The cesium frequency standard

Author: Jan Fišer
Advisor: assoc. prof. Igor Poberaj
Ljubljana, June 2014

Abstract
In the seminar the cesium atomic clock, which serves as the primary frequency standard used for the definition of the second, is described. First, a brief history of time measurement and accompanying clock development is described, followed by general considerations about clock design and the definition of Allan variance as a measure of frequency stability. Then, the definition of the second and its history are given. The main part of the seminar consists of the description of classical, laser pumped and fountain cesium standards, along with sources of systematic errors. At the end, the future prospect of the time standard is discussed and applications based on accurate time measurement are presented.
1 Introduction

Time has always played an important role in human lives. Surprisingly, people are often unaware of how exactly time is measured and its unit defined. The aim of this seminar is to dispel this ignorance.

A brief history of time measurement and accompanying clock development is described in Section 2, where we closely follow [1]. A lesson to be learnt from it is that the universal accessibility of time, nowadays, is the consequence of centuries-long struggles. General considerations about clock design and performance are derived in Sections 3 and 4 based on historical examples. Then, the definition of the second and its historical development is outlined in Section 5. From the formal definition of the second it is hard to imagine how it is measured in practice. This is clarified in Sections 6, 7 and 8, where different experimental apparatus are described, while Section 9 focuses on their systematic uncertainties. The future prospect of time standards is discussed in Section 10. The concluding Section 11 lists some applications of commercial and state-of-the-art atomic clocks.

2 A brief history of time measurement

The ancient civilizations recognized the cycles of the Sun, the Moon and the stars. Observation and measurement of their periodic motions led to the natural time units of days, months and years. Such time division sufficed for daily life, religious practices and agriculture, so it formed the basis for timekeeping.

The division of day into smaller units stimulated the development of man-made clocks. One of the first was the shadow clock, which was later refined into the sundial. Beside clocks based on heavenly bodies, other types of clocks were developed, e.g. water and sand clocks. The accuracy of all these clocks was approximately equal.

In the beginning of the 14th century weight-driven mechanical clocks were developed in Europe. However, they were highly inaccurate, with time discrepancies of about 15 minutes per day. A breakthrough occurred when Christian Huygens built the first pendulum-based clock in 1656 with an accuracy of 10 seconds per day.

A strong motivation for the development of a reliable and robust clock was the need for precise navigation (determining longitude) at sea. Pendulum clocks were obviously unsuitable, so mechanical clocks based on springs were developed. John Harrison built a clock in 1759 which lost only 5 seconds in 81 days at sea. The importance of accurate clocks further increased with the development of railroad transportation.

Throughout the 18th and 19th century mechanical clocks were steadily improved. In 1921 William Hamilton Shortt built a two-pendulum clock with an accuracy of a millisecond per day. It consisted of a master pendulum, which kept the time, and a slave pendulum, which provided impulses to the master (to compensate energy losses). The two pendulums were electrically coupled and housed in vacuum.

The complexity of Shortt’s clock indicated that mechanical clocks had more or less reached their highest attainable accuracy. A new approach was needed for any further significant improvement of the accuracy. A breakthrough occurred in 1927 when Marrison and Horton built the first quartz clock. The principle of operation is as follows: an electronic circuit forces a tiny tuning fork made of quartz crystal to vibrate at its resonant frequency via the inverse piezoelectric effect. Consequently, the tuning fork generates an electric signal at its resonant frequency via the direct piezoelectric effect. Another circuit detects the signal produced by the quartz oscillator and lowers its frequency to 1 Hz. These regular 1 Hz pulses power a stepping motor that turns the clock’s hands. With such design, many problems associated with pendulum clocks are greatly reduced, so that the accuracy of a good quartz clock is around one millisecond per year. The accuracy is limited by temperature variations, which cause slight changes in size of
the crystal and subsequent drifts of its resonant frequency.

Even greater accuracy is achieved by atomic clocks, which will be described in detail later.

3 General clock design

Roughly speaking, every clock (excluding ancient clocks) has three essential functional parts: an energy source, a system capable of stable periodic motion to serve as regulator and a mechanism to derive and display the time in the desired units [2].

The energy source is typically a falling weight, a coiled spring, a battery, or some other electric source. A mechanism to derive and display the time is usually a system of gear trains and a dial or an electronic display.

