GPS Receiver Calibration: Why Is It Necessary?

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Measurement uncertainty for a GPS receiver depends on the receiver's design and on the measurement method used. The majority of clients' GPS receivers operate with C/A code and use the one-way method having relatively low metrological parameters. The frequency stability for a GPS receiver expressed by Allan Deviation is larger than that for Cs-standard by 2-3 orders within a short-term interval (1-1000 s), and by one order within a long-term interval of about one day. A GPS receiver's time scale bias from the Coordinated Universal Time (UTC) can be in order of microseconds. Two user's GPS receivers can yield different frequency and time results even when connected to the same antenna at the same location because of the difference in performance. Not every GPS receiver is suitable for use as a traceable frequency and/or time standard. Moreover, traceability to the National Time and Frequency Standard is required. Therefore, GPS receiver calibration against the National Time and Frequency Standard (for example, the Cs-atomic clock) traceable to UTC via high accuracy GPS technique is of great importance and implies the calibration of both frequency and time scale.

Introduction

Global Positioning System (GPS) is well known as a tool for both positioning and for high accuracy time and frequency transfer. Hundreds of companies sell GPS products, and many of manufacturers advertise their units as being time and frequency standards. Such a statement leads to the erroneous opinion that it is not necessary to calibrate them.

Characteristics of a GPS receiver depend on its design and applications. GPS receivers are used for navigation, positioning, time dissemination and for scientific research. Navigation receivers are made for aircraft, ships, ground vehicles, and for hand carrying. Precise positioning is used, for example, in surveying and geodetic controls.

Time and frequency dissemination is based on the precise Cs- and Rb-clocks located on space vehicles (SV) and controlled by the monitor stations. High accuracy time and frequency transfer finds its application in telecommunication, astronomical observations and in time and frequency metrology. GPS technique is used also for evaluation of atmospheric parameters, for example, atmospheric humidity.

The majority of clients' GPS receivers operate with C / A code and use the one-way method having relatively low metrological parameters. The frequency stability for a GPS receiver expressed by Allan Deviation is larger than that for Cs-standard by 2-3 orders within a short-term interval (1 – 1000 s), and by one order within a long-term interval of about one day. A GPS receiver's time scale bias from the Coordinated Universal Time (UTC) can be in order of microseconds. Two user's GPS receivers can yield different frequency and time results even when connected to the same antenna at the same location because of the difference in performance. Not every GPS receiver is suitable for use as a traceable frequency and / or time standard. Moreover, traceability to the National Time and Frequency Standard is required. Therefore, GPS receiver calibration against the National Time and Frequency Standard (for example, the Cs-atomic clock) traceable to UTC via high accuracy GPS technique is of great importance and implies the calibration of both frequency and time scale.

In the present paper reasons for GPS receivers calibration are discussed using an example of such calibration at the National Physical Laboratory of Israel (INPL).

GPS Uncertainty Sources

GPS measurement uncertainty consists of the GPS system uncertainty and GPS receiver's uncertainty. The main error sources in GPS measurements are expressed by the basic equation for pseudo-range p [1,2]:

$$p = \rho + d\rho + c(dt_{SC} - dt_{RC}) + d_{Ion} + d_{Trop} + \varepsilon_\rho + \rho_{mult}, \qquad (1)$$

where ρ is the calculated geometric range between satellite and receiver (i.e. $\rho=[(X_S-X_R)^2+(Y_S-Y_R)^2+(Z_S-Z_R)^2]^{1/2}$); X_S, Y_S, Z_S and X_R, Y_R, Z_R are the coordinates of the satellite and the receiver, respectively; $d\rho$ is the orbital error; dt_{SC} and dt_{RC} are the satellite and the receiver clock errors, respectively; d_{Ion} is the ionospheric delay; d_{Trop} is the tropospheric delay; ε_ρ is the receiver code noise; ρ_{mult} is the multipath error; c is the light velocity.

