Proceedings of the 2003 IEEE International Frequency Control Symposium and PDA Exhibition Jointly with the 17th European Frequency and Time Forum

DISCUSSION OF THE UNCERTAINTY BUDGET AND OF LONG TERM COMPARISON OF PTB'S PRIMARY FREQUENCY STANDARDS CS1, CS2 AND CSF1

A. Bauch, R. Schröder, and S. Weyers
Physikalisch-Technische Bundesanstalt, Bundesallee 100, D-38116 Braunschweig, Germany

Abstract - **PTB continuously operates two primary clocks, the more than 30 year old CS1 and the CS2. The clocks' standard uncertainties (1σ) to realize the SI second were estimated as u_B(CS1) = $7\cdot10^{-15}$ and u_B(CS2) = $12\cdot10^{-15}$. Since 2000, the caesium atomic fountain CSF1 has been operated quasi continuously during 14 intervals, each of at least 15 days duration, in the so-called routine operation mode for which an uncertainty u_B(CSF1) of typically $1\cdot10^{-15}$ was specified. During these intervals the CS2 and the CSF1 agreed well within the uncertainty u_B(CS2). On the contrary, the CS1 frequency deviates slightly more from CSF1 than u_B(CS1). The σ_E of the CS2 comparison data can be explained as white frequency noise of the CS2 (calculated from the CS2 signal parameters) combined with an extra contribution of less than $1\cdot10^{-15}$, whereas an extra noise contribution of $3.7\cdot10^{-15}$ is needed to explain the σ_E of the CS1 comparison data. In view of this, the individual contributions to the clocks' uncertainty budget are analyzed.**

Keywords **- SI second, primary clocks, uncertainty budget, TAI**

I. INTRODUCTION

The operation of primary clocks is of particular importance for the realization of International Atomic Time TAI. The Bureau International de Poids et Mesure (BIPM) constructs a so-called free atomic time scale EAL (Echelle atomique libre) for the world-wide ensemble of atomic clocks. A linear function of time is added to EAL with the slope adjusted in order to generate TAI as an international time reference which conforms to the definition of the SI second [1]. This so-called steering of TAI is based on comparisons between EAL and a few primary clocks of national metrology institutes, which realize the SI second with a specified uncertainty. In recent years, data representing frequency comparisons "clock minus EAL" over a certain period of time were available from four fountain frequency standards using laser-cooled caesium atoms, NIST-F1 [2], PTB CSF1 [3,4], and FO2 and FOM of BNM-SYRTE (France) [5] and from four thermal beam clocks, the primary frequency standards CRL-01 (Japan) [6] and JPO (BNM-SYRTE) [7] using optical pumping both for state selection and detection, and from CS1 and CS2 of the Physikalisch-Technische Bundesanstalt (PTB) using magnetic state selection [8,9].

The combination of the individual data requires the knowledge of the clocks' uncertainty values of type A and B of relevance for the specific period. u_A is made up of contributions due to the clock's inherent frequency instability, and to the time link between the clock and TAI. u_B is made up of individual contributions, reflecting the effect of the various physical parameters on the clock frequency, see e. g. [2, 3, 7, 10] for details. The usual statistical treatment of these individual contributions as well as of the clocks' combined u_B in the determination of the steering of TAI assumes that each of the contributions is a statistical variable which obeys a Gaussian distribution law. It has been further assumed that the estimate of u_B made for a given period is unique and independent of previous values of the same clock. It will be reported subsequently to which extent these assumptions are valid for the clocks of PTB. The writing of is paper was motivated in part by the discussion of this matter [11].

PTB has been operating two primary clocks with a thermal atomic beam for many years, the more than 30 years old CS1, and the 18 years old CS2. After completion of the development of the caesium atomic fountain CSF1 this standard serves now as the primary reference for the SI second in PTB. Since 2000, the CSF1 has been operated quasi continuously during 14 intervals, each of at least 15 days duration, in the so-called routine operation mode for which an uncertainty u_B(CSF1) of about $1\cdot10^{-15}$ [3,4] was specified. The operation of all clocks in parallel allowed the verification of the previous uncertainty estimates and of the overall performance of the CS1 and the CS2 with respect to the CSF1, which is superior in accuracy and frequency stability. The observations stimulated a detailed discussion of the clocks' uncertainty budgets, which is also helpful regarding the TAI issue of correctly combining individual clock data.

The organization of this paper is as follows. At first a brief description of the operation of the thermal beam clocks is given, including a discussion of their long-term performance. Similar information is then provided for the CSF1, followed by a presentation of the comparison results in detail. The main part of the paper consists of a discussion of relevant uncertainty contributions in view of the questions raised before. A conclusion rounds off the paper.

II. OPERATION OF THE CS1 AND THE CS2

The design of the clocks was described previously and is not repeated here [8,10]. They have been operated as clocks in which a quartz oscillator in a control loop is the source of a 5 MHz signal used for frequency comparisons, and of a 1 pulse per second (1 pps) signal which is continuously compared with UTC(PTB). Operational parameters have been checked periodically and validated to estimate the uncertainty u_B for any given period. These parameters are the Zeeman frequency, the temperature of the beam tube (vacuum enclosure), the linewidth of the clock transition, the microwave power level, the spectral purity of the microwave excitation signal, and some characteristic signals of the electronics. Typically four beam reversals have been made per year in each clock so that the end-to-end cavity phase difference could be monitored. The short-term frequency instability $\sigma_y(\tau = 1\ \mathrm{h})$ was determined from regular comparisons with an active hydrogen maser as (80 to 85)$\cdot 10^{-15}$ and (65 to 70)$\cdot 10^{-15}$ for the CS1 and the CS2, respectively, during the last years. These values agree with the expectations based on atomic shot noise, thermal detector noise, and line quality factor.

