

**FREQUENCY COMPARISON (H\_MASER 140 0810) - (LNE-SYRTE-Sr2)  
For the period MJD 59639 to MJD 59669**

The secondary frequency standard LNE-SYRTE-Sr2 has been compared to the hydrogen Maser 140 0810 of the laboratory, during a measurement campaign between MJD 59639 and 59669 (1<sup>st</sup> March 2022 – 31<sup>st</sup> March 2022). The optical lattice clock operation covers ~ 56.9 % of the total measurement duration.

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

Period (MJD)	Date of the estimation	$y(\text{HMaser}_{140\ 0810} - \text{Sr2})$	$u_A$	$u_B$	$u_{A/\text{lab}}$	$u_{B/\text{lab}}$	$u_{\text{SecRep}}$
59639 – 59669	59654	-1060.4	0.1	0.23	1.0	0.3	4

Table 1: Results of the comparison in  $1 \times 10^{-16}$ .

The calibration is made using the recommended value for the  $^{87}\text{Sr}$  secondary representation: 429 228 004 229 873.0 Hz (21<sup>st</sup> CCTF in 2017).

$u_B$  is the  $^{87}\text{Sr}$  optical lattice type B uncertainty.

$u_{\text{SecRep}}$  is the recommended uncertainty of the secondary representation (21<sup>st</sup> CCTF in 2017).

The Sr2 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  $\sim 10^4$   $^{87}\text{Sr}$  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 microwave local oscillator. 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 Sr2 clock is  $1 \times 10^{-15}$  at 1 s, averaging down to  $10^{-17}$  after 10000 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. Although the frequency instability is expected to average much below  $10^{-17}$  over the 30 days report interval, no experimental evidence supports this claim yet. As a result, we conservatively estimate  $u_A$  to  $10^{-17}$ .

We verified the results 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 optical lattice clock 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  $0.3 \times 10^{-16}$ , which is consistent with the estimations 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 <sup>-18</sup> )	Uncertainty (10 <sup>-18</sup> )
Black body radiation	4997	10
Quadratic Zeeman effect	226	3
Lattice light-shift	-29	3
Lattice spectrum	0	1
Density shift	0	10
Line pulling	0	10
Probe light shift	0.4	0.4
AOM phase chirp	0	<1
Servo error	0	3
Blackbody radiation oven	0	10
Background gas collisions	5	2
<b>Total</b>	<b>5199.4</b>	<b>21</b>
Red shift	-6086.0	10
<b>Total with red shift</b>	<b>-886.6</b>	<b>23</b>

Table 2: Budget of systematic effects and uncertainties for SYRTE-Sr2 optical lattice for the MJD 59639-59669 period

$$u_B = 0.23 \times 10^{-16}$$

## 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  $0.5 \times 10^{-16}$ .

-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  $5 \times 10^{-16}$  at 1 d and a flicker frequency noise component of  $5 \times 10^{-16}$  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  $0.9 \times 10^{-16}$ .

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 at the level of  $3 \times 10^{-17}$  by comparison to 2 other combs of different technology. 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  $u_{B/lab}$ .