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FAX MESSAGE

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Dear Dr. Arias,

Attached is the report of our most recent formal evaluation of NIST-F1, a cesium fountain frequency standard. The report period is for the 30 day interval from MJD 53529 to 53559, whereas the fountain was operated in a near continuous fashion over a shorter evaluation interval from MJD 53532.0 to 53556.9. Details of the standard's design, construction, and performance are presented in references 1 - 6 listed on page 7. Two new papers on the operation and performance of NIST-F1 have been submitted to Metrologia [2, 3]. [2] has recently been accepted. 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.

Only minor changes have been made to the standard since the last report. These include improvements to the optical detection electronics and low noise quartz local oscillator. These improvements have resulted in a further improvement in the frequency stability of NIST-F1. This allowed a lower atom density to be used for the same fountain frequency stability. As is standard now we have included the uncertainty due to the determination of the spin exchange shift as part of the type A uncertainty.

Thomas E. Parker
Group Leader

SUMMARY

June, July 2005 Evaluation of NIST-F1

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

$$Y_{(NISTF1\text{-}maser)} = -290.99 \times 10^{-15}$$

is the average fractional frequency difference between NIST-F1 and the hydrogen maser ST0005, (clock # 40205) over the 30 day report period MJD 53529 to 53559. The type A uncertainty of the fountain for this evaluation (statistical confidence on the frequency measurement including a component due to spin exchange, but not including dead time) is 0.43×10^{-15} (1σ). The type B uncertainty from known biases (not including spin exchange) is 0.31×10^{-15} (1σ). The combined uncertainty (type A and type B) is 0.53×10^{-15} (1σ). The uncertainty becomes 0.56×10^{-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.

RESULTS IN BIPM FORMAT

Report period		MJD 53529 to 53559
Maser frequency (ST0005), clock # 40205)		$Y_{(NISTF1\text{ - }maser)} = -290.99 \times 10^{-15}$
Statistical	u_A	0.43×10^{-15}
Systematic	u_B	0.31×10^{-15}
Link to clock	$u_{link/lab}$ (30 days)	0.18×10^{-15}
Link to TAI	$u_{link/TAI}$ (30 days)	1.00×10^{-15}
Combined	u	1.15×10^{-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 30 days, but the fountain was operated only over the 24.9 day evaluation interval of MJD 53532.0 to 53556.9. Of the 24.9 days intended for the measurement of the maser frequency, only 22.0 days of data were collected (88.4% run time). The lost run time was from a combination of intentional and unintentional interruptions to the fountain operation. A time line of the entire 30 day report period is shown in Table 1 below. More time was spent at medium density in order to accommodate a comparison with our optical frequency standards than would have been desirable for the lowest overall uncertainty in the evaluation. The report period was not extended to 40 days since construction work in the vicinity of the time scale caused unusually large temperature fluctuations in the clock rooms and degraded the stability of the masers in the time period after the operation of NIST-F1.

Table 1: Time Line

MJD	Event
53529.0	Start report period
53532.0	Start fountain run, low density
53536.0	End low density, start medium density
53539.1	End medium density, start low density
53542.9	End low density, start high density
53544.0	End high density, start low density
53548.9	End low density, start medium density
53553.0	End medium density, start low density
53556.9	End low density
53559.0	End report period

A factor of 10 in atom densities was covered in this evaluation and the frequency for zero density was obtained by a weighted linear least-mean-square fit [3]. 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 resulting bias and uncertainty are shown below.

Bias	Type B Uncertainty
+36.53	0.02

B. Spin Exchange Bias

Measurements were made over a range of atom densities. A factor of 10 in atom density was covered and the frequency for zero density was obtained from the zero density intercept of a weighted linear least-mean-square fit of frequency versus atom density [3]. Twenty four data points (each nominally 24 hours) were used in the fit and a reduced chi squared of 0.92 was obtained. This indicates that the frequency stability of the maser ensemble used as a frequency reference is not significantly corrupting the quality of the fit. By using a range of atom densities there is no fixed spin exchange bias, however the bias in fractional frequency from the lowest measured density to zero density was -0.16×10^{-15} with an uncertainty of 0.068×10^{-15}. These values are shown below for information purposes only. They are not included in the type B biases and uncertainties of Table 2 since they are already incorporated into the intercept and its uncertainty (type A uncertainty). Note that 67% of the fountain run time was at the lowest atom density.

