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Attached is the report on accuracy evaluation by our caesium atomic fountain primary frequency standard NICT-CsF1 performed over the 10 days period of MJD 54534 to 54544. The detail of the evaluation is discussed in this report.

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1. Evaluations of primary frequency standard NICT-CsF1

Interval	MJD 54534 UTC 0:00 - 54544 UTC 0:00 (10days)
Cycle duty	98.3%
Frequency difference	Y(NICT-CsF1 – UTC(NICT)) = $+9.4 \cdot 10^{-15}$
Type B uncertainty u_B	$1.5 \cdot 10^{-15}$
Type A uncertainty u_A	$1.0 \cdot 10^{-15}$
Link to clock $u_{link/lab}$	$0.3 \cdot 10^{-15}$
Link to TAI $u_{link/TAI}$	$0.9 \cdot 10^{-15}$ (10 days, estimated value)
Combined uncertainty	$2.0 \cdot 10^{-15}$ (estimated)

A brief description of the various biases and uncertainties is presented in the following sections of this report. A detailed description of NICT-CsF1 and the uncertainty evaluation is given in [1].

2. Frequency Measurement of NICT-CsF1

In CsF1, the interrogated microwave frequency is locked to the narrow Ramsey resonance by the frequency modulation locking method. Using the result of one cycle, the microwave frequency f_0 is controlled by steering the output frequency of the synthesizer so that the signal intensities at the two toggled frequencies should be equal. The series of the frequency f_0 are recorded as the frequency realized by CsF1 against the hydrogen maser. At present, the data of our hydrogen maser is not reported to the BIPM. The frequency difference between the hydrogen maser and UTC(NICT) is obtained from time comparison of 1pps signal by a time-interval counter. Combining two differences, the frequency difference between NICT-CsF1 and UTC(NICT) is obtained and reported.

During campaigns, CsF1 is operated at two different atomic number densities in the alternative mode to correct for the collisional shift. The bias of the collisional shift is calculated using 1 day (exactly 85800 seconds) averaging data everyday. The transition frequency of (F=4, m_F =1) – (F=3, m_F =1) transition is tracked for 10 minutes everyday to check the unexpected variation of the magnetic field. The other corrected biases are checked before and after the campaign. Finally, all biases-corrected value is obtained by averaging 10 sets of 1 day averages.

3. Systematic (Type B) Uncertainty of NICT-CsF1

As for the uncorrected shifts, the biases and uncertainties are the same as those described in the last report.

A. Second-order Zeeman shift

Before and after the evaluation campaign, we measured the central frequency of the (F=4, m_F =1) – (F=3, m_F =1) transition and made a map of the time-averaged magnetic field $\langle B \rangle$ over atomic path. The variance in time of C-field is less than 1%. The offset due to the magnetic inhomogeneity is on the order of 10^{-19}, which is practically negligible. By this field mapping, we measured the central frequency of the (F=4, m_F =1) – (F=3, m_F =1) transition at practical operation as 890.7Hz with respect to the clock transition, which determined the second-order Zeeman shift of 75.1×10^{-15}. The uncertainty of the second-order Zeeman shift is dominated by the temporal instability of B. In this campaign, the temporal variation of the monitored transition frequency over 10 days is 0.7Hz, leading to an uncertainty of less than 1×10^{-16}.

B. Collisional Shift

From the previous results, we estimate the frequency shift due to the cold collisions with 20% uncertainty. This large uncertainty is attributed to the fact that the number of the launched atoms is not counted directly but estimated indirectly from the signal intensity of the fluorescence induced by the probe laser. During the measurement campaign, we do not use the historical slope constant for the zero-density extrapolation. CsF1 is operated alternatively with two different atomic number densities (high and low densities) to correct for the collisional shift at each measurement. The averaged value is -6.3×10^{-15} and then the associated uncertainty is 1.3×10^{-15} in this campaign.

C. Black Body Radiation Shift

The frequency shift due to a black body radiation is given by [2]

$$\frac{\Delta\nu_{BBR}}{\nu_0} = -1.717\times10^{-14}\left(\frac{T}{300}\right)^4 \times \left[1+0.013\left(\frac{T}{300}\right)^2\right].$$

CsF1 is operated at 298 K in equilibrium, which generates a bias of -16.9×10^{-15}. Considering the thermal gradient and the thermal conductivity, we estimate an uncertainty of 0.4×10^{-15} corresponding to ± 2 K.