In general the measurement methods used in GPS technique can be divided into classical coarse acquisition (C/A) code, dual-frequency precise P(Y) code, which allows the so-called GPS TAI P3 analysis, and carrier-phase (GPS CP) measurements. The C/A code modulates the L1 carrier and it is the basis for the majority of user's GPS measurements. The P(Y)-code modulates both the L1 and L2 carrier phases and it is the basis for the precise positioning service. The main equation for carrier-phase measurements is as follows [1,2,3]:

$$\lambda\Phi = \rho + d\rho + c(dt_{SC} - dt_{RC}) + \lambda N - d_{Ion} + d_{Trop} + \varepsilon_{\Phi} + \rho_{mult}, \quad (2)$$

where Φ is the observed carrier phase; λ is the carrier wavelength; ε_{Φ} is the receiver carrier phase noise; λN is the carrier phase ambiguity; N is the integer number of cycles.

Generally, the number of cycles and the atmospheric delays are the most difficult parameters for determination.GPS errors are a combination of noise, bias, and blunders. Since the bias caused by Selective Availability (SA) was removed on May 2, 2000, it reduces the uncertainty of GPS measurements. The major error sources of the GPS measurements after removing SA, as follows from main equations 1 and 2, are: orbital error, SV clock, GPS receiver's clock, tropospheric delay, ionospheric delay, multipath, and the receiver's code or phase noise. The order of magnitude of these uncertainty components is given in Table 1. As can be seen, the combined uncertainty of these components is about 22-108 ns.

This list of errors is not complete because it does not include all errors of the GPS receiver and of the user site of measurements. In the next paragraph we consider the GPS receiver's uncertainty sources and some other reasons for GPS receiver calibration.

GPS receiver errors from software or hardware failures can cause blunder errors of any size. All the above-mentioned factors lead to deviation of the GPS receiver's output frequency from the nominal value and to the time scale bias from the UTC scale.

GPS uncertainty sources	Order of magnitude, ns [2,4]
Orbital error	3-10
SV clock	3-10
Ionospheric delay	20-100
Tropospheric delay	7-20
Multipath	3-30
C/A code noise	1 –10
P(Y) code noise	0.1-1
Carrier phase noise	0.01
Combined uncertainty	22-108

Table 1. GPS uncertainty sources.

Some Reasons for GPS Receiver Calibration

There are two common key factors that contribute to a GPS receiver performance: the quality of the receiver's internal oscillator and the quality of the software algorithm that processes data obtained from satellites [4, 5].

In general, the uncertainty of the user's GPS receiver is caused by the following factors: receiver noise, internal oscillator instability, software error, uncertainty of time delay in antenna and antenna cable, in connecting cables, and finally GPS receiver internal delay. The purpose of GPS receiver calibration is to determine: 1) the frequency deviation from its nominal value and stability of this deviation expressed by Allan Deviation; 2) the GPS receiver time scale deviation from the UTC.

Different GPS receivers select different satellites for the timing solution. Software algorithms used to select satellites are different, and each receiver has its own thresholds at which it chooses to keep or to omit a satellite. Some algorithms limit the timing solution to just one or to a few satellites. Others can use as many as 12 satellites in a solution. For this reason, two GPS receivers can yield different results even when connected to the same antenna at the same location.

Since each GPS satellite is visible at a given location for a limited time, all GPS receivers must add and remove satellites from the group used to obtain time and frequency information. Often, adding and/or removing a satellite from the timing solution cause an instantaneous frequency change.

Various receivers handle GPS broadcast errors differently. Some receivers have built-in software designed to remove "bad" data, other have no such software. But all GPS receivers might bias their time scale or even fail under certain conditions, such as strong ionospheric disturbances (for example, ionospheric scintillations).

Different types of GPS receivers are applied in different types of GPS measurements. These measurements in the field of time and frequency metrology can be divided into five general categories: one-way, single-channel common-view, multi-channel common-view (all-in-view), carrier-phase, and two-way satellite time and frequency transfer (TWSTFT) [4]. Timing and frequency uncertainty and timing offset for these types of GPS measurement technique are shown in Table 2 [3,4,5]. It can be seen that the one-way techniques provide relatively low metrological parameters, and the best one is provided by the TWSTFT technique.

