Frequency comparison between H-maser 1404821 and NIM5 for the period MJD 60979 to 61009

I. SUMMARY

The primary frequency standard NIM5 was used to measure the average fractional frequency difference of the H-maser 21, identified by the clock code 1404821, during an evaluation campaign over 30 days in nov. 2025. The results are given in table 1, together with the total uncertainties in relating NIM5 to maser 21.

Table 1 Summary of the frequency measurements of H-maser 21 (1404821)

Period	MJD 60979.0 to 61009.0
$y_{(\mathrm{H21-NIM5})}$ [$\times 10^{-15}$]	-31.63
Duty cycle [%]	89.1%
u_A [$\times 10^{-15}$]	0.34
u_B [$\times 10^{-15}$]	0.68
$u_{link/lab}$ [$\times 10^{-15}$]	0.10
u_{total} [$\times 10^{-15}$]	0.77

The combined total uncertainty u_{total} is the square sum of the three uncertainties as following:

$$u_{total} = \sqrt{(u_A)^2 + (u_B)^2 + (u_{link/lab})^2} \quad (1)$$

Type A uncertainty u_A is the statistical uncertainty on the frequency measurement, u_B is the Type B uncertainty from bias evaluations, and $u_{link/lab}$ is the uncertainty induced by the link between NIM5 fountain clock and the H-maser 21, which includes the dead time and the phase noise of the link between NIM5 and H-21. All the above uncertainties are calculated at 1σ.

II. Measurement methods

The primary frequency standards NIM5 already been moved into the new laboratory.. Following the optimization of a portion of the electronic control system, the reconnection of fiber optic and electrical cables, and the subsequent debugging of functions, NIM5 has now resumed its operational capabilities. We re-evaluated frequency accuracy of NIM5 and a summary of the systematic frequency shift evaluations for NIM5 is listed in Table 2, some frequency shift terms changed.

We have redesigned and developed an microwave interferometric switch, and measured the phase fluctuations introduced by it, and the uncertainty introduced by the switch was 1×10^{-17}.

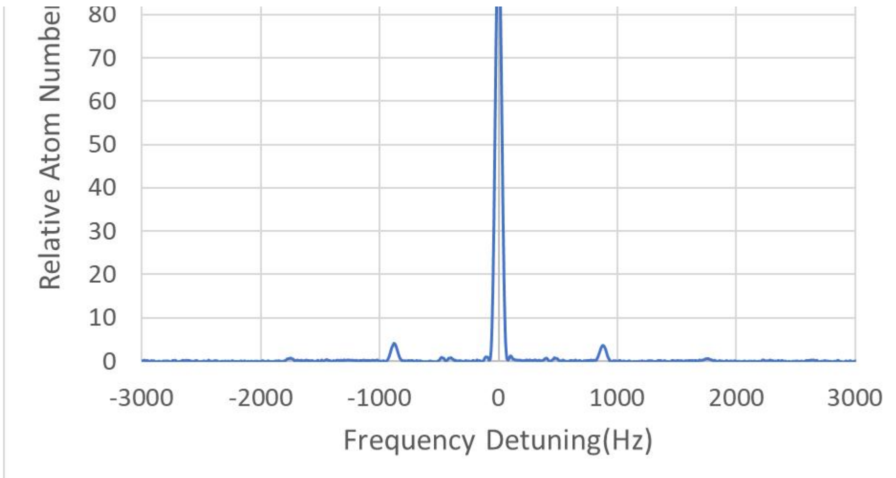
The gravitational red shift is given by [1]

$$\left(\frac{\Delta f}{f}\right)_{\mathrm{G}} = -\frac{W_{\mathrm{QB}} - gH - W_0}{c^2} \tag{2}$$

where W_0 is the gravitational potential for TT/TAI, W_0=62636856.0 m^2s^{-2}, as a reference. W_{QB}=62636852.95± 0.49 m^2s^{-2} [2] is the gravitational potential at the mean sea level at the tide gauge station in Qingdao, China.The orthometric height of the Ramsey cavity is 78.4(0.2) m which is measured by the dimensional metrology laboratory of NIM and traced to a leveling benchmark inside our campus, so the gravitational red shift is changed to 85.8×10^{-16} with the uncertainty 2×10^{-17} .

