Submission of frequency evaluations of the Swiss Primary Frequency Standard FoCS-2 for a contribution to TAI

Preamble

In 2017, three informal comparisons to TAI were made [1]. A summary of these three comparisons is presented in this document as a support for a contribution of FoCS-2 to TAI.

Summary

The primary frequency standard FoCS-2 was compared to the METAS hydrogen maser (BIPM clock code 1405701) during 3 Circular-T periods, from March 2017 to July 2017. The results of the comparisons are given in Table 1.

#	Evaluation period	u_A	u_B	u_{lab}	u_{TAI}	u_{total}	y(FoCS-2-HM)
1	57809-57839	0.11	2.01	0.07	0.20	2.02	-52.67
2	57919-57934	0.20	2.01	0.13	0.53	2.09	-57.76
3	57944-57964	0.17	2.01	0.10	0.30	2.04	-60.89

Table 1: Summary of the frequency comparison measurements performed between FoCS-2 and the METAS hydrogen maser (HM, BIPM clock code 1405701). The values are expressed in 1 x 10^{-15}.

The uncertainty u_{total} is the combined standard uncertainty obtained from the quadratic sum of four contributions: u_A, the uncertainty originating in the instability of the standard; u_B, the combined uncertainty arising from systematic effects; u_{lab}, the uncertainty of the link between the standard and the clock participating in TAI; and finally u_{TAI}, the uncertainty of the link to TAI. A frequency correction of 66.68×10^{-15} was applied to the raw data in order to calculate the unbiased relative frequency difference y(FoCS-2-HM). This correction directly comes from the sum of the frequency shifts listed in the uncertainty budget (Table 2).

Measurement procedure

The three evaluations were realized without dead time. At each interrogation cycle of the standard (performed by phase modulation with f_m=*0.96* Hz), the detected signal was used to generate a servo-loop error signal, which was integrated to get a frequency correction signal δf. This frequency correction signal was then sent to the microwave synthesizer to adjust its frequency. The frequency of the standard was then calculated as $\upsilon_i = \delta f$ + 9 192 631 770 Hz. The fountain frequency over a measurement period was then calculated as the average of the frequencies υ_i over the period. More precisely, we calculated the average fractional frequency difference: *Mean* $[\frac{\upsilon_i - \upsilon_0}{\upsilon_0}]$, where i is the index of each cycle and ν_0=192 631 770 Hz. The microwave signal used to interrogate the atoms was provided by a commercial synthesizer referenced to the 5 MHz signal given by the hydrogen maser.

Evaluation of the systematic frequency shifts and of their uncertainties

The fountain systematic relative frequency shifts and their uncertainties are presented in Table 2 and are detailed in [1] and [2] and are expressed in 1 x 10^{-15}. The total standard uncertainty is $u_{\mathrm{B}} = 2.01 \times 10^{-15}$ and is strongly dominated by the Cs-Cs collisional effect and by the Distributed Cavity Phase Shift (DCPS).
The uncertainty budget was the same for the three measurement periods. For that purpose, the reported shifts and their uncertainties were evaluated over time periods longer than the reported evaluated periods, and consequently include the uncertainty related to possible long term drifts. For example, the Second-order Zeeman and the Blackbody radiation were evaluated with variation of, respectively, the magnetic field and the temperature over a year. The estimate of the uncertainty for the collisional shift, for its part, takes into account a variation of the atomic signal of 50% over 5 months.

Physical effect	**Frequency shift**	**Uncertainty**
Second-order Zeeman	23.59	0.21
Gravitational	59.72	0.02
Second-order Doppler	-0.01	<0.01
Blackbody radiation	-16.67	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	-1.91	1.49
Light shift from detection	-0.10	0.41
RF leakage	0.00	0.47
Majorana transitions	0.00	0.50
DCPS	—	1.03
Total	66.68	2.01

Table 2: Frequency shifts and uncertainty budget of FoCS-2. The values are expressed in 1 x 10^{-15}.

Other uncertainties

The uncertainty u_{A} was obtained by considering the Allan deviation over the whole period of measurement. Its value was calculated as being the short term stability divided by the square root of the duration of the measurement period, assuming that the standard is dominated by a white frequency noise. The relative frequency stability of FoCS-2 at one second varied during the three periods from 1.7×10^{-13} to 2.3×10^{-13}.