The reason is that the one-way GPS technique uses the signals obtained from a GPS receiver as the reference for a calibration. The purpose of the measurement is either to synchronize an on-time pulse or to calibrate a frequency source. The GPS signal is used in real time, and no post processing of the measurement results is required.

GPS Technique	Timing Uncertainty 2σ, 1 day	Frequency Uncertainty 2σ, 1 day	Timing Offset [5]
One way C/A code	200ns (for a few minutes averaging)-20ns (for 1 day averaging) [3,4]	10^{-11}-$2x10^{-13}$ [3,5]	500ns (calibrated for equipment delay)
Single-channel common-view	10-5ns [3]	$1x10^{-13}$ – $5x10^{-14}$ [3]	< 5 ns
Multi-channel common-view	5-1 ns [3]	< $5x10^{-14}$ [3]	< 5 ns
Carrier-phase common-view	< 500 ps [3]	$5x10^{-15}$ – $1x10^{-15}$ [6]	< 5ns
TWSTFT	100 ps [4]	$5x10^{-15}$ – $1x10^{-15}$ [6]	< 5 ns

Table 2. Time and frequency uncertainties of different GPS measurement techniques.

Common-view and carrier-phase measurements are more precise measurements and require post-processing of the measurement data. The collected data are analyzed and processed using precise satellite orbit information and detailed models of the ionosphere and troposphere. These types of GPS measurements are used for international time and frequency comparisons between National Metrological Institutes (NMIs).

In common-view time transfer, the time difference between two clocks is determined by simultaneous observation of the same satellites in two different laboratories. The measurement results are then exchanged and the difference between two time scales is obtained. This technique gives improved performance over the one-way technique. It eliminates satellite clock errors, and reduces orbital errors, ionospheric and tropospheric errors [4]. The accuracy of single channel common-view time transfer is typically in the 5 to 10 ns range.

By forming the double and triple difference [4] using multi-channel observations, the receiver clock errors also can be eliminated, thus the uncertainty of multi-channel common-view is in the 1 to 5 ns range.

The TWSTFT technique eliminates nearly all of the propagation delay errors because the signal path symmetry for both stations [4]. Therefore BIPM has started using the two-way technique as a primary time transfer technique. The uncertainty of TWSTFT over a 24 hour period is better than 1 ns and has been be as low as 100 picoseconds in some systems [4].

Carrier-phase tracking of GPS signals has resulted in a revolution in land surveying. The L1 and L2 carrier phase are used in this type of measurement. All carrier-phase tracking is differential and requires both a reference and remote receiver tracking carrier phase at the same time. In this type of measurement the uncertainty of ten millimeters is possible.

TWSTFT and GPS CP analysis have allowed a frequency comparison between remote standards with a measurement uncertainty of $1x10^{-15}$ at averaging time $\tau = 1$ day [6]. The GPS CP requires extra computational efforts whereas TWSTFT is done routinely.

Since the majority of customers' GPS receivers use the one-way method and C/A code, they need to be calibrated against the primary time and frequency standard — Cs-standard traceable to UTC via a more accurate GPS measurement technique.

Traceability Requirements for Time and Frequency Measurement

According to the VIM [7], metrological traceability is "the property of a measurement result relating the result to a stated metrological reference through an unbroken chain of calibrations of a measuring system or comparisons each contributing to the stated measurement uncertainty." The traceability chain for measurements in time and frequency is shown in Fig. 1 [5]. The traceability chain begins from a measuring instrument (Device Under Test – DUT), for example, a crystal oscillator. Link A is the link between the DUT and the user's GPS receiver. Measurement uncertainty sources in link A are: user's GPS receiver uncertainty, uncertainty of calibration procedures, and human errors. Link B connects the user's

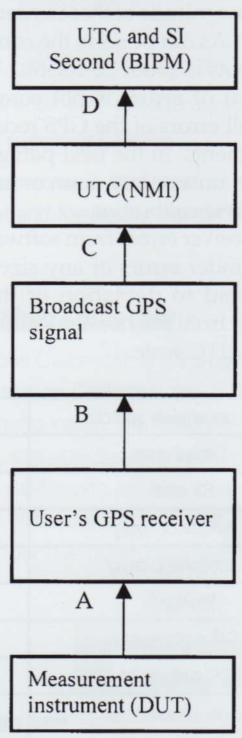

Figure 1. The traceability chain for time and frequency measurements.

