Evaluation of the frequency of H-maser 1401708 by primary frequency standard NPL-CsF2

National Physical Laboratory

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The primary frequency standard NPL-CsF2 was used to measure the frequency of hydrogen maser HM2, identified by clock code 1401708, over several evaluation periods between December 2019 and October 2020. Maser 1401708 is a physical realisation of UTC(NPL). These evaluations were performed by measuring mean frequency differences over the reporting periods. Results of the frequency measurements for each period are listed at the end of this report.

For a period of time we observed some inconsistencies in both the short-term stability and accuracy of NPL-CsF2. After reconfiguring the grounding arrangement of the microwave synthesis chain, fountain and associated devices, and removing a residual magnetisation of the magnetic shields near the cavity, this behaviour was no longer seen. Since then we have operated the fountain for approximately a year to regain confidence in its performance.

Since our last report there have been only minor changes to the physics package of NPL-CsF2, but we have upgraded a number of auxiliary systems and modified some of the measurement procedures. We describe each of these below, along with any effects that they have on the performance of the fountain.

Microwave local oscillator

We have implemented a low noise microwave synthesiser referenced to an ultrastable laser whose stability is down-converted to the microwave domain via a frequency comb. When used as the local oscillator for NPL-CsF2 we can obtain short-term stabilities of 3.3×10^{-14} at 1 second with negligible contribution from microwave noise. The new synthesiser is a shared resource and its reliability requires further improvement. While this may occasionally degrade the measurement uptime, a significantly lower overall type-A uncertainty can be achieved. When this system is unavailable, a second synthesiser based on a BVA quartz crystal is used.

Lasers and optical systems

Both the primary and repump lasers that are used for cooling, atom launch, state preparation and detection have been replaced, along with all of their associated optics. These new systems, similar to those described in [1], have higher output power and greatly enhanced robustness such that we can now operate with higher atom numbers and fountain uptimes close to 100%.

The optics that define the shape of the beams used for atom state detection have also been replaced. The detection beams now have a larger horizontal width, leading to a more uniform illumination of the atom cloud. This significantly reduces the size of the distributed cavity phase (DCP) m=2 component, which was previously calculated in [2] to cause a systematic bias of $(+1.38 \pm 0.78) \times 10^{-16}$. The calculations of DCP and microwave lensing have been updated to incorporate the larger beam sizes [3] (following methods in [4]). The DCP m=2 shift is reduced to $(+0.01 \pm 0.52) \times 10^{-16}$. Other DCP components and the microwave lensing shift are not significantly affected. We now correct for a total DCP bias of $(+0.2 \pm 1.0) \times 10^{-16}$.

Temperature control of the physics package

We no longer actively stabilise the temperature of the flight tube. Instead we rely on the lab temperature stabilisation and use the existing calibrated thermocouples to measure its temperature and determine the magnitude of the BBR shifts experienced by the atoms during the Ramsey interrogation. The thermal insulation surrounding the flight tube gives it a highly uniform temperature and we do not observe any significant thermal gradients.

A new data logging system was installed in July 2020. Blackbody radiation shifts for data recorded between December 2019 and July 2020 were determined from calibrated laboratory temperature data. The process of correlating the flight tube and laboratory temperatures results in a larger measurement uncertainty of 0.7°C, which corresponds to a total BBR shift uncertainty of 1.6×10^{-16} for these data. From August 2020 onwards the flight tube temperature is known to within 0.4°C, leading to a BBR shift uncertainty of 1.0×10^{-16}.

Temperature changes also affect the resonance frequency of the microwave cavity. The laboratory temperature is stable to better than ±1°C of a setpoint that is chosen such that the cavity is close to resonance at the operating frequency. Under these conditions, and providing the Ramsey pulse areas are set within 20% of the optimum $\pi/2$, second-order cavity pulling effects are within 6×10^{-17}. We have increased the cavity pulling uncertainty to this value.

