# Time and frequency comparisons using radiofrequency signals from satellites

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## Summary:

The comparison of distant clocks has always been an important part of time metrology. It is important in science in general as well as in everyday applications. Signals from the satellites of the Global Positioning System (GPS) started to be used for the purpose in the early 1980s. The methods of signal processing have improved to an extent that time transfer with ns-accuracy and frequency transfer with $10^{-15}$ relative instability have become routine. The usage of signals from other Global Navigation Satellite Systems gets more and more common and examples of the improvements related to that will be given. Two-Way Satellite Time and Frequency Transfer (TWSTFT) is another method relying on the exchange of signals in the microwave range. Time transfer accuracy at the 1 ns level was demonstrated, and recently new signal structures and processing schemes showed the way for further improvements.

## Résumé:

La comparaison d'horloges distantes, qui a toujours été une part importante de la métrologie du temps et des fréquences, concerne aussi bien la science en général que les applications quotidiennes. Une des techniques utilisées repose sur les signaux des systèmes de radionavigation par satellites (GNSS pour Global Navigation Satellite System), qui ont commencé à être exploités au début des années 1980 avec les signaux du Global Positioning System (GPS) américain. Les méthodes de traitement de ces signaux se sont améliorées au cours du temps, permettant d'obtenir aujourd'hui de façon routinière des transferts de temps avec une exactitude de l'ordre de la nanoseconde, et des transferts de fréquence avec une instabilité de $10^{-15}$ en fréquence relative. L'utilisation de signaux d'autres constellations GNSS se développe de plus en plus, et des exemples d'améliorations attendues sont présentés. Une autre technique de transfert de temps à "deux voies" (TWSTFT pour Two-Way Satellite Time and Frequency Transfer) est basée sur l'échange de signaux dans la gamme des fréquences micro-ondes, via des répéteurs de satellites géostationnaires de télécommunications. Une exactitude des transferts de temps au niveau de 1 ns a été démontrée, et de nouvelles structures de signal associées à de nouveaux traitements ont récemment montré la voie pour d'autres améliorations.

## Keywords:

Frequency standards, time and frequency metrology, GNSS, TWSTFT

## Mots clé:

Etalon de fréquence, Métrologie temps-fréquence, GNSS, TWSTFT

## 1) Introduction

In our daily life we take it for granted that mobile communication, distribution of electrical power, and location-based services on smartphones are available at all times. The operation of the underlying systems requires time synchronization at various levels of accuracy. Time and frequency references of superior quality and traceable to the SI unit of time ensure inter-operability of such services over country borders and continents. One gets so used to the function of these systems that one disregards the need for stable and reliable frequency sources, subject of other contributions in this Special Issue, and, at the same time, means of comparison at the required uncertainty. Time and frequency comparisons on local and regional scale can be achieved with electrical signals transported in cables, but the utmost accuracy could be demonstrated by using optical fibers to transport either stabilized laser radiation or modulated laser signals [1, 2]. On a global scale, however, the transmission of radio signals via satellites is the first choice [3, 4]. In this contribution I report on two satellite-based methods, the reception of signals of Global Navigation Satellite Systems (GNSS), subject of Section 2, and Two-Way Satellite Time and Frequency Transfer (TWSTFT), subject of Section 3. When signals from the satellites of the Global Positioning System (GPS) started to be used for the purpose in the early 1980s, time-keeping was revolutionized [5]. The methods of signal processing have improved to an extent that time transfer with ns-accuracy and frequency transfer with $10^{-15}$ relative instability have become routine. The usage of signals from other Global Navigation Satellite Systems gets more and more common and examples of the improvements related to that are given below. TWSTFT was introduced as early as 1980, but its routine use started in the early 1990s only [6]. It is another method relying on the exchange of signals in the microwave range, and the smallest uncertainty for time transfer could be verified [7]. The literature on the achievements over the years is abundant, and the reader is referred to the compilations of the Precise Time and Time Interval (PTTI) meetings that allow following the historical development quite nicely. Section 4 briefly deals with time transfer equipment calibration which is prerequisite for accurate time transfer. The paper is concluded with an outlook on current developments.

## 2) Current Status of GNSS-Based Time Transfer

### 2.1) General Introduction

Signals from the satellites of the Global Positioning System (GPS) – the first Global Navigation Satellite System (GNSS) [8, 9] - started to be used since the late 1980s for time comparisons. The primary purpose of GPS (as all GNSS) is to serve as a positioning and navigation system, but the entire system relies on precise timing, in more detail, the satellite ranges used to calculate position are derived from propagation time measurements of the signals transmitted from each satellite. The result of such a measurement, when multiplied by the speed of light, represents not the true geometric range but rather the so-called pseudorange. Deviations come from the lack of time synchronization between the satellite clock and the receiver clock, by delays introduced by the ionosphere and troposphere, and by multipath and receiver noise. The signals broadcast by GNSS satellites are derived from onboard atomic clocks (caesium beam clocks, rubidium gas cell clocks, passive hydrogen masers) and contain timing and positioning information. In details, the signals transmitted and the on-board configuration of the satellites differ between the GNSS existing today [4]. Here we restrict ourselves to a brief explanation of the measurement principle using GPS signals. The nominal output frequency of the GPS onboard clocks is $f_0$ = 10.23 MHz. From this fundamental frequency the two microwave frequencies $f_1$ = 1575.42 MHz (L1) and $f_2$ = 1227.60 MHz (L2) are derived. More recently, signals on two more frequencies are transmitted but have not been used widely in the context of time transfer yet. The two carriers are phase modulated with pseudorandom noise codes (PRN-codes). These are binary codes with a chip rate of 1.032 MHz on L1, named coarse/acquisition (C/A) code, and a binary code with 10.23 MHz chip rate on both frequencies, called precision (P) code. These codes are unique for each satellite. All satellites transmit their signals on the same frequencies. A receiver generates a local copy of the PRN-code derived from its internal oscillator. This local copy is electronically shifted in time and multiplied with the incoming antenna signal. If the received satellite PRN-coded signal, which is extremely weak and hidden in the noise, and the replica signal coincide, the receiver's tracking loops can lock to the satellite signal. When this has happened data at a rate of 50 bit per second can be transferred to the receiver, reporting the almanac, orbit parameters and parameters that refer the individual satellite clock to the underlying GPS time (the system time which is calculated from an ensemble of clocks in the satellites and on Earth).

Specific GPS timing receivers have been developed, which come in two distinct configurations. Receiver type one uses the received signal to discipline an inbuilt oscillator to GPS time and delivers a one pulse per second electrical signal (1 PPS) or even a set of output signals (standard frequency signals, signals for telecommunication applications). This application, although widespread, is not covered further here.

