

The PTB primary clocks CS1 and CS2

Andreas Bauch

Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

Abstract

The primary clocks CS1 and CS2 have been developed and operated by the Physikalisch-Technische Bundesanstalt, Braunschweig, Germany. By their contributions to the definition of the scale unit of International Atomic Time they have provided access to the realization of the SI second over decades with exceptional accuracy. They have stood out against other primary clocks by the novelty of their design concept, their robustness of construction, and last but not the least by their almost continuous operation for many years. Their properties have changed with time, but during the last seven years their uncertainty u_B has been estimated as 8×10^{-15} (CS1) and 12×10^{-15} (CS2). Comparisons with PTB's cold-atom frequency standard CSF1 ($u_B = 1 \times 10^{-15}$) during 3.5 years revealed that CS2 and CSF1 agreed well within the uncertainty $u_B(\text{CS2})$, whereas CS1 frequency deviates slightly more from CSF1 than $u_B(\text{CS1})$.

1. Introduction

Since the definition of the unit of time is based on the hyperfine splitting in the caesium-133 ground state it is the particular role of primary frequency standards or primary clocks to realize the second with a specified uncertainty. The term *primary* has the meaning that the physical parameters of the clock which could, according to the accepted theories, lead to a deviation of the realized second from the SI value are quantitatively known and that appropriate frequency corrections are applied. Throughout the years, there has been a continuous struggle to improve the knowledge of the theories and of these parameters which has resulted in an increase of the clock's accuracy by almost an order of magnitude per decade. The Physikalisch-Technische Bundesanstalt (PTB) entered into that race in the mid sixties of the last century when the CS1 development started. The saying of W. M. Markowitz at the 1964 International Conference on Chronometry in Lausanne (CIC64) that "Physics requires time interval but not epoch; no requirement for the epoch of atomic time has yet been given" [1] probably reflected the common attitude at that time. Accordingly, primary frequency standards were designed to be operated only during limited periods for calibration of the scale unit of atomic time scales realized with commercial equipment. Initially PTB also followed this practice, but later CS1 became what it is still today, a primary clock providing an almost continuous series of time marks separated by highly accurate SI seconds. Its successor, CS2, was immediately designed to be operated in this fashion, and since 1986,

CS2 has served as a reliable and accurate reference for the SI second for the international timing community.

This article and those of Vanier and Audoin [2] and of Guinot and Arias [3] in this issue of *Metrologia* complement each other. In [2], the basic principles underlying the operation of caesium atomic frequency standards and the progress accomplished during the last fifty years since its invention are laid down. In [3], among other subjects, the particular role of primary clocks in the realization of International Atomic Time TAI is discussed. Here I provide some notes on the development of CS1 and CS2 and of their operations. I will, however, not document in detail the stepwise development of CS1 with all required bibliographic references. In Section 4 I will try to explain how the construction principle led to the rather small uncertainty achieved. Part of the knowledge required for this was gained from experimental work done with the CSX device, subject of Section 5. In Section 6 I will present results of long-term frequency comparisons before rounding-off in my conclusions. During recent years, the operation and uncertainty evaluation of PTB's clocks were documented in several articles [4, 5, 6] which contain many of the details which cannot be given here due to the restricted length of this article.

2. How CS1 and CS2 came into being

2.1 Concept and history of CS1

In what we now call "classical" caesium clocks, a beam of atoms effuses from an oven and passes through a state-selecting magnet which deflects atoms in one of the hyperfine states, $F = 3$ and $F = 4$, so that they subsequently pass through the microwave cavity. Here the atoms are irradiated with a microwave probing field, and, in resonance, the transition to the other hyperfine state is induced. The analyzer magnet deflects these atoms to a hot wire detector. The atoms are ionized and the ion current is processed to yield the control signal for the quartz oscillator from which the microwave signal is synthesized. Around 1965, discussions arose as to how this fundamental concept, already developed by Essen and Parry ten years earlier [7] and explained in more detail in [2], could be best put into practice. A seminal contribution was that of Holloway and Lacey at the CIC64, in which they discussed the principal sources of error in a caesium atomic beam frequency standard and finally proposed an atomic beam geometry with magnetic multipole fields for the state selection, an axial C-field, a coaxial microwave cavity, and an annular ionization detector [8]. In Figure 1a) I reproduce one of their design drawings.

At that time the development of an active hydrogen maser [9] was pursued at PTB and the focusing of hydrogen atoms by magnetic multipole fields was discussed by Becker and Fischer at the CIC64 [10]. So the development of a primary caesium clock in PTB could profit

by the research activities already made and could immediately incorporate the advantages of the design concept advertised by Holloway and Lacey. In 1967 G. Becker reported on the current state of atomic clock development and advocated the new design concept as it could

- provide an increased signal-to-noise ratio by two-dimensional focusing of the atoms,
- allow the minimization of the end-to-end phase difference of the resonator because of the ease of precise manufacture of a body with rotational symmetry,
- reduce the error due the inhomogeneity of the quantization field which could be generated by a solenoid.

Altogether, this should allow one to reduce the uncertainty by a factor of 10 compared to what had been achieved up to then [11]. Becker's design principle is reproduced as Figure 1b).

During the process of the development of CS1 [12], two features were finally given up, namely the coaxial resonator and the annular ionization detector. The final CS1 design is reproduced in Figure 1c). Apparently, it was not possible to develop a cavity with a stable and suitable resonating mode of the microwave standing wave. The annular detector was replaced by a spot-sized detector at the position designated as P in Figure 1b). Such a detector produces a minimum of non-caesium background, it has the lowest possible stray capacitance, and it is mechanically stable and more durable than an annular structure. The price to be paid is that the hyperfine transitions are detected in a flop-out mode so that the signal-to-noise ratio is about a factor of 3 lower than if the same resonance amplitude would be observed in the flop-in mode. In 1969 CS1 was put in operation, intermittently serving as the reference for the unit of time and frequency in Germany. Figure 2 shows an early photo which was taken at that time.

During the following years, comparisons of CS1 with the ensemble of commercial clocks maintained at PTB revealed an annual frequency variation of the commercial clocks so that the concept of "using the clock ensemble for maintaining the SI unit as realized with CS1 now and then" [12] proved inadequate. Following also the example of the Canadian NRC's clocks of that time, from 1978 on CS1 was operated continuously. Inevitably, many components of CS1 were subsequently subject to ageing and about 15 years later it was decided to undertake major refurbishing. The vacuum system, in particular, had remained untouched since 1978. New ion getter pumps were installed. At the same time, an improved microwave cavity was installed inside a newly-built central vacuum chamber, and also the quantization field was perfected. This work was accomplished between summer 1995 and early 1996. Quasi-routine operation was restarted on May 1st, 1997, [4] and persists until the time of writing. The entries in Table 1 reflect the CS1 operational parameters of today.

2.2 Development of CS2

When the CS1 design concept had proven as mostly favourable, the design of a second primary clock was started. The construction drawings of its stainless steel vacuum chamber dated 1974 bear witness to that early work. In Figure 3 I reproduce one of my photos taken when finally in 1985 the Ramsey cavity was mounted inside the triple magnetic shield. CS2 operation started in fall 1985, so with this article we coincidentally contribute to the celebration of fifty years of atomic timekeeping and, being optimistic, of 20 years of CS2. A horizontal section of the CS2 beam tube is shown in Figure 4. CS2 was equipped with one oven and one detector in each end chamber so that a reversal of the atomic beam direction, whose relevance will be subsequently explained, can be done without an effect to the vacuum and thus only requires a few minutes of interruption of continuous operation. The cylindrical C-field coil support surrounding the Ramsey cavity represents the UHV enclosure which is separated from the large recipient (see Figure 4) in which a pressure of 10^{-4} Pa is maintained. The inner structure and thus the cavity can be adjusted in the vertical direction with respect to the beam axis which is defined by the axes of the magnets in both end chambers. This feature was used to determine the transversal phase distribution in the CS2 cavity in situ (see Sections 2.3 and 4). Although no individual part in CS2 looks like its counterpart in CS1, the similarities in performance are quite high. In Table 1, I also include the CS2 operation parameters as they are valid today. There are only minor changes compared to the initial parameters presented in 1986 [13].

2.3 Description of the construction principles common to CS1 and CS2

The basic construction principle of a caesium clock as laid down before was put in practice in CS1 and CS2. The most significant feature in which these clocks differ from other primary clocks [2] is the use of magnetic multipole fields for state selection. Their action is comparable to that of optical lenses with a strong “chromatic aberration”, i. e., the focal length of the fourpole and sixpole lenses is strongly dependent on the atomic velocity v . Only atoms in a narrow velocity interval out of the thermal distribution can contribute to the signal reaching the detector (See e. g. [10], written in a different context). The center of this interval can be chosen lower than the most probable velocity in an effusive thermal beam. This helps to obtain a narrow clock transition linewidth and in general to minimize all velocity-dependent frequency shifts [2].

One particular shift is caused by an almost inevitable phase difference ϕ existing between the microwave fields in the two interaction regions of the Ramsey cavity. The phase difference is typically caused by a construction asymmetry in the cavity arms with respect to the feed together with the finite conductivity of the cavity wall material. The frequency shift scales as $\sim \phi \times v$, and it can be understood as due to the Doppler effect caused by a running wave component superimposed on the standing wave pattern in the cavity. This interpretation also

explains the effect of a spatial variation of ϕ in the interaction region entailing the so-called distributed cavity phase shift.