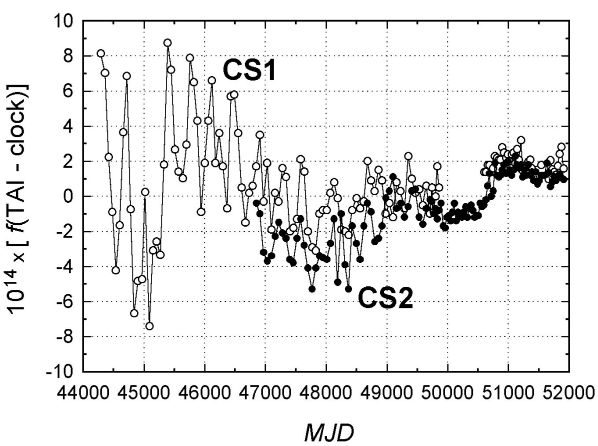


Fig. 1. Long-term comparison of PTB CS1 and CS2 with TAI, based on data published in Annual Reports of the Bureau International de l'Heure before 1988, and of the BIPM Time Section until now: Relative frequency deviations f between the clocks and TAI for CS1 (O) and CS2 (•) between 1979-03 and 2000-12. MJD is the Modified Julian Date, MJD 52000 = 2001-04-01.

After having been operated intermittently for some time, this mode of continuous operation was started in 1978 for the CS1 and in 1986 for the CS2. The CS1 operation was stopped in 1995 for a major refurbishment. New vacuum pumps, a new Ramsey cavity, and a new central vacuum chamber were installed. Finally the oven was filled with a fresh 5-gram charge of caesium. No such measures were ever necessary for the CS2 which at the time of writing (May 2003) still runs on the first 5-gram charges of caesium in its two ovens.

The long-term performance of both clocks is illustrated in Fig. 1 in which the results of comparisons with respect to TAI during more than two decades are shown. The data reveal several details of historical interest when considering that the clocks' performance was not intentionally changed to a substantial extent, with only the one exception that the refurbishment of the CS1 improved its stability by almost a factor 2. In earlier years, the CS1 and the CS2 had each got a new version of electronics (microwave synthesis, frequency servo), but no records prove that the clock stability was much better thereafter than before. In Fig. 1 one recognizes the large frequency excursions in the pre-GPS era which lasted up to about 1984, reflecting the properties of TAI and the LORAN-C time link to PTB. The next major improvement came with the advent of the new generation of commercial caesium clocks and their gradual introduction into EAL after 1992 [12]. The last feature to be seen is the gradual change of the TAI scale unit when the frequency shift due to the electric field of thermal radiation (AC Stark effect) was taken into account following Recommendation S2 of the 1996 Session of the CCDS [13]. Only during the recent years the reduced instability of TAI and the quality of the time links allowed to identify the instability in the data shown as representing the characteristics of the PTB clocks.

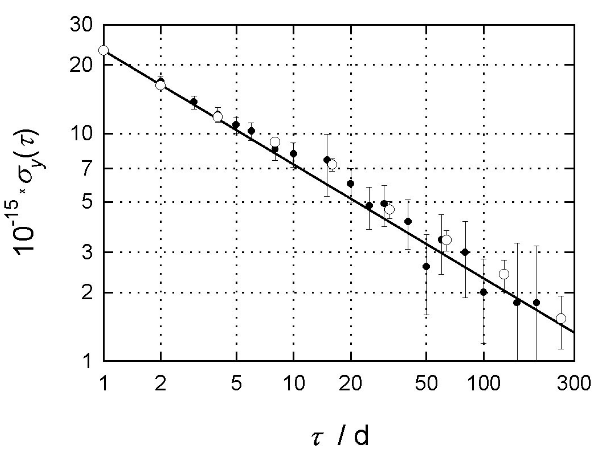


Fig.2. Relative frequency instability $\sigma_y(\tau)$ of the comparison between CS1 and CS2 during 1900 days (1997-12 – 2003-03). The comparison is based on 1 pps time interval measurements performed daily at 0:00 UTC with a counter whose measurement noise is < 100 ps. $\sigma_y(\tau)$ is calculated in the classical way (symbol •) and in the overlapping mode (symbol O).

In Fig. 2 the frequency instability observed in the local comparisons during the recent 1900 days (5.2 years) is depicted. The general behavior, illustrated as a solid line, is essentially consistent with a white frequency noise level of $23 \cdot 10^{-15} \cdot (\tau/\mathrm{d})^{-1/2}$ which is calculated from the clocks' short term frequency instability mentioned above. A small excess noise becomes significant at averaging times around 15 to

30 days. This is consistent with the findings reported in section IV. A frequency measurement which is significant with respect to the u_B values of the clocks requires a few days, but it would require prohibitively long averaging to reach a 10^{-15} statistical uncertainty. The advantage of using laser-cooled atoms in a fountain is unquestionable.

