Measurements with Multiple Operational Fountain Clocks

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***Abstract*—Performance of the first two operational rubidium fountains at the USNO is presented using relative measurements and comparisons against other timescales. Recent results with four fountains indicate frequency agreement at the 10^{-15} level and good agreement with the primary frequency standards contributing to TAI.**

I. INTRODUCTION

The U. S. Naval Observatory (USNO) maintains an ensemble of atomic clocks for generation of a Master Clock, the physical realization of UTC(USNO). As many as 20 hydrogen masers and 70 commercial cesium clocks can contribute to the ensemble. The timescale used to generate UTC(USNO) relies on the short-term frequency stability of the masers and the long-term stability of the cesium clocks. In order to advance timekeeping activities, 7 rubidium fountain clocks are being added to the clock ensemble.

The fountains will serve as a long-term frequency reference, similar to but better than the lower-stability cesium clocks, but will not provide any tie to the SI second. In order for a fountain to be integrated into the USNO clock ensemble like any other clock, it generates a continuous 5 MHz output that can be measured against the Master Clock. The 5 MHz is generated from a precision synthesizer referenced to a maser that also serves as the LO reference for a fountain; the fountain adjusts the synthesizer's output based on its measurement of the maser frequency. The maser can act as a flywheel to minimize the effect of interruptions to fountain operation, but the fountains have been designed to operate continuously for long periods of time.

II. NRF2 AND NRF3

The design and operation of the first operational fountains, NRF2 and NRF3, have been described in [1]. The fountains were installed in a new clock building at the end of 2008, and have been under evaluation for about 2 years. During that time, much has been learned about obstacles to continuous, uninterrupted operation. Imperfections in the environmental controls in the clock building and faulty commercial electronics have disrupted fountain performance. Additionally, the semiconductor laser systems that we use need to be serviced at intervals of 1 to 2 years.

A. Relative Comparison

Despite these obstacles, several good periods of evaluation were obtained. Data from an uninterrupted 100-day comparison between NRF2 and NRF3 are shown in Fig. 1. The plot in Fig. 1(a) is the relative phase between the fountains after a single relative phase and frequency have been subtracted. The relative frequency removed from the data is 7.4×10^{-16}. A linear fit to the corresponding frequency data returns a slope of $4.2(2.7)\times10^{-18}$/day. The uncertainty is derived from the result in [2] for determining errors on frequency drifts in the presence of white frequency noise. In general, we measure frequency drifts that are consistent with zero (see section III. D.)

The Allan deviation between the two fountains, shown in Fig. 1(b), exhibits white frequency noise out to an averaging time of at least 23 days, with an average stability per fountain of $1.6\times10^{-13}/\tau^{1/2}$. During this 100-day comparison, each fountain operated virtually hands-free.

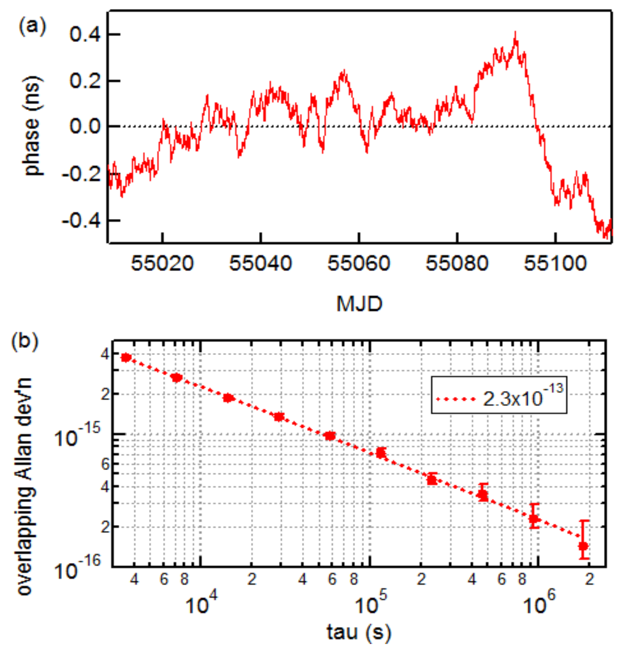

Figure 1 Data from 100-day comparison of NRF2 and NRF3. (a) Relative phase after removing single relative frequency and phase. (b) Overlapping Allan deviation versus integration time.

