Performance and Applications of an Ensemble of Atomic Fountains

Steven Peil [1], James Hanssen [1], Thomas B. Swanson [1], Scott Crane [2], and Christopher R. Ekstrom [1]

[1]United States Naval Observatory, 3450 Massachusetts Ave., NW, Washington, DC USA
[2]Naval Research Laboratory, 4555 Overlook Ave., SW, Washington DC USA
steven.peil@usno.navy.mil

Abstract—The United States Naval Observatory (USNO) has four rubidium fountains that have been in operation for the past 1.7 years. Fountain performance and applications to timekeeping and to tests of Local Position Invariance are presented.

Key words: atomic fountain, rubidium

I. INTRODUCTION

Atomic timescales benefit from averaging a large number of clocks. Globally, more than 300 atomic clocks contribute to the generation of International Atomic Time (TAI), and locally dozens of institutions maintain their own ensemble of clocks for precise time. These clocks are predominantly commercial cesium beam clocks and commercial hydrogen masers. The first cold-atom clocks to find application to timekeeping are atomic fountains, which have been contributing to TAI as primary frequency standards and in some cases have been incorporated into local timescales [1-3]. Because they serve as primary standards, periods of evaluation of frequency biases are necessary; still, some systems seem to achieve more-or-less continuous operation. At some institutions, only one fountain clock contributes to the ensemble at a given time, although two clocks at PTB and three at SYRTE seem to run regularly.

At the U. S. Naval Observatory (USNO), four rubidium atomic fountains have been built to use in the timing ensemble and two more fountains are close to being operational. These devices run continuously, without systematic evaluations, and serve as stable frequency references for timing applications as opposed to absolute frequency standards. The continual operation of the ensemble of fountains should result in improved performance, as well as reliability and robustness, compared to a single device.

II. OPERATIONAL OVERVIEW

The four fountains in operation at USNO are designated as NRF2, NRF3, NRF4, and NRF5. These systems were built in two generations, according to slightly different designs, as discussed in previous reports [4]. All four began continuous operation in a dedicated clock facility in March 2011.

Each fountain has a local oscillator that is referenced to a hydrogen maser, which also serves as the reference for an auxiliary output generator (AOG). Every 20 seconds, the average relative frequency of the fountain and maser is used to steer the AOG output, providing a continuous nominal 5 MHz signal that reflects the fountain frequency and is measured against the USNO master clock and other clocks in the ensemble. The fountain switches to holdover mode, in which the maser serves as a flywheel, and back automatically. Detection of some problem in operation will cause the fountain to apply a steer that is the median frequency over the previous hour; resolution of the problem results in the fountain steering normally again.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2012**	2. REPORT TYPE	3. DATES COVERED **00-00-2012 to 00-00-2012**

4. TITLE AND SUBTITLE **Performance and Applications of an Ensemble of Atomic Fountains**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **United States Naval Observatory,3450 Massachusetts Ave., NW,Washington,DC,20392**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

44th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**5**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

The combination of reliance on the maser as a flywheel and the general robustness of the fountains over the past 1.7 years has resulted in high uptime. The percentage of time that each fountain has generated a good, steered output is 99.1%, 99.7%, 98.3%, and 100% for NRF2 through NRF5. Some of the down time is not indicative of failure, but rather corresponds to intentional intervention for upgrades and modifications.

Figure 1 shows a stability plot for the three highest performing fountains, NRF3, NRF4, and NRF5, obtained using a 3-cornered hat analysis. The second-generation clocks, NRF4 and NRF5, exhibit a white-frequency noise level of 1.8×10^{-13} and integrate into the 10^{-17}s over the analysis interval of 83 days, while NRF3 has a higher white-frequency noise level and passes below 2×10^{-16} at 40 days.

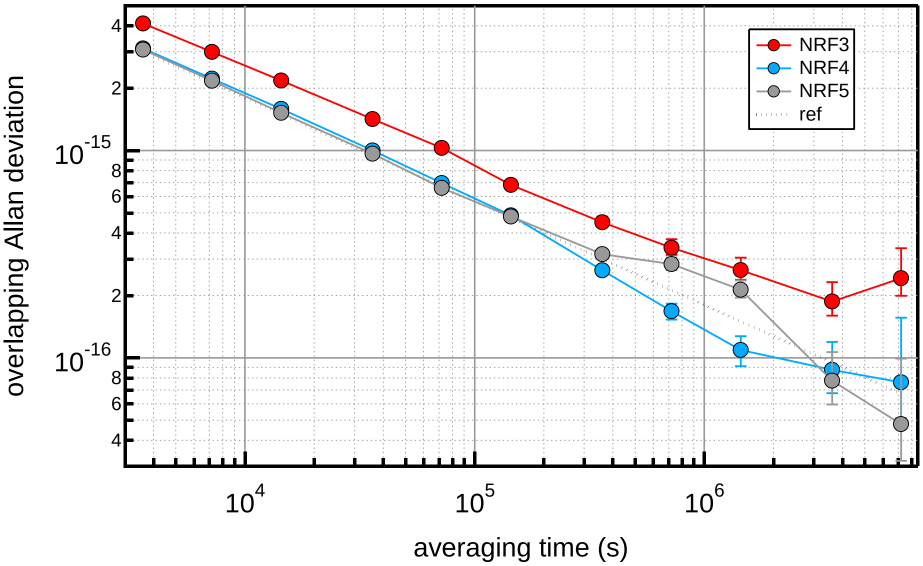

Figure 1. Stability plot for NRF3, NRF4 and NRF5. The white-frequency noise reference line extends to 6.7×10^{-17} at 83 days, which is consistent with the average performance for NRF4 and NRF5.

