Frequency comparison (NRC-FCs2) – (H-maser 1400307)
For the period MJD 58754 to 58994

Frequency comparisons of the Cs fountain primary frequency standard NRC-FCs2 have been made with respect to the hydrogen maser 1400307 (BIPM code) during evaluation campaigns between October 2019 and May 2020. The average measurement uptime for the eight campaigns is 93.5%.

The first frequency evaluation of NRC-FCs2 has recently been completed [1]. These eight measurement campaigns shown in Table 1 below constitute the first results reported to the BIPM for NRC-FCs2.

Campaign	Period (MJD)	y(FCs2-VM1) [10^{-16}]	u(total) [10^{-16}]
1	58754 - 58784	-233.6	2.5
2	58784 - 58814	-235.7	2.7
3	58814 - 58844	-235.0	3.7
4	58844 - 58879	-229.0	3.7
5	58879 - 58904	-223.1	3.4
6	58904 - 58939	-217.0	4.2
7	58939 - 58969	-209.9	5.7
8	58969 - 58994	-194.3	4.2

Table 1 – Summary of frequency measurements (NRC-FCs2) – (H-maser 1400307)

Methods

The influence of systematic effects was investigated in [1]. The effects for which NRC-FCs2 is corrected are:
- 2^{nd} order Zeeman effect
- blackbody radiation
- gravitational red shift
- cold collisions
- microwave lensing
- microwave leakage
- distributed cavity phase shift

Several other systematic effects did not produce a measurable bias (and are therefore uncorrected for), but do contribute to the overall uncertainty of FCs2 and are included in the uncertainty budget.
The cold collisional shift was actively corrected for by toggling the operation of the fountain between high and low densities and extrapolating the measured frequencies to zero density. The type B uncertainty of the collisional shift is due to the uncertainty in the ratio of high density to low density. A full uncertainty budget for the evaluation period of MJD 58754 - 58784 is given in Table 2.

The operating procedure of FCs2 is described in detail in [1]. The measurements of FCs2 are related to the H-maser 1400307 (designated as VM1), as it is used to lock the timebase of the synthesizer producing the microwaves used to interrogate the atoms in the fountain clock. The maser is located in the same building but in a separate room from FCs2, and a 5 MHz signal from the maser is brought across a hall to the fountain clock lab to provide a frequency reference for the synthesizer used to generate our Ramsey microwaves. The average fractional frequency difference for each evaluation period, y(FCs2 – VM1), is evaluated from a linear fit of the 2-hour averaged data.

Uncertainties

Short term stability and type A uncertainty
The typical short term stability of FCs2 for the collisional shift-corrected frequency was 1.7 x 10^{-13} after 1 second of averaging. The reported values of the type A uncertainty, u_A, assume white FM as the dominant noise source during the averaging period. The averaging period is calculated as (reporting period – dead time).

Type B uncertainties
A detailed description of the evaluation of the systematic shifts and associated uncertainties is described in [1]. A systematic uncertainty budget table is given for each evaluation period. Here, the gravitational redshift is calculated using the CVGD2013 geoid model which uses a reference potential of W_0 = 62 636 856.0 m^2/s^2.

Link to local timescale
The uncertainty of the link with our local timescale, u_{l_Lab}, is the quadratic sum of two terms: the first term is the uncertainty in the frequency transfer between the maser 1400307 and FCs2, and the second term is the result of measurement dead time. In FCs2, the former uncertainty is attributed to phase fluctuations in cables between H-maser 1400307 and FCs2 and is estimated to be no larger than 10^{-16}.

The effects of measurement dead time arise due to both scheduled and unscheduled interruptions in the fountain operation. The unscheduled interruptions were rare, and generally caused by a failure in laboratory environmental control, or a broken laser lock. The contribution of dead time to the uncertainty is estimated using a numerical simulation that models the measurement noise as having two contributions: white FM (1.7 x 10^{-13} $\tau^{-1/2}$) and flicker FM (4.0 x 10^{-16}) [1].

Results

In the tables below we report all uncertainties associated with the frequency measurement of (NRC-FCs2) – (H-maser 1400307) for the evaluation period MJD 58754 - 58784.