GPS receiver to the broadcast signal monitored by the NMI. Link D is the chain between the UTC scale and the local Coordinated Time Scale UTC(NMI) maintained by the NMI.

UTC is calculated by averaging data collected from about 300 atomic clocks located in 55 national laboratories worldwide and reported to BIPM. The uncertainty of link D can be evaluated using BIPM's Circular T.

The SI second is defined as the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom. Frequency (expressed in hertz) is derived from a second and equals to the number of events over a 1-second interval. Thus, a GPS receiver cannot be used as a primary frequency and time standard, it is usable as secondary frequency and time standard only.

As for every traceability chain, the measurement uncertainty in the chain shown in Fig. 1 is increases in the direction opposite to traceability, i.e. from link D to link A.

GPS Receiver Frequency Calibration at INPL

Results of measurements and calibrations in field of time and frequency in Israel are traceable to the National Standard of Time – the UTC(INPL) scale [8] maintained by INPL.

In order to show traceability of a GPS receiver to UTC(INPL), an unbroken chain must be established between the measurements made by GPS receiver at the user's site and the UTC(INPL) time scale.

The block diagram of the GPS receiver calibration system used at INPL is shown in Fig. 2 [9,10]. The calibration system comprises: Cs-standard traceable to UTC via GPS common-view link; the unit under test (UUT), for example, user's GPS receiver; a time interval counter; a pulse distribution amplifier; a 1 pps generator; a personal computer (PC1) for GPS time transfer data processing; a INPL GPS receiver applied for common-view measurements; a satellite antenna; a microprocessor with time interval counter; a monitor; a printer; an ionospheric calibration receiver (ICR) with a satellite antenna; a commutation switch box; a personal computer (PC2) for calibration data processing; a high frequency (5 MHz) signal distribution amplifier.