### 2.2) Code-based time and frequency transfer

Receiver type two determines the pseudorange of each satellite in view with respect to the local reference signal connected to the receiver and uses the correction data transmitted in the signal in space to provide output data in the form of local reference (local time scale) minus GPS time. Another option is the use of the IGS time, a time scale calculated by the International GNSS Service (IGS) [10], which is used as the reference for various IGS products [11]. To facilitate the data exchange for time transfer and dissemination, directives on a common format and standard formulae and parameters have been provided jointly by the International Bureau of Weights and Measures (Bureau international des poids et mesures, BIPM) and the Consultative Committee for Time and Frequency (CCTF) [12].

The popular common-view (CV) method has been in use for the comparison of distant clocks in the last decades [13] and is built upon simultaneous reception of the transmitted signal from the same satellite at two Earth laboratories. It minimizes the impact of common errors in the GPS signals caused by errors in the satellite position, instabilities of the satellite clocks and the effects of the intentional degradation (known as "selective availability") that was applied to the GPS signal until May 2000. Receivers of the first generation used for time comparison were single-channel, single-frequency (L1) C/A code receivers and data of this kind are still in use and reported as L1C-data. The propagation of the signal and thus the measurement results are affected by atmospheric effects. The ionosphere provokes delays that can be modelled on a global scale only to a limited extent, and substantial errors occur, particularly during periods of high solar activity. Fortunately, the ionosphere is a dispersive medium, group velocity and phase velocity being affected with opposite sign. This property is used in advanced receivers that are capable to receive and process signals on both frequencies $f_1$ and $f_2$ to determine the ionospheric delay in situ. Data generated in this way are labelled as L3P-data [14]. Multi-channel, dual-frequency receivers have thus started to replace older equipment in most laboratories, leading to an increased accuracy of time transfer. Figure 1 illustrates the advantage of dual-frequency reception in a comparison between PTB Braunschweig and Nairobi over a baseline of 6440 km. Data collection happened during 2013 in support of the operations establishment of the time laboratory at Kenia Bureau of Standards (KEBS).

The common-view method has almost been replaced by a new one, named “GPS all-in-view” (AV) [15], which is in practice simpler to implement. After exchange of the (standardized) data files among the laboratories, the individual observation data are corrected for the above mentioned effects based on IGS products before averages over convenient intervals are formed. Subtraction of corresponding data allows the comparison of the local time scales or frequency standards. Comparisons within Europe practically give the same results in CV and AV, even without the use of external products. AV is, however, particularly useful in intercontinental comparisons and thus widely used today by BIPM in its undertaking to realize Coordinated Universal Time, UTC.

### 2.3) Carrier-phase based time and frequency transfer

During recent years it has become more and more common to build on techniques initially developed for positioning also in time and frequency transfer. Here to mention is Precise Point Positioning (PPP) which is a technique providing a priori position with a high accuracy on a global scale of a single isolated GNSS receiver. A software package in frequent use has been developed by National Resources Canada and the software has been generously made available to several timing laboratories for local installations and an online service is also available [16]. PPP builds on the precise satellite orbits and clock products generated by the IGS [11]. The use of PPP appeared particularly attractive for the generation of UTC by the BIPM as it is adapted to a global, but sparse, network of stations. The BIPM processes the time transfer links between all participating institutes based on the RINEX files provided during the full month covered by the BIPM Circular T [17] in one batch. The results are published on its ftp site [18]. To give an example, taken from [18], the link between PTB and United States Naval Observatory (USNO), Washington DC, was chosen. The results obtained during June and July 2014 via a code based dual frequency evaluation and a PPP solution are contrasted in Figure 2. Individual data points represent 16 min averages.

Signals from the Russian GLONASS have been routinely used by BIPM for time transfer along some links between PTB and institutes that operate GLONASS receivers (in Russia, Kazachstan, Turkey), and studies are underway to make full benefit of that second operational GNSS [19]. The (future) use of Galileo satellite signals has been discussed as well, and the available signals may give access to improved performance [20]. Based on the indications contained in [21], the internal delays for Galileo signals in two GNSS receivers operated in the Czech metrology institute UFE and in PTB, respectively, were determined by R. Piriz [22], such that Galileo dual frequency common-view time transfer could be made between the two institutes using the temporarily available Galileo satellites, in addition to GPS comparisons. Results of a few days in April 2014 are depicted in Figure 3. The CV time transfer results (5-minute averages) are plotted in dependence of the elevation of the respective satellite over UFE (Prague). We note that the dispersion of the Galileo results for a given elevation is smaller than that of GPS results, which is caused by the fact that the noise introduced by forming the linear combination of observations on individual frequencies is smaller in case of Galileo because of the wider separation in frequency of the two processed signals. Further studies are of course needed to assess the possibilities of Galileo time transfer once a more complete fleet of Galileo satellites will be operational.

## 3) Two-way satellite time and frequency transfer (TWSTFT)

### 3.1) General Introduction

TWSTFT activities started in the 1980s [6] and have led over the years to a widely used technique of time and frequency transfer between laboratories that contribute with their atomic clocks to the realization of UTC and for the synchronization of timing facilities in general. TWSTFT is thus used in two areas, for accurate time transfer by comparing local time scales and for accurate frequency comparisons between atomic fountain frequency standards and hydrogen masers [23]. A detailed description of operational use, data processing and reporting is provided in [24].

### 3.2) Description of the method

TWSTFT is based on the exchange of radiofrequency signals through geostationary telecommunication satellites. Currently TWSTFT is made using fixed satellite services in C-Band (China, India), and X-band (US), but metrology institutes in Asia, Europe and the US use signals in the Ku-band. Pseudorandom Noise (PN) coded signal with Binary Phase-Shift Keying (BPSK) modulated carriers are transmitted. The phase modulation is synchronized with the local clock's 1 PPS output. Each station uses its characteristic PN sequence in the transmitted signal. The receiving equipment generates the PN sequences of the remote stations and reconstitutes a 1 PPS from the correlation signal between the received and the locally generated PN signal. This 1 PPS signal is compared to the local clock via a time-interval counter (TIC).

To be more specific, the measurement result obtained at site 1 comprises the difference between the two time scales realized at the two linked sites and the propagation delay between site 2 and 1. This delay consists of the remote site transmitter delay, the overall signal path delay from site 2 to the satellite through the transponder and down to site 1 on Earth, the local receiver delay, and the delay due to the Sagnac effect [25], which is computed from the positions of the ground stations and the geostationary satellite. At site 2, the equivalent measurement is carried out simultaneously, and the time scale difference is calculated from the difference of the two measurement results. Following a pre-arranged schedule both stations of a pair lock on the code of the corresponding remote station for a specified period, measure the signal's time of arrival, and store the results. After exchanging the data records the difference between the two clocks can be computed.

