Operation of the SYRTE PSFS in 2019

In 2019, 12 calibration reports of the reference maser by each of the four SYRTE fountains, the primary frequency standards (PFS) FO1, FO2Cs and FOM and the secondary frequency standard (SFS) FO2-Rb, have been transmitted to BIPM to participate to the steering of TAI, leading to a total number of 48 contributions. The interval durations range from 15 to 35 d. The uptime of the fountains is typically 90% or higher.

The operation of the four fountains is similar. The microwave synthesizer of each fountain is referenced to the signal provided by an ultra-low phase noise cryogenic sapphire oscillator phase locked to a hydrogen maser, allowing to reach the quantum projection noise limit. The relative frequency instability is typically $\sigma_y(\tau) \sim 5 \times 10^{-14}\ \tau^{-1/2}$ for FO1, FO2-Cs and FO2-Rb. Because FOM uses optical molasses only, its relative frequency instability is limited to $\sigma_y(\tau) \sim 9 \times 10^{-14}\ \tau^{-1/2}$. These instabilities result from the combination of low and high atomic density operations required for the real time extrapolation of the cold collisions frequency shift.

The typical uncertainty budgets are presented in Table 1 for the caesium fountains and in Table 2 for the rubidium fountain. As previously, the maser frequency is corrected from the quadratic Zeeman, the blackbody radiation, the cold collisions (+ cavity pulling), the first order Doppler, the microwave lensing shifts, and the redshift. The magnetic field and the temperature around the interrogation zone is measured every 1 hour or less in order to evaluate in real time the quadratic Zeeman and the blackbody radiation shift. To evaluate the cold collision shift and extrapolate to zero density, we alternate measurements between full and half atomic density either using the method proposed by K. Gibble [1] in FO1, FO2-Rb and FOM, or using the adiabatic passage method in FO2-Cs. The distributed cavity phase shift is verified from time to time with differential measurements alternating the cavity feeds. Against possible residual microwave leakages, the microwave interrogation is pulsed and absence of synchronous phase transients is tested periodically. Improved relativistic redshift corrections with reduced uncertainties have been determined in the frame of the ITOC (International Timescales with Optical Clocks) project [2, 3]. This involved a combination of GNSS based height measurements, geometric levelling and a geoid model over Europe, refined by local gravity measurements, together with a fine determination of the average atomic trajectory with respect to the local reference points. In the context of TAI calibrations, we use a conservative uncertainty of 2.5×10^{-17}.

The dead time uncertainty is estimated according to the method described in [4, 5]. We apply a conservative uncertainty of 5×10^{-17} to account for possible phase fluctuations due to the cables between the maser and the PSFS. The $u_{Link\ Lab}$ uncertainty corresponds to the quadratic sum of these two terms.

The calibration values are given with typical uncertainties $u_A = 1.5 – 5.0 \times 10^{-16}$, and $0.5 – 1.6 \times 10^{-16}$ for the uncertainty due to the link between the reference maser and the standard. For FO1, FO2-Cs and FO2-Rb, the systematic uncertainty u_B is $\sim 2.0\text{-}3.5 \times 10^{-16}$, and for FOM, $\sim 6\text{-}7 \times 10^{-16}$.
The FO2-Rb SFS calibration reports were made using the 2017 recommended value (21st CCTF, [6]).

Throughout 2019, the frequency calibrations of the reference H-maser by the SYRTE fountains were also used to produce a daily steering of the H-maser output signal for the generation of the French timescale UTC(OP) [7].

Fountain	FO1		FO2-Cs		FOM	
Physical origin	Correction	Uncertainty	Correction	Uncertainty	Correction	Uncertainty
2nd order Zeeman	-1280.85	0.40	-1935.93	0.30	-322.82	1.90
Blackbody Radiation	169.73	0.60	174.63	0.60	166.73	2.30
Cold Collisions + cavity pulling	129.17	1.48	149.63	1.19	27.25	4.09
Distributed cavity phase shift	-0.07	2.4	-0.90	1.00	-0.70	2.75
Microwave lensing	-0.65	0.65	-0.70	0.70	-0.90	0.90
Microwave Leaks, spectral purity	0	1	0	0.50	0	1.50
Ramsey & Rabi pulling	0	0.2	0	0.10	0	0.10
Second order Doppler	0	0.1	0	0.10	0	0.10
Background gas collisions	0	0.3	0	1.00	0	1.00
Red shift	- 69.08	0.25	- 65.54	0.25	- 68.26	0.25
Total uncertainty u_B		**3.2**		**2.2**		**6.1**

Table 1: Typical accuracy budgets for the SYRTE PFS FO1, FO2-Cs and FOM adapted from those given in [8] and [9]. (Values given in units of 10^{-16})

Fountain	FO2-Rb	
Physical origin	Correction	Uncertainty
2nd order Zeeman	-3502.25	0.70
Blackbody Radiation	126.10	1.45
Cold Collisions + cavity pulling	2.35	0.84
First order Doppler	-0.35	1.00
Microwave lensing	-0.70	0.70
Microwave Leaks, spectral purity	0	0.50
Ramsey & Rabi pulling	0	0.10
Second order Doppler	0	0.10
Background gas collisions	0	1.00
Red shift	- 65.45	0.25
Total uncertainty u_B		**2.5**

Table 2: Typical accuracy budgets for the SYRTE SFS FO2-Rb adapted from those given in [8] and [9]. (Values given in units of 10^{-16})

The SYRTE Strontium optical lattice clocks SrB and Sr2 did not contribute to TAI in 2019, but are expected to provide new calibration values in 2020.

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