Initially, in CS1 two sets of magnets of different length were installed whose position could be interchanged easily. Figure 5 provides a view along the CS1 atomic beam axis with the “short” magnet in place while the “long” magnet is seen out of action below. Two atomic velocities, either $v_1 = 110$ m/s or $v_2 = 180$ m/s could be obtained. In addition, the position of the oven and detector chamber could be interchanged without breaking the vacuum in these chambers and in the middle section. Frequency measurements at atomic velocities $\pm v_1$ and $\pm v_2$ were used to interpolate at $v = 0$ and thus to determine ϕ . For different reasons, a completely new beam optics, still in use today, was installed in 1978 by which a single mean velocity of about 95 m/s is obtained. It consists of a pair of fourpole and sixpole magnets similar to what is used in CS2, which was designed to provide a large collection efficiency for atoms in a narrow velocity interval.

There has always been a substantial difference regarding the construction of the microwave cavity used in CS1 and CS2. Here I detail only the present situation. In CS2, the central waveguide is completed by two corner shaped end parts whose dimensions were chosen in such a way that the standing wave pattern in the straight part of the cavity is not distorted inside the end parts. The atomic beam intersects the cavity one half wavelength away from the short. A linear dependence of the microwave field phase on the vertical position of (83 ± 3) $\mu\text{rad}/\text{mm}$ was found for such a type of cavity in studies performed in a separate frequency standard (see Section 5) [14] and of (94 ± 10) $\mu\text{rad}/\text{mm}$ with CS2 itself [13]. This value combined with the estimated capability that after a beam reversal the atomic trajectories are the same as before leads to the respective contribution to the CS2 uncertainty - which actually is the largest of all - as depicted further below in Figure 8.

In CS1, two terminal parts of ring-shaped design, as proposed by De Marchi et al. [15], have been used since 1996. A microwave field with a maximum of the magnetic field amplitude and a zero Poynting vector (no “running wave”) 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 minimum of phase variations in such 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 PTB had yielded less favorable results when the first model of such a cavity was tested [16]. As a consequence, a worst case estimate of those results (20 $\mu\text{rad}/\text{mm}$) became the basis for the CS1 uncertainty estimate [4]. The experiments were repeated in 2000, using a cavity end

piece manufactured together with those two units built into the CS1 and gave a similar result. Therefore the uncertainty estimate was kept at the old value.

In summary, it can be stated that the construction principle of CS1 and CS2 is favourable to obtain a small uncertainty for the realization of the unperturbed hyperfine transition frequency. This was indeed partially predicted very early [8, 11], but some further advantages listed below were identified only much later. These are:

- The confinement of the atomic beam to a narrow cylindrical cross-section of 3 mm and 2.6 mm diameter in CS1 and CS2, respectively, defined by the bore diameter in the magnets, reduces the distributed phase shift and the effect of the transversal components of the magnetic microwave field which increases with the beam diameter.
- The confinement of the atomic velocities to a narrow interval around a rather low mean value facilitates the determination of the frequency shift due to time dilation, and it reduces the sensitivity of the output frequency to the power of the interrogating microwave field. (This sensitivity is due to cavity pulling and the end-to-end cavity phase difference.)
- The axial C-field and the shielding geometry actually make the accurate determination of the magnetic shift due to second-order Zeemann effect a simple undertaking despite its large magnitude.
- The cosine-shaped axial variation of the magnetic microwave component in the cavity end sections minimizes the amplitude of the far-off-resonance side lobes of the Ramsey patterns and thus the so-called Rabi pulling [17].

The main disadvantage lies in the fact that the population in terms of number and velocity of the Zeeman sublevels characterized by m_F is by nature of the magnetic state selection and velocity filtering a function of m_F . The relevant population numbers were included in Table 1, and they show that the number of atom in the state (4, +1) is about twice as large as that in state (4, -1). Therefore, the frequency shifts due to Rabi- and Ramsey pulling and due to Majorana transitions must be considered carefully. A few details on the latter are given in the next Section.

Continuous clock operation requires a design of the electronics for microwave field generation and signal processing very much like that common in commercial atomic clocks. The currently used systems are identical in both clocks and represent the fourth generation in CS1 and the second generation in CS2, A commercial 5 MHz BVA voltage-controlled quartz oscillator (VCXO) is slaved by means of the control loop to yield an output frequency

in accordance with the definition of the second. The control loop has the elements VCXO, frequency-synthesis unit, caesium-beam tube, and signal-processing unit. The design criteria have been laid down in [18]. In the frequency-synthesis unit the signal of the VCXO at $f_n = 5$ MHz is converted to the signal in the microwave region at frequency f_p . It is

$$f_p = 1840 \cdot f_n - f_s = f_0 + f_e \quad (1)$$

with $f_e \approx 2.919$ Hz and $f_0 = 9\,192\,631\,770$ Hz.

In closed-loop operation, f_p is steered to the actual line centre of the clock transition, which differs from f_0 by the sum of all systematic frequency shifts. This implies that f_e is approximately equal to the frequency shift due to the quadratic Zeeman effect (by far the largest of the systematic effects, $\approx 3.175 \times 10^{-10}$, relatively) which in turn is dictated by the C-field of about $8.27 \mu\text{T}$. Ultimately, the value of f_s and thus that of f_e are determined by the frequency-synthesis electronics [18]. To determine the line centre, the frequency f_p is square-wave modulated with a modulation period T_m of 260 ms. The total time constant of the control loop is about $30 \times T_m$. The modulation width can be set to $f_H = 62$ Hz, which corresponds to the width of the central Ramsey fringe, or the threefold value $f_H = 186$ Hz ($3 \times W$). When the modulation width f_H is changed, some systematic frequency shifts may emerge and can be studied. Rather than changing the synthesizer output frequency f_s , the magnetic field is adjusted in both beam directions so that the sum of all frequency corrections exactly compensates the offset produced by the frequency synthesis, which explains the two entries in Table 1.

3. Operation of CS1 and CS2

Continuous operation requires first of all the continuous availability of an atomic resonance signal. A simple calculation based on kinetic gas theory predicts that at the actually prevailing temperature of the caesium reservoir in CS1 and CS2 of about 170°C the atomic flux through the nozzle of 0.1 mm diameter and 0.5 mm length amounts to 5.6×10^{13} at/s, and the reservoir which initially contains 5 grams of caesium will be depleted after about 13 years. This in mind, it is not surprising that CS2 still runs on the initial fill of the two ovens. For me it is more astonishing that since 1983, when I joined the laboratory, of the three detectors of CS1 and CS2 we had just one detector filament burnt out.

Since all the necessary frequency corrections are applied on-line, the CS1 and CS2 quartz oscillators are thus delivering 5 MHz in real-time *exactly*, neglecting for a moment the uncertainty and instability of the clocks. A 1 pulse per second signal is generated by a

divider, and the time differences $UTC(PTB)-T(clock)$ are measured, stored, and transferred monthly to BIPM without further processing. Operational parameters are checked periodically and validated to estimate the clock uncertainty for any given period. These parameters are the Zeeman frequency, the temperature of the beam tube (vacuum enclosure), the line width of the clock transition as a measure of the mean atomic velocity, the microwave power level, the spectral purity of the microwave excitation signal, and some characteristic signals of the electronics.

In recent years, typically three to four beam reversals were made per year in each clock. For this to take place, the positions of oven and detector at each end of the clock have to be interchanged. Clock operation of the CS1 has to be interrupted for about 6 hours, and Figure 6 illustrates the procedure. As said before, the equivalent procedure is much simpler in the case of CS2. The beam reversals performed since 2001 gave the results depicted in Figure 7. Half of the mean values of the beam reversal frequency shift y_{BR} as determined by averaging over a few previous beam reversals are applied as a correction during operation (see Table 1). For both data sets the standard deviation around the mean values is in close agreement with the expectations based on shot-noise limited performance of CS1 and CS2.

Of course, the quartz control loop has to be opened during such service work. In order to avoid a loss of coherence in the 5 MHz signal and the occurrence of a time step, the quartz oscillator is phase-locked during the servicing work to an external 5 MHz signal provided by a hydrogen maser or a commercial clock whose frequency deviates by less than 2 parts in 10^{14} from that of the primary clock. The accumulated time error in this slaved mode is thus below 100 ps during the period required for “normal” servicing work. If the interruption lasts longer, such as after a CS1 beam reversal, the time difference $[UTC(PTB) - T(CSn)]$ is reset to the predicted value with a precision of 100 ps. Following this practice, a quasi continuous time scale is obtained from each clock.

4. Discussion of the CS1 and CS2 uncertainty budget

In their paper and earlier in their text book, Vanier and Audoin discussed in detail the factors which determine the accuracy of a primary frequency standard [2,19]. The determination of the individual uncertainty contributions of CS1 and CS2 as they are valid today were detailed in [4-6, 13, 20]. A critical analysis was recently presented when a reference standard of superior accuracy, CSF1, a cold-atom caesium fountain frequency standard, became available at PTB [21]. In [21] we proposed the concept of discriminating between static and dynamic uncertainty contributions due to the various physical effects. The static values are of

relevance for calculating the standard uncertainties u_B which in turn determine the contributions of the primary clocks in the generation of TAI and Terrestrial Time [3, 22] and which are relevant when the mean deviation among the clocks shall be discussed. The dynamic values are relevant if the long-term frequency variations of the clocks shall be assessed. In Figure 8, these contributions are depicted as one bar labelled “_total” and one bar labelled “_var” per item for each clock. The largest contributions are related to the end-to-end cavity phase difference ϕ , and their magnitudes are 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. This statement is true only to the extent that the procedure of reversing the atomic beam does not influence ϕ , which requires that the mean temperature and the temperature profile along the cavity remain unchanged [23]. In order to achieve this, the two CS2 ovens are kept at the same temperature independent of the beam direction, however the unused oven is mechanically closed to economize the caesium consumption. The CS2 cavity temperature can be inferred only indirectly [5] since there is no temperature probe attached to the CS2 inner vacuum structure. Since 1996 three temperature probes are attached to the CS1 C-field coil, and the temperature distribution is kept fixed independent of the oven position by adjustment of a variable heat source at the detector chamber. This had not been done in earlier times.