III. Operation of the CSF1

In the CSF1, caesium atoms are trapped and cooled in a standard MOT setup consisting of 4 laser beams in the horizontal plane, two vertical beams and a magnetic quadrupole field. The laser diode system includes two extended-cavity diode lasers and an injection-locked 150 mW laser diode. Loading of about 10^7 atoms requires about 0.2s. The atom cloud is then allowed to cool to about 1.8 μK in a molasses phase during which the MOT magnetic field coils are turned off. The atoms are launched to an apogee 0.83 m above the MOT center. They spend about 0.57 s above the TE011 microwave cavity, resulting in a full width at half maximum of the central Ramsey fringe of 0.88 Hz. Before entering the TE011 cavity whose design was described in [14] the atoms are state-selected in the hyperfine sub-state (F=3, m_F = 0) in a state-selection cavity. The microwave field in the TE011 cavity is square-wave frequency modulated so that the central fringe is probed on opposite sides during subsequent fountain cycles. Such a fountain cycle lasts roughly 1.2 s in the routine operation mode and up to 2.6 s when a large atom number is collected during studies of the collisional shift. The signal processing electronics delivers a control voltage to frequency lock a quartz oscillator on the central fringe frequency, in a similar way as in the traditional clocks. More details about the CSF1 design can be found in [3,4] and references therein.

The CSF1 has been operated as a primary frequency standard intermittently. Most of the operation time has up to now been devoted to study frequency shifting effects and thus to verify the previous uncertainty estimates. The data collected since 2000 have also been useful to study the long-term stability of international time links [15] and to establish more stringent limits on the validity of Local Position Invariance [15,16]. So-called routine operation conditions were defined, and the most recent uncertainty estimate of $1\cdot10^{-15}$ [4] is valid only as long as they are fulfilled. In Fig. 3, the relative frequency instability with reference to active hydrogen masers is depicted. The CSF1 instability is made up from essentially equal contributions due to atomic shot noise and local oscillator noise for averaging times up to half a day. It appears as if presently none of the hydrogen masers operated in PTB allowed to prove a frequency instability below one part in 10^{15} of the CSF1 at longer averaging times.

In total 14 routine operation intervals of 15, 20 or 25 days form the basis for the local comparisons in PTB discussed below. Data taken during 13 intervals were reported to BIPM as inputs to the steering of TAI. To obtain this kind of data, the CSF1 frequency is compared with the hydrogen masers as local references. These masers in turn are compared with the CS1 and the CS2 and with UTC(PTB), and the time differences UTC(PTB) – HM are reported to the BIPM in standard ALGOS format. Thus, the maser frequencies are known with respect to TAI , and also local comparison can be made.

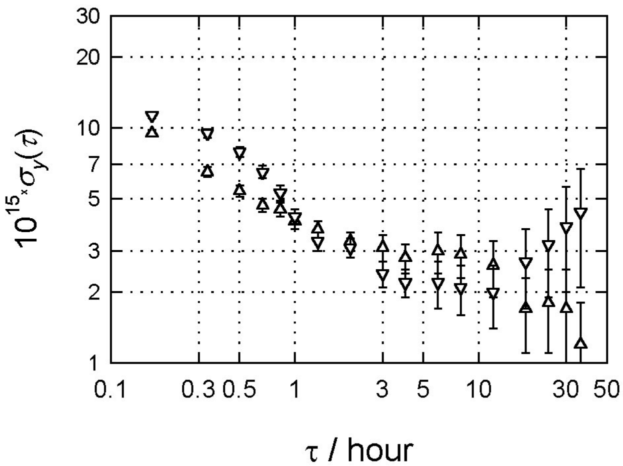


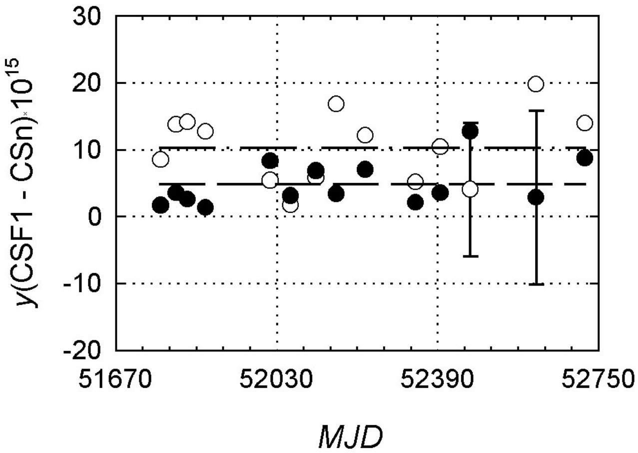
Fig. 3. Relative frequency instability $\sigma_y(\tau)$ obtained in a comparison between CSF1 and two active hydrogen masers, VREMYA-CH 1005M (symbol Δ) and KVARZ CH1-75 (symbol ∇), during 12 days in March 2003 (based on 8500 data at τ = 100 s). The comparisons are performed using 5 MHz signals from each standard and a VREMYA-CH phase comparator model 314 which contributes negligible noise.

IV. Results of local comparisons

The 14 individual comparisons between CSF1, CS1 and CS2 cover a period of more than 2.5 years. The results are depicted in Fig. 4 and tabulated in Tab. 1. The average τ is about 18 days. The uncertainty bars, for clarity only one per clock, reflect the combined u_B of the clocks and the u_A for the average τ. The horizontal lines show the mean frequency deviation. The CS2 and the CSF1 agreed well within the uncertainty u_B(CS2). In contrary, the CS1 frequency deviated slightly more from CSF1 than u_B(CS1).

