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Dear Dr. Arias,

Attached is the report of our most recent evaluation of NIST-F1, a cesium fountain primary frequency standard. The report period is for the 20 day interval from MJD 54654 to 54674. However, the fountain was operated in a nearly continuous fashion over a shorter evaluation interval from MJD 54658.8 to 54674.0. This report is like some others in which only one atom density was used. Again, we have used data from previous full evaluations to determine the spin exchange shift.

Details of the standard's design, construction, and performance are presented in references 1 - 8 listed on page 8. A detailed summary of the present evaluation is included in this report. The evaluation results using the BIPM format are given on pages 2 and 7. There are no significant changes in NIST-F1 since the last report.

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SUMMARY

July 2008 Evaluation of NIST-F1

The most recent evaluation of NIST-F1 is reported. The value

$$Y_{(NISTF1\text{-}maser)} = +270.28\text{x}10^{-15}$$

is the average fractional frequency difference between NIST-F1 and the hydrogen maser ST0022, (clock # 40222) over the 20 day report period MJD 54654 to 54674. The type A uncertainty of the fountain for this evaluation (statistical confidence on the frequency measurement, but not including dead time) is $0.29\text{x}10^{-15}$ (1σ). The type B uncertainty from known biases, including spin exchange, is $0.32\text{x}10^{-15}$ (1σ). The combined uncertainty (type A and type B) is $0.43\text{x}10^{-15}$ (1σ). The uncertainty becomes $0.53\text{x}10^{-15}$ (1σ) when the contribution from dead time, $u_{link/lab}$, is included. A detailed description of the various biases and uncertainties is given in the following sections of this report.

<u>RESULTS IN BIPM FORMAT</u>

Report period		MJD 54654 to 54674
Maser frequency (ST0022), clock # 40222)		$Y_{(NISTF1 - maser)} = +270.28\text{x}10^{-15}$
Statistical	u_A	$0.29\text{x}10^{-15}$
Systematic	u_B	$0.32\text{x}10^{-15}$
Link to clock	$u_{link/lab}$ (20 days)	$0.30\text{x}10^{-15}$
Link to TAI (estimated)	$u_{link/TAI}$ (20 days)	$0.47\text{x}10^{-15}$
Combined (estimated)	u	$0.71\text{x}10^{-15}$

1. DETAILS OF EVALUATION

An accuracy evaluation of NIST-F1 has been completed in which the frequency of a hydrogen maser was determined with respect to the primary frequency standard. The report period is 20 days, but the fountain was operated only over the 15.22 day evaluation interval of MJD 54658.78 to 54674.00. Of the 15.22 days intended for the maser frequency measurement, 14.16 days of data were collected (93.0% run time). The lost run time was from intentional and unintentional interruptions to the fountain operation. The percentage run time for the entire report period is 70.8%. A time line of the 20 day report period is shown in Table 1 below.

Table 1: Time Line

MJD	Event
54654.00	Start report period
54658.78	Start fountain run, low density (8)
54674.00	End low density, end fountain run
54674.00	End report period

Only one atom density was used in this evaluation, so spin exchange shift data from previous full evaluations were used to estimate the spin exchange shift for this run (see section 1B for details). The atom density in laboratory units is shown in parentheses in Table 1. For the 14.16 days of data the Birge ratio was 0.97. Other corrections are also made to the raw frequency data in order to compensate for known biases which are described below [2]. Units for all biases are fractional frequency x10^{-15} and all uncertainties are 1 sigma.

A. Quadratic Zeeman Bias

The quadratic Zeeman bias was determined by measuring the linear Zeeman splitting of the microwave spectrum. The magnetic field was monitored during the entire run. No significant changes were made to the Zeeman bias since the last run. The resulting bias and uncertainty are shown below.

Bias	Type B Uncertainty
+180.60	0.013

B. Spin Exchange Bias

Measurements were made using only one value of atom density for this evaluation (a value of 8 in laboratory units). The average slope of -0.051 +/- 0.009 per unit atom density was used from the previous five full evaluations made in 2007 and 2008 to estimate the frequency at zero density. These five runs were all statistically consistent. No changes in fountain configuration have been made over the course of the 5 evaluations used to determine the slope of the atom number vs. frequency curve, so there is no reason to expect the spin exchange shift to have changed.

