THE TIMES THEY ARE CHANGING

What time is it? What is time? Time keeps running, but how can you keep up? Although the position of the earth with respect to the sun or other celestial objects is still a useful indicator for the time of day, modern timekeeping with the highest accuracy can only be done by using atomic clocks. This article discusses the past, present and future of accurate timekeeping and some of its applications.

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Past

In 1967, the international organisation coordinating the use of all measurement units, the *Bureau International des Poids et Mesures* (BIPM), proposed the definition of the unit of time interval, the second, based on the cesium atom. The definition of the second (after the last revision in 2020) is as follows:

> The unit resulting from the fixed numerical value of the cesium frequency $\Delta\nu_{Cs}$, the frequency of the undisturbed hyperfine transition of the cesium-133 atom in the ground state, which is fixed at 9 192 631 770, expressed in the unit Hz, which is equal to s^{-1}.

In addition to this definition of the second, a common internationally accepted time scale is also important for many practical matters. By means of radio transmissions of time signals, coordinated by the International Telecom Union (ITU), the first international comparisons of atomic clocks (see the text box on the next page) were carried out about 52 years ago. Based on this, BIPM started calculating the International Atomic Timescale (TAI).

The TAI is much more accurate than the former universal time (UT1) based on the rotation of the earth. However, over time it was seen that the TAI and the UT1 were starting to diverge. Therefore, the ITU proposed a universal coordinated time (UTC) running at the same pace as TAI and in which a step of 1 second is introduced occasionally to remain close to UT1. We call these correction steps ‘leap seconds’. At first this seemed like a good compromise, but because practical implementation proves difficult in time-critical systems, the leap second has been under discussion for quite some time.

Present

Currently, there are about 90 time laboratories around the world that together have more than 400 atomic clocks. These clocks are compared with each other continuously, day and night, mostly by means of microwave measurement techniques using satellites. All measurement data from these laboratories is collected at BIPM and once a month, based on this data, the official UTC from the previous month is computed. Since this delay of more than a month is undesirable for certain applications, an unofficial “UTC rapid” (UTCr) was introduced several years ago, which is computed every week. In the monthly “Circular T”, BIPM reports to all time laboratories in 5-day intervals how much the timescale realisation of laboratory *k*, denoted by UTC(*k*), deviated from the computed UTC. And similarly, a weekly report is published that shows the differences between the UTC(*k*) and UTCr at 1-day intervals.

In the computation of the UTC, there is a distinction in the types of atomic clocks. Most of the clocks included in the UTC calculation are first-generation atomic clocks, which have already been commercially available for a long time. These are cesium-beam clocks and hydrogen masers. They generate a very stable (precision) frequency, but because the atoms are not completely brought into their ground state first, they still have a small deviation from the definition of the second (accuracy). In addition, there are several dozen second-generation atomic clocks worldwide; cesium or rubidium fountain clocks (in which atoms are launched upwards; while weightless, they are measured to set the frequency). In these clocks, the atoms are first brought to their ground state by means of laser cooling. As a result, the frequency coming from these clocks is not only extremely precise, but also accurate to the definition of the second.

For the computation of International Atomic Time (TAI), the clocks of the first generation are like a large flywheel of frequency standards, each of which has a stable deviation from the group mean. This group mean is a weighted mean in which the weight of each clock is determined by the stability of the individual clock relative to the mean of the

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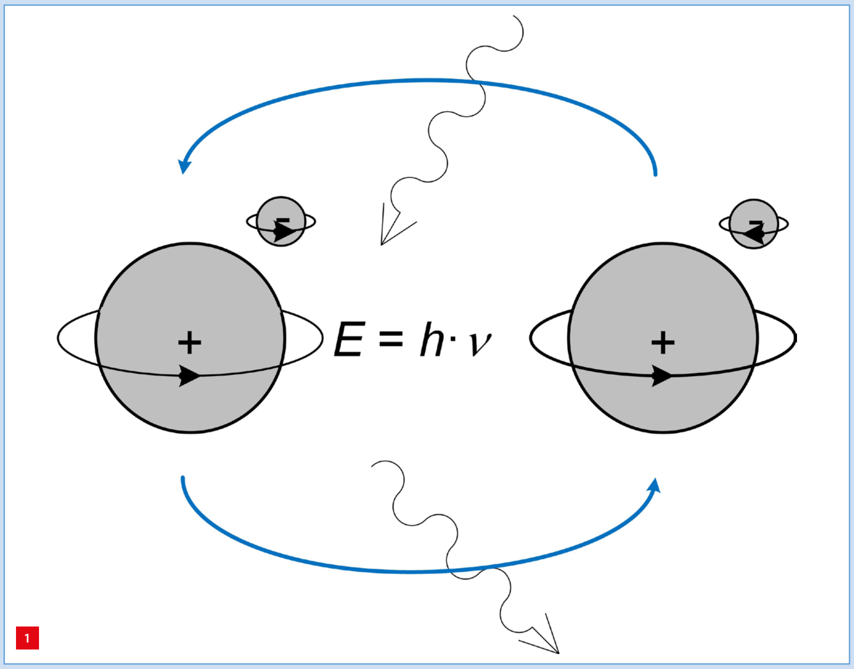
Principle of an atomic clock