The most critical is the regulating system. The ideal situation would be the one in which the regulator would oscillate freely at its resonant frequency, regardless of external conditions. Furthermore, the control of energy transmission from the energy source to the rest of the clock mechanism would leave the regulator unperturbed. However, this is never realised in practice. Firstly, the oscillator’s period is always a function of environmental conditions. But with careful design we can control them and calculate their influence on the oscillator’s period. Secondly, energy losses are always present in the regulator, so a small driving force must act on it to maintain constant oscillations. This contradicts the requirement of an unperturbed regulator. To accommodate these opposing requirements, the oscillator must have very small inherent energy losses, so that only a very weak driving force is needed [2].

An ideal oscillator would be one that, given a single initial push, would run forever. As stated above, this is never realised in practice because of energy losses. The quality factor $Q$ is introduced as the ratio of the total energy in a system to the energy lost per cycle. If we restate this in resonance-curve language, the quality factor is expressed as

$$Q = \frac{\omega_{\text{res}}}{\Delta\omega},$$

where $\omega_{\text{res}}$ is the resonant frequency and $\Delta\omega$ is the bandwidth (full width at half maximum) of the curve [1]. Oscillators with high $Q$ are obviously more suitable for regulators, because they need weaker driving forces and their oscillation frequency is more sharply determined.

4 Stability

The stability of frequency (time) standard is obviously of fundamental importance. The standard is subject to fluctuations and long-term drifts. The former are assumed to be random and stationary, while the latter are deterministic. In time-domain description, errors in frequency over different sampling intervals (sources of instability may have different time dependence) of time are statistically analysed [2]. The accepted measure of instability is Allan variance, defined by [1]

$$\sigma^2 = \frac{1}{2(N-1)} \sum_{i=1}^{N-1} (n_{i+1} - n_i)^2,$$

where $n_i$ denotes frequency count on the $i$-th measurement of the same sample interval, which is measured $N$ times. By subtracting the previous frequency count $n_i$ (instead of the mean) from each frequency count $n_{i+1}$ in the summation, Allan variance eliminates any systematic error contribution.
5 The definition of the second and its history

The concept of an hour being divided into 60 minutes, each in turn composed of 60 seconds, was already present in the middle of the 14th century (the base 60 was probably chosen because it is divisible by: 2, 3, 4, 5, 6, 10, 12, 15, 20 and 30). However, the concept did not find widespread usage because clocks were not capable of measuring minutes and seconds reliably. Clocks with second hands did not appear until the 18th century [1].

The first formal definition of the second was proposed by Tito Livio Burattini in 1675 as 1/86400 of a mean solar day.

The definition of the second based on the Earth’s variable rotation became impractical for precise timekeeping in the 20th century. In 1960 a new definition of the second was established as the fraction 1/31556925.9747 of the length of the tropical year for 1900. This was called the Ephemeris second.

The development of the cesium (Cs) frequency standard took place at the same time as the discussion and adoption of the Ephemeris second. The first Cs beam atomic clock was built by Essen and Parry in 1955. The frequency of the Cs standard had to be calibrated against the Ephemeris second. This was done by Markowitz in 1958 [3]. Soon after the adoption of the Ephemeris second, it became evident that the atomic standard of time could be realized and reproduced more accurately. In 1967 the SI definition of the second was established: 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 cesium 133 atom. This definition refers to a Cs atom at rest at a temperature of 0 K [1]. The definition of the second should be understood as the definition of the unit of proper time: it applies in a small spatial domain which shares the motion of the caesium atom used to realize the definition. The proper second is obtained after application of the special relativistic correction for the velocity of the atom in the laboratory [4].

6 The classical Cs beam standard

First, a rough description of the classical Cs beam standard is given. After the principle of operation is clarified, each component is described in detail.

6.1 The classical Cs beam standard scheme

The first operational Cs beam atomic clock was built in 1955 by Essen and Parry [1]. Its scheme is shown in Fig. 1.

Figure 1: A beam of Cs atoms leaves the oven. A state-selective magnet deflects atom’s trajectory according to their quantum state. Atoms in the chosen group of states pass through a region of a weak uniform magnetic field and are irradiated by microwaves. If the frequency of the microwaves is appropriate, transitions between the chosen quantum states occur. Another state-selective magnet acts as an analyser, separating atoms that made the transition from the rest and directing them at the detector. (Figure taken from [1].)

