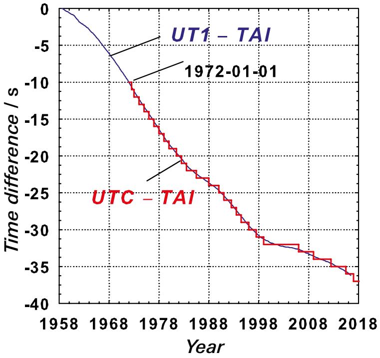
Physikalisch-Technische Bundesanstalt
National Metrology Institute

About Time

Realization and Dissemination of Legal Time in the Federal Republic of Germany

Coordinated Universal Time (UTC) is the worldwide uniform basis for determining legal time used in daily life. Its scale unit is the SI second, which is realized with the primary atomic clocks of PTB and of other timing institutes. UTC is the basis of all global time zones which generally differ from one another by whole hours. Since (in spite of the impact of atomic clocks) our daily life continues to be based on the apparent position of the Sun, i.e. based upon the non-uniform rotation of the Earth, care is taken that UTC corresponds within ± 0.9 s with "Universal Time" (UT1, mean solar time at the null meridian through Greenwich) derived from astronomic observations. For this purpose, leap seconds are inserted into UTC as necessary. In the figure above, a comparison between UT1, UTC and International Atomic Time (TAI), which is independent of Earth's rotation, is illustrated. When TAI was introduced at the beginning of 1958, TAI was adjusted to UT1. UTC has only been in existence since 1 January 1972, when the difference between UT1 and TAI amounted to about 10 s. Since the Earth does not rotate at a regular speed, leap seconds are inserted at irregular time intervals.



Through the Units and Time Act, PTB is entrusted with realizing and disseminating standard time for "official business and commercial matters" in the Federal Republic of Germany. For this purpose, a group of atomic clocks is operated at PTB, and the time scale UTC(PTB) is realized, which is consistent with UTC within some ten billionths of a second. From UTC(PTB), the legal time effective in Germany (Central European Time (CET) or Central European Summer Time (CEST)) is derived and the following applies:

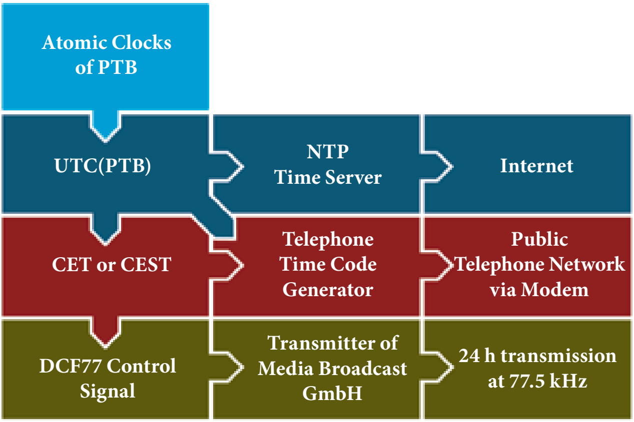
CET = UTC(PTB) + 1 hour, and
CEST = UTC(PTB) + 2 hours.

For the introduction of daylight saving time (called “Summer Time” in Germany), the following regulations (BGBl. 2001 [Federal Law Gazette], part 1, No. 35, p. 1591) apply:

Section 1: From 2002 on, Central European Summer Time (Section 1, Subsection 4 of the Time Act of 1978) will be introduced for an indefinite time.

Section 2: (1) Central European Summer Time begins on the last Sunday in March, at 02.00 a.m (CET). At the moment of the beginning of Summer Time, the clock is put forward by one hour from 02.00 a.m. to 03.00 a.m.

Section 2: (2) Central European Summer Time ends on the last Sunday in October at 03.00 a.m. CEST. At the moment of the end of Summer Time, the clock is set back one hour from 03.00 a.m. to 02.00 a.m. The hour from 02.00 a.m. to 03.00 a.m. thereby appears twice. The first hour (from 02.00 a.m. to 03.00 a.m. CEST) is designated with 2 A and the second hour (from 02.00 a.m. to 03.00 a.m. CET) with 2 B.



