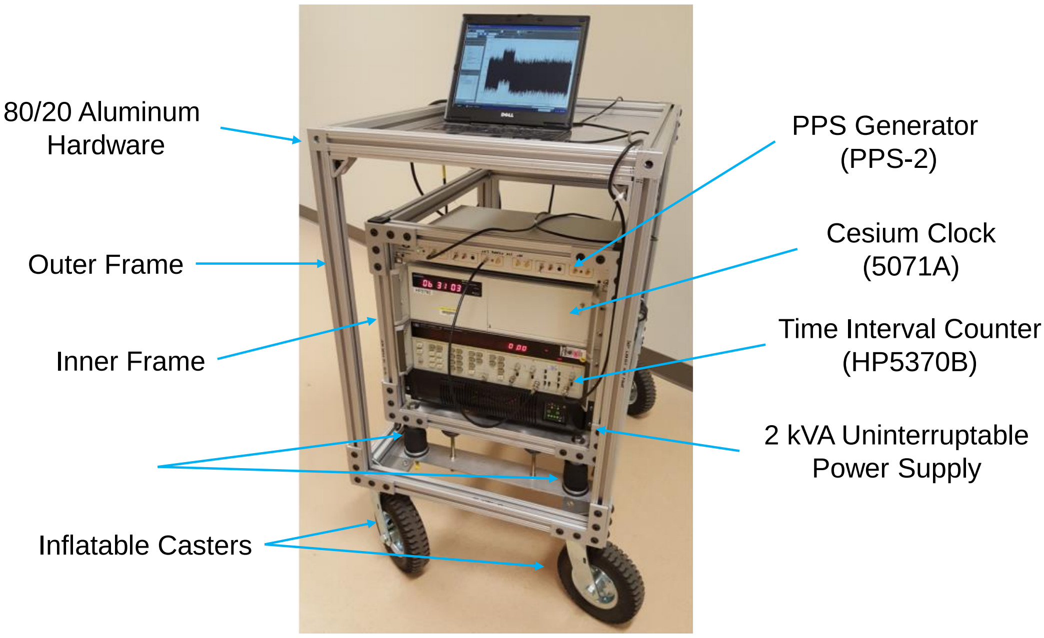

Figure 2. The clock cart designed and built at NIST to transport a 5071A cesium clock and the hardware required for all measurements in a clock trip

CLOCK TRIP MEASUREMENT PROTOCOL AT NIST

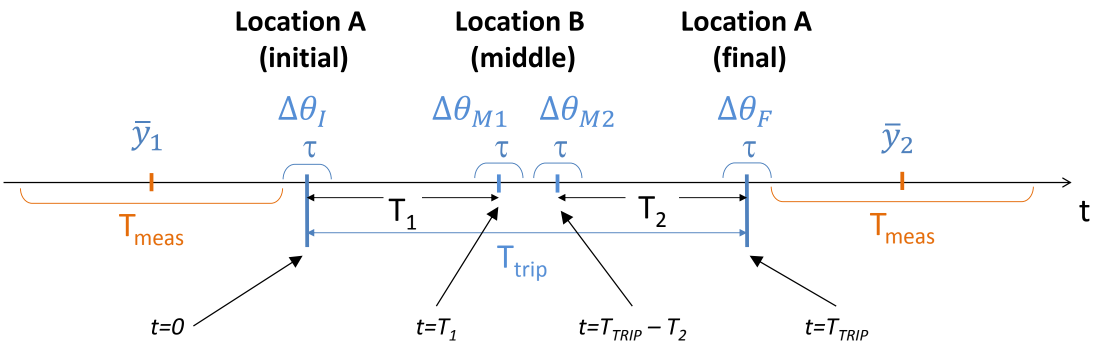

Figure 3. Typical timeline for a clock trip at NIST. The duration of each time difference measurement is τ, the time elapsed in the first and second half of the trip is T_1 and T_2, respectively.