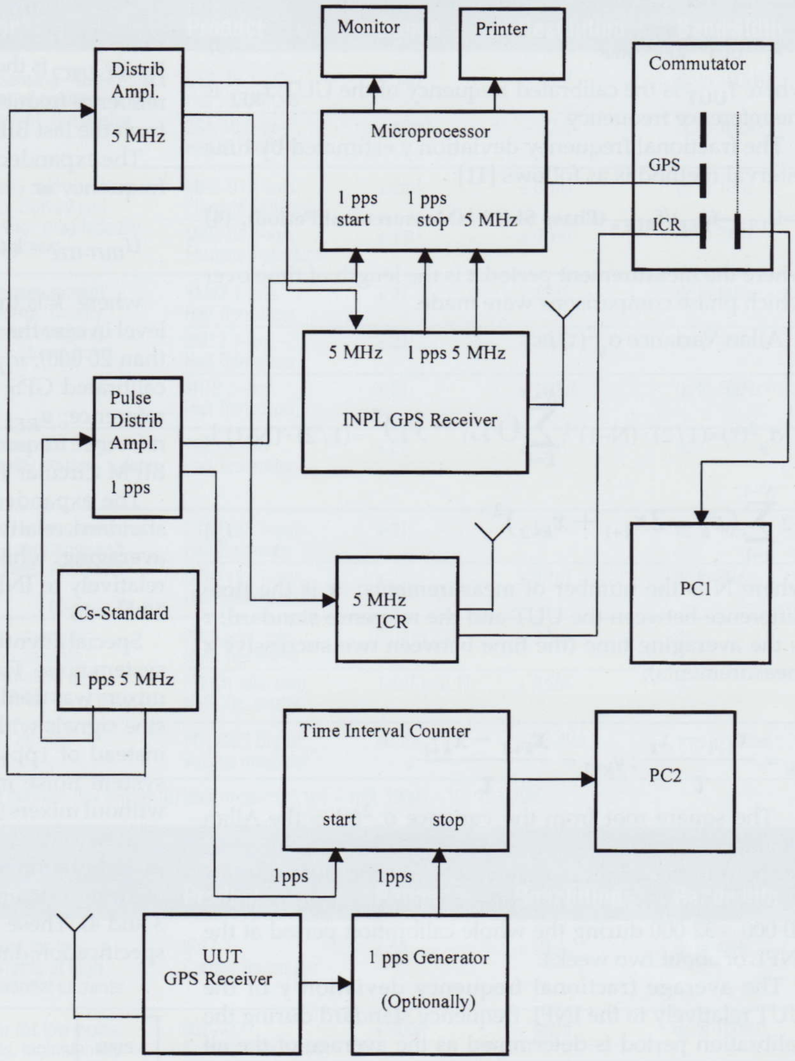

Figure 2. Block diagram of GPS receiver calibration system.

A frequency calibration measures whether a UUT meets or exceeds its uncertainty requirement [11]. The frequency calibration of UUT is performed through comparison with the reference frequency. This is normally done by phase comparison between the frequency produced by the UUT and the reference frequency. The amount of phase shift between the UUT and the reference frequency is then converted to time unit. The time interval counter measures the time differences between calibrated and reference signals (the time interval method [11]).

Frequency standards and oscillators stability is described by the fractional frequency deviation and Allan variance

[12, 13]. The fractional frequency deviation is:

$$y=(f_{UUT}-f_{REF})/f_{REF}, \quad (3)$$

where f_{UUT} is the calibrated frequency of the UUT; f_{REF} is the reference frequency.

The fractional frequency deviation y estimated by time interval method is as follows [11]:

$$y=(f_{UUT}-f_{REF})/f_{REF} = \text{(Phase Shift) / (Measurement Period)}, \quad (4)$$

where the measurement period τ is the length of time over which phase comparisons were made.

Allan Variance $\sigma_y^2(\tau)$ is:

$$\sigma_y^2(\tau)=(1/2)\cdot(N-1)^{-1}\sum_{k=1}^{N-1}(y_{k+1}-y_k)^2=(1/2)\cdot(N-1)^{-1}\cdot \tau^{-2}\sum_{k=1}^{N-1}(x_k-2x_{k+1}+x_{k+2})^2, \quad (5)$$

where N is the number of measurements; x is the time difference between the UUT and the reference standard; τ is the averaging time (the time between two successive x measurements);

$$y_k=\frac{x_{k+1}-x_k}{\tau};\ y_{k+1}=\frac{x_{k+2}-x_{k+1}}{\tau}.$$

The square root from the variance $\sigma_y^2(\tau)$ is the Allan Deviation $\sigma_y(\tau)$.

The number of measurements N of time differences x between the UUT and the reference Cs-standard is about 20 000 – 32 000 during the whole calibration period at the INPL of about two weeks.

The average fractional frequency deviation y of the UUT relatively to the INPL frequency standard during the calibration period is determined as the average of the all measured y_k values for minimal time interval τ as follows:

$$y=\frac{\sum_{k=1}^{N-1} y_k}{N-1}=\frac{\sum_{k=1}^{N-1}\frac{x_{k+1}-x_k}{\tau}}{N-1} \quad (6)$$

And the measurement uncertainty of y relatively to the INPL reference frequency is determined as the statistical standard uncertainty.

To determine the metrological characteristics of the calibrated GPS receiver relatively to UTC, the reference frequency deviation y_{REF} and its uncertainty U_{REF} should be taken into account. Thus, the corrected value of the UUT frequency deviation $y_{UUT\text{-}UTC}$ and its uncertainty $U_{UUT\text{-}UTC}$ are calculated by the following equations:

$$y_{[UUT\text{-}UTC]}=y_{[UUT\text{-}INPL]}+y_{REF}, \quad (7)$$

where $y_{[UUT\text{-}INPL]}$ is the fractional frequency deviation of the UUT relatively to INPL reference frequency; $y_{REF}=y_{[INPL\text{-}UTC]}$ is the fractional frequency deviation of the INPL reference frequency relatively to UTC frequency, computed from the last BIPM Circular T.