Evaluation period (MJD)	58754 - 58784
Fractional uptime	98.0%
y(FCs2- 1400307) [10^{-16}]	-233.6
u_A (1 σ)	1.0
u_B (1 σ)	2.1
U_{l_lab} (1 σ)	1.0
u_{total}	2.5

Evaluation period (MJD)	58754 - 58784	
Physical effect	Bias [10^{-16}]	Uncertainty [10^{-16}]
Zeeman effect	724.90	0.2
Blackbody radiation	-162.33	0.7
Gravitational redshift	104.52	0.03
Cold collisions	-	0.4
Background gas	-	< 0.1
AC Stark	-	< 0.1
Rabi, Ramsey pulling	-	< 0.1
Cavity pulling	-	< 0.1
Majorana transitions	-	< 0.1
DCP m=0	0.07	0.4
DCP m=1	-0.71	1.3
DCP m=2	0.040	0.2
Microwave lensing	0.60	0.2
Microwave leakage	0.10	1.0
Microwave spectrum	-	< 0.1
Synchronous phase transients	-	0.8
Total	667.2	2.1

Table 2. Contributions to type B uncertainty for FCs2 for period MJD 58754 – 58784. The bias due to cold collisions is corrected actively by toggling between high and low densities and extrapolating to zero. The uncertainty associated with cold collisions varies between measurement periods, however, no other biases vary significantly from month to month.

The frequency measurement results and associated uncertainties as well as a full systematic budget table for the other evaluation periods are reported as follows.

Evaluation period (MJD)	58784 - 58814
Fractional uptime	98.0%
y(FCs2- 1400307) [10^{-16}]	-235.7
u_A (1 σ)	1.0
u_B (1 σ)	2.2
U_{l_lab} (1 σ)	1.0
u_{total}	2.7

Evaluation period (MJD)	58784 - 58814	
Physical effect	Bias [10^{-16}]	Uncertainty [10^{-16}]
Zeeman effect	724.90	0.2
Blackbody radiation	-162.29	0.7
Gravitational redshift	104.52	0.03
Cold collisions	-	0.9
Background gas	-	< 0.1
AC Stark	-	< 0.1
Rabi, Ramsey pulling	-	< 0.1
Cavity pulling	-	< 0.1
Majorana transitions	-	< 0.1
DCP m=0	0.07	0.4
DCP m=1	-0.71	1.3
DCP m=2	0.04	0.2
Microwave lensing	0.60	0.2
Microwave leakage	0.10	1.0
Microwave spectrum	-	< 0.1
Synchronous phase transients	-	0.8
Total	667.2	2.2

Measurement period (MJD)	58814 - 58844
Fractional uptime	85.0%
y(FCs2- 1400307) [10^{-16}]	-235.0
u_A (1 σ)	1.0
u_B (1 σ)	3.3
U_{l_lab} (1 σ)	1.2
$\mathbf{u_{total}}$	3.7

Evaluation period (MJD)	58814 - 58844	
Physical effect	Bias [10^{-16}]	Uncertainty [10^{-16}]
Zeeman effect	724.90	0.2
Blackbody radiation	-162.24	0.7
Gravitational redshift	104.52	0.03
Cold collisions	-	2.6
Background gas	-	< 0.1
AC Stark	-	< 0.1
Rabi, Ramsey pulling	-	< 0.1
Cavity pulling	-	< 0.1
Majorana transitions	-	< 0.1
DCP m=0	0.07	0.4
DCP m=1	-0.71	1.3
DCP m=2	0.04	0.2
Microwave lensing	0.60	0.2
Microwave leakage	0.10	1.0
Microwave spectrum	-	< 0.1
Synchronous phase transients	-	0.8
Total	667.3	3.3

Measurement period (MJD)	58844 - 58879
Fractional uptime	97.0%
y(FCs2- 1400307) [10^{-16}]	-229.0
u_A (1 σ)	0.8
u_B (1 σ)	3.5
U_{l_lab} (1 σ)	1.0
$\mathbf{u_{total}}$	3.7

Evaluation period (MJD)	58844 - 58879	
Physical effect	Bias [10^{-16}]	Uncertainty [10^{-16}]
Zeeman effect	724.75	0.2
Blackbody radiation	-162.22	0.7
Gravitational redshift	104.52	0.03
Cold collisions	-	2.9
Background gas	-	< 0.1
AC Stark	-	< 0.1
Rabi, Ramsey pulling	-	< 0.1
Cavity pulling	-	< 0.1
Majorana transitions	-	< 0.1
DCP m=0	0.07	0.4
DCP m=1	-0.71	1.3
DCP m=2	0.04	0.2
Microwave lensing	0.60	0.2
Microwave leakage	0.10	1.0
Microwave spectrum	-	< 0.1
Synchronous phase transients	-	0.8
Total	667.1	3.5

