I. SUMMARY

The primary frequency standard NIM5 was used to measure the average fractional frequency difference of the H-maser H271, identified by the clock code 1404871, during an evaluation campaign over 15 days in Sep. 2017. The results are given in table 1, together with the total uncertainties in relating NIM5 to maser H271.

Table 1 Summary of the frequency measurements of H-maser H271 (1404871)

Period	MJD 58009.0 to 58024.0
$y_{(NIM5-H271)}$ [$\times 10^{-15}$]	4138.7
Duty cycle [%]	94.4%
u_A [$\times 10^{-15}$]	0.3
u_B [$\times 10^{-15}$]	0.9
$u_{link/lab}$ [$\times 10^{-15}$]	0.2
u_{total} [$\times 10^{-15}$]	1.0

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

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

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 H271, which includes the dead time and the phase noise of the link between NIM5 and H271. All the above uncertainties are calculated at 1σ.

II. Measurement methods

A new microwave synthesizer has been used. The 5 MHz output of the BVA oscillator is multiplied to 100 MHz, and phase locked to the H271 H-maser 100 MHz signal. This 100 MHz output is locked to the signal from a dielectric resonator oscillator (DRO) at a frequency of 9.3 GHz. A new 100 MHz microwave interferometric switch is used with the same design as before but different a RF switch and a directional coupler. The instability is improved. The instability results are shown in figure 1.

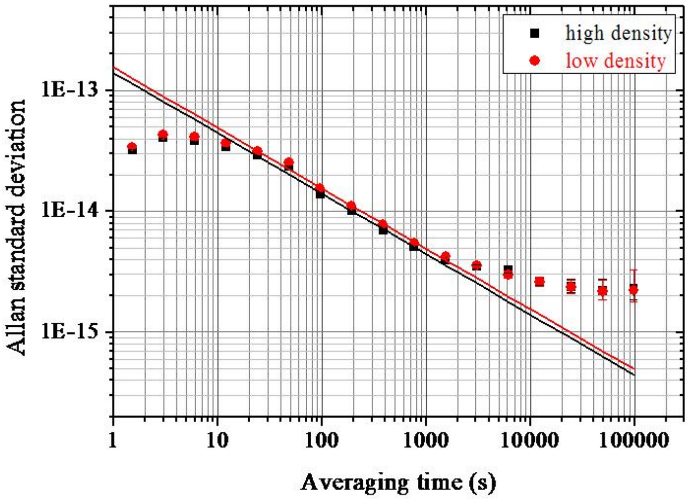


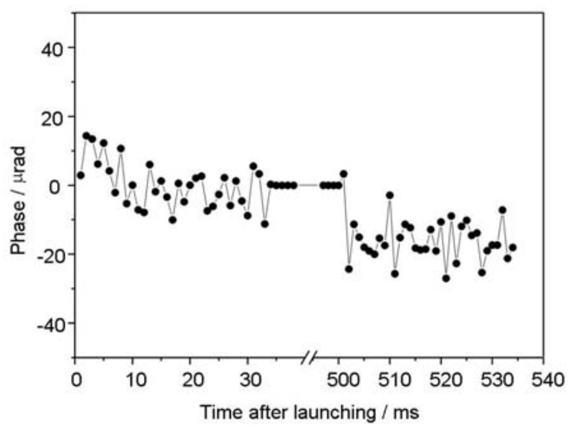
Fig. 1 Standard Allan deviation $\sigma_y(\tau)$ of NIM5 measured against the H271maser over a period of 15 days (The red dots and black triangles denote the stability at low and high atom density respectively).

From figure 1, we can see that for averaging times from 20 - 1000 seconds, the relative frequency instabilities are dropping as $\sqrt{\tau}$, $1.4\times10^{-13}(\tau/s)^{-1/2}$ and $1.55\times10^{-13}(\tau/s)^{-1/2}$ are obtained for the high and low densities respectively. For averaging times above 1000 seconds, the instabilities are limited by the H-maser, and drifted up in both cases. The uncertainty in frequency, eliminating the collisional shift, is [1]