Compared to the GNSS based time transfer, it is the major advantage of TWSTFT that the propagation delays for the signal in both propagation directions are equal to first order, so they go away when the difference is formed [6]. Looking in closer detail there are several effects causing non-reciprocities which are discussed in detail in the literature [24, 26]. Most of the propagation related effects can account for non-reciprocities typically not exceeding 0.1 ns, depending on the geometry of stations and transmission frequencies. The delay through the satellite transponder cancels only if both ground stations transmit via a single transponder on the satellite, which requires that both stations are within the same antenna footprint of the satellite. This “ideal” transponder configuration is available for the European laboratories but not in long-baselines like that between Europe and the US. Here two transponders are used for the two directions through the satellite, and the propagation delays through the satellite equipment cannot be assumed to be equal. It could be shown that the delay in the two transponders may vary with time of day due to temperature effects on the satellite resulting in diurnal variations in the measurement results. But some diurnal variations observed (see Fig. 5 later) cannot be explained thereby.

A large unknown is the signal-delay difference between the transmitter and the receiver part of the ground terminal. These delays are hard to determine individually, but this problem may be solved in the near future due to work done in several institutes (see e. g. [27]). For the time being, the delays need to be calibrated by referring to another time transfer method or using a mobile TWSTFT station [7].

### 3.3) Current performance

Examples given in this Section are from the network of two laboratories in the US and twelve in Europe that use the Telstar T11-N satellite in early 2014. In order to limit the transponder lease cost, only 1.6 MHz of bandwidth have been leased since 2011, and the exchanged signals carry a phase modulation of only 1 MChip/s. Figures 4 to 6 illustrate the current operational practice and performance. Results of reception at PTB of the signal transmitted from the Laboratoire National de Métrologie et d’Essais – Systèmes de Référence Temps-Espace (SYRTE, France), located at Observatoire de Paris, and realizing the local timescale UTC(OP), during one standard 2-minutes measurement interval are shown in Figure 4. The midpoint of a quadratic fit to such kind of data is typically combined with those recorded at SYRTE (in this example), to give the time difference UTC(PTB)-UTC(OP). It is illustrative to look at Figure 5 which shows the results of ranging to the satellite from PTB (reception of the own transmitted signal) during two days. The variation of the position of the satellite with time is obvious – note the µs-scale for $\Delta T$. Such variations would – in the selected example - lead to significant systematic variations in the apparent time differences UTC(PTB)-UTC(OP) if the timing of the signal transmission from both stations would deviate by more than about 5 ms. This is usually carefully avoided by all stations involved. The results of ten days of comparisons between PTB on the one side and the Istituto Nazionale di Ricerca Metrologica (INRIM), Italy, which realizes UTC(IT), National Institute of Standards and Technology, USA (NIST), SYRTE, and United States Naval Observatory (USNO) on the other side show a quite smooth performance as demonstrated in Figure 6. All these institutes “k” generate their time scale realizations UTC(k) from steered active hydrogen masers. Diurnal variations can be seen in some links whereas other links are essentially free of such disturbance or at least such diurnals are buried in the measurement noise.

### 3.4) Recent developments

To improve the short and medium frequency stability of TWSTFT, several efforts were proposed and some were tested. It was demonstrated that increasing the chip rate is a valid way to decrease the measurement noise using code-based TWSTFT [28]. Figure 7 demonstrates the decrease of the scatter of 1 s data around the linear regression line (denoted as $\sigma(\Delta T@1s)$) during 2 minutes of "ranging" data, when PTB receives its own transmitted signal, with increasing chip rate of the PN modulation. Similar behaviour could also be verified in time transfer data. The higher the chip rate, however, the more expensive gets the cost of operation, because the lease fee for a transponder is proportional to the occupied bandwidth.

In the spirit of the foregoing, at the time of writing this article a campaign of operating TWSTFT links with 20 MChip/s chiprate is being prepared as part of the activities in the frame of the European Metrology Research Programme. It involves the institutes INRIM, NPL (National Physical Laboratory, Teddington, UK), OP and PTB. The aim of this current activity that includes thorough characterization of the involved equipment is demonstrating the suitability of broadband TWSTFT for comparing optical frequency standards. Optical frequency transfer using fiber networks is clearly the first choice for this task [1], but will remain a point-to-point method over continental distances for quite some time (not to mention the economic and logistic challenges), and seems out of reach for intercontinental distances for a while.

Another avenue was followed by colleagues in the Japanese National Institute of Information and Communications Technology, NICT, with partial support by Taiwanese institutes when they studied the use of either dual PRN codes modulated to carrier signals in Ku band [29], or the measurement of the phase of the Ku band carrier signal for frequency transfer [30], resuming an (old) idea published in 1999 [31]. Both cases represent point-to-point TWSTFT links which require a very moderate bandwidth lease (thus low cost). Two-way carrier phase was successfully tested along the 10 000 km link between NICT and PTB, relative uncertainties for frequency transfer of $2\times10^{-13}$ at averaging times of $\tau = 1$ s, $1\times10^{-15}$ at $\tau =$ 40 000 s were achieved [32]. During the same campaign, two $^{87}$Sr lattice optical frequency standards operated at NICT and PTB, respectively, were compared. Based on a total measurement time of 83 640 s relative frequency difference of $(0.8 \pm 1.6)\times10^{-15}$ between the two standards was obtained, where the statistical measurement uncertainty is the biggest contribution to the combined uncertainty.

### 3.5 ACES

"Atomic Clock Ensemble in Space" (ACES) is a scientific mission that relies on the availability of the International Space Station (ISS). It comprises a space segment and a ground segment [33]. The space segment comprises two atomic clocks, PHARAO (Projet d'Horloge Atomique par Refroidissement d'Atomes en Orbite), a primary frequency standard based on laser-cooled caesium atoms (see XXX et al. in this Special Issue [34]), and an active hydrogen maser (named SHM for Space Hydrogen Maser). The two frequency standards will be used to generate an on-board time scale that should reflect the short-term stability of SHM and the long-term stability and accuracy of PHARAO. Connection to the ground is going to be provided by the so-called Microwave Link (MWL) and the European Laser Timing (ELT) space terminals. All that will be installed on the Columbus External Payload Facility.

The ground segment consists of a set of Microwave Link ground terminals (MWL-GT), to be installed at selected timing institutes all over the world that operate different types of high-quality atomic clocks. In addition, the optical laser link between space and ground will allow performing time and frequency comparison between the on-board time reference and various ELT ground sites that will in general differ from those equipped with a MWL-GT. The ISS orbit is almost circular at an altitude of about 400 Km and an inclination of 52.6°. The orbital period is thus close to 90 minutes and each ground site will have 4 or 5 direct visibilities each day allowing direct time-frequency comparison between the space and the ground clocks.

