Time – the SI Base Unit "Second"

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Structure

1 Introduction

"Time is a strange thing ..."[1] . In fact, the SI base unit "the second" has a special position among the units: It is the SI unit which has been realized by far with the highest precision – and this is why other base units are defined or realized with reference to it. The metre, for example, has been a derived unit since 1983, defined as the length of the path travelled by light in vacuum during a time interval of 1/ 299 792 458 of a second. The realization of the volt – the unit of the electrical voltage – makes use of the Josephson effect, which links the volt with a frequency via the ratio of two fundamental constants, $h/(2e)$ (e: elementary charge, h: Planck's constant). All this will be dealt with in the various articles of this publication. But there are other remarkable facts: The only measuring instrument most people have on them in daily life is a watch. Time touches every person every day (at least in our civilization). For decades, indicating the time – an essential task for everyday life – has been the privilege of the authorities in town and in the country, and doing so is associated with prestige and has a direct influence on the life of the people. The transition from astronomic time determination to time determination on the basis of atomic clocks – which will be the subject of Section 2 of this article – has, therefore, been associated with all kinds of disputes in the scientific circles involved. In countries where the legal responsibilities are less clearly regulated than in Germany (in Germany, the regulation is based on the *Units and Time Act*), the rivalry between the interest groups continues to this day. The work which was started at the *Physikalisch-Technische Reichsanstalt* (Imperial Physical Technical Institute – PTR) in the early 1930s and continued at PTB in Braunschweig after 1950 has given an essential impetus to this transition.

In the following, a short survey of earlier definitions of the unit of time will be given, followed by sections dealing with the current definition and, thus, with the caesium atomic clock and international cooperation in the field of time measurement. Section 6 will then deal with the popular services which PTB makes available for the dissemination of legal time in Germany. To this day, research in the field of clock development is undertaken intensively. A research group announcing that it has achieved progress towards an even more exact clock can be sure to find the interest of the media. In Section 7, an answer will be given as to whom this will benefit.

2 The Definitions of the Unit of Time

2.1 The rotation of the Earth as the measure of time

People's natural measure of time is the day. It is defined by the rotation of the Earth around its axis. Following an old cultural tradition, it is subdivided into 24 hours, each comprising 60 minutes, with each minute comprising again 60 seconds [1, 2]. If one assigns the moment 12 o'clock to the zenithal culmination of the Sun, the true solar day is obtained as the period of time in-between. Due to the inclination of the Earth's axis relative to the plane of the Earth's orbit around the Sun, and due to the elliptical Earth's orbit, its duration changes during one year by up to ± 30 s. Averaging over the length of days of 1 year leads to the mean solar time, whose measure is the mean solar day d_m. Until the year 1956, its 86 400[th] part served as the unit of time, the "second". It was realized with the aid of high-precision mechanical pendulum clocks and, later on, with quartz clocks, to make – on the one hand – time measures and – on the other hand

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[1] Hugo von Hoffmannsthal, Libretto to the opera "The Rose Cavalier"

– the unit hertz (Hz = 1/s) available for frequency measurements. The mean solar time related to the zero meridian passing through Greenwich is called *Universal Time* (UT).

If time measures and time scales are derived directly from the recordings of the moments of star passages through the local meridian, these are falsified by the changes in the position of the axis of rotation in the Earth's body, the so-called "polar motion". This polar motion occurs, in particular, at a period of approx. 14 months and, in addition, accidentally. In the time scale called UT1, the predictable periodic portions have been eliminated so that UT1 is (almost) proportional to the angle of rotation of the Earth. The recordings of the planets' positions and of the Moon's orbit relative to the starry sky – dated in UT1 – collected over many years – revealed, however, that the duration of the mean solar day, too, is subjected to continuous changes [3]. There is, on the one hand, a gradual deceleration of the Earth's rotation by tide friction. 400 million years ago, for example, the year had 400 days. Mass shifts inside the Earth's body and large-scale changes in the sea currents and in the atmosphere lead, on the other hand, to a change in the moment of inertia of the rotating Earth and, thus, in its period of rotation. These effects which have been – partly – understood and are – partly – unpredictable, conceal the gradual deceleration. And as regards proof of the resulting seasonal variations – this is a topic we will still have to talk about!

2.2 Time and frequency at the PTR and in the early days of PTB

If we compare the quartz clock shown in Figure 1 – which was developed at the PTR in the 30s of the last century – with what we are wearing today as wrist watches, it becomes clear why we speak of a "quartz revolution" [4]. Although the contribution of the PTR – and later that of PTB – to this modern development has been comparably small, the success of the PTR was, however, of essential importance for the abandoning of the astronomic time determination. The motivation for the activities at PTR was the emerging of wireless communication traffic and the necessity of measuring the transmitter frequencies in the kHz and MHz range. For this purpose, E. Giebe and A. Scheibe developed frequency standards in the shape of luminous resonators: small quartz rods equipped with electrodes in glass flasks filled with a neon-helium gas mixture which were excited to a glow discharge as soon as the frequency of an electrical a. c. field at the electrodes agreed with one of the mechanical resonance frequencies of the tuning fork [5]. The relative measurement uncertainty was between 10^{-6} and 10^{-7}. Maintaining the form of the tuning forks, these were later integrated into an electric oscillator circuit, as had been shown before in a similar way by W. G. Cady, G. W. Pierce and W. A. Marrison [6]. Until 1945, a total of 13 quartz clocks had been developed at the PTR. Their rate stability, which was superior to that of pendulum clocks, motivated the *Geodätisches Institut Potsdam* and the *Seewarte Hamburg* to fabricate four of these clocks – or two, respectively – in accordance with the design principle of the PTR.

To link the frequency which had been realized with the quartz clocks up with the astronomically defined unit, the PTR received the signals of the time signal transmitter Nauen, checked by the *Seewarte Hamburg*, and of the transmitters Rugby (UK) and Bordeaux (F) which – in the course of 1 day – all emitted time signals in the frequency band around 16 kHz (wavelength: 18.5 km). In the rate of the quartz clocks, long-term – and obviously deterministic – fluctuations occurred relative to the time signals received and were corrected by the "improvements" of the broadcasting times subsequently published. When these fluctuations occurred on several clocks of sufficiently different construction, A. Scheibe and U. Adelsberger judged this – already in 1936 – as an indication of periodic fluctuations of the period of the Earth's rotation [7]. Meticulously, they tried to improve and to document the quality of their clocks. In doing so, they – first of all – had to convince the protectionists of the superiority of mechanical pendulum clocks, rather than the astronomers, who were very well informed about the irregularity of the Earth's rotation [8]. Figure 2 shows the – probably most frequently published – measurement result obtained with quartz clock III. After

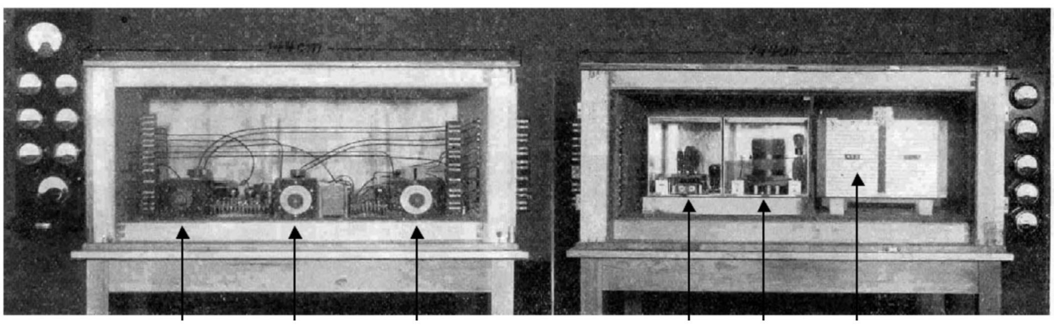


Figure 1:
Quartz clock of the PTR, constructed after 1935; the arrows – from left to right – point to 3 frequency dividers, 3:1, 10:1, 6:1, to amplifiers, control transmitter and, at the far right, to the internal thermostat with the tuning fork.

the war, A. Scheibe and U. Adelsberger described this phase of the PTR's work in detail [9]. Later on, they tried very hard to furnish proof of a regularity of the oscillations of the Earth's rotation period. Meanwhile, it has been shown by means of considerably improved observation methods and clocks that from the Earth's rotation, the time unit cannot be derived better than to a relatively few 10^{-8}: In addition to the periodic changes, there are also non-predictable changes in the Earth's moment of inertia.