Atomic clocks often work with atoms that have just one electron in the outer valence band. ^{1}H, ^{85}Rb and ^{133}Cs atoms are the most well-known elements used in microwave atomic clocks. The atom can be in two energy states. In one case (low energy), the electron spin is opposite to the nuclear spin, and in the other case (high energy), the electron spin is in the same direction as the nuclear spin. To get from the low state to the high state, the atom must absorb energy, and when the atom falls back from the high state, energy is released (Figure 1). The difference in energy can be directly linked via Planck's constant, h, to the frequency, v, of the electromagnetic (EM) radiation that is released when the atom falls back to its low-energy state. Conversely, radiation of the same frequency must be added to return the atom to its high-energy state.

In a Cs-tube clock, the atoms in the low-energy state are separated from the atoms in the high-energy state by means of a magnetic field. The atoms in the low-energy state are exposed to an EM-field, with a frequency that is as close as possible to a frequency to which the atom is sensitive. This field is generated with a very stable crystal oscillator, the frequency of which can be adjusted. The atoms coming out of the EM-field are separated again into low- and high-energy-state atoms. The ratio of high- to low-energy-state atoms shows how close the generator is to the optimal frequency – the higher the ratio, the closer.



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Transition of an atom between two hyperfine levels, in which electromagnetic radiation is absorbed or emitted. On the left, the high-energy state (nucleus and electron have the same spin direction); on the right, the low-energy state (opposite spins).

The generator is automatically adjusted to the optimum point via a feedback mechanism. The output frequency of the generator in a Cs clock is 9 192 631 770 Hz. Since this is not a useful value for many practical applications, this signal is converted via frequency dividers to signals of 10 MHz and 1 pulse per second. These signals are used as frequency and time references.

rest of the group. We call this weighted average of first-generation atomic clocks the "free atomic timescale" (*Échelle Atomique Libre*, EAL). Daily, the mean frequency deviation of this EAL is determined with respect to the second generation of atomic clocks.

Due to the complexity of second-generation clocks, it is difficult to keep them running continuously, but because of the stability of the EAL's flywheel, a continuous comparison of individual second-generation clocks with respect to the flywheel is not necessary, as long as there is sufficient data to monitor the average frequency of the EAL. The TAI calculation is based on the EAL corrected with the integrated frequency offset with respect to the second-generation atomic clocks. Finally, the TAI is corrected with leap seconds to get the coordinated universal time, UTC.

The Dutch national timescale

In the Netherlands, the National Metrology Institute, VSL, has been appointed by the government for the centralised maintenance of national measurement standards, including the standard for absolute time, time interval and frequency. VSL is one of about 90 time laboratories in the world with atomic clocks contributing to the computation of UTC. For this purpose, VSL has four first-generation atomic clocks that contribute to the EAL flywheel. From the monthly Circular T produced by BIPM, VSL knows the small deviations of its clocks and corrects for this deviation with a frequency offset generator. We call this corrected frequency and time UTC(VSL) – it is the physical realisation of Dutch time.

Comparing atomic clocks over large distances

For determining the difference between the calculated UTC and the realisation of UTC(VSL) as accurately as possible, VSL has always been at the forefront in developing measurement methods for comparing clocks over long distances. Two techniques are currently used at VSL for (semi-)continuous international clock comparisons.

