Frequency comparison NRC-SrIOC1 – SM1
For the period MJD 57914 – 57924

Frequency comparison of the $^{88}Sr^+$ secondary frequency standard NRC-SrIOC1 (1780301) have been made with respect to an active H-maser SM1 (1400306) during evaluation campaign of MJD 57914 – 57924. Table 1 below summarizes the evaluation result as well as the associated uncertainties.

Table 1: Summary of results

Evaluation period (MJD)	57914 – 57924
Fractional uptime	22.0%
y(SM1 – SrIOC1) [10^{-15}]	55.9008
u_A (1 σ) [10^{-15}]	0.0069
u_B (1 σ) [10^{-15}]	0.0117
U_{l_lab} (1 σ) [10^{-15}]	0.3391
u_{total} [10^{-15}]	0.3393

Methods

The influence of systematic effects of the $^{88}Sr^+$ secondary frequency standard NRC-SrIOC1 was investigated in [1]. Effects for which NRC-SrIOC1 is corrected are:
- blackbody radiation field
- thermal motion
- quadratic Zeeman shift
- collisional frequency shift
- 1092 nm ac Stark shift
- 674 nm ac Stark shift
- 422 nm ac Stark shift
- gravitational redshift

Several other systematic effects did not produce a measurable bias and are therefore uncorrected for, but do contribute to the overall uncertainty of SrIOC1 and are included in the uncertainty budget. A full uncertainty budget for the evaluation period of MJD 57914 – 57924 is given in Tab. 2.

The operating procedure of SrIOC1 is described in detail in [1]. A femto-second Er:fiber frequency comb system referenced to the H-maser VM1 (1400307) was used for the frequency measurement of the SrIOC1 clock transition frequency. The frequency comb system was firstly referenced to the H-maser SM1 (1400306) for the first three days of the measurement (MJD 57916 – 57919) and was referenced to the H-maser VM1 (1400307) for the rest of the measurement. We converted the frequency measurement data against SM1 to that against VM1 by using the frequency difference data between SM1 and VM1 from a 100 MHz phase comparator. In this way, the frequency evaluation can be made with respect to VM1 as a single flywheel oscillator and a low dead time uncertainty can be obtained thanks to the superior stability of VM1. Details can be found in ref [1]. The intermittent frequency measurement had a total uptime of 52.7 h which is 22% of the frequency evaluation period from 57914 – 57924. The fractional frequency offset of SrIOC1 was calculated with respect to the CIPM 2021 recommended value for $^{88}Sr^{+}$ ion clock transition, i.e., 444 779 044 095 486.3 Hz [3]. The frequency measurement data was firstly corrected for the systematic shifts of SrIOC (Tab. 2) and a weighted linear fit was used to find the average frequency for the frequency evaluation period (Fig. 1). We finally converted the frequency evaluation of SrIOC1 against VM1 to that against SM1 using the continuous phase measurement data between VM1 and SM1 for the period of MJD 57914 – 57924.

Uncertainties

Type A uncertainty

The typical long-term stability of SrIOC1 follows $\sigma_y = 3 \times 10^{-15}/\sqrt{\tau}$ where σ_y is the Allan deviation and τ is the averaging time (Fig. 2) [2]. The reported value for type A uncertainty, u_A, is calculated from $u_A = 3 \times 10^{-15}/\sqrt{\tau} = 6.9 \times 10^{-18}$ with τ = 189734 s the averaging period.

Type B uncertainties

The exhaustive list taken from Ref. [1] is given in Tab. 2.

Link to local timescale

The uncertainty of the link with our local reference VM1, $u_{A,\,Lab}$, is the sum of two terms added in quadrature (Tab. 3). The first term is the statistical uncertainty of the frequency comb system used for the measurement and it was estimated as 1.5×10^{-16} [1]. The second term was attributed to the measurement deadtime and calculated following the procedure described in [1]. It is calculated using the uptime distribution and the noise model of the flywheel oscillator VM1 of WPM $3.5 \times 10^{-13}\,\tau^{-1}$, WFM $0.8 \times 10^{-13}\,\tau^{-1/2}$, and FFM 3.0×10^{-16}. The 100 MHz phase comparator (PCO) data between VM1 and SM1 was used to convert the frequency evaluation of SrIOC1 against VM1 to that against SM1 and the noise of the PCO was negligible.

