Evaluation of the frequency of the H-maser 1401701 by the primary frequency standard NPL-CsF1

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Summary

The primary frequency standard NPL-CsF1 was used to measure the frequency of the H-maser HM1 identified by the clock code 1401701 during a period of 30 days in October and November 2004. The evaluation was performed by measuring a mean frequency difference over the reporting period. The frequency difference is given in table 1, together with the total uncertainty in relating NPL-CsF1 to maser1401701.

Period (MJD)	y(CsF1) - y(HM1) [$\times 10^{-15}$]	*u(total)* [$\times 10^{-15}$]
53299 – 53329	5.6	1.2

Table 1. Summary of the frequency measurement of clock 1401701 (HM1) including the total uncertainty.

A brief description of the measurement procedure and a discussion of the uncertainties are presented in this report. A detailed description of the measurement procedure together with a complete evaluation of the systematic frequency biases and their uncertainties is given in reference [1].

Systematic frequency biases

Those biases and uncertainties used to calculate the total contribution to the frequency of NPL-CsF1 (including the contribution from the gravity potential relative to the Earth's geoid) are listed in table 2:

Effect	Bias ($\times 10^{-15}$)	Uncertainty ($\times 10^{-15}$)
2nd order Zeeman	142.4	0.1
AC Stark (BBR)	-16.8	0.4
Collisions	n/a*)	0.8
μ-w leakage	1.0	0.3
Cavity pulling	0.0	0.1
μ-w spectrum	0.0	<0.1
Cavity phase	0.0	0.3
Rabi, Ramsey pulling	0.0	0.1
AC Stark (lasers)	0.0	0.1
Gravity	1.3	0.1
Total (1σ), u_B		1.0

*) The actual value of the collisional shift is computed continuously and standard's frequency is extrapolated to zero atomic density.

Table 2.

Measurement procedure

The frequency of NPL-CsF1 was related to a hydrogen maser HM3 (not reported to BIPM), which in turn was linked to the maser HM1. The two masers were located 0.8 km apart and an underground cable maintained a 10 MHz link between them.

During the measurement campaign the fountain was run exclusively in the alternating mode between high and low atom number. The noise due to the correction procedure and the link between HM1 and HM3 resulted in a short-term stability of the NPL-CsF1 – HM1 frequency difference of 7.2×10^{-13} in 1s.

Corrections due to effects other than collisions were sufficiently stable over the campaign period, so that a single correction value could be applied. Nevertheless, the validity of that value, where possible, was checked during a campaign. All the corrections were checked at the start and end of a campaign (e.g. a detailed map of the magnetic field was made). The temperature of the vacuum vessel was recorded at one-minute intervals. The microwave leakage level and the C-field value for the operating launch height (31 cm above the microwave cavity) were checked every two or three days.

Uncertainties of the measurement

Stability

The short-term stability of the measurement of the frequency extrapolated to zero atomic density was typically 7.2×10^{-13} in 1s (7.2×10^{-15} in 10^4 s). The type A uncertainty of the complete measurement u_A was obtained by assuming white FM noise over the effective period of integration (effective period = reporting period × duty cycle).

Link with the local time scale

The uncertainty of the link with the local time scale $u_{l/lab}$ is a quadratic sum of two contributions:

$$(u_{l/lab})^2 = (u_{link})^2 + (u_{dt})^2$$

where u_{link} is the uncertainty associated with the frequency transfer between CsF1 and HM1 by the 0.8 km long 10 MHz link, and u_{dt} is an additional uncertainty of the measured maser frequency due to gaps (dead time) in the operation of the fountain standard.

In order to estimate the u_{link}, which arose predominantly from instabilities of the temperature of the linking cable, the round-trip phase-delay in the cable was monitored and the following value was ascribed to the uncertainty:

$$u_{link} = 0.4\times10^{-15}$$

Duty cycle (dead time)

During the evaluation period there were gaps in the data collection (dead time) due to both intentional and unintentional breaks. The uncertainty introduced by the dead time, u_{dt}, was approximated by calculating the time deviation (TDEV) of each gap, using the relation between TDEV and the modified Allan deviation (MDEV):

$$\sigma_x{}^2(\tau) = \tau^2/3 \; mod \; \sigma_y{}^2(\tau),$$

where $\sigma_x(\tau)$ is the TDEV and $mod\ \sigma_y(\tau)$ is the MDEV.

The stability of the maser 1401701 has been shown to be dominated by flicker frequency modulation (ref. [2]) and the Hadamard deviation has been measured to be

$$\sigma_h(\tau) \cong 1.2\times10^{-15};\; 500 < \tau[\mathrm{s}] < 6\times10^5.$$

The approximation, $mod\ \sigma_y(\tau) = \sigma_h(\tau)$, was used.

The fractional frequency uncertainty, u_{dt}, arising from the dead time was approximated by the square root of the sum of the time variances, normalised by the length of the measurement campaign, thus:

$$u_{dt} = \frac{1}{T}\sqrt{\sum_{i=1}^{N}\left[\sigma_x(\tau_i)\right]^2}$$

where $\sigma_x(\tau_i)$ is the time deviation (TDEV) of the maser over a duration τ_i; and T is the duration of the campaign.

The longest dead time was 40 hours. The uncertainty arising from the dead time for the campaign was:

$$u_{dt} = 1.1\times10^{-16}.$$

The uncertainty due to an uncorrected frequency drift of the maser 1401701 for the longest gap is known (ref. [2]) to be negligible when compared to the type A uncertainty of NPL-CsF1 over the same duration. The frequency drift of the maser was therefore omitted from the total uncertainty.

Evaluation results

Detailed parameters and results of the evaluation of the UTC(NPL) rate for the reporting period are listed in table 3. The total uncertainty u_{total} of the measurement is defined as:

$$(u_{total})^2 = (u_A)^2 + (u_B)^2 + (u_{l/lab})^2$$

MJD		53299-53329
duration	days	30
duty cycle	%	86.7
$y(CsF1) - y(HM1)$	$\times10^{-15}$	5.64
u_A	$\times10^{-15}$	0.48
u_B	$\times10^{-15}$	1.0
$u_{l/lab}$	$\times10^{-15}$	0.41
u_{total}	$\times10^{-15}$	1.2

Table 3.

References:

[1] K. Szymaniec, W. Chalupczak, P.B. Whibberley, S.N. Lea, D. Henderson, *Metrologia*, **42**, pp. 49-57, (2005).

[2] J.A. Davis, C.A. Greenhall, P.W. Stacey, *Metrologia*, **42**, pp. 1-10, (2005)