Frequency evaluation of the NIST-F4 PFS for the period MJD 61309-61344

Frequency Measurement Summary

The NIST Primary Frequency Standard NIST-F4 [1] was used to measure the fractional frequency offset of the NIST iodine optical clock VA0021 (BIPM code 1442021) during the time interval:

MJD 61309 00:00 UTC and MJD 61344 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 the phase noise in the local oscillator, 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 61309 00:00 UTC - MJD 61344 00:00 UTC
Reference clock (HM)	VA0021 (BIPM code 1442021)
Fractional dead time	98.7%
Fractional frequency instability at 1s (high-density)	1105.8×10^{-16}
Fractional frequency instability at 1s (low-density)	2454.4×10^{-16}
Duty cycle low/high density	4.5
Frequency difference $y(\text{NIST-F4 - HM})$	9702.0×10^{-16}
Type A uncertainty u_A	2.1×10^{-16}
Type B uncertainty u_B	2.3×10^{-16}
Clock link statistical uncertainty $u_{A/Lab}$	0.1×10^{-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. For this campaign, the radio frequency outputs of the VA0021 were used to drive the fountain synthesizer. 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. 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* $u_{A/Lab}$

In this campaign, the radio frequency outputs from VA0021 were used to drive the fountain's microwave synthesizer directly. This eliminates a possible contribution to $u_{A/Lab}$ from the imperfect link between the reference clock and an OCXO based local oscillator. In this configuration, $u_{A/Lab}$ arises from measurement dead time.

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

The frequency bias 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 bias uncertainty is obtained by multiplying the time difference and the uncertainty of the maser drift.

For the current measurement campaign, there is a gap in the data. We consider both bias and excess uncertainty from the reference clock's linear frequency drift and random noise during the non-measured (dead time) interval. We estimate the bias due to drift as 0.8×10^{-16}. We correct for this bias and include a contribution to $u_{A/Lab}$ equal to 10% of the bias. We estimate the uncertainty due to the combination of dead time and maser frequency noise as 0.13×10^{-16}, which is included as 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	1369.90	0.20
Blackbody radiation	-170.05	0.60
Cold collisions	-10.93	1.09
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 $\boldsymbol{u_B}$		2.3

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.