After the war, the development of quartz clocks was resumed at PTB and continued until the 1960s in the quartz clock cellars of the Giebe Building [10]. The aim was to minimize the dependence of the clock frequency on temperature, air pressure, electric operating parameters, and on the typical aging of the quartz resonator which leads to a drift of the clock frequency. Until mid-year 1970, the generation of standard frequency and time signals for emission with the long-wave transmitter DCF77 (see Section 6) was based on quartz clocks, before rubidium atomic clocks were installed at the Mainflingen transmitter [11].

2.3 The course of the year as a measure of time – the ephemeris second

The Earth apparently revolves uniformly around the Sun. For this reason, it was suggested to use the period of the Earth's revolution to determine the unit of time and, in 1956, the second was redefined as a fraction of the so-called "tropical year" – called the *ephemeris second*. The tropical year is the period between two successive spring equinoxes. As this period is alterable in a known, regular way due to the precession and nutation of the Earth's axis, the 31st of December 1899, 12 o'clock Universal Time of the differential tropical year, was referred to as the centre point [12, 13]. The defined number of the Universal Time seconds in this tropical year is based on a calculation by Simon Newcomb from 1895; he had evaluated astronomic observations from the years 1750 – 1892 and had determined the mean ratio of the periods of Earth rotation and Earth revolution.

From the Earth's revolution, however, points in time cannot be read so exactly that a more precise unit of time could actually ever be derived for practical use. Here, only the "atomic" definition of the unit of time led to real progress. One could shrug this off as an episode in history, but the effects have lasted up to the present day. As – during the period of time observed by Newcomb – the Earth had rotated faster than it does today, both atomic seconds as well as ephemeris seconds are, by definition, shorter than Universal Time seconds nowadays. This has brought us – to this day – the leap seconds [13].

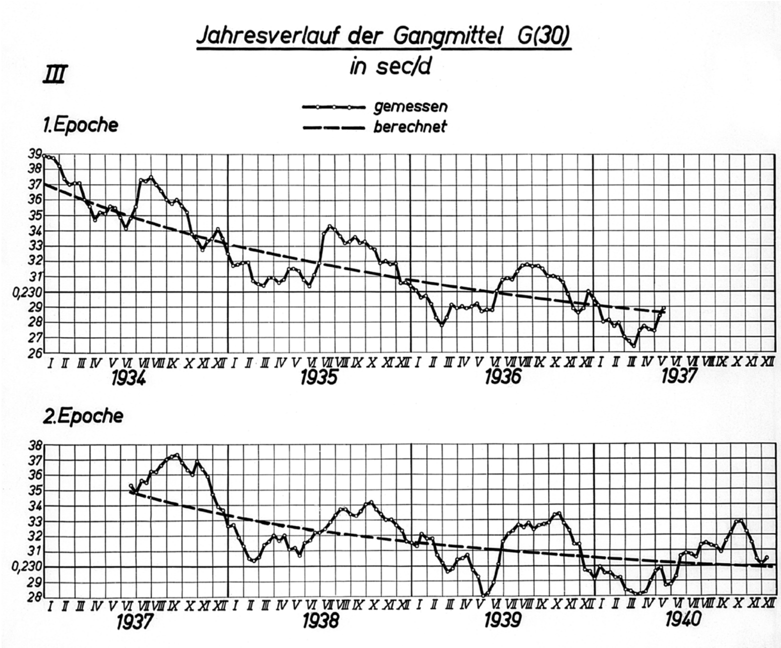


Figure 2:
Rate of quartz clock III of PTR, related to a pilot clock connected to the astronomic time scale; the seasonal oscillations superimpose the systematic rate change due to aging (broken curve); the vertical scale corresponds to the length of day minus 86 400 s, given in seconds.

2.4 The "atomic" definition of the second

The interaction between the positively charged nucleus and the shell of negatively charged electrons of the atoms causes the formation of stable configurations of the electron shell, whose regularities are indicated by quantum mechanics. This theory predicts, among other things, how the binding energy of these configurations – also called *eigenstates* of the atom – depends on fundamental constants such as, for example, the electron-to-proton mass ratio, the elementary charge, the speed of light and the so-called fine-structure constant α. One of the basic assumptions of most of the physical theories is that the designation "constants" is justified and that the energy distance between eigenstates is, therefore, also constant. Already in 1870, the English physicist James Clerk Maxwell had proposed using such fundamental constants – as a matter of principle – for the determination of the physical units, and not to refer to measures furnished by the Earth – such as the length of day for the second, or the circumference of the Earth for the metre.

A transition between two atomic eigenstates with an energy difference ΔE is associated with the absorption or emission of electromagnetic radiation of the frequency $f = \Delta E/h$. Accordingly, the frequency f or the period $1/f$, respectively, of such a radiation is basically constant – in contrast to the period of the Earth's rotation and, even more, the oscillation period of a pendulum. A specific multiple of $1/f$ could be defined as a new unit of time – this had already been proposed by the Englishman Louis Essen in 1955 – using the transition between the hyperfine structure level of the basic state of the caesium-133 atom. But the time for such a radical change in the concept for the definition of the second was not yet mature then. Shortly before, Essen and his colleagues had put the first caesium atomic clock (abbreviation: Cs clock) into operation at the English National Physical Laboratory, Teddington [14]. From 1955 to 1958, the duration of the unit of time valid at that time – that of the ephemeris second – was determined in cooperation with the United States Naval Observatory, Washington, to be 9 192 631 770 periods of the Cs transition frequency [15]. A discussion of the measurement uncertainty for this numerical value furnished the value 20 – although nobody seriously believes that it was possible to indicate the duration of the ephemeris second to relatively $2 \cdot 10^{-9}$. Nevertheless, this measurement result provided the basis for the definition of the unit of time in the International System of Units (SI) which was decided in 1967 by the 13th General Conference of Weights and Measures (CGPM) and which is still valid today:

"The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom."

In the middle of the 1950s, PTB started to work on atomic frequency standards. In addition to initial tentative work on caesium, the 23.8 GHz inversion oscillation in the NH3 molecule was excited in the so-called ammonium maser and later, the 1.4 GHz transition in atomic hydrogen was used for the construction of a hydrogen maser. However, in the end, only the development of the caesium atomic clock in the "Unit of Time" laboratory, directed by Gerhard Becker, was successful and will be described in further detail below.

