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Date: January 4, 2012

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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 55894 to 55924. However, the fountain was operated in a nearly continuous fashion over a shorter evaluation interval from MJD 55897.95 to 55923.95. Details of the standard's design, construction, and performance are presented in references 1 - 8 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 6. This is a full evaluation in which a range of atom densities were used in order to determine the spin exchange shift.

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SUMMARY

December 2011 Evaluation of NIST-F1

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

$$Y_{(\text{Maser-NISTF1})} = -356.88\text{x}10^{-15}$$

is the average fractional frequency difference between NIST-F1 and the hydrogen maser ST0022, (clock # 40222) over the 30 day report period MJD 55894 to 55924. 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 $0.31\text{x}10^{-15}$ (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 $0.44\text{x}10^{-15}$ (1σ). The uncertainty becomes $0.48\text{x}10^{-15}$ (1σ) when the contribution from dead time, $u_{\text{link/lab}}$, 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 55894 to 55924
Maser frequency (ST0022), clock # 40222)		$Y_{(\text{Maser-NISTF1})} = -356.88\text{x}10^{-15}$
Statistical	u_A	$0.31\text{x}10^{-15}$
Systematic	u_B	$0.31\text{x}10^{-15}$
Link to clock	$u_{\text{link/lab}}$ (30 days)	$0.20\text{x}10^{-15}$
Link to TAI (estimated)	$u_{\text{link/TAI}}$ (30 days)	$0.20\text{x}10^{-15}$
Combined (estimated)	u	$0.52\text{x}10^{-15}$

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 26.00 day evaluation interval of MJD 55897.95 to 55923.95. Of the 26.00 days intended for the measurement of the maser frequency, only 21.55 days of data were collected (82.9 % 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 71.8 %. A time line of the 30 day report period is shown in Table 1 below.

Table 1: Time Line

MJD	Event
55894.00	Start report period
55897.95	Start fountain run, low density (8)
55909.99	End low density,
55910.01	Start high density (40.0 avg.)
55911.98	End high density
55911.99	Start low density (8)
55918.00	End low density,
55918.69	Start high density (39.3 avg.)
55919.72	End high density
55919.73	Start low density (8)
55923.95	End low density, end fountain run
55924.00	End report period

A factor of up to 5.0 in atom density was covered in this evaluation and the current atom density slope was obtained by a weighted linear least-mean-square fit [3]. The atom densities in laboratory units are shown in parentheses in Table 1. The zero density frequency was obtained using only the current atom density slope data. 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.

1A. 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
+180.28	0.03

1B. Spin Exchange Bias

Measurements were made over a range of atom densities. A factor of up to 5.0 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 six data points (most nominally 24 hours duration) were used in the fit and a reduced chi squared of 1.38 was obtained. This corresponds to a Birge ratio of 1.18. 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 -0.67×10^{-15} with an uncertainty of 0.16×10^{-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).

Bias	Type B Uncertainty
-0.67	0.16

1C. 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
-21.79	0.28

1D. 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

1E. 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 $1\text{x}10^{-16}$. 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 $\text{x}10^{-15}$)

Physical Effect	Bias	Type B Uncertainty
Gravitational Red shift	+179.95	0.03
Second-Order Zeeman	+180.28	0.03
Blackbody	-21.79	0.28
Microwave Amplitude Shift	-0.026	0.12
Spin Exchange shift from lowest density	(-0.67)*	(0.16)*
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	$3\text{x}10^{-3}$	$3\text{x}10^{-3}$
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 55897.95 to 55923.95)

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

Corrected Frequency	Type A Uncertainty	Total Type B Uncertainty – does not include spin exchange	Combined Uncertainty
-357.06	0.31	0.31	0.44

3. INFLUENCE OF DEAD TIME

NIST-F1 was operated for a total of only 21.55 days during this 30 day report period so the dead time has a small 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 and ensemble are well known. A small dead time correction of $0.18x10^{-15}$ is necessary and the dead time contributes an additional type A uncertainty of $0.20x10^{-15}$. See references 10 - 12. A special procedure can be used to handle distributed dead time [12]. This results in an improved estimate of the dead time uncertainty.

4. FINAL REPORT PERIOD RESULTS

Applying the correction resulting from dead time to the evaluation interval results yields the following 30 day final report period results. All uncertainties 1σ.

