Rubidium-Fountain Characterization Using the USNO Clock Ensemble

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Abstract—**We have carried out stability comparisons between our rubidium fountain, built as a prototype for a continuously operating clock, and the USNO Maser Mean timescale. Long, continuous runs of the prototype system allow us to demonstrate fractional frequency-stability comparisons to the Maser Mean that integrate as white frequency noise, with a stability of 5×10^{-16} at one day. We have measured the frequency sensitivity of the rubidium fountain to various experimental parameters in order to establish the regulation required to reach a long-term stability of order 1×10^{-16}.**

I. Introduction

Since their introduction more than 50 years ago, atomic clocks have revolutionized time and frequency applications. The advent of laser cooling of atoms brought about dramatic improvements in atomic-clock performance, particularly in the area of primary standards, resulting in the transformation from systems based on beams of atoms to ones that interrogate a cloud of cold atoms tossed in a fountain geometry. Atomic-fountain clocks are being operated at several laboratories throughout the world and have been contributing to the BIPM for almost a decade. The U. S. Naval Observatory has a program to construct six operational rubidium fountains to include in its clock ensemble and improve its time-keeping capabilities.

One of the challenges introduced by improvements in clock technology is the determination of the performance of the (purportedly) best clocks. All frequency and time measurements are referential, and comparing a state-of-the-art clock to one that is less precise reveals little about the performance of the better clock. Typically, the frequency of a fountain clock is compared to the frequency of a hydrogen maser, which usually has superior short-term performance. This enables characterization of the fountain for averaging times on the order of several hours. Beyond this duration, maser frequency fluctuations tend to dominate the stability comparison, making further fountain characterization difficult.

Because of this difficulty, many timing laboratories build at least two fountains or other high-stability clocks for characterization. We carried out a comparison between our rubidium fountain prototype, NRF1, and our research cesium fountain, NCF, but because the older cesium system was not built for continuous operation, the measurement times were limited to several days [1]. In this paper, we present further characterization of NRF1 by comparing its continuous phase output during several long runs to the observatory's most stable timescale. We also present measurements of the stability of various systematic frequency shifts and project the required regulation of particular operational parameters to reach our goal of long-term fractional-frequency reproducibility of order 1×10^{-16}.

II. Design Improvements

The design of NRF1 has been discussed in detail previously [2]. Two of the major technical challenges to building a continuously operating fountain clock are the laser and optical systems. We use a miniature optical table that is very robust and stable, which has not been an obstacle to continuous operation at any point in the past two years [3]. This optical table provides the agile frequency tuning, intensity modulation, and power division for the fiber outputs that connect to the physics package. Improved air filtration and optical isolation have made our Ti:sapphire laser more robust, enabling us to carry out long, continuous runs with NRF1. We successfully demonstrated continuous operation for a month, at which point we intentionally terminated the run to pursue other measurements. However, maintaining operation over this time required occasional (once to several times a week) adjustments to some part of the Ti:sapphire laser system.

For a more robust laser solution, we have implemented an all-semiconductor system, consisting of an external-cavity diode laser (ECDL) followed by a tapered-diode amplifier. The ECDL exhibits an intrinsic line width of several hundred kilohertz for short averaging times and delivers up to 50 mW of power. The tapered amplifier can generate 1 W of output power with a gain of 40. The two laser heads, 60 dB of optical isolation, and fiber launching components are all located on a small optical breadboard that we intend to rack mount. Sensitivity of the ECDL to acoustic noise necessitates isolation of this laser table using a lead-lined foam box. Several months of experimentation and fountain operation with the system give us confidence that it will serve as a suitable laser source for NRF1 and it will be used in our future fountain systems.

