Recent Improvements in NIST-F1 and a Resulting Accuracy of $\delta f/f = 0.61 \times 10^{-15}$

T. P. Heavner, S. R. Jefferts, E. A. Donley, J. H. Shirley, and T. E. Parker

***Abstract*—Over the last several years, we have made many improvements to NIST-F1 (a laser-cooled cesium fountain primary frequency standard) resulting in nearly a factor of 2 reduction in the uncertainty in the realization of the SI second at the National Institute of Standards and Technology. We recently submitted an evaluation with a combined standard fractional uncertainty of 0.61×10^{-15} to the Bureau International des Poids et Mesures (BIPM). The total fractional uncertainty of the evaluation (including dead time and time transfer contributions) was 0.88×10^{-15}. This is the smallest uncertainty in a frequency standard yet submitted to the BIPM.**

***Index Terms*—Atomic clocks, cesium, standards, time measurement.**

I. INTRODUCTION

NIST-F1 is a laser-cooled cesium fountain at the National Institute of Standards and Technology (NIST) in Boulder, CO, and is the primary frequency standard for the U.S. Government [1]. Presently, four other cesium fountains in addition to NIST-F1 have contributed to Temps Atomique International/International Atomic Time (TAI) which is operated by the Bureau International des Poids et Mesures (BIPM). Two fountains are located at the Bureau National de Métrologie-Systémes de Référence Temps Espace (BNM-SYRTE) [2], and both the Physikalisch-Technische Bundesanstalt (PTB) [3] and the Istituto Elettrotecnico Nazionale "Galileo Ferraris" (IEN) [4] have a single fountain. The total number of atomic fountains in operation or under development worldwide is large and growing. As a result of Cs fountain frequency standards, the SI second is now realized with a fractional uncertainty of $\sim 1 \times 10^{-15}$.

In the past several years, since the publication of a complete description of the evaluation procedure in NIST-F1, we have made many improvements [1]. While these changes individually seem minor, the net result has been significant. We routinely perform accuracy evaluations of NIST-F1 with combined standard fractional uncertainties well below 1×10^{-15} and recently we reported a frequency evaluation with a combined standard fractional uncertainty of 0.61×10^{-15}, nearly a factor of 2 smaller than reported in [1].

This paper outlines the improvements to the physics package, laser and optics system, and control system of NIST-F1, resulting in a more reliable and robust apparatus. Presently, we achieve nearly continuous, long run times (~40 days). This has reduced the type A uncertainty (statistical) and has also allowed for the improved evaluation of several type B uncertainties (systematic), most notably, the Cs spin-exchange shift. The uncertainties in the spin-exchange shift and the second-order Zeeman shift corrections have been reduced to the point that the uncertainty in the blackbody shift correction is now the dominant systematic uncertainty.

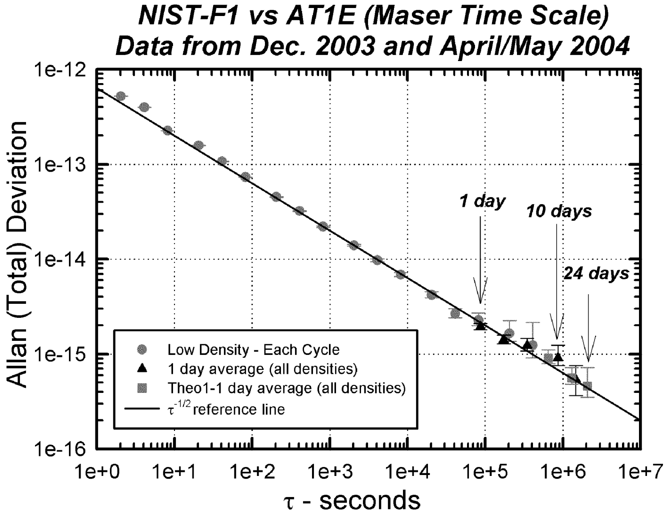

Fig. 1. Long-term Allan deviation plot of NIST-F1 against AT1E. The data at short sampling times were obtained by calculating the Allan deviation of frequency measurements from 14 days of continuous fountain operation at low atomic density. The Allan deviation at longer sampling times was calculated using the 24-h average frequency of all individual runs. Measurements taken at high atomic densities, where the stability is better, have been included by removing a frequency offset due to the spin-exchange shift. Theo-1 is a statistic designed to increase the confidence at large τ.