A further observation applies to the scatter in the data. The standard deviation σ_E found for the CS2 comparison data can be explained as due to white frequency noise of the CS2 (calculated from the CS2 signal parameters as $3.2\cdot10^{-15}$) combined with an extra contribution of less than $1\cdot10^{-15}$. An extra noise contribution of $3.7\cdot10^{-15}$ is needed to

Fig. 4. Relative frequency difference y(CSF1-CSn) obtained between 2000-08 and 2003-03 for CS1 (O) and CS2 (•). See text for explanations.



explain the observed σ_E of the CS1 comparison data, as the shot-noise limited frequency instability was $3.8\cdot10^{-15}$ instead of the value of $5.3\cdot10^{-15}$ observed. (All numbers have been rounded to one decimal place.) The excess noise was previously noticed in the discussion of Fig. 2. In the remainder of the paper it shall be discussed which of the systematic biases and u_B contributions could vary in time to explain the observed instability. It is immediately obvious that the CS1 uncertainty was estimated slightly too optimistic. But as will be seen, the effect to be blamed for causing the frequency offset is not easy to identify.

TABLE I

Results of frequency comparisons between CSF1, CS1 and CS2 during about 2.5 years. The clocks' standard uncertainties (1σ) to realize the SI second were previously estimated as u_B(CSF1) = 0.8 to $2\cdot10^{-15}$, u_B(CS1) = $7\cdot10^{-15}$ and u_B(CS2) = $12\cdot10^{-15}$.

	y(CSF1-CS1)	*y*(CSF1-CS2)
Mean frequency deviation	$10.3\cdot10^{-15}$	$4.8\cdot10^{-15}$
Standard Deviation of the data	$5.3\cdot10^{-15}$	$3.4\cdot10^{-15}$

V. DISCUSSION

Apart from the fundamental difference between a clock using a thermal beam and a cold-atom fountain there is a further slight deviation in the operation of the CSF1 on one hand and of the CS1 and the CS2 on the other hand. In case of the CSF1, the microwave signal coupled into the main cavity has the nominal frequency of f_0 = 9 192 631 770 Hz (plus and minus half the modulation width). Due to systematic frequency shifts, the true line center deviates from that value by typically less than 0.001 Hz (see Tab. 2), and the quartz oscillator is detuned from 5 MHz by the commensurate relative amount. The measured frequency differences between CSF1 and the hydrogen masers are then in retrospect corrected for the known shifts before the data are analyzed, stored, and published.

TABLE II

Relative frequency corrections applied in routine operation of the primary clocks CSF1, CS1, CS2 of PTB. If necessary, two values for each entry are given, which are valid for the two beam directions. The data reflect the situation at the time of writing, May 2003, and may thus deviate slightly form previously published data. (*) The correction is not applied in real time operation.

Cause of frequency shift	CSF1	CS1	CS2
Magnetic field (quadr. Zeeman)	$-46.4\cdot10^{-15}$	$-3.1784\cdot10^{-10}$ $-3.1722\cdot10^{-10}$	$-3.1778\cdot10^{-10}$ $-3.1728\cdot10^{-10}$
Relativistic Doppler effect	0	$51\cdot10^{-15}$	$48\cdot10^{-15}$ $50\cdot10^{-15}$
Cavity phase difference	0	$322\cdot10^{-15}$ $-322\cdot10^{-15}$	$250\cdot10^{-15}$ $-260\cdot10^{-15}$
AC Stark effect due to thermal radiation	$-16.7\cdot10^{-15}$	$-17\cdot10^{-15}$ (*)	$-17\cdot10^{-15}$ (*)
Collisional shift	$5.5\cdot10^{-15}$ (typ. value)	0	0

The frequency synthesis chain used in the thermal beam clocks produces a frequency which is higher by about 2.919 Hz than f_0 which reflects mainly the frequency shift due to the magnetic field through the quadratic Zeeman effect. The magnetic field is adjusted in both beam directions so that the sum of all frequency corrections exactly compensates this offset produced by the frequency synthesis [8]. Ideally, the CS1 and CS2 quartz oscillators are thus delivering 5 MHz *exactly*, neglecting for a moment the uncertainty and instability of the clocks. The time differences *UTC(PTB)–T(clock)* are measured, stored, and transferred monthly to BIPM without further processing. In Tab. 2 the corrections and their physical causes are specified for the three clocks.

In the following, the uncertainty of these corrections and the uncertainty contributions related to those effects for which the correction is estimated as zero will be discussed next for CS1 and CS2 and afterwards for the CSF1.

A. Discussion of the stationary part of the CS1 and CS2 uncertainty budget

In Fig. 5 the individual uncertainty contributions due to the various physical effects are depicted. For each clock one bar, labeled "_total", reflects the previously published u_B contributions [8] which are of relevance when the mean deviation among the clocks shall be discussed. The largest contribution is related to the end-to-end cavity phase shift ϕ, and its magnitude is determined by the estimate of the reproducibility of the beam positions in both beam directions and of the spatial distribution of the phase of the microwave field. Regarding this effect, one notices the largest difference between the CS1 and CS2 design. The cavities of both clocks consist of a central wave guide, 28 half-wavelengths in length. In the CS2, corner shaped end parts are attached whose dimensions were chosen in such a way that the standing wave pattern in the straight part of the cavity is not distorted in the end parts. The atomic beam intersects the cavity one half wavelength away from the short, and a linear dependence of the microwave field phase on the position of (83 ± 3) µrad/mm is prevailing [17]. In the CS1, terminal parts of ring-shaped design, as proposed by De Marchi et al. [18] are used. A microwave field with a maximum magnetic field and a zero Poynting vector at the midpoint of the irradiation section should be sustained in such a ring structure. The spatial dependence in the horizontal direction of the phase ϕ around the phase minimum of a ring cavity should be only quadratic, and it should remain within 4 µrad over the 3 mm diameter of the atomic beam. No such dependence is expected in the vertical direction.