Figure 3 shows the timeline of a typical clock trip at NIST, starting at Location A, going to location B and returning to location A for the trip's closure. The time differences between the travelling clock and the time references at all locations are measured with the time-interval counter on the clock cart for a duration τ and are indicated with $\Delta\theta_I, \Delta\theta_{M1}, \Delta\theta_{M2}$, and $\Delta\theta_F$. Two separate time difference measurements are performed at the trip's midpoint (Location B): this allows the separation of each clock trip in two independent halves, yielding two independent estimates of the time difference between the time references at A and B that can be averaged to increase the confidence on the final result. In order to predict the time difference between the travelling clock and time reference B the relative frequency offset of the traveling clock with respect to UTC(NIST) is required. This relative frequency offset is acquired through an *a priori* (y_1) and *a posteriori* (y_2) comparison of 5 MHz signals from the travelling clock and UTC(NIST) on a dual-mixer phase measurement system. The average values are estimated by calculating the difference between the initial phase and final phase differences $\Delta\theta_1$ and $\Delta\theta_2$ over a measurement duration of T_{meas} as shown below:

$$\bar{y} = \frac{\overline{\Delta\nu}}{\nu_0} = \frac{\Delta\theta_2 - \Delta\theta_1}{T_{meas}}. \quad (1)$$

Using this frequency offset the time difference between the travelling clock and the time reference A at the mid-point, in Location B, over the elapsed time T_1 is predicted to be:

$$\Delta\hat{\theta}_{M1} = \Delta\theta_I + \bar{y}_1 T_1. \quad (2)$$

Similarly, the second half of the trip yields a predicted time difference between time reference A and the travelling clock at Location B as:

$$\Delta\hat{\theta}_{M2} = \Delta\theta_F - \bar{y}_2 T_2. \quad (3)$$

The difference between each predicted time difference and the one measured at the mid-point location is a measure of the time offset D between the time references A and B:

$$D_1 = \Delta\theta_{M1} - \Delta\hat{\theta}_{M1} \quad (4)$$
$$D_2 = \Delta\theta_{M2} - \Delta\hat{\theta}_{M2}. \quad (5)$$

A weighted average of these two results, based on the uncertainty associated with each number, gives the time offset D between the time reference in location A (room 1G124A or room 4016) and the time reference in location B (UTC(NIST) time reference point). Finally, the closure (*C*) of the trip is defined as the difference between the time difference $\Delta\theta_F$, measured between the travelling clock and the time reference A at the end of the trip, and its value as predicted over the total time elapsed in the trip:

$$C = \Delta\theta_F - \Delta\theta_I - \bar{y}_1 T_{trip}. \quad (6)$$

Uncertainty considerations

The uncertainty of the calculated time offset consists of three components: the uncertainty of the frequency measurement, the phase noise of the TIC measurements, and the phase noise of the clock. In the case of the frequency measurement, the noise floor of the dual-mixer phase measurement system is below the clock noise at all times, so it is neglected. The uncertainty associated with the average relative frequency offset at the beginning (or at the end) of the clock trip is therefore simply the Allan deviation (σ_y) of the clock's noise at an averaging time of T_{meas}:

$$\delta y = \sigma_y(T_{meas}). \quad (7)$$

The frequency noise of a high-performance 5071A cesium clock remains white out to several days, so a T_{meas} of 24 hours was chosen as a reasonable averaging time.

The time differences measured at each location by the TIC transported with the travelling clock are averaged over a time τ that was chosen to be approximately 10 seconds, which is the measurement time required to average the white TIC noise to reach the underlying clock noise. The uncertainty of the predicted time differences at location B is, applying the usual propagation of errors to (2) and (3):

$$\delta\Delta\hat{\theta}_{M1} = \sqrt{\delta\Delta\theta_I^2 + \delta\theta_{ck}^2(T_1) + [T_1 \cdot \delta y_1(T_1)]^2} \quad (8)$$
$$\delta\Delta\hat{\theta}_{M2} = \sqrt{\delta\Delta\theta_F^2 + \delta\theta_{ck}^2(T_2) + [T_2 \cdot \delta y_2(T_2)]^2}. \quad (9)$$

Where $\delta\Delta\theta_I$and $\delta\Delta\theta_F$ are the TIC's measurement noise at t=0 and t=T_{trip}, respectively, and $\delta\theta_{ck}^2$ is the uncertainty contribution due to the travelling clock's phase noise, after elapsed times T_1 and T_2. In the presence of white FM noise, which is the case for the entire duration of the clock trip when using a 5071A cesium clock, the optimum predictor for the standard deviation of time is the Allan deviation [14], resulting in:

$$\delta\theta_{ck}(T) = T \cdot \sigma_y(T). \quad (10)$$

Finally, using again the law of propagation of errors, the uncertainty associated with D_1 and D_2, the time offset between the time references A and B estimated by the two halves of the trip, can be written as:

$$\delta D_1 = \sqrt{\delta\Delta\theta_{M1}^2 + \delta\Delta\hat{\theta}_{M1}^2} = \sqrt{\delta\Delta\theta_{M1}^2 + \delta\Delta\theta_I^2 + \left[T_1 \cdot \sigma_y(T_1)\right]^2 + \left[T_1 \cdot \sigma_y(T_{meas})\right]^2} \quad (11)$$

$$\delta D_2 = \sqrt{\delta\Delta\theta_{M2}^2 + \delta\Delta\hat{\theta}_{M2}^2} = \sqrt{\delta\Delta\theta_{M2}^2 + \delta\Delta\theta_f^2 + \left[T_2 \cdot \sigma_y(T_2)\right]^2 + \left[T_2 \cdot \sigma_y(T_{meas})\right]^2}. \quad (12)$$

The travelling clock's noise is white FM throughout the entire clock trip, including the *a priori* and *a posteriori* measurements used to estimate its average fractional frequency offset. Under this assumption the Allan deviation for a generic averaging time T can be written as $\sigma_y(T) = T^{-1/2} \cdot \sigma_y(1s)$, and (11) can be rewritten as:

$$\delta D_1 = \sqrt{\delta\Delta\theta_{M1}^2 + \delta\Delta\theta_I^2 + T_1\left(1 + \frac{T_1}{T_{meas}}\right)\left[\sigma_y(1s)\right]^2} \quad (13)$$

where the importance of executing a clock trip in the shortest amount of time (T_1) possible is apparent. Similarly, it shows the need to perform the longest (reasonable) measurement (T_{meas}) for the estimation of the fractional frequency offset of the clock. The final time offset D is the weighted average of the two values D_1 and D_2 as:

$$D = \frac{\left(\frac{D_1}{\delta D_1^2} + \frac{D_2}{\delta D_2^2}\right)}{\frac{1}{\delta D_1^2} + \frac{1}{\delta D_2^2}} \quad (14)$$

with an uncertainty of:

$$\delta D = \sqrt{\frac{1}{\frac{1}{\delta D_1^2} + \frac{1}{\delta D_2^2}}}. \quad (15)$$

Similar considerations are used to compute the uncertainty on the trip's closure C, using the propagation of errors applied to (4) and (5):

$$\delta C = \sqrt{\delta\Delta\theta_I^2 + \left[T_{trip} \cdot \sigma_y(T_{trip})\right]^2 + \left[T_{trip} \cdot \sigma_y(T_{meas})\right]^2 + \delta\Delta\theta_F^2}. \quad (16)$$

A clock trip with a closure that is statistically consistent with zero confirms the predictability of the travelling clock (within its uncertainty), allowing for the use of its results. When the closure is not consistent with zero the results should be discarded, if possible, and a new clock trip should be performed. An uncertainty level of $2\delta C$ was administratively selected as it provides a tight constraint on the validity of the measurements, yet only rejects ~5% of potentially valid data.

The clock trip analysis procedure described in this section was automated using NI LabVIEW. The automation of this procedure reduces the time required to compute a results, the risk of computation errors and allowed the regular performance of clock trips without excessive burden on NIST personnel. As is apparent in the discussion that follows, the repetition of our clock trips provides statistical information on the measured delay resulting in increased confidence in the results and monitoring of the distribution system for degradation or failure. For documentation purposes the same analysis program also generates a report including the results and clock trip parameters.

DISCUSSION OF RESULTS

As described earlier in the paper, the purpose of these clock trips is to measure the time offset between two secondary reference points (in rooms 1G124A and 4016) and the UTC(NIST) time reference point. These two time offsets are measured with separate sets of clock trips: one where Location A is room 1G124A and the other one where Location A is room 4016. In both sets the UTC(NIST) time reference point is at Location B (the trip mid-point).

