Traceable calibration of a GPS Disciplined Oscillator

By Staffan Johansson (Pendulum Instruments AB) & Dave Coombes (Fluke Precision Measurements)

Abstract:

GPS-disciplined frequency standards (GPSDO = GPS-Disciplined Oscillator) have become the industry standard for accurate reference frequency generation. A GPSDO is **not** automatically traceable to international standards, although the Cesium-derived transmitted signal from the GPS satellites is traceable to USNO and NIST. The output frequency of the GPSDO is only traceable if the unit is correctly designed. The concept of *traceability* calls for a comparison of the disciplined local oscillator with the received GPS transfer standard via a process where "the measurement is producing documented results for which the total measurement uncertainty is quantified". The only way to ensure traceability of traditional GPSDO's is to build a measurement system (calibration system) involving the actual GPSDO, an external frequency standard and a frequency or phase comparator.
This paper presents a new concept in GPSDO design (model 910 from Fluke precision measurements) with a built-in measurement system that produces, documents and saves calibration data from the comparison between the GPS-transfer standard and the local oscillator. Frequency offset, and frequency adjustment data are stored in a non-volatile memory, that can accommodate more than two years of unbroken consecutive calibration data. Via a connected PC, the disciplining process of the GPSDO is fully visible to the user, without the need for external instrumentation.

1. What's traceability?

According to ISO's International Vocabulary of Basic and General Terms in Metrology (VIM) from 1993 [1], traceability is defined as:

> ”The property of a result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties."

This definition of traceability is very general and does not take into account for example the time factor. How often should a user calibrate his equipment to ensure traceability? Traceable calibrations are perishables, like fresh food. The longer you wait until the next calibration, the less "fresh" is the calibration. The traceability is there, no doubt, at the moment of calibration, but for how long? The definition from VIM gives no answer. Therefore a demand for a more stringent definition has been brought forward.

In 1996, Dr. R. E. Hebner, Acting Deputy Director of NIST proposed an extension to the definition of traceability [2]:

> ”It is noted that traceability only exists when scientifically rigorous evidence is collected on a continuing basis showing that the measurement is producing documented results for which the total measurement uncertainty is quantified"

The new element in the proposed additional paragraph is the demand for comparison on a ”continuing basis". This should not be interpreted as "continuous" but "periodically", where the length of the period in some way is related to the required uncertainty level of the standard being calibrated. There must exist a well thought-out plan for periodic calibration. It is not in accordance with the traceability concept to calibrate "ad hoc".

Furthermore, it is stressed that a comparison (calibration) only is traceable if the calibration process produces *documented* measurement results. As we will see, this demand excludes almost all GPS-receiver standards from being traceable to international standards (e.g. NIST) on their own merits only.

2. Primary, secondary and transfer standards

Time and frequency are two sides of the same coin, since frequency is the inverse of period time. The unit of frequency, 1 Hertz (1 Hz) equals 1 s^{-1}. The international SI-definition of the unit of time, 1 s, is based on the atomic properties of the Cesium 133 atom. The resonance frequency for the transition between two hyperfine levels in the fundamental atomic state is 9192631770 Hz and the SI-definition for 1s is thus the time for 9192631770 cycles.

A frequency standard that is designed to use this atomic property of the Cesium atom is an *intrinsic (primary) standard*, since it generates a frequency reference that is directly deducted from the SI-definition of the unit of time.

If you accept the manufacturers stated level of uncertainty, you do not need to calibrate a primary Cesium standard. That is to compare it with a standard “with a higher order of accuracy”. But also Cesium standards need to be monitored to avoid mal-functioning. National laboratories responsible for maintaining a country’s primary time and frequency standard do continuously compare their primary standard (Cesium standard) with at least one and preferably two other Cesium standards. They also compare their primary standard with other national primary standards, through common view measurements via defined GPS-satellites.

Commercial Cesium standards have a typical relative frequency uncertainty in the order of 10^{-12}. National laboratories that continuously make comparisons with other national standards can reduce the uncertainty to the order of 10^{-13} or better.

