Evaluation of the frequency of the H-maser 1401708 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 HM2 identified by the clock code 1401708 during two campaigns in July and August 2007. These evaluations were performed by measuring mean frequency differences over the reporting periods. The frequency differences are given in table 1, together with the total uncertainty in relating NPL-CsF1 to maser 1401708.

Period	MJD	y(CsF1) - y(HM2) [$\times 10^{-15}$]	*u(total)* [$\times 10^{-15}$]
I	54284 – 54319	15.8	1.9
II	54319 – 54344	-9.3	1.9

Table 1. Summary of the frequency measurement of clock 1401708 (HM2) including the total uncertainty.

A brief description of the measurement procedure, and a discussion of the uncertainties is 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 references [1] and [2].

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	143.0	0.1
AC Stark (BBR)	-16.2	0.4
Collisions	-1.4 *)	0.3
μ-w leakage	0.0	1.7
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		1.8

*) The average value of frequency bias due to cold collisions is given for example only. The actual value is computed continuously and standard's frequency is extrapolated to zero atomic density.

Table 2.

Notes:

1) The procedure for estimation of the microwave leakage frequency shift and its uncertainty in NPL-CsF1 has been revised since the publication in [1] and previous evaluations reported to BIPM (see ref. [2]).
2) The physics package of the NPL-CsF1 frequency standard has not been modified since the previous evaluations.
3) The NPL-CsF1 standard was operated with reduced collisional frequency shift by adjusting the clock state fractional populations (ref. [3]). The type B uncertainty of the collisional shift is conservatively estimated at 20% of the shift itself allowing for possible discrepancy between the density ratios and the detected atom number ratios (ref. [4]), which may affect the extrapolation results.

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 HM2. The two masers were located within the same building and a cable (led entirely in temperature controlled environment) 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 standard's frequency was continuously extrapolated to zero atomic density.

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. The temperature of the vacuum vessel was recorded at one-minute intervals

Uncertainties of the measurement

Stability

The short-term stability of the measurement of the frequency extrapolated to zero atomic density was typically 8.1×10^{-13} in 1s (8.1×10^{-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 in general 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 HM2, 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 our current arrangement the u_{link}, which normally arises from instabilities of the temperature of the linking cable, can be neglected on the 10^{-15} scale, giving:

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

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 intentional breaks were required to verify the C-field value and the microwave leakage level. Most of the unintentional breaks were caused by failures of the laser stabilisation system.

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 1401708 has been shown to be dominated by flicker frequency modulation (ref. [5]) 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 76 hours. The uncertainty arising from the dead time for the campaigns was:

$u_{dt}(\mathrm{I}) = 1.6\times10^{-16}$

$u_{dt}(\mathrm{II}) = 1.4\times10^{-16}$

The uncertainty due to an uncorrected frequency drift of the maser 1401708 for the longest gap is known (ref. [5]) 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 two campaign periods are listed in table 3. The total uncertainty u_{total} of the measurement is defined as:

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

Period		I	II
MJD		54284-54319	54319-54344
duration	days	35	25
duty cycle	%	74.8	76.0
y(CsF1) - y(HM2)	$\times 10^{-15}$	15.8	-9.3
u_A	$\times 10^{-15}$	0.54	0.63
u_B	$\times 10^{-15}$	1.8	1.8
$u_{l/lab}$	$\times 10^{-15}$	0.16	0.14
u_{total}	$\times 10^{-15}$	1.9	1.9

Table 3.

References:

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

[2] K. Szymaniec, W. Chalupczak, P.B. Whibberley, S.N. Lea, D. Henderson, *Metrologia*, **43**, pp. L18-L19, (2006).

[3] K. Szymaniec, W. Chalupczak, E. Tiesinga, C.J. Williams, S. Weyers, R. Wynands, *Phys. Rev. Lett.* **98**, 153002, (2007).

[4] F. Pereira dos Santos, H. Marion, S. Bize, Y. Sortais, A. Clairon, C. Salomon, *Phys. Rev. Lett.* **89**, 233004, (2002).

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