The MWL is building on the expertise gained with standard TWSTFT equipment and represents a much advanced variant, using 100 MChip/s modulation rate. Space and ground segment have been developed by TimeTech GmbH, Stuttgart. It is expected that the frequency reference in space with a fractional instability (at 1-day averaging) and inaccuracy of $3x10^{-16}$ will be operational for at least 18 months, starting late 2016. The MWL shall be used to compare the space clocks with high-performance ground clocks in a worldwide network and thereby also allow comparisons between ground clocks, using the common view or non-common view techniques, with the aim of probing fundamental laws of physics to high accuracy. The MWL was designed under very stringent requirements in order not to compromise the performance of the space clocks in these comparisons. At the time of writing this article, preparations for the installation of the first MWL-GT at PTB are underway.

## 4) A word on calibrations

Time transfer using GNSS signals and TWSTFT has become an important technical component in the process of the realization of International Atomic Time. It is also used for time transfer between the elements of the Ground Segment of the European Satellite Navigation System Galileo which comprises two so-called Galileo Precise Timing Facilities and European metrology institutes [35]. To employ the full potential of the techniques, especially for accurate time transfer, the internal delays of the ground terminals – GNSS receivers as well as TWSTFT equipment - need to be determined. Unfortunately, such exercises are quite time consuming and need to be repeated periodically if the accuracy of time transfer shall indeed be at the 1 ns level. Figure 8 illustrates the results of almost 6 years of assessment of time comparison UTC(OP)-UTC(PTB), the difference between GPS P3 and TWSTFT data (daily mean values). The time series of the double-difference data contains several messages. Note that the data generation involved two GNSS receivers and two TWSTFT terminals, including their local connections to the local time scales. Overall the peak-to-peak excursions are for most of the period under study within 3 ns, except some critical period at the beginning that could be traced to software issues fixed afterwards. Both kinds of time links were independently calibrated over the years with uncertainties ranging from 1 ns to 5 ns, and only this ensured the almost perfect match of the two methods. The data show, however, not only noise but also systematic effects at the level of the order of 1 ns/500 days. If that could be attributed to just one technique, the selected one would allow frequency comparisons with an inaccuracy of about 2 parts in $10^{17}$ at averaging times of one year to be made. This is clearly below the uncertainty of caesium fountains for a while. Nevertheless, the apparent systematic variations motivate repeated calibrations of the time links.

The need for the calibration of GPS time transfer links was recognized quite early, and the link between OP and NIST was calibrated for the first time as early as in 1983 [36]. Nevertheless, still today discussions are ongoing about how to do such calibrations in the most efficient way, how to make use of the results, and in particular how to state the uncertainty achieved for such calibrations (see Rapports and publications referred to in [36]), a debate which shall not be renewed here.

A GNSS calibration campaign involves shipment of a receiver which is in sequence operated in common-clock configuration at various institutes. Conceptually, either the travelling receiver is itself considered as the “golden receiver” for which the delays are all known accurately, or it is considered only as a transfer standard that carries the respective information from its home institute. During 2014 the BIPM published a comprehensive guide for future GNSS calibration exercise [37], and first applications have been reported. For the time being, the uncertainty for a calibrated GPS P3 time link is conventionally set as 5 ns, with the intention to reduce this value based on coming experiences.

Calibrations involving mobile TWSTFT stations were described in details in [7] and it was shown that for most of these exercises, estimated uncertainties around 1 ns (1 $\sigma$) were achieved. Consecutive campaigns confirmed reproducibility at the nanosecond level in many cases, but also significant variations of calibration values were noted.

## 5) Conclusions and Outlook

For some applications, the time and frequency transfer technique of choice may depend on the operational distance that it can bridge. The GPS all-in-view technique is unique: it allows comparisons among laboratories wherever they are located on Earth. For the GNSS CV time transfer and for TWSTFT, the maximum distance is approximately 10 000 km because both sites must simultaneously be in the field of view of the same satellite. The synchronization of the ground stations of the deep space tracking networks maintained by NASA and ESA has practically to rely on GNSS comparisons for such reasons. The TWSTFT link with the longest baseline currently in routine operation is that between NICT and PTB. If longer distances shall be overcome two-hop configurations appear feasible, but additional measurement noise would be unavoidable. Such a link is currently in an experimental stage, connecting USNO and NICT using a relay station in Hawaii.

As pointed out in the previous section, the use of two independent techniques of similar quality for time transfer between important laboratories is recommended. This refers to the time transfer links in GNSS ground segments as well as between major laboratories collaborating with BIPM in the realization of UTC. In the future, the performance of GNSS-based time transfer is likely to improve at moderate scale with the new signals now available [38]. An example is the Galileo signal transmitted in the frequency band E5 and carrying a very broadband PRN modulation, designated as ALTBOC [39]). A second such ALTBOC signal in a different frequency band other than E5 would likely bring a major improvement for time transfer as it would entail a reduced noise level in the ionosphere-free combination. For sure, TWSTFT offers high potentials in terms of achievable measurement noise and accuracy, but with the disadvantage of a priori requiring substantially higher operational cost.

The use of the advanced signal structures referred to in Section 3.4 will likely allow point-to-point high-performance frequency transfer at reasonable cost.


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[38] M. C. Martinez-Belda, P. Defraigne, and C. Bruyninx, Trans. Ultrason. Ferroelectr. Freq. Control, vol. 60 (2013) 121.

[39] G. W. Hein et al., Proc. European Navigation Conference GNSS 2004, Rotterdam, NL, (2004) on CD-ROM.