Bias	Type B Uncertainty
-0.41	0.07

C. Blackbody Bias

The blackbody bias is calculated from the temperature of the drift region. The resulting bias and its uncertainty are shown below. A slight refinement to the measurement of the blackbody temperature was made.

Bias	Type B Uncertainty
-22.98	0.28

D. Microwave Amplitude Shift

No additional measurements on the microwave amplitude dependence were made for this evaluation, so the bias is unchanged from the previous run. The observed bias is consistent with zero, but we have chosen to include it in the list of corrected biases.

Bias	Type B Uncertainty
-0.026	0.12

E. Combined variable and fixed biases

There are additional biases that do not change under normal circumstances. The complete list of all biases (run dependent and fixed) and their corresponding uncertainties are shown in Table 2. This table is based on [2]. Only the first 5 biases are explicitly corrected for since the rest are all well under $1x10^{-16}$. The maximum magnitudes of all uncorrected biases are indicated in blue.

Table 2: Known Frequency Biases and Their Type B Uncertainty.
(Units are fractional frequency $x10^{-15}$)

Physical Effect	Bias	Type B Uncertainty
Gravitational Red shift	+179.95	0.03
Second-Order Zeeman	+180.60	0.013
Blackbody	-22.98	0.28
Microwave Amplitude Shift	-0.026	0.12
Spin Exchange (density =8)	-0.41	0.07
AC Zeeman (heaters)	0.05	0.05
Cavity Pulling	0.02	0.02
Rabi Pulling	10^{-4}	10^{-4}
Ramsey Pulling	10^{-4}	10^{-4}
Majorana Transitions	0.02	0.02
Fluorescence Light Shift	10^{-5}	10^{-5}
Cavity Phase (distributed)	0.02	0.02
Second-Order Doppler	0.02	0.02
DC Stark Effect	0.02	0.02
Background Gas Collisions	10^{-3}	10^{-3}
Bloch-Siegert	10^{-4}	10^{-4}
RF Spectral purity	$3x10^{-3}$	$3x10^{-3}$
Integrator offset	0	0.01
	Total Type B Standard Uncertainty	0.32

2. EVALUATION INTERVAL RESULTS (MJD 54658.78 to 54674.00)

When corrections for the biases of Table 2 are applied, the following result for the measurement of $Y_{(NISTF1\text{-}maser)}$ is obtained. Units are fractional frequency $x10^{-15}$.

Corrected Frequency	Type A Uncertainty	Total Type B Uncertainty - includes spin exchange	Combined Uncertainty
+270.28	0.29	0.32	0.43

3. INFLUENCE OF DEAD TIME

NIST-F1 was operated for a total of only 14.16 days during this 20 day report period so the dead time has an impact on the overall uncertainty. However, NIST has a well characterized ensemble of hydrogen masers so this impact can be quantified. The frequency stability and drift of the reference maser are well known. No drift correction was required because the frequency drift of the time scale is very small and the fountain data is reasonably well centered in the report interval. The dead time contributes an additional type A uncertainty of $0.30x10^{-15}$. See references 10 - 13. A new procedure was used to handle distributed dead time [13]. This results in an improved estimate of the dead time uncertainty.

4. FINAL REPORT PERIOD RESULTS (without time transfer uncertainty)

Applying the correction resulting from dead time to the evaluation interval results yields the following 20 day final report period results.

Report period	MJD 54654 to 54674
Maser frequency (ST0022, clock # 40222)	$Y_{(NISTF1\ -\ maser)} = +270.28\text{x}10^{-15}$
Type A uncertainty (not including dead time)	$0.29\text{x}10^{-15}$ (1σ)
Type B uncertainty	$0.32\text{x}10^{-15}$ (1σ)
Combined uncertainty (fountain only)	$0.43\text{x}10^{-15}$ (1σ).
Type A uncertainty from dead time	$0.30\text{x}10^{-15}$ (1σ)
Combined uncertainty with dead time	$0.53\text{x}10^{-15}$ (1σ).

