State Scientific Center
of the Russian
Federation
VNIIFTRI

National Research Institute for
Physical-Technical and Radio Engineering Measurements

FREQUENCY COMPARISON (H_MASER 40 3810) - (SU-CsFO2)
For the period MJD 56439 to MJD 56469.

The primary frequency standard SU-CsFO2 has been compared to the hydrogen Maser 40 3810 of the laboratory, during a measurement campaign between MJD 56379 and 56469 (28th March 2013 - 26th June 2013). The fountain operation covers ~ 84 % of the total measurement duration for the period MJD 56379-56409**,** ~ 96 % for MJD 56409 – 56439, ~ 88 % for 56379-56409.

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

Period (MJD)	**Date of the estimation**	**y(HMaser40 3810 – CsFO2)**	u_B	u_A	u_{Link_Maser}
56379-56409	**56394**	**-90.1**	**5.0**	**3.6**	**1.1**
56409 – 56439	**56424**	**-118.4**	**5.0**	**2.8**	**1.0**
56439 – 56469	**56454**	**-134.1**	**5.0**	**2.6**	**1.0**

Table 1: Results of the comparison in 1 × 10-16.

The relative frequency instability of CsFO2 was :

3.7×10^{-13} $(\tau/s)^{-1/2}$ during the 30 days (MJD 56379-56409)

2.7×10^{-13} $(\tau/s)^{-1/2}$ during the 30 days (MJD 56409 – 56439)

3.2×10^{-13} $(\tau/s)^{-1/2}$ during the 30 days (MJD 56439 – 56469)

For the uncertainty due to the clock link $\mathbf{u}_{Link\_Lab} = 0.1\times10^{-15}$ is obtained by taking into account the actual measurement time.

The CsFO2 standard uncertainty $\boldsymbol{u}_{\mathbf{B}}$ is estimated as 0.5×10^{-15} (1σ) for the relevant periods.

Figure 1 shows the shot by shot data measurements during the period MJD 56379 to MJD 56409.

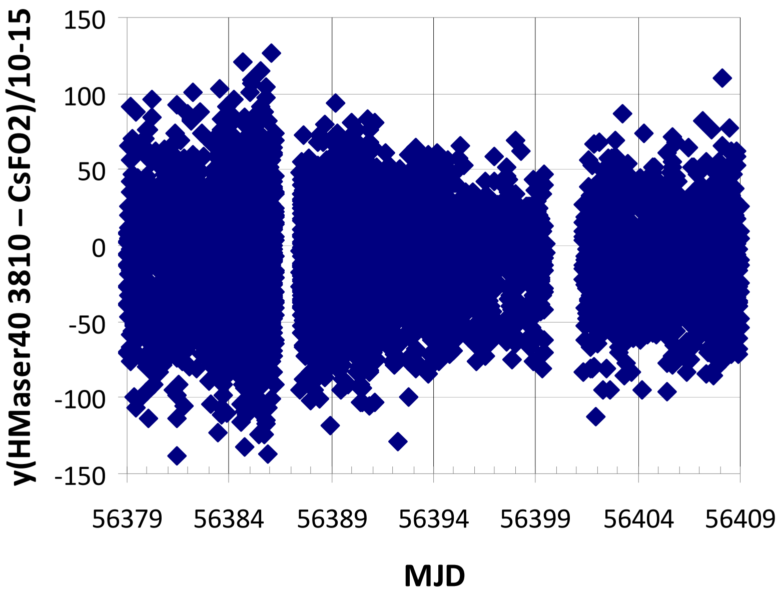

Figure 1: shot by shot data measurements during the period MJD 56379 to MJD 56409

Figure 2 shows the shot by shot data measurements during the period MJD 56409 to MJD 56439.

