Frequency evaluation of the NIST-F4 PFS for the period MJD 61129-61159

Frequency Measurement Summary

The NIST Primary Frequency Standard NIST-F4 [1] was used to measure the fractional frequency offset of the NIST Hydrogen Maser ST0008 (BIPM code 1412108) during the time interval:

MJD 61129 00:00 UTC and MJD 61159 00:00 UTC

The results of the measurement campaign are summarized in Table 1. The frequency shifts applied to NIST-F4 and the fountain uncertainty budget are summarized in Table 2. In these tables, entries in red are evaluated in each measurement campaign while entries in black are based on prior experiments. The current values of "instability at 1 second" and "Type B uncertainty" differ from the Metrologia evaluation mainly due to fluctuations in the atom number and variations in the measured shift due to collisions between cold Cs atoms.

Table 1. Relevant parameters for the frequency evaluation.

Measurement interval	MJD 61129 00:00 UTC - MJD 61159 00:00 UTC
Reference clock (HM)	ST0008 (BIPM code 1412108)
Fractional dead time	0.5%
Fractional frequency instability at 1s (high-density)	1279.7×10^{-16}
Fractional frequency instability at 1s (low-density)	2627.4×10^{-16}
Duty cycle low/high density	4.5
Frequency difference $y(\text{NIST-F4 - HM})$	86118.7×10^{-16}
Type A uncertainty u_A	2.6×10^{-16}
Type B uncertainty u_B	2.2×10^{-16}
Clock link statistical uncertainty $u_{A/Lab}$	0.3×10^{-16}
Clock link systematic uncertainty $u_{B/Lab}$	0.1×10^{-16}

Statistical frequency uncertainties:

The fractional frequency instability of NIST-F4 is limited by quantum projection noise and phase noise of the local oscillator. The local oscillator is an OCXO phase-locked to the hydrogen maser with a time constant of approximately 100 s. During the measurement, NIST-F4 operated alternatively between high and low-density modes. These two modes were used to extrapolate to the limit of zero-density to correct for the frequency shift due to collisions between cold Cs atoms. The effective frequency instability for the zero-density extrapolation is given in Table 1. An additional alternating servo measures the value of the quantization field (C-field) for the calibration of the quadratic Zeeman frequency shift.

Clock link statistical and systematic uncertainties $u_{A/Lab}$ and $u_{B/Lab}$

- *Contributions to* $u_{A/Lab}$

We estimate $u_{A/Lab}$ as the quadrature sum of two effects:

1. Link between the hydrogen maser and the fountain's local oscillator (OCXO):

The uncertainty resulting from phase comparisons between the hydrogen maser reference and the fountain's local oscillator is quantified by the timescale measurement system that compares the phase of the OCXO and the maser. We find that there is a slow phase drift between the OCXO and the reference maser during the reported interval, which amounts to a fractional frequency offset of approximately 0.2×10^{-16}. We correct the measured frequency of NIST-F4-maser for this error and include a contribution of 0.2×10^{-16} to $u_{A/Lab}$ as a conservative estimate of the uncertainty in this bias.

2. Measurement dead time

Measurement dead time or gaps in the fountain operation during a measurement campaign can cause a bias in the frequency measurement due to the frequency drift of the maser, which must be corrected. The correction uncertainty is limited by the uncertainty in the maser drift measured during the campaign.

The frequency correction is calculated as the product of the maser drift and the difference between the mean MJD of the measurement period and the mean value of the timestamps of all frequency measurements during the campaign. The correction uncertainty is obtained by multiplying the time difference and the uncertainty of the measured maser frequency drift.

For the current measurement campaign, the dead-time is distributed approximately uniformly. We estimate that the bias due to dead time is negligible in this case. We also consider the dead time uncertainty due to the frequency noise of the hydrogen maser in addition to the maser's frequency drift. We estimate the dead time uncertainty as 0.1×10^{-16} for maser frequency noise other than the linear drift and include this is a contribution to $u_{A/Lab}$.

- *Contributions to* $u_{B/Lab}$

It is possible for the microwave synthesizer servo to accumulate a frequency error during the measurement interval. We include this as a contribution to $u_{B/Lab}$. This error is constrained by the sum of all the frequency corrections required to keep the microwave synthesizer on resonance during a measurement campaign. It is typically $< 1 \times 10^{-17}$. To account for this uncertainty, a contribution of 1×10^{-17} is included for $u_{B/Lab}$ in Table 1.

Applied Corrections and Uncertainty budget

The systematic frequency shifts applied to NIST-F4 and their uncertainties are listed in Table 2. A more detailed description of the shifts and uncertainties is given in [1]. The relativistic shift has been updated according to the newest geodetic survey of NIST, JILA, University of Colorado, and Table Mountain Laboratories and the North American-Pacific Geopotential Datum of 2022 (NAPGD2022) [2]. Entries highlighted in red are evaluated in each measurement campaign.

Table 2. Systematic frequency shifts and total type B uncertainty σ_y in 10^{-16} fractional frequency units.