Schematic diagram of the time services of PTB

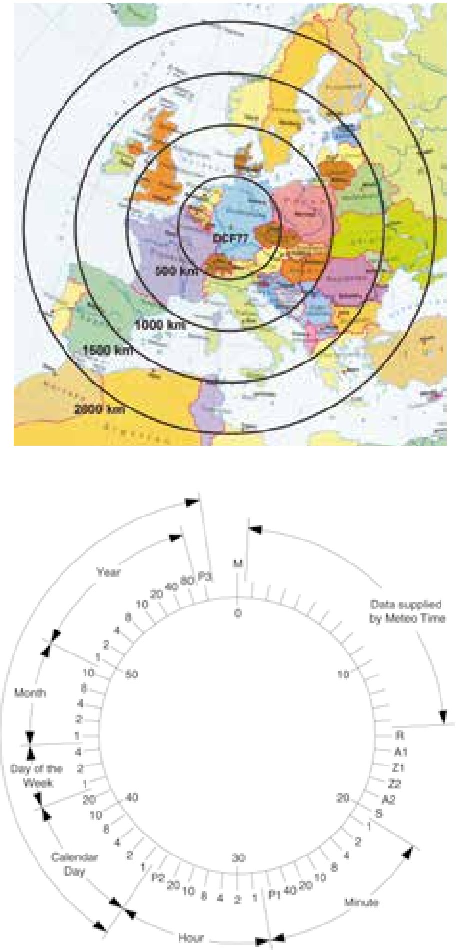
UTC and legal time are made available to the public by means of various transmission services. The most well-known is the emission of time signals and of the standard frequency via the DCF77 transmitter. In addition, PTB's Telephone Time Service enables computers and data acquisition devices to be supplied with the accurate time via telephone modems and the public telephone network. To synchronize computer clocks, UTC(PTB) can be queried via the internet. These services will be presented below. For further technical details, please visit www.ptb.de/zeit, click on "EN" for the English version, and then select "4.42" on the left.

The Standard Frequency and Time Dissemination Transmitter DCF77

Operating agency:	Media Broadcast GmbH
Site:	Mainflingen Transmitting Station near Frankfurt/Main (50° 01′ North, 09° 00′ East)
Carrier frequency:	77.5 kHz, standard frequency derived from PTB's atomic clocks (relative uncertainty on average over one day $\leq 2 \times 10^{-12}$)
Transmitter power:	50 kW, radiated power approx. 30 kW
Range of reception:	up to 2000 km
Time of transmission:	24-hour continuous operation
Modulation:	Amplitude modulation with second markers (0.1 s or 0.2 s reduction of the carrier amplitude to 15 %) and pseudorandom modulation of the carrier phase (equivalent to a binary random sequence of 2^9 bits, clock frequency 77 500/120 Hz, peak phase deviation ± 14.3°)

Time Code

In the course of each minute, the numbers of the minute, hour, day, day of the week, month and year applicable to the following minute are transmitted (coded) by pulse-width modulation of the second markers. Second markers with a duration of 0.1 s thereby correspond to the binary zero, and second markers with a duration of 0.2 s to the binary one. The assignment of the individual second markers to the time information transmitted is shown in the coding scheme.



DCF77: range of reception (top), encoding scheme (bottom)
M: minute marker; R: call bit; A1: announcement of an imminent change from CET to CEST or vice versa; Z1 (Z2): time information corresponds to CEST (CET); A2: announcement of a leap second; S: start bit of the encoded time information (0.2 s); P1, P2, P3: parity check bits

Pseudorandom Modulation of the Carrier Phase

In addition to the amplitude modulation (AM) described, a pseudorandom phase noise is modulated onto the carrier of DCF77. To this end, the phase is keyed according to a binary random sequence by ±14.3°, whereby the mean value of the carrier phase remains unchanged. In the case of the modulation of the carrier phase, coding is effected by inverting the pseudorandom sequence used. At the receiver end, the pseudorandom sequence used can be reproduced as a search signal and cross-correlated with the phase noise received. This allows a more accurate determination of the time of arrival of the time signals received. The phase noise does not interfere with the receipt of the AM time signals. Neither are the properties of DCF77 as a standard frequency transmitter appreciably influenced.