Since 1999, NIST-F1 has undergone 13 formal frequency evaluations which have been submitted to the BIPM to be included in TAI. Comparisons made with other laser-cooled Cs fountain standards, most notably direct two-way satellite comparisons with CSF1 at PTB [5], showed agreement within the stated one-sigma uncertainties ($\sim 1.7 \times 10^{-15}$) of the fountains.

An accuracy evaluation of NIST-F1 relies on a NIST time scale AT1E [6], which the fountain uses, as a flywheel oscillator during evaluations as well as the time transfer system which is used to submit the measurements to the BIPM. AT1E is a post-processed NIST timescale generated using five cavity-tuned hydrogen masers and four high-performance commercial Cs beam standards. Fig. 1 is a long-term Allan deviation plot comparing NIST-F1 against AT1E and demonstrates that the system shows white noise properties out to 24 days, where the stability is estimated as $\sigma_y \sim 4 \times 10^{-16}$. This verification of the performance of the AT1E time scale shows the type A (statistical) uncertainties presented here are valid and confirms our methods used to

---

Manuscript received July 2, 2004; revised November 1, 2004.

The authors are with the Time and Frequency Division, National Institute of Standards and Technology, Boulder, CO 80305 USA.

Digital Object Identifier 10.1109/TIM.2005.843812

measure the spin-exchange shift. The high reliability exhibited by NIST-F1 has resulted in long, near uninterrupted runs, allowing the analysis of the long-term behavior shown in Fig. 1.

II. IMPROVEMENTS MADE TO NIST-F1

A. *Laser and Optics*

Since the publication of [1], the NIST-F1 laser system and the optical layout have changed considerably. The main laser system used for the optical molasses presently consists of a diode-pumped, frequency-doubled $\mathrm{Nd:YVO_4}$ laser and provides up to 10 W of 532 nm light. This 532 nm light pumps a Ti:Sapphire ring laser which can generate more than 1 W of narrow band light at 852 nm. The original repump laser was replaced due to a diode failure. The new repump system uses an 852 nm DBR diode to injection lock a higher power 852 nm diode to provide ~25 mW of light which enters the fountain through a polarization-maintaining (PM) fiber optic cable.

Both new laser systems have displayed a high level of ease of use and reliability. Lock times for the lasers are now measured in weeks. This reliability has improved statistics because our “live time,” the fraction of time in which useful data is collected divided by the intended run time, is presently ~95%. In the past, the live time was typically about 70% to 80%. This is now limited by planned shutdowns to tune up systems, software maintenance, or other rare failure modes which we have not yet addressed.

The mechanical shutters used to block resonant light during Ramsey interrogation have been greatly improved from the previous shutter design. The new system looks for proper shutter operation during each launch and measurement cycle by measuring the light level on a photodiode monitor when the shutters are commanded to be closed. The new shutters and an improved optical layout have allowed us to reduce the uncertainty in the fluorescence light shift from 0.2×10^{-15} to much less than 0.1×10^{-15}.

B. *Optical Molasses*

The new laser system provides more than twice the useful laser light power than the previous system. This has allowed for larger horizontal beams in the (0, 0, 1) molasses geometry while still providing enough intensity for a good optical molasses. The result is a larger optical molasses in the vertical dimension and has allowed for fountain operation with a reduced spin-exchange shift (lower density), without loss of stability. Improved laser control has resulted in atom temperatures of less than 0.6 μK.

C. *Microwave Synthesis Chain and Time-Transfer Into the Laboratory*

The synthesizer module used to generate 9.192 GHz is the same as described in [1], but the overall synthesis chain, from maser reference to the atoms, has been modified. The addition of a high-quality quartz BVA crystal oscillator in a phase lock loop ($\tau \approx 10$ s) has reduced the fast noise from the 100 MHz reference originating from a maser in the NIST clock ensemble. This circuit topology exhibits the superior short-term performance of the BVA crystal oscillator while maintaining the long-term stability of the maser. The improved microwave system contains a second, parallel synthesis chain which serves as an error monitor. Problems in the synthesis chain resulting in excessive phase noise are logged by software.