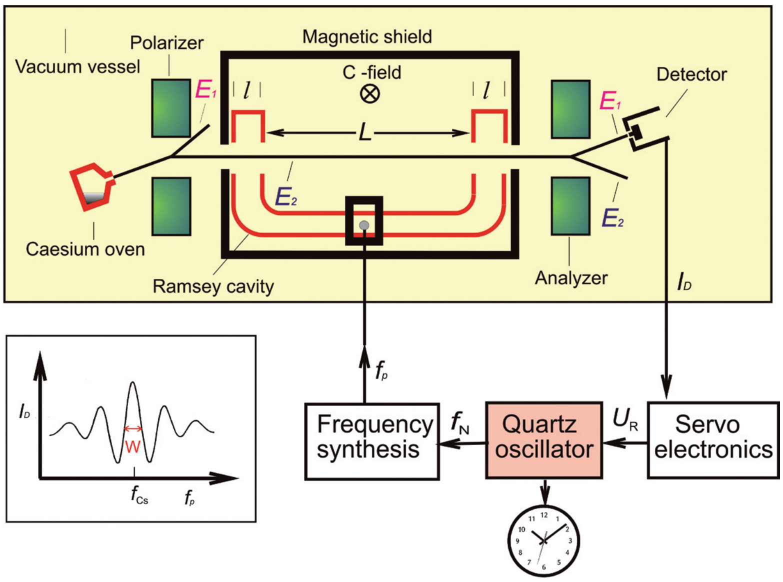


Figure 3:
Cs-clock, schematic representation; f_N: standard frequency, f_p: frequency for irradiation of the atoms, I_D: detector signal, U_R: signal for regulation of the quartz oscillator; Insert on the left: detector signal I_D as a function of the frequency of the microwave field f_p if it is tuned across the resonance point at f_{Cs}; the linewidth W is indicated.

3 Realization of the SI Second

3.1 The caesium atomic clock

Any clock can be imagined to consist of 3 parts: an internal clock generator (pendulum, balance, oscillation of a quartz); a counting mechanism, which counts the clock rate events and indicates their number; and an energy source (weights, spring, electric energy from battery or electrical connection). The special feature of an *atomic clock*, however, is that the clock rate is derived from single, free atoms, which is basically possible with different elements. The isotope caesium-133 has proved to be particularly suited for this because it allows a high-precision, infallible and compact clock to be constructed with comparably simple means.

Figure 3 illustrates the functional principle of a Cs clock as it has been built since the middle of the 1950s and is still used today: Based on a quartz oscillator, a microwave field of the frequency f_p is generated by means of a frequency generator and coupled into the resonance apparatus (see the large rectangle shaded in yellow). f_p already suits the transition frequency of the caesium atoms f_{Cs} quite well. In the apparatus, a Cs atomic beam is produced in vacuum by heating caesium to approx. 100 °C in the oven. The beam passes a first magnet – called the "polarizer" – which diverts only atoms in the energy state E_2 into the desired direction. These atoms fly through the Ramsey cavity (named after Norman F. Ramsey, who won the Nobel Prize in 1989). In the two end sections of the length l of the resonator, the atoms are irradiated with the microwave field. In this way, the transition between the two energy levels is excited with a certain probability. This maximum probability and, thus, the maximum number of atoms in the state E_1 behind the resonator are achieved when the resonance condition is complied with, i.e. when f_p and f_{Cs} exactly agree. The analyzer magnet now deflects especially E_1-atoms onto the detector where Cs atoms become Cs^+ ions, and from the ionic current an electrical signal I_D is obtained. If f_p is tuned over the resonance point, a so-called "resonance line" (see Figure 3) appears when the signal I_D is recorded. Its linewidth W is given by $W \approx 1/T$, with T being the time-of-flight of the atoms through the resonator having the length L. Now: How can the resonance point be found? For this purpose, f_p is modulated around f_{Cs}, and the resulting modulation is detected in the detector signal I_D. From this, the voltage bias U_R is obtained by means of which the quartz oscillator is tuned in such a way that f_p gets, on average, into agreement with f_{Cs}. In this way, the natural oscillations of the quartz frequency are suppressed in accordance with the adjusted control time constant. The atomic resonance then determines the quality of the emitted standard frequency f_N (usually 5 MHz). However, if a short electrical impulse is generated after each 5 million periods of f_N, the successive impulses have the temporal distance of 1 second – with atomic accuracy.

3.2 Systematic frequency uncertainty and frequency instability

Much ado is made of the accuracy of the atomic clocks, and the question is posed what this accuracy is good for (see Section 7). In the following, we will, therefore, briefly describe what is to be understood – in the narrow sense – by “atomic accuracy”. When the transition between atomic energy levels is excited, the maximum transition probability – i. e. the middle of the resonance line – is recorded at a value of the excitation frequency which never agrees exactly with the resonance frequency f_0 (here: 9 192 631 770 Hz) for undisturbed atoms at rest. As the term “accuracy” is used in English, we use the composite term *frequency accuracy* in German to describe the agreement between the actual value and the desired value of the output frequency (1 Hz, 5 MHz, etc.) of a clock. Metrologically correct is the following procedure: A detailed list of all possible “disturbing” effects is laid down in the so-called uncertainty budget of a (primary) clock. This uncertainty budget contains the quantitative assessment of all effects which lead to a deviation of the realized transition frequency from that which is to be expected in undisturbed atoms at rest. As the relevant physical parameters as well as the theoretical relations are known to a limited extent only, such an assessment is affected by an uncertainty. As the final result, a combined uncertainty value is determined, and this quantity will be mentioned several times in the following. The practical consequence of this – not really exact – knowledge is: Not even an atomic clock is perfect: two clocks will always exhibit slightly different rates. *Rate* refers to the change in the *reading* of a clock relative to a reference clock: If yesterday, the difference of the reading was ΔT_1 and it is ΔT_2 today, the rate of the clock is calculated to be $(\Delta T_2 - \Delta T_1)/1$ day. Typical of atomic clocks is a rate of a few nanoseconds per day. If this is written as a relative frequency difference, one obtains multiples of 10^{-14}.

The uncertainty budget of Cs clocks contains contributions which depend on the velocity of the atoms (Doppler effect), but also on electric and magnetic fields along the trajectory of the atoms. This is why the magnetic shielding shown in Figure 3 is used.

The output frequency of atomic clocks – and generally of electric oscillators – is, as has already been said, subject to systematic – but also statistical – influences. The oscillations of the output frequency of a Cs clock are, for example, associated with the statistically varying number of atoms arriving at the detector, and these variations – quite clearly – become smaller, the larger the number of atoms and the larger the processed signal. In literature, a great number of representations of the respective characteristics, of their calculation and of their interpretation can be found [16] which are indispensable for both the understanding of the properties of the clocks and the selection in special applications. In the following, some terms will be briefly presented.

