

**FREQUENCY COMPARISON (H\_MASER 140 0809) - (LNE-SYRTE-FO2Rb)  
For the period MJD 56624 to MJD 56654**

The secondary frequency standard LNE-SYRTE-FO2Rb has been compared to the hydrogen Maser 140 0809 of the laboratory, during a measurement campaign between MJD 56624 and 56654 (28<sup>th</sup> November 2013 – 28<sup>th</sup> December 2013). The fountain operation covers ~ 90.0 % of the total measurement duration. There was a change in the frequency drift of the maser at about MJD 56639. Therefore the collected data have been separated into two intervals of 15 days.

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

Period (MJD)	Date of the estimation	$y(\text{HMaser}_{140\ 0809} - \text{FO2Rb})$	$u_B$	$u_A$	$u_{\text{link/maser}}$	$u_{\text{SecRep}}$
56624 – 56639	56631.5	-2182.5	2.8	2.0	1.0	13
56639 – 56654	56646.5	-2242.1	2.8	3.0	1.1	13

*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: 6 834 682 610.904 312 Hz (19<sup>th</sup> CCTF in 2012 and 102<sup>nd</sup> CIPM in 2013).

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

$u_{\text{SecRep}}$  is the recommended uncertainty of the secondary representation (19<sup>th</sup> CCTF in 2012 and 102<sup>nd</sup> CIPM in 2013).

The FO2-Rb 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 on the maser 140 0809. It uses a synthesizer to lock the microwave signal on 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 calculate with the average points, a linear unweighted fit to determine the average frequency given in Table 1. The statistical uncertainty is estimated with the Allan variance of the frequency residuals, after removing the drift. We estimate a conservative statistical uncertainty  $u_A = 2.0 \times 10^{-16}$  and  $3.0 \times 10^{-16}$  for the two segments respectively.

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 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  $1.2 \times 10^{-16}$  and  $1.1 \times 10^{-16}$ , respectively for the two segments, which is consistent with the estimations 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	-3466.1	0.7
Black body radiation	125.54	1.4
Cold collisions and cavity pulling	6.39	1.34
First order Doppler	0.4	1.0
Microwave spectral purity&leakage	0	<0.5
Ramsey & Rabi pulling	0	<0.1
Microwave lensing	-0.7	0.7
Second order Doppler effect	0	<0.1
Background gas collisions	0	<1.0
<b>Total</b>	<b>-3334.5</b>	<b>2.6</b>
Red shift	- 65.4	1.0
<b>Total with red shift</b>	<b>-3399.9</b>	<b>2.8</b>

Table 2: Budget of systematic effects and uncertainties for SYRTE-FO2Rb fountain for the MJD 56624 – 56654 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 fountain 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 0810.

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

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

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 stability degradations of  $0.2 \times 10^{-16}$  and  $0.5 \times 10^{-16}$  for the two segments respectively.