Antenna support mast of DCF77 in Mainflingen, southeast of Frankfurt/Main

Applications of DCF77

The vast majority of DCF77 receivers evaluate the time code transmitted via AM. Radio-controlled clocks all over Germany and in the neighboring European countries can thus be kept more accurately than a millisecond in accord with legal time if the signal's runtime, due to the distance between the clock and the emitter, is taken into account. Radio and TV stations, Deutsche Bahn, and Deutsche Telekom all use DCF77 to a considerable extent. DCF77 receivers are found in traffic-monitoring facilities, traffic lights, and measuring systems in industry. Numerous radio-controlled clock models are available for private use. Receivers which evaluate the carrier phase modulation are used in the network management of the power supply companies and in telecommunications. Standard frequency generators controlled by DCF77 are used in calibration laboratories in industry and at research facilities.

PTB’s Telephone Time Service via the Public Telephone Network

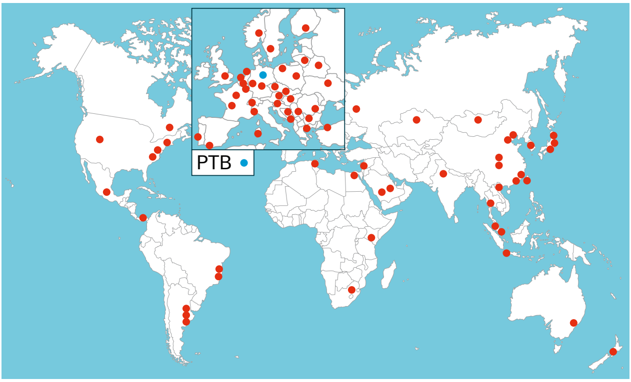
PTB offers time information via the public telephone network. Computers and data acquisition facilities can retrieve the accurate time from PTB with the aid of telephone modems, calling the number 0531 51 20 38. The telephone time code consists of a series of 80 ASCII characters which are transmitted once every second with a firm temporal reference to the start of a second. Each sequence contains a great amount of information, e.g. the calendar date, the legal time, the number of the day of the week, of the calendar week, of the day of the year, the date and time of a forthcoming change from CET to CEST or vice versa as well as Coordinated Universal Time (UTC). The time code generator employed offers the opportunity to correct for the one-way propagation time and thus a time transmittance with an uncertainty of approx. one millisecond. The majority of phone calls come from measurement stations along the gas pipelines in Germany.

PTB’s Internet Time Service

PTB offers a public time synchronization service via the internet. This service can be used for the time synchronization of computers, mobile devices or network components by means of the “Network Time Protocol” (NTP, RFC 5905). This service is currently being provided by three time servers with the following addresses: **ptbtime#.ptb.de (# = 1, 2 or 3)**. For more detailed information about NTP, please visit www.ntp.org. The protocol is available for all relevant operating systems. As a rule, the accuracy that can be reached for time synchronization depends on the latency of the network connection between the remote terminal and PTB’s time server. When using internet connections, accuracies on the order of one to ten milliseconds can be achieved. This PTB service is currently called up approx. 600 million times a day.

At the web address “uhr.ptb.de”, PTB provides a graphic representation of legal time in the browser used. When a query is initiated, the transport of time between PTB and the user is authenticated and checked for integrity via the https protocol. For this purpose, the optimized web socket protocol, which has been optimized to achieve lower latency, is used, so that accuracy similar to that described for NTP can be attained. Depending on the remote terminals concerned, the indication can, however, be subject to diverse representation delays. As an option, it is possible to display the deviation of the local computer clock from PTB’s time indication, and thus to obtain the uncertainty resulting from the delay.