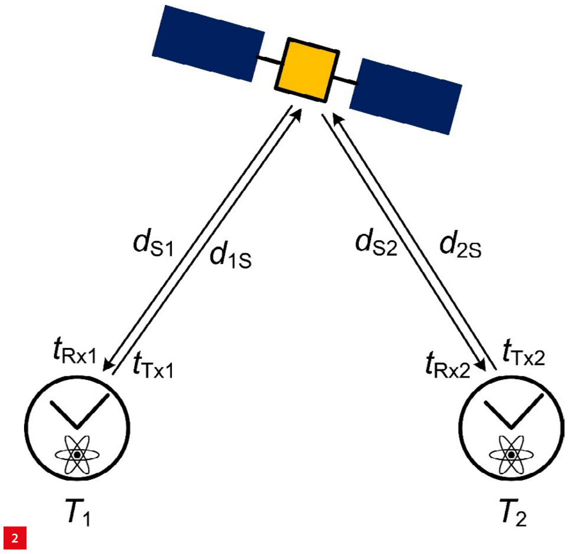
The first method uses geostationary communication satellites and is called “Two-way satellite time and frequency transfer (TWSTFT)”. The second method uses global navigation satellite systems (GNSS) such as GPS, Galileo, GLONASS and BeiDou; it is called “GNSS common view (GNSS CV)”.

TWSTFT

In TWSTFT, two time laboratories send a time signal simultaneously to a communication satellite (Figure 2). This communication satellite sends the signals back to earth so that the laboratories can receive each other’s time signal. Each laboratory measures the time interval between the time of transmit of its own time signal, $t_{\mathrm{Tx}i}$ (where Tx stands for transmit), and the time of receipt of the other time signal, $t_{\mathrm{Rx}i}$ (where Rx stands for receipt). By combining the two measurements, the difference between the two timescales T_1 and T_2 can be calculated. The accuracy of this measurement method is within approximately 5 ns.

GPS/GNSS CV

In the GNSS CV measurement method, time signals transmitted by navigation satellites (Figure 3) are used to determine clock differences. Each navigation satellite broadcasts navigation signals of which the time and frequency properties are derived from an atomic clock on board the satellite. Further, the satellite also broadcasts information on its position and orbit. When two time laboratories simultaneously ‘listen’ to the time signals from the same satellite and, based on their location relative to the satellite, correct for the transfer time of the signal from the satellite to the receiver, the combination of the two measurements determines the difference between the two timescales T_1 and T_2. The total uncertainty in this measurement method is approximately 7 ns.



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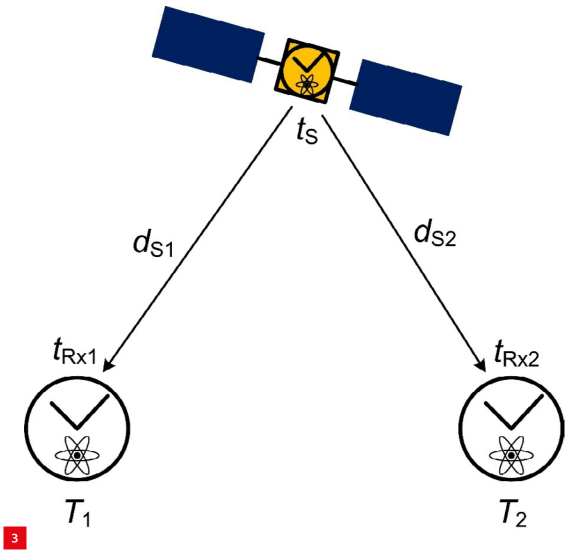
Schematic representation of a TWSTFT measurement in which the difference between the time scales T_1 and T_2 is measured via a communication satellite. The delays of the signals d_{iS} and d_{Si} (where S stands for satellite and i stands for clock 1 or 2) are almost completely eliminated from the calculation because the two signals follow exactly the same path nearly simultaneously, only in opposite directions.



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Schematic representation of a GNSS common view measurement method in which the difference between the timescales T_1 and T_2 is determined by simultaneous measurements of time signals transmitted by a GNSS satellite. Based on the known position of the laboratories and the known orbit of the satellite, the measurements are corrected for the delay of the signal from the satellite to the laboratories.

Optical fibre

In addition to clock comparisons via satellites, a lot of research has also been done in recent years on clock comparison and time distribution via fibre-optic networks. Optical fibre has the advantage of being a very stable medium in which access can be strictly regulated. As a result, the chance of intended or unintended disruption of the time signals is very small.

However, a disadvantage of this technique is that it is difficult to realise long-distance connections. Although the attenuation of the signal can be compensated for by amplifiers, the biggest challenge is often in linking connections from different operators. A European or global fibre-optic network for international comparisons of atomic clocks is therefore still a challenge for the future. Nevertheless, on a national scale, both in the Netherlands and in other countries, significant progress has been achieved on time distribution networks via optical fibres for distributing accurate time from the atomic clocks to end users.

