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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 40 day interval from MJD 53724 to 53764. However, the fountain was operated in a near continuous fashion over a shorter evaluation interval from MJD 53733.0 to 53754.0 Details of the standard's design, construction, and performance are presented in references 1 - 6 listed on page 7. 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.

No major changes have been made to the standard since the last evaluation so its performance is essentially unchanged. The 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 are no changes to the Type B uncertainties. In Appendix A all accumulated changes to bias uncertainties are listed since the state of NIST-F1 as discussed in references 2 and 3.

Thomas E. Parker
Group Leader

SUMMARY

December 2005, January 2006 Evaluation of NIST-F1

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

$$Y_{(NISTF1\text{-}maser)} = -297.39\text{x}10^{-15}$$

is the average fractional frequency difference between NIST-F1 and the hydrogen maser ST0005, (clock # 40205) over the 40 day report period MJD 53724 to 53764. 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 $0.37\text{x}10^{-15}$ (1σ). The type B uncertainty from known biases (not including spin exchange) is $0.31\text{x}10^{-15}$ (1σ). The combined uncertainty (type A and type B) is $0.48\text{x}10^{-15}$ (1σ). The uncertainty becomes $0.61\text{x}10^{-15}$ (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 53724 to 53764
Maser frequency (ST0005), clock # 40205)		$Y_{(NISTF1\text{ - }maser)} = -297.39\text{x}10^{-15}$
Statistical	u_A	$0.37\text{x}10^{-15}$
Systematic	u_B	$0.31\text{x}10^{-15}$
Link to clock	$u_{link/lab}$ (40 days)	$0.38\text{x}10^{-15}$
Link to TAI	$u_{link/TAI}$ (40 days)	$0.75\text{x}10^{-15}$
Combined	u	$0.97\text{x}10^{-15}$

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 40 days, but the fountain was operated only over the 21 day evaluation interval of MJD 535733.0 to 53754. Of the 21 days intended for the measurement of the maser frequency, only 19.4 days of data were collected (92.1% run time). The lost run time was from a combination of intentional and unintentional interruptions to the fountain operation. The percentage run time for the entire report period is 48.5%. A time line of the 40 day report period is shown in Table 1 below.

Table 1: Time Line

MJD	Event
53724.0	Start report period
53733.0	Start fountain run, low density
53745.0	End low density, start high density
53747.0	End high density, start low density
53754.0	End low density, end fountain run
53764.0	End report period

A factor of about 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 magnetic field was monitored during the entire run. The magnetic field uniformity was improved by shield degaussing and shimming, and this resulted in a small decrease in the Zeeman bias, but there is no change in the uncertainty. The resulting bias and uncertainty are shown below.

Bias	Type B Uncertainty
+36.21	0.02

B. Spin Exchange Bias

Measurements were made over a range of atom densities. A factor of about 10 in atom density was covered and the frequency at zero density was obtained from the zero density intercept of a weighted linear least-mean-square fit of frequency versus atom density [3]. Twenty data points (each nominally 24 hours) were used in the fit and a reduced chi squared of 1.13 was obtained. This indicates that the frequency stability of the maser ensemble used as a frequency reference is not significantly degrading 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 -0.31×10^{-15} with an uncertainty of 0.057×10^{-15}. These values are shown below for information purposes only. They are not included in the total of 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 83% of the fountain run time was at the lowest atom density.

Bias	Type B Uncertainty
(-0.31)	(0.057)

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 is 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	+36.21	0.02
Blackbody	-21.21	0.26
Spin Exchange (low density)	(-0.31)*	(0.057)*
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 53733.0 to 53754.0)

When corrections for the biases of Table 2 are applied, the following result for the measurement of $Y_{(NISTF1\text{-}maser)}$ is obtained. Because the type A uncertainty 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 $\times 10^{-15}$.

Corrected Frequency	Type A Uncertainty - includes spin exchange	Total Type B Uncertainty - does not include spin exchange	Combined Uncertainty
-297.39	0.37 (0.25)	0.31	0.48

3. INFLUENCE OF DEAD TIME

NIST-F1 was operated for a total of only 19.4 days during this 40 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 0.38×10^{-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 40 day final report period results.

Report period	MJD 53724 to 53764
Maser frequency (ST0005, clock # 40205)	$Y_{(NISTF1\text{ - }maser)} = -297.39\times10^{-15}$
Type A uncertainty (not including dead time)	0.37×10^{-15} (1σ)
Type B uncertainty	0.31×10^{-15} (1σ)
Combined uncertainty (fountain only)	0.48×10^{-15} (1σ).
Type A uncertainty from dead time	0.38×10^{-15} (1σ)
Combined uncertainty with dead time	0.61×10^{-15} (1σ).

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

Report period		MJD 53724 to 53764
Maser frequency (ST0005), clock # 40205)		$Y_{(NISTF1 - maser)} = -297.39 \times 10^{-15}$
Statistical	u_A	0.37×10^{-15}
Systematic	u_B	0.31×10^{-15}
Link to clock	$u_{link/lab}$ (40 days)	0.38×10^{-15}
Link to TAI	$u_{link/TAI}$ (40 days)	0.75×10^{-15}
Combined	u	0.97×10^{-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.

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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.