

**FREQUENCY COMPARISON (H\_MASER 140 0810) - (LNE-SYRTE-FO2Rb)  
For the period MJD 58149 to MJD 58174**

The secondary frequency standard LNE-SYRTE-FO2Rb has been compared to the hydrogen Maser 140 0810 of the laboratory, during a measurement campaign between MJD 58149 and 58174 (31<sup>st</sup> January 2018 – 25<sup>th</sup> February 2018). The fountain operation covers ~ 74.4 % of the total measurement duration.

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

Period (MJD)	Date of the estimation	$y(\text{HMaser}_{140\ 0810} - \text{FO2Rb})$	$u_B$	$u_A$	$u_{\text{link/maser}}$	$u_{\text{SecRep}}$
58149 – 58174	58161.5	-6026.9	2.8	2.0	1.1	7

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

The calibration is made using the recommended value for the <sup>87</sup>Rb secondary representation: 6 834 682 610.904 310 Hz (20<sup>th</sup> CCTF in 2015).

$u_B$  is the <sup>87</sup>Rb fountain type B uncertainty.

$u_{\text{SecRep}}$  is the recommended uncertainty of the secondary representation (20<sup>th</sup> CCTF in 2015).

The FO2-Rb fountain was operated in two different modes during the period. Between MJD 58149 and MJD 58162, the interrogating signal is based on the multiplication of a 1 GHz signal provided by a cryogenic oscillator phase locked to the maser 140 0810. Between MJD 58162 and MJD 58174, the interrogating signal is based on the multiplication of a 1 GHz signal generated from the maser 140 0810 directly. In both case, a synthesizer is used to lock the microwave signal to the atomic resonance. The frequency difference between this 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 a conservative statistical uncertainty  $u_A = 2.0 \times 10^{-16}$ .

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 value given in Table 1 within  $1.3 \times 10^{-16}$ , which is consistent with the estimation of the statistical uncertainty  $u_A$  and the uncertainty due to the link.

## Accuracy

The frequency is corrected from the quadratic Zeeman, the Black Body radiation, the cold collisions and cavity pulling, the first order Doppler, the microwave lensing, and the red shift effects. 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 ( $10^{-16}$ )	Uncertainty ( $10^{-16}$ )
Quadratic Zeeman effect	-3504.00	0.70
Black body radiation	126.54	1.35
Cold collisions and cavity pulling	4.07	1.31
Distributed cavity phase shift	-0.35	1.00
Microwave spectral purity&leakage	0	<0.50
Ramsey & Rabi pulling	0	<0.10
Microwave lensing	-0.70	0.70
Second order Doppler effect	0	<0.10
Background gas collisions	0	<1.00
<b>Total</b>	<b>-3374.44</b>	<b>2.62</b>
Red shift	- 65.40	1.00
<b>Total with red shift</b>	<b>-3439.84</b>	<b>2.81</b>

Table 2: Budget of systematic effects and uncertainties for SYRTE-FO2Rb fountain for the MJD 58149 – 58174 period

$$u_B = 2.8 \times 10^{-16}$$

## 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. It is estimated to be  $10^{-16}$ .

-The uncertainty due to the dead times of the frequency comparison.

To estimate this contribution, we use the comparison between the reference Maser and Maser 140 0890.

We calculate the time deviation of the normalized phase differences with the linear frequency drift removed. The uncertainty is given by:

$$\sigma_{\text{Dead Time}} = \frac{\sqrt{\sum_i \sigma_{x_i}^2}}{T}$$

where  $\sigma_{x_i}$  are the extrapolated TVar for each dead times. We applied the method to the dead times longer than 600 s and obtained a stability degradation of  $0.4 \times 10^{-16}$ .