The quasi-sinusoidal output voltage of a frequency standard is described by

$$V(t) = V_0\,(1 + \varepsilon(t)) \cdot \sin\{2\pi\nu_0 t + \Phi(t)\}, \tag{1}$$

V_0, ν_0 being the nominal amplitude and frequency, and $\varepsilon(t)$ and $\Phi(t)$ the momentary amplitude or phase variations. As additional quantities, we introduce the relative frequency deviations $y(t) = \mathrm{d}\Phi/\mathrm{d}t\,/\,(2\pi\nu_0)$. The statistical parameter most widely used for the relative frequency instability is the Allan variance

$$\sigma_y^2(\tau) = \left\langle \left(\bar{y}_{k+1}(\tau) - \bar{y}_k(\tau)\right)\right\rangle^2, \tag{2}$$

which links successive frequency differences with each other which, then in turn, present mean values over time τ. The usual case is a double-logarithmic plotting of $\sigma_y(\tau)$ as a function of τ. In this representation, different instability contributions can, in many cases, be identified by means of the slope of the $\sigma_y(\tau)$ graph. Figure 4 (on the right) and Figure 5 represent such “sigma tau diagrams”. They show the duration of the observation times needed to achieve a desired measurement uncertainty – and they also show whether the frequency standard is possibly not at all suited for the measurement task.

3.3 Commercial atomic clocks

Since the end of the 1950s, Cs-clocks have been offered commercially, and today approximately 200 of them are produced annually worldwide. Already in the early 1960s, PTB made use of a commercial atomic clock – called the “atomichron” [17] – to monitor the rates of the quartz clocks in Braunschweig and Mainflingen. Over the course of years, we have come to understand the interfer-

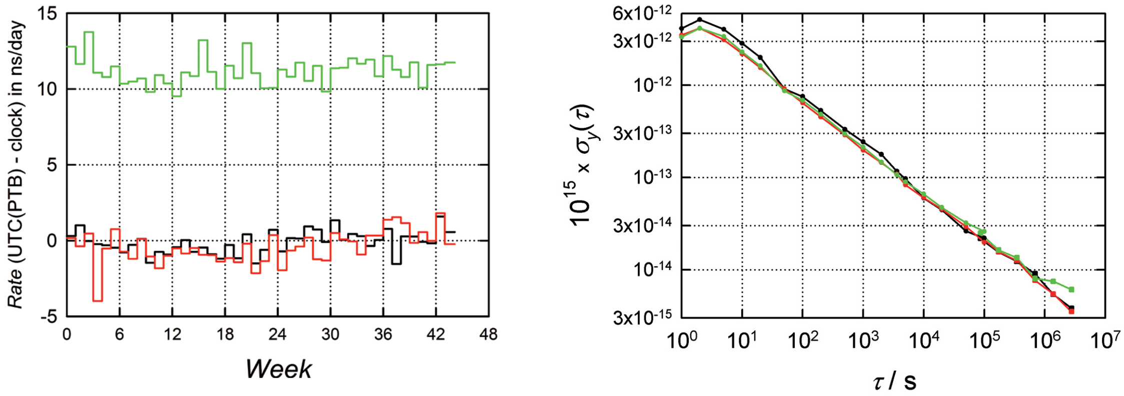


Figure 4:
Rates (on the left) and relative frequency instability (on the right) of the three commercial caesium clocks of PTB during 43 weeks of the year 2010. The week referred to with "0" starts with 28 January. UTC(PTB) serves as a reference for the investigations.

ing parameters and the regularities of its effect better and better and to reduce the uncertainty. At present, the best models realize the SI second with a relative uncertainty of a few 10^{-13} and a relative frequency instability of a few 10^{-14} averaged over a period of 1 day. They are used in the following fields of work: Navigation, geodesy, space science, telecommunications and in the time-keeping institutes (such as PTB). At present, PTB operates, for example, 6 of these clocks – three in Braunschweig and three at the DCF77 transmitter (see Section 6). Figure 4 shows the rates of the clocks in Braunschweig, recorded in 2010, and their relative frequency instability.

The principle of the atomic clock can also be realized with elements other than caesium. In most atomic clocks produced worldwide, the respective hyperfine-structure transition in the atom rubidium-87 is used. The number of these clocks produced per year probably amounts to some ten thousands, and they can be found in telecommunications facilities, in the fixed network and in base stations of the mobile services. The hydrogen maser is based on the hyperfine structure transition in the ground state of the atomic hydrogen at 1.4 GHz and is – due to its particularly stable output frequency – used for averaging periods of up to a few hours, in particular as a frequency reference in radioastronomy. Figure 5 shows the stability properties of commercial frequency standards that are presently available, along with values of primary clocks. These will be discussed below.

3.4 The primary clocks CS1 – CS4 of PTB

In the mid 1960s, PTB started to make efforts to develop a caesium atomic clock of its own and these efforts were – eventually – successful. Holloway and Lacey had proposed improving essential details of the construction principles selected originally by Essen and Parry [18] and, in the next few years, the new ideas were implemented by PTB in CS1. The following points were regarded as essential advantages [19]:

- Reduced instability due to a two-dimensional focussing of the atoms with magnetic lenses (instead of the dipole magnets sketched in Figure 3);
- Axial-symmetric geometry of the atomic beam with small radial extension;
- Improvement of the inhomogeneity of the magnetic field by use of a long cylindrical coil and cylindrical shielding – instead of a magnetic field transverse to the beam direction.

In 1969, CS1 was used for the first time [20]. In the years thereafter, a gradual reduction in the frequency uncertainty was achieved so that PTB took a leading position in the development of primary clocks. As early as in 1974, work on CS2 started on the basis of CS1. It would, however, take several years – until 1985 – for the clock to be put into operation [21] (but then all good things are worth waiting for!). In addition to a small frequency uncertainty, it was their robustness as well as the simplicity of everyday operation which was characteristic of the two clocks and, therefore, they were operated continuously in the next decades and became – deservedly – the showpiece of the laboratory. They were updated in several steps, and since 1999, their relative frequency uncer-

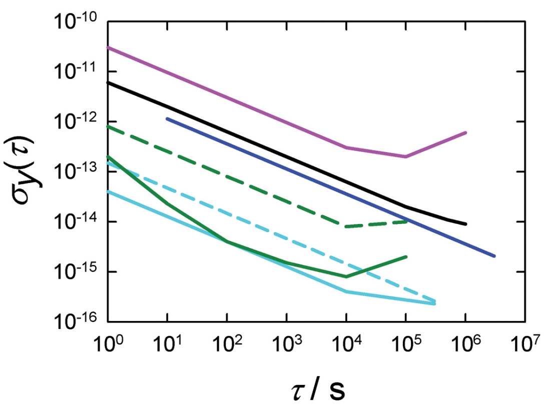


Figure 5:
Relative frequency instability $\sigma_y(\tau)$ of different atomic frequency standards. Magenta: rubidium standard, standard values; black: caesium atomic clock Symmetricom 5071A (see Figure 4) broken green line: passive hydrogen maser; green line: active hydrogen maser, standard values; cyan: measured instability of the fountain clocks FO-2 of the LNE-SYRTE and CSF1 of PTB (broken line); blue: measured instability of the primary caesium clocks CS1 and CS2 of PTB compared over 8 years.

tainty has been assessed to be $8 \cdot 10^{-15}$ (CS1) and $12 \cdot 10^{-15}$ (CS2) [22]. Their role in the realization of the International Atomic Time is acknowledged in Section 4, whereas a detailed description of their development and properties can be found in [23]. Figure 6 shows a current photo of the two clocks.

Less successful was the development of other clocks on the basis of the same construction principle, CS3 and CS4, which began as early as in 1980. The idea to select slower atoms by constructing the magnetic lenses correspondingly and, thus, achieve a smaller linewidth was – basically – correct, and the objective to reach also a smaller frequency uncertainty was also almost reached. But – in spite of the great commitment of the staff – the desired operational reliability was never achieved. Finally after completion of the – much more exact – caesium fountain CSF1, this effort did not make sense any more, and the clocks were dismounted.

