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Dear Dr. Arias,

Attached is the most recent report of a formal evaluation of NIST-F2, a cryogenic cesium fountain primary frequency standard. The report period is for the 20 day interval from MJD 57069 to 57089. However, the fountain was operated in a nearly continuous fashion over a shorter evaluation interval from MJD 57072.00 to 57087.68. 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.

During this fountain run we observed what appeared to be a time step of about -0.8+/-0.3 ns in our two-way link with PTB that occurred at approximately MJD 57077.0. We were not able to confirm that this did in fact occur in the two-way link until well after the February data was published in Circular T #326. This time step biases the fractional frequency difference of UTC(NIST)-UTC(PTB) by $-5(+/-2)\text{x}10^{-16}$. This will of course erroneously move y(TAI-NISTF2) in a positive direction by $5(+/-2)\text{x}10^{-16}$. Since there does not seem to be any way of including a frequency transfer bias in the PFS data reporting procedure (perhaps there should be), we have decided to handle this particular problem by making a onetime increase in the uncertainty of the link to TAI, $u_{link/TAI}$, to $0.57\text{x}10^{-15} = [(0.28\text{x}10^{-15})^2 + (0.5\text{x}10^{-15})^2]^{1/2}$, where $0.28\text{x}10^{-15}$ is the normal link uncertainty for 20 days and $0.5\text{x}10^{-15}$ is the additional uncertainty due to the time step in the two-way link.

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SUMMARY

February/March 2015 Evaluation of NIST-F2

The most recent evaluation of NIST-F2 is reported. The number

$$Y_{(\text{Maser-NISTF2})} = -405.47\text{x}10^{-15}$$

is the average fractional frequency difference between NIST-F2 and the hydrogen maser ST0022, (clock # 40222) over the 20 day report period MJD 57069 to 57089. 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 $0.43\text{x}10^{-15}$ (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 $0.46\text{x}10^{-15}$ (1σ). The uncertainty is $0.49\text{x}10^{-15}$ (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.

SUMMARY OF RESULTS

Report period		MJD 57069 to 57089
Maser frequency (ST0022), clock # 40222)		$Y_{(\text{Maser-NISTF2})} = -405.47\text{x}10^{-15}$
Statistical	u_A	$0.43\text{x}10^{-15}$
Systematic	u_B	$0.15\text{x}10^{-15}$
Link to clock	$u_{\text{link/lab}}$ (20 days)	$0.19\text{x}10^{-15}$
Link to TAI*	$u_{\text{link/TAI}}$ (20 days)	$0.57\text{x}10^{-15}$
Combined*	u	$0.75\text{x}10^{-15}$

* See page 1 of this report.

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 20 days, but the fountain was operated only over the 15.68 day evaluation interval of MJD 57072.00 to 57087.68. Of the 15.68 days intended for the measurement of the maser frequency, only 14.82 days of data were collected (94.5 % 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 74.1 %. A time line of the 20 day report period is shown in Table 1 below.

Table 1: Time Line

MJD	Event
57069.00	Start report period
57072.00	Start fountain run, start low density (2)
57072.00 to 57078.91, 57080.94 to 57087.68	Nominal times of low density runs (2)
57078.92 to 57080.93	Nominal times of high density runs (5.98 to 6.41)
57087.68	End low density (2), end fountain run
57089.00	End report period

A factor of up to 3.2 in atom density was covered in this evaluation and the current atom density slope was obtained by a weighted linear least-mean-square fit [4]. 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 $\times 10^{-15}$ 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
+289.10	0.02

1B. Spin Exchange Bias

Measurements were made over a range of atom densities. A factor of up to 3.2 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]. Sixteen data points (most nominally 24 hours duration) were used in the fit and a reduced chi squared of 1.37 was obtained. This corresponds to a Birge ratio 1.17. 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 -0.47×10^{-15} with an uncertainty of 0.22×10^{-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
-0.47	0.22

1C. Blackbody Bias

The blackbody bias is calculated from the temperature of the drift region [5]. The resulting bias and its uncertainty are shown below.

Bias	Type B Uncertainty
-0.086	0.004

1D. Microwave Amplitude Effects

No new measurements on the microwave amplitude dependence were made for this evaluation. Consequently the microwave power bias and uncertainty are the same as in the previous report.