Concerning most other physical parameters, CS1 and CS2 are very similar. The inhomogeneity and instability of the magnetic field contributes to the next largest uncertainty contribution (see Figure 8). A more careful examination and documentation was done in the case of the CS1 in 1996 than a decade before when CS2 was assembled. “Ramsey pulling” and “Majorana transitions” (see below) stand for shifts which were rather difficult to determine experimentally since it was difficult to deliberately increase these effects compared to standard operation conditions in CS1 and CS2. Experimental verification was also hampered by the rather large frequency instability of the clocks which required long-term experiments, and by the reluctance to introduce major operational changes.

As motivated before, 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 in the clock hall fails). Zeeman frequency measurements show small but substantial variations of fractions of some 0.1 Hz. The mean atomic velocity never changed by more than 0.2 %. Deviation of the microwave field amplitude from the optimum condition ($\pi/2$ pulses) never exceeded 0.3 dB.

Recorded variations of the integrator offset voltage, of the spectral properties of the microwave signal, and of other electronic parameters could, according to theory, not explain a relative frequency variation larger than 5×10^{-16} . In consequence the variable parts of the uncertainty contributions “_var” are estimated as depicted in Figure 8. The estimate regarding ϕ included in Figure 8 assumes that ϕ is constant and that the mean velocity undergoes changes as observed.

In continuation of the earlier description of the practice of performing beam reversals, I wish to stress why this is considered a reasonable practice. Firstly, we assume that ϕ is constant and independent of the beam direction. As y_{BR} is known only with a statistical uncertainty the correction applied may be in error. It requires averaging over several cycles of operation in both beam directions to make this error no longer relevant. Secondly, we know that ϕ could be affected by changes of temperature and temperature distribution in the clock and one could be suspicious that the caesium deposition could change the surface properties inside the cavity with time. Thirdly, the frequency shifting effect of spurious microwave fields to which the atoms might be subjected in the flight region between the two state-selecting magnets is a matter of concern [24]. In principle, such shifts can be tracked down by operating the clock at different microwave power levels and frequency modulation widths. Using TAI as the frequency reference, no statistically significant frequency changes were observed when related experiments were performed, except once when a soldered joint between two copper pieces from which one CS1 cavity end section is made was faulty. If these spurious fields have stable amplitude and phase, their frequency shifting effect changes sign with the beam direction, another motivation to retain the operational practice.

It has been common practice to express the uncertainty for the realization of the SI second as one numerical value u_B which is calculated as the square-root of the sum of squares of the individual “_total” contributions in Figure 8. The result is 7.23×10^{-15} for CS1 and 12.08×10^{-15} for CS2. In order not to underestimate the CS1 uncertainty, the value officially reported to BIPM was increased to 8×10^{-15} since 2000. Subsequently this value was used in calculating the CS1 contribution to the determination of the TAI scale unit [3] and in the calculation of TT(BIPMxx) [22]. In Section 6, I will discuss the frequency comparisons among CS1, CS2, CSF1, TAI, and TT(BIPM04) and will refer to the two types of uncertainty contributions introduced here.

5. Accompanying research activities: CSX

Continuous operation of CS1 and CS2 entailed the drawback that studies regarding the mechanisms of frequency shifts and the validation of the uncertainty estimates could be made only to a small extent. The attitude not to disturb the clocks prevailed most of the time.

A great deal of knowledge required for estimating the uncertainties was gained from studies involving another atomic beam frequency standard maintained at PTB, named CSX, which was initially built for the study of cavity properties [14]. It has many similarities with CS1 and CS2, but the mean atomic velocity is 405 m/s and the line width is thus 253 Hz. As a peculiarity, the cavity can be rotated around two orthogonal axes through the centre of the first interaction region so that the phase distribution in the second region can be measured. As explained before, the findings entered into the respective uncertainty contributions of CS1 and CS2. Only after a prototype of the CS2 cavity had been tested in CSX the final copy was built and then installed (see Figure 3).

Later CSX proved a versatile tool for other studies. In CSX the homogeneity of the magnetic field could be intentionally degraded and the effect of Majorana transitions on the operational parameters and on the output frequency of a caesium atomic frequency standard was studied in great detail [25, 26]. Majorana transitions occur when the atomic beam passes through weak inhomogeneous fields in the flight region between the two state-selecting magnets. Observations of frequency shifts had been reported from a few groups (see references in [25]), but only specifically designed experiments in CSX allowed to explain their occurrence. It turned out that the occurrence of frequency shifts requires that

- the condition for Majorana transitions to be induced is fulfilled, i. e., the transport of the state-selected atoms between polarizer and analyzer magnet is non-adiabatic,
- the population of Zeeman sublevels in the atomic beam with respect to total number and velocity is a function of the quantum number m_F ,
- $\Delta F = \pm 1$, $\Delta m_F = \pm 1$ transitions are induced in the microwave interaction region by microwave magnetic field components transverse to the longitudinal C-field.

In CS1 and CS2, the last two prerequisites are inevitably fulfilled (see Table 1), so that the findings obtained with CSX were very relevant. The velocity distributions of the atoms in the states $(4, m_F)$ served as indicators of a potential violation of the adiabatic transport condition in CS1 and CS2. Changing the strength of the C-field (and its direction) and of guiding fields which are designed to provide a smooth transition from the C-field region to the state-selecting magnets should have had an effect according to [25]. Changing also the microwave power level should have strongly affected the transition probability for the $\Delta F = \pm 1$, $\Delta m_F = \pm 1$ transitions, but frequency measurements with TAI as the reference did not reveal statistically significant shifts. A substantial uncertainty contribution was nevertheless retained.

Using CSX, the shift of the ground-state hyperfine transition frequency in caesium due to the electric field of blackbody radiation was measured as a function of the temperature of heated

surfaces surrounding the atomic beam. A relative frequency shift of $-17.9 (1,6) \times 10^{-15}$ at room temperature was derived [26], in good agreement with the theoretical prediction -16.9×10^{-15} [27]. The experimental uncertainty reflects the inability to separate the effect of the heat sources on the CSX cavity dimensions from the effect of the AC electric fields under study. No beam reversal can be performed in CSX. Ideally, the experiment should have been conducted in CS2, taking data at a given blackbody radiation intensity in both beam directions. This idea was discussed but finally discarded in view of the difficulty to install the necessary heaters, heat shields, and multiple temperature probes inside CS2.

6. Long-term comparisons of CS1 and CS2

6.1 Internal comparisons

In this section I wish to report on recent internal comparisons among CS1, CS2, and PTB's fountain frequency standard CSF1. Since the refurbishment of CS1 in 1996, we have recorded continuous time differences between CS1 and CS2 during 2500 days. On average, the CS2 frequency was found higher, $\gamma(\text{CS2} - \text{CS1}) = 6 \times 10^{-15}$, where γ denotes the relative frequency difference, and after removal of this mean offset the time residuals as depicted in Figure 9 are obtained. The mean relative frequency difference (seen as the slope in the residuals) during the last 500 days is higher by 3×10^{-15} than that obtained during the first 500 days. The overall curvature in the residuals translates into a relative frequency drift of $\delta\gamma(\text{CS2} - \text{CS1})/t = 1.92(0.66) \times 10^{-18}/\text{d}$ which is barely discernible from very low frequency noise. The plot of the relative frequency instability shown in Figure 10 illustrates that white frequency noise dominates for averaging times up to 300 days. The solid line in Figure 10 is an estimate of the average expectation value of $\sigma_\gamma(\tau)$ based on the average beam signal, detector noise, and line width in both clocks. Splitting the data into five samples of 500 days each, and calculating $\sigma_\gamma(\tau)$ for each sample does not point to significant performance changes with time.

CSF1, PTB's fountain frequency standard using laser-cooled caesium atoms, was essentially completed in 1999 and described in detail in [29, 30]. For the routine operating conditions, the CSF1 standard uncertainty u_B was estimated as 1×10^{-15} [28] and a relative frequency instability of $2 \times 10^{-13} (\tau/\text{s})^{-1/2}$ is usually observed in comparisons with an active hydrogen maser. Thus, in comparisons of CS1 and CS2 with CSF1 all apparent frequency differences and the frequency instability observed can be attributed to be caused by the older clocks [21].

16 individual comparisons between CSF1, CS1 and CS2 were performed which cover a period of almost 3.5 years. The results are depicted in Figure 11 and are tabulated in Table 2. The average duration of the comparisons τ was 18 days. The uncertainty bars, for clarity only one per clock, reflect the combined u_B of the clocks and the statistical measurement uncertainty u_A for the average τ under typical conditions. The standard deviation around the mean found for the CS2 comparison data can be explained as due to white frequency noise of CS2. An extra noise contribution of about 2.5×10^{-15} is needed to explain the observed standard deviation of the CS1 comparison data (all numbers have been rounded to one decimal place). The existence of such an excess noise could also explain the deviation of some of the data points from the straight line in Figure 10.

