FREQUENCY COMPARISON (H_MASER 40 0890) - (LNE-SYRTE-FOM)
From MJD 54054 to MJD 54069

The primary frequency standard LNE-SYRTE-FOM was compared to the hydrogen Maser (40 0890) of the laboratory, from MJD 54054 to MJD 54064.

The mean frequency differences measured between the hydrogen Maser 40 0890 and fountain FOM during this period is given in table 1.

Period (MJD)	y(HMaser$_{40\ 0890}$ - FOM)	u_B	u_A	$u_{link\ /\ maser}$
54054 – 54069	-3674.60	12.26	4.58	1.83

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

Figure 1 collects the measurements of fractional frequency differences during the 15th to 30th November 2006 period averaged by interval of 12 hours from MJD 54054 to 54069.

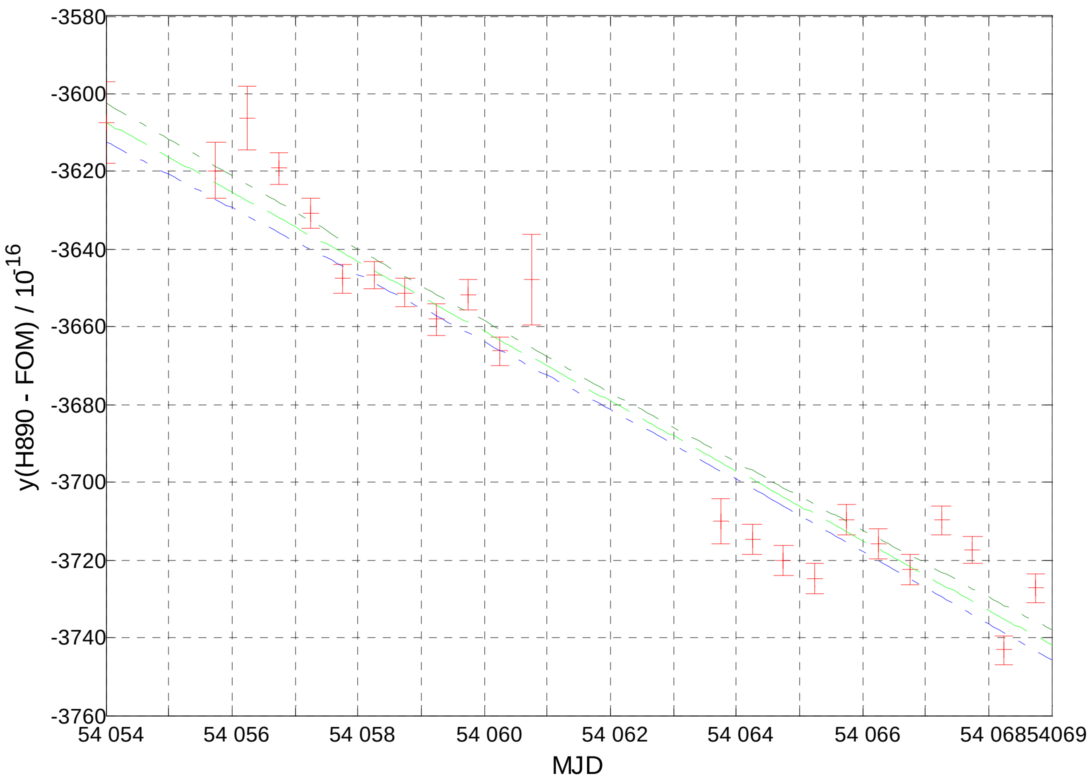

Figure 1: Fractional Frequency averaged over 12H and associated uncertainty of H890-FOM during the period 54054 to 54069. The weighted linear fit and, the confidence bounds up and low at ± 1σ were represented in dashed lines.

Frequency average between the Maser 40 0890 and the SYRTE fountain FOM

FOM measurements were avaraged over interval of 12H from MJD 54054 to MJD 54064 (see figure 1) and a linear fit weighted by the statistical uncertainties on each 12H interval was calculated (see bellow for more details on the uncertainties calculation). The missing frequency measurement at MJD 54054 was extrapolated by the linear fit. A second linear fit was calculated with this additional frequency and the mean frequency over this period was interpolated at the middle date MJD 54061.5 .Uncertainty at this mean frequency was obtained with the confidence level for the confidence bounds of 0.67 corresponding to a dispertion of 1σ.

