Guidelines on the Use of GPS Disciplined Oscillators for Frequency or Time Traceability

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Guidelines on the Use of GPS Disciplined Oscillators for Frequency or Time Traceability

Purpose

This document has been produced to enhance the equivalence and mutual recognition of calibration results obtained by laboratories employing GPS disciplined oscillators for frequency or time traceability.

Content

1 INTRODUCTION

The aim of this document is to provide guidelines on the use of GPS disciplined oscillators as reference standards for frequency, time interval or time scale by accredited calibration laboratories. Frequency standards adjusted using the signals transmitted by the Global Positioning System (GPS) navigation satellites, known as GPS disciplined oscillators (GPSDOs), have become widely used in European calibration laboratories as reference standards for time or frequency. A GPSDO contains an internal oscillator, usually a temperature-controlled quartz crystal oscillator (TCXO) or a rubidium (Rb) oscillator, that provides signals with the desired short-term frequency stability. Long-term accuracy is obtained by steering the oscillator to the time scale broadcast by the GPS satellites, known as GPS Time. A GPSDO is therefore a 'self-adjusting' standard that can offer a high level of performance and maintain that performance indefinitely, which is a combination that cannot readily be achieved in any other way.

GPS is a navigation and positioning service that also disseminates accurate time and frequency information derived from the reference time scale of the U.S. Naval Observatory, UTC(USNO), which is maintained in close alignment with the international time scale Coordinated Universal Time (UTC). In addition, monitoring measurements of GPS Time with respect to UTC(*k*), the realization of UTC at laboratory "*k*", are published by a number of National Metrology Institutes (NMIs) or Designated Institutes (DIs). Hence a metrological link to UTC is established through the participation of laboratory *k* in the CIPM MRA Key Comparison CCTF-K001.UTC, which provides regular values for UTC – UTC(*k*). A GPSDO may as a result provide traceability to UTC for frequency or time, provided that certain conditions are met.

This document provides advice on how to satisfy these conditions when setting up a GPSDO as a laboratory reference standard, demonstrating traceability, and constructing an uncertainty budget.

Other Global Navigation Satellite Systems (GNSS) are being developed to work alongside GPS, including the Russian GLONASS, the Chinese BeiDou, and the European GALILEO. As the large majority of disciplined oscillators in use in calibration laboratories employ GPS only, this document will use the more widely-used term GPSDO rather than GNSSDO. However, much of the information provided here would apply equally to disciplined oscillators that utilise signals from other GNSS.

2 SETTING UP AND OPERATING A GPSDO

A GPS disciplined oscillator consists of a laboratory unit, containing the GPS receiver module and the oscillator, and an antenna intended for mounting externally, connected by a suitable cable. This section discusses some of the factors that should be considered when setting up a GPSDO for the first time and during routine operation of the equipment.

2.1 Initial calibration

Some but not all Accreditation Bodies recommend calibration of a GPSDO by a National Metrology Institute (NMI), Designated Institute (DI) or accredited calibration laboratory before installation as a frequency or time scale reference standard. The calibration will evaluate the accuracy and instability of the standard-frequency output, and in some cases also the conformity of the output one-pulse-per-second (1 PPS) epoch with an agreed international reference time scale, usually UTC or its national realisation UTC(*k*) in laboratory *k*. Such a calibration is performed by operating the GPSDO at an NMI, DI or other suitable accredited calibration laboratory. When possible, the GPSDO should be sent to the calibration laboratory with the antenna and cable that will be used during routine operation of the GPSDO, so that the complete system can be evaluated and, for time scale calibration, its total delay determined.

However, the actual performance of a GPS receiver depends on its local environment (including the antenna installation, multipath environment, and temperature fluctuations at the receiver and the antenna). To evaluate these effects, the calibration of a GPSDO may be undertaken after its installation in the environment in which it will operate routinely, using another well-characterised GPSDO, a dedicated GPS timing receiver or a portable frequency standard as a transfer standard.

Some but not all Accreditation Bodies permit the operation of a GPSDO as a reference frequency standard in a calibration laboratory without an initial calibration being performed, provided that the specified level of frequency accuracy can be justified in other ways. In this situation, a model of GPSDO should be chosen for which the manufacturer provides specifications for the frequency accuracy and for the instability as a function of averaging time. The specifications should in particular refer to averaging times appropriate to the measurement tasks for which the instrument is intended to serve as the frequency reference. If the specifications are not sufficiently complete or trustworthy to justify the required frequency uncertainty, or if the GPSDO is to be used as a time reference, it should be calibrated by an NMI, DI or accredited laboratory before use.

2.2 Laboratory environment

The GPSDO should be operated in a laboratory that provides adequate temperature control since the internal delay of the device is likely to exhibit some temperature dependence. Temperature stability to within ±1ºC is desirable, although ±3ºC may be more typical in practice. The laboratory temperature should be measured at frequent intervals and a record kept. Logging of the outdoor temperature close to the antenna is also desirable to assist in identifying the cause of any daily variations observed in the GPSDO output.

To ensure continuous operation of the GPSDO, mains power should be supplied through an uninterruptible power supply (UPS). As well as protecting against power outages, an in-line UPS will filter any transient dropouts or spikes from the power supplied to the equipment.

2.3 Installation

The GPS antenna must be mounted externally in a location that has a clear view of the sky and is well away from potential sources of electrical or RF interference. It should be raised up above any nearby structures that might cause multipath reflections of satellite signals into the antenna. A lightning protector installed in the antenna cable is desirable for safety reasons. The antenna cable should be positioned out of direct sunlight where possible, and any excess length of cable should be kept inside the laboratory rather than outdoors to minimise the effect of temperature changes on the delay.

The receiver will normally observe signals from at least 6 GPS satellites, and usually more. If the number of satellites drops well below the usual number at times, the most likely cause is a partial obstruction of the view of the sky. A GPSDO intended to act as a laboratory standard should be capable of displaying or logging the number and identity of all satellites that it is receiving signals from, usually together with their elevation and azimuth. This information can be plotted in the form of a 'sky map' to help in identifying the position of any obstruction in the line of sight.