The findings are essentially the same as reported previously for a reduced data set [21]. Based on the knowledge of physical laws and on the observation of parameter variations in time it was predicted that the clock frequencies should not vary in time by more than 0.76, 1.30 and 1.93 parts in 10^{15} (1σ) for CSF1 [21], CS1, and CS2, respectively. The last two numbers represent the square-root of the sum of the squared uncertainty contributions “_var” in Figure 8. Such variations would represent a flicker-floor in comparisons against a superior standard. In case of CS2 this statement is supported by the observations as one notices agreement between the observed instability in $y(\text{CSF1} - \text{CS2})$ (Figure 11 and Table 2) and the predicted potential variations in systematic CS2 frequency shifts. No contribution can be identified immediately which would, however, explain the variations in $y(\text{CSF1} - \text{CS1})$. Again, one may be suspicious that the variations of the frequency shift due to ϕ might have been underestimated. In case of CSF1 repeated comparisons with other frequency standards of similar accuracy and stability would be required to verify the predictions made in [20], which has not yet been possible.

Typically, the mean frequency difference among primary clocks is of great public interest. CS2 and CSF1 agreed well within the uncertainty $u_B(\text{CS2})$, in contrary hereto the CS1 frequency deviates slightly more from CSF1 than $u_B(\text{CS1})$. It is indeed probable that the CS1 uncertainty might have been estimated overlooking one effect or being slightly too optimistic.

6.2 External comparisons and measurements of the TAI scale unit

Historically, CS1 and CS2 represent the two primary clocks in the world which have contributed to the realization of TAI for the longest period and with the largest amount of data. For a couple of years CS1 - even before its refurbishment - and CS2 were the most accurate clocks from which data were used to adjust the TAI scale unit to the SI second. Even after 1996, when the clocks had lost this status, the regularity of measurements has

compensated for the lack of accuracy and the statistical weights which CS1 and CS2 get until today are substantial [3, 31]. It is thus natural that in the very long term the scale unit of TAI is close to the seconds provided by CS1 and CS2. In Figure 12 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 performance of the clocks was never intentionally changed to a substantial extent, with the one exception that the refurbishment of CS1 (visible as the gap in the CS1 data) improved its frequency stability by almost a factor 2.

Some features in Figure 12 reflect the properties of TAI and of the available time links at the time. One recognizes the large frequency excursions with a clear annual signature which lasted up to about 1984 (MJD \approx 46000), reflecting the combined properties of TAI and the LORAN-C time link to PTB [31]. GPS common view time comparisons helped to reduce the link instability in the following period. The next major improvement came with the advent of the new generation of commercial caesium clocks and their gradual integration in timing institutes after 1993 (MJD \approx 49000). The last feature to be seen is the 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 [32]. Only since the instability of TAI was reduced and the quality of the time links was improved to the current level, the data shown in Figure 12 reflect the characteristics of the PTB clocks. The plot has not been continued until today since now a higher resolution appears appropriate.

Recently TT(BIPM04), a post-processed realization of Terrestrial Time, was published [22, 3] which can be regarded as the most stable reference available. In Figure 13 the relative frequency difference y between CS1, CS2 and TT(BIPM04) normalized by the respective uncertainty

$$u = (u_A^2 + u_B^2 + u_{\text{Link}}^2)^{1/2} \quad (2)$$

($u = 9.6 \times 10^{-15}$ and 12.5×10^{-15} for CS1 and CS2, respectively, for most of the time) are depicted. Here u_A is the statistical measurement uncertainty due to the finite duration of each comparison (30 days typically), and u_{Link} is the uncertainty introduced due to the time transfer technique used. In such a plot, ideally the points should scatter around zero. In case of CS2, u_B is much larger than u_A and u_{Link} , but following my earlier arguments, only the small variable contributions to u_B determine the scatter of the data, so the scatter should remain well below ± 1 . One obtains 0.13 as the mean value and 0.29 as the standard deviation around the mean. Note that during the 5.5-year period data from several more accurate primary standards were available [3, 30, 34] so that the good agreement found in the case of CS2 truly reflects the property of CS2. Similar to the observations reported in Section 6.1, one

notices that CS1 shows a slight deviation (mean = 0.76) and a larger scatter (standard deviation 0.53) of the points. Actually, variations with a period of one year can be identified in the CS1 data points which indicates that probably the small residual temperature variations in the clock hall have an influence on the clock frequency.

Before concluding, I would like to show in Figure 14 that comparisons of CS2 with fountains operated world-wide for which data were provided since 1996 also prove its excellent long-term stability and accuracy. The fountain data represent mean values for quite different averaging times, from 10 days to 30 days, but typically the standards are not continuously operated during these intervals. The CS2 data points were connected by lines to illustrate the very different kind of operation.

7. Conclusion

PTB's CS1 and CS2 have been internationally recognized as the principal references for the SI second over many years. I have tried to identify the reasons for that. Both clocks stood out against other primary clocks operated during the same period of time by their novelty of the design concept and the robustness of their construction so that it was possible to operate them continuously for many years. These features made them particularly suitable for their primary mission of supporting the realization of TAI. By definition, the duration of the TAI scale unit should be as close as possible to the SI second on the rotating geoid. The latter requirement is taken into account by the application of a frequency correction determined from the height of the clocks' atomic beam above mean sea level (see Table 1). The contributions of individual primary frequency standards are combined, and the statistical weight [22, 31] is determined by the combined uncertainty u defined before (2). Continuous operation helps to minimize the terms u_A and u_{Link} in (2). This seems to be a distinct advantage compared to the property of fountain frequency standards, at least given the current practice of their operations. For some of these standards, the terms u_A or u_{Link} become dominant. If the properties of the local frequency reference used as a fly-wheel during intermittent fountain operations are not well enough predictable, an underestimation of u_{Link} or u_A may result. This is one possible interpretation of the large scatter in the data of some fountains presented in Figure 14. Despite the fact that these devices are capable to realize the SI second with much lower uncertainty u_B than CS1 and CS2 [34], the two thermal beam clocks are still very valuable in the steering of TAI and thus in the realization of an accurate and stable time scale for world wide public and scientific use.

Acknowledgement

Three type of ingredients are needed to obtain success as reported in this paper, scientifically and technically skilled staff, discipline and devotion to work, and stable funding. I always found it a privilege to be employed at a place where all this has been available for a long time. Many colleagues, most of whom I still have or have had the pleasure to work with since 1983, made their particular contributions, and I wish at least to mention a few names in the time order in which they contributed: Gerhard Becker, Günter Kramer, Bernd Fischer, Engelbert Müller, Horst Fuhrmann, Harald Brand, Herbert Schneider, Roland Schröder, Lothar Rohbeck, Thomas Heindorff, Christof Richter, and Thomas Leder. I owe thanks to Amitava Sen Gupta for providing his inspiring ideas on the manuscript while he was on leave from NPL India at PTB and to Robert Wynands of PTB for careful reading of the manuscript.

References

- [1] Markowitz W., Proc. Intern. Conf. Chronometry (CIC64) (Lausanne, Switzerland, 1964), 1964, 157-177.
- [2] Vanier J., Audoin C., Metrologia, 2005, **42**, S31–42.
- [3] Guinot B., Arias F., Metrologia, 2005, **42** S20–30.
- [4] Bauch A., Fischer B., Heindorff T., Schröder R., Metrologia, 1998, **35**, 829-845.
- [5] Bauch A., Fischer B., Heindorff T., Hetzel P., Petit G., Schröder R., Wolf P., Metrologia, 2000, **37**, 683-692.
- [6] Heindorff T., Bauch A., Hetzel P., Petit G., Weyers S., Metrologia, 2001, **38**, 497-501.
- [7] Essen L., Parry V. I., Nature, 1955, **176**, 280-284.
- [8] Holloway J. H., Lacey R. F., Proc. Intern. Conf. Chronometry (CIC 64) (Lausanne, Switzerland, 1964), 1964, 317-331.
- [9] Goldenberg H. M., Kleppner D., Ramsey N. F., Phys. Rev. Lett. , 1960, **5**, 361-362.
- [10] Becker G., Fischer B., Proc. Intern. Conf. Chronometry (CIC 64) (Lausanne, Switzerland, 1964), 1964, 305 -316.
- [11] Becker G., Jahrbuch der Deutschen Gesellschaft für Chronometrie, 1967, **18**, 35-40.
- [12] Becker G., Fischer B., Kramer G., Müller E. K., 1969, PTB-Mitteilungen, **69**, 77-80.
- [13] Bauch A., Dorenwendt K., Fischer B., Heindorff T., Müller E. K., Schröder R., IEEE Trans. Instrum. Meas., 1987, **IM-36**, 613-616.
- [14] Bauch A., Heindorff T., Schröder R., IEEE Trans. Instrum. Meas., 1985, **IM-34**, 136-138.
- [15] De Marchi A., Shirley J., Glaze D. J., Drullinger R., IEEE Trans. Instrum. Meas., 1988, **IM-37**, 185-190.
- [16] De Boer H., Fischer B., Heindorff T., Schröder R., Proc. 4th European Frequency and Time Forum (Neuchâtel, Switzerland, March 1990), 1990, 523-526.

