Frequency evaluation of the hydrogen maser H9 of PTB (1400509) between MJD 60854 and MJD 60884 using the single-ion optical frequency standard PTB-Yb1E3

During the period MJD 60854 – 60884 (28 June 2025 – 28 July 2025), we evaluated the frequency of the hydrogen maser PTB H9 (BIPM code 1400509) using the secondary frequency standard PTB-Yb1E3 that employs the $^2S_{1/2}$ (F=0) – $^2F_{7/2}$ (F=3) electric octupole (E3) transition of ^{171}Yb$^+$ as the reference. The evaluation is based on the CCTF 2021 recommended frequency for this transition as a secondary representation of the second, f(^{171}Yb$^+$, E3) = 642 121 496 772 645.18 Hz with a relative standard uncertainty of $u_{\mathrm{Srep}} = 1.7 \times 10^{-16}$ [1]. The results of the evaluation are summarized in Tab. 1. Details on the optical frequency standard, its uncertainty budget and the employed infrastructure are given in Refs. [2-4] and shortly summarized below.

Table 1: Results of the comparison of hydrogen maser H9 (1400509) and PTB-Yb1E3

Evaluation period (MJD)	y(H9 – PTB-Yb1E3) (10^{-15})	u_{A} (10^{-15})	u_{B} (10^{-15})	$u_{\mathrm{A/Lab}}$ (10^{-15})	$u_{\mathrm{B/Lab}}$ (10^{-15})	u_{Srep} (10^{-15})	Uptime
60854 – 60884	-55.15	0.00	0.00	0.02	0.01	0.17	84.23%

Frequency evaluation

To evaluate the frequency of the hydrogen maser, we employ optical frequency combs as described in Ref. [2]. In this way, we compare the optical output signal of PTB-Yb1E3 and the 100 MHz radio frequency (rf) output signal of PTB's maser H9. Comparisons between measurements performed with different frequency combs inside the same laboratory indicate frequency differences well below 10^{-17}. We also performed comparisons with a frequency comb located in a separate building at about 200 m distance from the other two frequency combs via optical and rf link. With a 10^{-17} systematic uncertainty to account for phase distortions of the rf signal distribution over 30-day measurements, we find consistent frequency measurement results between all frequency combs. All frequency counters used are dead-time free and use a common reference for synchronization of the measurement intervals. Based on these investigations, we consider the systematic uncertainty from the link between optical frequency standard PTB-Yb1E3 and hydrogen maser H9 $\left(u_{\mathrm{B/Lab}}\right)$ to be 10^{-17}.

Frequency standard PTB-Yb1E3

The optical frequency standard PTB-Yb1E3 has been described in Ref. [4] with further details published in an earlier work [3]. In addition to the uncertainty as published in Ref. [4], frequency shifts from radio-frequency magnetic fields have been evaluated following Ref. [5] and have been added to the uncertainty budget. The electric quadrupole shift is determined using spectroscopy of the $^2S_{1/2}$ (F=0) – $^2D_{3/2}$ (F=2) electric quadrupole (E2) transition and found to be constant within the given uncertainty over periods of years. The spectroscopy of the E2 transition is regularly performed interleaved to that of the E3 transition, see Ref. [6] for details. In contrast to previous published works [3,4] the dc magnetic field has been adjusted, which causes the difference in the corresponding frequency shift.

The relativistic redshift was determined relative to the reference potential W_0 = 62 636 856.0 m^{2}s^{-2} [7].