The expanded uncertainty of the calibrated GPS receiver frequency is:

$$U_{UUT\text{-}UTC}=k\,(u^2_{UUT\text{-}INPL}+u^2_{REF})^{1/2}, \quad (8)$$

where k is the coverage factor (k=2 for 95% confidence level in case the number of degrees of freedom N-1 is larger than 20 000); $u_{UUT\text{-}INPL}$ is the standard uncertainty of the calibrated GPS receiver frequency relatively to the INPL reference; u_{REF} is the standard uncertainty of the INPL reference frequency y_{REF} relatively to UTC, computed from BIPM Circular T for the minimal τ.

The expanded uncertainty of the INPL cesium atomic standard relatively to UTC is about 10^{-14} over one week averaging, while the uncertainty of user's GPS receivers relatively to INPL frequency reference $u_{UUT\text{-}INPL}$ is about 10^{-13} – 10^{-11}.

Special attention was made to reduction of the calibration system noise. For this purpose the special system with two mixers was used (see Fig. 3) [9]. In this method two harmonic sine signals with high frequency either 10 MHz or 5 MHz instead of 1pps are compared. The results of calibration system noise measurements for two different systems: without mixers (direct comparison of two 1pps signals) and with two mixers are shown in the Fig. 4, curves 1 and 2. Also the calibration results for Cs-standard, measured by means of the two aforementioned systems are shown (Fig. 4, curves 3 and 4). These results confirm the HP 5071A Cs-standard specification data (Fig. 4, curve 5) except at the averaging

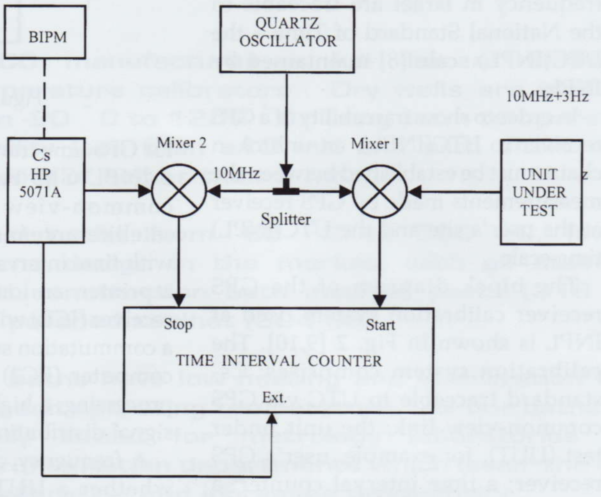

Figure 3. Block diagram of the calibration system by means of two mixers.

time range $\tau < 100s$ for measurements by means of 1pps signal (Fig. 4, curve 3), where the measurement results have exceeded the specification data.

In case of calibration using the 1pps signals the measurement system noise was relatively large in averaging time interval $1s \leq \tau \leq 100\ s$, and in time interval $\tau > 100\ s$ it was negligible and did not affect the calibration results (see Fig. 4, curve 2).

The use of the two mixers reduces the noise strongly and in this case the measurement system noise was negligible in the whole averaging time interval range (see Fig. 4, curve 1). Since it is more convenient to work with 1pps signals, the calibration data, presented in the calibration certificates issued by INPL, are composed from two series of results: series of measurements with two mixers for $\tau < 100\ s$, and series of measurements by means of 1pps signals for $\tau > 100\ s$.

