Frequency Evaluation of the Primary Frequency Standard NIM5

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I. SUMMARY

The primary frequency standard NIM5 was used to measure the average fractional frequency of the H-maser H271, identified by the clock code 1404871, during four periods from January to April in 2014. 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	y(NIM5-H271) [$\times 10^{-15}$]	Duty cycle [%]	u_{total} [$\times 10^{-15}$]
1	56669.0-56684.0	2156.7	94.7	1.5
2	56699.0-56714.0	2205.9	94.7	1.5
3	56729.0-56749.0	2261.3	99.2	1.6
4	56759.0-56779.0	2308.5	98.3	1.6

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 due to link between NIM5 fountain clock and the H-maser H271, which including the dead time and the phase noise of the link between the fountain and H-maser. All the above uncertainties are calculated at 1σ.

II. Measurement methods

Operation procedure

The primary frequency standard NIM5 and the H-maser H271 are located in the same building and share the same air conditioning system. The 5 MHz signal from the maser is sent to the fountain through a 40 m long cable. NIM5 was running in the alternate modes of high and half atom densities during each period. The ratio *k* of the atom densities between high and low was maintained at about 2. The fountain's frequency at zero density is then calculated by extrapolating the frequencies of high and low density frequencies according to:

$$f_0 = \frac{k\bar{f}_{\mathrm{L}} - \bar{f}_{\mathrm{H}}}{k-1}, \text{ and } k = \frac{n_H}{n_L} \tag{2}$$

The average frequency of NIM5 is obtained by calculating the f_0 each day and averaging over the whole report period. Before and after each report period, the routine fountain inspections are taken by checking microwave-power-related frequency shifts and light shifts. C-field magnitude is checked each week. The room temperature and humidity, and the temperatures on the flight tube are recorded regularly.

Type A (statistical) uncertainty of NIM5

During a report period, NIM5 was operating between high and low densities switching every 100 cycles. The resulting frequency instability after extrapolating to the zero density can be calculated from the following equation:

$$\sigma_0^2 = \left(\frac{k}{k-1}\right)^2 \sigma_{\mathrm{L}}{}^2(\tau_{\mathrm{L}}) + \left(\frac{1}{k-1}\right)^2 \sigma_{\mathrm{H}}{}^2(\tau_{\mathrm{H}}) + \left(\frac{\bar{f}_{\mathrm{L}} - \bar{f}_{\mathrm{H}}}{(k-1)^2}\right)^2 \sigma_k{}^2 \tag{3}$$

Here, σ_{L} and σ_{H} are fractional frequency instabilities at low and high densities obtained from Allan deviation by assuming white frequency noise, and σ_{k} is uncertainty of the ratio *k*. The first two terms are related to the statistical frequency uncertainties, and the last term is the cold-collision-induced type B uncertainty. Type A (statistical) uncertainty over one report period is:

$$u_A^2 = \left(\frac{k}{k-1}\right)^2 \sigma_{\mathrm{L}}{}^2(\tau_{\mathrm{L}}) + \left(\frac{1}{k-1}\right)^2 \sigma_{\mathrm{H}}{}^2(\tau_{\mathrm{H}}) \tag{4}$$

The frequency instability at 1 s is derived from the fitting of the Allan deviations, and the instability during a whole report period (σ_{L} and σ_{H}) is the instability at 1 s divided by the square root of the period time.

Systematic frequency biases and related Type B uncertainties

A number of systematic effects were identified for NIM5. The complete list of those effects is given in the attached reference [1], together with a detailed description of the methodology for their evaluations.

NIM5 was corrected for frequency shifts due to the following effects:

- cold collision (spin-exchange);
- second order Zeeman;
- blackbody radiation;
- gravitation red shift.

The Type B uncertainty due to collision shift is the third term in equation (3), and σ_k is assigned to be 0.15, as stated in reference [1]. The frequency biases due to all other physical effects are negligible for the evaluation uncertainty levels at this moment.

Although the frequency bias due to microwave-power-related frequency shift is set to be zero, the largest Type B fractional frequency uncertainty comes from this effect. This is because that an RF Mach-Zehnder interferometric switch is applied in NIM5 to eliminate the microwave leakages when atoms are outside the top or bottom below-cutoff waveguide attached on the Ramsey cavity. The design of the switch is adapted from [2], and its performance was tested and reported in [3]. A summary of typical systematic frequency shift evaluations for NIM5 is listed in Table 2. The combined relative Type B uncertainty is approximately 1.4×10^{-15}.