Caesium vapour source

NPL-CsF2 was built with two sources of Cs vapour – an ampoule containing Cs metal in a thermally controlled section of the vacuum chamber and, additionally, two Cs dispensers that initially were not used. The metal in the ampoule has now been exhausted and we have been operating the fountain with the dispensers for approximately 18 months. Atom number and the quality of vacuum are not significantly affected, and we can control the vapour density by varying the current passed through the dispensers.

State selection microwave source

We now generate the state selection microwaves by mixing a fixed 9.2 GHz signal with an RF signal produced by direct digital synthesis. This allows us to rapidly detune the state selection microwaves through frequency shift keying, and hence further suppress any microwave leakage effects from this source.

Measurement deadtime

By making use of optical clock measurements of the maser's short-term frequency instability, our computation of the effect of deadtime on the frequency uncertainty for a measurement has been extended to include deadtimes that are smaller than 500 seconds in duration. Though this is significant for short differential measurements used for checking systematics it has little influence on the uncertainty for the long measurement intervals presented here.

Revised accuracy evaluation

All other systematic biases and operating procedures remain unchanged from those described in previous reports. For data recorded between December 2019 and July 2020 the larger uncertainty on the BBR shift raises the overall systematic uncertainty to 2.4×10^{-16}. Data recorded from August 2020 have a total systematic uncertainty of 2.0×10^{-16}. A complete breakdown of the systematic uncertainties is given in Table 1. Note that the uncertainty contribution from cold collisions varies and the values listed here are purely indicative. Specific values are computed for each measurement period.

	Dec 2019 – Jul 2020 uncertainty / 10^{-16}	**Aug 2020 to date** uncertainty / 10^{-16}
Second order Zeeman	0.8	0.8
Blackbody radiation	<u>1.6</u>	<u>1.0</u>
AC Stark (lasers)	0.1	0.1
Microwave spectrum	0.1	0.1
Gravity	0.5	0.5
Cold collisions	0.4†	0.4†
Background gas collisions	0.3	0.3
Rabi, Ramsey pulling	0.1	0.1
Cavity phase (distributed)	<u>1.0</u>	<u>1.0</u>
Cavity phase (dynamic)	0.1	0.1
Cavity pulling	<u>0.6</u>	<u>0.6</u>
Microwave leakage	0.6	0.6
Microwave lensing	0.3	0.3
2nd-order Doppler	0.1	0.1
Total u_B (1σ)	**2.4**	**2.0**

Table 1: Revised accuracy evaluation for NPL-CsF2. Underlined values differ from those in previous reports and have been discussed above. All other values are as presented in [2] and [5]

† The exemplary values here correspond to the type B uncertainty contribution for a ratio of high to low atom density of 8 and a measured frequency difference between the two of below 2.5×10^{-15} [6].

References

[1] R. J. Hendricks, F. Ozimek, K. Szymaniec, B. Nagórny, P. Dunst, J. Nawrocki, S. Beattie, B. Jian and K. Gibble, *IEEE Trans. UFFC,* vol. 66, no. 3, pp. 624-631, 2019.

[2] R. Li, K. Gibble and K. Szymaniec, *Metrologia,* vol. 48, pp. 283-289, 2011.

[3] K. Gibble, *private communication*, 2020.

[4] S. Weyers, V. Gerginov, M. Kazda, J. Rahm, B. Lipphardt, G. Dobrev and K. Gibble, *Metrologia,* vol. 55, pp. 789-805, 2018.

[5] K. Szymaniec, S. N. Lea and K. Liu, *IEEE Trans. UFFC,* vol. 61, pp. 203-206, 2014.

[6] K. Szymaniec and S. E. Park, *IEEE Trans. Instrum. Meas.,* vol. 60, pp. 2475-2481, 2011.

Measurement results

Results of the frequency measurements for each evaluation period are listed in the tables below. Frequency biases are given for information only and represent the mean values of the biases that the data are corrected for. The listed fractional frequency differences y(CsF2-HM2) are values corrected for these biases. The total uncertainty u_{total} is defined as:

$$(u_{\text{total}})^2 = (u_{\text{A}})^2 + (u_{\text{B}})^2 + \left(u_{\text{A/lab}}\right)^2 + \left(u_{\text{B/lab}}\right)^2$$

Maser 1401708 is steered on a regular basis and the measurements listed are a weighted average of the measurements throughout each period.