The uncertainty u_{lab} is the uncertainty of the link between the fountain and the maser. It may originate from dead-times during the period of measurement and from phase fluctuations introduced by the cables that connect the standard to the maser and by the phase fluctuations of the multi-channel phase comparator used to compare the clocks that participate to UTC(CH). As there were no dead-times in these three periods of measurements, a worst-case estimate of $u_{\mathrm{lab}} = 0.07 \times 10^{-15}$ was used, considering a RMS time deviation of 100 ps over 30 days.

The uncertainty u_{TAI} is the uncertainty between the H-maser and UTC. This uncertainty depends on the link-based techniques used by the BIPM (TWSTFT, TWGPPP/TWGPP3 or INT LK)[1] and on the time of measurement. If we keep the previous example of a 30-day period of measurement, the uncertainty will be 0.20×10^{-15}.

Comparison to TAI

For these three periods of measurement, we estimated the value of *d*(FoCS-2-TAI), and we compared it with the *d*(CircT) given in the BIPM *Circular T* corresponding to the period of measurement. The values *d*(FoCS-2-TAI), *d*(CircT) and their difference Δ*d*= *d*(FoCS-2-TAI) - *d*(CircT) are shown together with their standard uncertainty in Table 3 and in Figure 1 for each period of measurement.

#	Evaluation period	*d*(FoCS-2-TAI)	*d*(CircT)	Δ*d*
1	57809-57839	-0.78 ± 2.01	-0.75 ± 0.22	-0.03 ± 2.02
2	57919-57934	-0.23 ± 2.09	0.09 ± 0.22	-0.32 ± 2.10
3	57944-57964	-0.11 ± 2.04	0.07 ± 0.26	-0.17 ± 2.06

Table 3: Summary of the frequency measurements performed between FoCS-2 and TAI (via the H-maser 145701). The uncertainty of d(FoCS-2-TAI) is u_{total}, as presented Table 1. The values are expressed in 1×10^{-15}.

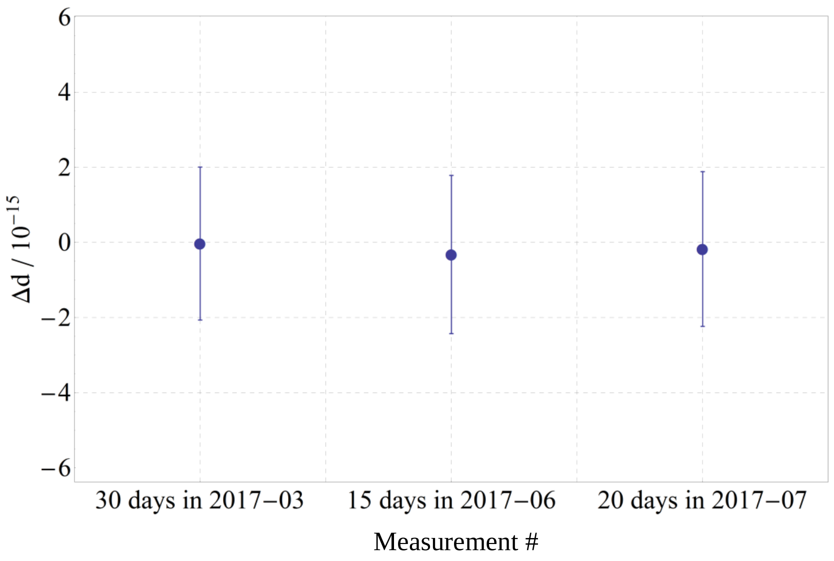

Figure 1: Graphic representation of the three calculated Δd values with their uncertainty bars.

Future contributions

METAS is intending to deliver measurement reports for a contribution to TAI on a regular basis, namely about 8 measurement reports per year, each with a minimum of 20 days of measurements.

References

[1] A Jallageas et al 2018 Metrologia **55** 366
[2] L Devenoges et al 2017 Metrologia **54** 239.

[1] TWSTFT for two-way satellite time and frequency transfer,
TWGPPP/TWGPP3 for the combined smoothing of TWSTFT and GPS PPP/GPS P3,
INT LK for internal cable link