Table 2 Typical uncertainty budget of NIM5.

Physical Effect	Bias [$\times10^{-15}$]	Uncertainty [$\times10^{-15}$]
2nd order Zeeman	73.4	0.2
Collisional shift	-1.1*	0.2
Microwave interferometric Switch	0.0	1.2
Microwave leakage	0	<0.1
DCP	0.0	0.6
Microwave spectral impurities	0.0	0.1
Blackbody radiation	-16.2	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	67.9*	1.4 *

* The collision shift is calculated at low density.

Uncertainty of the link in the laboratory $u_{link/lab}$

The uncertainty induced from the link in the laboratory is obtained by,

$$u_{link/lab} = \sqrt{(u_{dead-time})^2 + (u_{link/maser})^2} \tag{5}$$

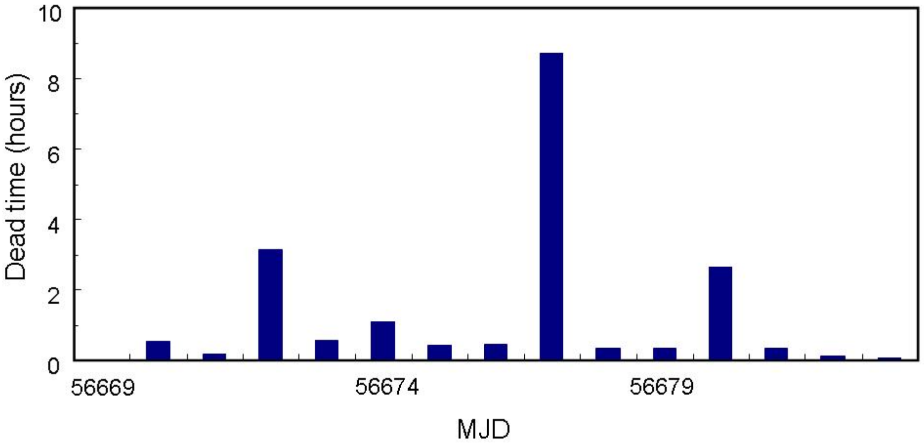
Here $u_{dead\text{-}time}$ is the uncertainty due to operational dead time of NIM5, which comes from both intentional breaks for system maintenance and checks and occasionally unintentional breaks such as laser unlocks and lab temperature control failures. $u_{dead\text{-}time}$ is the square root of the sum of the time deviations (TDEVs) of the H-maser over a duration τ_i and divided by the duration of the report period T:

$$u_{dead-time} = \frac{1}{T}\sqrt{\sum_{i=1}^{N}[\sigma_x(\tau_i)]^2} \tag{6}$$

The TDEVs are calculated from the modified Allan deviation (MDEV) by:

$$\sigma_x^2(\tau_i) = \frac{\tau^2}{3}\mathrm{mod}\,\sigma_y^2(\tau_i) \tag{7}$$

The dead time distributions during 4 report periods are shown in the following figures:



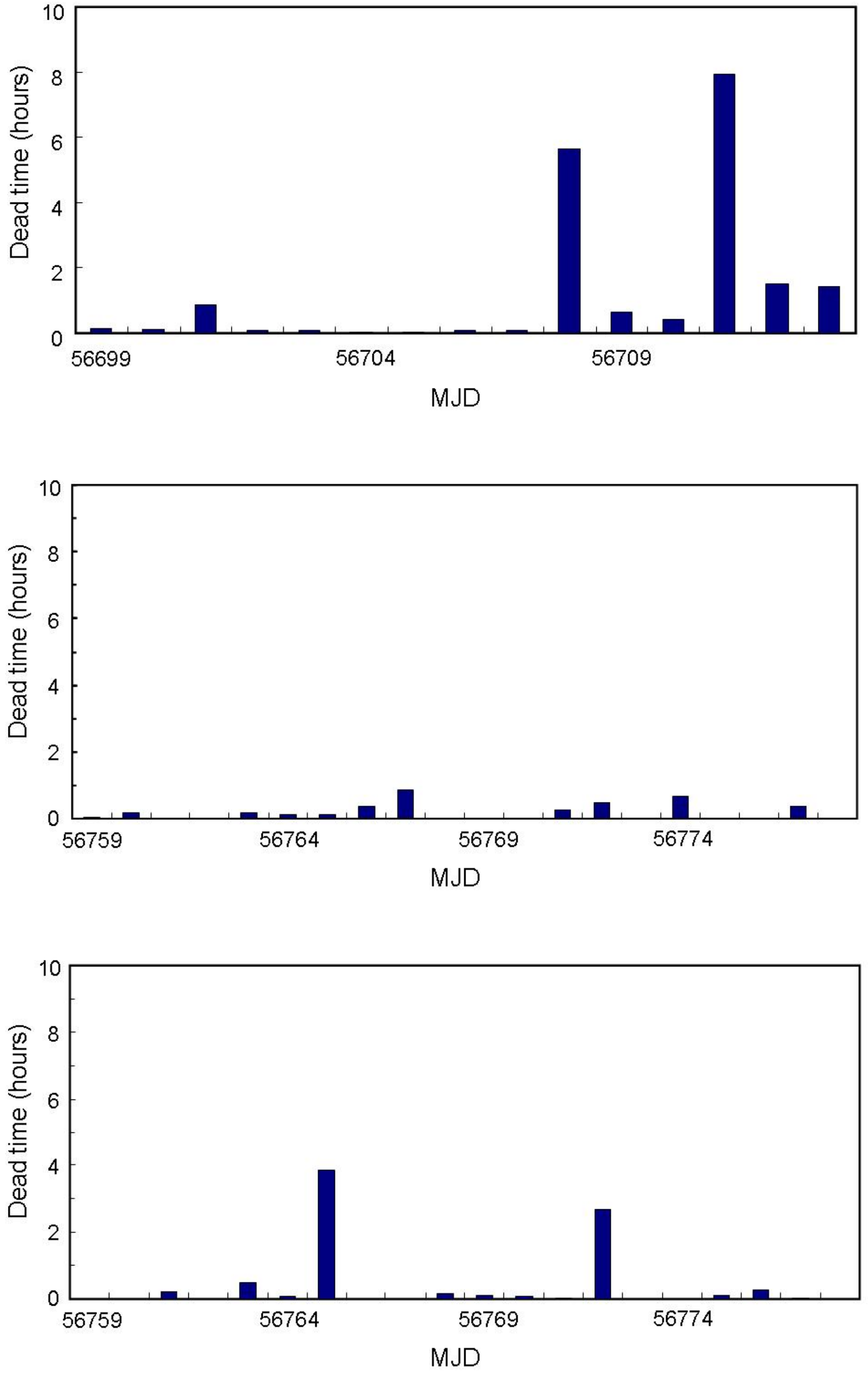


Figure 1 Dead time distributions during the four report periods.

The $u_{link/maser}$ is the uncertainty associated with the frequency transfer between NIM5 clock and H271 maser, and estimated to be less than 1.2×10^{-16}.

III. RESULTS

Results of the frequency measurements for the four report periods are listed in the tables below.

Report period 1

Period	MJD 56669.0 to 56684.0
H271 maser frequency [$\times10^{-15}$]	2156.7
Dead time [%]	5.3
u_A [$\times10^{-15}$]	0.6
u_B [$\times10^{-15}$]	1.4
$u_{link/lab}$ [$\times10^{-15}$]	0.2
u_{total} [$\times10^{-15}$]	1.5

Report period 2

Period	MJD 56699.0 to 56714.0
H271 maser frequency [$\times10^{-15}$]	2205.9
Dead time [%]	5.3
u_A [$\times10^{-15}$]	0.5
u_B [$\times10^{-15}$]	1.4
$u_{link/lab}$ [$\times10^{-15}$]	0.2
u_{total} [$\times10^{-15}$]	1.5

Report period 3

Period	MJD 56729.0 to 56749.0
H271 maser frequency [$\times10^{-15}$]	2261.3

Dead time [%]	0.8
u_A [$\times 10^{-15}$]	0.8
u_B [$\times 10^{-15}$]	1.4
$u_{link/lab}$ [$\times 10^{-15}$]	0.1
u_{total} [$\times 10^{-15}$]	1.6

Report period 4

Period	MJD 56759.0 to 56779.0
H271 maser frequency [$\times 10^{-15}$]	2308.5
Dead time [%]	1.7
u_A [$\times 10^{-15}$]	0.8
u_B [$\times 10^{-15}$]	1.4
$u_{link/lab}$ [$\times 10^{-15}$]	0.1
u_{total} [$\times 10^{-15}$]	1.6

REFERENCES

1. Fang F, et al, 2014, submitted to *Metrologia*.

2. Santarelli G, et al, 2009, *IEEE Trans. Ultrason. Ferroelectr. Freq.* Control, 56, 1319.

3. Zhang Y. et al, 2014, submitted to IFCS 2014 Taipei.