- [17] DeMarchi, A., Rovera G. D., Premoli A., *Metrologia*, 1984, **20**, 37-47.
- [18] Schröder R., Proc. 5th European Frequency and Time Forum (Besançon, France, March 1991), 1991, 194-200.
- [19] Vanier J., Audoin C., *The Quantum Physics of Atomic Frequency Standards*, 1989, Bristol and Philadelphia, Adam Hilger.
- [20] Bauch A., de Boer H., Fischer B., Heindorff T., Schröder R., Proc. 42nd Ann. Frequency Control Symp. (Baltimore, MD, USA, 1988), 1988, 490-495.
- [21] Bauch A., Schröder R., Weyers S., Proc. of the 2003 IEEE Intern. Frequency Control Symp. jointly with the 17th European Frequency and Time Forum (Tampa, FL, USA, June 2003), 2003, 191-199.
- [22] Petit G., Proc. 35th Annual Precise Time and Time Interval (PTTI) Meeting (Washington DC, USA, Dec. 2004), 2004, 307-317. Data were retrieved from <ftp://ftp2.bipm.org/pub/time/tai/scale/ttbipm04>.
- [23] Schröder R., Augustin R., Bauch A., Proc. 15th European Frequency and Time Forum (Neuchâtel, Switzerland, March 2001), 2001, 428-433.
- [24] Dorenwendt K., Bauch A., Proc. of the Joint Meeting of the European Frequency and Time Forum and the IEEE Intern. Frequency Control Symp. (Besançon, France, April 1999), 1999, 57-61.
- [25] Bauch A., Schröder R., *Annalen der Physik*, 1993, **2**, 421-449.
- [26] Schröder R., Bauch A., Proc. 7th European Frequency and Time Forum (Neuchâtel, Switzerland, March 1993), 1993, 483-488.
- [27] R. Augustin, A. Bauch, R. Schröder, Proc. 11th European Frequency and Time Forum (Neuchâtel, Switzerland, March 1997), 1997, 47-52.
- [28] W, M, Itano, L. L. Lewis, D. J. Wineland, *Phys. Rev. A*, **25**, 1233-1236.
- [29] Weyers S., Hübner U., Schröder R., Tamm Chr., Bauch A., *Metrologia*, 2001, **38**, 343-352.
- [30] Weyers S., Bauch A., Schröder R., Tamm Chr., Proc. 6th Symp. on Frequency Standards and Metrology, P. Gill, ed., 2001, World Scientific, Singapore.
- [31] Thomas C., Weighting factors attributed to measurements of primary frequency standards in estimating the accuracy of TAI, Rapport BIPM-98/2, BIPM; Sèvres, France, 1998.
- [32] See, e.g., Becker G., Proc. 11th Annual Precise Time and Time Interval (PTTI) Meeting (Goddard Space Flight Centre, Greenbelt MD, USA, Nov. 1979), 1979, 113-143, in particular the documented discussions.
- [33] Comité Consultatif pour la définition de la seconde, Report of the 13th Meeting 1996, BIPM 1996.
- [34] Wynands R and Weyers S 2005 *Metrologia* **42** S64–79.

Table Captions and Tables

Table 1. Operational parameters of CS1 and CS2 as valid during the last years. Two entries refer to the two possible beam directions, see end of Section 2. The short-term frequency instability (last line) was determined from repeated comparisons with an active hydrogen maser. These values typically agree with the expectations based on atomic shot noise, thermal detector noise, and line quality factor of the clocks.

Parameter	Parameter value CS1	Relative frequency correction in parts in 10^{15} applied in CS1	Parameter value CS2	Relative frequency correction in parts in 10^{15} applied in CS2
Separation L between interaction regions	73.2 cm		76.8 cm	
Mean atomic velocity	94.7 m/s	51	\approx 95 m/s	48 50
Width of the velocity distribution	8.2 m/s		8.7 m/s	
Linewidth of the clock transition	63.2 Hz		58.9 Hz 59.9 Hz	
Mean C-field strength	8.27 μ T	-317 840 -317 220	8.27 μ T	-317 780 -317 280
Normalized population of the Zeeman states $F = 4$, $m_F = (1), [0], \{-1\}$	(1.5), [1], {0.7}		(1.3), [1], {0.6}	
End- to end cavity phase difference	140 μ rad	310 -310	120 μ rad	250 -260
Height above geoid	79.5 m	8.7	79.5 m	8.7

Relative frequency instability $\sigma_y(\tau=1h)$ in parts in 10^{15}	75 – 95		65 – 75	
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Table 2. Results of 16 frequency comparisons of a mean duration of 18 days between CSF1, CS1, and CS2 during about 3.5 years. The clocks' standard uncertainties (1σ) to realize the SI second were previously estimated as $u_B(\text{CSF1}) = 0.8 \times 10^{-15}$ to 2×10^{-15} , $u_B(\text{CS1}) = 8 \times 10^{-15}$, and $u_B(\text{CS2}) = 12 \times 10^{-15}$.

	$y(\text{CSF1-CS1})$	$y(\text{CSF1-CS2})$
Mean frequency deviation	10.3×10^{-15}	5.0×10^{-15}
Standard Deviation of the data	4.9×10^{-15}	3.1×10^{-15}

Figures and Figure Captions

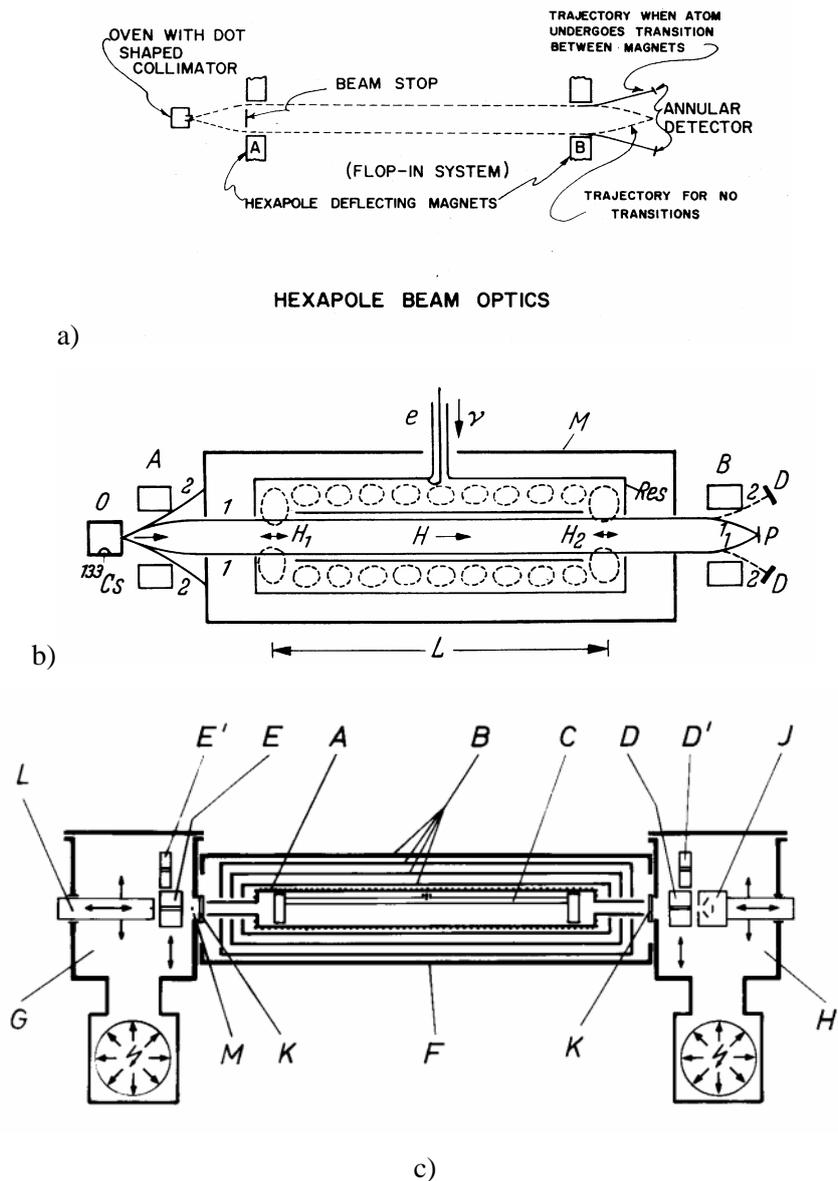


Figure 1. Caesium beam tube design;

- a) axially symmetric design according to Holloway and Lacey [8];
- b) design concept discussed in PTB [11]: A, B state-selecting magnets, O oven, D annular detector, P location of a point-size detector for flop-out detection, M magnetic shield, Res microwave resonator with coupling through feed e, H static magnetic field (C-field), H_1 , H_2 microwave magnetic field component, L interaction length;
- c) final design principle of PTB CS1 [12]: A C-field coil, B magnetic shields, C Ramsey cavity, D, D' and E, E' state-selecting magnets, F outer soft-iron case, G, H vacuum end chambers, J detector, K valve for separation of the three sections of the vacuum chamber, L oven, M beam stop. Arrows indicate the degrees of freedom to adjust the various elements.



Figure 2. PTB's primary clock CS1 with the first generation of electronics, photo taken in the clock hall in 1969. The chamber containing the detector (item H of Figure 1c) is facing the viewer. Note the handle on its upper right corner which mediated the sliding of the two magnets inside the chamber.



Figure 3. Final assembly of CS2 in 1985; Technician Harald Brand mounts the Ramsey cavity inside the nested triple magnetic shield.