2.4 Antenna coordinates

When a calibration laboratory operates a GPS receiver as a reference standard for frequency or time interval, rather than for time scale, precise determination of the antenna coordinates is not critical although substantial coordinate errors may significantly increase the instability of the output signals from a GPSDO. It is good practice when possible to configure the receiver so that once the antenna coordinates have been determined, they are stored and not updated further. This mode is often referred to by a term such as 'manual coordinate entry' or 'position hold', but not all GPSDOs have the capability.

If the 1 PPS output of the GPSDO is to be used as a time scale reference traceable to UTC, then the antenna coordinates must be determined with care. The receiver is normally able to perform this calculation itself, but it should if possible be done using measurements taken over at least complete 24-hour periods, starting and stopping at the same time of day, to ensure that the effect of any diurnal variations is minimised and that all satellite tracks are given equal weighting in the calculation.

3 VALIDATION AND TRACEABILITY

A GPSDO is most often employed by a calibration laboratory as a frequency standard, with the 5 MHz or 10 MHz output signal from the GPSDO acting as the laboratory reference. In a few instances a GPSDO is also (or instead) used as a time scale standard, in which the 1 PPS output of the receiver provides a time reference related to UTC. In this section, a range of methods that may be used to demonstrate correct operation of the GPSDO and to establish measurement traceability for frequency, time interval or time scale will be considered. In general, an additional connection with an NMI or DI participating in the CIPM MRA Key Comparison CCTF-K001.UTC is required.

3.1 Establishing traceability

The traceability of a measured value is based on the demonstrated relationship between the measurement and the primary reference standard for that quantity by means of an unbroken chain of comparisons that all have known uncertainties, allowing a combined total uncertainty to be determined for the measurement result. A calibration laboratory must be able to demonstrate to an Accreditation Body an understanding of the steps in the traceability chain for its internal reference quantities, including the frequency or time outputs of a GPSDO, and to justify its evaluation of the uncertainty assigned to each step.

In the case of a GPSDO in use as a laboratory reference standard for either frequency or time scale, the upper end of the traceability chain will be Coordinated Universal Time (UTC), and the links in the chain will include those shown in figure 1.

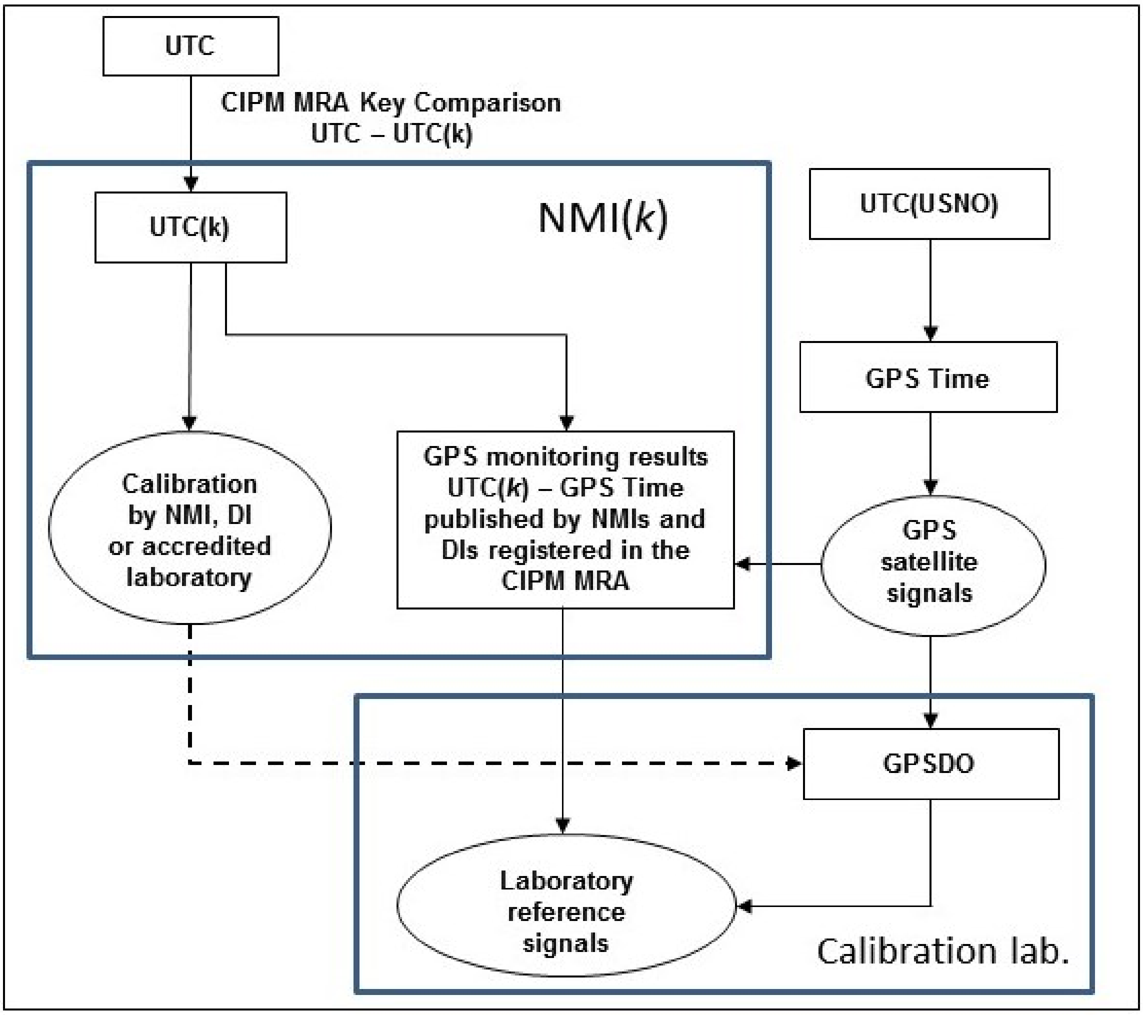

Figure 1: Traceability chain for the use of a GPSDO as a frequency or time scale reference standard. The arrow indicating calibration of the GPSDO is shown dashed since some Accreditation Bodies allow use of a GPSDO as a frequency standard without calibration.