Cs vapour is heated in the oven to $T \approx 100^\circ$C. Cs atoms leave the oven through the narrow
slit, forming a beam. The A-magnet produces strong nonuniform magnetic field, which acts as a state selector, because Cs atoms are deflected according to their quantum state. The chosen group of states passes to the region of a weak uniform magnetic field, called the C-field. On their way through the C-field area, atoms pass through a microwave cavity. If the frequency of the microwave field is appropriate, transitions between chosen quantum states occur. The atoms pass through another state-selective magnet, called the B-magnet. Those that made the transition are deflected away from the rest of the Cs beam in the direction of the detector. The number of atoms that hit the detector is converted into an electric signal. By adjusting the microwave frequency, the electric current is maximized. At its maximum, the frequency of the microwave field is equal to the “frequency between chosen quantum states”. This frequency is used in the SI definition of the second.

6.2 Components of the classical Cs beam standard

In this subsection components of the classical Cs beam standard are described in detail. Further explanations are found in [2].

Cs is heated in the oven to around 100°C. The Cs vapour passes through the collimator, so that the emerging beam of Cs atoms is as narrow as possible. Higher temperatures are not used, because collisions between atoms would be more probable, which could lead to Cs build-up in the collimator and causing fluctuations in the beam intensity.

Knowing the detailed structure of the Cs energy spectrum is crucial for understanding the effect of state-selective magnets A and B. We limit ourselves to listing the facts, which are explained in [5].

The ground state electronic configuration of cesium is [Cs] = [Xe] 6s^1. Completely filled electronic shells have no angular momentum. Orbital angular momentum \( L \) and spin angular momentum \( S \) of the outermost electron are \( L = 0 \) and \( S = \frac{1}{2} \), hence its total angular momentum \( \mathbf{J} = \mathbf{L} + \mathbf{S} \) has magnitude \( J = \frac{1}{2} \). The Cs nucleus also possesses angular momentum \( \mathbf{I} \) with magnitude \( I = \frac{7}{2} \). The total angular momentum of the Cs atom \( \mathbf{F} = \mathbf{J} + \mathbf{I} \) can thus have a magnitude of either \( F = 3 \) or \( F = 4 \). Nuclear and electronic angular momenta are coupled by hyperfine interaction (\( H_{hf} \propto \mathbf{J} \cdot \mathbf{I} \)). Consequently, states with lower \( F \) have lower energy. In external magnetic field \( \mathbf{B} \), states are split according to their magnetic quantum number \( m_F \) as shown in Fig. 2.

**Figure 2:** External magnetic field lifts the degeneracy of the hyperfine levels. Each hyperfine level fans out into \( 2F + 1 \) magnetic sublevels, characterized by \( m_F \). (Figure taken from [5].)

The energy shift due to the applied magnetic field represents a potential energy, whose gradient determines the magnetic force on the atom. In the limit of strong magnetic field, two groups of states are formed (Fig. 2). These two groups are separated by the A-magnet. The group containing \( |F = 3, m_F = 0\rangle \) is led further into the apparatus, while the group containing \( |F = 4, m_F = 0\rangle \) is absorbed on the getters.
The Cs beam then enters a magnetically shielded area, where transitions between $|F = 3, m_F = 0\rangle$ and $|F = 4, m_F = 0\rangle$ are induced. These hyperfine states are chosen because they are the least magnetic-field-sensitive sublevels. Inside the shielded area, a weak magnetic field, called the C-field, is produced. The C-field has to be weak, so that $m_F = 0$ states do not experience significant energy shifts (Fig. 2). On the other hand, it has to be strong enough to cause sufficient energy separation between $m_F = 0$ and $m_F \neq 0$ states, so that transitions between states $|F = 3, m_F = 0\rangle$ and $|F = 4, m_F \neq 0\rangle$ are not induced as well.

Transitions between $|F = 3, m_F = 0\rangle$ and $|F = 4, m_F = 0\rangle$ are induced with microwaves. In principle, when energy and polarization of microwave photons are appropriate, the transition is likely to occur. Achieving this in practice is a difficult task, plagued with many technical details, which can be found in [2, 6, 7].

The purpose of the B-magnet is to separate the atoms that made the transition from the rest. The principle of operation is the same as in the case of the A-magnet.

The detector is a “hot-wire detector” based on surface ionization of Cs atoms. The impinging Cs atoms give their outermost electrons to the material of the wire and leave as positively charged ions. This process is possible when the metal’s work function is greater than the binding energy of the outer electron in Cs ($\approx 3.87$ eV). The wire is made of certain pure metal, which has to be hot to prevent surface adsorption of gases. The materials in use are tungsten, niobium, molybdenum and Pt-Ir alloy [2]. The Cs ions are gathered by the cathode of an electron multiplier, which produces a measurable electric signal, proportional to the number of incident Cs ions. These are again proportional to the number of Cs atoms that made the transition. Maximizing the electric signal means that the frequency (and thus energy) of microwaves matches the frequency (energy) difference between chosen hyperfine states.