Other stand-alone time and frequency standards are *secondary standards* and need to be periodically compared to (calibrated against) a “better” standard that is traceable to a Cesium standard. Common examples are frequency standards based on Rubidium or quartz crystal oscillators.

A GPSDO use the signals from the GPS satellites as a *transfer standard* for time and frequency, that is the radio signal information is controlled by a Cesium frequency standard at the transmitter side. Transfer standards have the *possibility* of being traceable to national and international frequency standards, if the design is right. Like all radio-received signals, also the directly received GPS signal has a high amount of jitter and cannot on its own perform as a stable frequency reference. The received GPS-signal is however used to control a local secondary oscillator, which can be anything ranging from simple crystal oscillators to high-end Rubidium oscillators.

It is unfortunately a common misunderstanding among users, that a GPS-receiver is automatically traceable to international standards, since the local oscillator is controlled via a transfer standard (the received radio signal), which is traceable to USNO and NIST. As noted above, this is only true if the comparison process produces documented measurement results, which is normally not the case.

3. Traceability chain for time and frequency

The international time standard UTC (Coordinated Universal Time) is a “coordinated” average time between a large number (over 200) of primary standards in the world. UTC is administrated by the BIPM (Bureau International de Poid et Mesure) in Paris. The various time standards are inter-compared via common view of GPS-satellites. Via UTC various national time standards can be traced to each other. The relative offset to UTC of individual national standards is published monthly by BIPM in the so-called “Circular T”.

The Cesium standards of the GPS-satellites are controlled by the USNO (US Naval Observatory) whose master clock is continuously monitored by NIST (National Institute of Standards and Technology). NIST also continuously compares the frequency received from GPS directly with its own frequency standard and presents the result in the NIST GPS data archive, available on the World Wide Web. This database is updated daily.

Both NIST and USNO contribute to and are traceable to UTC. Due to the continuous comparison of the master clock of USNO with UTC (NIST), the GPS-satellite signals can be used as transfer standards for time and frequency that are directly traceable to NIST and indirectly (via the common view measurements and reporting to BIPM) to all other national time standards of the national metrology laboratories that contribute to UTC.

The traceability chain for a GPSDO is illustrated in figure 1.

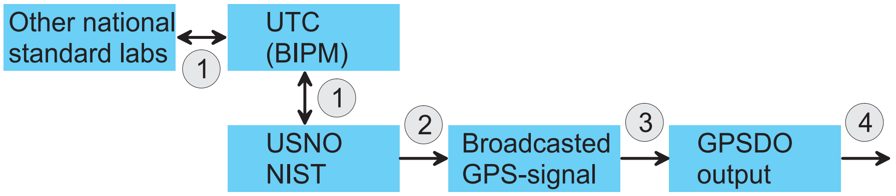

Figure 1 Traceability chain

Traceability calls for an “unbroken chain” of comparisons, each having a “stated uncertainty” and documented results? Let us take a closer look at the individual links in the chain in figure 1.

Link number 1 is the comparison between the time and frequency standard of national standard labs (including NIST) and UTC. The offset, based on GPS common view measurements, is published in BIPM's Circular T. The uncertainty of GPS Common View measurements has been published in several papers [6].

Link number 2 is the comparison between the GPS transfer standard and NIST (USNO). The offset and uncertainty is published daily on NIST GPS data archive on Internet.

Link number 3 is the broadcasting process from transmitter input to the receiver’s 1pps output. Contributing uncertainty factors are for example signal path variations, multi-path interference and solar intensity variations. The largest contributor to uncertainty is however the applied SA (Selective Availability) to the transmitted signal. The overall uncertainty of this link is strongly correlated to the averaging period. Over longer periods, e.g. days and weeks, the uncertainty is below 10^{-12}, whereas the uncertainty over 1 s can amount to 10^{-7}. Multi-channel receivers can average a number of satellite signals to reduce this uncertainty. The short-term uncertainty is also influenced by the receiver’s position status (search or hold).

Link number 4 involves the disciplining process of the local oscillator in the actual GPSDO. Contributing uncertainty factors are for example the uncertainty of the comparison circuitry, the algorithm used, the aging and susceptibility for temperature variations of the local oscillator.