Measurement period (MJD)	58879 - 58904
Fractional uptime	96.0%
y(FCs2- 1400307) [10^{-16}]	-223.1
u_A (1 σ)	0.9
u_B (1 σ)	3.1
U_{l_lab} (1 σ)	1.1
u_{total}	3.4

Evaluation period (MJD)	58879 - 58904	
Physical effect	Bias [10^{-16}]	Uncertainty [10^{-16}]
Zeeman effect	724.78	0.2
Blackbody radiation	-162.18	0.7
Gravitational redshift	104.52	0.03
Cold collisions	-	2.4
Background gas	-	< 0.1
AC Stark	-	< 0.1
Rabi, Ramsey pulling	-	< 0.1
Cavity pulling	-	< 0.1
Majorana transitions	-	< 0.1
DCP m=0	0.07	0.4
DCP m=1	-0.71	1.3
DCP m=2	0.04	0.2
Microwave lensing	0.60	0.2
Microwave leakage	0.10	1.0
Microwave spectrum	-	< 0.1
Synchronous phase transients	-	0.8
Total	667.2	3.1

Measurement period (MJD)	58904 - 58939
Fractional uptime	87.0%
y(FCs2- 1400307) [10^{-16}]	-217.0
u_A (1 σ)	0.9
u_B (1 σ)	3.9
U_{l_lab} (1 σ)	1.2
$\mathbf{u_{total}}$	4.2

Evaluation period (MJD)	58904 - 58939	
Physical effect	Bias [10^{-16}]	Uncertainty [10^{-16}]
Zeeman effect	724.83	0.2
Blackbody radiation	-162.18	0.7
Gravitational redshift	104.52	0.03
Cold collisions	-	3.3
Background gas	-	< 0.1
AC Stark	-	< 0.1
Rabi, Ramsey pulling	-	< 0.1
Cavity pulling	-	< 0.1
Majorana transitions	-	< 0.1
DCP m=0	0.07	0.4
DCP m=1	-0.71	1.3
DCP m=2	0.04	0.2
Microwave lensing	0.60	0.2
Microwave leakage	0.10	1.0
Microwave spectrum	-	< 0.1
Synchronous phase transients	-	0.8
Total	667.3	3.9

Measurement period (MJD)	58939 - 58969
Fractional uptime	90.7%
y(FCs2- 1400307) [10^{-16}]	-209.9
u_A (1 σ)	1.1
u_B (1 σ)	5.4
U_{l_lab} (1 σ)	1.2
u_{total}	5.7

Evaluation period (MJD)	58939 - 58969	
Physical effect	Bias [10^{-16}]	Uncertainty [10^{-16}]
Zeeman effect	724.88	0.2
Blackbody radiation	-162.18	0.7
Gravitational redshift	104.52	0.03
Cold collisions	-	5.0
Background gas	-	< 0.1
AC Stark	-	< 0.1
Rabi, Ramsey pulling	-	< 0.1
Cavity pulling	-	< 0.1
Majorana transitions	-	< 0.1
DCP m=0	0.07	0.4
DCP m=1	-0.71	1.3
DCP m=2	0.04	0.2
Microwave lensing	0.60	0.2
Microwave leakage	0.10	1.0
Microwave spectrum	-	< 0.1
Synchronous phase transients	-	0.8
Total	667.3	5.4

Measurement period (MJD)	58969 - 58994
Fractional uptime	95.7%
y(FCs2- 1400307) [10^{-16}]	-194.3
u_A (1 σ)	1.1
u_B (1 σ)	3.9
U_{l_lab} (1 σ)	1.1
$\mathbf{u_{total}}$	4.2

Evaluation period (MJD)	58969 - 58994	
Physical effect	Bias [10^{-16}]	Uncertainty [10^{-16}]
Zeeman effect	724.85	0.2
Blackbody radiation	-162.25	0.7
Gravitational redshift	104.52	0.03
Cold collisions	-	3.3
Background gas	-	< 0.1
AC Stark	-	< 0.1
Rabi, Ramsey pulling	-	< 0.1
Cavity pulling	-	< 0.1
Majorana transitions	-	< 0.1
DCP m=0	0.07	0.4
DCP m=1	-0.71	1.3
DCP m=2	0.04	0.2
Microwave lensing	0.60	0.2
Microwave leakage	0.10	1.0
Microwave spectrum	-	< 0.1
Synchronous phase transients	-	0.8
Total	667.2	3.9

References:

1. S. Beattie, B. Jian, J. Alcock, M. Gertsvolf, R. Hendricks, K. Szymaniec and K. Gibble, *Metrologia*, **57** (2020) 035010, DOI https://doi.org/10.1088/1681-7575/ab7c54