**Figure Caption**

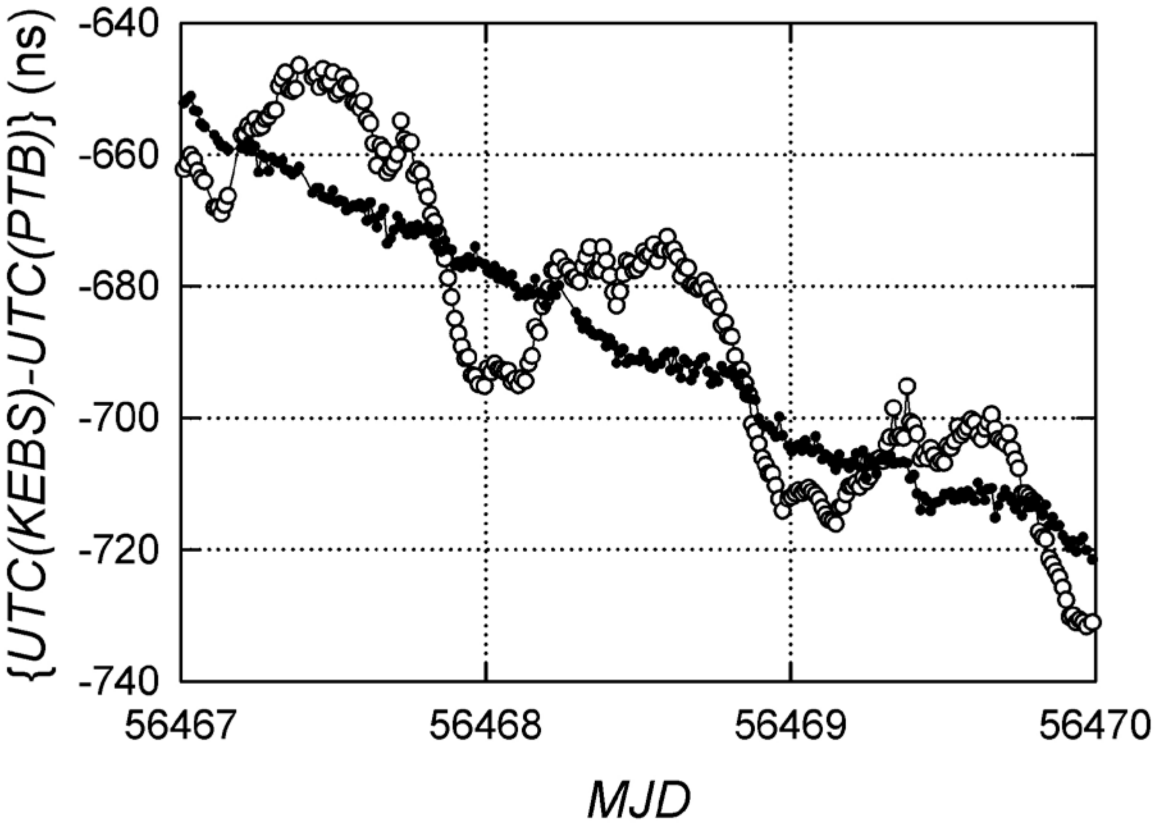


Figure 1 GPS CV time comparisons between Kenia Bureau of Standards and PTB; open symbols: L1C single frequency data, full symbols: dual frequency L3P data obtained from the same receivers.

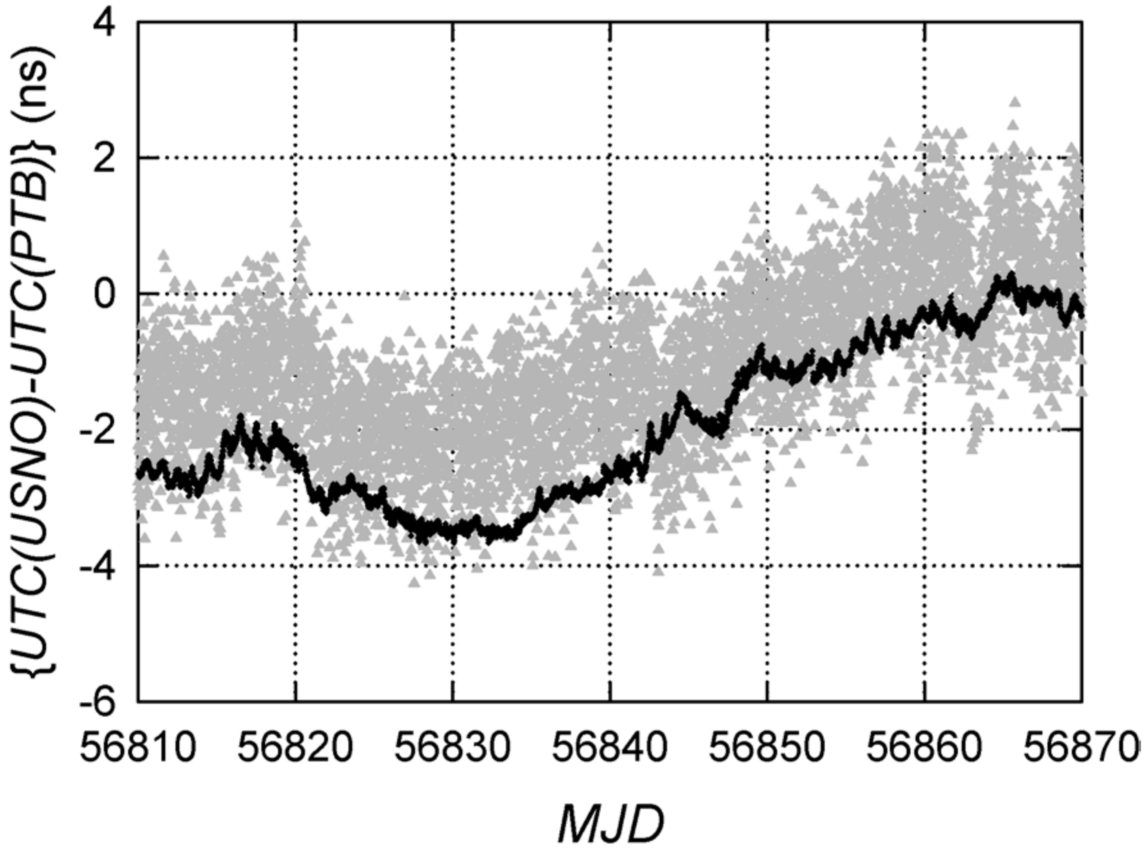


Figure 2 Time comparison UTC(USNO)-UTC(PTB), GPS L3P (grey symbols) and GPS PPP (black symbols) during the months June and July 2014 (16 min averages). Source of data: BIPM ftp server (see text); the small but apparent offset between the two data sets is likely caused by the fact that the USNO data come from two different GPS receivers.