Measurements at the PTB had yielded less optimistic results when the first model of such a cavity was tested [19]. A worst case estimate of those results was the basis for the CS1 uncertainty estimate [10], since it was assumed that the phase variations might be as large as 20 µrad/mm, much more than predicted for a ring cavity. The experiments were repeated in 2000, using a cavity end piece manufactured in sequence with those two units built into the CS1 and gave a similar result. It proved of disadvantage that ring end parts have the characteristic of a strongly coupled cavity with a distinctive frequency sensitivity. Thus differences in the dimensions of the rings and of the material properties have a stronger impact than in the simpler corner shaped cavities. The recent observations could be explained if the damping term α of the cavity material differed by as much as 8,5 % for the two arms of the particular ring end-part under study. It is not clear whether the manufacturing process may result in such differences. In retrospect, it would have been wise to examine the CS1 cavity separately in a dedicated device [18,19] prior to its final installation in 1996.

A systematic CS1 frequency offset caused by an erroneous correction for ϕ would require not only a substantial spatial phase dependence which may indeed exist but also a systematic deviation of the position of the atomic beam in the two directions. The examinations made while the CS1 was rebuilt excluded that to be the case.

Concerning most other physical parameters, the CS1 and the CS2 are very similar. Historically, the CS2 was designed after the first years of CS1 operations, adopting most of its successful features. The inhomogeneity and instability of the magnetic field contributes to the next largest uncertainty contribution (see Fig. 5). A more careful examination and documentation was done in case of the CS1 than a decade before when the CS2 was assembled. "Ramsey pulling" and "Majorana transitions" stand for shifts which are rather difficult to prove experimentally since one cannot easily deliberately increase these effects compared to standard operation conditions. Experimental verification was always hampered by the large frequency instability of the clocks. Anyway, it is difficult to believe that there are much differences between the two clocks.

There exists almost no knowledge about the pressure of the background gas and its composition in the cavity region of both clocks, and whether this has an impact on the clock frequency. The only information is from the discharge current in the ion pumps and from two ionization vacuum meters in the CS2 end chambers whose readings (typically $1.5\cdot10^{-6}$ Pa) generally serve as an indication that the status of the vacuum is "okay". The vacuum pressure close to the CS1

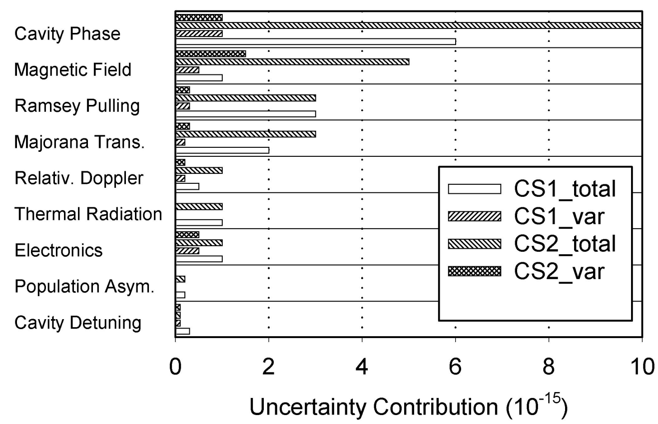


Fig. 5. Contribution to the uncertainty to realize the SI second with the primary clocks CS1 and CS2. Distinction is made between stationary contributions and variable contributions. The variable part is estimated based on the underlying physical laws and the observed variations of experimental parameters. The inset specifies the meaning of the four bars for each cause of (potential) frequency shifts.

cavity is probably worse by a factor of 5 to 10 than it is the case in the CS2 due to the different construction of the vacuum chambers, but there is no way to prove that or to modify that in a systematic way during operation. Whether this causes the CS1 frequency offset or not remains an open question.

B. Discussion of the variable part of the CS1 and CS2 uncertainty budget

It was tried to estimate to which extent the systematic frequency corrections could vary in consequence of the observed variations of parameters external or internal to the clocks. The following observations were made. The ambient temperature recorded next to the location of the clocks exhibits an annual cycle with a peak-to-peak amplitude of about 0.3 K (neglecting rare spikes when temperature control fails). Zeeman frequency measurements show small but substantial variations of fractions of 1 Hz. Like in previous studies [8], the magnetic field generation in the CS2 was found slightly less stable than that in the CS1. The beam reversals performed since 2001 gave the results depicted in Fig. 6. Half of the mean values of y_{BR} are applied as corrections during operation (see Tab. 1). The standard deviation around the mean is for both data sets in close agreement with the expectations based on shot-noise limited performance of the CS1 and the CS2.

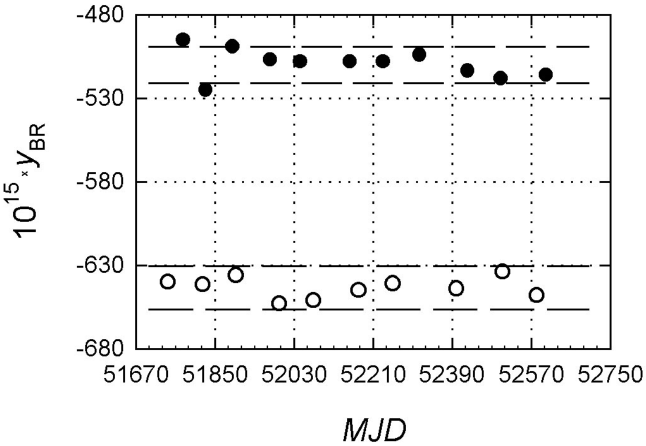


Fig. 6. Relative beam reversal frequency shift y_{BR}, determined for the clocks CS1 (O) and CS2 (•) since early 2001. Each data point represents the frequency difference of CS1 and CS2 in the two beam directions, respectively, referenced to a variable group of reference clocks and averaged over 14 days. The dashed lines represent the inevitable 2-σ limits based on the shot-noise limited performance for each clock.