In the frame of the CIPM MRA, traceability of a GPSDO to UTC may be demonstrated by means of an initial calibration and periodic recalibrations. It is recommended that the calibrations are supplemented by the UTC(*k*) - GPS Time monitoring measurements issued by some NMIs and DIs that realize UTC(*k*) time scales as local realizations of UTC and participate in the CIPM MRA Key Comparison CCTF-K001.UTC, plus the UTC – UTC(*k*) data provided in Section 1 of Circular T. Circular T is published monthly by the BIPM and can be downloaded from their server at www.bipm.org/jsp/en/TimeFtp.jsp.

As the performance of a GPSDO is very much dependent on the installation and operating conditions, evidence that the GPSDO is operating correctly (discussed in section 3.2) has to be gathered at all times when it is in use as a reference standard. Assuming that this requirement is met, some Accreditation Bodies allow the use of a GPSDO as a frequency standard traceable to UTC without a further requirement for calibration. These ABs accept traceability based on evidence that the GPSDO is operating correctly (discussed in section 3.2), together with the UTC(*k*) - GPS Time monitoring measurements published by an NMI or DI.

In practice, there is generally no need to consider each step in the traceability chain shown in figure 1 separately. Instead, the establishment of traceability for a GPSDO in use as a reference standard in a calibration laboratory requires two steps.

1. Validation that the GPSDO is operating correctly at all times when in use as a reference standard. Procedures for achieving this are discussed in section 3.2.
2. Assignment of an uncertainty to the reference signals generated by the GPSDO. Some methods for determining the uncertainty are discussed in section 3.3.

3.2 Validation of correct operation

The GPSDO should be operated for a sufficient period, usually at least 3 hours, for it to stabilize at the laboratory temperature and complete any start-up procedures before any measurements are taken. Any calibration measurements that aim at the lowest uncertainty should be taken over a period of continuous operation of at least 72 hours so that any diurnal frequency variations can be observed or averaged out. A shorter measurement time may be appropriate when the frequency output is to be used for less demanding applications, such as an oscilloscope time-base or stop-watch calibrations.

Although a GPSDO is often considered to be a “self-calibrating” standard, some means of detecting and recording anomalous behaviour must be implemented before correct operation can be assumed by a calibration laboratory. Incorrect operation may result not only from malfunctioning of the device but also from interference to or errors in the GPS signals in space, as for any system relying on radio signals, and the user should be aware of both aspects. Several methods may be used to demonstrate correct behaviour of the device, and the most common are discussed here.

3.2.1 Periodic recalibration

Some Accreditation Bodies require the recalibration of GPSDOs at regular intervals, typically every 1 or 2 years, by an NMI, DI or other suitably accredited calibration laboratory, as discussed in section 2.1 and shown as a dashed line in figure 1. When justified, for example when the required standard uncertainty of a GPSDO serving as a frequency reference is no better than 1×10^{-11} (1σ) at 1 day averaging, the period between calibrations may be extended appropriately.

The preferred calibration method is to employ a transportable transfer standard, either another GPS receiver or a free-running oscillator, to verify the correct functioning of the GPSDO in its normal operating location. The transportable standard would be installed and operated for some time in the calibration laboratory alongside the GPSDO under calibration, and their output signals compared. This procedure has the advantage of identifying any anomalous behaviour arising from the location of the receiver, such as multipath interference, and avoids the risk of changes in the behaviour of the GPSDO occurring during transit, but is not always possible.

Alternatively, the recalibration may be performed by sending the GPSDO to an NMI, DI or other suitable accredited calibration laboratory, as discussed in section 2.1. The periodic recalibration of the GPSDO may be also performed by remote comparison using the GPS common-view or all-in-view methods, as discussed in section 3.2.5.

It is important to note that a calibration measurement only evaluates the performance of the GPSDO at the time of the calibration, so the possibility of a fault developing later in the GPSDO or an error appearing in the signals in space for a short period remains a possibility. Other means must therefore be used to verify that the device is operating correctly between calibrations. Some appropriate methods are described in the following sections.

3.2.2. Monitoring the GPSDO parameters

All GPSDOs should provide a visual indication that the oscillator is locked correctly to the received GPS satellite signals, and the front panel lights and indicators should be checked regularly and their status noted during a calibration. Most GPSDOs will have some form of log or parameter file that can be downloaded automatically, and information such as the number of observed and locked satellites, the strength of the received signals, and the health of the local oscillator can all help give confidence that the receiver is operating correctly. A calibration laboratory should inspect and validate the log file recording the steering of the local oscillator (or equivalent data) during any period when the GPSDO is being used as a local reference standard in a calibration.

Since a GPSDO contains the oscillator that is being disciplined, often either a TCXO or a rubidium oscillator, monitoring of the oscillator control voltage can provide valuable information about the condition of the device. Access to the control voltage is usually available in the receiver menu system, and some devices make the control voltage available as an analogue output. Any problem in signal reception or the locking process will give rise to unexpected changes in the control voltage pattern. Normally, the control voltage will change slowly, and approximately linearly, as the control loop compensates for the natural drift of the local oscillator. A sudden step change, or departure from the normal rate of change, will indicate that investigation is needed. Monitoring of the control voltage is also useful in case of loss of power to the receiver – once power is restored, the control voltage should return to its previous value and its normal rate of change, and this behaviour is a good indication that the system has re-stabilised.

3.2.3 Comparison with another GPS receiver or disciplined oscillator

A straightforward method of validating the behaviour of a GPSDO is to compare its output signals continuously with those from another GPS receiver. The second receiver may be another GPSDO, or a GPS receiver that generates a 1 PPS output directly from the received satellite signals. The comparison measurements may record either the frequency difference between the receivers or the time difference, but in either case any sudden change in the measured values will indicate a problem with one of the receivers that should be investigated.

If the second receiver is also a GPSDO then it should be from a different manufacturer to remove the possibility of both receivers displaying similar anomalous behaviour at the same time, which would not be detected by the difference measurements, due to the receivers running the same faulty steering algorithm.

An oscillator disciplined to other off-air standard-frequency and time signals, such as DCF77, MSF or eLoran, may be used in the same way to monitor the GPSDO.