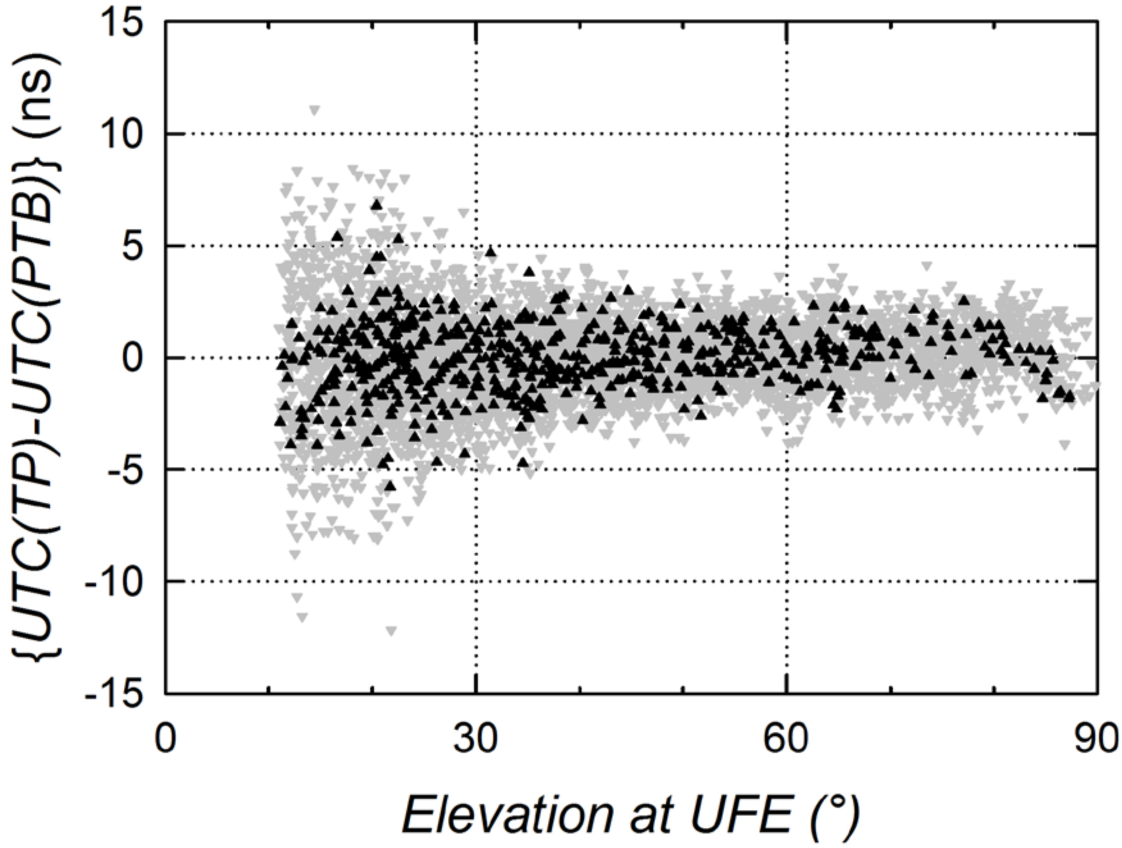


Figure 3 CV time comparison UTC(TP)-UTC(PTB) via GPS (grey symbols) and Galileo (black symbols) during five days in April 2014 (5-min averages), results of individual satellite observations. The daily mean time scale difference was subtracted from the data. TP stands for Tempus Pragensis, UTC(TP) is realized at UFE (Prague). The horizontal axis denotes the elevation of the satellite in common view above Prague.

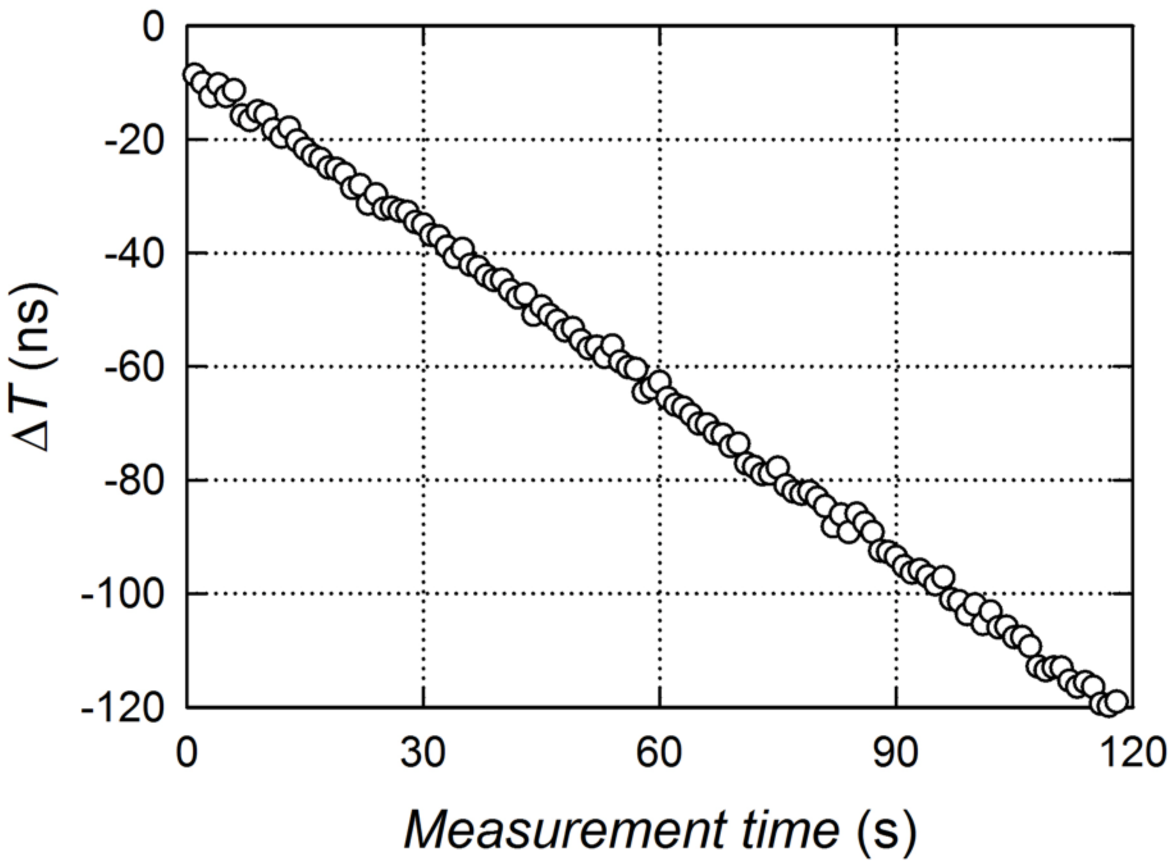


Figure 4 Reception of TWSTFT signals transmitted from SYRTE (Observatoire de Paris) at PTB on 2014-05-08 between 02:19:00 and 02:20:59 UTC (120 points). $\Delta T$ represents the time difference recorded minus 0.26458 s.