However, the Cs beam resonator is a passive device, which merely serves as a frequency reference. We chose that when electric signal from Cs clock is at its maximum, the frequency of microwaves is by definition $9,192,631,770$ Hz. For a functional clock, a time display and an electronic circuit, which locks the tunable oscillator’s frequency on the Cs resonance frequency, is needed. The latter is achieved with a phase-locked loop. The conceptual scheme of the atomic clock is shown in Fig. 3. The actual clock’s size depends on its purpose – primary standard clocks are the size of a small car, but commercial (and less accurate) clock are typically the size of a suitcase.

Figure 3: The conceptual scheme of the atomic clock. A tunable oscillator generates the frequency of the microwaves, which is locked to the Cs resonant frequency with a phase-locked loop. The atomic resonator serves merely as a frequency reference. The tunable oscillator generates another signal, whose frequency is stepped down to 1 Hz, used for controlling the time display. (Figure taken from [1].)

7 The laser-pumped cesium beam standard

The laser-pumped Cs beam standard differs from the classical Cs beam standard in the aspect of state selection and the detection of clock transitions. State-selective magnets are replaced
by optical pumping and hot-wire detector by fluorescence detector. Otherwise everything is left unchanged, so the overall complexity of the clock remains approximately the same as in the case of classical Cs beam standard. The first optically pumped Cs clock was made in 1980 by Arditi and Picque [1].

By using the A-magnet, the blue branch of states in Fig. 2 is discarded. This results in substantial signal-to-noise (SNR) decrease. The main idea of optical pumping is to increase the difference between $|L = 0, F = 3\rangle$ and $|L = 0, F = 4\rangle$ states before Cs atoms enter the microwave cavity. This can be achieved by many different schemes. The following example highlights the concept of optical pumping.

When Cs atoms leave the oven, the population of $|L = 0, F = 3\rangle$ and $|L = 0, F = 4\rangle$ levels are approximately the same [8]. The transition $|L = 0, F = 4\rangle \rightarrow |L = 1, F = 4\rangle$ is excited with an appropriate laser (Fig. 4). The excited state decays back to $|L = 0, F = 3\rangle$ and $|L = 0, F = 4\rangle$ with a certain branching ratio. The result is a net transfer from $|L = 0, F = 4\rangle$ to $|L = 0, F = 3\rangle$ state, so more Cs atoms are “available” to make the resonant transition and therefore SNR is increased.

![Figure 4: The concept of optical pumping.](image)

The optical detection scheme is based on fluorescence. Instead of the B-magnet, a laser is tuned to one of the cyclic (closed) transitions from $|L = 0, F = 4\rangle$ state, i.e. a transition when atom after the excitation falls back to its original $|L = 0, F = 4\rangle$ state because of selection rules [10]. The emitted fluorescent light is proportional to the number of atoms that made the transition to $|L = 0, F = 4\rangle$ state in the microwave cavity. Cyclic transition enables nearly 100 % fluorescence detection efficiency since every atom can be analysed as long as it is illuminated by the detecting laser.

Beside superior SNR and detecting efficiency, the trajectories of atoms do not depend on their thermal velocities as they do in the case of the classical Cs beam standard.

## 8 The cesium fountain standard

Further improvement in accuracy of the Cs standard is achieved by the Cs fountain standard. It differs drastically from both Cs beam standards. The concept was first proposed by Jerrold Zacharias in 1953 [11]. However, lacking suitable technology, the first operational Cs fountain standard was not built until 1994 [2].

A group of approximately $10^7$ Cs atoms is laser trapped in 3D space and cooled by three mutually orthogonal laser pairs (Fig. 5). The group of atoms is vertically launched with velocity $v \approx 4 \text{ m/s}$. This is accomplished by introducing a change in the frequency of the vertical pair of lasers. After launching, the lasers are shuttered and atoms move only under the influence of
gravity. Atoms are optically pumped to the $|L = 0, F = 3, m_F = 0 \rangle$ state on their way toward the microwave cavity, where they are irradiated by microwaves. Gravity decelerates the atoms and eventually causes them to fall downwards. On their way down, the atoms are irradiated for the second time in the same microwave cavity. The number of atoms that make the transition is detected optically via fluorescence. This cycle is repeated when another group of atoms is prepared.

