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Dear Dr. Arias,

Attached is the report of our most recent formal evaluation of NIST-F1, a cesium fountain primary frequency standard. The report period is for the 30 day interval from MJD 54009 to 54039. However, the fountain was operated in a near continuous fashion over a shorter evaluation interval from MJD 54015.0 to 54036.92 Details of the standard's design, construction, and performance are presented in references 1 - 7 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.

Since the last reported evaluation NIST-F1 has been moved to a room with better temperature and humidity 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 and drift tube were replaced, as well as part of the source region. Because of the change in location and the repairs, the Zeeman and blackbody corrections are slightly larger, but there are only minor changes in the uncertainties. The gravitational red shift is slightly smaller due 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 have been re-measured and they are slightly larger.

Thomas E. Parker
Leader, Atomic Frequency Standards Group

SUMMARY

October 2006 Evaluation of NIST-F1

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

$$Y_{(NISTF1\text{-}maser)} = -299.25\text{x}10^{-15}$$

is the average fractional frequency difference between NIST-F1 and the hydrogen maser ST0005, (clock # 40205) over the 30 day report period MJD 54009 to 54039. 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 $0.36\text{x}10^{-15}$ (1σ). The type B uncertainty from known biases (not including spin exchange) is $0.36\text{x}10^{-15}$ (1σ). The combined uncertainty (type A and type B) is $0.51\text{x}10^{-15}$ (1σ). The uncertainty becomes $0.56\text{x}10^{-15}$ (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 54009 to 54039
Maser frequency (ST0005), clock # 40205)		$Y_{(NISTF1\text{ - }maser)} = -299.25\text{x}10^{-15}$
Statistical	u_A	$0.36\text{x}10^{-15}$
Systematic	u_B	$0.36\text{x}10^{-15}$
Link to clock	$u_{link/lab}$ (30 days)	$0.24\text{x}10^{-15}$
Link to TAI (estimated)	$u_{link/TAI}$ (30 days, estimated)	$0.39\text{x}10^{-15}$
Combined	u	$0.68\text{x}10^{-15}$

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 30 days, but the fountain was operated only over the 21.92 day evaluation interval of MJD 54015.0 to 54036.92. Of the 21.92 days intended for the measurement of the maser frequency, only 20.23 days of data were collected (92.3% 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 67.4%. A time line of the 30 day report period is shown in Table 1 below.

Table 1: Time Line

MJD	Event
54009.0	Start report period
54015.0	Start fountain run, high density (40)
54016.0	End high density, start low density (4)
54035.9	End low density, start high density (40)
54036.9	End high density, end fountain run
54039.0	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]. The atom densities in laboratory units are shown in parentheses in Table 1. 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. As a result of the move the bias is 24% larger and there were some changes in the field uniformity. There is a slight increase in the uncertainty from 0.02 to 0.03. The resulting bias and uncertainty are shown below.

Bias	Type B Uncertainty
+44.84	0.03

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 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 two data points (each nominally 24 hours) were used in the fit and a reduced chi squared of 0.81 was obtained. This corresponds to a Birge ratio of 0.90 and indicates that the frequency stability of the maser ensemble used as a frequency reference is causing no significant degradation to 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 -0.40×10^{-15} with an uncertainty of 0.058×10^{-15}. These values are shown below for informational 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
(-0.40)	(0.058)

C. Blackbody Bias

The blackbody bias is calculated from the temperature of the drift region. The cavities and drift tube are now operated at a slightly higher temperature and as a result the bias is 8% larger and there is a small increase in the uncertainty from 0.26 to 0.28.

Bias	Type B Uncertainty
-22.84	0.28

D. Microwave leakage

During the move the microwave cables were rearranged and therefore the microwave leakage was reevaluated using a new understanding of microwave leakage [4]. Since only a relatively short time has been spent evaluating the leakage biases the uncertainty is larger than before the move. The observed bias is consistent with zero, but we have chosen to include it in the list of corrected biases.

Bias	Type B Uncertainty
-0.22	0.22

E. Gravitational Red Shift

The gravitational red shift has changed because the fountain was moved to a lower floor, and there was a small change in table height. Also we used the results of a more recent survey [8].

Bias	Type B Uncertainty
+179.95	0.03

F. 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 4 biases are explicitly corrected for since the rest are all well under 1×10^{-16}. The maximum magnitudes of all uncorrected biases are indicated in blue. 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 $\times10^{-15}$)

Physical Effect	Bias	Type B Uncertainty
Gravitational Red shift	+179.95	0.03
Second-Order Zeeman	+44.84	0.03
Blackbody	-22.84	0.28
Microwave Leakage	-0.22	0.22
Spin Exchange (low density)	(-0.40)*	(0.058)*
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	0.36

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

2. EVALUATION INTERVAL RESULTS (MJD 54015.0 to 54036.9)

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 $x10^{-15}$.

Corrected Frequency	Type A Uncertainty - includes spin exchange	Total Type B Uncertainty - does not include spin exchange	Combined Uncertainty
-299.25	0.36 (0.25)	0.36	0.51

3. INFLUENCE OF DEAD TIME

NIST-F1 was operated for a total of only 20.2 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, there was relative little dead time, and the run time was reasonably well centered. However, the dead time contributes an additional type A uncertainty of $0.24x10^{-15}$. See references 9 - 11.

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 54009 to 54039
Maser frequency (ST0005, clock # 40205)	$Y_{(NISTF1\text{ - }maser)} = -299.25x10^{-15}$
Type A uncertainty (not including dead time)	$0.36x10^{-15}$ (1σ)
Type B uncertainty	$0.36x10^{-15}$ (1σ)
Combined uncertainty (fountain only)	$0.51x10^{-15}$ (1σ).
Type A uncertainty from dead time	$0.24x10^{-15}$ (1σ)
Combined uncertainty with dead time	$0.56x10^{-15}$ (1σ).

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

Report period		MJD 54009 to 54039
Maser frequency (ST0005), clock # 40205)		$Y_{(NISTF1 - maser)} = -299.25x10^{-15}$
Statistical	u_A	$0.36x10^{-15}$
Systematic	u_B	$0.36x10^{-15}$
Link to clock	$u_{link/lab}$ (30 days)	$0.24x10^{-15}$
Link to TAI	$u_{link/TAI}$ (30 days, estimated)	$0.39x10^{-15}$
Combined	u	$0.68x10^{-15}$

6. REFERENCES

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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.

(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.