# Frequency evaluation of HM1405628 by KRISS-Yb1 for the period MJD 58994 to MJD 59029

The frequency of the hydrogen maser HM1405628 was evaluated during the period MJD 58994 – 59029 (May. 25, 2020 – Jun. 29, 2020) using the Yb optical lattice frequency standard KRISS-Yb1 and an optical frequency comb. The KRISS-Yb1 absolute frequency was assumed to be the most recently recommended BIPM value: 518,295,836,590,863.6 Hz [1]. The results of the evaluation are given in the table below. More details of the KRISS-Yb1 operation and the uncertainty budget can be found in Ref. 2.

## 1. Results

(a) Results of the frequency evaluation in $1\times10^{-16}$

| Period (MJD) | $y$(HM1405628 – KRISS-Yb1) | $u_A$ | $u_B$ | $u_{A/Lab}$ | $u_{B/Lab}$ | $u_{SecRep}$ | Uptime (%) |
|---|---|---|---|---|---|---|---|
| 58994 – 59029 | -2744.30 | 0.07 | 0.37 | 4.87 | 0.69 | 5 | 6.5 |

(b) Budget of uncertainties in $1\times10^{-16}$

| | | |
|---|---|---|
| $u_A$ | Yb statistics | 0.07 |
| | **$u_A$ total** | 0.07 |
| $u_B$ | Yb systematics | 0.16 |
| | Gravitational redshift (1) | 0.33 |
| | **$u_B$ total** | 0.37 |
| $u_{A/Lab}$ | Yb-HM comparison | 3.28 |
| | HM drift | 0.17 |
| | Dead time in HM –Yb | 3.59 |
| | **$u_{A/Lab}$ total** | 4.87 |
| $u_{B/Lab}$ | Frequency comb (2) | 0.69 |
| | **$u_{B/Lab}$ total (3)** | 0.69 |

(1) The height of Yb atoms in the optical lattice of KRISS-Yb1 from the conventionally adopted geoid

potential (62 636 856.0 $m^2/s^2$) was measured to be 74.66(9) m. The height from the earth ellipsoid (WGS84) [3] was measured by a GPS antenna and orthometric height leveling. The geoid undulation was obtained by a regional geoid model KRGG14, which is based on the Earth Gravitational Model (EGM2008) [4] and utilizes gravity measurement data for regional geoid undulation determination. The offset of the EGM2008 geoid potential from the conventionally adopted geoid potential was considered [5]. The overall height uncertainty was conservatively estimated by the quadratic sum of uncertainties from the local geoid model (7 cm), the interpolation with the discrete local geoid data (3 cm), the GPS measurement (3 cm), the spirit levelling measurement (0.1 cm), and the omission error of EGM2008 (4 cm, [6]). The uncertainty of the local geoid model was conservatively estimated to be 7 cm by taking the standard deviation of the difference between EGM2008 and KRGG14. It is expected that the tidal effect will be averaged out to be small because of the long duration of the measurement campaign. However, because KRISS-Yb1 is operated only intermittently, the average out of the tidal effect might not be sufficient in ~30 day measurement. Thus, we conservatively took typical variations from tides to be 0.3 m [7]. Accordingly, the gravitational shift was conservatively estimated to be $81.4(3)\times10^{-16}$, considering the tidal effect.

(2) The systematic uncertainty of the frequency conversion by the optical frequency comb from RF to optical frequency was estimated by comparing the simultaneous measurement of the 1156 nm clock laser by two similar optical frequency combs. The weighted mean of the measurement values of the difference between the two comb systems was $6.6(6.9)\times10^{-17}$. There was no difference between the two comb measurements within the uncertainty. The uncertainty was statistically limited despite long total measurement time because the combs were referenced to a hydrogen maser.

(3) $u_B$/Lab caused by the cables distributing the hydrogen maser signal was ignored. The HM reference signal was located in the same building as KRISS-Yb1 and most part of the cable path was in the temperature-stable laboratory. Also, we used cables with low sensitivity to the temperature variation. Thus, it is expected that the systematic uncertainty due to the cable is negligible. We evaluated the effect from the cable by measuring the frequency difference between the original HM reference signal and the round-tripped signal (using the two cables of same type along the same path between KRISS-Yb1 and HM). The measured frequency difference is less than the statistical uncertainty, which is given by the Allan deviation value of $2.5\times10^{-18}$ at 100 000 s. There was no bump for the diurnal thermal cycle. Instead we observed a bump of $4\times10^{-16}$ at about 500 s due to the room temperature control cycle of about 1000 s. As we did not perform the experiment at fixed time of the day and the typical duration of the experiment was several tens of thousand seconds, it is expected the effect of the ~500-s-moduation of the cable should be averaged out to zero.

