Note added by BIPM Time section July 23, 2004:
The last three pages of this report provide additional information on the estimation of the frequency shifts and the associated uncertainties (message by NIST dated July 22, 2004).
End of note added by BIPM Time section July 23, 2004.

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FAX MESSAGE

Date: June 14, 2004

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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 60 day interval from MJD 53109 to 53169, whereas the fountain was operated in a near continuous fashion over a shorter evaluation interval from MJD 53116 to 53158. Details of the standard's design, construction, and performance are presented in references 1 - 5 listed on page 8. A new paper updating the fountain operation and uncertainties is being prepared and is expected to be submitted for publication later this year. A detailed summary of the present evaluation is included in this report. The evaluation results using the BIPM format are given on pages 3 and 8.

An improved re-pump laser and new software for operating the fountain have greatly increased the reliability of NIST-F1. We had no laser dropouts during this entire run. During the 36.9 days we were operating NIST-F1 for the purposes of measuring the maser frequency we had a 94% run time. (Some of the 6% down time was intentional). See Section 1 for a time line of the operation of the fountain during this report period. Other than the improved run time there were no other significant hardware changes affecting the uncertainties in NIST-F1 since our last evaluation. The most unusual feature of this fountain evaluation is its 60 day report length. We felt that we could characterize the uncertainty due to dead time at least as well as the time transfer

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uncertainty was known. Therefore, we decided to increase the dead time by deliberately increasing the report period beyond the evaluation interval to the point where the uncertainty due to dead time was nearly equal to the uncertainty due to the time transfer. (The time transfer uncertainty goes down as the interval increases while the dead time uncertainty goes up.) This is a more optimum balance between dead time and time transfer uncertainties and has resulted in a total uncertainty for this run of less than 0.9×10^{-15}. We do not anticipate performing such long evaluations very often.

Another change we have made in this report is in how the statistical and spin exchange uncertainties in the fountain are reported. After many discussions we have come to the conclusion that when a range of densities are used during an evaluation to provide an intercept (at zero density) and its uncertainty, it is not appropriate to split the intercept uncertainty into a type A (statistical) uncertainty and a type B (spin exchange) uncertainty. The uncertainty on the intercept should be treated entirely as a type A uncertainty. Consequently the tables in this report have been changed. We now report a fountain type A uncertainty (an "effective" statistical uncertainty) that contains a component due to the spin exchange. In Table 2 we list, for information purposes only, a spin exchange bias and uncertainty but these are not included in the total type B uncertainty. They are already included in the value of the intercept and its associated uncertainty. ***Note that the combined type A and B uncertainty of the fountain is entirely consistent with previous NIST-F1 reports. The only change has been in the way the type A and B components are apportioned.*** A paper explaining these changes is being prepared for submission later this year.

There are also two other minor changes. The small bias due to pulsed heaters (see ref. 2) has been eliminated by going to un-pulsed heater operation. This did, however, require that we verify that the AC Zeeman effect did not cause a significant bias. It does not, and this will also be discussed in a future paper. We have further reduced the microwave leakage uncertainty with additional measurements.

Sincerely,

Thomas E. Parker

Steven R. Jefferts

SUMMARY

April/June 2004 Evaluation of NIST-F1

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

$$Y_{(NISTF1\text{-}maser)} = -81.08\text{x}10^{-15}$$

is the average fractional frequency difference between NIST-F1 and the hydrogen maser ST0022, (clock # 40222) over the 60 day report period MJD 53109 to 53169. 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 0.51x10^{-15} (1σ). The type B uncertainty from known biases (not including spin exchange) is 0.33x10^{-15} (1σ). The combined uncertainty (type A and type B) is 0.61x10^{-15} (1σ). The uncertainty becomes 0.73x10^{-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 53109 to 53169
Maser frequency (ST0022), clock # 40222)		$Y_{(NISTF1\text{ - }maser)} = -81.08\text{x}10^{-15}$
Statistical	u_A	0.51x10^{-15}
Systematic	u_B	0.33x10^{-15}
Link to clock	$u_{link/lab}$ (60 days)	0.40x10^{-15}
Link to TAI	$u_{link/TAI}$ (60 days)	0.50x10^{-15}
Combined	u	0.88x10^{-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 60 days, but the fountain was operated only over the 41.9 day evaluation interval of MJD 53116.0 to 53157.9. (Three days during this latter interval were devoted to measurements unrelated to the evaluation and 2 days were devoted to high microwave power measurements which were not used in the determination of the value of the maser frequency.) Of the 36.9 days intended for the measurement of the maser frequency 34.7 days of data were collected (94% run time). The lost run time was from a combination of intentional and unintentional interruptions to the fountain operation. A time line of the entire 60 day report period is shown in Table 1 below.