The frequency stability for user's GPS receiver expressed by Allan Deviation is larger than that for Cs-standard by 2-3 orders for a short-term interval (1 – 1000 s), and by one order for a long-term interval of about one day. Examples of Allan Deviation dependence on time obtained at the INPL for some frequency sources are shown in the Fig. 5. It can be seen from Fig. 5, that the Allan Deviation for presented GPS receiver is larger than that for Cs-standard by 1.5 order for $\tau = 1000$ s and by one order for τ=1 day. The best results are obtained for GPS controlled Rb frequency standard (curve 5 in Fig. 5). However, even for this type of GPS receiver the Allan Deviation is larger than that for Cs-standard by factor 9 for $\tau = 1$ day.

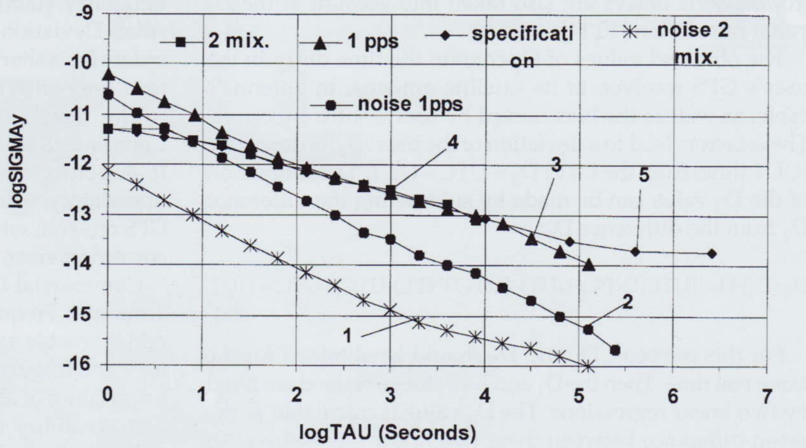

Figure 4. The results of the calibration system's noise measurement: 1) system noise with two mixers; 2) system noise without mixers; 3) calibration results for Cs-standard obtained by system without mixers; 4) calibration results for Cs-standard obtained by system with two mixers; 5) HP 5071A Cs-standard specifications.

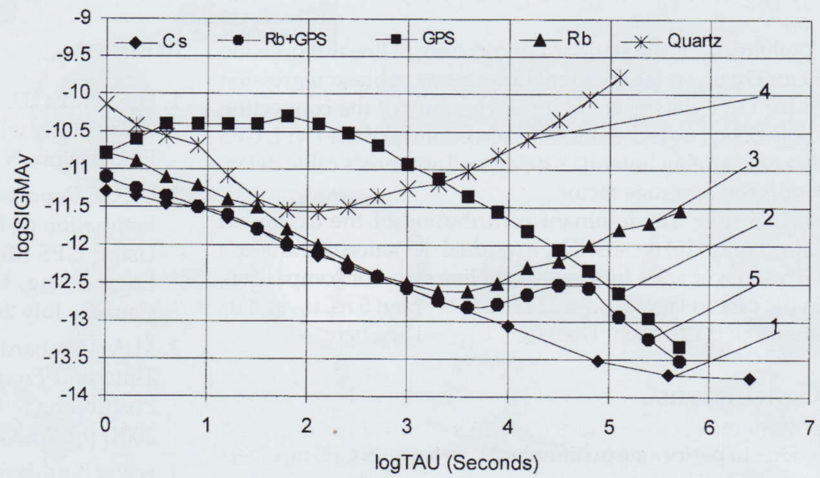

Figure 5. The results of the different frequency sources calibration: 1) Cs-standard; 2) GPS receiver; 3) Rb-standard; 4) quartz oscillator; 5) GPS controlled Rb frequency standard.

GPS Receiver Time Scale Calibration at INPL

The calibration of user's GPS receiver time scale is performed at INPL according to the block diagram shown in Fig. 2. The measurements are performed simultaneously in two parallel channels. In the first channel, the user's GPS receiver time scale is compared with the UTC(INPL). For this purpose, the 1-second signals (1 pulse per second) of the user's GPS receiver and the INPL Cs-standard's are compared by the time interval counter. The obtained difference between UTC(INPL) and UUT time scales is D_1 = UTC(INPL) – UUT. Connecting cables delay is subtracted from the difference in the D_1 value calculation.