Bias	Type B Uncertainty
(-0.16)	(0.068)

C. Blackbody Bias

The blackbody bias is calculated from the temperature of the drift region. The resulting bias and its uncertainty are shown below.

Bias	Type B Uncertainty
-21.21	0.26

D. Combined variable and fixed biases

There are additional biases that do not change under normal circumstances, for example the gravitational red shift correction. The complete list of all biases (fixed and run dependent) and their corresponding uncertainties are shown in Table 2. This table has been updated based on [2]. Only the first 3 biases are explicitly corrected for since the rest are all well under 1×10^{-16}. The spin exchange bias is not corrected in the same manner as the others since it is included in the intercept of the weighted least-mean-square fit of frequency versus atom density.

Table 2: Known Frequency Biases and Their Type B Uncertainty.
(Units are fractional frequency $\times 10^{-15}$)

Physical Effect	Bias	Type B Uncertainty
Gravitational Redshift	+180.54	0.03
Second-Order Zeeman	+36.53	0.02
Blackbody	-21.21	0.26
Spin Exchange (low density)	(-0.16)*	(0.068)*
Microwave Leakage	0	0.14
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	3×10^{-3}	3×10^{-3}
Integrator offset	0	0.01
	Total Type B Standard Uncertainty	0.31

*For information purposes only. Not used in total, see section 1-B for details

2. EVALUATION INTERVAL RESULTS (MJD 53532.0 to 53556.9)

When corrections for the biases of Table 2 are applied, the following result for the measurement of $Y_{(NISTF1-maser)}$ is obtained. Because the type A uncertainty now includes the spin-exchange bias uncertainty, we include (in parentheses in the table below) the combined statistical uncertainty of all the data collected in this evaluation (as if there were no need for a linear fit). This is included only for its informational value. Units are fractional frequency x10^{-15}.

Corrected Frequency	Type A Uncertainty - includes spin exchange	Total Type B Uncertainty - does not include spin exchange	Combined Uncertainty
-290.99	0.43 (0.25)	0.31	0.53

3. INFLUENCE OF DEAD TIME

NIST-F1 was operated for a total of only 22.0 days during this 30 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 on this maser is very small and the run time was well centered. However, the dead time contributes an additional type A uncertainty of 0.18x10^{-15}. See references 7 - 9.

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

Applying the correction resulting from dead time to the evaluation interval results yields the following 30 day final report period results.

Report period	MJD 53529 to 53559
Maser frequency (ST0005, clock # 40205)	$Y_{(NISTF1 - maser)} = -290.99\text{x}10^{-15}$
Type A uncertainty (not including dead time)	0.43x10^{-15} (1σ)
Type B uncertainty	0.31x10^{-15} (1σ)
Combined uncertainty (fountain only)	0.53x10^{-15} (1σ).
Type A uncertainty from dead time	0.18x10^{-15} (1σ)
Combined uncertainty with dead time	0.56x10^{-15} (1σ).

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

Report period		MJD 53529 to 53559
Maser frequency (ST0005), clock # 40205)		$Y_{(NISTF1\text{ - }maser)} = -290.99\text{x}10^{-15}$
Statistical	u_A	$0.43\text{x}10^{-15}$
Systematic	u_B	$0.31\text{x}10^{-15}$
Link to clock	$u_{link/lab}$ (30 days)	$0.18\text{x}10^{-15}$
Link to TAI	$u_{link/TAI}$ (30 days)	$1.00\text{x}10^{-15}$
Combined	u	$1.15\text{x}10^{-15}$

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," to be published in *Metologia*.

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," submitted to *Metologia*.

4 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 Contro,* vol. 5l, pp 652-653, 2004.

5 S.R. Jefferts, D.M. Meekhof, J.H. Shirley, T. E. Parker and F. Levi, "Preliminary Accuracy Evaluation of a Cesium Fountain Primary Frequency Standard at NIST," *in Proc. 1999 Joint Meeting of European Freq. and Time Forum and IEEE International Freq. Control Symp.*, pp 12-15, 1999.

6 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.

7 T.E. Parker, "Hydrogen Maser Ensemble Performance and Characterization of Frequency Strandards," *in Proc. 1999 Joint Meeting of European Freq. and Time Forum and IEEE International Freq. Control Symp.*, pp 173-176, 1999.

8 T.E. Parker, D.A. Howe and M. Weiss, "Accurate Frequency Comparisons at the $1\text{x}10^{-15}$ Level," *in Proc. 1998 IEEE International Freq. Control Symp.*, pp 265-272, 1998.

9 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.