Frequency evaluation of the NIM6 PFS against H-maser 1404821 for the period from MJD 61159 to MJD 61189

1. Summary

During the period from MJD 61159 to MJD 61189 (29 April 2026–28 May 2026), the NIM Primary Frequency Standard NIM6 [1] was used to measure the fractional frequency offset of the NIM H-maser (BIPM code 1404821). During the measurement, NIM6 operated alternatively between high and low-density modes. Table 1 below summarizes the evaluation result as well as the associated uncertainties.

Table 1. Results of NIM6 compared to H-maser 1404821.

Measurement period	MJD 61159-MJD 61189
Reference clock (H-maser)	BIPM code 1404821
Uptime ratio	96.7%
Frequency difference y (NIM6-HMaser$_{1404821}$)	408.6×10^{-16}
Type-A uncertainty u_{A}	1.7×10^{-16}
Type-B uncertainty u_{B}	2.0×10^{-16}
Link to H-maser $u_{\mathrm{A/lab}}$	$< 1.0\times10^{-16}$
Link to H-maser $u_{\mathrm{B/lab}}$	$< 0.1\times10^{-16}$

The final uncertainty into TAI u_{total} is the square sum of the five uncertainties as following:

$$u_{\mathrm{total}} = \sqrt{\left(u_{\mathrm{A}}\right)^2 + \left(u_{\mathrm{B}}\right)^2 + \left(u_{\mathrm{A/lab}}\right)^2 + \left(u_{\mathrm{B/lab}}\right)^2 + \left(u_{\mathrm{link/TAI}}\right)^2} \tag{1}$$

where u_{A} is the statistical uncertainty on the frequency measurement, and u_{B} is the systematic uncertainty of the NIM6 [1]. The link uncertainty $u_{\mathrm{A/lab}}$ comprises two terms and is determined through the quadratic summation of these two terms [1]. $u_{\mathrm{B/Lab}}$ represents the systematic uncertainty of the frequency link. The 100 MHz reference signal from H-maser 1404821 is directly connected to the microwave synthesizer of NIM6 via a long cable. This signal is looped back from NIM6's laboratory to the lab housing H-maser 1404821, where the frequency difference and stability are monitored. No frequency difference has been observed within the measured stability limits. Therefore, the associated type B uncertainty due to the link $u_{\mathrm{B/lab}}$ is estimated to be less than 1.0×10^{-17}. The frequency transfer uncertainty $u_{\mathrm{link/TAI}}$ arises from H-maser 1404821 to TAI through the remote frequency comparison link. All the above uncertainties are calculated at 1σ.

During the period from MJD 61159 to MJD 61189, the fountain clock NIM6 was alternately operated at two different atomic densities with $k=N_{\mathrm{H}}/N_{\mathrm{L}}\approx7.65$. According to the measured data, the 30-day measurements yield a fractional uncertainty of 1.7×10^{-16}.

2. Systematic frequency corrections and uncertainties

The following frequency corrections are applied to the raw NIM6-HMaser$_{1404821}$ data, and the corresponding systematic frequency uncertainties are incorporated into the fountain fractional uncertainty budget. The values are listed in Table 2.

——***Second-order Zeeman shift***

In routine operations of the NIM6, a time-averaged magnetic field of 125.03 nT was measured, which yields a calculated relative second-order Zeeman frequency shift of 72.69×10^{-15}.

——***Cold collisions shift***

The cold collisions shift [1] was estimated during the measurement by operating alternatively between high and low atomic densities (or atom number) through adjusting the power of the state selection microwave pulse. According to the measured relative frequencies, along with the detected atomic numbers at the high and low densities, the relative frequency extrapolated to zero density is given by

$$f_{\mathrm{Zero}}=\frac{kf_{\mathrm{L}}-f_{\mathrm{H}}}{k-1} \tag{2}$$

where k is the ratio ($N_{\mathrm{H}}/N_{\mathrm{L}}$) between high and low densities, and f_{H} and f_{L} are the measured frequencies at high and low densities respectively. At low and high density, the collisional shifts are given by $(f_{\mathrm{H}}-f_{\mathrm{L}})/(k-1)$ and $k(f_{\mathrm{H}}-f_{\mathrm{L}})/(k-1)$, respectively.