3.2.4 Comparison with a free-running oscillator

The procedure to be followed when a free-running oscillator is available in a calibration laboratory in addition to the GPSDO is essentially the same as when performing comparison measurements with a GPS or off-air disciplined oscillator, except that the frequency or phase difference will change steadily over time. Any sudden step change in the difference or change of slope will indicate a problem that requires investigation. Occasional adjustment of the free-running oscillator may be needed to prevent the size of the time or frequency difference increasing beyond the limits of the measurement system.

3.2.5 Remote comparison by GPS common-view

A number of NMIs and DIs offer remote calibration services that allow the reference standard in a calibration laboratory to be compared with the national time and frequency standard at the NMI or DI by the GPS common-view (CV) or all-in-view (AV) techniques. In the CV method, GPS timing receivers at the NMI (or DI) and at the calibration laboratory measure the time difference between the local time reference (which at the calibration laboratory may be generated from the reference frequency with a constant but uncalibrated time offset) and the signals from the same GPS satellites. Data files are typically produced daily and conform to an agreed standard format, such as the CGGTTS common-view format. (CGGTTS stands for Common GNSS Generic Time Transfer Standard, and CCTF is the Consultative Committee for Time and Frequency.) Differencing the measurements from the two receivers provides frequent values for the time or frequency offset between the GPSDO at the calibration laboratory and the national standard at the NMI, with a standard uncertainty (1σ) of typically 10-20 ns for the time offset or $1x10^{-13}$ for the normalised frequency offset at 1 day averaging time, respectively. The AV method makes use of additional products available from the IGS (International GNSS Service) to compute comparisons using GPS Time as the reference rather than individual satellite clocks, allowing it to be used over intercontinental baselines, but it is of limited relevance for services within a given country.

Some NMIs and DIs may install a GPS timing receiver at a calibration laboratory on request for a few days so that a calibrated time link to the NMI or DI can be temporarily established.

3.2.6 Reference to GPS monitoring results

Some European NMIs or DIs, including INRIM, LNE-SYRTE, NPL, PTB and VSL, publish regular reports containing measurements of the time difference between GPS Time derived from the satellite signals and the local reference time scale. These reports give confidence that the broadcast GPS signals provide a good approximation to UTC in both time and frequency, and Accreditation Bodies usually require accredited calibration laboratories to subscribe to the GPS monitoring reports from their NMI or other UTC(*k*) laboratory as part of the process of demonstrating traceability.

As discussed in section 3.1, the CIPM MRA allows a GPSDO to provide traceability to UTC only when supplemented by the GPS Time monitoring results published by an NMI or DI that maintains a UTC(*k*) time scale (and so participates in the CIPM MRA Key Comparison CCTF-K001.UTC), together with the UTC – UTC(*k*) data published by the BIPM in Section 1 of Circular T.

3.3 Assignment of uncertainty

There are several available methods that can enable a calibration laboratory to assign an uncertainty to an output signal from a GPSDO used as a laboratory reference. These methods are in some cases closely related to the procedures for validating correct operation. An example of a typical uncertainty budget is included as Appendix B.

3.3.1 Calibration by an NMI or accredited laboratory

Calibration of the GPSDO by an NMI or other suitably accredited calibration laboratory, as discussed in sections 2.1 and 3.2.1, will result in an uncertainty being assigned to the GPSDO's frequency or time output signals. The duration of the calibration measurements should be long enough to provide reliable uncertainty values for the averaging times over which the GPSDO will be used as a reference standard. Because a calibration measurement only evaluates the performance of the GPSDO at the time of the calibration, other methods such as those discussed in section 3.2 must be used to verify correct operation of the GPSDO between calibrations.

3.3.2 Direct evaluation of the uncertainty

For time scale measurement uncertainties worse than 1 microsecond (1σ) for a relative frequency uncertainty of 1×10^{-11} (1σ) or worse at 1 day averaging time, some Accreditation Bodies allow a calibration laboratory to assign uncertainties to the GPSDO output signals based on other evidence, as an alternative to a formal calibration. The simplest option is to take the manufacturer's published specifications as the basis of the uncertainty determination. These specifications may be based on a calibration of one example of a particular model of GPSDO, with allowance being made for the variations between notionally identical receivers. The specification should refer to averaging times which are relevant for the measurement tasks for which the instrument is going to be employed. Whatever method is used to evaluate the uncertainty, the calibration laboratory must also employ one of the procedures discussed in section 3.2 to verify correct operation of the GPSDO when in use as a laboratory reference standard.

3.3.3 Remote comparison by GPS common-view

As discussed in section 3.2.5, some NMIs and DIs offer a remote calibration service that monitors the reference standard in a calibration laboratory against the national time and frequency standard by the GPS CV or AV techniques. The time scale or frequency offset between the GPSDO at the calibration laboratory and the national standard at the NMI or DI is computed at regular intervals, and an uncertainty assigned to the results.

3.4 Additional considerations for time scale measurements

A small proportion of calibration laboratories operating a GPSDO employ its 1 PPS output as a time scale reference traceable to UTC. The requirements for validation of correct operation and traceability discussed earlier (especially in sections 3.2.1, 3.2.2 and 3.2.6) apply in these situations, but in addition there is a requirement for the time offset of the GPSDO output signal to be known relative to UTC in addition to the stability of the output. An appropriate calibration of the GPSDO by an NMI, DI or suitably accredited calibration laboratory to determine its total delay will meet this requirement provided the traceability is obtained from a connection with an NMI or DI which participates in the CIPM MRA Key Comparison CCTF-K001.UTC by maintaining a physical representation of UTC.

When the required uncertainty is no better than 1 microsecond (1σ), determination of the uncertainty from the manufacturer's specifications or type testing of the model of GPSDO in use may be sufficient for some Accreditation Bodies, as discussed in section 3.3.2.

4 EXAMPLES OF PERFORMANCE

In the 1997 NPL study on this subject [1], the performance of many of the GPSDOs available at that time was compared. No similar study has been carried out for this Technical Guide since the variety of products has grown substantially, and the life cycles of individual models are often rather short. Instead, a few examples are given to illustrate typical observed performance.