Statistical uncertainty on FOM measurements

For each 12H interval the stability of FOM measurements was analyzed using the normal Allan deviation. A power law of $\sigma_y(\tau) = \sigma_y(10\tau_0)\sqrt{(10\tau_0/\tau)}$ is overlapped and uncertainty associated to the frequency average over 12H interval is estimated by extrapolating the power law of $\tau^{-1/2}$ at τ=T , T representing the effective duration of the measurement in the interval. The statistical uncertainty associated to the frequency average is calculated using the confidence bounds corresponding to +/-1σ around the linear fit at the middle MJD 54061.50. We found

$$u_A = 4.58 \times 10^{-16}$$

Uncertainty due to the dead times and due to the link between Maser890 and the fountain FOM

Uncertainties due to the dead time were calculated by stability analyses of Maser 40 0890 with respect to the Maser 40 0889 during the November 2006. These uncertainties were extrapolated from the time deviation between Maser 40 0890 and 40 0889 for each dead time duration observed during this period of FOM measurements. We found $\sigma_{Dead\_Time} = 1.53 \times 10^{-16}$.

Uncertainty due to the link between Maser890 and the fountain FOM is

$$u_{link\_Maser} = \sqrt{\sigma_{link\_Lab}^2 + \sigma_{dead\_time}^2}$$

With $\sigma_{link\_Lab} = 1.0 \times 10^{-16}$ and is the uncertainty due to the dead times during measurements and we found

$$u_{Link/Maser} = 1.83 \times 10^{-16}$$

Modifications of SYRTE-FOM fountain since the last TAI report:

The FOM fountain has been deeply modified since the last report (2004). It is operating since October 2006 and the performances evaluation is still under study and will improve during the next months. The FOM modifications concern all its components: the optical set-up and drivers, the caesium tube and the micro-wave chain.

- The optical set-up and the electronic drivers are new. The goal was to obtain an automatic operation of the clock especially for frequency control and locking of the lasers. A second ion pump has been added to the caesium tube and the inner magnetic shield has been lengthened to improve the magnetic homogeneity.
- We have studied and improved the thermal homogeneity along the atomic paths. 3 calibrated platinum probes (PT100) monitor the temperature outside the vacuum chamber. To evaluate the temperature gradient between these probes and the microwave cavity (to improve the thermal homogeneity a copper cylindrical tube screwed to the microwave cavity surrounds the atoms during their free flight) we have compared the probe measurements with 3 calibrated platinum probes temporarily fixed on the microwave cavity and the cylindrical tube. These measurements have been made under a vacuum level of 10^{-4} Pa. The temperature gradients

between all the probes remain within 0.2 K between 25 °C and 35°C. To limit thermal current, we have chosen to operate the clock in ambient temperature (~23°C).

- An active magnetic compensation reduces the external fluctuations by a factor of 10.
- The microwave chain has the same design as the FO1 fountain and uses the 1 GHz signal provided by the sapphire cryogenic oscillator. Thus the frequency stability reaches 8. 10^{-14} $t^{-1/2}$ in nominal operation. The symmetric feeding of the cavity and the non-dephasing switch is not yet implemented.

As before, FOM operates with a pure optical molasses loaded from a caesium vapour. The maximum detected atoms is 5.5×10^5 atoms which limits the frequency stability.

Uncertainties budget of systematic effects in the FOM fountain

Systematic effects taken into account are the quadratic Zeeman, the Black Body, the cold collision and cavity pulling, the microwave leakage and the 1st Doppler effects, the Ramsey Rabi pulling, the recoil, the 2nd Doppler and the background collisions. The red shift effect is also included in the systematic uncertainty budget. Systematic uncertainty is estimated by the sum of quadratic systematic uncertainties. The following table summarizes the budget of systematic effects and their associated uncertainties. More details on systematic effects are developed in the next paragraphs.

	Correction (10^{-16})	**Uncertainty (10^{-16})**
Quadratic Zeeman effect	- 210.2	1.1
Black body radiation	160.45	0.6
Cold collisions and cavity pulling	39.5	6.7
Microwave power dependence	0	10
Ramsey & Rabi pulling	0	< 0.1
Microwave recoil	0	< 1.4
Second order Doppler effect	0	< 0.1
Background gas collisions	0	<1.0
Total		**12.22**
Red shift	- 68	1.0
Total with red shift		**12.26**

Table 1: budget of systematic effects and uncertainties for SYRTE-FOM fountain

For the November 2006 period it gives:

$$u_B = 12.26 \times 10^{-16}$$

1 - Measurement of the 2nd order Zeeman frequency shift

The central fringe frequency of the field linearly dependant transition $f_{11}=(|F=3, m_F=1\rangle \quad |F=4, m_F=1\rangle)$ is measured (the proportionality constant is 7,0084 $Hz.nT^{-1}$ **[1]**). Its value is 471.23 Hz. The transition $f_{00}=(|F=3, m_F=0\rangle \quad |F=4, m_F=0\rangle)$ is shifted by quadratic Zeeman effect and depend on squared magnetic field with a constant of $4,2745 \times 10^{-8}$ $Hz.nT^{-2}$ **[1]**. Measuring f_{11} allows good estimation of Zeeman quadratic shift as:

$$\frac{f_{00}}{\nu_0} = \frac{4.2745 \times 10^{-8}}{9192631770}\left(\frac{f_{11}}{7.0084}\right)^2 = 210.2 \times 10^{-16}$$

$$\Delta f_{00} = 2 \times 4.2745 \times 10^{-8} \frac{f_{11}}{(7.0084)^2} \Delta f_{11}$$