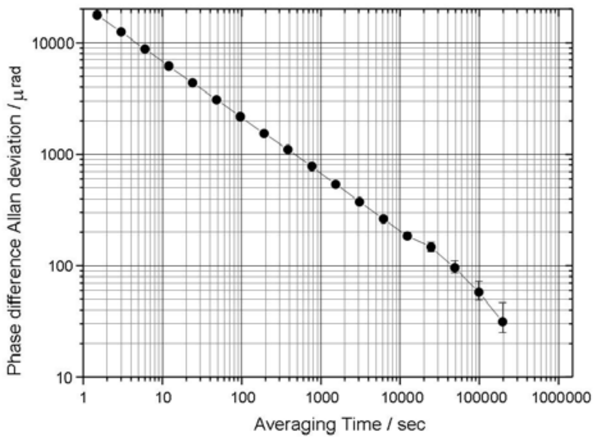
$$\sigma_0^2 = \left(\frac{k}{k-1}\right)^2 \sigma_{\mathrm{L}}{}^2(\tau_{\mathrm{L}}) + \left(\frac{1}{k-1}\right)^2 \sigma_{\mathrm{H}}{}^2(\tau_{\mathrm{H}}) + \left(\frac{\bar{f}_{\mathrm{L}} - \bar{f}_{\mathrm{H}}}{(k-1)^2}\right)^2 \sigma_k{}^2 \tag{1}$$

Here, the first two terms are related to the statistical uncertainties for the high and low densities respectively, and the last term is mixed with the cold collisional frequency shift, and included in type B uncertainty calculations as before. Assuming the relative instability of the frequency measured at high and low densities will fall according to the square root of averaging times, 15 days of averaging will give type A instabilities of 3×10^{-16} (sum of the first two terms).

The thermal effect of the new interferometric switch is also reduced. The interrogation Ramsey microwave signal was sampled out with a directional coupler and beat with a continuous microwave signal during 15 days of campaign. The detailed method is described in reference [2] and the results are shown in figure 2.



(a)



(b)

Fig. 2 (a) The phase variations of two Ramsey pulses in one fountain cycle against a continues 9.192 GHz microwave signal over a period of 15 days; (b) Allan Standard deviation $\sigma_y(\tau)$ of the phase difference between 2 Ramsey pulses.

From the above figure, it shows that the thermal effect has been reduced a lot compared with before. Two Ramsey pulse phase difference is dropping with $\sqrt{\tau}$. Assuming the white noise, phase difference instability will keep dropping with $\sqrt{\tau}$. The instability is 19.7 μrad for 15 days of averaging time, corresponding to 0.6×10^{-15} in relative frequency difference. This is treated as type B uncertainty due to the interferometric switch.

No other change has been made. A summary of the systematic frequency shift evaluations for NIM5 is listed in Table 2. The combined relative Type B uncertainty is approximately 0.9×10^{-15}.

Table 2 Uncertainty budget of NIM5 in these evaluations.

Physical Effect	Bias [$\times 10^{-15}$]	Uncertainty [$\times 10^{-15}$]
2nd order Zeeman	73.2	0.2
Collisional shift	-2.4*	0.2
Microwave interferometric Switch	0.0	0.6
Microwave leakage	0	<0.1
DCP	0.0	0.6
Microwave spectral impurities	0.0	0.1
Blackbody radiation	-16.4	0.1
Gravitational red shift	11.8	0.1
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	<0.1
Total	66.2*	0.9*

* The collision shift is calculated at low density.

The dead time distribution during the report period is shown in the figure 1:

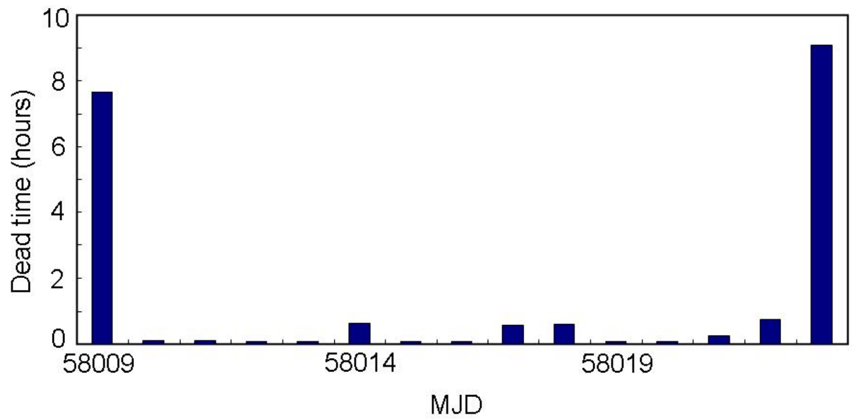


Figure 3 Dead time distributions in Sep., 2017 report period.

References:

1. Fang Fang, et al, Metrologia, **52**, 454(2015)
2. Liu Kun, et al, ACTA Metrologica sinica, **36**, 112(2015)