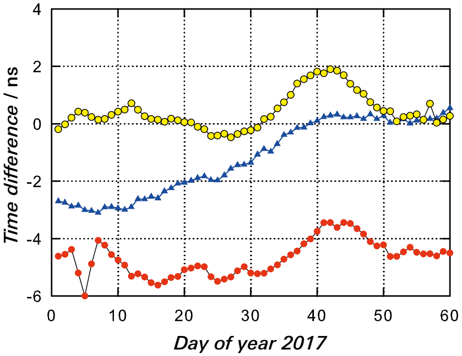
Realization of UTC



Network of the time institutes for the realization of UTC

Coordinated Universal Time (UTC) is based on atomic clocks operated at more than 70 timing institutes “k” shown in the figure above. The atomic time scales UTC(k) realized there and the atomic clocks in operation there (approx. 450) are compared with each other. To this end, signals from the U.S. Global Positioning System (GPS) and, increasingly, from the Russian GLONASS system and from the European Galileo system are recorded. The figure (top right) shows some antennas located at PTB which enable the reception of signals from navigation satellites. The three antennas of the same type in the foreground are connected to corresponding receivers for all available navigation systems. Alternatively, time signals are exchanged via telecommunications satellites using the two “satellite dishes” to establish a connection with institutes in Europe, Asia and the United States. The graphic below shows the results thus obtained when comparing the UTC(PTB) time scale with the time scales realized by the Observatoire de Paris (OP), the National Metrology Institute (NIM) in Peking and the United States Naval Observatory in Washington DC. Each data point has a measurement uncertainty of less than 2 ns.

Three antennas for the reception of signals from navigation satellites and two antennas for time comparisons via telecommunications satellites on the roof of the Meitner Building at PTB



Result of the time comparison via telecommunications satellites between UTC(PTB) and UTC(OP) (blue); UTC(NIM) (red) and UTC(USNO) (yellow), daily mean values

Data analysis and the calculation of UTC take place at the International Bureau of Weights and Measures (BIPM) in Paris. The BIPM calculates a free atomic time scale by averaging all these clocks. This results in the International Atomic Time (TAI) whose scale unit is kept in line with that of the second realized by primary clocks. The primary atomic clocks PTB has built and operated for more than four decades contribute to this considerably. In the last step, UTC is obtained from TAI by inserting leap seconds. The instructions in this case come from the International Earth Rotation and Reference Systems Service (IERS – www.iers.org).

Atomic Clocks and the SI Second

The second is one of the base units of the International System of Units (SI) and has, since 1967, been defined as follows: *The second is defined as 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 cesium 133 atom*. According to this definition, the unit of time is realized with cesium atomic clocks which are manufactured by industry or constructed and operated by research laboratories to meet the highest accuracy demands. Only about a dozen specimens of the latter, the so-called primary clocks, are in existence worldwide.

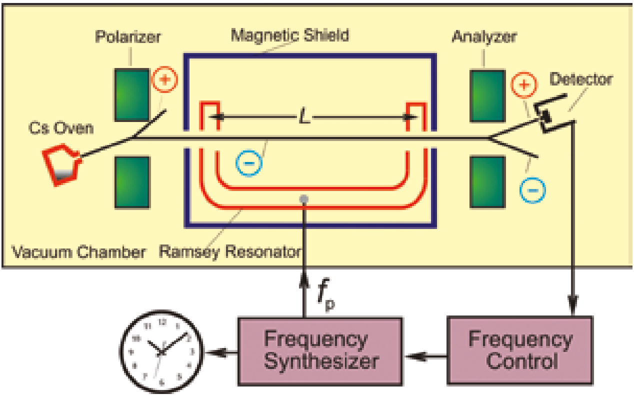
The primary atomic clock CS2 of PTB which went into operation in 1986

The Basic Principles Behind Atomic Clocks

Atoms may occur in various energy states of their electron shell. The transition from one state to another can be excited by resonant excitation via electromagnetic radiation. According to the laws of atomic physics, at a transition between two atomic eigenstates with an energy difference ΔE, this radiation has a frequency $f = \Delta E/h$ (h: Planck's constant). The frequency f and/or the period duration $1/f$ of such radiation is therefore – as a fixed and characteristic property of the atoms – a natural constant, in contrast to the period of the Earth's rotation or the oscillation period of a pendulum. In practice, the observed atomic transition frequency is, however, subject to various disturbances and statistical fluctuations. The development of atomic clocks has, over the past 50 years, contributed to an increasingly efficient reduction of such disturbances. The inaccuracies of these clocks have decreased by a factor of approx. 10 per decade.