TABLE I

Known Frequency Biases and Their Type B Uncertainties in Units of fractional frequency $\times 10^{-15}$. Items Designated With an Asterisk Are Shown Below for Information Purposes Only. The Spin Exchange Shift Is Not Included in the Type B Biases and Uncertainties Because it Is Already Incorporated Into the Intercept and Its Uncertainty. However, the Shift in Fractional Frequency From the Lowest Measured Density to Zero Density Was -0.53×10^{-15} With an Uncertainty of 0.15×10^{-15}. Note That 68% of the Fountain Run Time Was at the Lowest Atom Density

Physical Effect	Bias	Type B Uncertainty
Second-Order Zeeman	+36.46	0.10
Second-Order Doppler	<0.1	<0.1
Cavity Pulling	<0.1	<0.1
Rabi Pulling	<0.01	<0.1
AC Zeeman (heaters)	<0.1	<0.1
Cavity Phase (distributed)	<0.1	<0.1
Fluorescence Light Shift	<0.1	<0.1
Adjacent Transitions	<0.1	<0.1
Spin Exchange	(-0.53)*	(0.15)*
Blackbody	-21.21	0.26
Gravitation	+180.54	0.10
RF Spectral Purity	0	<0.1
Integrator Offset	0	<0.1
AM on Microwaves	0	<0.1
Microwaves	0	0.14
Total Type B Standard Uncertainty		0.33

TABLE II

Breakdown of the Final Uncertainty of the Most Recent Accuracy Evaluation of NIST-F1 Illustrating the Contributions From Dead Time and Time Transfer Into TAI. Here $u_{\mathrm{link/lab}}$ Is the Added Uncertainty Due to Dead Time in the Operation of the Fountain and $u_{\mathrm{link/TAI}}$ Is the Uncertainty Due to Time Transfer Into TAI. Values Are in fractional frequency $\times 10^{-15}$

Stability u_{A}	0.51
Systematic u_{B}	0.33
Combined u_{A} and u_{B}	0.61
Link to Clock $u_{\mathrm{link/lab}}$	0.40
Link to TAI $u_{\mathrm{link/TAI}}$	0.50
Final Uncertainty into TAI	0.88

D. *Temperature Control*

Improved temperature sensing instrumentation was added along the microwave cavity and copper flight tube including a Pt RTD temperature sensor which has an accuracy of ±0.1 K.

E. *Control System*

We have developed and are using new software to control NIST-F1 that is flexible and easy to modify while still being robust. The new software architecture has error monitoring in the form of logged digital inputs which represent the health and status of many of the fountain’s subsystems. This effective error monitoring system has thus increased the fountain “live time.”

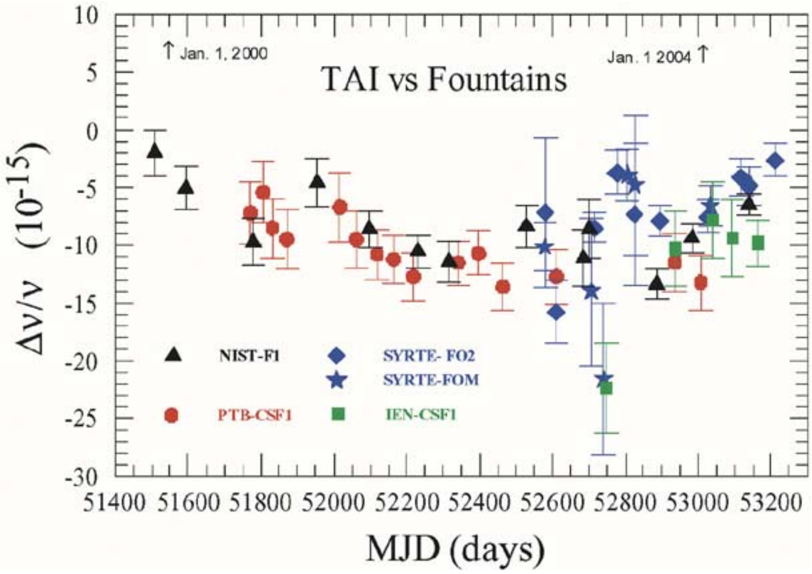

Fig. 2. Long-term performance of NIST-F1 and other Cs fountain frequency standards with respect to TAI.