Figures 2 and 3 show time scale and frequency comparisons between a typical GPS-disciplined Rb oscillator and UTC(PTB). The time difference in figure 2 was left uncalibrated. In figure 3, spikes due the steering of phase and frequency in this particular model can be seen. The frequency instability of the 5 MHz output signal of this GPSDO is illustrated in figure 4. The manufacturer's specifications only cover averaging times of 1 s, 10 s and 100 s, which may not be sufficient in many applications. Data points in blue in figure 4 refer to operation of the device on a window sill (but avoiding direct sunshine), i.e. with non-optimized environmental conditions.

For comparison, figure 5 shows time difference measurements between UTC(PTB) and the 1 PPS output signals from three different GPSDOs, offset by arbitrary values for clarity. The central (red) plot is of data from the same receiver as shown in figures 2 and 3. It can be seen that there are significant differences in the stability of the signals from the three receivers.

As an example of the time required for stabilisation, figure 6 shows the performance of a GPSDO just after a restart of the GPS control process. In this model, the control time constant is variable, so the performance will depend on the chosen value which may be dictated by the environmental conditions and the intended application.

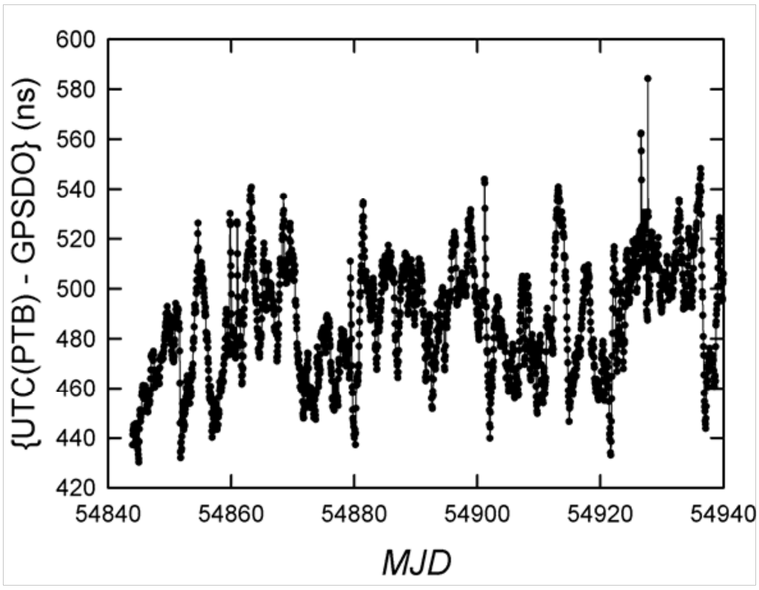

Figure 2: Time difference between UTC(PTB) and a GPSDO 1 PPS output, including uncalibrated offsets due to antenna, receiver and cable delays; data taken over 95 days in 2009.

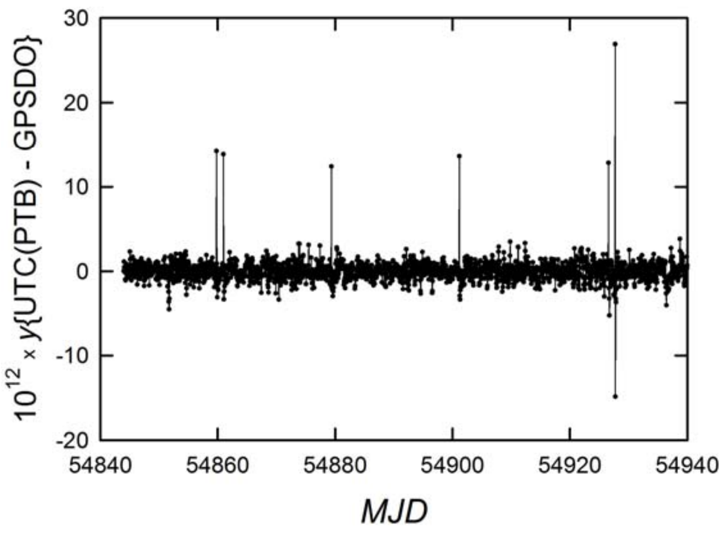

Figure 3: Relative frequency difference between UTC(PTB) and a GPSDO, based on the 1 PPS time comparisons shown in figure 2; data taken over 95 days in 2009.

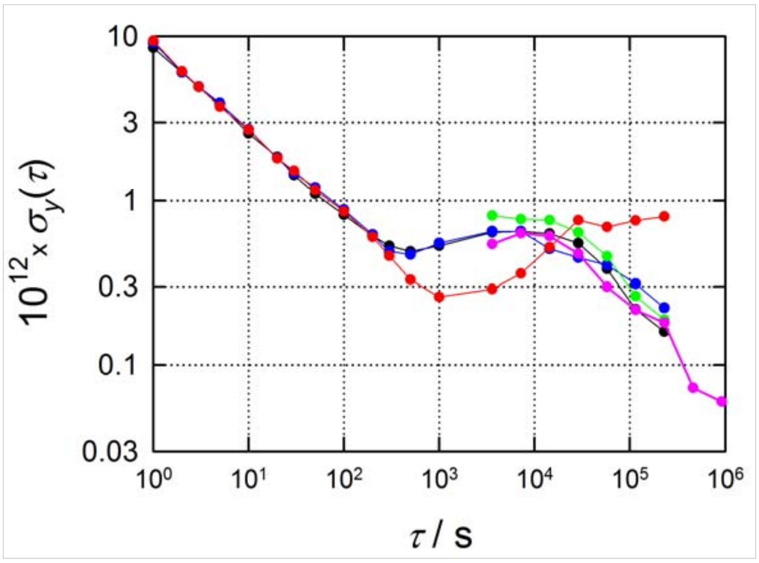

Figure 4: Relative frequency instability of the output of the same GPSDO as in figures 2 and 3 with respect to UTC(PTB), based on 5 MHz standard frequency signals, showing the free running Rb oscillator (red) and normal operation with GPS control over several tens of days (other colours).