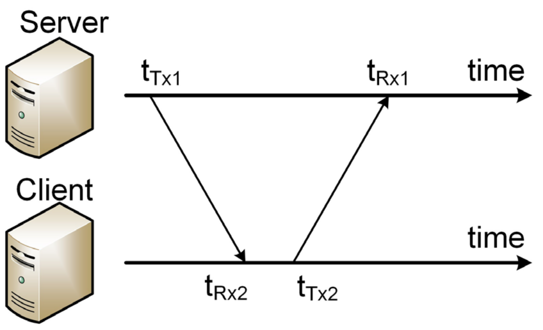
Synchronisation techniques via networks, such as the network time protocol (NTP), are almost as old as the internet but are limited in accuracy to approximately 5 ms. The improved version, the precision time protocol (PTP), was developed about 20 years ago and achieves an accuracy of about 1 µs. About 10 years ago, the European research organisation CERN started to develop an improved version of the PTP that performs extremely well on fibre-optic networks. This variant is called the “White Rabbit (WR) protocol” or “PTP high accuracy profile”. Research by VSL, among others, has shown that uncertainties of less than 1 ns can be achieved over distances of several hundred kilometers.

Like TWSTFT over communication satellites, NTP, PTP and WR are also two-way synchronisation techniques, thus (largely) eliminating the delay due to signal transit time, assuming that the forward signal propagation delay is as long as the reverse delay (Figure 4). The degree to which the assumption of equal forward and reverse delays is satisfied and the accuracy with which the times are measured, ultimately determine the total uncertainty in the synchronisation. An uncertainty of less than 1 ns is achievable with WR.

Which time?

Via satellite and network techniques, ‘time’ is made available for all kinds of applications, but which time is this actually? The UTC is the common universal timescale, but it essentially exists only on paper or in a text file. Time signals broadcast from satellites or via network time servers are from a physical realisation of UTC that corresponds approximately to the calculated UTC.

A time signal transmitted from a navigation satellite is derived from an atomic clock on board the satellite. This atomic clock is approximately equal to the GNSS system time realised with atomic clocks on earth. The atomic clocks that realise the GNSS system time run at approximately the same pace as UTC. However, no leap seconds are inserted into the GNSS system time. As a result, from the start of the American GPS, the difference between the GPS system time and UTC has increased to 18 s. In the signal transmitted by a navigation satellite, a message is included that provides a prediction of the difference between the clock in satellite and the UTC. This allows the user to correct the received time for synchronising as closely as possible to UTC.



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Schematic representation of synchronisation via network protocols such as NTP, PTP and WR. A time server sends a time signal at time t_{Tx1}. The time client receives this signal at time t_{Rx2} and immediately returns a time signal to the time server, which receives this message at time t_{Rx1}. If the assumption of equal forward and reverse path delays is correct, then the path delay t_p of the signal and the difference between the clock of the client and the clock of the server ($T_2 - T_1$) can be calculated from the four timestamps. With this information the client can adjust its clock to synchronise with the server.

In addition, the user must also correct for the path delay of the signal from the satellite to the receiver. Navigation satellites fly in an orbit of about 20,000 km above the earth’s surface. The signal therefore takes approximately 70 ms to travel from the satellite to the receiver. The satellite transmits data about its orbit, and the receiver’s position can be determined from the navigation signals from four satellites. This allows the receiver to correct for the path delay of the signal.

The time being sent via network protocols can come from a GNSS receiver or can be linked directly to an atomic clock in a time lab that contributes to the realisation of UTC. Network time servers using the NTP send signals approximately equal to UTC. This signal already contains leap seconds and can also announce when another leap second is about to be inserted.

Network time servers using the PTP or White Rabbit send a signal that is approximately equal to the TAI and has therefore yet to be corrected for leap seconds. The time server or the user must keep track of the integer number seconds of difference between TAI and UTC.

As NTP, PTP and White Rabbit are all two-way protocols, the path delay of the signal can be estimated to a certain level of accuracy and the client (receiver) can correct for this.

Applications

All kinds of applications – the clock on the church tower, the train station clock, the computer network, the stock exchange, the electric power grid, the telephone network, navigation systems, scientific experiments – need a more or less accurate time that can be traced back to UTC in one way or another.