A factor of 5.3 in atom densities was covered in this evaluation and the frequency for zero density was obtained by a weighted linear least-mean-square fit. Other corrections are also made to the raw frequency data in order to compensate for known biases which are described below. Units for all biases are fractional frequency $x10^{-15}$ and all uncertainties are 1 sigma.

Table 1: Time Line

MJD	Event
53109	Start report period
53116	Start fountain run, low density
53127	End low density, start medium density
53130	End medium density, start high density
53134	End high density, start medium density
53137	End medium density, start unrelated measurements
53140	End unrelated measurements, start medium density high microwave power
53142	End medium density high power, start medium density
53144	Stop medium density, start low density
53158	Stop low density, end fountain run
53169	End report period

A. Quadratic Zeeman Bias

The quadratic Zeeman bias was determined by measuring the linear Zeeman splitting of the microwave spectrum. The resulting bias and uncertainty are shown below.

Bias	Type B Uncertainty
+36.46	0.10

B. Spin Exchange Bias

Measurements were made for a range of atom densities. A factor of 5.3 in atom density was covered and the frequency for zero density was obtained from the zero density intercept of a weighted linear least-mean-square fit. Using this approach there is no fixed spin exchange bias, however the shift in fractional frequency from the lowest measured density to zero density was -0.53×10^{-15} with an uncertainty of 0.15×10^{-15}. These are shown below for information purposes only. They are not included in the type B biases and uncertainties since they are already incorporated into the intercept and its uncertainty. Note that 68% of the fountain run time was at the lowest atom density.

Bias	Type B Uncertainty
(-0.53)	(0.15)

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 uncertainty are shown in Table 2.

Table 2: Known Frequency Biases and Their Type B Uncertainty.
(Units are fractional frequency x10^{-15})

Physical Effect	Bias	Type B Uncertainty
Second-order Zeeman	+36.46	0.10
Second-order Doppler	< 0.1	< 0.1
Cavity pulling	< 0.1	< 0.1
Rabi pulling	< 0.01	< 0.1
AC Zeeman (heaters)	< 0.1	<0.1
Cavity phase (distributed)	< 0.1	< 0.1
Fluorescence light shift	< 0.1	<0.1
Adjacent atomic transitions	< 0.1	< 0.1
Spin exchange	(-0.53)*	(0.15)*
Blackbody	-21.21	0.26
Gravitation	+180.54	0.10
Electronics		
RF spectral purity	0	< 0.1
Integrator offset	0	< 0.1
AM on microwaves	0	< 0.1
Microwave leakage	0	0.14
	Total Type B Standard Uncertainty	0.33

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

2. EVALUATION INTERVAL RESULTS (MJD 53116.0 to 53157.9)

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 now 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. 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
-81.22	0.51 (0.28)	0.33	0.61

3. INFLUENCE OF DEAD TIME

NIST-F1 was operated for a total of 34.7 days during this 60 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 accurately quantified. The frequency stability and drift of the reference maser are well known. A small drift correction of $+0.14x10^{-15}$ is required for this evaluation because the run time was not perfectly centered in the report period. The dead time also contributes an additional type A uncertainty of $0.40x10^{-15}$. See references 6 - 8.

4. FINAL REPORT PERIOD RESULTS (without time transfer uncertainty)

Applying the correction resulting from dead time to the evaluation interval results yields the following 60 day final report period results.

Report period	MJD 53109 to 53169
Maser frequency (ST0022, clock # 40222)	$Y_{(NISTF1 - maser)} = -81.08x10^{-15}$
Type A uncertainty (not including dead time)	$0.51x10^{-15}$ (1σ)
Type B uncertainty	$0.33x10^{-15}$ (1σ)
Combined uncertainty (fountain only)	$0.61x10^{-15}$ (1σ).
Type A uncertainty from dead time	$0.40x10^{-15}$ (1σ)
Combined uncertainty with dead time	$0.73x10^{-15}$ (1σ).