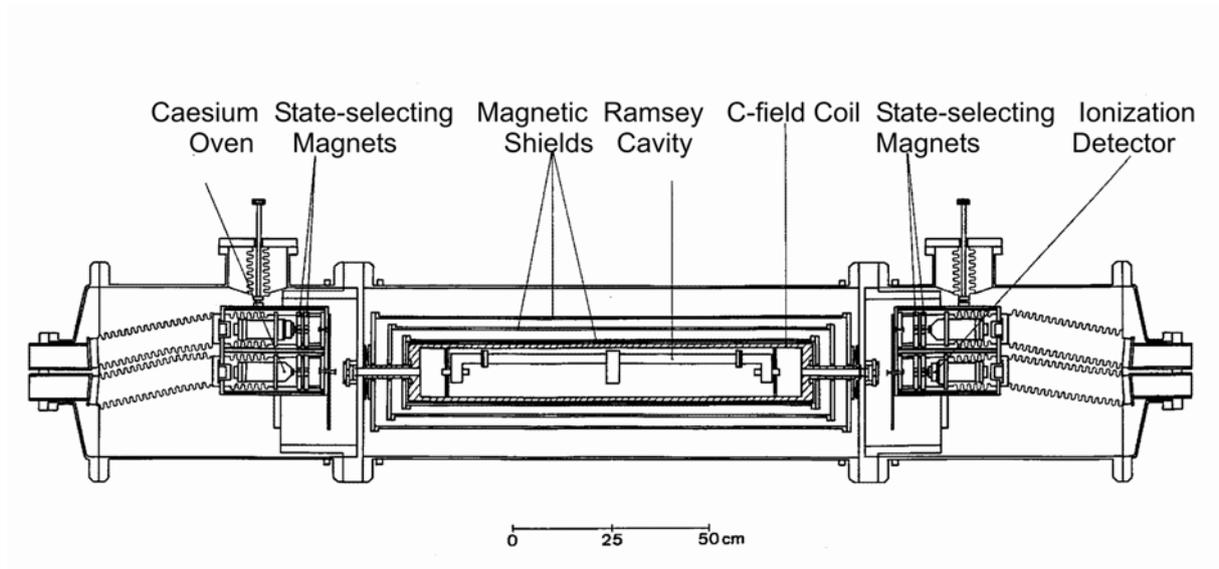


Figure 4. Horizontal section of CS2; for illustration the cavity is shown rotated by 90° around the horizontal axis, i.e., it is actually bent in a vertical plane. The units comprising an oven, a detector and associated magnets can be shifted between mechanically defined stops using handles. In addition, ovens and detectors can be adjusted with respect to their associated magnet stack.

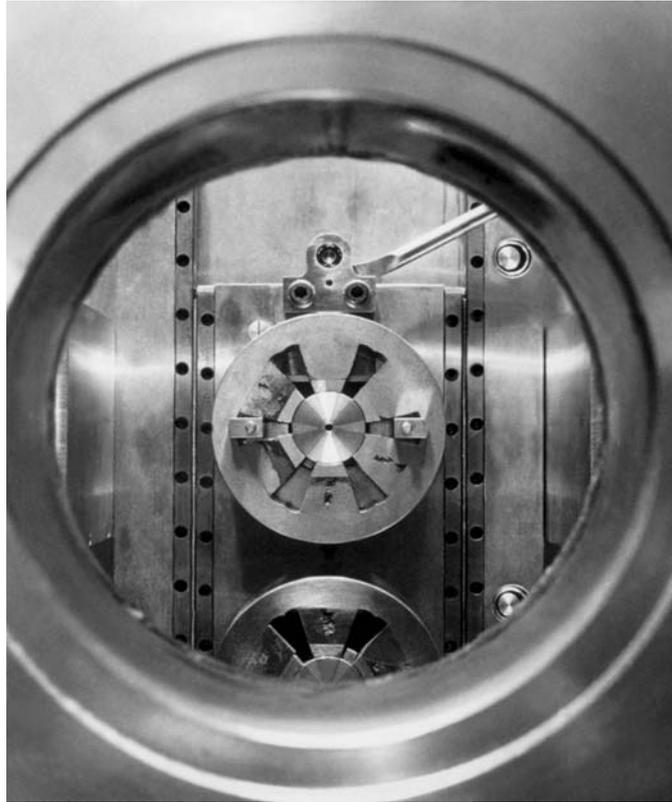


Figure 5. Photographic view through the outer flange into one of the CS1 end chambers along the atomic beam axis (before 1978).

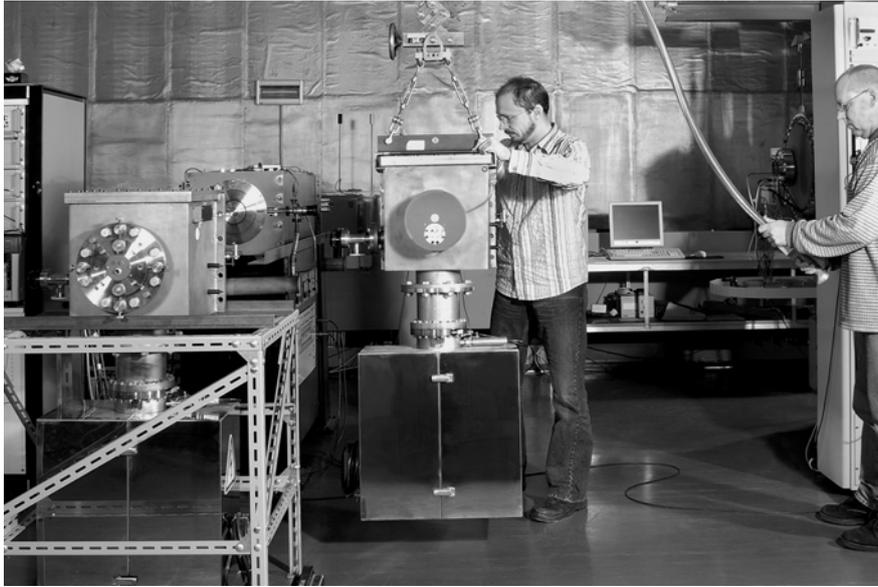


Figure 6. Snap-shot of CS1 operation practice: exchange of the oven and the detector vacuum chambers on 2005-01-13. The detector chamber rests aside while the oven chamber is carried around for being attached to the central vacuum chamber (T. Leder and C. Richter performing the work).

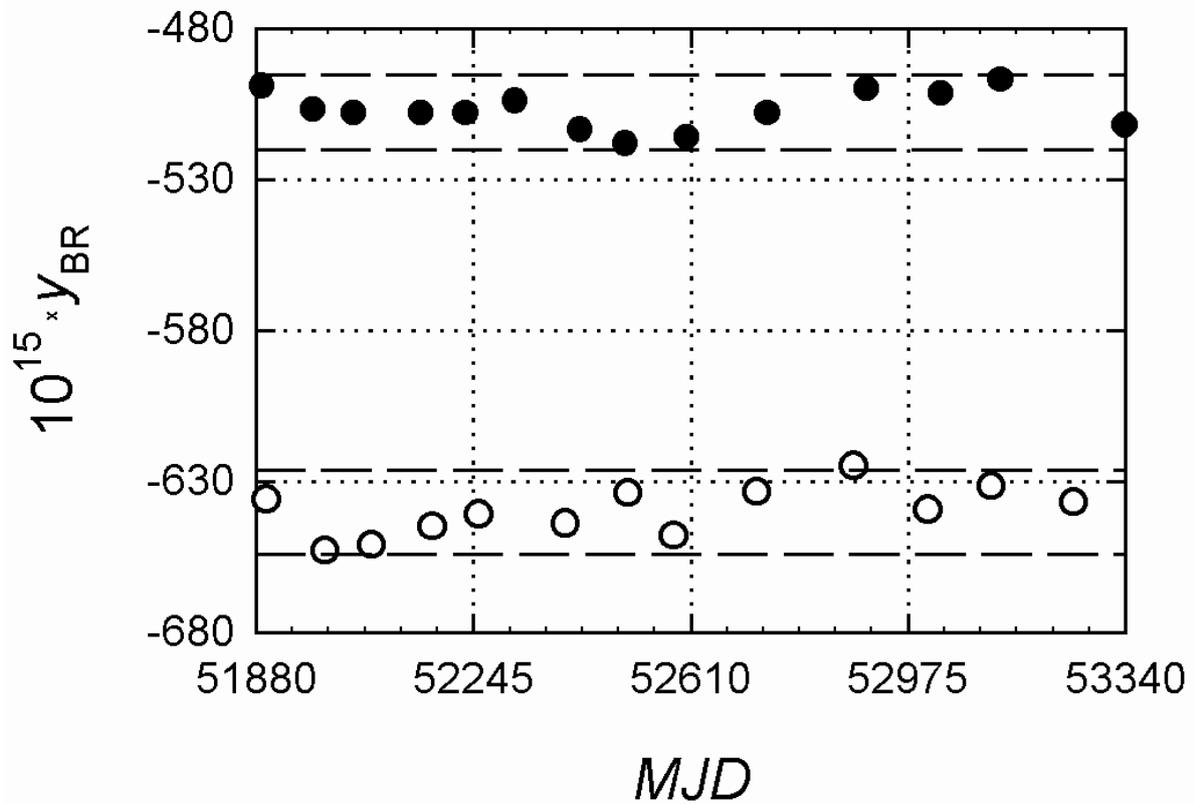


Figure 7. Relative beam reversal frequency shift y_{BR} , determined for CS1 (symbol O) and CS2 (symbol ●) since early 2001. Each data point represents the frequency difference of CS1 and CS2 in the two beam directions, respectively, referenced to a variable group of reference clocks and averaged over 14 days. The dashed lines represent the $2\text{-}\sigma$ limits based on the shot-noise limited performance for each clock. MJD is the Modified Julian Date, MJD 53340 = 2004-12-01.