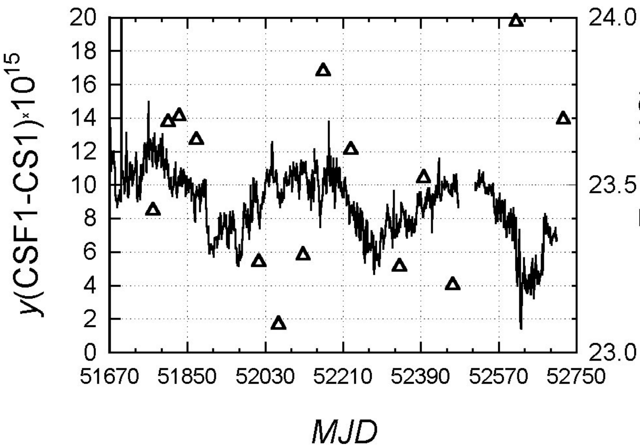


Fig. 7. Record of the ambient temperature in PTB's clock hall using a calibrated PT-100 resistance thermometer in a black housing (right axis, solid lines) and relative frequency difference y(CSF1-CS1) (symbol Δ) obtained during the same period (left axis).

The mean atomic velocity never changed by more than 0.2 % relatively. Deviation of the microwave field amplitude from the optimum condition (π/2 pulses) never exceeded 0.3 dB. Observed variations in the integrator offset voltage, the symmetry of the microwave signal, and other electronic parameters could, according to theory, not explain a relative frequency variation > $5\cdot 10^{-16}$. In consequence the variable part of the uncertainty contributions is estimated as depicted in Fig. 4, labeled "_var". There is agreement between the observed instability in y(CSF1–CS2) (Fig. 4 and Tab.1) and the small potential variations in systematic CS2 frequency shifts. The variations of CSF1 frequency shifts can be neglected here, as will soon become clear. However, no contribution can be identified immediately which would explain the variations in y(CSF1–CS1). Again one may be suspicious that the variations of the frequency shift due to ϕ might have been underestimated. The estimate regarding ϕ included in Fig. 5 assumes that ϕ is constant and that the mean velocity undergoes changes as observed. According to [20], however, ϕ itself could be a function of the ambient temperature. If the damping term α of the cavity material in the two end sections would differ by about 2 % this would suffice to explain the observations. This is a quite realistic value. But no correlation can be seen at first glance between the recorded temperature and y_{BR}(CS1) (Fig. 6) on one hand, or the data y(CSF1-CS1) on the other hand (Fig. 7).

C. Discussion of the CSF1 uncertainty budget

In the same way as above, in Fig. 8 the individual uncertainty contributions due to the various physical effects are depicted. Again one bar reflects the u_B contributions as published previously [4] whereas a second hatched bar reflects the variable part of the respective shift as introduced in section B. Any offset and variation between the clocks' frequencies are most probably due to the thermal beam clocks. Several CSF1 uncertainty contributions are negligibly small as the atomic velocity is very low, and the population in the atom cloud occurs predominantly in one magnetic hyperfine substate after the state selection process. Lengthy and ongoing studies have been made to verify the uncertainty contributions due to the Cs-Cs collisions and more recently due to the cavity phase difference.

First we consider the cavity-phase related shift, following the arguments laid down in [3]. A general advantage of an atomic fountain microwave frequency standard is that the atoms cross the same microwave cavity twice. If the atomic trajectories were perfectly vertical , frequency shifts due to axial and radial cavity phase variations would be cancelled as each atom would interact

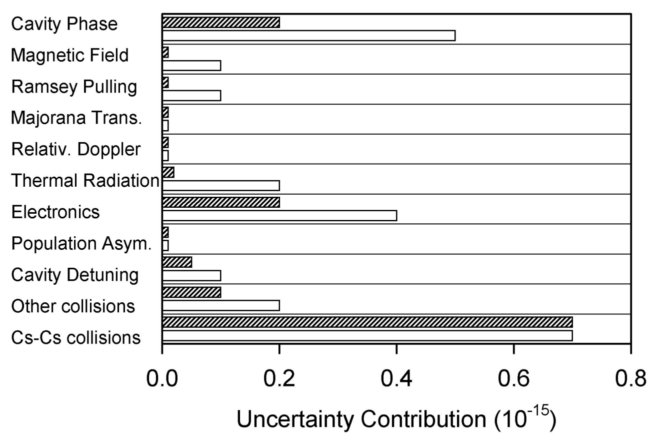


Fig. 8. Contribution to the uncertainty to realize the SI second with the primary clock CSF1. Distinction is made between stationary contributions (open bars) and variable contributions (hatched bars). The variable part is estimated based on the underlying physical laws and the observed variations of experimental parameters.

with the field once with velocity v (upwards) and once later with $-v$ (downwards). But the transversal residual thermal velocity and a possible misalignment of the launching direction cause a spread of the trajectories between the first and the second passage through the cavity. A non-vanishing transverse phase variation of the cavity field can entail a frequency shift in this case, unless the trajectories are symmetrically distributed around the vertical axis. The microwave field in the cavity can be described as a superposition of various field modes which are excited with different amplitudes and phases [14]. For exactly symmetric coupling, transverse electrical field modes TE*n*11 with $n = 0, 2, 4,...$ can be excited in the cavity, but the field modes TE*n*11 with $n = 1,3,...$ are suppressed. Hence the predominant first-order Doppler shift contribution results from the TE211 mode.