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III. Measurement Against Maser Mean

The ability to operate NRF1 continuously allows us to make comparisons to any clock or timescale at the observatory. We use a 5 MHz signal from a quartz oscillator phase-locked to a hydrogen maser to generate the 6.8 GHz microwave drive for the fountain and also as the reference for a high-precision frequency synthesizer (or AOG, for "Auxiliary Output Generator") [4]. The difference in frequency between the microwave drive and the atoms' clock transition is written via RS232 to the AOG with a gain of 0.28 once every 16 fountain cycles (19.2 seconds), making an effective time constant of 58 seconds. The AOG's steered frequency output is monitored on one channel of a dual-mixer measurement system. This system measures most of the observatory's masers and several physical timescales, using each of our primary and backup master clocks as a reference. These data are recorded, allowing for a large array of inter-comparisons between clocks as well as providing the measurements used to generate the observatory's timescales. While these phase data are recorded every 20 seconds, we use a decimated data set with hourly samples for the medium- and long-term analyses presented here.

The most stable reference for post-processing comparisons is the developmental USNO Maser Mean [5]. In Fig. 1 we show the results of measuring the stability of NRF1 against the Maser Mean over an event-free period of 11 days. After a single relative frequency and starting phase have been removed, the peak-to-peak phase deviation between NRF1 and the Maser Mean during this interval is less than 200 ps. The Allan-deviation plot shows that the relative frequency fluctuations integrate as white frequency noise at a rate of $1.5\times10^{-13}/\tau^{1/2}$ for averaging times up to 2.5 days, reaching 5×10^{-16} at one day and $\sim3\times10^{-16}$ at 2.5 days. While the fountain ran continuously for intervals as long as one month, significant humidity and temperature fluctuations in the lab prevented us from obtaining a more lengthy comparison.

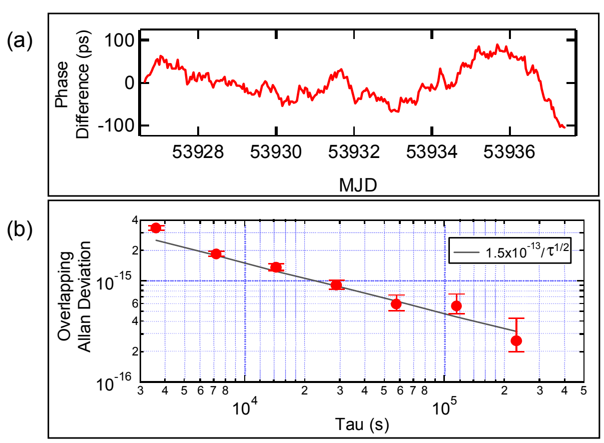

Figure 1. (a) Plot of phase comparison between NRF1 and the Maser Mean for an 11-day run. (b) Plot of overlapping Allan deviation versus integration time.

IV. Systematic Frequency Shifts

Even longer runs – and perhaps even better clocks for comparison – are required to analyze whether NRF1 will flicker at this level, and whether it will exhibit random walk, or drift. It is far more efficient to try to determine the limits to performance by considering the stability of known systematic frequency shifts. By measuring the sensitivity of NRF1 to large changes in experimental parameters we can infer the required regulation of those parameters to reach our long-term frequency stability goals. While these systematic measurements are often made for an accuracy evaluation of primary standards, we seek to determine the ultimate frequency reproducibility of our system and are only interested in the stability of these frequency shifts.

A. Methods

We measure the sensitivity of the fountain to a given experimental parameter by modulating it between two or more values. This modulation can be as fast as once every other fountain cycle, but we typically chose an interval of once every 30 minutes, during which time the measurement of the frequency shift from this modulation is still limited by the fountain rather than a single reference maser. We use comparisons to the Maser Mean for modulations that can not be changed rapidly, as detailed later in this paper. Most measurements of the sensitivity to these modulations reach an uncertainty of order 1×10^{-15} in one day. The sensitivity and uncertainty can be used to ascertain the regulation required to reach our long-term reproducibility goal of $1\text{-}3\times10^{-16}$. In Table 1, we summarize the results of all of the systematic frequency-shift stability measurements we have investigated to date and the regulation necessary to limit each effect to a contribution of 1×10^{-16} or less.

