NTSC
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Frequency comparison between H-maser 1415085 and NTSC-Sr2 for the period MJD 61009 to 61039

The secondary frequency standard NTSC-Sr2 has been compared to the local Hydrogen Maser 1415085, during the period MJD 61009-61039 (30th November 2025-30th December 2025). The optical clock operation covers 14% of the total measurement period. The mean frequency difference at the middle date of the period and associated uncertainties are summarized in the following table:

Table 1. Results of the frequency comparison in 1×10^{-16}

Period (MJD)	y(H-maser 1415085-NTSC-Sr2)	Uptime (%)	u_A	u_B	$u_{A/lab}$	$u_{B/lab}$	u_{SecRep}
61009-61039	1476.47	14	0.01	0.55	3.9	0.2	1.9

The calibration is made using recommended value for $^1S_0$-$^3P_0$ unperturbed optical transition in the ^{87}Sr neutral atoms: 429 228 004 229 872.99 Hz (2021 CCTF).

u_B is the ^{87}Sr optical lattice clock (OLC) systematic uncertainties (including gravitational redshift).

u_{SecRep} is the recommended uncertainty of the secondary representation (22nd CCTF in 2021).

The specific operation of NTSC-Sr2 OLC is shown in reference [1] and here we briefly summarize: After two-stages of laser cooling, approximately 1000 atoms are loaded in an inclined one-dimensional optical lattice with a trap depth of 39.8 E_R (E_R is the photon recoil energy of the lattice light). The lattice is inclined at 75° relative to the direction of gravity to suppress tunneling effect. The lattice light wavelength about 813.4278 nm is stabilized to the optical frequency comb (OFC). The repetition frequency (f_r) of the OFC is phase-locked to the clock laser, while its carrier-envelope offset (f_{ceo}) is stabilized relative to the hydrogen maser (HM) reference. The clock laser is phase-locked to a 20 cm-long ultralow expansion (ULE) cavity and delivered into the magneto-optical trap (MOT) chamber through a fiber with active fiber phase noise cancellation. An actively temperature-controlled blackbody radiation (BBR) shield is placed in the MOT chamber to provide a stable and uniform ambient temperature for atoms during clock transition interrogation.

During in-loop operation of the NTSC-Sr2 OLC, the clock laser delivered to the OFC is corrected in real time for systematic frequency shifts. After dividing the f_r by a factor of 20 using a frequency divider (FMFD20000), it is measured using a phase noise analyzer (Microchip, 53100A). The beat frequency ($f_{b,c}$) between the N_cth OFC tooth and the clock laser, as well as f_{ceo}, are simultaneously recorded by a multi-channel frequency counter (K+K FXE). Both the multi-channel frequency counter and the 53100A are referenced to the 10 MHz HM signal. The frequency of the NTSC-Sr2 OLC is given by $2f_{ceo}+f_{b,c}+N_c\times f_r$.

Average frequency and statistical uncertainty u_A

Following the exclusion of outliers, a linear regression is performed on the dataset from the entire reporting interval. The mean frequency is subsequently determined by evaluating the resulting fit at the midpoint of the interval.

The clock stability, shown in figure 1, is determined to be 3.6×10^{-16} $(\tau/s)^{-0.5}$ using the interleaved self-comparison method. Thus, the statistical uncertainty, u_A, is estimated to be 1×10^{-18}.

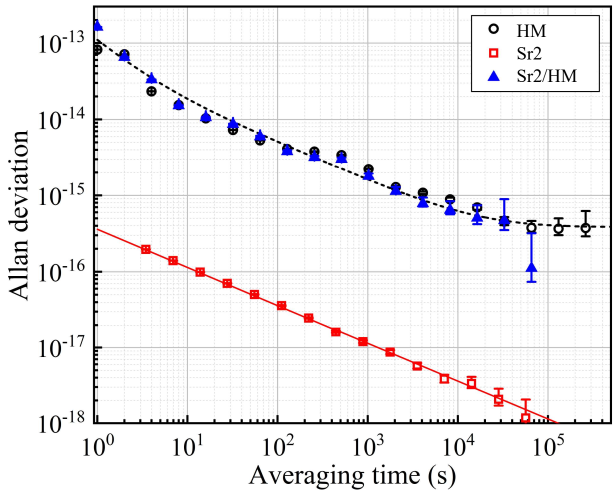

Figure 1. Stabilities of the HM 1415085 and NTSC-Sr2 OLC. The stability of Sr2/HM is determined by the residual values obtained after subtracting the linear fit from the HM frequencies measured by NTSC-Sr2 between MJD 61009 and 61039. The black dashed line shows the HM noise model and the red solid line represents a linear fit of the data with a slope of -0.5.