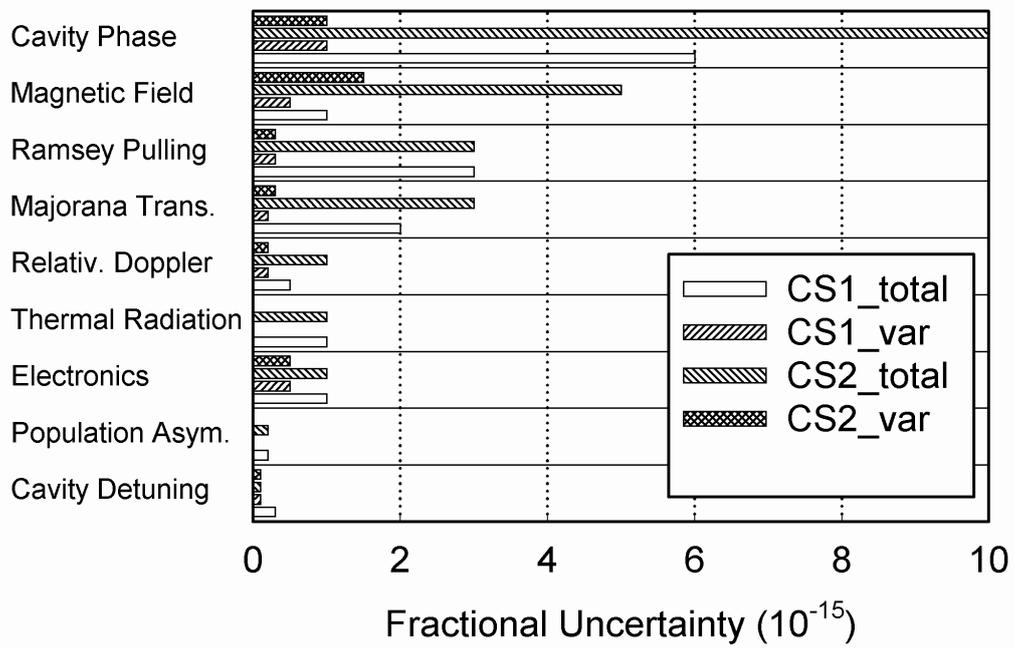


Figure 8. Contribution to the fractional uncertainty of the realization of the SI second with CS1 and CS2. Distinction is made between static (CS_n_total) and dynamic contributions (CS_n_var). The variable part is estimated based on the underlying physical laws and the observed variations of experimental parameters. The inset specifies the meaning of the four bars for each cause of (potential) frequency shifts.

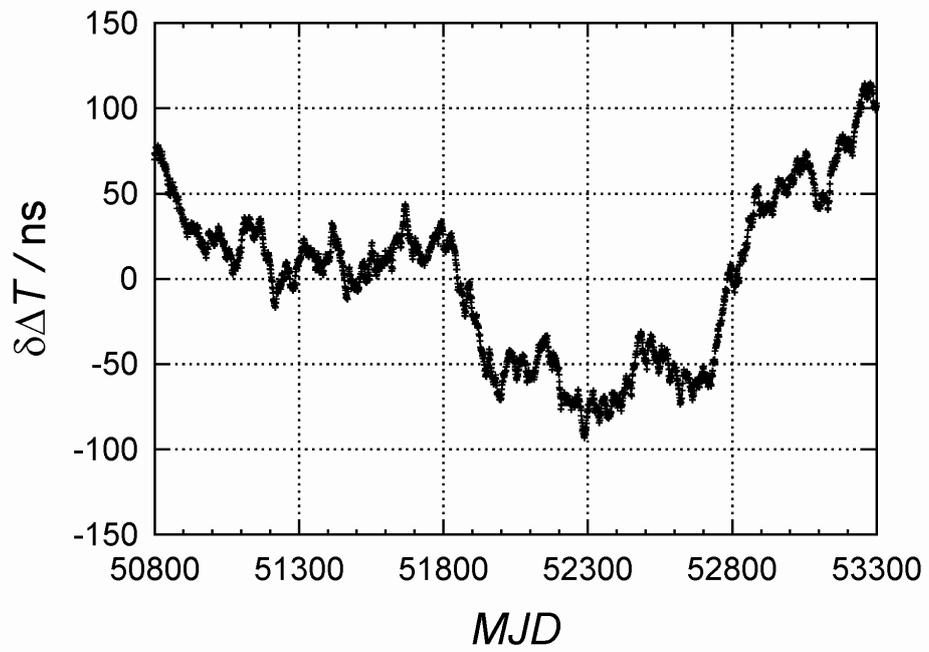


Figure 9. Residuals of a linear least squares fit to the time differences $T(\text{CS1} - \text{CS2})$ recorded between MJD 50800 (1997-12-18) and 53300 (2004-10-22).

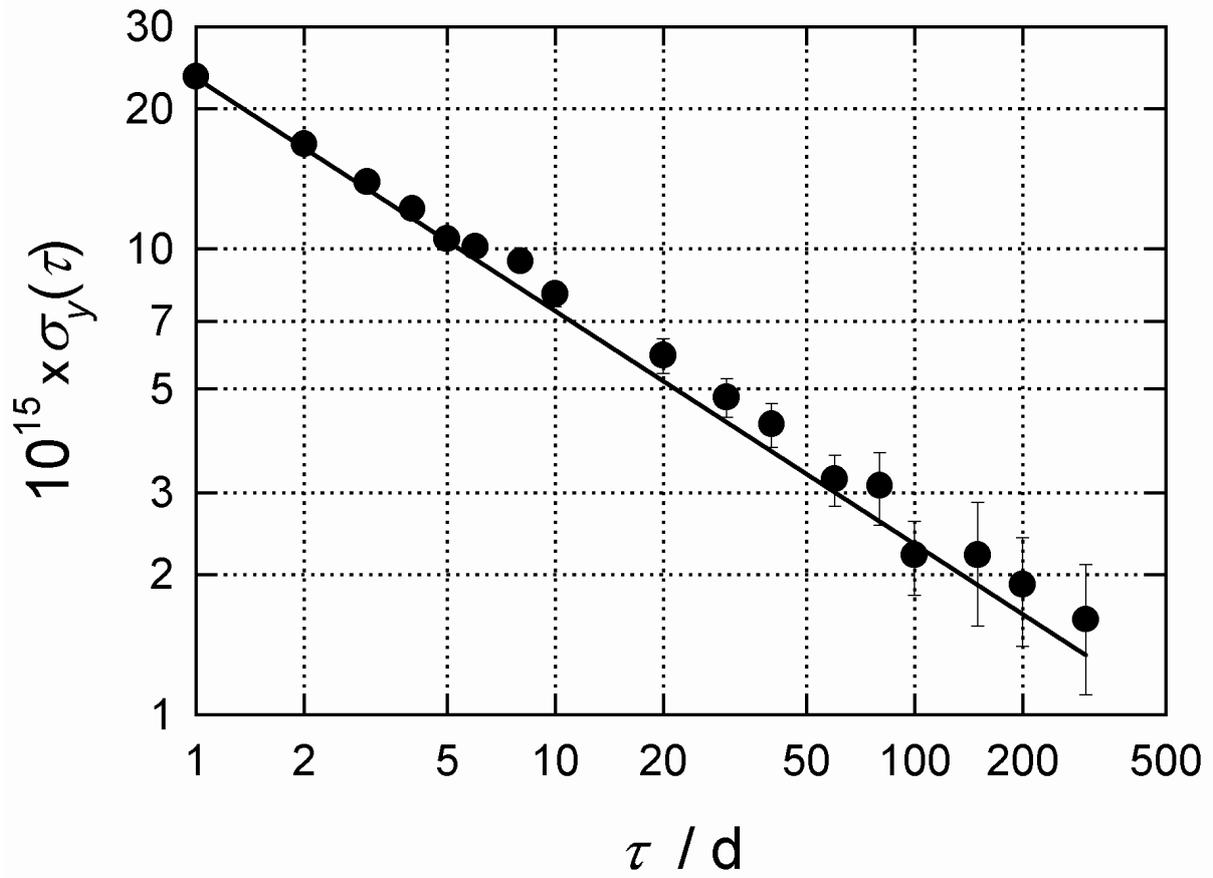


Figure 10. Relative instability of the frequency difference $y(\text{CS1} - \text{CS2})$, recorded between MJD 50800 and MJD 53300, expressed by the non-overlapping Allan deviation $\sigma_y(\tau)$.