B. Magnetic Fields

We run NRF1 with a Magneto-Optical Trap (MOT) for the atom-collection phase, which requires the application of a magnetic quadrupole field. This field is applied with coils that are inside three of the four magnetic shields, resulting in a frequency shift that depends on the trapping-field strength. Measuring this shift by modulating the strength of the trapping field gave results that varied depending on the frequency of the modulation cycle. We believe this is likely due to a slow relaxation of the magnetic shields to the changing MOT field. To obtain a value that corresponds to the shift we might be susceptible to when running continuously, we kept a particular value of the field for 2-3 days and measured NRF1's frequency versus the Maser Mean over that interval. This measurement for three different values of current in the MOT coils is shown in Fig. 2. The measured shift is $1.4(0.6)\times10^{-15}$/A, and we run at a MOT current of roughly 2.4 A. This requires a regulation of the MOT current of 2%, while our current is stable to much better than 1%.

TABLE I. TABLE SHOWING RESULTS OF SENSITIVITY OF NRF1 TO VARIOUS PARAMETERS. THE MEASURED VALUES FOR THE THIRD THROUGH SIXTH ENTRIES ARE CONSISTENT WITH ZERO FREQUENCY SHIFT. THE REQUIRED REGULATION FOR THESE PARAMETERS ARE THEREFORE WORST-CASE SCENARIOS, AND MAY BE MUCH LESS STRINGENT. THE LAST ENTRY IS A CALCULATION FOR WHICH NO UNCERTAINTY HAS BEEN INCLUDED.

PARAMETER	***SLOPE AND UNCERTAINTY***	***REGULATION FOR 1×10^{-16}***
MOT current	$1.4(0.6)\times10^{-15}$/A	2%
C-field current	$-3.5(0.2)\times10^{-15}$/µA at 100 µA	0.03% at 100 µA
Atom number	$-8(12)\times10^{-16}$/popn	5%
Microwave power	$3.9(4.0)\times10^{-15}$/nW	2%
Laser power	$-0.6(2.2)\times10^{-15}$/W	3%
Inclination	$0.4(5.2)\times10^{-16}$/mrad	0.15 mrad
Microwave power balance	$3.6(0.2)\times10^{-14}$/(full imbalance)	0.3%
Temperature (blackbody shift)	-1.7×10^{-16}/°C	1.5% at 32 °C

The size of this shift on the clock transition corresponds to a change in the magnetic field seen by the atoms of order 40 µG. This is a small addition to our C-field of 2.3 mG, therefore it is reasonable to expect a linear dependence of the frequency shift on MOT current.

In addition, there is a quadratic sensitivity of the clock frequency with magnetic field in the free-precession region. We were unable to characterize the magnetic field by running on the linearly sensitive Zeeman line due to a transverse magnetic field at the cavity of roughly 300 µG and its associated gradients. We did verify that the quadratic Zeeman shift has the expected form and magnitude, giving us confidence in using the theoretical sensitivity in our projected long-term stability. This projection dictates regulating the 100 µA current in the C-field to 0.03%. This level of regulation has been successfully demonstrated in our cesium research fountain.

C. Atom Number

We attempted to measure an atom number-dependent frequency shift by modulating the number of launched atoms. The number was changed by modulating the microwave power in the state-selection cavity between the nominal operating power and lower values. We saw no shift, measuring a statistically limited value of $-8(12)\times10^{-16}$, for a change from nominal operating conditions (on order of 10^5 detected atoms) to no atoms. This limit would require 5% regulation in the atom number. We plan on running these tests longer to reduce the statistical errors because we anticipate the actual shifts to be negligible for our operating conditions. Calculations based on parameters realized in our system and others' measurements [6,7] indicate a maximum collision shift of 5×10^{-17}, implying that this systematic shift should not cause instability at the level of 1×10^{-16} for any degree of atom-number fluctuations.