The temperature fluctuations of our new laboratory are smaller than before. taking the average temperature of the fight tube to be 296.15 K with 0.2 K uncertainty, the relative BBR shift of the NIM5 is calculated to be -164.4×10^{-16} with an uncertainty of 0.5×10^{-16}. Any interactions between atoms and scattered near-resonant light during interrogation will cause a frequency shift of the clock transition.The new measurements indicate that the additional attenuation of the mechanical shutter is at least three orders of magnitude, so the relative ac Stark shift due to the resonant light is estimated to be below 1×10^{-17}.

The effects of Rabi and Ramsey pulling, Majorana transitions are linked to transitions for Zeeman levels $m_F\neq0$. While these could be a significant shift for thermal beam standards, where all mF states are populated, they are effectively reduces for fountain clocks by selecting only the $m_F = 0$ clock state and eliminating the atoms on the $m_F\neq0$ states. The populations on different Zeeman levels are measured by a Rabi transition rates after the state selection as shown in the figure below.



The measured asymmetry in the populations of the mF = ±1 states is about 2.0×10^{-3} derived from the above figure, and the Rabi and Ramsey pulling induced frequency shift is below 10^{-17} as analyzed in [3-4].

Majorana transitions occurs when the magnetic field crosses zero or varies too fast along the path of the atoms between state selection cavity and Ramsey cavity, and can produce frequency shifts in atomic fountains. Such transitions in NIM5 Cs fountain are eliminated by carefully shaping the magnetic field along the entire atomic trajectory. The adopted methods include that, the entire vacuum system of NIM5 is wrapped by a layer of soft iron magnetic shield, and bias B field along the vertical direction is applied by a pair of coils as the quantization axis which is turned on after launching, and an additional coil above the detection chamber to provide a more uniform field near the shield. Based on the results from our previous simulations[5], the magnetic field does not cross zero along atoms' trajectory. The atomic numbers in the mF = ±1 states are less than 7% of the total numbers, and most of them are generated due to off resonance scattering of |F=4> state and jumped to |F=3> state during state selection. The magnetic field gradient changed slowly enough to ensure adiabatic condition, and the quantum axis of the atoms follow the changes of the magnetic field. The corresponding relative frequency shift due to

Majorana transition should be significantly small [6].

For NIM5 Cs fountain clock, the Ramsey cavity Q-factor is measured to be about 10000, the Ramsey cavity detuning δfc is about cavity detuning which is about 50 kHz for the NIM5 Ramsey cavity. The interrogating pulse used is within 10% of the optimum π/2 pulse, according equation (3), the uncertainty is below 1×10^{-17}

$$\left(\frac{\Delta f}{f_0}\right)_{\text{cavity-pulling}} = \frac{\delta f_c}{f_0}\frac{8}{\pi^2}\frac{Q_c^2}{Q_{at}^2} b\tau_{in}\cot(b\tau_{in}) \tag{3}$$

The combined relative Type B uncertainty is approximately 6.8×10^{-16}.

Table 2 Uncertainty budget of NIM5 in these evaluations.

Physical Effect	Bias [$\times10^{-16}$]	Uncertainty [$\times10^{-16}$]
2nd order Zeeman	730.1	2.0
Collisional shift	-34.5*	1.6
Microwave interferometric Switch	0.0	0.1
Microwave leakage	0	1.0
DCP	0.0	6.0
Microwave spectral impurities	0.0	1.0
Blackbody radiation	-164.4	0.5
Gravitational red shift	85.8	0.2
Majorana transition	0.0	<0.1
Light shift	0.0	<0.1
Rabi and Ramsey pulling	0.0	<0.1
Cavity pulling	0.0	<0.1
Collision with background gases	0.0	1.0
Total	617.0*	6.8*

* The collision shift is calculated at low density.

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[5] Fang F, Li M S, Lin PW, et al 2015 Metrologia 52 454-468
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