Frequency shift	Value	Uncertainty
Relativistic shifts	1808.89	0.01
Quadratic Zeeman	1370.3	0.20
Blackbody radiation	-170.0	0.60
Cold collisions	-10.7	1.1
Microwave lensing	0.90	(+0.20, -0.40)
DCP (m=0)	0.05	(+0.02, -0.08)
DCP (m=1)	0.00	1.70
DCP (m=2)	0.00	0.20
Microwave modulation and spurs	0.00	0.50
Microwave leakage	0.00	0.40
Cavity pulling	0.00	0.11
Rabi and Ramsey pulling	0.00	0.10
Majorana transitions	0.00	0.10
Background gas collisions	0.00	0.03
AC Stark (light)	0.00	0.01
Total uncertainty u_B		2.2

Allan deviation

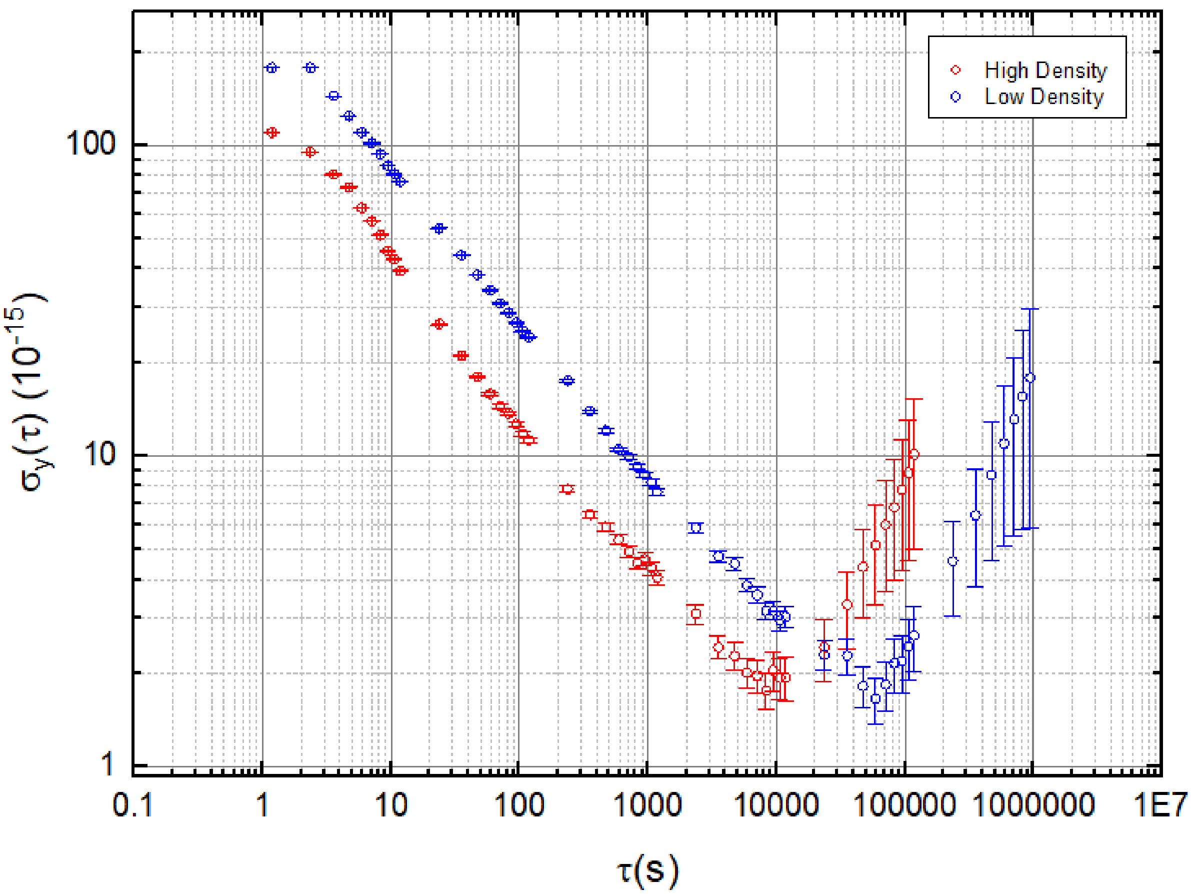

Figure 1. Allan deviation of the fractional frequency offset of the maser measured during the campaign for both high density (red) and low density (blue) modes.

References:

[1] V. Gerginov, G. W. Hoth, T. P. Heavner, T. E. Parker, K. Gibble and J. A. Sherman, "Accuracy evaluation of primary frequency standard NIST-F4", *Metrologia* **62** 035002, 2025

[2] V. Gerginov, G. W. Hoth, T. P. Heavner, T. E. Parker, K. Gibble and J. A. Sherman, “Corrigendum: Accuracy evaluation of primary frequency standard NIST-F4 (2025 Metrologia 62 035002)”, *Metrologia* **63** 019502, 2026.