The uncertainty in eliminating the collision frequency shift is derived from equation (2) as

$$\sigma_{\mathrm{Z}}^2(\tau)=\left(\frac{k}{k-1}\right)^2\sigma_{\mathrm{L}}^2(\tau/2)+\left(\frac{1}{k-1}\right)^2\sigma_{\mathrm{H}}^2(\tau/2)+\left(\frac{f_{\mathrm{L}}-f_{\mathrm{H}}}{(k-1)^2}\right)^2\sigma_k^2 \tag{3}$$

here, $\tau/2$ represents the averaging time for a single density measurement, σ_k is the uncertainty of the ratio k. The first two terms are treated as type-A uncertainty. The last term is treated as the cold-collision-induced type-B uncertainty and included in the systematic uncertainty budget, which includes the nonlinearity $\sigma_{\mathrm{nonlinear}}$ between the measured atom numbers and the average density, and the atom number uncertainties δN_{L}, δN_{H}, is expressed as [1]

$$\begin{cases}\delta\left(\dfrac{\Delta f}{f_0}\right)_{\mathrm{collision}}=\dfrac{1}{f_0}\left(\dfrac{f_{\mathrm{H}}-f_{\mathrm{L}}}{(k-1)^2}\right)\sigma_k\\ \sigma_k^2=\sigma_{\mathrm{nonlinear}}^2+\left[\left(\dfrac{\delta N_{\mathrm{L}}}{N_{\mathrm{L}}}\right)^2+\left(\dfrac{\delta N_{\mathrm{H}}}{N_{\mathrm{H}}}\right)^2\right]k^2\end{cases} \tag{4}$$

Given a k of 7.65, a $(f_{\mathrm{L}}-f_{\mathrm{H}})/f_0$ of 15.06×10^{-15}, a $\sigma_{\mathrm{nonlinear}}$ of 0.05 horizontally and 0.01 vertically, and atom number variations of less than 3%, the fractional uncertainty induced by cold collisions is evaluated to be 1.12×10^{-16}.

——***Blackbody radiation shift***

——***Relativistic red and second-order Doppler shifts***

The gravitational red shift [1] was calculated from the reference gravitational potential W_0=62636856.0 $\mathrm{m^2s^{-2}}$ for TT/TAI, the gravitational potential W_{QB}=62636852.95± 0.49 $\mathrm{m^2s^{-2}}$ at the mean sea level at the tide gauge station in Qingdao of China, the local gravitational acceleration g and the height of the fountain's Ramsey cavity. For an atomic cloud launched to a height of h_{ac}=0.336(7) m above the mid-plane of the Ramsey cavity, the combined fractional frequency shift due to the relativistic (red and second-order Doppler) effects can be expressed as $\Delta f/f_0=h_{\mathrm{ac}}g/(3c^2)$ [2]. For NIM6 fountain clock, this shift is evaluated to be 0.12×10^{-16} with a fractional uncertainty of 3×10^{-19}. In summary, the combined fractional frequency shift due to the relativistic red and second-order Doppler shifts is 86.52×10^{-16} with a fractional uncertainty of 0.2×10^{-16}.

——***Microwave lensing shift***

The following systematic frequency uncertainties are added to the NIM6 uncertainty budget. The values are listed in Table 2.

——***Microwave interferometric switch***

——***Microwave leakage***

——***Distributed Cavity Phase (DCP)***

——***Microwave spectrum impurity***

——***Light shift***

——***Majorana transitions***

——***Rabi and Ramsey pulling***

——***Cavity pulling***

——***Collision with background gases***

3. Frequency measurement results

The systematic frequency shifts and their uncertainties are listed in Table 2. A more detailed description of the shifts and uncertainties is given in [1].

Table 2. Uncertainty budget of the NIM6, listing physical effects, frequency corrections, and fractional type-B uncertainty in a unit of 10^{-16}.

Physical effect	**Bias /10^{-16}**	**Uncertainty/10^{-16}**
Second-order Zeeman	726.9	0.7
Cold collisions	0.0*	1.12
Blackbody radiation	-165.9	0.6
Relativistic red and second-order Doppler shifts	86.52	0.2
Microwave lensing	0.63	0.5
Microwave interferometric switch	0.0	1.0
Microwave leakage	0.0	0.1
DCP	0.0	0.87
Microwave spectral impurities	0.0	0.1
Light shift	0.0	0.01
Majorana transition	0.0	0.1
Rabi and Ramsey pulling	0.0	0.1
Cavity pulling	0.0	0.02
Collision with background gases	0.0	0.1
Total	**648.15**	**2.0**

*The fractional collisional shift is calculated to be 22.6×10^{-16} at low density and 173.2×10^{-16} at high density.

References

[1] F. S. Zheng, W. L. Chen, K. Liu, S. Y. Dai, N. F. Liu, Y. Z. Wang and F. Fang, "Uncertainty Evaluation of the Caesium Fountain Primary Frequency Standard NIM6," Metrologia, vol. 62, no. 3, 035005, 2025.

[2] 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, vol. 62, no. 3, p. 035002, 2025.