Systèmes de Référence Temps-Espace

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FREQUENCY COMPARISON (H_MASER 140 0890) - (LNE-SYRTE-FO2)
For the period MJD 55684 to MJD 55709

The primary frequency standard LNE-SYRTE-FO2 has been compared to the hydrogen Maser 140 0890 of the laboratory, during a measurement campaign between MJD 55684 and 55709 (3^{rd} May 2011 - 28^{th} May 2011). The fountain operation covers ~ 69 % 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(HMaser$_{140\ 0890}$ – FO2)**	u_B	u_A	$u_{link\ /\ maser}$
55684 – 55709	**55696.5**	**-462.7**	**2.6**	**3**	**1.3**

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

The FO2 fountain was operated in the same mode during all the period: the interrogating signal synthesis is based on the down conversion to 9.192 GHz of a 11.98 GHz signal provided by a cryogenic oscillator phase locked to the maser 140 0890. 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

This paragraph describes the calculation of the average frequency of HMaser$_{140\ 0890}$-FO2. The details of the calculation are given in figure 1:

The frequency data averaged over 0.2 day are plotted on the upper graph (blue points) together with a linear unweighted fit (red line).
The parameters of the fit y=a + b(x-x_middle_date) are respectively:

Period (MJD)	**a**	**b**
55684 – 55709	**(-462.7 +/-1.0) 10^{-16}**	**(-1.9 +/- 0.2) 10^{-16}/day**

Table 2: coefficients of the linear fit of HMaser$_{140\ 0890}$-FO2

These coefficients are used to remove the drift (data plotted in the graph in the middle, red points) and to calculate the average value at middle date, given in table 1. The lower graph gives the variance of the frequency residuals. We estimate a conservative statistical uncertainty u_A of 3×10^{-16}.