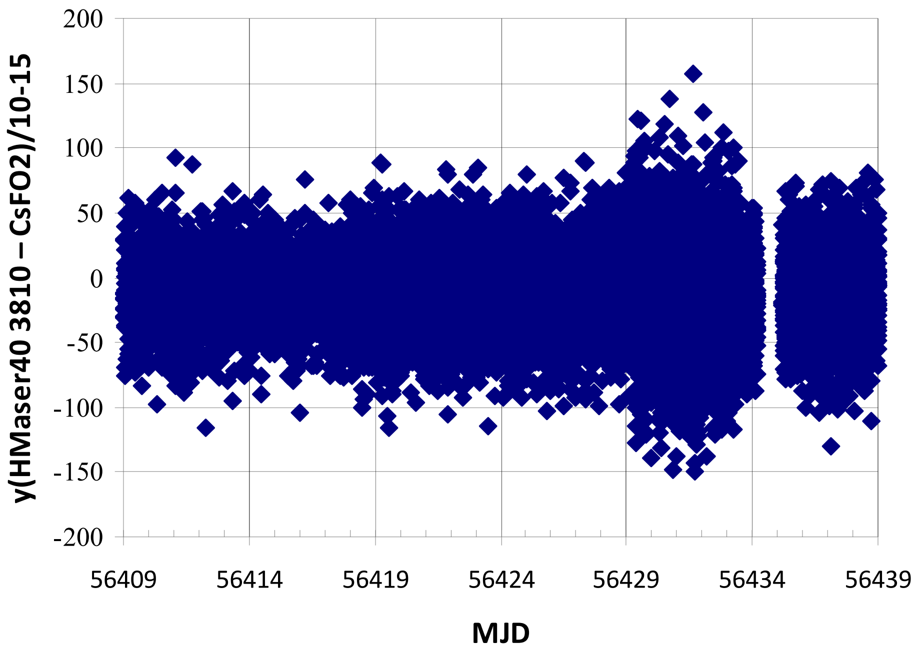

Figure 2: shot by shot data measurements during the period MJD 56409 to MJD 56439

Figure 3 shows the shot by shot data measurements during the period MJD 56439 to MJD 56469.

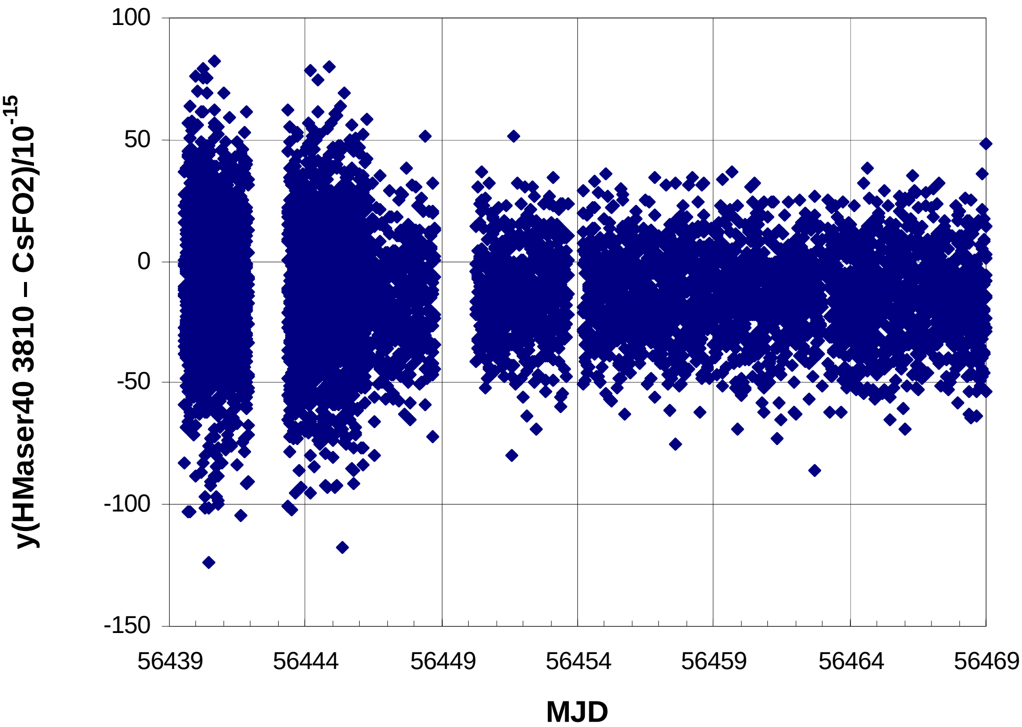

Figure 3: shot by shot data measurements during the period MJD 564394 to MJD 56469

Feature of fountain's measurement procedure

Frequency measurement of H-maser is shared by blocks, each block consists of one hundred shots. Fountain operating mode may differ from block to block or may be the same for all blocks. Fountain work can be programmed with a set of various modes in block.