Figure 6:
PTB's primary clocks CS1 and CS2.

3.5 The caesium fountains CSF1 and CSF2

One of the main objectives in the further development of atomic clocks has always been to extend the time in which the atoms interact with the microwave field and – thus – reduce the linewidth. This promised, at the same time, a smaller frequency instability and a smaller frequency uncertainty. When laser cooling was discovered and understood in the middle of the 1980s [24], its importance for clock development was recognized immediately. At PTB, the new atomic clocks CSF1 [25] and, later on, CSF2 were developed, which are shown in Figure 7 [26]. Although the principle shown in Figure 3 is still applied, the new – and very important – feature is that it is laser radiation which is used to influence the state of energy and the movement of the atoms [27]. Laser cooling in a magneto-optical trap or in optical molasses furnishes “cold” atoms with a thermal velocity of approx. 1 cm/s. Expressed in the temperature unit, this corresponds to a few millionths of kelvin – compared to the 300 kelvin of the environment. These cold atoms are placed on trajectories, as outlined in Figure 8. The time-of-flight T of the atoms above the microwave resonator is 50 times longer than the respective time-of-flight T in CS2. The resonance line, to the centre of which the microwave oscillator is stabilized, is correspondingly narrower. With a relative uncertainty of only approx. $1 \cdot 10^{-15}$, CSF1 and CSF2 already come quite close to an ideal clock. Comparisons with CS1 and CS2 allow their frequency uncertainty – which previously could only be estimated – to be verified now. According to these revisions, CS2 agrees well with CSF1 within the uncertainty of 1 σ. In the case of CS1, a deviation of approx. $9 \cdot 10^{-15}$ is found. Since the beginning of 2010,

Figure 7:
The two caesium fountains CSF1 and CSF2, with Dr. Stefan Weyers, Head of the “Time Standards” Working Group.

CSF1 has been used as a frequency reference for the realization of the time scale at PTB. Unlike conventional clocks, CSF1 does not furnish any second pulses which directly represent a time scale. In fact, the output frequency of CSF1 is compared with that of a hydrogen maser. From that comparison, a correction of the maser frequency is calculated, and the time scale is derived from the maser corrected with it.

4 Atomic Time Scales: TAI and UTC

A time scale is defined by a sequence of second marks which starts from a defined beginning. *International Atomic Time* TAI (Temps Atomique International) – and especially *Coordinated Universal Time* (UTC) – allow events in science and technology to be dated. At the same time,

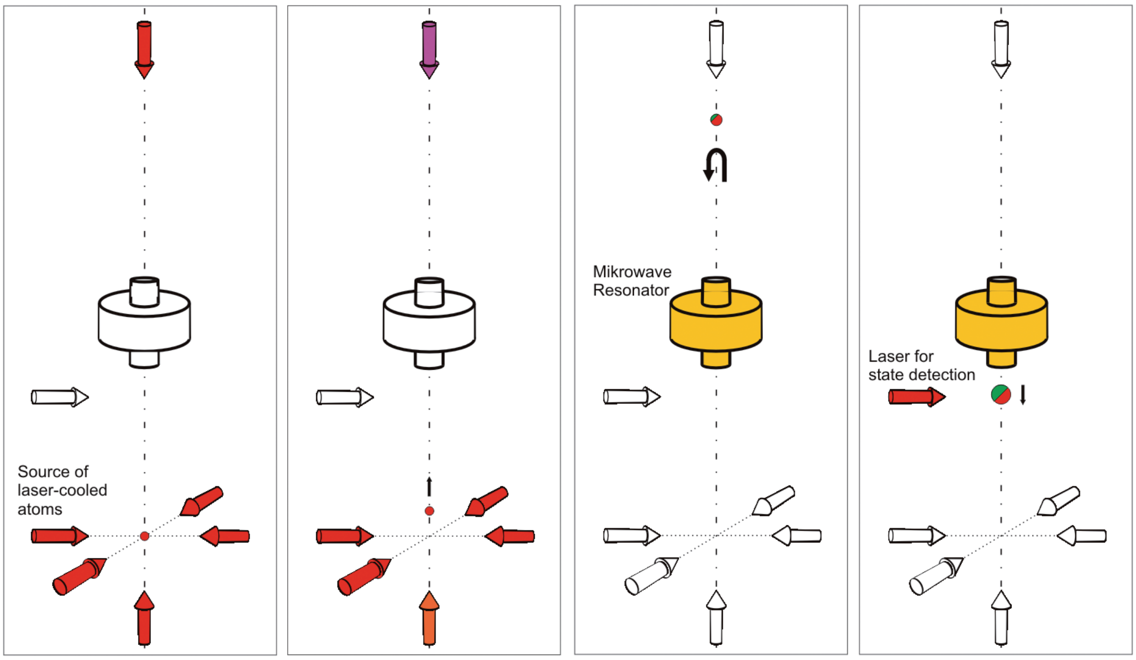


Figure 8:
Function of a fountain frequency standard, represented in four time-dependent steps from the left to the right; laser beams are illustrated by arrows (white, if blocked).
1) Loading of an atomic cloud;
2) Throwing the cloud up by detuning the frequency of the vertical lasers;
3) Dilatation of the initially compact cloud due to the thermal energy which remains in spite of the cooling. The atoms fly upwards and downwards through the microwave resonator, and a specific population of the two hyperfine structures is reached;
4) After the second passage of the microwave resonator, the population of the state is measured by laser irradiation and fluorescence detection.

UTC provides the basis of the “time” that is in use in everyday life. Since 1988, the *Time Department* of the BIPM (Bureau International des Poids et Mesures) has been charged with its calculation and propagation. For its calculation, approx. 350 clocks from approx. 70 time-keeping institutes, distributed all over the world, are used. From PTB, the measurement values of the primary clocks CS1 and CS2, of the three commercial caesium clocks and, since around 1990, of the hydrogen maser have been transmitted. The algorithm used to combine all data is designed in such a way that it reliably produces an optimized, stable time scale over an averaging period of 30 days. For this purpose, statistic weights – which follow from the rate behaviour of the clocks during the past 12 months – are assigned to the contributing clocks when their rates are averaged. The more stable the rate of a clock, the higher its statistic weight. The mean obtained in this way is called EAL (Echelle Atomique Libre, free atomic time scale). In a second step, TAI is obtained, whose scale unit is to agree with the SI second as it would be realized at sea level, i. e. it shall be as long as indicated in the definition of the second (see Section 2.4). For this purpose, the TAI second is adapted to seconds realized with primary standards. In 2009 and 2010, 14 standards were involved. With its clocks CS1 and CS2 and the two caesium fountains CSF1 and CSF2, PTB has, for many years, taken a prominent position worldwide. No other standard worldwide has transmitted so many measurement values as CS1 and CS2: From CS2, for example, values for 288 months in succession (including August 2010) were transmitted.[2] For a number of years, only these two clocks have been available worldwide for this purpose. Figure 9 shows current measurement values of all fountain clocks relative to the – already controlled – time scale TAI. Accordingly, the TAI second agrees very well with the SI second, the deviation is exactly known. A discussion of the mean offset and of the scattering of the single values would go beyond the scope of this essay.