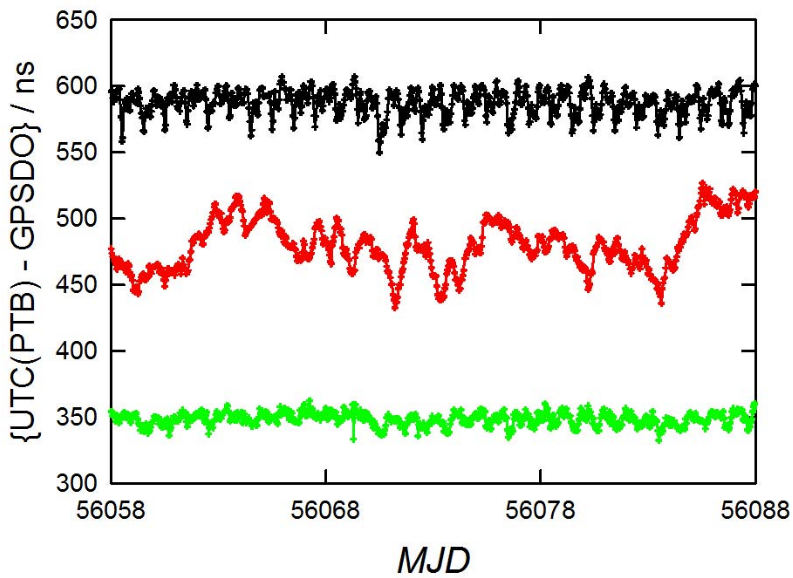

Figure 5: Time difference between UTC(PTB) and the 1 PPS output signals from three different GPSDOs. Uncalibrated offsets due to antenna, receiver and cable delays are included, and the plots are set apart by arbitrary values for clarity. The central red plot is from the same receiver as the data shown in figures 2 and 3. Data taken over 30 days in 2012.

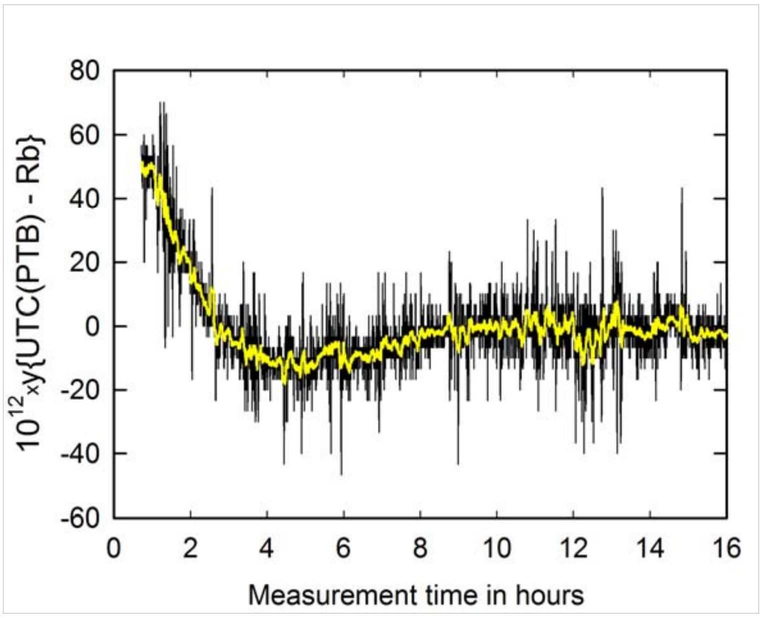

Figure 6: Relative frequency difference between UTC(PTB) and another GPSDO, based on 5 MHz frequency signals. Points in black are 30 s averages and those in yellow are based on a sliding 5-min average; the GPS disciplining process was started at hour 1.

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APPENDIX A: Principle of a GPS disciplined oscillator

A GPS disciplined oscillator or GPSDO combines a multi-channel GPS receiver card with a voltage controlled reference oscillator and a means of adjusting the oscillator to maintain alignment between its frequency output and the pulse output (usually 1 pulse-per-second – 1 PPS) from the GPS receiver. A typical block diagram of a GPSDO is depicted in figure 7.

A microprocessor device controls all the major functions of the GPSDO: it collects the measured time differences between the internal 1 PPS signal from the GPS receiver and the oscillator, applies a statistical filter to the measurements to reduce the effect of noise, and computes the frequency corrections to steer the local oscillator and the phase steps to be applied to the frequency divider to keep the output 1 PPS signal synchronized with GPS time. In addition, it generally allows the user to introduce initialisation parameters, to modify the operation mode and to read the operational status of the system through an I/O port. The oscillator can be a temperature-compensated quartz oscillator (TCXO), an oven-controlled quartz oscillator (OCXO), a small rubidium oscillator or even a caesium frequency standard. Some instruments can also discipline an external oscillator already available in the laboratory. The microprocessor runs a proprietary algorithm that adjusts the oscillator to the GPS signal using one or more servo loops that may have time constants ranging from seconds to days.

The most commonly delivered output signals are 1 PPS derived from the GPS card and one or more standard frequencies (usually 5 MHz or 10 MHz) from the disciplined oscillator. Additional information, such as whether the time displayed is UTC(USNO) or GPS Time, the antenna coordinates, the local oscillator disciplining process and the time tagging of external events, can be obtained through a display or a computer interface. In some cases a frequency error multiplier function is also implemented to characterise oscillators undergoing calibration.

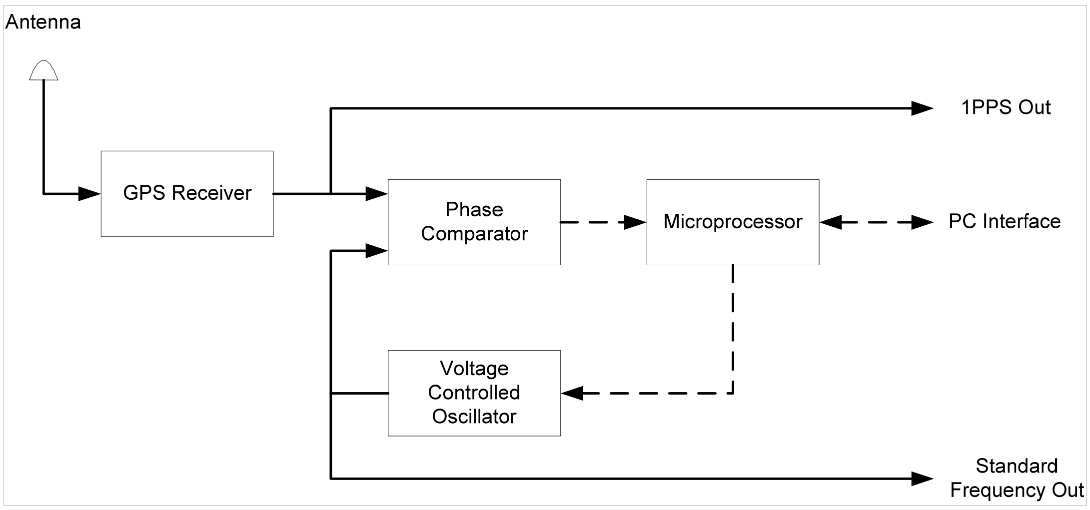

Figure 7: Block diagram of a typical GPS disciplined oscillator.