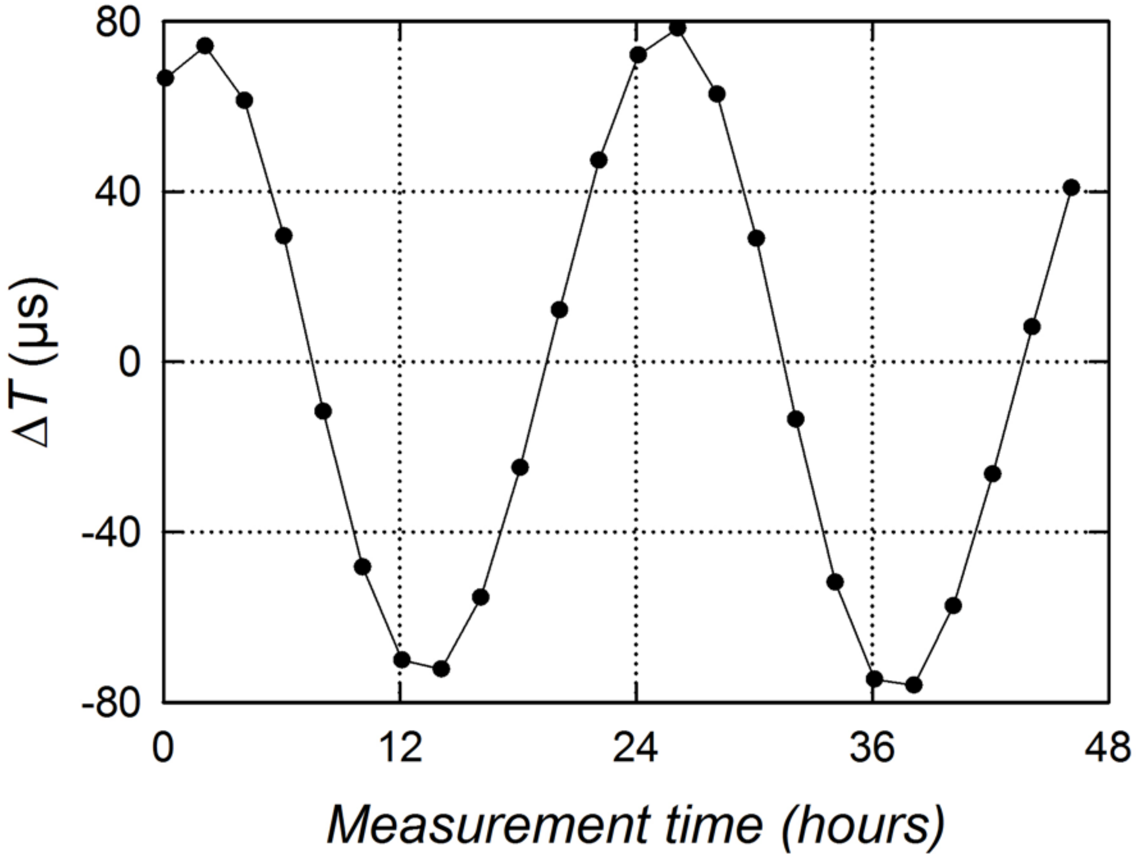


Figure 5 Example for ranging results: Reception of TWSTFT signals transmitted from PTB at PTB on 2014-05-07 and 2014-05-08, 12 points per day; each point represents the mean over the 120 data points collected between *hh*:07:00 and *hh*:08:59. $\Delta T$ represents the time difference recorded minus 0.2667 s, note the scale is µs, not ns as in Figure 4.

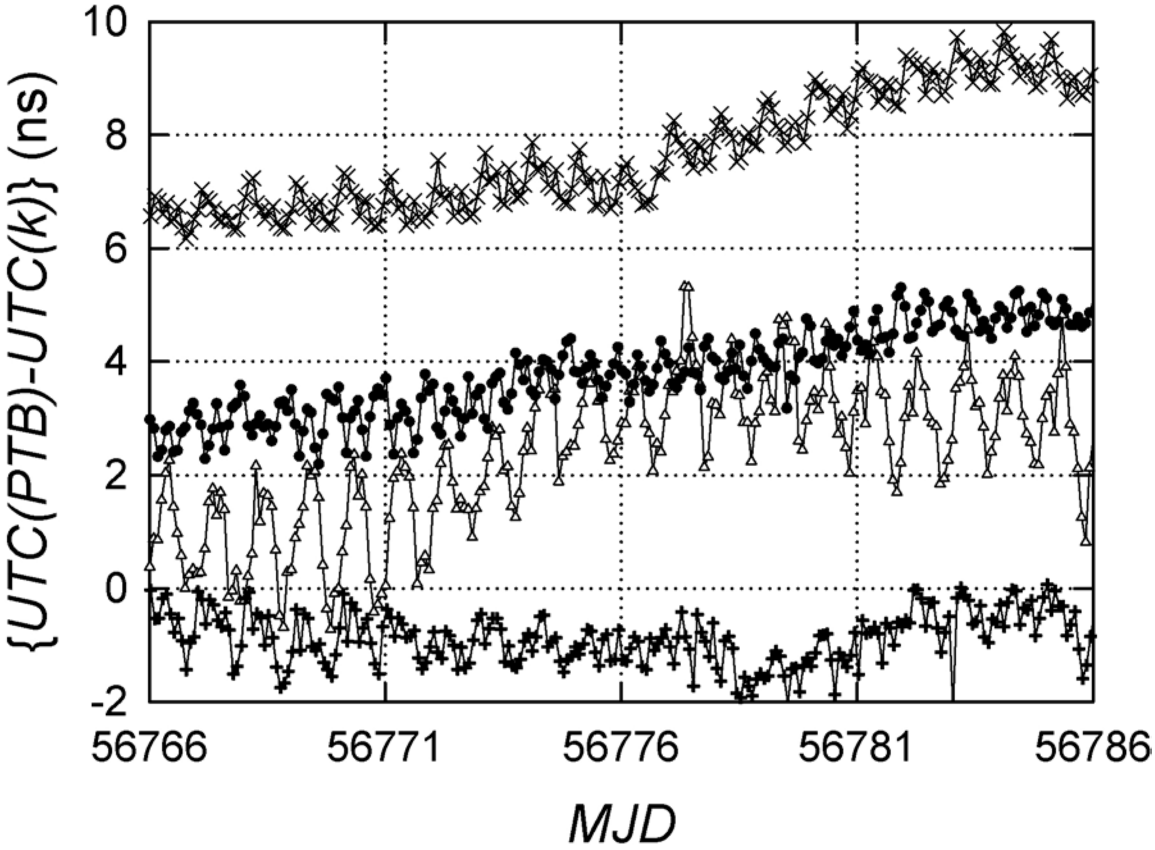


Figure 6 TWSTFT providing *UTC(PTB)-UTC(k)* during twenty days in April 2014, k = IT (INRIM), (symbol Δ), OP (SYRTE) (symbol •), NIST (symbol X) and USNO (symbol +).

