Evaluation of the frequency of the H-maser 1401708 by the primary frequency standard NPL-CsF2

National Physical Laboratory

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I. Summary

The primary frequency standard NPL-CsF2 was used to measure the frequency of the H-maser HM2 identified by the clock code 1401708 during an evaluation campaign in August and September 2010. These evaluations were performed by measuring mean frequency differences over the reporting periods. The frequency difference is given in table 1, together with the total uncertainty in relating NPL-CsF2 to maser 1401708.

No changes to the physics package of NPL-CsF2 have been introduced since the previous reported evaluation.

MJD	*y(CsF2 - HM2)* [$\times 10^{-15}$]	*u(total)* [$\times 10^{-15}$]
55404 – 55444	7.13	0.48

Table 1. Summary of the frequency measurements of clock 1401708 (HM2) including the total uncertainties.

II. Measurement methods

Operation procedure

The fountain was run in an alternating mode between high and low atomic densities with an optimised high-low density duty cycle. Similarly, the density (atom number) ratio $k = N_H / N_L$ was optimised for the current NPL-CsF2 operational parameters.

Uncertainties of the measurement

Short-term stability and type A uncertainty

The short-term stability of the measurement of the frequency extrapolated to zero atomic density was typically 2.7×10^{-13} in 1s. 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).

Type B uncertainty

The NPL-CsF2 frequency is corrected for the following four effects: second order Zeeman shift, blackbody radiation, cold collisions (spin exchange) and gravitational shift. Except for the gravitational shift, the actual values of the frequency offsets are specific for particular measurement campaigns. Corrections due to effects other than collisions were sufficiently stable over the campaign periods, so that single correction values were applied. Nevertheless, the validity of these values, where possible, was checked during a campaign. The C-field magnitude was verified approximately every week. The temperature of the flight tube was measured at one-minute intervals and recorded as two-hour averages. In a table below, we give a list of the identified systematic effects and their uncertainties.

Type B evaluation	Uncertainty / 10^{-16}
Second order Zeeman	0.8
Blackbody radiation	1.1
AC Stark (lasers)	0.1
Microwave spectrum	0.1
Gravity	0.5
Collisions with background gas	1.0
Rabi, Ramsey pulling	0.1
Cavity phase (distributed)	3.0
Cavity phase (dynamic)	0.1
Cavity pulling	0.2
Microwave leakage	1.0
Microwave recoil	1.5
Second-order Doppler	0.1
Total (excluding cold collisions)	**4.0**

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 NPL-CsF2 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, is estimated below 10^{-17}.

Dead time

During the evaluation period, there were gaps in the data collection (dead time) due to both intentional and unintentional breaks. Intentional breaks were required for system maintenance and checks. The unintentional breaks were infrequent and did not have a prevailing cause. Additional dead time was assumed when the measurement period did not match the BIPM reporting times (set every 5 days).

The total uncertainty due to the dead time is calculated as a quadratic sum of uncertainties due to individual gaps in the measurement:

$$u_{dt}{}^2 = \sum_{i=1}^{N} u_i{}^2$$

Assuming that a flicker frequency modulation dominates the instability of the H-Maser 1401708, we get

$$u_{dt}{}^2 = \sum_i \left(\frac{\tau_i \sigma_y}{T} \right)^2 ,$$

where τ_i is a duration of a gap, T is a duration of the entire campaign, and the maser instability is [1]:

$$\sigma_y(\tau) \cong 1.2 \times 10^{-15}; \;\; 500 < \tau[\mathrm{s}] < 6 \times 10^5.$$

References:

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

III. Results of the evaluation

Results of the frequency measurements for the two campaign periods are listed in the table below. Frequency biases are given for information only. The given fractional frequency difference *y(CsF2 – HM2)* is a value corrected for those biases. Note that the values for the collisional shift and its uncertainty vary, and so vary the total type B uncertainties u_B for particular campaigns. The value of collisional shift is a time-averaged value for the high and low densities. 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	(date)	27 Jul 2010 – 05 Sep 2010
Start	MJD	55404
Stop	MJD	55444
Duration	days	40
duty cycle	%	66.2
Biases: 2nd order Zeeman BBR shift cold collisions gravity	$\times 10^{-15}$	 336.20 −16.62 −0.20 1.30
y(CsF2 - HM2)	$\times 10^{-15}$	**7.13**
u_A	$\times 10^{-15}$	0.17
u_B	$\times 10^{-15}$	0.40
$u_{l/lab}$	$\times 10^{-15}$	0.20
$\boldsymbol{u_{total}}$	$\times 10^{-15}$	**0.48**