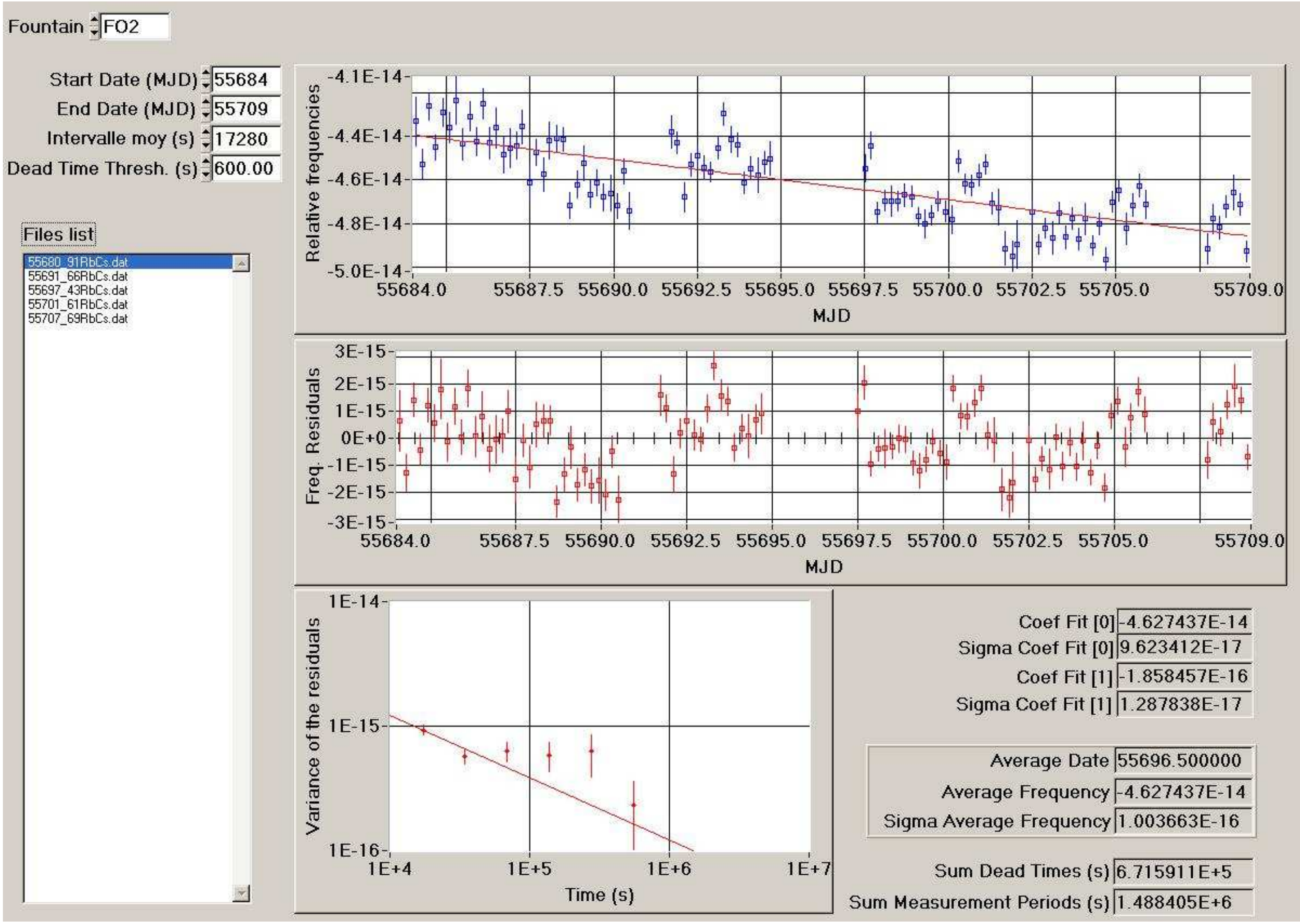

Figure 1: Processing of the data HMaser$_{140\ 0890}$-FO2 for the period MJD 55684-55709

We verified the result by applying a second method. We calculated the accumulated phase by integrating the data points, assuming a linear frequency drift 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 differences between the results and the value given in table 1 are in agreement within 1.2×10^{-16}, 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, and the red shift effects. Here the uncertainty in the cold collisions correction accounts for both a statistical uncertainty and a systematic uncertainty taken as 0.5% of the correction for high density measurements. 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	-1915.9	0.3
Black body radiation	167.7	0.6
Cold collisions and cavity pulling	112	1.2
First order Doppler	-0.75	0.93 (see footnote [1])
Microwave spectral purity&leakage	0	<0.5
Ramsey & Rabi pulling	0	< 0.1
Microwave lensing	0	< 1.4
Second order Doppler effect	0	< 0.1
Background gas collisions	0	<1.0
Total	**-1636.95**	**2.4**
Red shift	- 65.4	1.0
Total with red shift	**-1702.35**	**2.6**

Table 2: Budget of systematic effects and uncertainties for SYRTE-FO2 fountain for the MJD 55684 – 55709 period

$$\boxed{u_B = 2.6\times 10^{-16}}$$

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 0816. 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 σ_{xi} are the extrapolated TVar for each dead times. We applied the method to the dead times longer than 600 s and obtained stability degradation of 0.8×10^{-16}.

[1] The uncertainty on the first order Doppler shift has been modified, starting May 2011, on the basis of our recent experimental investigation of this effect, reported in **Phys. Rev. Lett. 106, 130801 (2011)**. This uncertainty is itself a sum of several contributions, some of them which depend on the uncertainty on the launch direction. This uncertainty on the launch direction can vary from one evaluation period to the other depending on several factors (such as the interval between checks of the launch direction, etc). The overall uncertainty on the first order Doppler shift is therefore subject to small changes from one TAI report period to the other.

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Notes on modifications to the accuracy budget of SYRTE fountains

The accuracy budgets of FO1, FO2 and FOM have been modified as follows:

The systematic shift so far denoted as "Microwave Recoil" [1] is now denoted "Microwave Lensing" following reference [2] and its physical interpretation for this effect in the case of atomic fountain clocks.

The accuracy budget of FO2 has been modified as follows, to account for a new evaluation of the residual first order Doppler effects:

The systematic correction and the related uncertainty corresponding to the residual first order Doppler frequency shift have been modified, starting May 2011, on the basis of our recent experimental investigation of this effect, as reported in [3]. The theory used to model this effect, to analyze the measurements and to determine the uncertainty of this effect is described in [4, 5]. The model relies on an azimuthal decomposition of the distributed cavity phase variations in the Ramsey cavity. Consequently, the corresponding uncertainty is the quadratic sum of several contributions of the lowest relevant terms in the azimuthal decomposition, namely m=0 (which turns out to have a negligible contribution for FO2 for nominal operation), m=1 (2 contributions for 2 possible components of the tilt of the launch direction), m=2. The m=1 term contributions to the uncertainty depend on the uncertainty on the tilt, which itself depends on several factors (such as the interval between checks of the launch direction, stability of the fountain environment, etc). The m=1 is therefore subject to changes from one TAI report period to the other. Correspondingly, the overall residual first order Doppler uncertainty is subject to small changes from one TAI report period to the other. The nominal overall uncertainty as established in [3] is 8.4×10^{-17}.

Based on [3], measurements are underway in FO1 and FOM to reduce the residual first order Doppler uncertainty. Until these studies are completed, the existing less sophisticated and less stringent estimation of the uncertainty due to the residual first order Doppler is kept for FO1 and FOM.

[1] P. Wolf and C. J. Bordé, arXiv:quant-ph/0403194v1 (2004)
[2] K. Gibble, Phys. Rev. Lett. 97, 073002 (2006)
[3] J. Guéna et al., Phys. Rev. Lett. 106, 130801 (2011)
[4] R. Li and K. Gibble, Metrologia 41, 376 (2004)
[5] R. Li and K. Gibble, Metrologia 47, 534 (2010)