III. NIST TIME SCALE

The NIST clock ensemble consists of five cavity-tuned hydrogen masers and four high-performance, commercial cesium standards and is used to generate AT1E, a postprocessed time scale, which has a stability of $\sigma_y \sim 2 \times 10^{-16}$ at averaging times of 30 days and a long-term frequency drift rate of less than $\pm 3 \times 10^{-15}$ per year [6]. Because AT1E is exceptionally stable and the noise properties have been well characterized, we are able to operate NIST-F1 using methods inaccessible to other fountain groups. For example, dead time in the operation of NIST-F1 results in only a small additional uncertainty to the frequency measurements and can therefore be tolerated [7].

IV. CORRECTED SYSTEMATIC FREQUENCY BIASES

Table I lists the all the frequency biases considered in the accuracy evaluations of NIST-F1. The biases for which corrections are applied are discussed here, except for the gravitational redshift which is discussed in [8].

A. *Spin-Exchange Shift*

Results from various groups as well as theoretical work [9] show that the spin-exchange frequency shift is strongly energy-dependent and thus is a function of the type of Cs source used, (MOT, molasses) and details of the atomic velocity and spatial distributions. But, given that these parameters remain constant, the shift is expected to be linear with atomic density.

Presently, we use a density-extrapolation method described in [1]. Frequency measurements are made at various atomic densities, and a least squares linear fit of the data yields an intercept and a slope that are used to correct for the spin-exchange shift and determine final uncertainties. The atomic density is set by controlling the detected atom signal. Measurements of the atomic spatial and velocity distributions in NIST-F1 show they are constant at ~1% over the range of parameters used to change the atom number and confirm that the detected signal level is proportional to the atomic density. Coarse control (× 10) of atom number is achieved by simultaneously making small changes to the molasses time, laser power, and temperature of the Cs oven. Fine control (~1%) is achieved using a servo which locks the detected atom signal to a set point by varying the microwave power entering the state selection cavity. We operate NIST-F1 most of the time (~70%) at a low density where the fractional spin-exchange shift is $\delta \mathrm{f}/\mathrm{f} \sim 0.53(15) \times 10^{-15}$.

B. *Second-Order Zeeman Shift*

In [1] we described the methods for determining the second-order Zeeman shift correction in NIST-F1. Two complementary methods using magnetic field sensitive transitions in Cs were described. In [1], we stated a fractional uncertainty in the second-order Zeeman correction of 0.3×10^{-15}, which corresponds to an uncertainty of ±1 fringe on the $|3,1\rangle \rightarrow |4,1\rangle$ manifold. This was an overly conservative uncertainty, since the two methods agree to within 0.04 ± 0.05 fringes. Presently, we state an uncertainty on the second-order Zeeman shift of 0.1×10^{-15}. This reflects the use of a smaller magnetic field ($\sim 0.8 \times 10^{-7}$ T), confidence that the fringe location is known to much better than ±1 fringe and long-term measurements on the $|3,1\rangle \rightarrow |4,1\rangle$ transitions which show a level of magnetic field noise corresponding to a fractional frequency shift of $\delta f/f < 10^{-17}$ on the $|3,0\rangle \rightarrow |4,0\rangle$ transition.

C. *Blackbody Shift*

While we have improved the temperature sensing instrumentation and reduced temperature gradients along the copper microwave cavity and time-of-flight structure, the uncertainty in the blackbody shift in NIST-F1 still reflects an uncertainty of ±1 K in the radiation environment as seen by the atoms. Presently, we report a fractional blackbody shift correction of -21.21×10^{-15} with an uncertainty in the correction of 0.26×10^{-15}. The expression and coefficients used to calculate the blackbody shift correction is outlined in [1].

V. UNCORRECTED FREQUENCY BIASES

The uncorrected frequency biases in Table I have been evaluated using leveraged measurements (for example, measuring the magnetic field using first-order field sensitive transitions), theoretical modeling or a combination of both to determine that they contribute a fractional shift of less than 10^{-16}. These shifts have been discussed thoroughly in [1]. In light of the overall reduction in the type A and type B uncertainties in NIST-F1, these small biases have been reconsidered [10].