The beginning of TAI was defined in such a way that the 1st of January 1958, 0 o'clock TAI, agreed with the respective moment in UT1 (see Section 2.1). From TAI one obtains UTC, which is the basis of today's universal time system with 24 time zones. UTC results from proposals of the CCIR (Comité Consultatif International des Radiocommunications) of the ITU (International Telecommunication Union). According to these proposals, the emission of time signals should be “coordinated” worldwide, i. e. it should be related to a common time scale. If TAI had been used for it, the time signals would have been shifted gradually with respect to the indication of a universal time clock, i. e. the moment 12:00 o'clock would have been shifted with respect to the highest position of the Sun at the zero meridian. The latter follows from the adaptation of the duration of the atomic second to the ephemeris second described above.

For navigation according to the position of celestial bodies, knowledge of UT1 is necessary, and time signals have been emitted since the early 20th century, in particular due to the requirements of navigation. Since in the 1960s, astronomic naviga-

[2] Then the whole thing stopped – the caesium filled in in 1989 had been used up. Since December 2010, CS2 has been ticking again!

tion was still important, it was decided to introduce the following rule [13]: UTC and TAI have the same scale unit, the difference between UTC and UT1 is, however, limited by leap seconds in UTC to less than 0.9 seconds. From this, the stair curve shown in Figure 10 follows for UTC–TAI (beginning with January 1, 1972) which closely follows the monotonous curve of UT1–TAI. The leap seconds are inserted at the turn of the year or in the middle of the year as the last second of December 31 or of June 30 in UTC. This is determined by the International Earth Rotation and Reference Systems Service (IERS, http://www.iers.org) as a function of the observed period of the Earth's rotation. Averaged over the decade 1999 – 2009, the mean solar day was 0.604 ms longer than 86 400 SI seconds. In the previous decade, the deviation amounted to approx. 1.962 ms.[3]

In practically all countries, UTC has become the basis for the "civil", "official" or "legal" time used in the respective time zone. UTC is published in the form of calculated time differences with reference to the time scales UTC(k) realized in the individual time-keeping institutes (k). The UTC(k) scales shall agree as well as possible with UTC – and thus also mutually. At the end of 2010, 46 time scales with a deviation UTC–UTC(k) of less than 100 ns were available worldwide, among them that of PTB. Figure 11 shows the difference between UTC and the realizations UTC(k) in four European time-keeping institutes during one year.

5 Clock Comparisons

Albert Einstein once said that time could be replaced by the position of the little hand of his clock [28]. By this, he aptly expressed that the time furnished by a clock is independent of its

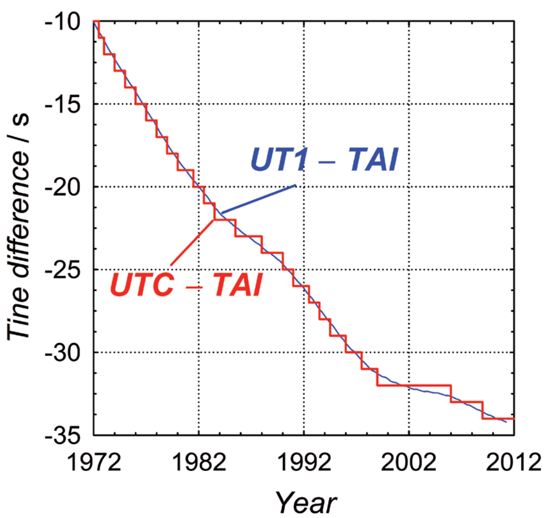


Figure 10:
Comparison of (astronomical) Universal Time UT1 and Universal Coordinated Time UTC with International Atomic Time TAI since 1971.

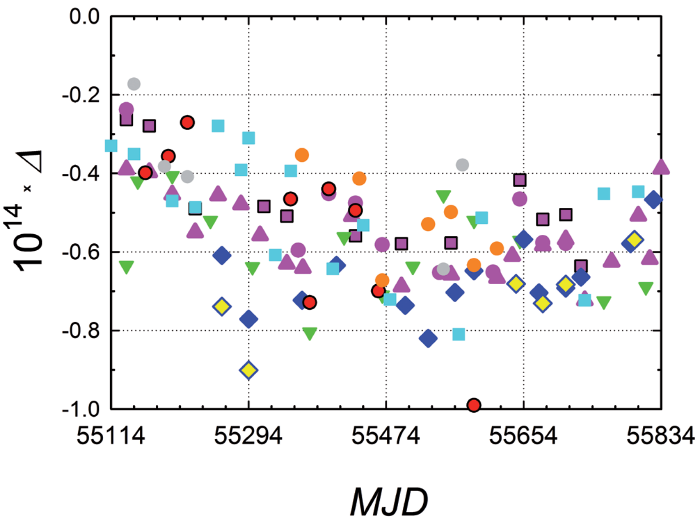


Figure 9:
Comparison of fountain frequency standards with TAI during two years, ending with MJD 55834, on September 30, 2011: The quantity Δ is the relative deviation of the second as it is realized with individual standards, from the scale unit of TAI during the respective operating time of the standards, typically 20 to 30 days. The uncertainty of the single measurement values varies between 0.05 and 0.4, depending on the standard and on the measurement period. Symbols: blue: PTB CSF1, yellow-blue_ PTB CSF2, cyan: NPL CsF2, orange: NMIJ-F1 (Japan), green NIST-F1 (USA), grey: NICT-CsF1 (Japan), red: IT-CSF1 (INRIM, Italy), magenta: LNE SYRTE/Observatoire de Paris, squares: FO1, triangles: FO2, points: FOM.

state of motion and of the gravitational potential in which it is located – but only for an observer in the same reference system. The definition of the second relates to this *proper time* (Section 2.1). Therefore, it is not necessary to point to the theory of relativity in the text of the definition. Today, this seems quite natural; in the 1960s it was, however, the subject of serious discussions [29]. Only if one intends to compare two clocks which move relative to each other, or in which atoms with different velocities are used, or which are subject to different gravitation – or, if it is intended, as described below – to combine the atomic clocks of all time-keeping institutes operating worldwide – only then must the rules of the theory of relativity be known and applied. Here it applies, however, that the velocity-dependent time dilatation due to the movement of the atoms in the atomic beam and the effect of the field of gravity of the Earth are by far larger than the frequency uncertainty of the best clocks achieved today. An interpretation is possible from two different perspectives: If the rates of atomic clocks are compared with each other to learn something about their quality – and thus about our understanding of the different physical effects which are effective in the clocks – the relativistic effects must be taken into account correctly. On the other hand, no objects on Earth are better suited to detect and quantitatively analyze relativistic effects than atomic clocks [30].