D. Microwave Power

Modulation of the microwave power applied to the clock cavity between our operating value of −57.5 dBm and several lower values revealed no frequency shift at the demonstrated level of precision. The statistical uncertainty allows us to put a limit on the required power regulation of 3%. The microwave power was adjusted by amplitude modulating the IF drive that is mixed with the 6.8 GHz signal to generate the microwaves for Ramsey interrogation. The reduced sensitivity to frequency fluctuations at the lower microwave powers was taken into account.

E. Laser Power

Several measurements were made in which different laser beams were left on during the free-drift time. These indicate the required degree of shuttering required for each individual beam, which is trivial to meet with a physical shutter as long as it closes completely. We also measured the sensitivity to stray light on our laser table by modulating the operation of a shutter before the input fiber. The result is consistent with zero frequency shift, with a statistically limited uncertainty corresponding to a requirement that the optical power on the laser table be stable to 3%. Operating with a shutter before the input fiber is problematic because of the proximity to the vibration-sensitive ECDL.

F. Inclination

We measured the frequency sensitivity to changes in the apparatus angle with respect to the vertical direction. When the microwave cavity is driven symmetrically from both sides, the measured change in frequency with tilt angle is consistent with zero, with a statistical uncertainty corresponding to a required vertical alignment of 0.15 mrad. The maximum frequency sensitivity we see for an unbalanced drive is $3.6(0.2)\times10^{-14}$ for no tilt, and $7.7(0.5)\times10^{-14}$ at a tilt of 5 mrad. This implies a requirement that the microwave drive be balanced to 0.3% when the vertical alignment is better than 0.3 mrad. However, this measurement did not exhibit the monotonic behavior expected for the distributed cavity-phase shift [8], most likely due to the magnetic-field gradient, discussed above, which complicates the atoms' frequency dependence on cavity position.

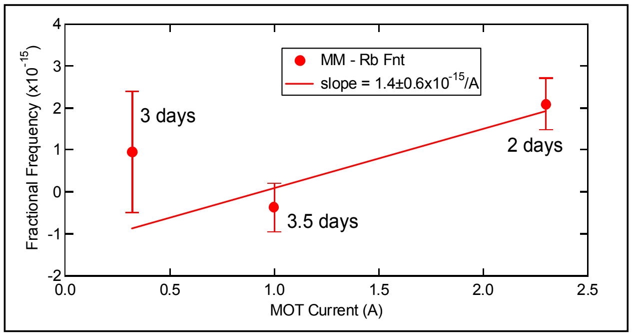

Figure 2. Results of measurement of frequency shift introduced by MOT magnetic field. The shift versus MOT coil current is plotted for three different values. For each current, the difference between the fountain frequency and the Maser Mean frequency was averaged for at least 2 days.

G. *Blackbody Radiation*

The frequency sensitivity to blackbody radiation has not been explicitly measured, but using known temperature coefficients for this effect, we determine that a temperature regulation of 0.5 °C at our operating temperature of 32 °C will be adequate. Although the uncertainty on the size of the blackbody shift is one of the largest contributions for primary standards, the sensitivity to temperature is not a serious concern for our application. The operational fountains will be housed in an environment regulated to 0.1 °C.

We are planning to investigate the sensitivity to cavity temperature due to cavity pulling, and we may improve the statistical limits on some of the measurements that we have carried out. The conclusion that can be drawn from all of these tests so far is that we have not identified any source of frequency instability that should prevent us from reaching long-term relative-frequency stability of order 1×10^{-16}.

V. Conclusion

To summarize, we have demonstrated long, continuous runs with our engineering-prototype rubidium fountain, and we have used the long averaging time to characterize the system against the observatory's Maser Mean timescale. These comparisons together with our measurements of the stability of systematic frequency shifts provide encouragement that we can meet our long-term frequency reproducibility goals.

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[4] USNO does not endorse any commercial product, nor does USNO permit any use of this document for marketing or advertising.

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