APPENDIX B: Example uncertainty budget

This section provides typical examples of uncertainty budgets for realising traceability using a GPS disciplined oscillator for time scale difference and for frequency.

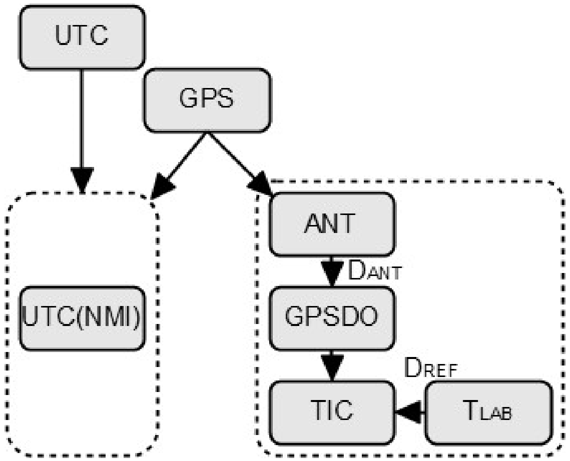

Figure 8: Diagram illustrating some of the terms used in the example GPSDO uncertainty budgets.

Time scale difference

Consider a calibration laboratory that uses a free-running oscillator to generate a time scale T_{LAB}, together with a GPS link to obtain its traceability from an NMI (note that in this example, where 'NMI' is written, it should be understood to mean either an NMI or a DI). The laboratory receives regular bulletins with information about UTC - UTC(NMI) and UTC(NMI) - T_{GPS}.

The time scale difference between UTC and T_{LAB} is now described by:

$$\mathrm{UTC} - T_{\mathrm{LAB}} = \left(\mathrm{UTC} - \mathrm{UTC(NMI)}\right) + \left(\mathrm{UTC(NMI)} - T_{\mathrm{GPS}}\right) + \left(T_{\mathrm{GPS}} - T_{\mathrm{LAB}}\right)$$

The laboratory's link to GPS is realised by a GPSDO. This GPSDO has a 1 PPS output signal, T_{DO}, which is compared to T_{LAB} by means of a time interval counter TIC. The signal T_{LAB} going to the TIC is delayed by a cable, D_{REF}. The GPS signal going to the GPSDO is delayed by the antenna cable, D_{ANT}. The internal delay of the GPSDO has been calibrated by an NMI or DI. In practice, the internal delay includes the delay of the antenna as well as the delay of the receiver itself, since it is not possible to measure the two components separately without disproportionate effort. Note that absolute calibrations of receiver and antenna internal delays have been discussed in the literature, but generally not in the context of GPSDO applications.

The difference between GPS Time (T_{GPS}) and T_{LAB} is now given by:

$$\left(T_{\mathrm{GPS}} - T_{\mathrm{LAB}}\right) = \left(T_{\mathrm{GPS}} + D_{\mathrm{ANT}} - T_{\mathrm{DO}}\right) + \left(T_{\mathrm{DO}} - \left(T_{\mathrm{LAB}} + D_{\mathrm{REF}}\right)\right)$$

Note that if the laboratory defines a time scale T_{LAB} at the 1 PPS output of the GPSDO ($T_{\mathrm{LAB}} = T_{\mathrm{DO}}$, and $D_{\mathrm{REF}} = 0$), then the TIC is not used and:

$$\left(T_{\mathrm{GPS}} - T_{\mathrm{LAB}}\right) = \left(T_{\mathrm{GPS}} + D_{\mathrm{ANT}} - T_{\mathrm{DO}}\right)$$

Environmental and ambient conditions such as temperature, humidity, ionosphere and troposphere will affect the time transfer via the GPSDO to some extent. Since these influences cannot be corrected, their total effect is evaluated within a *type A* uncertainty calculation of the "instability" of T_{DO}. The calculated uncertainty will also include the instability contribution arising within the GPSDO, which is often the dominant noise source, at least for short observation times.

The instability of the GPSDO can be improved by keeping it in a temperature-controlled room.

Furthermore, the intrinsic instability can be optimised by selecting a suitable antenna position that avoids reflections and multipath effects to the best possible extent.

A typical uncertainty budget is given in the table below. The values in the table are representative of a typical GPSDO and are not based on measurement results from a specific device.

Quantity	Estimate	Estimated Uncertainty (2σ)	Distribution	Standard uncertainty (1σ)	Sensitivity	Contribution
UTC - UTC(NMI)	4 ns	10 ns	Normal	5 ns	1	5.0 ns
UTC(NMI) - T_{GPS}	-3 ns	10 ns	Normal	5 ns	1	5.0 ns
TIC (T'_{LAB} - T_{DO})	70 ns	1 ns	Normal	0.5 ns	1	0.5 ns
D_{REF}	45 ns	1 ns	Normal	0.5 ns	1	0.5 ns
T'_{GPS} - T_{DO}	20 ns	40 ns	Normal	20 ns	1	20.0 ns
D_{ANT}	100 ns	2 ns	Normal	1 ns	1	1.0 ns
Stability	0 ns	5 ns	Normal	5 ns	1	5.0 ns
UTC - T_{LAB}	6 ns					21.8 ns
					k = 2	44 ns

Notes:

1. The estimated uncertainties are assumed to have a normal distribution and are given here with a probability interval of 95% (i.e. 2σ), so they are twice the corresponding standard uncertainties.
2. In this example, the term "NMI" should be taken to mean either an NMI or a DI.
3. The UTC - UTC(NMI) estimate and its uncertainty can be obtained from section 6 of the BIPM Circular T.
4. The widely-used Stanford SR620 time interval counter has a typical time interval (A-B) measurement uncertainty of 0.5 ns (1σ).
5. The 1 ns uncertainty assumed here for a cable delay measurement (e.g. D_{ANT}) is typical for a time interval counter such as an SR620.