In the second channel, the international comparisons between the local UTC(INPL) and UTC time scales are performed by the INPL GPS receiver operating in the common-view mode. The obtained difference between UTC(INPL) and UTC time scales is D_2 = UTC(INPL) – UTC. These comparisons are performed continuously, and their results are reported to BIPM once a week. The time delays in the INPL GPS receiver, its antenna, antenna's cables, and connecting cables are known with the uncertainty of ± 0.1 ns. Moreover, the corrections for ionospheric and tropospheric delays are also taken into account at the D_2 value calculation [10,14].

The obtained values of D_1 contain the time delay in the user's GPS receiver, in its satellite antenna, in antenna's cable, as well as the bias caused by user's software errors. These factors lead to a deviation of the user's GPS time scale (UUT time) from the UTC: D_3 = UTC – UUT. Determination of the D_3 value can be made by subtracting the difference D_2 from the difference D_1:

$$D_3=D_1-D_2=[UTC(INPL)-UUT]-[UTC(INPL)-UTC]=UTC-UUT \quad (9)$$

For this purpose, D_1 and D_2 should be obtained for the same real time. Then the D_1 and D_2 values obtained are fitted by two linear regressions. The D_3 value is calculated as the mean difference between these two linear regressions. An example of such calibration results is shown in Fig. 6. Here the mean D_3 value is 1.225 microseconds.

The uncertainty of the user's GPS receiver time scale deviation from the UTC time scale is:

$$U_{D3} = k\,(u^2_{D1} + u^2_{D2} + u^2_C + u^2_L)^{1/2}, \quad (10)$$

where u_{D1} is the standard uncertainty of linear regression fit for D_1; u_{D2} is the standard uncertainty of linear regression fit for D_2; u_C is the standard uncertainty of the connecting cable delay; u_L is the standard uncertainty of the INPL GPS receiver's delay, antenna's delay, and antenna's cable delay; k=2 is the coverage factor.

As a rule, the dominant contribution of the expanded uncertainty (10) is caused by a residual deviation of the user's GPS receiver scale from a straight line u_{D1}. For comparison, in the case in Fig. 6, u_{D1} = 23 ns, u_{D2} is about 5 ns, u_C and u_L are about 0.1 ns each. Therefore, U_{D3} = 47 ns here.

Conclusions

Due to performance differences, two user's GPS receivers can yield different frequency and time results even when connected to the same antenna at the same location. The

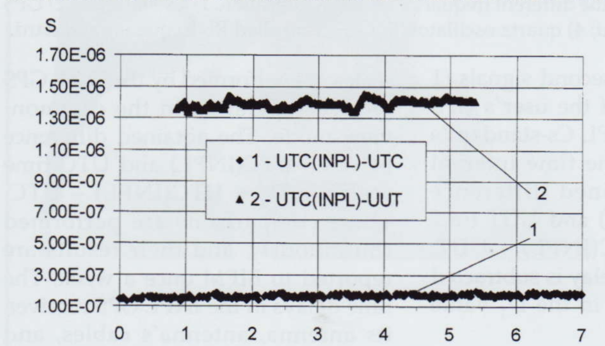

Figure 6. Evaluation of the user's GPS receiver time scale deviation from UTC.

frequency stability for user's GPS receiver expressed by Allan Deviation is larger than that for Cs-standard by 2-3 orders for a short-term interval (1 – 1000 s), and by one order for a long-term interval of about one day.

The user's GPS receiver time scale bias from the Coordinated Universal Time can be in order of microseconds. It depends on the GPS receiver's internal oscillator uncertainty, software errors, receiver noise, time delay in GPS receiver, satellite antenna, antenna's cable, atmospheric correction error, and other human errors.

Commercial GPS receiver calibration against National Time and Frequency Standard based on Cs-atomic clock and traceable to UTC via one of the high precision GPS time and frequency transfer technique ensure measurement uncertainty of about $1\times10^{-14} - 5\times10^{-15}$ for frequency, as well as traceability to the Coordinated Universal Time with uncertainty of about 10 – 1 ns and better.

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