Secondary reference point in 4016

The UTC(NIST) 5 MHz signal used to create this secondary reference point is brought to the room using a high-quality coaxial cable, and is expected to be largely stable (i.e. not drifting significantly) over long times. The periodic clock trips have the purpose of verifying the validity of this assumption and of detecting any anomalies. Several clock trips were performed over more than one year, the results of which are shown in Figure 4. On the left hand side are displayed the measured time offsets and their associated uncertainties, computed as described earlier in this paper, together with their weighted average shown in red, with the two dashed lines indicating the 1-sigma uncertainty on the mean estimated using the standard deviation of the set. The weighted average to date is the accepted time offset of this secondary reference point with respect to UTC(NIST) time reference point and is:

$$D_{4016-UTC(NIST)} = 495.76 \ \pm 0.04 \text{ ns}.$$

As expected from a simple coaxial cable, the time offset doesn't appear to significantly drift over time, at least out to one year. In the right hand side of Figure 4 are shown the closure values computed for all the clock trips with their 1-sigma uncertainties, together with their weighted average and the 1-sigma uncertainty of the average. All the clock trips for this location were statistically consistent with zero within 1-sigma, indicating a strong immunity of the transportation protocol from unwanted vibrational or shock-induced effect on the travelling clock's internal quartz oscillator.

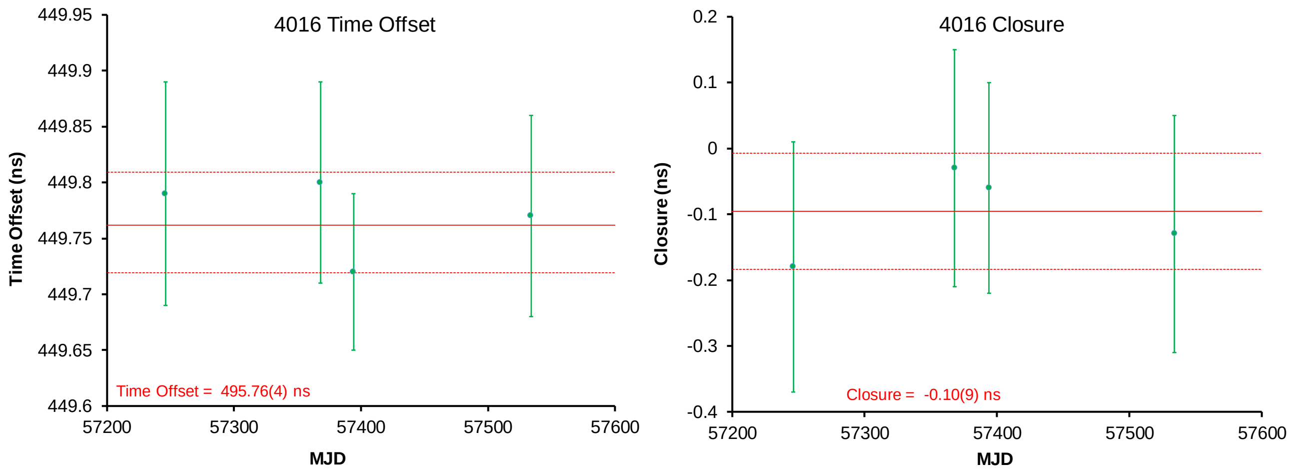

Figure 4. Results of the time offset (left) and closure (right) measurements to 4106. The solid red lines are a weighted average for the measurements and the dashed red lines represent the uncertainty.

Secondary reference point in 1G124A

This room is located in a different building on the NIST campus, and the UTC(NIST) 5 MHz signal used to create this secondary reference point is sent to this location using a two-way, fiber-based frequency transfer system over a distance of approximately 300 m. Measurements performed prior to the fiber transfer system's installation showed a long-term time drift of approximately 1 ps/day. To be able to maintain the uncertainty of the time offset between this secondary reference point with respect to UTC(NIST) within a few hundred picoseconds it is necessary to repeat a clock trip for this location approximately every 100 days. Several clock trips were performed, on average every 80 days, and the results are shown in Figure 5.