Report period	MJD 55894 to 55924	
Maser frequency (ST0022, clock # 40222)	$Y_{(maser\text{-}NISTF1)} = -356.88x10^{-15}$	
Type A uncertainty (not including dead time)	$0.31x10^{-15}$	
Type B uncertainty	$0.31x10^{-15}$	
Combined uncertainty (fountain only)		$0.44x10^{-15}$
Type A uncertainty from dead time	$0.20x10^{-15}$	
Combined uncertainty with dead time		$0.48x10^{-15}$
Uncertainty in link to TAI for 30 days (estimated)	$0.20x10^{-15}$	
Combined total uncertainty (estimated)		$0.52x10^{-15}$

5. REFERENCES

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Appendix

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

(1) <u>30 day evaluation of June/July 2005 (MJD 53529-53559)</u>
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) <u>40 day evaluation of September/October 2005 (MJD 53629-53669)</u>
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) <u>40 day evaluation of December 2005/January 2006 (MJD 53724-53764)</u>
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) <u>40 day evaluation of February/March 2006 (MJD 53784-53824)</u>
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) <u>30 day evaluation of October 2006 (MJD 54009-54039)</u>
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) <u>20 day evaluation of February 2007 (MJD 54134-54154)</u>
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) <u>15 day evaluation of April 2007 (MJD 54204-54219)</u>
No significant changes were made to NIST-F1 since the February 2007 evaluation.

(8) <u>15 day evaluation of May 2007 (MJD 54219-54234)</u>
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) 25 day full evaluation of January 2008 (MJD 54469-54494)
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.

(15) 25 day full evaluation of November 2008 (MJD 54764-54799)
No significant changes were made to NIST-F1 since the July 2008 evaluation other than adjustments to the optical system which resulted in a modest improvement to the frequency stability of NIST-F1. Also, a change was made in the method for calculating the spin exchange shift and its uncertainty. The new method uses slopes from previous full evaluations as well as the current slope.

(16) 15 day "micro" evaluation of December 2008 (MJD 54814-54829)
No changes were made to NIST-F1 since the November 2008 evaluation.

(17) 15 day "micro" evaluation of January 2009 (MJD 54844-54859)
No changes were made to NIST-F1 since the November 2008 evaluation.

(18) 15 day "micro" evaluation of February 2009 (MJD 54864-54879)
No changes were made to NIST-F1 since the November 2008 evaluation.

(19) 15 day "micro" evaluation of March 2009 (MJD 54904-54919)
No changes were made to NIST-F1 since the November 2008 evaluation.

(20) 15 day "micro" evaluation of April 2009 (MJD 54924-54939)
No changes were made to NIST-F1 since the November 2008 evaluation.

(21) 10 day "micro" evaluation of May 2009 (MJD 54969-54979)
No changes were made to NIST-F1 since the November 2008 evaluation.

(22) 15 day "micro" evaluation of June 2009 (MJD 54994-55009)
No changes were made to NIST-F1 since the November 2008 evaluation.

(23) 20 day full evaluation of October 2009 (MJD 55114-55134)
The main Ti/Sapphire laser failed and had to be repaired. This resulted in significant changes to the optical alignment so previous spin exchange slopes were not used. Other parameters were not affected.

(24) 15 day "micro" evaluation of November 2009 (MJD 55134-55149)
No changes were made to NIST-F1 since the October 2009 evaluation.

(25) 10 day full evaluation of December 2009 (MJD 55184-55194)
No significant changes were made to NIST-F1 since the November 2009 evaluation.

(26) 25 day full evaluation of February 2010 (MJD 55219-55244)
No significant changes were made to NIST-F1 since the December 2009 evaluation.

(27) 25 day full evaluation of April 2010 (MJD 55274-55299)
No significant changes were made to NIST-F1 since the December 2009 evaluation.

(28) 20 day full evaluation of June 2010 (MJD 55354-55374)
No significant changes were made to NIST-F1 since the December 2009 evaluation.

(29) 15 day full evaluation of August 2010 (MJD 55404-55419)
No significant changes were made to NIST-F1 since the December 2009 evaluation. The density range was a bit low due to problems with the repump laser.

(30) 25 day full evaluation of September 2010 (MJD 55444-55469)
No significant changes were made to NIST-F1 since the December 2009 evaluation. The repump laser was replaced and therefore the density range was back to normal.

(31) 15 day full evaluation of October 2010 (MJD 55494-55509)
No significant changes were made to NIST-F1 since the December 2009 evaluation.

(32) 20 day full evaluation of December 2010 (MJD 55529-55549)
No significant changes were made to NIST-F1 since the December 2009 evaluation.

(33) 15 day full evaluation of January 2011 (MJD 55574-55589)
No significant changes were made to NIST-F1 since the December 2009 evaluation.

(34) 15 day full evaluation of March 2011 (MJD 55634-55649)
No significant changes were made to NIST-F1 since the December 2009 evaluation.

(35) 15 day full evaluation of July 2011 (MJD 55744-55759)
No significant changes were made to NIST-F1 since the December 2009 evaluation.

(36) 20 day full evaluation of August/September 2011 (MJD 55794-55814)
No significant changes were made to NIST-F1 since the December 2009 evaluation.

(37) 30 day full evaluation of December 2011 (MJD 55894-55924)
No significant changes were made to NIST-F1 since the December 2009 evaluation.