During the period 54054-54069 the tracking of the central fringe f11 shows a stability of +- 0.2 Hz. By measuring the f_{11} frequency when the atoms are launched at different height we have measured several Hz inside the microwave cavity (this has been improved subsequently). To be conservative, we apply an uncertainty of a fringe width : 1.2 Hz. Thus the quadratic zeeman uncertainty is

$$\frac{\Delta f_{00}}{\nu_0} = \frac{2 \times 4.2745 \times 10^{-8}}{9192631770} \frac{f_{11}}{(7.0084)^2} \Delta f_{11} = 1.1 \times 10^{-16}$$

2 - Measurement of the collisional frequency shift and the cavity pulling

This effect is measured by performing differential measurements with different atom numbers. During the period 54054-54069 we have compared the clock frequency with respectively 5.5×10^5 detected atoms and 2×10^5. The atom number is varied by changing the laser power during the cooling process. The uncertainty on the determination of the collisional shift has 2 contributions: the comparison statistics and the linearity of the law with the number of detected atoms; FOM has not an adiabatic passage system.
We have measured a coefficient effect of 7.2×10^{-21} per detected atom with a statistic uncertainty of 10%. This result is in agreement with the previous results obtained from 1999 to 2004. These measurements will be refined by accumulating measurements and verifying the linearity of the effect with the atom number. Thus we keep the previous uncertainty of 17%.
The collisional shift is 3.95×10^{-15} with an uncertainty of 6.7×10^{-16}.

3 - Measurement of the Blackbody Radiation shift

An ensemble of 3 platinum thermistors monitors the temperature and its gradient inside the vacuum chamber. The average temperature is T=22,7°C= 295.85 K with a gradient of 0.2 K along the atom trajectory. The correction is

$$\left(\frac{\delta f)}{\nu_0}\right) = \frac{K_B T^4 \left(1 + \frac{\varepsilon T^2}{T_0^2}\right)}{T_0^4}$$

with $K = -1.573 \times 10^{-4} \pm 3 \times 10^{-7}$ **[2]**, $\varepsilon = 0.014$ and T_0=300K. The Blackbody Radiation shift is assorted of uncertainty dominated by the temperature uncertainty of 0.2 K:

$$\boxed{\left(\frac{\delta f}{\nu_0}\right) = -1.64045 \times 10^{-14} \pm 0.6 \times 10^{-16}}$$

4 - Effect of the Microwave power

Practically all the systematic effects depend on the microwave power. We have performed differential measurements by varying the microwave power. The first Doppler effect and the microwave leakage effect have power dependency and are then taken into account during these measurements. That has been performed by using alternatively the two feedthroughs of the microwave cavity. During these experiments we have detected a time variation of the microwave power when the level is changed with a time constant of about 40s. By analyzing the data, we do not give rise to a phase variation linked to this power variation. But the statistic uncertainty of this analysis is 10^{-15}. Consequently we apply a conservative uncertainty of 10^{-15} for the period 54054-54069.

$$\left(\frac{\delta f}{\nu_0}\right)_{MicrowavePower} = 0 \pm 10 \times 10^{-16}$$

These experiments correspond to the period 54061-54063 and the data has been removed owing to this power effect.

6 – Rabi and Ramsey effect and Majorana transitions effect

An imbalance between the residual populations and coherences of $m_F < 0$ and $m_F > 0$ states can lead to a shift of the clock frequency estimated below 10^{-17} for the current population imbalance.

7 – Microwave recoil effect

The shift due to the microwave photon recoil was investigated in **[3]**. It is smaller than 1,4 x 10^{-16} .

8 – Gravitational red-shift and 2nd order Doppler shift

The relativistic effect is evaluated as:

$$\left(\frac{\delta f}{\nu_0}\right)_{\mathrm{Re}\,dShift} = \frac{gh}{c^2}$$ with h=62.5±1m

$$\left(\frac{\delta f}{\nu_0}\right)_{\mathrm{Re}\,dShift} = 68 \times 10^{-16}(1)$$

The 2nd order Doppler shift is less than 0,08 x 10^{-16} .

9 – Background collisions effect

The vacuum pressure inside the fountains is typically 10^{-7} Pa. Based on early measurements of pressure shift (see **[1]**) the frequency shift due to collisions with the background gas is $< 10^{-16}$.

References

[1] - J. Vanier, C. Audouin, « The Quantum Physics of Atomic Frequency Standards », **Adam Hilger, Bristol & Philadelphia (1989)**.

[2] – E. Simon, PhD thesis, Paris VI, 1997.

[3] - P. Wolf of LNE SYRTE, C.J. Bordé of LPL, "Recoil effects in microwave Ramsey spectroscopy", arxiv: **quant-ph/0403194**.