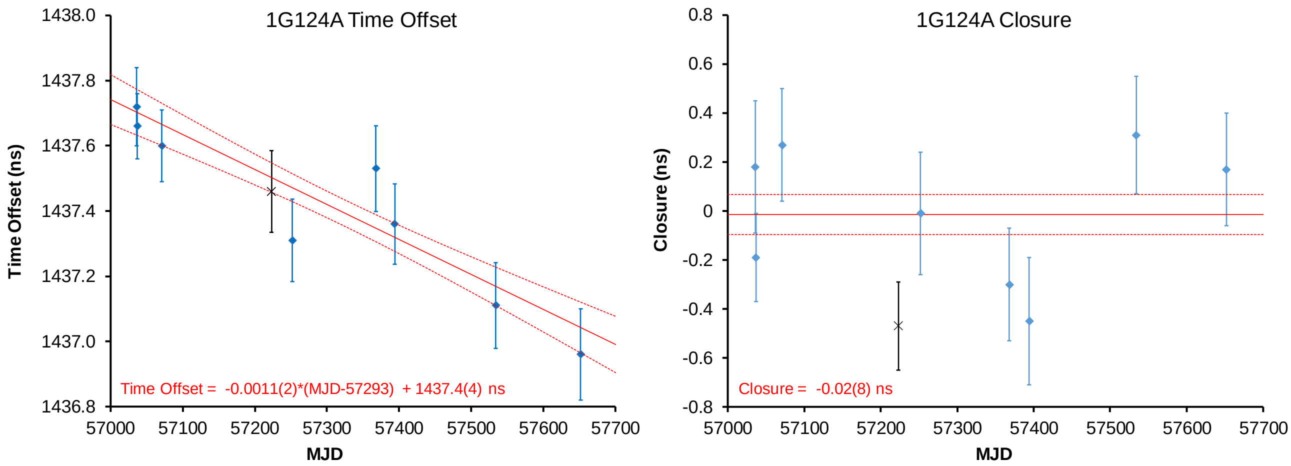

Figure 5. Results of the time offset (left) and closure (right) measurements to 1G124A. The solid red lines are a weighted average for the measurements and the dashed red lines represent the uncertainty. The points marked with a black x were rejected due to a statically non-zero closure value at the 2-sigma level.

The left hand side of Figure 5 shows the results of all the clock trips for this location. As expected, they show a small time drift in the fiber-base transfer system between the two buildings, which is evaluated by fitting the data set to a straight line (in red) using a weighted least square fitting routine. The value for the time drift yielded by the fit is 1.1 ± 0.2 ps/day, in agreement with the number that was measured in the preliminary characterization of the fiber transfer system. The value of the time offset between the secondary reference point in room 1G124A and UTC(NIST) is, to date:

$$D_{1G124A-UTC(NIST)}(57652) = 1437.04 \pm 0.08 \text{ ns.}$$

The right hand side of Figure 5 shows the closures computed for all clock trips to this location, with their 1-sigma uncertainty error bars. The weighted average of the closure values is also shown in red, together with its uncertainty (red dashed). There is a high degree of symmetry around an average that is almost exactly zero, and using a 2-sigma rejection criterion only one trip was rejected over the past year, indicated in black. The results of the rejected clock trip were not included in the computation of the weighted average and its uncertainty.

Considerations of systematic effects

The uncertainty of a time difference measurement is dependent on the equipment and measurement parameters used as well as the pulse shape of the timing signals [12]. To this end, the time base of the TIC was referenced to the traveling clock to reduce the effects of rate errors, and for consistency a trigger voltage of 1V was used for all measurement. Common mode biases due to the cabling and TIC were removed by performing differential measurements (see "pivot" in [12]): the time offset of interest is always obtained by subtracting two separate time difference measurements. The travelling clock was connected to the stop channel of the TIC, while the reference points of interest were always connected to the start channel, and the same cables were used for all measurements. Most of the common mode biases in the TIC and cabling can be removed assuming that the pulse shape is the same. Our situation is close to ideal as all the PPS signals discussed in this paper are measured directly from pulse distribution amplifiers of the same model with similar pulse profiles.

Additionally, the transportation of stable atomic clocks between locations requires, in general, a careful consideration of several systematic effects due to gravitational time dilation, Doppler shifts and Sagnac effects [4-5]. A preliminary evaluation of these effects for the paths of our clock trips showed them to be irrelevant with respect to the stated Type A uncertainties. The average of all accepted closures is statistically consistent with zero with a reasonably symmetric distribution of the values. This suggests a minimal impact of unaccounted Type B uncertainties (such as unaccounted biases in the time interval counter).

CONCLUSIONS

In order to calibrate remote reference points at NIST, a transport system for a 5071A cesium clock was constructed. Additionally, an analysis protocol was developed, and automated, to maximize the information acquired by each clock trip and to facilitate regular repetitions of the measurements. The results of delay measurements to two remote locations on campus show that measurements with a statistical uncertainty of less than 100 ps are routinely possible. The closure measurement suggests that vibration and the transportation of the clock don't significantly affect the quality of our results. In the future we plan to investigate the impact of error correlation, and unaccounted biases on the accuracy of these measurements.

DISCLAIMER

Certain commercial equipment, instruments, or materials are identified in this paper for informational purposes only. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

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