5. FINAL RESULTS USING BIPM FORMAT (includes time transfer uncertainty)

Report period		MJD 54654 to 54674
Maser frequency (ST0022), clock # 40222)		$Y_{(NISTF1\ -\ maser)} = +270.28\text{x}10^{-15}$
Statistical	u_A	$0.29\text{x}10^{-15}$
Systematic	u_B	$0.32\text{x}10^{-15}$
Link to clock	$u_{link/lab}$ (20 days)	$0.30\text{x}10^{-15}$
Link to TAI (estimated)	$u_{link/TAI}$ (20 days)	$0.47\text{x}10^{-15}$
Combined (estimated)	u	$0.71\text{x}10^{-15}$

6. REFERENCES

1. S.R. Jefferts, J. Shirley, T. E. Parker, T.P. Heavner, D.M. Meekhof, C. Nelson, F. Levi, G. Costanzo, A. DeMarchi, R. Drullinger, L. Hollberg, W.D. Lee and F.L. Walls, "Accuracy Evaluation of NIST-F1," *Metrologia*, vol. 39, pp 321-336, 2002.
2. T.P. Heavner, S.R. Jefferts, E.A. Donley, J.H. Shirley, and T.E. Parker, "NIST-F1: Recent Improvements and Accuracy Evaluations," *Metologia*, vol. 42, pp 411-422, 2005.
3. T.E. Parker, S.R. Jefferts, T.P. Heavner, and E.A. Donley, "Operation of the NIST-F1 Caesium Fountain Primary Frequency Standard with a Maser Ensemble, Including the Impact of Frequency Transfer Noise," *Metologia*, vol. 42, pp 423-430, 2005.
4. J.H. Shirley, F. Levi, T.P. Heavner, D. Calonico, D. Yu and S.R. Jefferts, "Microwave Leakage Induced Frequency Shifts in the Primary Frequency Standards NIST-F1 and IEN-CSF1," *IEEE Trans. on Ultrasonics, Ferroelectrics, and Frequency Control,* vol. 53, pp. 2376-2385, 2006.
5. S.R. Jefferts, J.H. Shirley, N. Ashby, E.A. Burt, and G.J. Dick, "Power Dependence of Distributed Cavity Phase-Induced Frequency Biases in Atomic Fountain Frequency Standards," *IEEE Trans. on Ultrasonics, Ferroelectrics, and Frequency Control,* vol. 52, pp 2314-2321, 2004
6. S.R. Jefferts, T.P. Heavner, E.A. Donley and T.E. Parker, "Measurement of Dynamic End-to-End Cavity Phase Shifts in Cesium-Fountain Frequency Standards," *IEEE Trans. on Ultrasonics, Ferroelectrics, and Frequency Control,* vol. 5l, pp 652-653, 2005.
7. T.P. Heavner, J.H. Shirley, F. Levi, D. Yu, and S.R. Jefferts, "Frequency Biases in Pulsed Atomic Fountain Frequency Standards Due to Spurious Components in the Microwave Spectrum," *in Proc. 2006 IEEE International Freq. Control Symp.*, pp 273-276, 2006.
8. S.R. Jefferts, R.E Drullinger, A. DeMarchi, "NIST Cesium Fountain Microwave Cavities," *in Proc. 1998 IEEE International Freq. Control Symp.*, pp 6-8, 1998.
9. N. K. Pavlis and M. Weiss, "The Relativistic Redshift with $3x10^{-17}$ Uncertainty at NIST, Boulder, Colorado, USA," *Metologia*, vol. 40, pp 66-73, 2003.
10. T.E. Parker, "Hydrogen Maser Ensemble Performance and Characterization of Frequency Standards," *in Proc. 1999 Joint Meeting of European Freq. and Time Forum and IEEE International Freq. Control Symp.*, pp 173-176, 1999.
11. T.E. Parker, D.A. Howe and M. Weiss, "Accurate Frequency Comparisons at the $1x10^{-15}$ Level," *in Proc. 1998 IEEE International Freq. Control Symp.*, pp 265-272, 1998.
12. R.J. Douglas and J.S. Boulanger, "Standard Uncertainty for Average Frequency Traceability," *in Proc. 11th European Freq. and Time Forum.*, pp 345-349, 1997.
13. Dai-Hyuk Yu, Marc Weiss and Thomas E. Parker, "Uncertainty of a Frequency Comparison with Distributed Dead Time and Measurement Interval Offset," *Metologia*, vol. 44, pp 91-96, 2007.

