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Evaluation of the METAS-FOC2 primary frequency standard
Period 60644-60674

The Swiss primary frequency standard METAS-FOC2 was operated between MJD 60644, 0:00 UTC and MJD 60674, 0:00 UTC. The frequency comparison was made with respect to the METAS Hydrogen Maser (BIPM clock code: 1405701).

The standard was measured continuously during 30 days with several dead-times (total uptime is 81.1 %). The frequency instability of the standard over the period of measurement was $16.0 \times 10^{-14}(\tau/s)^{-1/2}$. For a 30-days integration time, this yields a statistical uncertainty $u_A = 0.11 \times 10^{-15}$.

A frequency correction of 67.13×10^{-15} was applied to the raw data to obtain the relative frequency difference *y(FOC2-HM)*. This correction is the sum of all the frequency shifts reported in the uncertainty budget (Table 1). This correction includes the following effects:

- Second-order Zeeman
- Gravitational red shift
- Second-order Doppler
- Blackbody radiation
- Light shifts (from source and from detection parts)
- Ramsey pulling
- End-to-end
- Collisional Cs-Cs
- Collisions with background gases

The combined standard uncertainty of the standard is $u_B = 1.84 \times 10^{-15}$.

Summary of results

Evaluation period	u_A	u_B	$u_{A/lab}$	$u_{B/lab}$	$y(FOC2 - HM)$	*Uptime (%)*
60644-60674	0.11	1.84	0.27	0.05	-28.31	81.1

All uncertainties are given with $k = 1$ standard uncertainties and are expressed in 10^{-15} unit.

Operation

METAS-FOC2 was operated continuously with several dead-times during the period of measurement. The microwave signal used to interrogate the atoms is generated by a commercial synthesizer, which uses the 5 MHz active hydrogen maser output as external reference. Due to its continuous interrogation scheme, the frequency stability of METAS-FOC2 is not limited by the Dick effect but by the atomic shot noise [1].

The relative frequency difference *y(FOC2-HM)* is estimated from the average correction applied to the synthesizer and from the relative frequency correction from the uncertainty budget. For this period of measurement, we obtained:

$$y(FOC2 - HM) = -28.31 \times 10^{-15}$$

Uncertainties

1. u_A uncertainty

During this period of measurement, the Allan deviation is $\sigma_y(\tau) = 16.0 \times 10^{-14}(\tau/s)^{-1/2}$ for the relative frequency difference *y(FOC2-HM)*. For a 30-day integration time, this leads to the value:

$$u_A = 0.11 \times 10^{-15}$$

2. u_B uncertainty

The detailed evaluation of the uncertainty budget of METAS-FOC2 was published in [2] and [3].

A new evaluation of the second order Zeeman shift was realized. The related uncertainty takes into account the long-term drift of the magnetic field. We consider that the result of this evaluation is valid for the whole reported period.

The collisional shift dependence has been reevaluated in 2020 and is consistent with the value reported in [2]. The frequency shift due to the collisional shift has been updated for this measurement period.
All the other effects are assumed to be the same as in [2], leading to a total uncertainty of:

$$u_B = 1.84 \times 10^{-15}$$

In table 1, we report the updated total uncertainty budget valid for this evaluation period.

3. $u_{A/lab}$ uncertainty

This uncertainty comes from statistical fluctuations including the uncertainty due to the dead-time. A total dead-time of 490'283 s was accumulated during the period of measurement which represents 18.9 % of the 30 days. By using a dead-time model that takes into account the actual master clock stability, we calculated the relative frequency uncertainty:

$$u_{A/lab} = 0.27 \times 10^{-15}$$

4. $u_{B/lab}$ uncertainty

This uncertainty comes from systematic effects in the link between the fountain and the hydrogen maser using as a transfer standard. A worst-case estimation of the uncertainty in local phase comparisons is ± 100 ps leading to the fractional frequency uncertainty:

$$u_{B/lab} = 0.05 \times 10^{-15}$$

Uncertainty budget

Physical effect	Frequency shift	Uncertainty
Second-order Zeeman	23.86	0.21
Gravitational	59.72	0.02
Second-order Doppler	-0.01	<0.01
Blackbody radiation	-16.68	0.04
Microwave spectrum purity	0.00	0.05
Light shift from source	-0.16	0.04
Cavity pulling	0.00	<0.01
Rabi pulling	0.00	0.02
Ramsey pulling	0.05	0.10
End-to-end	2.17	0.27
Collisional Cs-Cs	-1.04	0.54
Background collisions	-0.69	1.12
Light shift from detection	-0.10	0.41
RF leakage	0.00	0.47
Majorana transitions	0.00	0.50
DCPS	—	1.03
Total	67.13	1.84

Table 1: Frequency shifts and uncertainty budget of METAS-FOC2 during the period 60644-60674 (in 10^{-15} unit).

References

[1] A. Joyet, G. Mileti, G. Dudle and P. Thomann, "Theoretical study of the Dick effect in a continuously operated Ramsey resonator," in *IEEE Transactions on Instrumentation and Measurement*, vol. 50, no. 1, pp. 150-156, Feb. 2001.
[2] A. Jallageas et al 2018 Metrologia **55** 366.
[3] L. Devenoges et al 2017 Metrologia **54** 23.