**Figure 5:** The scheme of the Cs fountain standard. Three mutually orthogonal laser pairs trap and cool a group of Cs atoms. The group of atoms is launched upwards by introducing a change in the frequency of the vertical pair of lasers. The lasers are then shuttered and atoms move only under the influence of gravity. Atoms are then optically pumped and irradiated by the microwaves. Gravity decelerates the atoms and causes them to fall downwards. The same microwave field irradiates the atoms for the second time. Finally, the number of atoms that make the transition is detected optically via fluorescence. (Figure taken from [14].)

As it turns out, the time atoms need to travel from the first to the second microwave cavity, $\Delta t$, determines the width of the observed resonance – longer $\Delta t$ produce sharper resonances [2]. In the classical and the laser-pumped Cs beam standard $\Delta t \approx 10$ ms. It is determined by the mean thermal velocity of Cs atoms $v_t$, which is $v_t \approx 250$ m/s at 100°C, and the tube length $L$, which is $L \approx 1$ m, limited by the beam deflection due to gravity. The corresponding frequency width of the observed resonance peak is $\approx 100$ Hz, so the quality factor is $\approx 10^8$. In the Cs fountain standard, $\Delta t \approx 1$ s, because Cs atoms are laser-cooled to temperatures on the order of $\mu$K and launched from a laser trap with velocity $v \approx 5$ m/s [8]. In such low-velocity regime, gravity effects become dominant. Instead of the horizontal path of Cs atoms, a vertical path has to be chosen. The width of the observed resonance peak is $\approx 1$ Hz and the quality factor $\approx 10^{10}$.

### 8.1 Laser cooling

Laser cooling techniques were developed in the 1970s [1]. We shall briefly explain only their principle. Further explanations can be found in [2, 12, 13].

Two counter-propagating laser beams with equal intensities and high spectral purity are directed at an atom (Fig. 6). The laser frequency is tuned slightly below the transition frequency between its ground state and some excited state (in practice the excited state is determined by the availability of lasers with suitable wavelength). The atom is moving, so in its reference frame, the two laser beams frequencies are Doppler-shifted by the same amount, but in the opposite
direction. The laser beam, whose direction of propagation is anti-parallel to the atom’s velocity, is shifted toward the resonant frequency and vice-versa. Consequently, the atom absorbs more photons from the direction of its motion and because of momentum exchange, its motion is slowed down.

**Figure 6:** The principle of so-called Doppler laser cooling in one dimension. Two counter-propagating laser beams with equal intensities are directed at an atom. Their frequency is tuned slightly below the transition frequency between the ground state and some excited state. In the reference frame of the moving atom, the frequency is Doppler-shifted. Consequently, the atom absorbs more photons from the direction of its motion and because of momentum exchange, its motion is slowed down. (Figure taken from [13].)

Temperatures on the order of 100 $\mu$K can be reached by the described method. For further cooling, more sophisticated methods have to be used. They are described in [2, 12, 13].

### 9 Sources of systematic errors

Systematic errors are persistent errors that affect the observed Cs resonance in a deterministic way. They are not caused by unpredictable random fluctuations. The Cs standard has many sources of systematic errors, but that does not mean it is unsuitable for the definition of the second, since sources are well understood and their effect calculable [2]. We limit our discussion to a few of them. More on this topic can be found in [9, 10, 15].

Even in weak magnetic fields, the states $|F = 3, m_F = 0\rangle$ and $|F = 4, m_F = 0\rangle$ are not completely field-independent. The energy shift is quadratic in $B$ (Breit-Rabi formula). The associated frequency shift, divided by the resonance frequency, $\frac{\delta \nu}{\omega_{\text{res}}}$, is on the order of $10^{-10}$ [10]. This is the most important frequency shift.

In the reference frame of moving Cs atoms the frequency of microwaves is shifted due to the Doppler effect. The first-order (classical) Doppler effect disappears when the atom moves perpendicularly to the electromagnetic propagation (which is the case in all Cs standards). Since ultra high precision is required of the standard, the relativistic Doppler effect also has to be taken into the account. The second-order Doppler effect shift is negligibly small in the fountain standard. In the classical standard it causes $\frac{\delta \nu}{\omega_{\text{res}}} \approx 10^{-13}$ [9, 10].