Appendix A

Summary of accumulated changes in biases and uncertainties since the state of NIST-F1 discussed in references 2 and 3

(1) 30 day evaluation of June/July 2005 (MJD 53529-53559)
Modifications to the optical detection electronics and the low noise quartz oscillator improved the stability (u_A) of NIST-F1. More measurements with respect to microwave leakage reduced this uncertainty from $2x10^{-16}$ to $1.4x10^{-16}$.

(2) 40 day evaluation of September/October 2005 (MJD 53629-53669)
A magnetic field monitor was added to NIST-F1. No change was needed in the second order Zeeman bias uncertainty. Also, no other Type B uncertainties have been changed.

(3) 40 day evaluation of December 2005/January 2006 (MJD 53724-53764)
The fountain cycle time was shortened a bit and this resulted in a small improvement in short-term stability. Also the magnetic field uniformity was improved by shield degaussing and shimming, and this resulted in a small decrease in the Zeeman bias. There were no changes in the Type B uncertainties.

(4) 40 day evaluation of February/March 2006 (MJD 53784-53824)
No significant changes were made to NIST-F1 other than a slight increase in the average atom density. There were no changes in the Type B uncertainties.

(5) 30 day evaluation of October 2006 (MJD 54009-54039)
NIST-F1 was moved to a room with better environmental control and which is closer to the hydrogen masers and the time scale (shorter cables). The fountain was damaged in the move and as a result the microwave cavities, drift tube, and source region were replaced with nearly identical parts. All of the replaced parts are functionally the same as the originals. Because of the change in location and the repairs, the Zeeman and blackbody corrections are slightly larger, along with their uncertainties. The gravitational red shift is slightly smaller due primarily to the fact the fountain is now one floor lower than before, but there is no change in uncertainty. The bias and uncertainty for microwave leakage below the cavities are slightly larger.

(6) 20 day evaluation of February 2007 (MJD 54134-54154)
No significant changes were made to NIST-F1 for this evaluation, except that the magnetic field above the Ramsey cavity was increased by a factor of 2 in order to improve the field uniformity and decrease the possible effects of off resonant transitions. As an indirect result of these changes the atom cloud was slightly larger and probably colder. This resulted in a higher atom number at the lowest density used and consequently an improved short-term stability. Also additional microwave amplitude measurements were made to reduce the uncertainty on the microwave amplitude shift. This resulted in a slight decrease in the overall Type B uncertainty.

(7) 15 day evaluation of April 2007 (MJD 54204-54219)
No significant changes were made to NIST-F1 since the February 2007 evaluation.

(8) 15 day evaluation of May 2007 (MJD 54219-54234)
No changes were made to NIST-F1 since the April 2007 evaluation.

(9) 25 day evaluation of August 2007 (MJD 54314-54339)
No changes were made to NIST-F1 since the May 2007 evaluation other than additional microwave power measurements which resulted in a slight decrease in the Type B uncertainty.

(10) 15 day "mini" evaluation of October 2007 (MJD 54384-54399)
No changes were made to NIST-F1 since the August 2007 full evaluation.

(11) 10 day "mini" evaluation of November 2007 (MJD 54409-54419)
No changes were made to NIST-F1 since the August 2007 full evaluation.

(12) 30 day evaluation of January 2008 (MJD 54464-54494)
The state selection synthesizer was replaced, but this had no impact on the accuracy or operation of NIST-F1.

(13) 15 day "mini" evaluation of April 2008 (MJD 54554-54569)
The repump laser was replaced, but this had no impact on the accuracy or operation of NIST-F1.

(14) 20 day "mini" evaluation of July 2008 (MJD 54654-54674)
No changes were made to NIST-F1 since the April 2008 evaluation other than a slight refinement to the blackbody temperature.