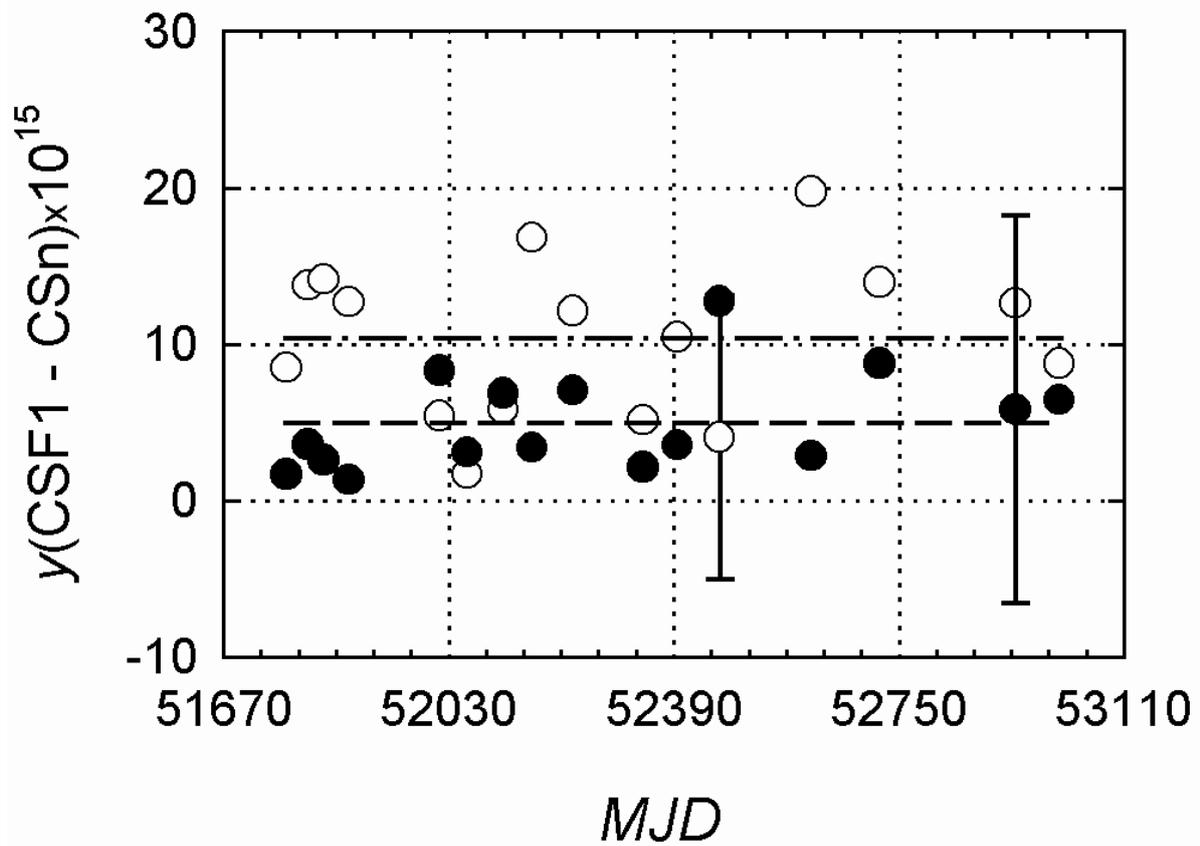


Figure 11. Relative frequency difference $y(\text{CSF1} - \text{CSn})$ obtained between 2000-08 and 2004-01 for CS1 (symbol O) and CS2 (symbol •). The horizontal lines show the mean frequency deviation. See text for explanations.

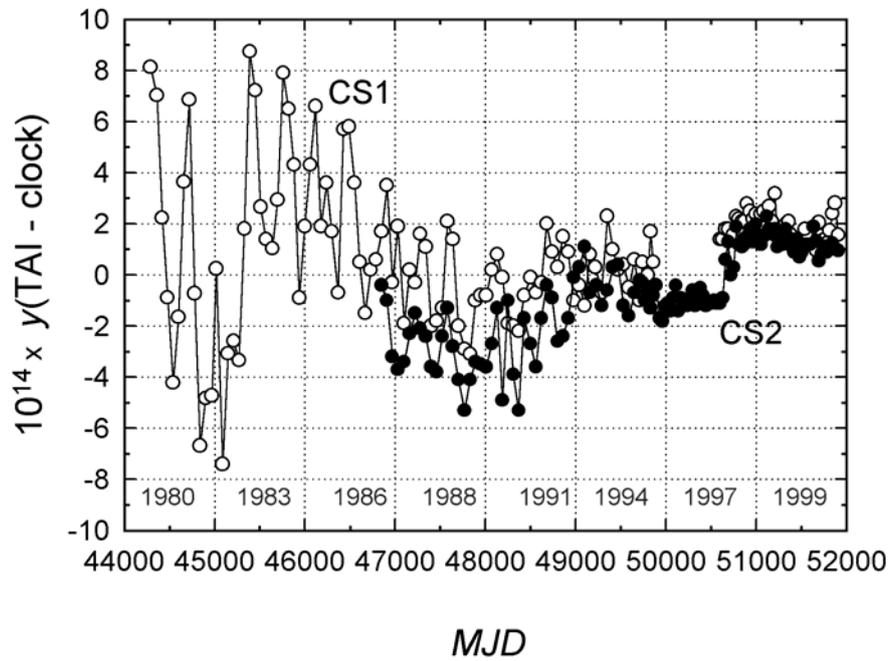


Figure 12. Long-term comparison of CS1 and CS2 with TAI, based on data published in Annual Reports of the Bureau International de l'Heure before 1988, and of the BIPM Time Section afterwards; relative frequency deviations y between the clocks and TAI for CS1 (symbol O) and CS2 (symbol •) between 1979-03 and 2000-12; year numbers below the plots allow an approximate orientation.

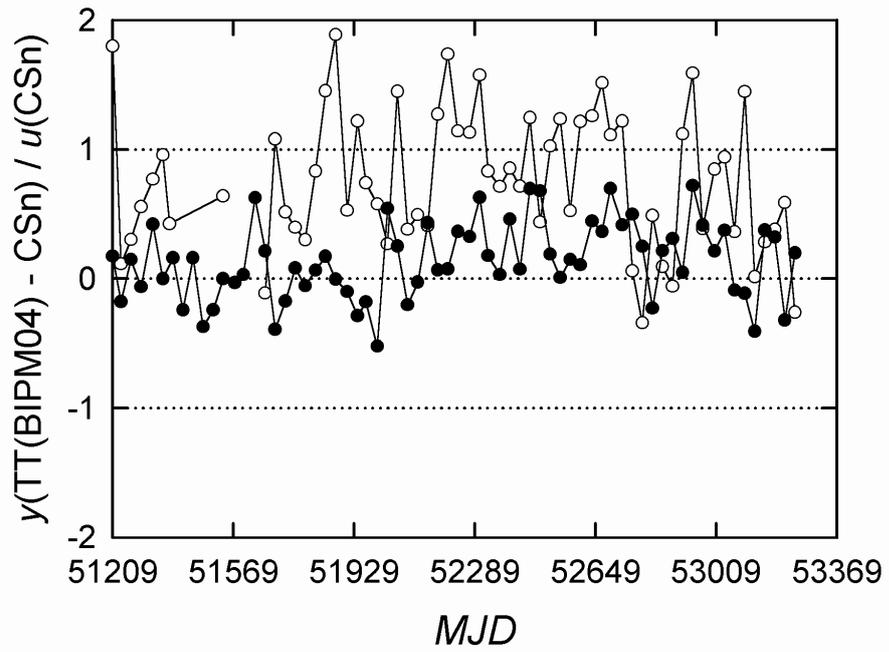


Figure 13. Comparison of CS1 (symbol O) and CS2 (symbol •) with TT(BIPM04) [22] between 1999 and mid 2004. The motivation for plotting the deviation normalized by the uncertainty u is given in the text.

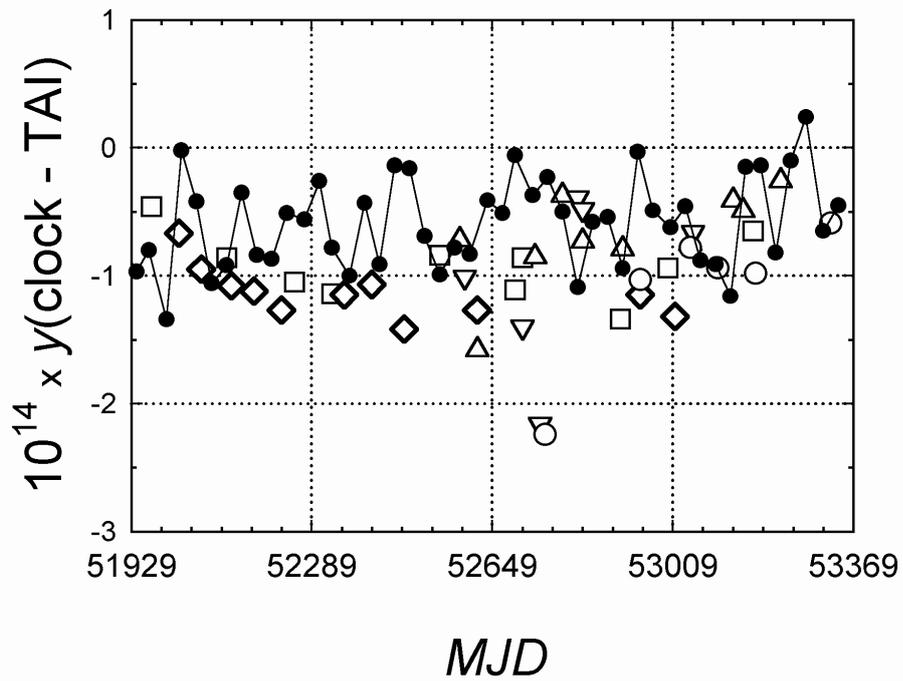


Figure 14. Comparison of CS2 (symbol •) and the fountain frequency standards FO2 (symbol Δ) and FOM (symbol ∇) of BNM Syrte, Paris, NIST-F1 (symbol \square), IEN-CSF1 (symbol \circ), and PTB CSF1 (symbol \diamond) with TAI during four years ending in November 2004. Source: BIPM Circular T, Section 6.