To get a quantitative estimate, it is assumed that all atoms are concentrated in a negligibly small cloud. If the atoms pass upwards along the cavity symmetry axis and descend next to one of the coupling slits on one side of the cut-off bore the residual relative first-order Doppler frequency shift is estimated as less than $0.5 \cdot 10^{-15}$. For asymmetric coupling, further first-order Doppler shift contributions are due to the TE111 mode and the TE311 mode. For a coupling asymmetry of 10%, which is much larger than the asymmetry expected from the prevailing mechanical tolerances [14], one calculates a residual frequency shift of less than $0.2 \cdot 10^{-15}$ assuming that all atoms ascend through the cavity aperture next to one coupling slit and descend next to the other slit. The extension of the atomic cloud is non-negligible, so that all effects are strongly averaged in reality. A maximum relative frequency uncertainty of $0.5 \cdot 10^{-15}$ was initially estimated.

Experimental studies on that matter were motivated by observations in fountains operated at BNM-SYRTE (Paris Observatory). Tilting one of their fountain frequency standards by up to a few milliradians led to unexpected significant frequency shifts when, at the same time, the microwave field amplitude was increased by factors of 3 or 5 above the normal value ($\pi/2$ pulses) [21]. Similar and still ongoing experiments done with the CSF1 gave no indication on a significant frequency shift, but at present the noise level attributed to the hydrogen maser references at 2 to 3 parts in 10^{15} ($1\ \sigma$) for $\tau = 1$ day is prohibitive to reach a definite conclusion (see e.g. Fig. 3). Occasionally, frequency excursions of $5 \cdot 10^{-15}$ were noticed if $3\pi/2$-pulses were applied, but these were not reproducible and were not related to the tilt angle. Until there is better knowledge the previous uncertainty estimate, $0.5 \cdot 10^{-15}$, is kept, and it is assumed that the shift may vary by half that amount between operation periods.

It is generally assumed that the collisional frequency shift in a fountain clock depends linearly on the mean density $\langle n \rangle$ of the atomic cloud between the two microwave interactions. It is common practice that S, the normalized total fluorescence signal of the atoms in both hyperfine states obtained from the two detection channels is regarded as a measure of $\langle n \rangle$. This is valid as long as launching height, background gas pressure, initial size and temperature of the atomic cloud, and number of collected fluorescence photons per atom are constant. This is difficult to prove in detail.

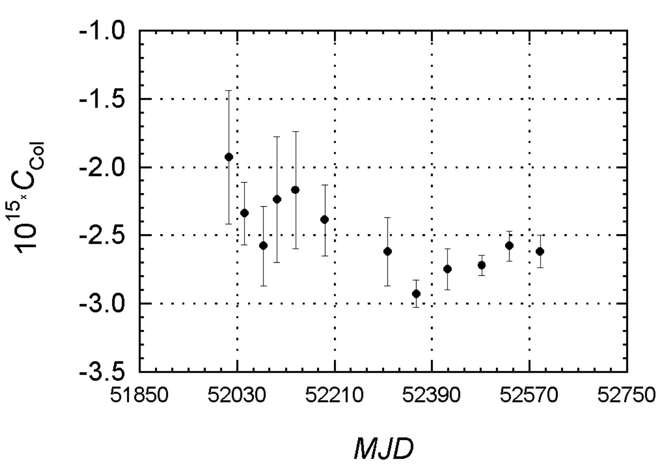


Fig. 9. CSF1 frequency shift coefficient C_{col} determinations since 2000. The collisional frequency shift is obtained by multiplying C_{Col} with S which is between 1 and 2.5 during routine operation.

The collisional shift was repeatedly determined from the dependence of the realised CSF1 clock frequency on S, where S was varied by changing the loading time in the MOT or S was varied in the state selection process. In Fig. 9 the results of all such measurements done since a state selection process has become part of the CSF1 operations is depicted. The frequency correction (Tab. 2) is obtained by multiplying the shift coefficient C_{Col} (Fig. 9) by S which in the routine operation conditions has been between 1 and 2.5. The evaluation of the collisional shift during the 14 measurement campaigns (Fig. 4) was usually based on the average of the two determinations of C_{Col} done before and afterwards. The uncertainty estimate [4] (Fig. 8) takes the variations of C_{Col} from epoch to epoch and its statistical uncertainty into account. The variable part could be as large as the full uncertainty contribution.

VI. Conclusion

The primary clocks CS1 and CS2 were compared with the caesium atomic fountain clock CSF1 which provided superior accuracy and frequency stability. The CS2 and the CSF1 agreed well within the uncertainty u_B(CS2), and the σ_E of the individual results could be explained as white frequency noise of the CS2 (calculated from the CS2 signal parameters) combined with an extra contribution of less than $1 \cdot 10^{-15}$. Similarly, comparisons of the CS2 with all fountains world-wide having provided data since 1996 also proved its excellent long-term stability [22]. In contrary, the CS1 frequency deviates slightly more from CSF1 than u_B(CS1) and the observed σ_E in the CS1 comparison data proves that systematic frequency shifts show larger variations than expected. With some probability both observations are related with the construction of the CS1 microwave Ramsey cavity, but no strict evidence could be found.

