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Evaluation of the METAS-FOC2 primary frequency standard

Period 58939-58969

The Swiss primary frequency standard METAS-FOC2 was operated between MJD 58939, 0:00 UTC and MJD 58969, 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 4 dead times (total 1.7%). The frequency instability of the standard over the period of measurement was $9.5 \times 10^{-14}(\tau/s)^{-1/2}$. For a 30-day integration time, this yields a statistical uncertainty $u_A = 0.06 \times 10^{-15}$.

The uncertainty due to the clock link u_{lab} is 0.04×10^{-15} .

A frequency correction of 67.47×10^{-15} was applied to the raw data to obtain the relative frequency offset $y(\text{FOC2-HM})$. This correction is the sum of all the frequency shifts reported in the uncertainty budget (Table 1). This correction includes 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

The combined standard uncertainty of the standard is $u_B = 1.42 \times 10^{-15}$.

Summary of results

Evaluation period	u_A	u_B	u_{lab}	$y(\text{FOC2-HM})$
58939-58969	0.06	1.38	0.04	-215.34

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

Operation

METAS-FOC2 was operated continuously with 4 dead times during the period of measurement. The microwave signal used to interrogate the atoms is provided by a commercial synthesizer, which uses the 5 MHz 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 offset $y(\text{FOC2-HM})$ is estimated from the average correction applied to the synthesizer. For this period of measurement, we obtained:

$$y(\text{FOC2} - \text{HM}) = -215.34 \times 10^{-15}$$

Type A uncertainty of METAS-FOC2

During this period of measurement, the Allan deviation is $\sigma_y(\tau) = 9.5 \times 10^{-14} (\tau/s)^{-1/2}$ for the relative frequency difference $y(\text{FOC2-HM})$. For a 30-day integration time, this leads to the value:

$$u_A = 0.06 \times 10^{-15}$$

Type B uncertainty of METAS-FOC2

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 was also reevaluated at the beginning of this year and is consistent with the value reported in [2].

All the other effects are assumed to be the same as in [2], leading to a total uncertainty of:

$$u_B = 1.42 \times 10^{-15}$$

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

Uncertainties of the link

The uncertainty u_{lab} is the uncertainty of the link between the fountain and the maser and includes two contributions arising from the local phase comparison and from dead times.

Concerning the first one, a worst-case estimation of the uncertainty in local phase comparisons is ± 100 ps leading to fractional frequency uncertainty of 0.04×10^{-15} .

A total deadtime of 42 644 s was accumulated during the period of measurement which represents 1.7% of the 30 days. By using a dead time model that takes into account the actual master clock stability, we calculated a relative frequency uncertainty of 0.02×10^{-15} .

The quadratic sum of these two contributions leads to the uncertainty:

$$u_{\text{lab}} = 0.04 \times 10^{-15}$$

Uncertainty budget

Physical effect	Frequency shift	Uncertainty
Second-order Zeeman	23.32	0.20
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	-0.84	0.44
Light shift from detection	-0.10	0.41
RF leakage	0.00	0.47
Majorana transitions	0.00	0.50
DCPS	—	1.03
Total	67.47	1.42

Table 1: Frequency shifts and uncertainty budget of METAS-FOC2 during the period 58939-57969 (in 10^{-15}).

References

- [1] A. Joyet, G. Mileti, G. Duddle 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