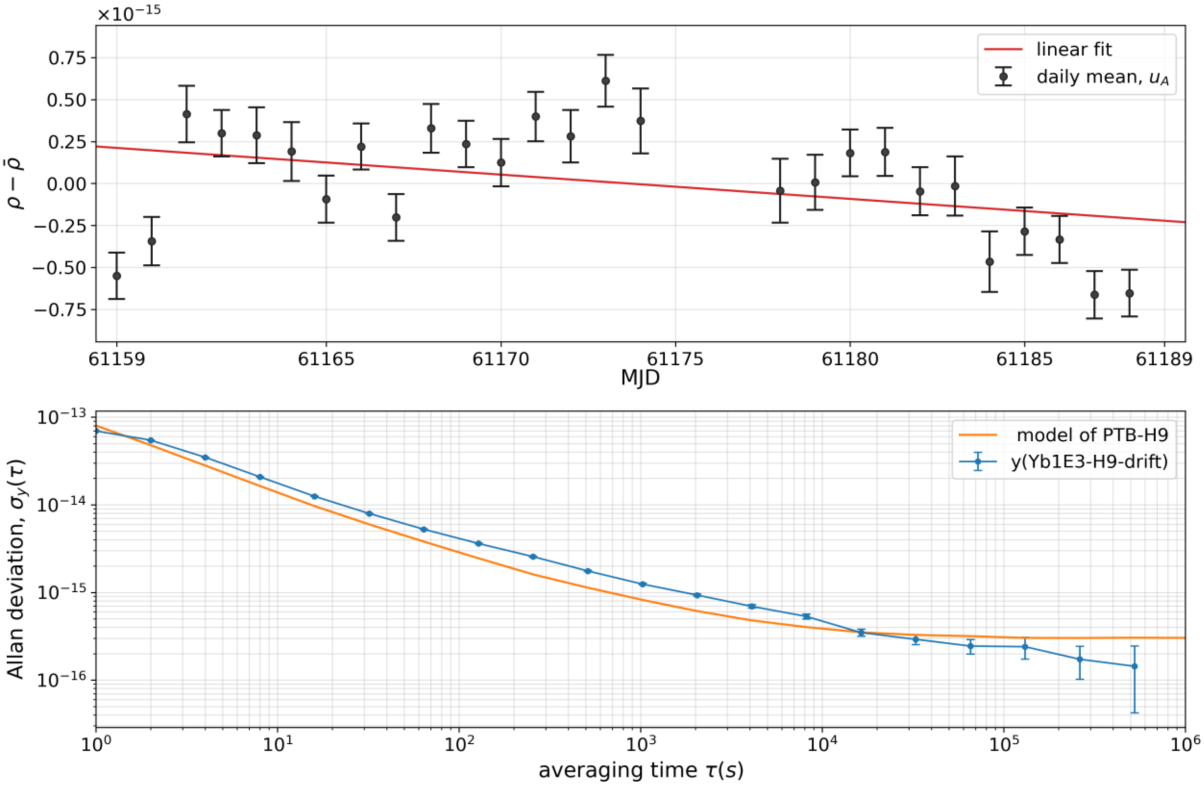
Because of the $10^{-15}/\sqrt{\tau(\mathrm{s})}$ frequency instability of the optical frequency standard, the statistical uncertainty u_A is well below 10^{-17} and significantly smaller than the statistical uncertainty resulting from dead times in the comparison. We estimated the corresponding uncertainty $u_\mathrm{A/Lab}$ using the model described in Ref. [8]. For this, we modeled the noise of H9 of PTB with flicker phase modulation (7×10^{-14}), white frequency modulation (2.4×10^{-14}) and flicker frequency modulation (3×10^{-16}).

All relevant systematic frequency shifts of PTB-Yb1E3 are summarized in Tab. 2. The frequency of the optical frequency standard has been corrected for these shift effects. The PTB-Yb1E3 standard uncertainty u_B is estimated as 3.6×10^{-18} for the relevant period.

Table 2: Relevant systematic frequency shift effects and corresponding systematic uncertainties for PTB-Yb1E3.

Effect	Shift (10^{-18})	Uncertainty (10^{-18})
Second-order Doppler	-2.3	1.5
Blackbody radiation	-71.6	1.8
Probe light	0.0	0.8
Second-order Zeeman (dc)	-28.8	0.2
Second-order Zeeman (ac)	0.6	0.6
Quadratic dc Stark	-0.8	0.6
Quadrupole	-4.4	0.5
Background gas	0.0	0.5
Servo	0.0	0.2
Total	-107.3	2.7
Relativistic redshift	8487.4	2.4
Total incl. rel. redshift	8380.1	3.6

Figure 1: The upper figure shows the daily mean fractional frequency deviation ρ from the mean frequency $\bar{\rho}$ over the measurement interval. The red line is a linear approximation to the data. The lower figure indicates the Allan deviation for different averaging times τ(s). The orange line shows the frequency instability of the model employed to describe the noise of the hydrogen maser H9 of PTB (1400509).



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