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B. *Comparison to USNO Timescales*

Fig. 2 shows a plot of the relative phase of NRF3 versus the USNO cesium mean and maser mean. The cesium mean is a timescale based solely on the cesium clocks and represents a long-term frequency reference; the maser mean tracks the cesium mean because each maser is characterized against the cesium timescale before the maser mean is generated. The plot in Fig. 2 demonstrates a relative drift between the long-term reference and the two rubidium fountains measured to be $2.1(0.5)\times10^{-17}$/day.

While the comparison between NRF2 and NRF3 was limited to 100 days, NRF3 ran uninterrupted for a period of 6 months. Over this period of time, NRF3 served as an internal UTC predictor; because the Circular T provides UTC some number of days in the past, the present value of UTC needs to be estimated.

III. Fountain Ensemble

A. *Fountain Mean*

Recently a second pair of fountains, NRF4 and NRF5, has begun operation, and all four fountains have been running for about 2 months. One of the ways the rubidium fountains will be used for timekeeping is to characterize the frequencies and frequency drifts of individual masers, which is currently carried out with the cesium clocks. With four fountains running, a fountain mean is in the process of being implemented as part of standard timescale generation.

Fig. 3 shows the relative phase of a preliminary fountain mean over 60 days versus the maser mean, as well as the relative phase of the cesium mean and the maser mean. No relative frequencies have been removed, and the masers are characterized by the cesium mean in each case. The plot demonstrates the dramatic improvement in short-term noise of a timescale generated with only four fountains compared to that generated with dozens of commercial cesium clocks, which directly translates to improved efficiency with which the masers can be characterized, as well as the relative drift between the fountain mean and cesium mean.

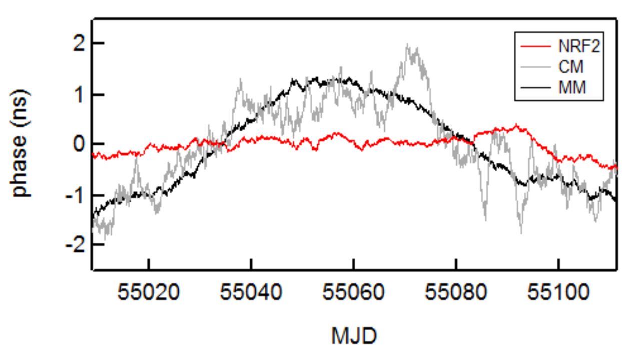

Figure 2 Relative phase of NRF3 and the cesium mean (grey), maser mean (black) and NRF2 (red), versus MJD. Each set of data has had its own relative phase and frequency removed. The NRF2 curve is the same data as in Fig. 1(a).

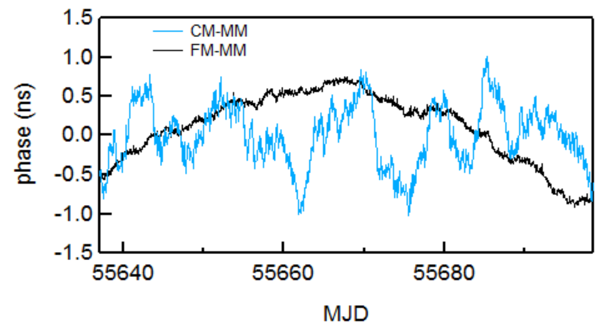

Figure 3 Plot of the relative phase of the fountain mean and the maser mean (black) and the cesium mean and the maser mean (blue) versus MJD.

B. *Relative Frequencies*

How well the frequencies of the four fountains agree is an interesting question. This is a question of the reproducibility of building and fielding these systems; in addition, the two pairs of fountains (NRF2 and NRF3 versus NRF4 and NRF5) have some different design elements.

The most significant potential source of frequency differences between fountains is the second-order Zeeman shift. The size of this shift is $575B^2$ (Hz/G^2). The fountains' magnetic fields are adjusted to be very close in value, to better than 1 μG, using the frequency of the central fringe of the magnetic field-sensitive $1\rightarrow1$ transition. Any error in determining this central fringe could lead to a frequency difference between fountains. The other most significant frequency biases, the black-body and gravitational shifts, should be common mode to a very high degree for the four systems. Other potential biases that could introduce frequency differences among the fountains are the cold-collision shift, cavity pulling, distributed cavity phase shift, and AC stark shift from stray laser light. The parameters determining these biases vary among some of the fountains.

Using data from the first 60 days when all of the fountains were running, the relative frequencies of all fountain pairs are measured. The results are shown in Fig. 4, where the error bars represent statistical uncertainties corresponding to the Allan deviation for a given comparison assuming white frequency noise. The raw frequencies (no biases adjusted for) all agree at the level of 10^{-15} or better.