Now, how is it possible to establish a common time scale from 350 clocks that are distributed all over the world? This requires, first of all, local time

[3] Volume 48(3) of *Metrologia* deals with the history and significance of time scales and the leap second issue

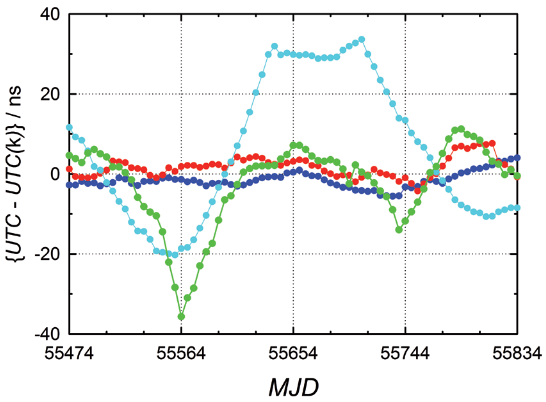


Figure 11: Comparison of Universal Coordinated Time UTC with atomic time scales UTC(k) realized in four European timekeeping institutes (k) during one year; MJD 55834 refers to September 30, 2011; red: Istituto Nazionale di Richerca di Metrologia, INRiM, Turin; cyan: NPL, Teddington, UK; green: METAS, Swizerland blue: PTB.

comparisons between the clocks and the respective time scales UTC(k) of the institutes k operating the clocks, and then comparisons of UTC(k) among each other. The former is quasi trivial. For the latter, a standard procedure exists which uses the signals emitted by the satellites of the American Satellite Navigation Systems GPS and of the Russian GLONASS. Special time receivers determine the arrival times of the signals of all satellites which are simultaneously visible above the horizon with respect to the local reference time scale and furnish original data of the kind {local time scale minus GPS time T(GPS)} (or GLONASS time). To compare the time scales of two institutes (i) and (k) with each other, the time differences are determined, the measurement data are exchanged and (e.g.) the differences [*UTC(i)-T(GPS)]–[UTC(k)-T(GPS)*] formed. By averaging typically 500 daily observations with a duration of approx. 15 minutes, the time scales of two time-keeping institutes can be compared worldwide with a statistic uncertainty of approx. 2 – 4 ns (1 σ).

Not only the clocks themselves, but also the methods of the intercontinental comparisons were – and still are – continuously further developed. By a combination of all methods available, the comparison of caesium fountains could – in an international collaboration – be realized with a statistic uncertainty of $1 \cdot 10^{-15}$. The values were averaged over 1 day each [31]. PTB intensively pursues the use of geostationary telecommunication satellites for time comparisons – called "Two-Way Satellite Time and Frequency Transfer (TWSTFT)" – and operates ground stations for the traffic with Europe/USA and Asia. Figure 12 shows a mobile station for the calibration of signal transit times [32] located next to the permanent installations on the Laue Building.

The time comparison data collected worldwide can largely be retrieved on servers which are publicly available. A time and frequency comparison of the highest accuracy can, thus, be performed with respect to UTC(PTB), with respect to many other realizations UTC(k), or to UTC and TAI und – thus – to the SI second – and this with the accuracy suited for almost every application.

6 Dissemination of Time for Society

The dating of events and the coordination of the various activities in a modern society have been recognized as being so important that in many countries how legal time is to be indicated is regulated by law. This is also the case in Germany. International traffic and communications make it necessary for the times of the countries which are fixed in this way to be coordinated with each other. The basics for this were laid down in October 1884 by the Washington Standard Time Conference [1, 2]. Thereby, the position of the zero meridian and the system of the 24 time zones – each one having a geographic longitude of 15° – were determined.

After the second had been redefined on the basis of quantities of atomic physics in 1967, the regulation for the legal time valid in Germany also had to be adapted. This was realized by the *Time Act* of 1978 in which PTB was entrusted with the realization and dissemination of the time which is decisive for public life in Germany. Central European Time (CET) or – if introduced – Central European Summer Time (CEST) were determined as the legal time. CET and CEST are derived from UTC, adding one or two hours:

$$\mathrm{CET(D)} = \mathrm{UTC(PTB)} + 1\mathrm{h},$$
$$\mathrm{CEST(D)} = \mathrm{UTC(PTB)} + 2\mathrm{h}.$$

Figure 12:
Establishment of a transportable satellite terminal for calibration of the time comparisons via TWSTFT with the stationary facility (background).

In addition, the *Time Act* also authorizes the German Federal Government to introduce, by way of a statutory ordinance, Summer Time between 1 March and 31 October of each year. The dates for the beginning and the end of CEST are determined by the Federal Government in accordance with the currently valid directive of the European Parliament and of the Council of the European Union and are announced in the Federal Law Gazette. The *Time Act* of 1978 and the *Units in Metrology* Act of 1985 were combined to a new, joint act, i.e. the *Units and Time Act*, which was adopted in 2008 and in which all regulations concerning the determination of time have been taken over without changes.

During the past few decades, PTB has used different procedures to disseminate time and frequency information to the general public and to use it for scientific and technical purposes. The long-wave transmitter DCF77 of Media Broadcast GmbH is the most important medium for this because the number of receivers in operation is estimated to be more than 100 million. It is often the case that PTB is known to many Germans and to many people in Europe only due to one service: the control of radio-controlled clocks. The carrier oscillation 77.5 kHz of this emission is used for the calibration of standard frequency generators. Before the war, PTR had already offered a comparable service, using the "Deutschlandsender". With DCF77, the time and date of legal time are transmitted in an encoded form via the second marks. In 2009, in memory of 50 years of DCF77 broadcasting, topics such as the current state of the broadcasting programme, the receiver characteristics, radio-controlled clocks and the history of time dissemination in Germany were intensively addressed in publications [33]. Corresponding services on long-wave also exist in England, Japan and the USA [34].

Since the mid 1990s, PTB has been offering time information via the public telephone network. Computers and data acquisition facilities can retrieve the exact time from PTB with the aid of telephone modems, calling the number 0531 512038. The major part of the calls (presently approx. 1700 calls per day) comes from the measuring stations of different energy suppliers who need this information for the fiscal measurement of natural gas.

With the advent of the Internet, a new medium for time dissemination came into being which has meanwhile become extraordinarily popular. Publicly available servers with the addresses *ptbtimeX.ptb.de (X = 1, 2, 3)* serve to synchronize computer clocks in the Internet with UTC(PTB). Figure 13 shows the number of current accesses to the three servers in the course of one week. During the past few years, the number of accesses has increased to approx. 3000 per second (as shown in the diagram).

7 Further developments and applications

For a great number of technical, military and – last but not least – scientific applications, exact and stable clocks and frequency references are indispensable. In the previous sections, the – seemingly – constant improvement of the accuracy of time measurement has been outlined. This – and also PTB's role – is impressive, but inevitably, the ques-

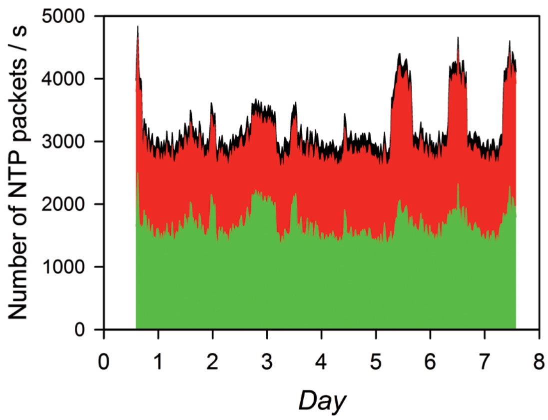


Figure 13:
Number of the NTP packages received during one week from the three externally accessible NTP servers ptbtimeX: 0 corresponds to 15.12.2010, 0:00 UTC; green: X = 1, red: X = 2, black: X = 3.

tion arises: What is the use of all this? Where will the development take us?

