Operation of the SYRTE PSFS in 2020

In 2020, a total of 44 calibrations reports of the reference maser by the SYRTE fountains PSFS have been transmitted to BIPM to participate to the steering of TAI: 12 by the primary frequency standard (PFS) FO1, 12 by the PFS FO2-Cs, 12 by the secondary frequency standard (SFS) FO2-Rb, and 8 by the PFS FOM. The interval durations range from 10 to 35 d. The uptime of the fountains is typically 90% or higher. FO2-Cs and FO2-Rb are the 2 parts of the dual fountain FO2 which operates simultaneously with caesium and rubidium atoms. FO2-Rb calibrations are included in Circular T as SYRTE-FORb SFS.

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 in full atomic density is typically $\sigma_y(\tau) \sim 3\text{-}4 \times 10^{-14}\ \tau^{-1/2}$ for FO1, FO2-Cs and FO2-Rb. Because FOM uses optical molasses only, its relative frequency instability in full atomic density is limited to $\sigma_y(\tau) \sim 6\text{-}7 \times 10^{-14}\ \tau^{-1/2}$.

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 [2]. 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 [3, 4]. 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 statistical uncertainty $u_{A/lab}$ of the link between the maser and the PSFS corresponds to the quadratic sum of two terms: the dead time uncertainty, which is estimated according to the method described in [5, 6], and the effect of possible phase fluctuations in the signal distribution between the maser and the PSFSs, which is expected to be lower than 5×10^{-17}.
The systematic uncertainty of the link $u_{B/lab}$ is expected to be negligible, because in the signal distribution chain between the maser and the fountain, all the intermediate oscillators are phase locked using proportional/integrator phase lock loops. In addition, the comparison between the maser and UTC(OP) is performed using a time interval counter.

The calibration values are given with typical uncertainties $u_A = 1.5 – 5.0 \times 10^{-16}$, and $0.5 – 2.1 \times 10^{-16}$ 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 ~ $2.1\text{-}3.5 \times 10^{-16}$, and for FOM, ~ $6\text{-}7 \times 10^{-16}$.
The FO2-Rb SFS calibration reports were made using the 2017 recommended value (21st CCTF, [7]).

Throughout 2020, 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) [8].

Fountain	FO1		FO2-Cs		FOM	
Physical origin	Correction	Uncertainty	Correction	Uncertainty	Correction	Uncertainty
2nd order Zeeman	-1277.79	0.40	-1937.02	0.30	-314.42	1.90
Blackbody Radiation	169.97	0.60	172.26	0.80	166.50	2.30
Cold Collisions + cavity pulling	131.95	1.66	105.71	1.06	20.60	3.09
Distributed cavity phase shift	-0.07	2.40	-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	1.00	0	0.50	0	1.50
Ramsey & Rabi pulling	0	0.20	0	0.10	0	0.10
Second order Doppler	0	0.10	0	0.10	0	0.10
Background gas collisions	0	0.30	0	1.00	0	1.00
Red shift	- 69.08	0.25	- 65.54	0.25	- 68.26	0.25
Total uncertainty u_B		**3.3**		**2.2**		**5.5**

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

Fountain	FO2-Rb	
Physical origin	Correction	Uncertainty
2nd order Zeeman	-3503.75	0.70
Blackbody Radiation	127.22	1.45
Cold Collisions + cavity pulling	4.34	1.26
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		**2.6**

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

The SYRTE Strontium optical lattice clocks SrB and Sr2 did not contribute to TAI in 2020, but are expected to provide new calibration values in 2021.

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