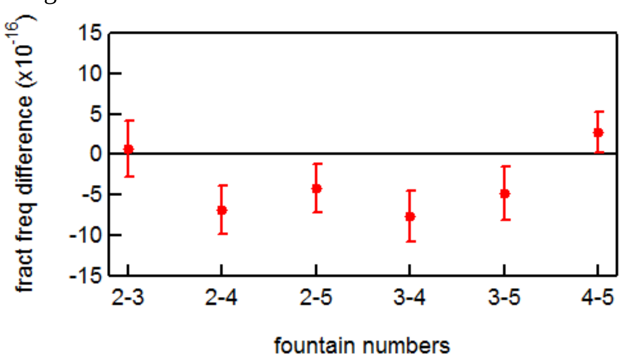

Figure 4 Fractional frequency difference between two fountains for all fountain pairs.

C. Frequencies Compared to Primary Standards

A rough measurement can be made of the fountain frequencies versus the frequencies of the primary standards used in determining International Atomic Time (TAI). The master clock is USNO's physical realization of UTC, which has the same frequency as TAI; a measurement of a fountain's frequency against the master clock, then, constitutes a measurement of the fountain compared to TAI. The frequency difference between TAI and the primary frequency standards is provided by the Circular T. The difference between these terms gives the frequency difference between a fountain and the primaries, which should correspond to the frequency bias of a given fountain.

We estimate the three most significant contributions to the frequency bias for a given fountain and remove them from the raw frequency difference between the fountain and the primaries. The results are shown in Table I. The values of the biases accounted for are -1.17×10^{-14} for the black-body shift for rubidium at T=295 K, 9.2×10^{-15} for the gravitational shift at an elevation of 84 m, and 6.97×10^{-14} for the second-order Zeeman shift at a bias field of 0.910 mG. In each case the uncertainty of the comparisons to the world's primary standards is dominated by the tie through TAI and UTC(USNO), which is estimated conservatively at 3×10^{-15}.

fountain number	$\Delta\nu$ $(\times10^{-15})$
NRF2	−.7
NRF3	−.8
NRF4	0
NRF5	−.3

Table I Average frequency difference between fountains and the primary frequency standards contributing to TAI after removing the frequency bias for each rubidium fountain.

D. Relative Frequency Drifts

The plot in Fig. 5 shows the measured relative frequency drift between all possible pairs of fountains over 60 days. All measured values are consistent with zero. The uncertainty is derived from the result in [2] for determining errors on frequency drifts in the presence of white frequency noise.

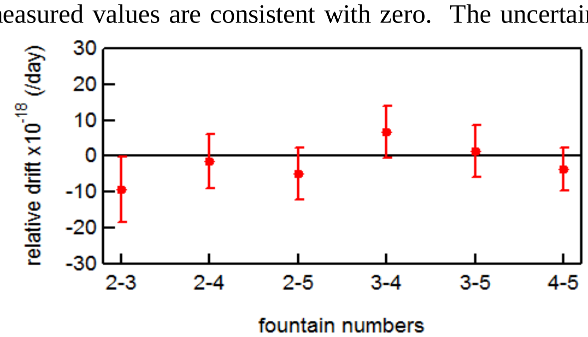

Figure 5 Plot of relative frequency drift for each pair of fountains.

IV. Scientific Application of Operational Fountains

Atomic clocks have found applications to fundamental science in addition to their roles in precise time and frequency metrology. According to current physical theories, which may need to be modified in order to arrive at a theory of quantum gravity, the relative frequencies of two atomic clocks using different atoms should be constant in both time and space. In particular, the principle of Local Position Invariance, an element of Einstein's Equivalence Principle, applied to atomic clocks dictates that the frequency difference between two different atomic clocks should stay constant as the clocks experience the same, varying gravitational potential. The varying gravitational potential that has been used to test this principle is provided by the elliptical orbit of the earth about the sun. This test therefore requires looking for an annual oscillation in the relative frequencies of two different types of atomic clocks.

The best test of this type to date has been carried out by comparing cesium primary frequency standards to hydrogen masers over the span of 7 years [3]. The discrete frequency measurements obtained with primary standards, typically several measurements per year, necessitates a long period of time to look for an annual variation. The authors of [3] relied on several primary standards to increase the rate of available measurements. Operation of a continuous fountain provides a high rate of frequency measurements against the reference maser (or other clock) that enables an annual variation to be searched for more efficiently. Estimates using a 6 month data set from NRF3 indicate that the statistical uncertainty achievable on a search for an annual term is comparable to the total uncertainty on the best current test of Local Position Invariance [3].

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