- When the clock on the church tower is delayed or advanced by 5 minutes, there is a risk that we will arrive at our appointment too early or too late.
- When the station’s clock is running 1 minute ahead, there is a risk that the train will leave too early and that passengers don’t catch the train.
- When computers on a network fail to synchronise within 1 s, there is a risk that the user can no longer

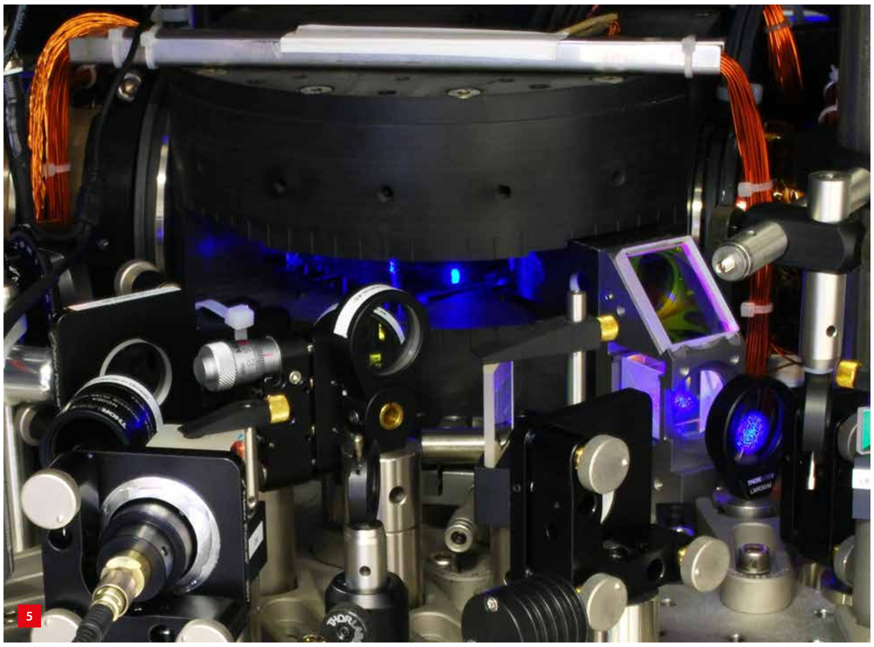
log in to the corporate network, or that encrypted messages can no longer be decrypted by the recipient.
- When the computers in the stock exchange are not synchronised within 1 ms, the order in which purchases and sales of shares have been made cannot be traced properly, and therefore the price of the share cannot be fixed at the time of the transaction.
- When measuring equipment in the electricity network is not is synchronised within 50 μs, it is more difficult to determine whether the supply and demand of electricity are still balanced, resulting in the risk that the electricity supply is shut down as a precaution to avoid larger grid instabilities.
- When phones in a mobile phone network are not synchronised within 1 μs, there is a risk that a phone call drops out because the digitised conversation does not run smoothly over the connection.
- When the clocks of a satellite navigation system are out of sync by more than 100 ns, navigation for vehicles within cities or for ships in a harbour is much more difficult because the position of the receiver has become too inaccurate.
- When the clocks in a scientific experiment to determine the speed of particles are not synchronised with each other within a nanosecond, there is a risk that a wrong conclusion is drawn about particles moving faster than the speed of light...

All in all, there are countless reasons why it is important that all clocks are properly synchronised with the UTC.

Future

New clocks
Since the invention of the atomic clock, ‘time’ has progressed. With advances in microwave and optical techniques, it was found that atoms other than cesium would be better candidates for the definition of the SI-second. New clocks have been developed that are based on atoms like strontium (Sr) and ytterbium (Yt), producing frequencies in the terahertz range. These are optical frequencies, and therefore these clocks are called optical clocks (see Figure 5). Simply speaking, these signals are more accurate for timekeeping because they include more vibrations per second, which increases the resolution for determining time intervals.

The technology of optical clocks has now come to the point where about 15 laboratories worldwide have them operational. Not yet continuously operational, but with sufficient operating time that they can be used to better determine the stability of the EAL timescale, which is the basis of UTC. The discussion on redefining the SI-second began several years ago, and the roadmap towards this redefinition is now becoming steadily clearer. Although there is still a lot of work to be done, a new definition of the SI-second is expected between 2030 and 2040. This definition will then be based on energy transitions of atoms or ions that produce electromagnetic radiation in the optical range.



An optical clock based on Sr atoms is under development at the University of Amsterdam. (Source: www.strontiumbec.com, courtesy of University of Amsterdam)

New UTC
Initially, it seemed to make sense to keep the atomic timescale (UTC) quite close to the traditional timescale based on the rotation of the earth (UT1) by introducing corrections of 1 second if the difference became too large. By now, we see that accurate time and synchronisation are necessary ingredients for operating critical infrastructures like electric power grids, navigation systems, telecommunication networks and computer networks. In these infrastructures, introducing leap seconds always runs the risk of temporarily losing synchronisation and consequently critical infrastructure potentially going down.