Atoms interact with ambient thermal blackbody radiation. At $T \approx 300$ K the shift is $\frac{\delta \nu}{\omega_{\text{res}}} \approx 10^{-14}$ [10].

According to the general theory of relativity clock rate is a function of the gravitational potential at the location of the clock. Therefore, the Cs standard frequency is a function of its altitude relative to the geoid. The shift is $\frac{\delta \nu}{\omega_{\text{res}}} \approx 10^{-16}$ m$^{-1}$ [10].

Asymmetric imperfections in the fabrication of the microwave cavity also cause a frequency shift. This shift is evaluated by reversing the atom beam direction. The fountain standard uses only one cavity, so this problem does not arise at all.

Spatial variation in the magnetic field is seen by moving the atoms as an oscillatory field. It could cause transitions between $m_F$ sublevels of the same $F$, known as Majorana transitions. Again, this is problematic only in magnetic state selection scheme [10].
The relative frequency uncertainty, $\Delta \omega_{\text{res}}$, of the classical Cs beam standard is on the order of $10^{-13}$ [16], while the laser-pumped Cs beam standards reach the order of $10^{-15}$ [17]. The current value of the fountain Cs standard is on the order of $10^{-16}$ [18]. It is limited by the statistical measurement uncertainty.

10 Future development of the time standard

The reasons for choosing Cs for a frequency standard are historical. Firstly, Cs is a hydrogen-like atom with a single outer electron, so its spectrum is fairly simple. Its fundamental state has only two hyperfine levels and at operating temperatures all Cs atoms are in that fundamental state. Secondly, the $|L = 0, F = 4\rangle$ state has long decay time compared to the observation time. Thirdly, the transition frequency is in the microwave range, which was easily detectable with the equipment in the 1950s [1].

However, the next generation of frequency standards will probably be based on optical transitions. Since optical frequencies are approximately $10^5$ times higher than microwave frequencies, the relative frequency error, $\Delta \omega_{\text{res}}$, is lower (the order of $10^{-18}$ has already been reached [19]), so they are inherently more suitable. Unfortunately, no electronics exists that is fast enough to directly count at optical frequencies. Therefore, a lot of research was devoted to this problem in the past two decades. The problem was overcome with the development of frequency combs, which link optical frequencies to lower (microwave) frequencies. There are two major directions of research: a single ion isolated in an ion trap and many neutral atoms trapped in an optical lattice. Both have already surpassed the performance of the Cs standard, but there is still plenty of research to be done, before they are adopted as the new frequency standard.

11 Applications based on accurate time measurement

There are many everyday applications which rely heavily on accurate time measurement: satellite navigation, synchronization of telecommunications networks, distribution of electrical power and time stamping of financial transactions, to name just a few examples [1]. Miniaturization of atomic clocks led to the development of commercially available chip-scale atomic clocks. Their lesser accuracy ($\Delta \omega_{\text{res}} \sim 10^{-11}$) is compensated by low power consumption ($\approx 100 \text{ mW}$), small volume ($\approx 20 \text{ cm}^3$) and weight ($\approx 40 \text{ g}$) [20]. Currently their price is around $\$1500$, but when it drops, chip-scale atomic clocks will probably become part of everyday devices.

The above examples require time accuracy on the order of nanoseconds, which is easily accommodated with commercial atomic clocks. An application that requires today’s state-of-the-art time accuracy is the measurement of time dilatation predicted by both Einstein’s theories of relativity. The ticking rate of two clocks depends on their relative motion and gravitational potential they feel. By using two aluminium optical clocks (one clock served as a reference), which keep time to within 1 s/3.7 billion years [21], both effects were measured. The clocks’ relative velocity was 10 m/s and altitude difference merely 33 cm [22]. Previous experiments of this sort had to be carried out in space, because of lower accuracy of Cs clocks.

Many unifying theories (e.g. string theory) suggest possible variations of the dimensionless fundamental physical constants such as the fine structure constant $\alpha$. Atomic transitions in different atoms depend differently on $\alpha$. The explanation of dependence is beyond the scope of this seminar, but can be found in [23]. A time variation of $\alpha$ induces a change in the frequency of one clock relative to the other. Comparing the rates of different atomic clocks over several years allows us to put bounds on the local change of $\alpha$ with time. The fractional variation of the fine structure constant $\frac{\Delta \alpha}{\alpha}$ was found to be below $10^{-17} \text{yr}^{-1}$ [24]. If variations of fundamental constants are confirmed, Einstein’s equivalence principle (and with it general relativity) is violated.
References


