FREQUENCY COMPARISON (H_MASER 140 0810) - (LNE-SYRTE-FOM)
For the period MJD 58359 to MJD 58479

The primary frequency standard LNE-SYRTE-FOM has been compared to the hydrogen maser 140 0810 of the laboratory, during between MJD 58359 and 58479 (29th August 2018 – 27th December 2018) covering the four last months. The fountain operation covered 97.4%, 98.0%, 82.1% and 75.9% 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$_{140\ 0810}$ – FOM)	u_B	u_A	$u_{link\ /\ maser}$
58359 – 58389	**58374**	**-6370.7**	**8.5**	**2.5**	**0.5**
58389 – 58419	**58404**	**-6425.3**	**11.3**	**2.0**	**0.5**
58419 – 58449	**58434**	**-6467.3**	**8.1**	**5.0**	**0.7**
58449 – 58479	**58464**	**-6508.1**	**6.3**	**2.5**	**0.9**

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

The FOM fountain was operated in the same mode during all the period: the interrogating signal synthesis is based on the multiplication of a 1 GHz signal provided by a cryogenic oscillator phase locked to the maser 140 0810. It uses a synthesizer to lock the microwave signal to 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 2.5×10^{-16}, 2.0×10^{-16}, 5.0×10^{-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 0.6×10^{-16}, 0.8×10^{-16}, 1.3×10^{-16} and 1.1×10^{-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

The last calibration report with the LNE-SYRTE FOM fountain was sent to the BIPM in August 2012. The FOM fountain was then transported to the French space agency CNES, in Toulouse, where it was operated for two years to serve as a reference for the ground tests of the space cold atom clock PHARAO. It came back at LNE-SYRTE in summer 2014 and installed in a new room, but was not in operation for a while, until a proper reference signal distribution was set-up. The vacuum chamber was open in winter 2016 in order to replace the cesium reservoir and to renew the pumping system.
A complete new evaluation of the systematic effects has been performed in 2017-2018, although there were no modification in the system.
As for the other fountains, 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.
The magnetic field and the temperature around the interrogation zone is sequentially measured every ~15 minutes in order to evaluate the quadratic Zeeman and the blackbody radiation shift.
To evaluate the cold collision shift, we alternate measurements every 100 clock cycles while varying the atomic density with the state selection microwave field. As proposed by K. Gibble (2012 EFTF Proceedings) the selection microwave is detuned and its amplitude readjusted to keep the atom number at maximum at both densities. This method preserves the state selection density distribution. For the 3 first maser frequency calibrations, a fixed collision coefficient based on previous measurements is used. For the last one, the collision coefficient is estimated in real time with the fountain operation alternating full and half atomic density. We estimate a conservative uncertainty of 15% of the average frequency shift.
To estimate the distributed cavity phase shift uncertainty, we operated the fountain alternating between three microwave cavity feeding modes: 1) asymmetric feeding from one side, 2) asymmetric feeding from the opposite side, and 3) symmetric feeding from both simultaneously. We obtained an upper value of 2.75×10^{-16}, taken as the uncertainty on the DCP.
The effect of possible residual microwave leakages has been studied while comparing pulsed and continuous operation. No frequency shift has been observed with a resolution of 1.5×10^{-16}. The absence of synchronous phase transients has also been tested.
As for the other LNE-SYRTE fountains, we use an improved relativistic redshift correction with reduced uncertainty (See FO2 April 2018 reports and FO1 May 2018 report). 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 FOM fountain reference marker is 60.282×10 m²/s², and the relevant atomic cloud position is 1.0685 m above this reference marker. Hence the redshift to be corrected for
FOM-redshift = $(60.282 \times 10$ m²/s² $+ 1.0685$ m $\times 9.809276476$ m/s²$)/c^2 = 6.824 \times 10^{-15}$. 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 December 2018 period. The accuracy is the quadratic sum of all the systematic uncertainties. The uncertainty budgets are similar for the four periods except for the cold collision shift that was larger because of a higher atomic density, especially for the October 2018 period.

	Correction (10^{-16})	Uncertainty (10^{-16})
Quadratic Zeeman effect	-323.06	1.90
Black body radiation	166.80	2.30
Cold collisions + cavity pulling	29.54	4.43
Distributed cavity phase shift	-0.7	2.75
Microwave lensing	-0.9	0.90
Microwave spectral purity&leakage	0	1.50
Ramsey & Rabi pulling	0	0.10
Second order Doppler effect	0	0.10
Background gas collisions	0	1.0
Total	-128.32	6.34
Redshift	- 68.24	0.25
Total with redshift	**-196.56**	**6.34**

Table 2: Budget of systematic corrections and uncertainties for SYRTE-FOM fountain for the MJD 58449 – 58479 period

$$\boxed{u_B = \mathbf{6.3 \times 10^{-16}}}$$

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 0.1×10^{-16}, 0.1×10^{-16}, 0.5×10^{-16} and 0.7×10^{-16} for the four periods, respectively.