For example, collision shift measurement cycle consists of three blocks. The number of atoms is determined by frequency of selection cavity signal. This frequency is adjusted to the peak or semi-slope resonance of cesium atoms.

- The first block: a low number of atoms. ($f = f_p - \Delta f$);
- the second block: a high number of atoms ($f = f_p$);
- the third block: a low number of atoms. The frequency of selection cavity is $f = f_p + \Delta f$.

Where f is the selection cavity frequency, f_p is the cesium resonance frequency, Δf is the semi-slope resonance of cesium atoms.

Then the cycle (three blocks) is repeated.

Measurement cycle of the microwave power shift may consist of six blocks. Such work allows to remove frequency drift of H-maser.

A detailed description of the measurement procedure together with a complete evaluation of the systematic frequency biases and their uncertainties is given in references [1].

Accuracy

The frequency is corrected from the quadratic Zeeman, the Black Body radiation, the cold collisions and cavity pulling, , microwave power dependence, and gravity.
The following table summarizes the budget of systematic effects and their associated uncertainties. The accuracy is the quadratic sum of all the systematic uncertainties.

Physical Effect	**Correction (10^{-16})**	**Uncertainty (10^{-16})**
Quadratic Zeeman effect	-1073.	0.10
Black body radiation	179.9	1.0
Cold collisions	5.2	2.3
Microwave power dependence	0.39	3.8
Gravity	-244.3	0.1
Total	**-1132**	**4.6**

Table 2: Budget of systematic effects and uncertainties for VNIIFTRI- CsFO2 *fountain for the MJD 56439 – 56469 period*

$$u_B = 5 \times 10^{-16}.$$

Uncertainty due to the dead times

During the evaluation period there were gaps in the data collection (dead time) due to both intentional and unintentional breaks. Most of the unintentional breaks were caused by failures of the laser locking systems(due to rapid change barometric pressure).

Start of date of measurements (MJD)	End of date of measurements (MJD)	Duration of dead Times H:m:s	second	σ_{x_i}
56379	56383.4541			
56383.474	56384.2709	0:28:39	1719	7.1130E-12
56384.5298	56386.2417	6:12:49	22369	2.7686E-11
56387.495	56391.2503	30:04:45	108285	7.8074E-11
56391.5112	56392.3654	6:15:42	22542	2.8069E-11
56392.5189	56393.262	3:41:02	13262	2.0702E-11
56393.5201	56394.4628	6:11:40	22300	2.7686E-11
56394.4832	56397.1556	0:29:23	1763	7.4462E-12
56397.5301	56398.2315	8:59:17	32357	3.6040E-11
56398.5111	56399.458	6:42:37	24157	2.9213E-11
56401.3041	56407.2169	44:18:23	159503	6.4246E-11
56407.2737	56409.0044	1:21:48	4908	1.2556E-11
56409.0097	56433.3626	0:20:01	1201	5.8090E-12
56433.4222	56434.193	1:25:49	5149	1.3246E-11
56435.2197	56436.1972	24:38:27	88707	5.6758E-11
56436.2052	56439.3719	0:11:31	691	4.5251E-12
56439.5516	56441.9041	4:18:46	15526.08	1.5869E-11
56443.3485	56446.2495	34:39:56	124796.16	3.2543E-11
56446.2652	56448.7692	0:22:36	1356.48	5.2488E-12
56449.3703	56449.7438	14:25:35	51935.04	2.6774E-11
56450.2608	56453.6486	12:24:29	44668.8	2.6490E-11
56454.1809	56463.008	12:46:31	45990.72	2.6635E-11
56463.1886	56469.2487	4:20:04	15603.84	1.5869E-11