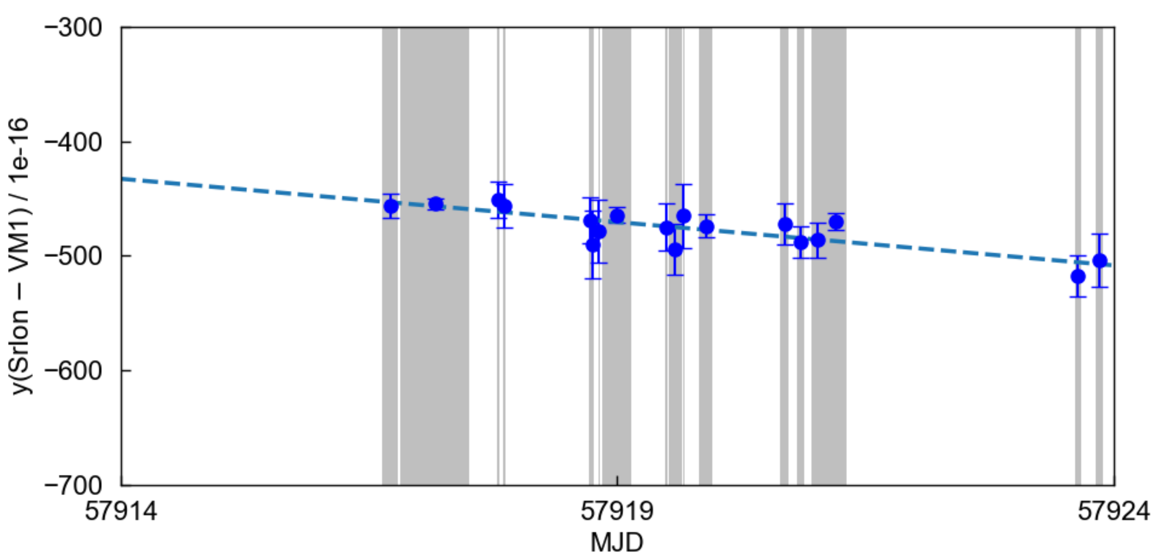

Fig. 1 Frequency measurement of NRC-SrIOC1 against VM1. The dashed line is a weighted linear fit to the data to calculate the averaged frequency of the SrIOC1. The shaded regions indicate the measurement duration for each intermittent measurement, i.e., the uptime of the measurement. The distribution of the measurement uptime is used for the estimate of the deadtime uncertainty together with the VM1 noise parameters.

Table 2: Uncertainty budget of NRC-SrIOC1. All values are in fractional units of 10^{-18}.

Evaluation period (MJD)	57914 – 57924	
Physical effect	Shift	Uncertainty
BBR field evaluation, $\langle E^2 \rangle_T$	555	11
Collisional frequency shift	-0.045	2.6
BBR coefficient, $\Delta\alpha_0$	0	0.83
Thermal motion	-3.2	0.8
AOM chirps	0	0.2
Excess micromotion	0	0.2
Servo tracking errors	0	0.1
1092 ns ac Stark shift	-0.16	0.07
Electric quadrupole shift	0	0.03
674 ns ac Stark shift	0.04	0.02
422 nm ac Stark shift	0.006	0.006
Tensor Stark shift	0	0.005
Quadratic Zeeman shift	0.106	0.00003
Total for SrIOC1	**551.7**	**11.4**
Gravitational redshift	10451.5	2.6
Total	**11003.2**	**11.7**

Table 3. Link uncertainty budget of NRC-SrIOC1. All values are in factional units of 10^{-18}.

Uncertainty source	**Uncertainty**
Frequency comb	150
Deadtime uncertainty	324
Total	**339**

References:

1. Bin Jian *et al.* (2023) Metrologia, **57** 015007.
2. Pierre Dubé *et al*. (2015) Phys. Rev. A **92** 042119.
3. Consultative Committee for Time and Frequency 2021 Recommendation CCTF PSFS 2 (2021): updates to the CIPM list of standard frequencies (available at: www.bipm.org/en/committees/cc/cctf/22-_2-2021).