Therefore, the operators of these infrastructures are calling more and more loudly for a new common universal timescale without the inconvenient steps of leap seconds. A joint working group with representatives from BIPM and ITU has now drafted a proposal for a new definition of UTC to solve the issue. The current proposal essentially allows for the difference between UTC and UT1 to increase to more than 1 s. So far, no new limitations for the difference between UTC and UT1 have been defined in the proposal. This has been left for further, future discussions.

The difference between UTC and UT1 will still be monitored by the International Earth Rotation and Reference System

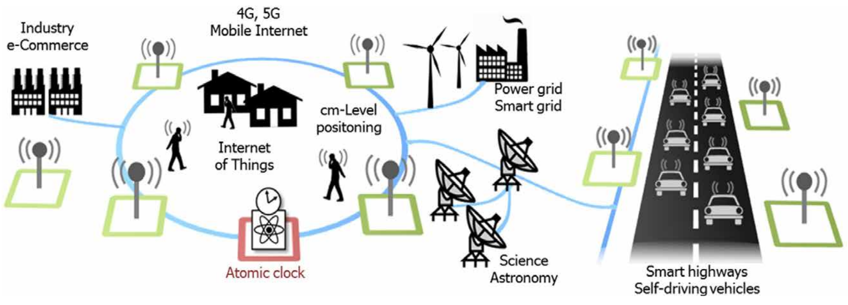
Service (IERS) and will be published to be easily accessible for applications that need this information, such as astronomic observatories.

Although some organisations do not wish to wait another year to abolish leap seconds, others have indicated that they need sufficient time to implement this revised definition of UTC. It has therefore been proposed that the new definition of UTC shall become effective from the year 2035. In the General Conference on Weights and Measures (CGPM) that will be held in November 2022, representatives of national governments will cast the final vote on this proposal for a new UTC.

New applications

With the improvements in timekeeping and time-distribution techniques, new applications are born as well. The relation between timekeeping and navigation is about as old as mankind. With each improvement in our ability to keep track of time, our abilities for positioning and navigating have improved as well. Only a few decades after the invention of atomic clocks, the Global Positioning System (GPS) was launched. With modern GPS receivers smaller than the size of a wristwatch, we can determine our position with an accuracy of about 10 m. However, because of the weak signal from GPS satellites, positioning only works well in open outside areas.

The new generation of atomic clocks, combined with new technologies for distributing time and frequency signals over optical fibre networks, allows us now to overcome this weakness of satellite navigation. In the research project SuperGPS, funded by the Dutch Research Council (NWO), scientists at TU Delft and VU Amsterdam have joined forces to develop the technology for a terrestrial navigation and positioning system (TNPS) that is based on a combined optical fibre and wireless network for accurate time and frequency distribution. A conceptual diagram is shown in Figure 6.



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Conceptual diagram of a terrestrial navigation and positioning system based on a combined optical-wireless telecom infrastructure for accurate time and frequency distribution. (Source: SuperGPS, www.tudelft.nl/citg/over-faculteit/afdelingen/geoscience-remote-sensing/research/projects/supergps, courtesy of TU Delft and VU Amsterdam)

The TNPS uses a backbone of optical fibres (blue lines) for distributing accurate time and frequency signals from a centralised timescale realisation based on atomic clocks (red box). These accurate time and frequency signals synchronise a network of wireless transmitters (green boxes). The transmitters are actually very similar to base stations for mobile-phone networks, except that an improved synchronisation device needs to be included. The transmitters then broadcast synchronised navigation messages in a similar way to navigation satellites. However, the structure of the navigation signal has been modified to be less susceptible to intended or unintended disturbances.

An interesting aspect of this concept is that it can be implemented in existing telecom infrastructures with limited modifications and without a significant loss of bandwidth for regular telecom services. And, alongside the advantage that this TNPS can also work indoors, a demonstration at The Green Village at TU Delft – with synchronisation support from the atomic clocks at VSL – has shown that a positioning accuracy of 10 cm can be achieved.

This achievement is a major step towards autonomously driving vehicles. Imagine yourself in a car, driving in auto-pilot mode, sitting back and relaxing – listening to Bob Dylan's “The Times They Are A-Changin'”.