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

Report period		MJD 53109 to 53169
Maser frequency (ST0022), clock # 40222)		$Y_{(NISTF1 - maser)} = -81.08x10^{-15}$
Statistical	u_A	$0.51x10^{-15}$
Systematic	u_B	$0.33x10^{-15}$
Link to clock	$u_{link/lab}$ (60 days)	$0.40x10^{-15}$
Link to TAI	$u_{link/TAI}$ (60 days)	$0.50x10^{-15}$
Combined	u	$0.88x10^{-15}$

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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7 T.E. Parker, D.A. Howe and M. Weiss, "Accurate Frequency Comparisons at the $1x10^{-15}$ Level," *in Proc. 1998 IEEE International Freq. Control Symp.*, pp 265-272, 1998.

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Supplement to the NIST-F1 Reports of December 2003 and June 2004

This supplement contains additional information related to the NIST-F1 evaluation reports of December 29, 2003 and June 14, 2004. Those evaluation reports should be read first in order to better understand this supplement.

Allan Deviation

Figure 1 shows an Allan (TOTAL) deviation plot of NIST-F1 versus the post-processed, maser ensemble based NIST AT1E time scale. (Note that information from the fountain is not used to change parameters in the scale during an evaluation.) Though the actual fountain measurements are made relative to one of the NIST masers we can relate these frequency difference measurements to the paper scale AT1E with no significant degradation because of our low noise dual mixer measurement system (the frequency noise on this system is well below $1x10^{-16}$ at one day). The AT1E scale is used as the reference for the fountain since it is less noisy than an individual maser and has low frequency drift (less than $2x10^{-17}$ per day).

This plot is a composite of information from the NIST-F1 evaluations of December 2003 and June 2004. The solid black circles out to τ = 1 day are calculated from individual cycle by cycle frequency measurements made over 14 days of continuous low density run time from the June evaluation (581,785 cycles). The last two black circles beyond one day are averages of the Allan deviation values for the December and June runs. This was done to increase the confidence on these last two points. To calculate the