III. FOUNTAIN TIMESCALE

Generating a timescale from an ensemble of clocks provides improved robustness and performance over a single clock. The white-frequency noise level of an average of N clocks is reduced by $\sqrt{N}$, and the effect of a frequency change in one clock on the average is reduced by N.

The current method for generating the USNO timescale includes creating a stable long-term frequency reference using the cesium clocks. This cesium timescale is used to detect non-stationary behavior in individual masers and to predict UTC for generating UTC(USNO). The rubidium fountain timescale will likely be used for these tasks as well. One of the relevant parameters for characterizing maser performance is the white-frequency noise level. With four fountains in the timescale, the white-frequency noise level is characterized by an Allan deviation of 1×10^{-13}, a factor of 10 improvement over the level obtained with approximately 70 commercial cesium clocks, which translates to a factor of 100 improvement in averaging time required to reach a particular level of stability. The long-term stability is the relevant parameter for prediction of UTC. The long-term frequency stability of the fountain timescale is perhaps best characterized by comparing to the primary frequency standards that contribute to TAI. This can be done by using UTC(USNO) to determine the relative frequency of the fountain mean and TAI and using the frequency difference between a primary standard and TAI as reported to BIPM by the standards lab. This measurement, averaged over the past 1.7 years, shows that there is no drift between the rubidium fountain timescale and the primary standards at the level of 1.5×10^{-18}/day.

IV. SCIENTIFIC APPLICATION

Atomic clocks have been used in a wide variety of interesting scientific applications. In the past decade, the dependence of the relative frequency of two clocks of different species on time and position has been used to test symmetries that underlie metric theories of gravity, including general relativity. While looking for a drift in time can be done with as few as two points (separated by a large interval in time), searching for position dependence – implemented by looking at the clocks' relative frequency as a function of the earth's position in its orbit about the sun – benefits from having a higher rate of relative frequency measurements to look for an annual oscillation.

Because our fountains run continuously, we have a high rate of frequency comparisons against clocks based on other species to look for a dependence of the relative frequencies on gravitational potential, which is a test of Local Position Invariance (LPI). While the fact that we are not making absolute frequency measurements introduces some complications, we have been able to place a new limit on violation of LPI in a shorter period of time than previous tests. This is done by measuring the amplitude of the annual oscillation in the relative frequency of a pair of clocks of different species that has the phase corresponding to the strength of the solar gravitational potential experienced on the earth. This amplitude is proportional to the differential gravitational redshift for the pair of atomic species, $\beta_1-\beta_2$, which is zero if LPI holds. We have made measurements of $\beta_{Rb}-\beta_{Cs}$ and $\beta_H-\beta_{Cs}$ with precisions comparable to previous measurements [5,6], and we have made the first measurement of $\beta_{Rb}-\beta_H$, with the highest precision for any pair of atomic species used to test LPI. Our measurement for $\beta_{Rb}-\beta_H$ is consistent with zero, with an uncertainty two times smaller than the next best LPI test.

Some theories attempting to encompass quantum gravity predict a spatial dependence of certain dimensionless constants, such as the fine structure constant α and the electron-to-proton mass ratio m_e/m_p, particularly with a correspondence to gravitational potential [7]. Using published values of the sensitivity of relevant atomic transitions to these constants, one can rewrite the measurement of the differential redshift as a measurement of a linear combination of the coupling of these constants to gravity [8]. Using the most precise measurements of differential redshifts to date, we are able to place stricter limits of the coupling of these dimensionless constants to gravity, with an average gain in precision of a factor of four compared to previous evaluations.

The LPI tests and constraints on constants coupling to gravity are described in detail in a paper to be submitted for publication.

ACKNOWLEDGMENT

We acknowledge assistance from Paul Koppang, Demetrios Matsakis, and Scott Crane. Atomic fountain development at USNO is funded by SPAWAR.

REFERENCES

[1] A. Bauch, S. Weyers, D. Piester, E. Staliuniene, and W. Yang, "Generation of UTC(PTB) as a fountain-clock based time scale," Metrologia 49, pp. 180-188 (2012).

[2] T. Parker, S. Jefferts, T. Heavner, and E. Donley, "Operation of the NIST-F1 caesium fountain primary standard with a maser ensemble, including the impact of frequency transfer noise," Metrologia 42, pp. 423-430 (2005).

[3] J. Guéna, et al., "Progress in atomic fountains at LNE-SYRTE," IEEE Trans. UFFC 59, 391 (2012).

[4] C. Ekstrom, S. Peil, T. Swanson, and S. Crane, in Frequency Standards and Metrology: Proceedings of the Seventh Symposium, Lute Maleki, ed., World Scientific, New Jersey, pp. 308-313 (2008).

[5] J. Guéna, et al., "Improved Tests of Local Position Invariance Using Rb87 and Cs133 Fountains," Phys. Rev. Lett. 109, 080801 (2012).

[6] N. Ashby, T. Heavner, S. Jefferts, T. Parker, A. Radnaev, and Y. Dudin, “Testing Local Position Invariance with Four Cesium-Fountain Primary Frequency Standards and Four NIST Hydrogen Masers,” Phys. Rev. Lett. 98, 070802 (2007).

[7] T. Damour and A. Polyakov, “The string dilation and a least coupling principle,” Nuclear Physics B 423, 532 (1994).

[8] V. Flambaum, “Variation of fundamental constants: theory and observations,” Int. J. Mod. Phys. A 22, 4937 (2007).