Design of a Classical Cesium Atomic Clock

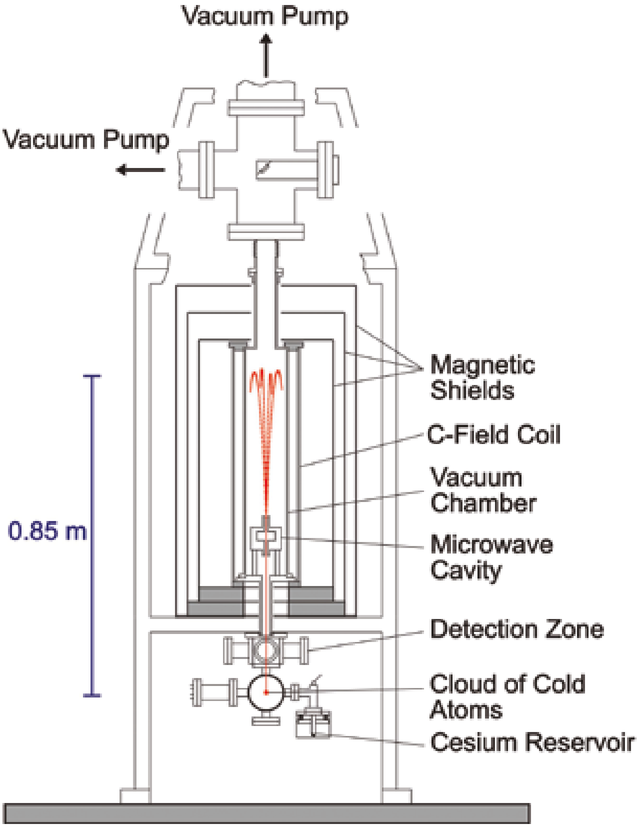
There is a suitable transition in the cesium atom at the frequency f_{Cs} = 9 192 631 770 Hz. This transition is basic to the functioning of a cesium atomic clock. In the vacuum chamber of an atomic clock, cesium atoms are evaporated and an atomic beam is formed. A magnet (polarizer) deflects the atoms such that only atoms in the (–) state reach the U-shaped Ramsey cavity. Here, the atoms are excited to the other (+) state by irradiation with a microwave field at frequency f_{p}. The second magnet (analyzer) then directs only those atoms to the collector which have suffered a change in state from (–) to (+). The number of atoms in the collector reaches a maximum when f_{p} has the value f_{Cs} which is characteristic of the cesium atom. An electronic control ensures that the frequency generator is kept at the frequency f_{Cs}. The time-of-flight (distance L divided by the atomic velocity) determines the sensitivity at which this control operates, namely the longer the time-of-flight, the better. By counting the 9 192 631 770 periods of the microwave radiation, second pulses are obtained from the generator signal; these pulses are counted with a clock unit.



Principle of a "classical" cesium atomic clock with a thermal atomic beam and magnetic selection. The two eigenstates of the cesium atom are labeled (+) and (–).