Table 3: Distribution of Dead Times for the MJD 56379 – 56469 period

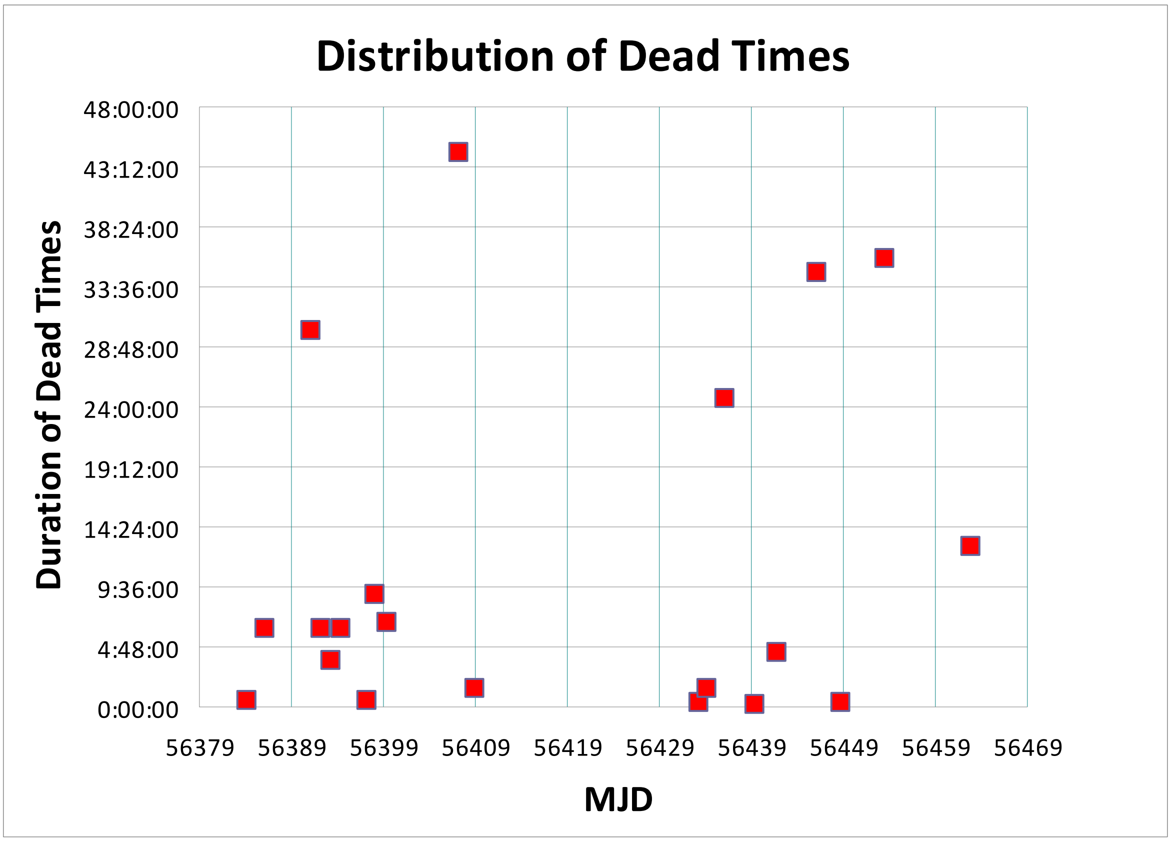

Figure 2: Dead times of measurements on y(HMaser40 3810 – CsFO2) during the period MJD 56379 to 56469

The standard deviation of the fluctuations of frequency due to the dead times in measurements is estimated by the ratio

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

Period	$\sigma_{\text{Dead\_Time}}$
56379 - 56409	2.32×10^{-17}
56409 – 56439	2.24×10^{-17}
56439 – 56469	2.32×10^{-17}

The uncertainty on the link Maser is obtained by the quadratic sum of the link lab uncertainty and the uncertainty due to the dead times calculated above:

$\mathbf{u}_{Link\_Lab}=1\times10^{-16}$,

$\mathbf{u}_{Link\_Maser}=\sqrt{(\sigma_{Dead\_Time})^2+(\sigma_{Link\_Lab})^2}$

Period	$\mathbf{u}_{Link\_Lab}$
56379-56409	1.1×10^{-16}
56409 – 56439	1.0×10^{-16}
56439 – 56469	1.0×10^{-16}

References

[1] Domnin, Yu.; Baryshev, V.; Boyko, A.; Elkin, G.; Novoselov, A.; Kopylov, L.; Kupalov, D., "The MTsR-F2 fountain-type cesium frequency standard", Measurement Techniques, Volume 55, Number 10, January 2013 , pp. 1155-1162(8)