Let's deal with the second question first: All atoms and ions have states of energy. Between these, transitions occur – at frequencies that are up to 10^5 times higher than those we have discussed up to now (i. e.: in the range of the visible or ultraviolet radiation). In that case, schoolbook physics teaches us that the transitions from the higher to the lower state of energy run rapidly and spontaneously. In special cases, the transition probabilities are, however, strongly suppressed and, at the same time, the transition frequencies depend only to a small extent on external parameters. If the frequency of a laser is stabilized to such a transition line, it represents a very good standard for the frequency and the wavelength [35, 36]. In the case of the selected "clock transitions", linewidths W in the Hz area are obtained which furnish – with a transition frequency from 10^{14} to 10^{15} Hz – a correspondingly high line quality and, thus, a small frequency instability. The quality gained with the transition from low to higher clock frequencies (mechanical clock: 1 Hz, quartz clock: 10 kHz, atomic clock, so far: 10 GHz) is continued and, consequently, also leads to a reduction in the frequency uncertainty.

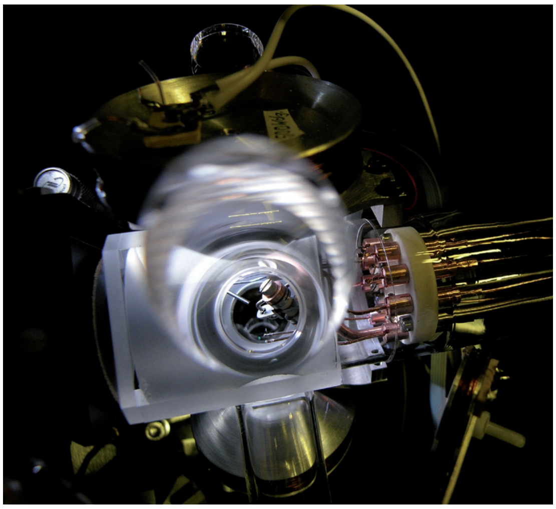
In the past few years, the development of optical frequency standards has been rapid. At the end of 2010, the smallest value of the frequency uncertainty published lay at $9 \cdot 10^{-18}$ [37]. From this, the perspective for a possible redefinition of the second results, and the question arises as to how the atomic transition best suited for it can be found. The category "secondary representation of the second" was created [38]. The categories which have been recognized so far are based on a microwave transition in rubidium and on optical transitions in the ions $^{88}Sr^+$ (strontium), $^{199}Hg^+$ (mercury) and $^{171}Yb^+$ (ytterbium) and in the neutral atom ^{87}Sr [36, 38]. Due to the development of frequency comb technology, the comparison of optical frequency standards with each other can be made with a smaller uncertainty than the realization of the SI second itself [39]. These comparisons can show whether the reproducibility of the optical standards – which so far have been operated only intermittently – confirms the assessed small uncertainty.

Already early in the 80s, work on the calcium frequency standard was started in the "Length" Group of the former "Mechanics" Division of PTB. In the past few years, work on strontium was started. (See also the article of H. Schnatz in this publication) [40]. For many years, work in the "Time and Frequency" Department has been concentrated on transitions in the ion of the isotope ytterbium-171. The core piece is a so-called "ion trap", in which a single ion (a positively single-charged atom) can be retained for weeks and months. Figure 14 shows the ytterbium ion traps presently used at PTB. The relative measurement uncertainty for the transition frequency of the selected clock transition of $1.1 \cdot 10^{-15}$ is – as can be seen by a comparison with the information given on CSF1 – determined decisively by the uncertainty of the realization of the time unit [41].

A completely new concept investigated at PTB is that of an optical clock which shall be based on a gamma radiation transition in the atomic nucleus (not – as is usual – in the electron shell) of the isotope thorium-229 [42]. The special feature of this transition is the energy which, for a nuclear transition, is extremely low, so that it can be excited with the radiation of a laser.

Where can this concept be used? In everyday life, time and frequency measurements are of extraordinary importance. Without atomic clocks or without the dissemination of exact time information, our telecommunications system, the quality of energy supplies across frontiers, and navigation with GPS – to give just a few examples – would not function the way we are used to. The integration of better (optical) clocks into these established technical systems cannot be achieved in a trivial way; in the long term, it can, however, lead to an improvement of these systems and also allow new applications in everyday life.

Less common and less obvious is the use of time measurement in Earth observation. Everyone uses the key words "climate change" and "tsunami", but only a very detailed understanding of our Earth and the measurement of a great number of quantities in SI units, with a correspondingly long-term comparability of measurements, allow reliable statements and forecasts to be made and behaviour guidelines to be given for politics and for society. To achieve this, the establishment of the "Global Geodetic Observation System" (GGOS) has been agreed upon [43]. With the equipment commonly used today in observation stations, various research aims can be reached to a limited extent only. Here, access



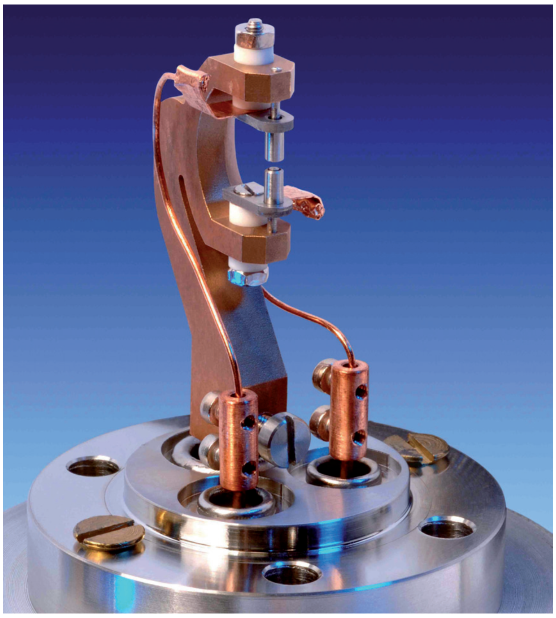


Figure 14:
on the left: Vacuum recipient with ion trap (in the centre) for the spectroscopy of single ytterbium ions [41]; on the right: Detail of the latest trap arrangement, a so-called end cap trap which has been used since the beginning of 2010.

to better clocks would help – be it that improved clocks are operated in the observation stations, be it that these stations are interlinked with time-keeping institutes via modern procedures [40, 44].

Where do time and frequency measurements play a role when it comes to answering fundamental questions of physics? Let us mention the development of quantum mechanics as an example from the past: This development progressed when the theoretical explanation of subtle characteristics of atomic spectra succeeded. In most cases, the experimental data were the result of frequency or wavelength measurements. Quantitative tests of the general and special theory of relativity are based on time and frequency comparisons [30,45,46]. The – although indirect – proof of the radiation of gravitational waves in a rotating double-star system was provided by the analysis of the arrival time of the pulse signals with respect to atomic time scales [47]. Many of the approaches searching for "new physics" concentrate on possible deviations from Einstein's Principle of Equivalence [30]. An experiment in this connection which can be easily carried out is the comparison of two atomic clocks with different atomic references (e. g. caesium clock versus hydrogen maser) in the time-dependent gravitational potential of the Sun – during the annual rotation of the Earth on its elliptical orbit [48]. In the past 20 years, hypothetical infractions of the Principle of Equivalence have – to an ever increasing extent – been gradually ruled out. The availability of more exact clocks and improved possibilities for the comparison of clocks were the prerequisite [49]. In future, this type of time measurement will continue to offer a wide field of activities for PTB which will excellently complement PTB's tasks of everyday routine.

8 Closing Remarks

"Sometimes I get up in the middle of the night and stop all the clocks. However, we should not fear time – it, too, is a creature of the Father who created all of us".(1)

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