## 2. KRISS-Yb1 operation

The uncertainty budget for KRISS-Yb1 for the reported period is given below [2]

| Effect | Relative shift ($\times 10^{-17}$) | Relative Uncertainty ($\times 10^{-17}$) |
|---|---|---|
| Density shift | -0.3 | 0.1 |
| Lattice Stark shift | 0.03 | 0.3 |
| Quadratic Zeeman shift | -6.7 | 0.1 |
| Blackbody radiation | -232.0 | 1.1 |
| DC Stark shift (4) | 0.0 | 1.0 |

| | | |
|---|---|---|
| Background gas shift (5) | -1.5 | 0.2 |
| Probe light shift | 0.1 | 0.03 |
| Servo error | 0.0 | 0.3 |
| Line pulling | 0.0 | 0.1 |
| AOM chirp | 0.0 | 0.3 |
| **Yb Total** | -240.4 | 1.6 |

(4) The evaluation of the DC Stark shift would be clearest if we could apply external DC electric field to the trapped Yb atoms. However, this was not possible because our vacuum chamber is made of a solid lump of stainless steel with 9 long and narrow bores (the largest bore diameter is about 35 mm), the external electric fields are attenuated by a factor of > $10^4$, which was estimated by a numerical simulation. However, the advantage of this Faraday shield is that the Yb atoms are insensitive to the electric fields outside the vacuum chamber including the DC electric field due to the charge on dielectric material outside the chamber. The only dielectric material inside the vacuum chamber are two lenses, which are 34.6 mm away from atoms. In our 2017 paper [8], we estimated the electric charges on these lenses would decay with time constant of about 90 days. Since the vacuum installation was done more than 6 years ago (~24 times of the decay time constant), it is estimated the possible Stark shift from the remaining charges is much below $1\times10^{-17}$ if there was no further accumulation of charges. We conservatively took the uncertainty of the DC Stark shift to be $1\times10^{-17}$ as we didn't measure the DC Stark shift directly. Initially, before the experiment for our 2017 paper, we irradiated UV light into the vacuum chamber through the lens pair to make it certain that there was no charge on the lenses. We cannot completely exclude the possibility of charges could newly accumulate. Because we do not have another Yb clock running now, it is not possible to observe the effect of the newly accumulated charges if the charge amount is small. We can estimate the upper limit of the possible DC Stark shift by investigating the Yb frequency with uptime, assuming that the laser exposure is the dominant reason for the generation of the charges. If we assume the new charges happen to be added on the lenses (by the photoelectric effect or the photo-ionization, for example), the steady-state charge on the lenses will be proportional to the rate of the new charge deposition and the charge decay constant. It is expected that the new charge deposition rate should be proportional to the uptime of the optical clock operation. Accordingly, the electric field due to the new charge will be proportional to the clock uptime, and the DC Stark shift will be proportional to the square of the uptime. In August 2021, the operation time of the optical clock was 40%, which includes the experiments for the absolute frequency measurement and also for the systematic evaluation. The absolute frequency in August 2021 was different from the CIPM recommended value by $2.5\times10^{-16}$ with the uncertainty of $5.3\times10^{-16}$. For the total measurement campaign for our 2021 paper [2], the average uptime was 5.7% and the f(Yb/SI) was $2.9\times10^{-16}$ from the CIPM recommended value with the uncertainty of $2.6\times10^{-16}$. When we compare the two results, there is no frequency difference within the uncertainties of the two measurements. The uptime ratio between the two measurements is 7.0 and there should be 49 times larger DC Stark shift in the 2021 August measurement, but the shift was not noticeable. Thus, it can be inferred that the upper limit of the DC Stark shift in August 2021 is given by the frequency measurement uncertainty of $5.3\times10^{-16}$, and the upper limit of the DC Stark shift for the total measurement campaign will be 49 times lower ($1.1\times10^{-17}$). Thus, it can be concluded that the estimated uncertainty of the DC Stark shift is not underestimated even in the worst case.

(5) The background gas was dominated by $H_2$, which was determined by a residual gas analyzer. This shift was known to be proportional to the trap loss rate. We took the coefficient to be $1.6(3)\times10^{-17}$ s from the INRIM work [9], in which the uncertainty includes possible contributions from Yb-Yb collisions as well as Yb–$H_2$ collisions.

## 3. Frequency measurement

The optical lattice clock was operated for 195,083 s (6.5% of the total evaluation period). We compared the frequency of KRISS-Yb1 with the frequency of one of the H masers used in the TAI computation (HM1405628 (BIPM code 1405628) during the period MJD 58864 – 59029 and HM1405626 (BIPM code 1405626) during the period MJD 59029 – 59299) using an optical frequency comb and a multi-channel dual-mixer time difference (DMTD) measurement system.

The mean fractional frequency deviation of the hydrogen maser over the evaluation period was obtained by the extrapolation of the frequency measurement data to the midpoint of the evaluation period considering the hydrogen maser frequency drift. The frequency drift of the hydrogen maser for each evaluation period was obtained using the clock comparison data relative to TT for 3~4 months (including the previous and the next month of the evaluation period). The dead time uncertainty due to the intermittent measurement was estimated using the experimentally determined noise model of the hydrogen maser; white phase noise $1.0\times10^{-13}$ $(\tau/s)^{-1}$, white frequency noise $1.2\times10^{-13}$ $(\tau/s)^{-1/2}$, and flicker frequency noise $3\times10^{-16}$. The uncertainty $u_A$ is the uncertainty originating from the instability of KRISS-Yb1, which was evaluated by interleaved measurements. The uncertainty $u_B$ is the sum of the Yb systematic uncertainty for the reported period and the uncertainty of the gravitational redshift relative to the conventional geoid potential $W_0$ = 62 636 856.0 $m^2s^{-2}$. The uncertainty $u_{A/Lab}$ is given by the square root of the square sum of the statistical uncertainties from the frequency comb measurement, the hydrogen maser drift compensation and the dead-time of the Yb clock measurement. The uncertainty $u_{B/Lab}$ is the systematic uncertainty in the comb link between the HM microwave signal and the Yb optical frequency signal, and was evaluated by comparing the simultaneous measurement of the 1156 nm clock laser by two similar optical frequency combs.

## References

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