FREQUENCY COMPARISON (H_MASER 140 0809) - (LNEOP-SrB)
For the period MJD 60794 to MJD 60824

The secondary frequency standard LNEOP-SrB has been compared to the hydrogen Maser 140 0809 of the laboratory, during a measurement campaign between MJD 60794 and 60824 (29^{th} April 2025 – 29^{th} May 2025). The optical clock operation covered 56.5 % of the estimation period.

The mean frequency difference at the middle date of the period is given in the following table:

Period (MJD)	Date of the estimation	y(HMaser$_{140\ 0809}$ – SrB)	u_A	u_B	$u_{A/lab}$	$u_{B/lab}$	u_{SecRep}
60794 – 60824	**60809**	**-3244.8**	**0.03**	**0.48**	**1.3**	**0.01**	**1.9**

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

The calibration is made using the recommended value for the ^{87}Sr secondary representation:
429 228 004 229 872.99 Hz (22^{nd} CCTF in 2021).
u_B is the ^{87}Sr optical lattice type B uncertainty.
u_{SecRep} is the recommended uncertainty of the secondary representation (22^{nd} CCTF in 2021).

The SrB optical lattice was operated in the same mode during all the period: a laser locked on an ultra-stable cavity is frequency shifted by an acousto-optic modulator and probes an ensemble of ~10^3 ^{87}Sr atoms in an optical lattice at the magic wavelength. A digital feedback loop controls the frequency of the AOM. The frequency of the ultra-stable laser is simultaneously measured by a frequency comb against the reference maser. The outcome of this measurement is then combined with the frequency correction of the AOM.

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 period, as given in Table 1.

The frequency stability of the SrB clock is 7×10^{-16} at 1 s, averaging down to 10^{-17} after 5000 s of integration. This frequency stability has been established by comparisons with other optical frequency standards prior to the time interval of this report, as well as differential measurements between interleaved clock sequences during the report interval. The latter show an instability down to 3×10^{-18} after a day of measurement. As a result, we conservatively estimate u_A to 3×10^{-18}.

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 duration. The results are in agreement with the values given in Table 1 within 1.0×10^{-16}, which is consistent with the estimation of the statistical uncertainty u_A and the uncertainty due to the link.

Accuracy

The following table summarizes the budget of systematic effects and their associated uncertainties. The accuracy is the quadratic sum of all the systematic uncertainties.

	Correction (10^{-18})	**Uncertainty (10^{-18})**
Black body radiation	5128	30
Quadratic Zeeman effect	527	8
Lattice light-shift	-7	3
Lattice spectrum	0	10
Density shift	0	15
Line pulling	0	5
Probe light shift	0.4	0.4
AOM phase chirp	0	<1
Servo error	0	<1
Blackbody radiation oven	0	10
Background gas collisions	30	30
Total	5678.4	48
Red shift	-6114.6	4
Total with red shift	**-436.2**	**48**

Table 2: Budget of systematic effects and uncertainties for LNEOP-FO2Rb fountain for the MJD 60794 – 60824 period

$$\boxed{u_B = \mathbf{0.48 \times 10^{-16}}}$$

Uncertainty of the link

The statistical uncertainty of the link $u_{A/lab}$ is the quadratic sum of 2 terms:
-A possible effect of phase fluctuations introduced by the cables that connect the frequency 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 60 s and obtained a stability degradation of 1.2×10^{-16}.

The systematic uncertainty of the link $u_{B/lab}$ between the maser and the frequency standard is mainly due to the uncertainty of the comb measurements linking the interrogation laser to the microwave local oscillator that is based on a cryogenic oscillator phase locked to the reference maser. The uncertainty on this measurement has been verified well below 10^{-18} by simultaneous measurements based on two operational optical frequency combs. The uncertainty on this verification is mainly statistical. The other elements of the signal distribution chain between the maser and the frequency standard have a negligible impact, because all the intermediate oscillators are phase locked using proportional/integrator phase lock loops. The comparison between the maser and UTC(OP) is performed using a time interval counter, thus adding a negligible contribution to $u_{B/lab}$.