Frequency

The frequency of a time scale signal, nominally equal to 1 Hz, is determined by the inverse of the time interval units ΔT that constitute the scale:

$$f = \frac{1}{\Delta T}$$

When two measurements are separated in time by $t_1 - t_0$, the fractional frequency deviation of f_{LAB} with respect to f_{UTC} is found from:

$$\frac{f_{\mathrm{UTC}} - f_{\mathrm{LAB}}}{f_{\mathrm{UTC}}} = \frac{\left(\mathrm{UTC}(t_1) - T_{\mathrm{LAB}}(t_1)\right) - \left(\mathrm{UTC}(t_0) - T_{\mathrm{LAB}}(t_0)\right)}{(t_1) - (t_0)}$$

So, in words, the fractional frequency offset can be found by measuring the phase time differences between the two time scales over repeated intervals. The interesting property of this equation is that all systematic delays in the phase time comparison that are stable over the interval t_0 to t_1 do not affect the result. For this reason, frequency transfer is in general easier than time scale transfer. This can be seen by expanding the equation above using the formulas for time scale differences:

$$\frac{f_{\mathrm{UTC}} - f_{\mathrm{LAB}}}{f_{\mathrm{UTC}}} = \frac{[(\mathrm{UTC\text{ - }UTC(NMI)}) + (\mathrm{UTC(NMI)\text{ - }T_{GPS}}) + (\mathrm{T_{GPS}} + D_{ANT} - T_{DO}) + (T_{DO} - (T_{LAB} + D_{REF}))](t_1) - [....](t_0)}{(t_1) - (t_0)}$$

In the numerator we find two differences between quantities in square brackets. It can be assumed that D_{ANT} and D_{REF} are constant over the typical time intervals considered here. Thus, when establishing the frequency traceability from f_{LAB} to f_{UTC} by using an NMI and GPS as intermediate frequency signals, the fractional frequency difference can be written as:

$$\frac{f_{\mathrm{UTC}} - f_{\mathrm{LAB}}}{f_{\mathrm{UTC}}} = \frac{f_{\mathrm{UTC}} - f_{\mathrm{NMI}}}{f_{\mathrm{UTC}}} + \frac{f_{\mathrm{NMI}} - f_{\mathrm{GPS}}}{f_{\mathrm{UTC}}} + \frac{f_{\mathrm{GPS}} - f_{\mathrm{DO}}}{f_{\mathrm{UTC}}} - \frac{f_{\mathrm{LAB}} - f_{\mathrm{DO}}}{f_{\mathrm{UTC}}}$$

The first term on the right-hand side of the equation can be provided by the NMI or can be deduced from the BIPM Circular T.

The second term can also be provided by the NMI.

The third term represents the fractional frequency offset of the GPSDO. If the GPSDO is operating correctly, this value should be small with respect to its uncertainty. Some NMIs offer services to check the frequency offset of GPSDOs.

The last term is computed from the time interval counter (TIC) measurements between the 1 PPS signal from the GPSDO output and the laboratory's reference 1 PPS signal. This term is not required if the laboratory uses the GPSDO output signal as a source of f_{LAB}, in which case $f_{LAB}=f_{DO}$.

A typical uncertainty budget is given in the table below.

Quantity	Estimate	Estimated uncertainty (2σ)	Distribution	Standard uncertainty (1σ)	Sensitivity	Contribution
$\frac{f_{UTC} - f_{NMI}}{f_{UTC}}$	0.020 $\times 10^{-12}$	0.05 $\times 10^{-12}$	Normal	0.025 $\times 10^{-12}$	1	0.025 $\times 10^{-12}$
$\frac{f_{NMI} - f_{GPS}}{f_{UTC}}$	-0.015 $\times 10^{-12}$	0.2 $\times 10^{-12}$	Normal	0.1 $\times 10^{-12}$	1	0.100 $\times 10^{-12}$
$\mathrm{TIC}(t_1) - \mathrm{TIC}(t_0)$	5 ns	0.1 ns	Normal	0.05 ns	1/86400 1/s	0.001 $\times 10^{-12}$
$t_1 - t_0$	86400 s	1.0 s	Normal	0.5 s	$5/(86400)^2$ ns/s^2	0.000 $\times 10^{-12}$
D_{REF}	45 ns					
$\frac{f_{GPS} - f_{DO}}{f_{UTC}}$	0.005 $\times 10^{-12}$	1 $\times 10^{-12}$	Normal	0.5 $\times 10^{-12}$	1	0.500 $\times 10^{-12}$
D_{ANT}	100 ns					
Stability	0.000 $\times 10^{-12}$	2 $\times 10^{-12}$	Normal	1 $\times 10^{-12}$	1	1.000 $\times 10^{-12}$
$\frac{f_{UTC} - f_{LAB}}{f_{UTC}}$	0.010 $\times 10^{-12}$					1.123 $\times 10^{-12}$
					k = 2	2.25 $\times 10^{-12}$

Notes:

1. The estimated uncertainties are assumed to have a normal distribution and are given here with a probability interval of 95% (i.e. 2σ), so they are twice the corresponding standard uncertainties.
2. In this example, the term "NMI" should be taken to mean either an NMI or a DI.
3. The $(f_{UTC} - f_{NMI})/f_{UTC}$ estimate and its uncertainty can be determined from the BIPM Circular T.
4. The sensitivity coefficient for the measurement interval $t_1 – t_0$ is dependent on the relative frequency difference, and in this example is given by the relative uncertainty of this term (1 s / 86400 s) multiplied by the relative frequency difference (5 ns / 86400 s).
5. Although the contribution due to the uncertainty of the measurement interval $t_1 – t_0$ is negligible, it has been retained in the uncertainty budget to show that it has been considered.
6. The dimensionless quantities in the table are here expressed in exponential form, but a quantity of 1 $x10^{-12}$ (for example) could also be given as 1 pHz/Hz.
7. Uncertainties relating to instability have been stated for an averaging time of 100 seconds.

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