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

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18 July 2010

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 two evaluation campaigns in December 2009 and January 2010. 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-CsF2 to maser 1401708.

No changes to the physics package of NPL-CsF2 have been introduced since the previous reported evaluation. However, the optical bench has been modified to create an additional optical pumping stage. This enabled accumulation of the atomic population in the $m_F = 0$ clock state and increased the detected atom number. Following this modification, the fountain operation protocol has been optimised, which resulted in an improved effective short-term stability.

Period	MJD	*y(CsF2 - HM2)* [$\times 10^{-15}$]	*u(total)* [$\times 10^{-15}$]
1.	55169 – 55194	–10.17	0.45
2.	55194 – 55224	–8.11	0.45

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

II. Measurement methods

Modifications introduced to NPL-CsF2 system

Hardware

An additional optical pumping stage was applied after the launch of the atomic cloud. A short pulse of linearly polarised light (π-polarisation), resonant with the $F = 4 \rightarrow F'$ = 4 transition and accompanied by a repumper pulse ($F = 3 \rightarrow F' = 4$) resulted in an accumulation of the atomic populations in one of the clock states, $F = 4$, $m_F = 0$, which is a “dark state” for this light pulses configuration (for details see [1] and [2]). The emission of spontaneous photons during the pumping/repumping process lead to a heating and additional expansion of the atomic cloud. Nevertheless, a net increase of the detected atoms number was achieved by up to a factor of four. The required optical pulses were derived from existing lasers on the optical table. No changes to the physics package of NPL-CsF2 were made. It was verified that the additional laser beams had not increased the level of AC Stark shift.

Operation procedure

As before, the fountain was run in an alternating mode between high and low atomic densities, but 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. For the given local oscillator noise level and for the detected atom numbers increased by the optical pumping technique, we found that the optimum k is between 6 and 8 [2]. The optimised operation has enabled the reduction of the short-term instability by a factor of 2, thus reduced by factor 4 the averaging time required to reach given statistical resolution, e.g. that matching the u_B.

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.

The type B contribution to the uncertainty of cold collisional frequency shift (spin exchange shift) was calculated according to [2] as:

$$u_{\mathrm{B}}^{(coll-shift)} = \delta k \frac{k}{(k-1)^2} \Delta F'_{\mathrm{H-L}} \,;$$

where δk is a fractional error of k (we take $\delta k = 0.1$) and $\Delta F'_{\mathrm{H-L}} = \sqrt{(\Delta F_{\mathrm{H-L}})^2 + (\delta F_{\mathrm{H-L}})^2}$ is the residual collisional shift enlarged by the statistical uncertainty of its determination. Because this $u_{\mathrm{B}}^{(coll\text{-}shift)}$ takes specific values for particular campaigns, it is not included in the table; it is included in total u_B values for the relevant campaigns in chapter III.

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.

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

$$u_{dt}^{2} = \sum_{i} u_{i}^{2}$$

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 [3]:

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

References:

[1] S.E. Park and K. Szymaniec, “Accumulation of a clock state population by optical pumping in caesium fountain”, *CPEM 2010 Digest*, p. 470.

[2] K. Szymaniec, S.E. Park, “Primary frequency standard NPL-CsF2: optimised operation near the collisional shift cancellation point”, *IEEE Trans. Instrum. Meas.* (submitted).

[3] 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 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)	04 Dec 2009 – 29 Dec 2009	29 Dec 2009 – 28 Jan 2010
Start	MJD	55169	55194
Stop	MJD	55194	55224
Duration	days	25	30
duty cycle	%	99.9	92.1
Biases:	×10^{-15}		
2nd order Zeeman		337.67	337.67
BBR shift		–16.60	–16.62
cold collisions		0.33	0.09
gravity		1.30	1.30
y(CsF2 - HM2)	×10^{-15}	**–10.17**	**–8.11**
u_A	×10^{-15}	0.19	0.18
u_B	×10^{-15}	0.40	0.40
$u_{l/lab}$	×10^{-15}	0.01	0.10
$\boldsymbol{u_{total}}$	×10^{-15}	**0.45**	**0.45**