Cesium Fountain Clocks

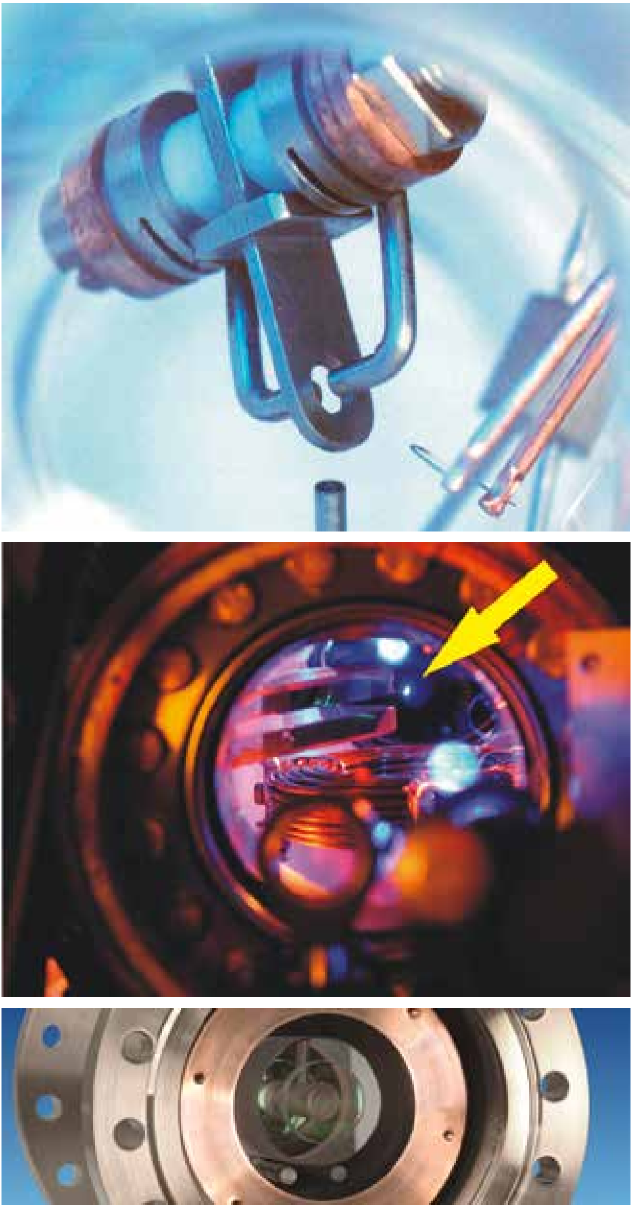
In PTB's latest atomic clocks (the cesium fountains CSF1 and CSF2), laser radiation is used for the preparation and detection of the atomic state. Laser cooling in a magneto-optical trap (MOT) or in optical molasses furnishes "cold" atoms with a thermal velocity of approx. 1 cm/s. These atoms are launched vertically upwards and fall back down again – like water in a fountain – under the influence of gravity. The atoms cross the microwave resonator twice during this trajectory. Detection of the state of the atoms after their second flight through the resonator is implemented via excitation with laser radiation and the detection of the fluorescence radiation. The time-of-flight of the atoms above the microwave resonator is 50 times longer than the corresponding time-of-flight in CS2. To a similar extent, various frequency-shifting effects are smaller, so that seconds from CSF1 and from CSF2 with an uncertainty of only some 10^{-16} s come very close to ideal SI seconds.



Vertical section through PTB's cesium fountain clock CSF1

A Glimpse into the Future

In the next generation of atomic clocks, the reference frequency used will no longer be in the microwave region as in the case of cesium, but rather in the region of visible light. Possible realizations of such "optical clocks" are based on the spectroscopy of a single electrically charged atom that is stored in a so-called "ion trap", or of many neutral atoms that are kept in a so-called optical trap. The frequency of optical radiation, which is considerably higher, allows the relative accuracy to increase further – to date by a factor of approx. 100 compared to a fountain clock.



Optical atomic clocks are based on the spectroscopy of either single ions in a radio-frequency trap (top) or of thousands of neutral atoms kept in an optical trap (center; the arrow points to the atomic cloud). The oscillator of the optical clock is a laser whose frequency is pre-stabilized to short time scales by means of an optical resonator (bottom; view into the vacuum chamber).

Cover picture
PTB’s CSF2 cesium fountain clock

Bibliographical references
An extensive literature list with publications by PTB authors as well as external publications is available at www.ptb.de/time following the link “Selected Publications and Bibliography” or can be requested from PTB’s Time and Frequency Department.

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