During operation of PTB's primary clocks, including the CSF1, several parameters which are known or suspected to cause frequency shifts have been periodically checked. The uncertainty u_B stated for each BIPM standard period is determined from a combination of measurements done during the very period and previous experiments. The determination is thus not completely independent from previous estimates. Based on the knowledge of the physical laws and on the observation of parameter variations in time it is expected that the clock frequencies should not vary by more than 0.76, 1.30 and 1.93 parts in 10^{15} (1 σ) for the CSF1, CS1, and CS2, respectively. These numbers represent the square-root of the sum of the squared uncertainty contributions labeled "_var" in Figs. 5 and 8, respectively, and would represent a flicker-floor in comparisons against a superior standard. In case of the CS2 this statement is supported by the observations. In case of the CSF1 this statement has to be proven by repeated comparisons with other frequency standards of similar accuracy and stability, preferentially in the future with PTB CSF2 which shall be assembled during summer 2003.

Acknowledgment

This paper reflects the outcome of many years of devotion to the development and operation of PTB's primary clocks of many colleagues in PTB, whose contributions are gratefully acknowledged, those of Bernd Fischer, Thomas Heindorff and Harald Brand working on the CS1 and the CS2, and those of Udo Hübner, Christian Tamm and Dieter Griebsch working on the CSF1.

References

[1] Thomas C., Wolf P., Tavella P., *Time Scales*, 1994, BIPM Monographie 94/1.
[2] S. R. Jefferts et al., "Accuracy evaluation of NIST-F1," *Metrologia,* vol. 39, pp. 321-336, 2002.
[3] S. Weyers, U. Hübner, R. Schröder, Chr. Tamm, and A. Bauch, "Uncertainty evaluation of the atomic caesium fountain CSF1 of PTB;" *Metrologia,* vol. 38, pp.343-352, 2001.
[4] S. Weyers, A. Bauch, R. Schröder, and Chr. Tamm, "The Atomic Caesium Fountain CSF1 of PTB," in *Proc. 6th Symp. on Frequency Standards and Metrology,*" P. Gill, ed., Singa-pore: World Scientific, 2002, pp. 64-71.
[5] H. Marion et al., "A Search for Variations of Fundamental Constants using Atomic Fountain Clocks," *Phys. Rev. Lett.*, vol. 90, 150801, 2003.
[6] A. Hasegawa et al., "Accuracy evaluation of optically pumped primary frequency standard CRL-01," in *Proc. Asia-Pacific Workshop on Time and Frequ.*, pp. 199-205, 2000.
[7] A. Makdissi and E. de Clercq, "Evaluation of the accuracy of the optically pumped caesium beam primary frequency standard of the BNM-LPTF," *Metrologia*, vol. 38, pp. 409-426, 2001.
[8] A. Bauch et al., "Comparisons of the PTB primary clocks with TAI in 1999," *Metrologia*, vol 37, pp. 683-692, 2000.
[9] T. Heindorff, A. Bauch, P. Hetzel, G. Petit, and S. Weyers, "PTB primary clocks: performance and comparison with TAI in 2000," *Metrologia*, vol. 38, pp. 491-501, 2001.
[10] A. Bauch, B. Fischer, T. Heindorff, and R. Schröder, "Performance of the reconstructed primary clock CS1 and an estimate of its current uncertainty," *Metrologia,* vol. 35, pp. 829-845, 1998.
[11] G. Petit, "Evaluating the Accuracy of TAI with Primary Frequency Standards," in *Proc. 27th URSI General Assembly,* paper A3.01, 2002.
[12] C. Thomas, "Impact of New Clock Technologies on the Stability and Accuracy of the International Atomic Time TAI," *IEEE Trans. Ultason. Ferroelect., and Freq. Control.*, vol.44, pp. 693-700, 1997.
[13] Comité Consultatif pour la définition de la seconde, Report of the 13th Meeting 1996, BIPM 1996.
[14] R. Schröder, U. Hübner, and D. Griebsch, "Design and Realization of the Microwave Cavity in the PTB Caesium Atomic Fountain Clock CSF1," *IEEE Trans. Ultason.*

Ferroelect., and Freq. Control., vol.49, pp. 383-392, March 2002.
[15] A. Bauch, L. Nelson, T. Parker, and S. Weyers, "Long-term time comparison between frequency standards at NIST and PTB for a test of the validity of local position invariance," this Proceedings.
[16] A. Bauch and S. Weyers, "New Experimental Limit on the Validity of Local Position Invariance", *Phys. Rev. D.*, vol. 65, 081101, 2002.
[17] A. Bauch, T. Heindorff, and R. Schröder, "Measurement of the Frequency Shift due to Distributed Cavity Phase Difference in an Atomic Clock," *IEEE Trans. Instr. Meas.*, vol. IM-34, pp. 136-138, 1985.
[18] A. De Marchi, J. Shirley, D. J. Glaze, and R. Drullinger, "A new cavity configuration for Cesium beam primary frequency standards," *IEEE Trans. Instrum. Meas.,* vol. IM-37, pp. 185-190, 1988.
[19] H. de Boer, B. Fischer, T. Heindorff, and R. Schröder, "Experimental Data on a New Ramsey Cavity for Cesium Atomic Clocks," in *Proc. 4th European Frequency and Time Forum*, pp. 523-526, 1990.
[20] R. Schröder, R. Augustin, and A. Bauch, "Improved Coupling of a Microwave Ramsey Cavity: Theoretical Studies and Experimental Verification," in *Proc. 15th European Frequency and Time Forum*, pp. 428-433, 2001.
[21] M. Abgrall, "Evaluation des performances de la fontaine atomique PHARAO, Participation à l'étude de l'horloge spatiale PHARAO," PhD thesis (in French), University Paris VI, unpublished, 2003.
[22] T. Parker, "Comparing and Evaluating the Performance of Primary Frequency Standards: Impact of Dead Time," in *Proc. 2001 IEEE Intern. Freq. Control Symposium and PDA Exhibition*, pp. 57-62, 2001.