VI. NIST-F1 PERFORMANCE IN TAI

Table II lists the type A and type B uncertainties of the most recent accuracy evaluation of NIST-F1 and additional uncertainties due to NIST-F1 dead time $u_{\mathrm{link/lab}}$ and the link into TAI $u_{\mathrm{link/TAI}}$. The accuracies reported by NIST-F1 are supported by comparisons with other Cs fountain frequency standards. Fig. 2 shows the long-term performance of NIST-F1 and other standards with respect to TAI.

VII. SUMMARY

The improvements outlined here have made NIST-F1 a very reliable apparatus capable of long, nearly continuous run times. Both the type A and type B uncertainties of accuracy evaluations have been reduced. Specifically, the uncertainties in both the spin-exchange and second-order Zeeman shift corrections are no longer dominant. Rather, the uncertainty in the blackbody shift correction is now the largest contributor to the type B uncertainty budget. Recently, we reported an evaluation with a combined standard fractional uncertainty of 0.61×10^{-15} which was submitted to the BIPM with a total fractional uncertainty (including dead time and time transfer contributions) of 0.88×10^{-15}. This is the smallest uncertainty in a frequency standard yet submitted to the BIPM.

REFERENCES

[1] S. R. Jefferts, J. H. Shirley, T. E. Parker, T. P. Heavner, D. M. Meekhof, C. W. Nelson, F. Levi, G. Costanzo, A. DeMarchi, R. E. Drullinger, L. Hollberg, W. D. Lee, and F. L. Walls, "Accuracy evaluation of NIST-F1," *Metrologia*, vol. 39, pp. 321–336, 2002.

[2] F. Pereira Dos Santos, H. Marion, M. Abgrall, S. Zhang, Y. Sortais, S. Bize, I. Maksimovic, D. Calonico, J. Grünert, C. Mandache, C. Vian, P. Rosenbuch, P. Lemonde, G. Santarelli, P. Laurent, and A. Clairon, "$^{87}\mathrm{Rb}$ and $^{133}\mathrm{Cs}$ laser cooled clocks: Testing the stability of fundamental constants," in *Proc. 2003 Joint Meeting IEEE Int. Freqency Control Symp. and EFTF Conf.*, 2003, pp. 55–67.

[3] S. Weyers, U. Hübner, R. Schröder, C. Tamm, and A. Bauch, "Uncertainty evaluation of the atomic caesium fountain CSF1 of the PTB," *Metrologia*, vol. 38, pp. 343–352, 2001.

[4] F. Levi, L. Lorini, D. Calonico, and A. Godone, "Systematic shift uncertainty evaluation of IEN CSF1 primary frequency standard," *IEEE Trans. Instrum. Meas.*, vol. 52, no. 2, pp. 267–271, Apr. 2003.

[5] T. E. Parker, P. Hetzel, S. R. Jefferts, S. Weyers, L. M. Nelson, A. Bauch, and J. Levine, "First comparison of remote cesium fountains," in *Proc. 2001 IEEE Int. Frequency Control Symp.*, 2001, pp. 63–68.

[6] T. E. Parker, "Performance of a hydrogen maser ensemble and characterization of frequency standards," in *Proc. 1999 Joint Meeting IEEE Int. Frequency Control Symp. and EFTF Conf.*, 1999, pp. 173–176.

[7] ——, "Comparing and evaluating the performance of primary standards: impact of dead time," in *Proc. 2001 IEEE Int. Frequency Control Symp.*, 2001, pp. 57–62.

[8] N. K. Pavlis and M. A. Weiss, "The relativistic redshift with 3×10^{-17} uncertainty at NIST, Boulder, Colorado, USA," *Metrologia*, vol. 40, pp. 66–73, 2003.

[9] P. J. Leo, P. S. Julienne, F. H. Mies, and C. J. Williams, "Collisional frequency shifts in $^{133}\mathrm{Cs}$ fountain clocks," *Phys. Rev. Lett.*, vol. 86, no. 17, pp. 3743–3746, 2001.

[10] T. P. Heavner, E. A. Donley, J. Shirley, S. R. Jefferts, and T. E. Parker, "NIST-F1: Recent improvements and accuracy evaluations," *Metrologia*, submitted for publication.