Systematical uncertainty u_B

Table 2 summarizes the corrections of the systematic frequency shifts and corresponding uncertainties, which also include the gravitational redshift. All known systematic shifts of the NTSC-Sr2 OLC have been carefully evaluated and detailed discussions are provided in reference [1]. Real-time corrections are applied for the density and second-order Zeeman shifts, with the average magnitudes of these corrections summarized in table 2. To ensure a more robust error budget, the uncertainty contribution from the background gas collision shift has been deliberately set to three times the value reported in reference [1]. The gravitational redshift can be given by $-(W-gh-W_0)/c^2$, where W=62636852.95 m^2s^{-2} is the gravitational potential at the mean sea level at the tide gauge station in Qingdao, China and W_0=62636856.00 m^2s^{-2} is the zero-reference potential for TT/TAI. g=9.79456(1) ms^{-2} is the local gravitational acceleration due to gravity derived from FG5-X absolute gravimeter measurement and h=481.22(50) m is the geoid height of the lattice from the earth ellipsoid (WGS84), traced to NTSC leveling benchmark relative to the China 1985 national height datum. The gravitational redshift correction is calculated to be -52476.90×10^{-18}, with an uncertainty of 54.49×10^{-18}. The total systematic uncertainty, u_B, is determined to be 0.55×10^{-16}.

Table 2 Budget of systematic effects and uncertainties for NTSC-Sr2 OLC for the MJD 61009 – 61039 period

Systematic effect	**Correction (10^{-18})**	**Uncertainty (10^{-18})**

BBR	3608.59	0.7
Lattice AC Stark	0.41	1.56
Density	4.89	0.43
Background gas	6.38	1.92
1st order Zeeman	0	<0.1
2nd order Zeeman	86.50	0.11
First order Doppler	0	0.5
DC Stark	0	<0.1
Tunneling	0	<0.1
Line pulling	0	<0.1
Servo error	0	0.12
Probe AC Stark	0	<0.1
AOM phase chirp	0	<0.1
Total	**3706.77**	**2.66**
Gravitational redshift	-52476.90	54.49
Total (with gravitational redshift)	**-48770.13**	**54.55**

Uncertainty of the link

The statistical uncertainty of link $u_{A/lab}$ accounts for the dead time in the comparison between HM and the NTSC-Sr2 OLC, as well as the phase fluctuation introduced by the cable that connect the HM and frequency standard.

Since the NTSC-Sr2 OLC cannot achieve completely continuous operation, there is dead time in the frequency comparison process between the NTSC-Sr2 OLC and HM, which brings about frequency shift and uncertainty. The uncertainty caused by dead time is quantified by simulating the HM noise model. As shown in figure 1, the frequency instability of the HM is determined by compared with another HM (HM 1415082) modeled by four noise contributions, including a white phase noise of 9.84×10^{-14} $(\tau/s)^{-1}$, a white frequency noise of 5.01×10^{-14} $(\tau/s)^{-0.5}$, a flicker frequency noise of 3.75×10^{-16} $(\tau/s)^{0}$ and a random walk frequency noise of 1.04×10^{-19} $(\tau/s)^{0.5}$. Based on this HM noise model, 1000 noise sequences were generated, each with a total length of 86400×30 points. The frequency difference between the average value of the uptime data and that of the full dataset was recorded for each sequence. The dead-time uncertainty was then determined by calculating the 1σ standard deviation of the distribution of all these frequency differences. In terms of an operating uptime of 14%, the extrapolation uncertainty of the HM frequency average over time period of MJD 61009 – 61039 is evaluated to be 3.9×10^{-16}.

The phase fluctuation resulting from the cables connecting HM to the OLC lab could introduced an uncertainty. It is conservative estimated to be 0.5×10^{-16} according to the results of loop-back measurements. The total statistic uncertainty of link $u_{A/lab}$ is 3.9×10^{-16}.

The systematic uncertainty of link $u_{B/lab}$ mainly primarily originates from the HM link, the optical comb, and the counter.

Daily delay variations in the transferred HM signal may introduce measurement error, known as the diurnal effect. Based on loop measurements, an uncertainty of 2×10^{-17} is adopted to conservatively characterize the possible contribution from this effect.

The frequency uncertainty resulted in the counter (53100A) is determined to be 3.3×10^{-18}.

The out-of-loop stability of the OFC corresponds to 2.9×10^{-16} $(\tau/s)^{-0.7}$, resulting in an uncertainty of less than 1×10^{-18}.

The total systematic uncertainty of link $u_{B/lab}$ is estimated to be 2.03×10^{-17}.

References

1. Xiao-Tong Lu *et al*. 2025, Metrologia, 62: 035007.