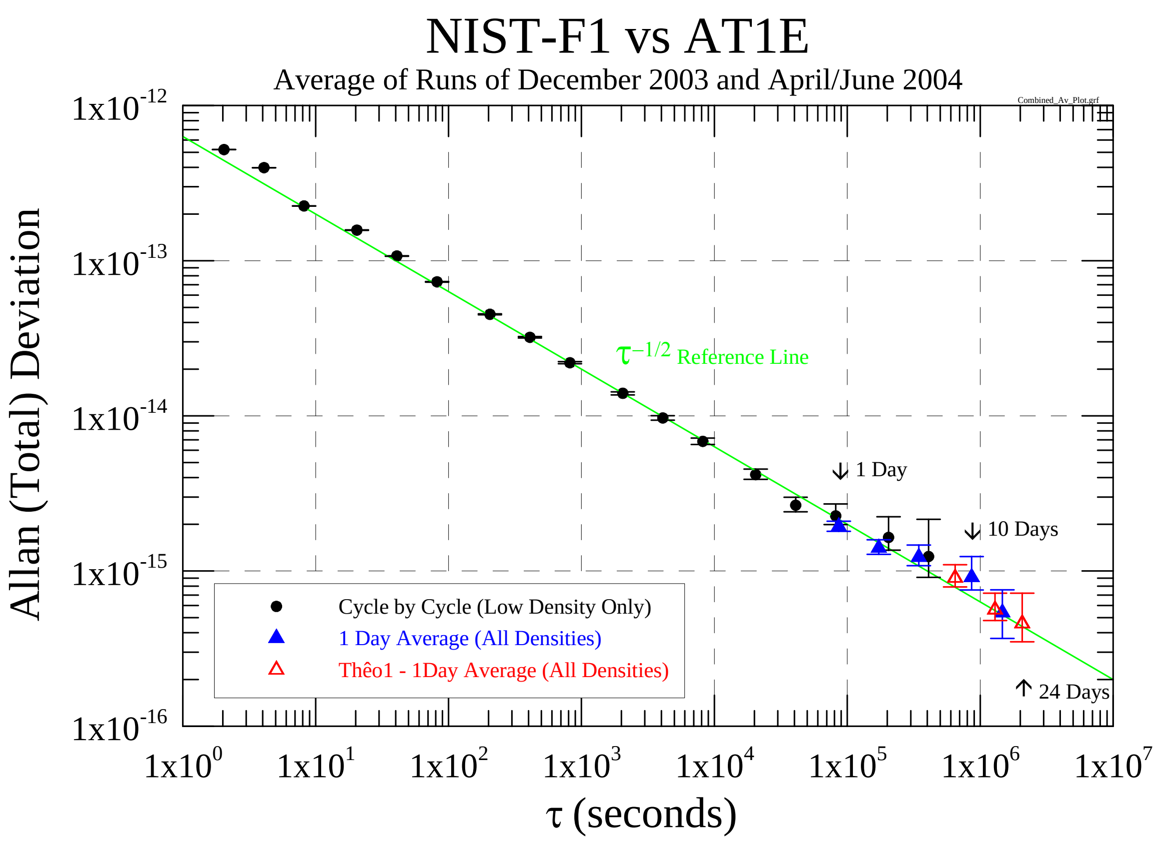

Figure 1. Composite Allan deviation of NIST-F1 vs AT1E

Allan deviation values for larger τ values we have used the 24 hour averages of the fountain frequency versus AT1E for all densities. This data is shown with the solid blue triangles. Data from all three densities values are used for this calculation in order to give a nearly continuous time series of fountain frequency versus AT1E over an interval of 40 days. The daily average frequencies for the medium and high densities are corrected to low density for the spin exchange shift. Using all the daily average data permits a stability calculation out to 24 days using Theo1 (see below). All of the blue triangle points are averages of Allan deviation values from both the December and June runs. The medium and high density data have lower Allan deviation values for a given τ than the low density points have, which results in a decrease in the calculated values. However, 72% of the data are from low density runs and consequently the higher density data reduces the composite result by only 10% relative to a pure low density plot. Finally, Theo1 [1] was used to extend the range and give a higher confidence for the largest τ values. These data are shown as hollow red triangles. The two points at 6.5×10^{5} and 1.3×10^{6} s are averages of the December and June runs, but the last point is only from the June run since it was longer.

The noise characteristic of the data in Fig. 1 is essentially white FM from 2 seconds to 24 days. The fountain is operated at low atom densities and consequently it is the dominant source of noise. Over almost the entire range of τ the noise of AT1E is negligible compared to the fountain noise. For example at τ = 1000 s the ensemble noise is about 2×10^{-15}, which is about a factor of ten lower than the fountain noise. Only beyond about 20 days does the ensemble noise of about 3×10^{-16} begin to approach that of the fountain. The slight elevation of the two points at 2 and 4 seconds is caused by servo noise. A purely high density plot is not shown but it also is white FM from 3 seconds to 1.4 days and is a factor of 2.2 lower. High density data does not yield much long-term information since we don't run for more than a few days at high density.

The data in Fig. 1 demonstrates two important points. One is that the noise characteristic of the fountain is white FM out to at least 24 days (the level is consistent with atom shot noise). The second point is that the maser ensemble noise is not a significant perturbation over this range of τ. Thus we have demonstrated that the fountain is well behaved over time intervals comparable to an evaluation period, and that we have corroborated the previous observation [2] that the maser ensemble is highly stable in the long term. It is stable enough that it can be used as a reference for the determination of biases in the fountain.

Magnetic Field Monitoring

We currently do not monitor the magnetic field in NIST-F1 during an evaluation. The field is mapped before the evaluation. Using this map, the central Ramsey fringe on the $|3,1\rangle \rightarrow |4,1\rangle$ manifold is identified, and the second order Zeeman frequency bias on the $|3,0\rangle \rightarrow |4,0\rangle$ transition calculated. We have monitored the position of the central fringe over several years of operation and have never found it to have moved outside its stated uncertainty without our having adjusted the magnetic field. This is all clearly discussed in [3].

Density Ratios

The range of densities covered in the June evaluation was 5.3 (ratio of highest atom density to lowest density), and 5.7 in the December run. We measure the density by monitoring the number of returned atoms and their spatial distribution. We believe that the assigned ratios are correct to better than 10%, far less than the statistical uncertainties associated with the spin exchange bias correction. This is discussed in [3] and the discussion will be extended in a paper currently under preparation.

References

1 D.A. Howe and T.K. Peppler, "Very Long-term Frequency Stability: Estimation using a Special-purpose Statistic", *Proc. 2003 Joint Mtg. IEEE Intl. Freq. Cont. Symp. and EFTF Conf.*, pp 233-238, 2003.

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