	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 [1,6]. Only the first 4 biases and microwave power were explicitly corrected for since the rest are all well under 1×10^{-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 $\times 10^{-15}$)

Physical Effect	Magnitude	Type B Uncertainty
Gravitational Red shift	+179.87	0.03
Second-Order Zeeman	+289.10	0.02
Blackbody	-0.086	0.004
Spin Exchange (low density)	(-0.47)*	(0.22)*
Spin Exchange Non-Linearity	0	0.02
<u>Microwave Amplitude Effects</u>		
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 57072.00 to 57087.68)

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

Corrected Frequency	Type A Uncertainty	Total Type B Uncertainty – does not include spin exchange	Combined Uncertainty
-405.53	0.43	0.15	0.46

3. INFLUENCE OF DEAD TIME

NIST-F2 was operated for a total of only 14.82 days during this 20 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 $+0.07x10^{-15}$ is necessary and the dead time contributes an additional type A uncertainty of $0.19x10^{-15}$ [7, 8]. A special procedure can also be used to handle distributed dead time [9]. 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 20 day final report period results. All uncertainties 1σ.

Report period	MJD 57069 to 57089	
Maser frequency (ST0022, clock # 40222)	$Y_{(maser\text{-}NISTF2)} = -405.47x10^{-15}$	
Type A uncertainty (not including dead time)	$0.43x10^{-15}$	
Type B uncertainty	$0.15x10^{-15}$	
Combined uncertainty (fountain only)		$0.46x10^{-15}$
Type A uncertainty from dead time	$0.19x10^{-15}$	
Combined uncertainty with dead time		$0.49x10^{-15}$
Uncertainty in link to TAI for 20days *	$0.57x10^{-15}$	
Combined total uncertainty*		$0.75x10^{-15}$

* See page 1 of this report

<u>5. REFERENCES</u>

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*, vol. 51, pp 174-182, 2014.
2. 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.
3. T.P. Heavner, S.R. Jefferts, E.A. Donley, J.H. Shirley, and T.E. Parker, "NIST-F1: Recent Improvements and Accuracy Evaluations," *Metologia*, vol. 42, pp 411-422, 2005.
4. 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, Including the Impact of Frequency Transfer Noise," *Metologia*, vol. 42, pp 423-430, 2005.
5. S.R. Jefferts, T.P. Heavner, T.E. Parker, J.H. Shirley, E.A. Donley, N. Ashby, F. Levi, D. Calonico, and G.A. Costanzo, "High-Accuracy Measurement of the Blackbody Radiation Frequency Shift of the Ground-State Hyperfine Transition in ^{133}Cs, *Physical Review Letters*, vol. 112, 050801, 2014.
6. N. K. Pavlis and M. Weiss, "The Relativistic Redshift with $3x10^{-17}$ Uncertainty at NIST, Boulder, Colorado, USA," *Metologia*, vol. 40, pp 66-73, 2003.
7. T.E. Parker, "Hydrogen Maser Ensemble Performance and Characterization of Frequency Standards," *in Proc. 1999 Joint Meeting of European Freq. and Time Forum and IEEE International Freq. Control Symp.*, pp 173-176, 1999.
8. 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.
9. Dai-Hyuk Yu, Marc Weiss and Thomas E. Parker, "Uncertainty of a Frequency Comparison with Distributed Dead Time and Measurement Interval Offset," *Metologia*, vol. 44, pp 91-96, 2007.

Appendix

Summary of accumulated changes in biases and uncertainties since the state of NIST-F2 discussed in reference 1

(1) <u>45 day evaluation of July/August 2013 (MJD 56489-56534)</u>
This was the first report of NIST-F2.

(2) <u>25 day evaluation of June 2014 (MJD 56804-56829)</u>
No changes were made to NIST-F2 since the last report.

(3) <u>35 day evaluation of August/September 2014 (MJD 56894-56829)</u>
No changes have been made to NIST-F2 since the report of July/August 2013.

(3) <u>20 day evaluation of February/March 2015 (MJD 57069-57089)</u>
No changes have been made to NIST-F2 since the report of July/August 2013.