FREQUENCY COMPARISON (H_MASER 140 0810) - (LNE-SYRTE-FO1)
For the periods MJD 58184 to MJD 58269

The primary frequency standard LNE-SYRTE-FO2 has been compared to the hydrogen maser 140 0810 of the laboratory, during a measurement campaign between MJD 58184 and 58269 (7th March 2018 – 31st May 2018) covering the three last months. Between MJD 58214 and 58219, around the middle of the April measurement period, the hydrogen maser presented a frequency step. Therefore this 5-day interval has been excluded and, in total, four estimations of the maser frequency have been provided from the collected data. The fountain operation covered 82.0%, 96.4%, 94.3% and 90.8% of the four estimation periods, respectively.

The mean frequency differences at the middle date of each period are given in the following table:

Period (MJD)	Date of the estimation	y(HMaser 140 0810 – FO1)	u_B	u_A	$u_{link\ /\ maser}$
58184 – 58199	58191.5	-6063.6	4.2	5.0	0.9
58199 – 58214	58206.5	-6045.4	4.3	2.5	0.5
58219 – 58234	58226.5	-6151.3	4.3	2.0	0.5
58234 – 58269	58251.5	-6198.8	4.1	2.5	0.6

Table 1: Results of the comparison in 1×10^{-16}.

The FO1 fountain was operated in the same mode during all the period: the interrogating signal synthesis is based on the multiplication of a 100 MHz signal provided by a cryogenic oscillator phase locked to the maser 140 0889. It uses a synthesizer to lock the microwave signal on the atomic resonance. The frequency difference between the maser and the fountain is deduced from the average correction applied to the synthesizer.

Average value and statistical uncertainty

The frequency data are averaged over 0.2 day intervals. We then perform a linear unweighted fit to the average data points to determine the average frequency at the middle date of the interval, as given in Table 1. The statistical uncertainty u_A is estimated using the Allan variance of the frequency residuals, after removing the drift. We estimate conservative statistical uncertainties u_A of 5.0×10^{-16}, 2.5×10^{-16}, 2.0×10^{-16} and 2.5×10^{-16} for the four periods, respectively.

We verified the result by applying a second method. We calculated the accumulated phase by integrating the data points, assuming a constant frequency during each segment, and during the dead times of the fountain operation. The average frequency is then obtained by dividing the total accumulated phase by the calibration period duration. The processing has been performed with segments of 0.01, 0.1 and 1 day durations. The results are in agreement with the values given in Table 1 within 1.0×10^{-16}, 0.2×10^{-16}, 0.2×10^{-16} and 0.2×10^{-16} for the four periods, respectively, which is consistent with the estimation of the statistical uncertainties u_A and the uncertainties due to the link.

Accuracy

During the 2 last years (2016-2017), a complete refurbishing of the fountain and its local environment has been performed. Most notably, the inner Stark plates dedicated to initial studies related to the black body (Stark) shift have been removed from the vacuum tube. Otherwise, the fountain geometry remains unchanged. The long term stability of the parameters and the reliability of the fountain have been notably improved.

The uncertainty budget has been revisited. 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 at last the redshift.

To evaluate the cold collision shift and extrapolate, we alternate measurements between full and half atomic density using the method proposed by K. Gibble (2012 EFTF Proceedings) : the state selection microwave field is detuned and its amplitude readjusted to keep the atom number at maximum at both densities, a method which preserves the state selection density distribution. The uncertainty in the cold collisions correction accounts for both a statistical uncertainty and a systematic uncertainty taken as 1% of the average correction.

Against possible residual microwave leakages, the microwave interrogation is pulsed and absence of synchronous phase transients has been tested. Besides, a long term comparison between pulsed and continuous interrogation at nominal power shows no difference to better than 10^{-16}.

As for LNE-SYRTE FO2-Cs and FO2-Rb fountains since April 2018, for FO1 we use an improved relativistic redshift correction with reduced uncertainty (See FO2 April 2018 reports). This correction is based on the new determination of the gravity potential at the location of the fountain performed within the ITOC (International Timescales with Optical Clocks) project. The relevant C(GNSS/Geoid) number at the LNE-SYRTE FO1 fountain reference marker is $61.337 \times 10 m^2/s^2$, and the relevant atomic cloud position is 0.7611 m above this reference marker. Hence the redshift to be corrected for

FO1-redshift = $(61.337 \times 10\ m^2/s^2 + 0.7611\ m \times 9.809276476\ m/s^2)/c^2 = 6.9077 \times 10^{-15}$. We take an uncertainty of 2.5×10^{-17}, as justified in FO2 April reports.

The following table summarizes the budget of systematic effects and their associated uncertainties for the May period. The accuracy is the quadratic sum of all the systematic uncertainties. The budget is very similar for the March – April 2018 periods.

	Correction (10^{-16})	**Uncertainty (10^{-16})**
Quadratic Zeeman effect	-1279.91	0.40
Black body radiation	168.96	0.60
Cold collisions + cavity pulling	293.92	3.02
Distributed cavity phase shift	-0.97	2.40
Microwave lensing	-0.65	0.65
Microwave spectral purity&leakage	0	1.0
Ramsey & Rabi pulling	0	< 0.2
Second order Doppler effect	0	< 0.1
Background gas collisions	0	< 0.3
Total	-818.65	4.12
Redshift	- 69.08	0.25
Total with redshift	**-887.73**	**4.12**

Table 2: Budget of systematic corrections and uncertainties for SYRTE-FO1 fountain for the MJD 58234 – 58269 period

$$\boxed{u_B = \mathbf{4.1 \times 10^{-16}}}$$

Uncertainty of the link

The uncertainty of the link is the quadratic sum of 2 terms:
-A possible effect of phase fluctuations introduced by the cables that connect the primary standard to the maser. A new characterization of the signal distribution leads to a still conservative value of 0.5×10^{-16}.
-The uncertainty due to the dead times of the frequency comparison.
We have updated the estimation of this contribution, applying the method described in *Metrologia*, vol. 44, pp 91-96, 2007, as we did for the initial calibration reports of the LNE-SYRTE Strontium SFS. The maser noise model includes a white frequency noise component of 5×10^{-16} at 1 d and a flicker frequency noise component of 5×10^{-16} at 1 d, which is pessimistic especially for short averaging periods. We applied the method to the dead times longer than 600 s and obtained a stability degradation of 0.8×10^{-16}, 0.2×10^{-16}, 0.3×10^{-16} and 0.3×10^{-16} for the periods, respectively.