D. Gravitational Red Shift

The height of CsF1 is measured as 114.7m in the GRS80 reference flame, which corresponds to 76.6m above the geoid surface. Here we used Japanese geoid model ‘GSIGEO2000’[3]. The frequency bias due to the gravity potential is calculated to be 8.4×10^{-15}. Considering lunar and solar tidal displacement of the Earth’s crust, we estimate the uncertainty in this shift to be 1×10^{-16}.

E. Microwave-Power Dependence Shift

In our estimation, the microwave power dependent shift is classified into two types; a term linear dependent on the microwave power and an oscillating term dependent on the microwave amplitude with referring to [4], [5], [6]. By the least square fitting with two contributions, the microwave power dependent shift to due to several effects at the amplitude of $\pi/2$ is estimated to be -2.1×10^{-15} with a standard deviation of 0.2×10^{-15}. Considering that the measurement points are not so many, from the aspect of freedom degree of the fitting, we make a modest estimation of an uncertainty of 0.3×10^{-15}.

4. Statistic (Type A) Uncertainty

The frequency stability of CsF1 is typically $5\times10^{-13}/\tau^{1/2}$. Suppose the FM white noise covers over the campaign period, the statistic uncertainty for 10 days period becomes the order of 10^{-16}. However, it is difficult to prove it because of the drift of the hydrogen maser. In CsF1, it has been confirmed that the flicker noise floor is no higher than 1.0×10^{-15} by the alternative operation, free from the instability of the reference. From this result, we estimate the Type A uncertainty to be 1.0 $\times 10^{-15}$ conservatively.

5. Uncertainties of Link

The uncertainty $u_{\mathrm{link/lab}}$ of the link to the local time scale, UTC(NICT) is given by a quadratic sum of the uncertainties associated with the frequency transfer between CsF1 and UTC(NICT), and the additional uncertainty due to the dead time during the evaluation campaign. As for the former, the uncertainties come from a measurement accuracy of time-interval counter and link cable fluctuation. There effects are estimated as 3×10^{-16} at most. As for the latter, in this time, the dead time is kept below 3%, which introduces the uncertainty of less than 1×10^{-16}. We evaluate the combined uncertainty associated with the link to be 3×10^{-16}.

The uncertainty in the link of a frequency transfer to TAI is calculated based on the recommendation from the Working Group on Primary Frequency Standards [7]. In this case, the uncertainty $u_{\mathrm{link/TAI}}$ is estimated to be 0.9×10^{-15} (for 10 days period).

Table.1. Summary of the systematic frequency biases and their uncertainty budgets of NICT-CsF1.

Physical Effect	Bias	Uncertainty
2nd Zeeman	75.1	<0.1
Collision (averaged)	-6.3	1.3
Blackbody Radiation	-16.9	0.4
Gravity Potential	8.4	0.1
MW-PW dependence	-2.1	0.3
Cavity Pulling	0.0	<0.1
Rabi Pulling	0.0	<0.1
Ramsey Pulling	0.0	<0.1
Spectral impurities	0.0	<0.1
Light Shift	0.0	<0.1
Distributed cavity phase	0.0	0.3
Majorana	0.0	<0.1
Background Gas	0.0	0.3
Total (Type B)		1.5

units are fractional frequency in 10^{-15}

Reference

[1] Kumagai M, Ito H, Kajita M, and Hosokawa M, 2008 *Metrologia*, 45, 139-148

[2] Rosenbusch P, Zhang S, and Clairon A, 2007 *Proc. Euro. Freq. Time Forum*, Geneva, 1060–1063

[3] Nakagawa H, Wada K, Kikkawa T, Shimo H, Andou H, Kuroishi Y, Hatanaka Y, Shigematsu H, Tanaka K, Fukuda Y 2003, *Bulletin of the Geographical Survey Institute* 49, 1

[4] Jefferts S R, Shirley J H, Ashby N, Burt E A, Dick G J 2005 *IEEE Trans. Ultraso. Feroel. Freq. Cont*. 12 2314-2321

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

[7] Parker T, Report to the 17th Session of the CCTF, CCTF/06-13, 2006.