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Dear Dr. Arias,

Attached is the report of our first formal evaluation of NIST-F2, a cryogenic cesium fountain primary frequency standard. The report period is for the 45 day interval from MJD 56489 to 56534. However, the fountain was operated in a nearly continuous fashion over a shorter evaluation interval from MJD 56490.96 to 56530.90. Details of the standard's design, construction, and performance are presented in references 1 - 4 listed on page 7. Many details of NIST-F1 are also relevant to NIST-F2. A detailed summary of the present evaluation is included in this report. The evaluation results are summarized 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

July/August 2013 Evaluation of NIST-F2

The first evaluation of NIST-F2 is reported. The number

$$Y_{(Maser\text{-}NISTF2)} = -\ 379.98\text{x}10^{-15}$$

is the average fractional frequency difference between NIST-F2 and the hydrogen maser ST0022, (clock # 40222) over the 45 day report period MJD 56489 to 56534. 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 $0.44\text{x}10^{-15}$ (1σ). The type B uncertainty from known biases (not including spin exchange) is $0.15\text{x}10^{-15}$ (1σ). The combined uncertainty (type A and type B) is $0.47\text{x}10^{-15}$ (1σ). The uncertainty is $0.49\text{x}10^{-15}$ (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>SUMMARY OF RESULTS</u>

Report period		MJD 56489 to 56534
Maser frequency (ST0022), clock # 40222)		$Y_{(Maser\text{-}NISTF2)} = -379.98\text{x}10^{-15}$
Statistical	u_A	$0.44\text{x}10^{-15}$
Systematic	u_B	$0.15\text{x}10^{-15}$
Link to clock	$u_{link/lab}$ (45 days)	$0.16\text{x}10^{-15}$
Link to TAI (estimated)	$u_{link/TAI}$ (45 days)	$0.14\text{x}10^{-15}$
Combined (estimated)	u	$0.51\text{x}10^{-15}$

1. DETAILS OF EVALUATION

An accuracy evaluation of NIST-F2 has been completed in which the frequency of a hydrogen maser was determined with respect to the primary frequency standard. The report period is 45 days, but the fountain was operated only over the 39.93 day evaluation interval of MJD 56490.96 to 56530.90. Of the 39.93 days intended for the measurement of the maser frequency, only 29.88 days of data were collected (74.8 % 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 66.4 %. A time line of the 45 day report period is shown in Table 1 below.

Table 1: Time Line

MJD	Event
56489.00	Start report period
56490.96	Start fountain run, start low density (~2)
56491 to 56493, 56495, 56500 to 56503, 56505, 56506, 56508, 56509, 56512, 56515, 56518, 56519, 56526 to 56530	Nominal times of low density runs
56504, 56507, 56510, 56511, 56514, 56516, 56517, 56524, 56525	Nominal times of high density runs (4.49 to 7.38)
56530.90	End low density (~2), end fountain run
56534.00	End report period

A factor of up to 4.05 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. Other corrections are also made to the raw frequency data in order to compensate for known biases which are described below [1]. 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. The resulting bias and uncertainty are shown below.

Bias	Type B Uncertainty
+286.06	0.03

1B. Spin Exchange Bias

Measurements were made over a range of atom densities. A factor of up to 4.05 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 [1,4]. Thirty data points (most nominally 24 hours duration) were used in the fit and a reduced chi squared of 0.87 was obtained. This corresponds to a Birge ratio of 0.93. 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 -0.71×10^{-15} with an uncertainty of 0.24×10^{-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
-0.71	0.24

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
-0.087	0.005

1D. Microwave Amplitude Effects

New measurements on the microwave amplitude dependence were made for this evaluation since changes were made to the microwave synthesizer. Consequently the microwave power bias and uncertainty are different than in [1].

	Bias	Type B Uncertainty
Distributed Cavity Phase (DCPS)		
m=0	< 0.01	< 0.01
m=1	0	0.028
m=2	0	0.05
Microwave Power	+0.14	0.13
Microwave Spurious	0	0.05

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 [1]. Only the first 4 biases and microwave power were 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	Magnitude	Type B Uncertainty
Gravitational Red shift	+179.87	0.02
Second-Order Zeeman	+286.06	0.03
Blackbody	-0.087	0.005
Spin Exchange (low density)	(-0.71)*	(0.24)*
Spin Exchange Non-Linearity	0	0.02
Microwave Amplitude Effects		
Distributed Cavity Phase		
m=0	< 0.01	< 0.01
m=1	0	0.028
m=2	0	< 0.02
Microwave Power	+0.14	0.13
Microwave Spurious	0	0.05
Cavity Pulling	0.015	0.015
Rabi Pulling	< 0.01	< 0.01
Ramsey Pulling	< 0.01	< 0.01
Majorana Transitions	< 0.01	< 0.01
Fluorescence Light Shift	< 0.01	< 0.01
DC Stark Effect	< 0.01	< 0.01
Background Gas Collisions	< 0.01	< 0.01
Bloch-Siegert	< 0.01	< 0.01
Integrator offset	< 0.01	< 0.01
	Total Type B Standard Uncertainty	0.15

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

2. EVALUATION INTERVAL RESULTS (MJD 56490.96 to 56530.90)

When corrections for the biases of Table 2 are applied, the following result for the measurement of $Y_{(Maser-NISTF2)}$ is obtained. Units are fractional frequency $x10^{-15}$.

Corrected Frequency	Type A Uncertainty	Total Type B Uncertainty – does not include spin exchange	Combined Uncertainty
-379.92	0.44	0.15	0.47

3. INFLUENCE OF DEAD TIME

NIST-F2 was operated for a total of only 29.88 days during this 45 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 $-0.06x10^{-15}$ is necessary and the dead time contributes an additional type A uncertainty of $0.16x10^{-15}$ [6, 7]. A special procedure can also be used to handle distributed dead time [8]. This can result in an improved estimate of the dead time uncertainty in situations with significant distributed dead time.

4. FINAL REPORT PERIOD RESULTS

Applying the correction resulting from dead time to the evaluation interval results yields the following 45 day final report period results. All uncertainties 1σ.

Report period	MJD 56489 to 56534	
Maser frequency (ST0022, clock # 40222)	$Y_{(maser-NISTF2)} = -379.98x10^{-15}$	
Type A uncertainty (not including dead time)	$0.44x10^{-15}$	
Type B uncertainty	$0.15x10^{-15}$	
Combined uncertainty (fountain only)		$0.47x10^{-15}$
Type A uncertainty from dead time	$0.16x10^{-15}$	
Combined uncertainty with dead time		$0.49x10^{-15}$
Uncertainty in link to TAI for 45 days (estimated)	$0.14x10^{-15}$	
Combined total uncertainty (estimated)		$0.51x10^{-15}$

5. REFERENCES

1. Thomas P. Heavner, Elizabeth A. Donley, Filippo Levi, Giovanni Costanzo, Thomas E. Parker, Jon H. Shirley, Neil Ashby, Stephan Barlow, and S. R. Jefferts, “First Accuracy Evaluation of NIST-F2,” *Metrologia*, submitted.
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