		12/12/2019-27/12/2019	27/12/2019-31/1/2020	31/1/2020-25/2/2020	25/2/2020-16/3/2020
Period start	MJD	58829	58844	58879	58904
Period end	MJD	58844	58879	58904	58924
Duration	days	15	35	25	20
Measurement uptime	%	84.5	92.0	91.4	58.8
Biases:	$\times 10^{-15}$				
cold collisions		-2.05	-0.72	-0.59	-1.70
2nd order Zeeman		247.47	247.49	247.48	247.47
BBR shift		-16.41	-16.43	-16.48	-16.51
gravity		1.30	1.30	1.30	1.30
microwave lensing		0.06	0.06	0.06	0.06
DCP		0.02	0.02	0.02	0.02
***y*(CsF2-HM2)**	**$\times 10^{-15}$**	**2.56**	**-0.12**	**-0.76**	**-0.82**
u_{A}	$\times 10^{-15}$	0.14	0.09	0.11	0.15
u_{B}	$\times 10^{-15}$	0.41	0.26	0.25	0.40
$u_{\text{A/lab}}$	$\times 10^{-15}$	0.15	0.07	0.06	0.16
$u_{\text{B/lab}}$	$\times 10^{-15}$	0.00	0.00	0.00	0.00
u_{total}	**$\times 10^{-15}$**	**0.46**	**0.28**	**0.28**	**0.46**

		15/5/2020-25/5/2020	30/5/2020-29/6/2020	29/6/2020-29/7/2020	29/7/2020-13/8/2020
Period start	MJD	58984	58999	59029	59059
Period end	MJD	58994	59029	59059	59074
Duration	days	10	30	30	15
Measurement uptime	%	94.8	85.8	99.4	88.6
Biases:	$\times 10^{-15}$				
cold collisions		-1.07	-2.52	0.34	-0.28
2nd order Zeeman		247.50	247.50	247.50	247.47
BBR shift		-16.37	-16.42	-16.42	-16.46
gravity		1.30	1.30	1.30	1.30
microwave lensing		0.06	0.06	0.06	0.06
DCP		0.02	0.02	0.02	0.02
***y*(CsF2-HM2)**	$\mathbf{\times 10^{-15}}$	**-0.16**	**-1.12**	**-0.35**	**-1.08**
u_A	$\times 10^{-15}$	0.29	0.17	0.14	0.23
u_B	$\times 10^{-15}$	0.29	0.48	0.24	0.20
$u_{A/lab}$	$\times 10^{-15}$	0.10	0.25	0.04	0.15
$u_{B/lab}$	$\times 10^{-15}$	0.00	0.00	0.00	0.00
$\mathbf{u_{total}}$	$\mathbf{\times 10^{-15}}$	**0.42**	**0.57**	**0.28**	**0.34**

		28/8/2020-27/9/2020	27/9/2020-27/10/2020
Period start	MJD	59089	59119
Period end	MJD	59119	59149
Duration	days	30	30
Measurement uptime	%	91.4	82.7
Biases:	$\times 10^{-15}$		
cold collisions		-0.16	0.27
2nd order Zeeman		247.44	247.57
BBR shift		-16.35	-16.35
gravity		1.30	1.30
microwave lensing		0.06	0.06
DCP		0.02	0.02
***y*(CsF2-HM2)**	$\mathbf{\times 10^{-15}}$	**-1.19**	**-0.03**
u_A	$\times 10^{-15}$	0.12	0.12
u_B	$\times 10^{-15}$	0.20	0.20
$u_{A/lab}$	$\times 10^{-15}$	0.05	0.25
$u_{B/lab}$	$\times 10^{-15}$	0.00	0.00
$\mathbf{u_{total}}$	$\mathbf{\times 10^{-15}}$	**0.24**	**0.34**