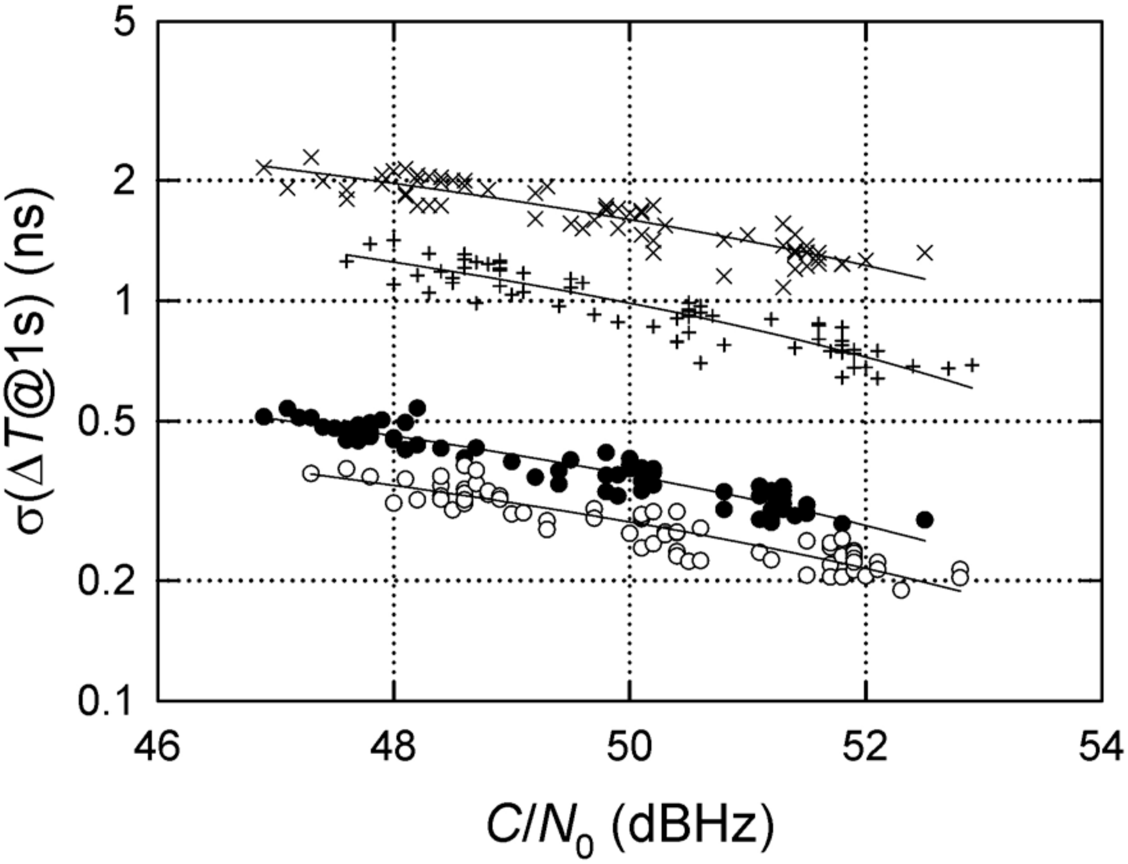


Figure 7 Scatter of 1-s ranging measurement results, σ(Δ*T*@1s), recorded at PTB using different PN chip rates: (x) 0.5 MChip/s, (+) 1 MChip/s, (•) 2.5 MChip/s, (O) 5 MChip/s. The use of 2.5 MChip/s was common at the time when the data were taken, but was later given up for cost reasons.

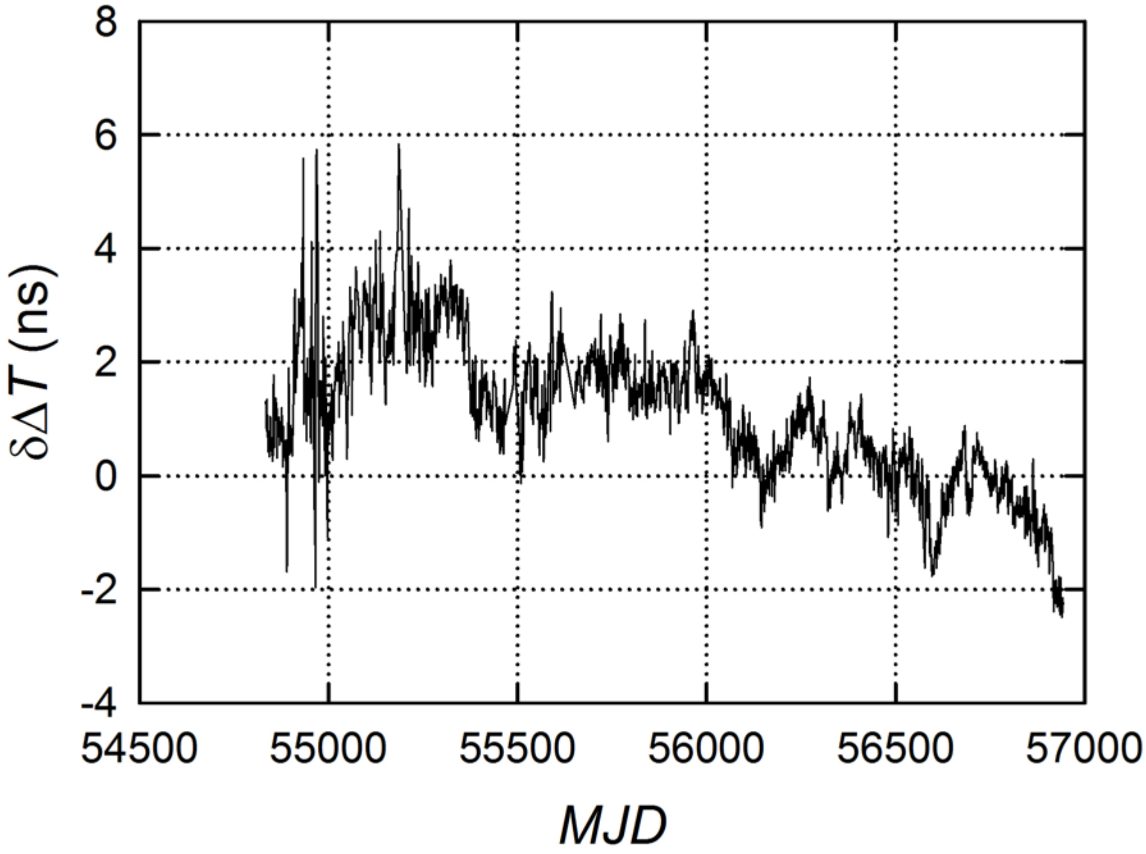


Figure 8 Long-term assessment of time comparison UTC(OP)-UTC(PTB), double-difference between GPS P3 and TWSTFT data (daily mean values), data by courtesy of Pierre Uhrich, SYRTE, data span 2009 until October 2014.