The uncertainties of link number 1 and 2 are very small and can in all practical cases be neglected compared to the uncertainties of link 3 and 4. [4]

Based on actual measurements at the Swedish National Metrology Institute SP (Borås, Sweden), the relative frequency offset /24h of the 1pps signal from an industry standard multi-channel GPS-receiver (Motorola OnCore 6-channel receiver) varies typically from day to day within ±2.5E-13, with an uncertainty of 5E-13 (k=1). See figure 2. The phase of the 1 pps output of the receiver is measured every 10 minutes, referenced to UTC (SP), giving 144 phase values/day. The frequency offset per 24 h equals the average phase change, calculated as a least-square line fitting of the phase vs. time data.

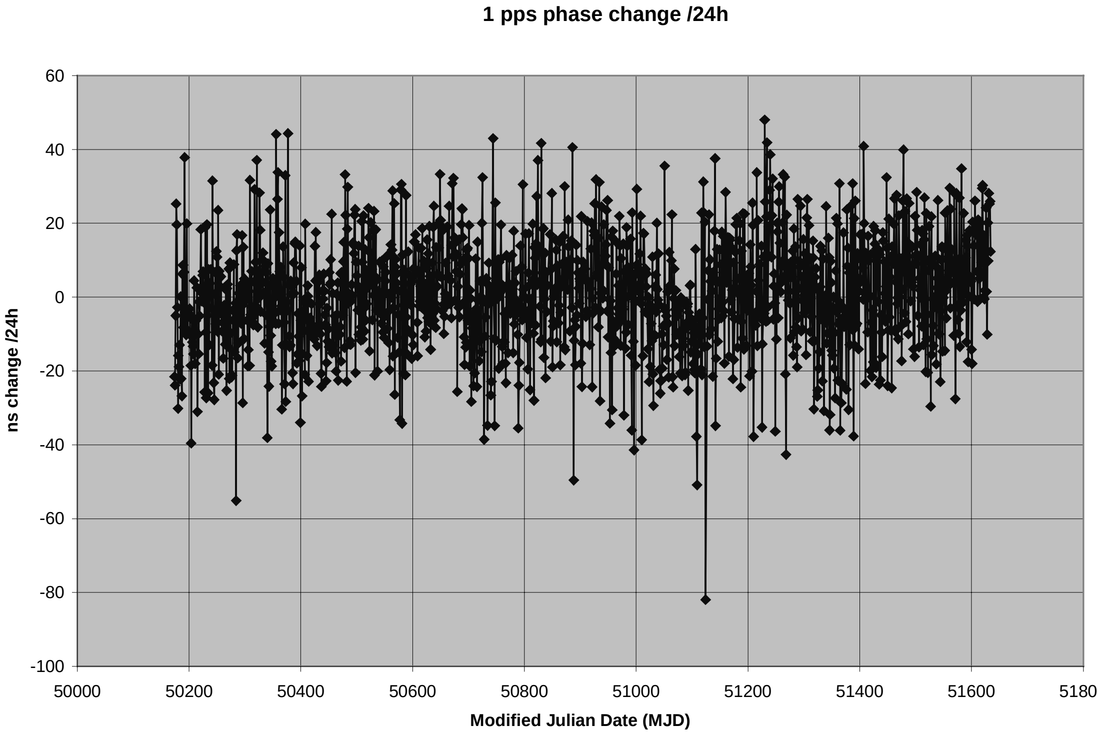

Figure 2. Graf showing average phase change per day of 1pps output from Motorola OnCore GPS-receiver’s vs. UTC (SP). Courtesy of Kenneth Jaldehag, Swedish National Metrology Institute (at SP, Borås Sweden).

These results indicate that a GPS-receiver with a good signal reception at a known position has a 24h mean frequency uncertainty of the nominal 1 pulse per second, which can be estimated to 5E-13 (k=1). This estimation is supported by published data from NIST [3], [4] where it is stated that a carefully designed GPS-based frequency calibration system ("FMAS" from NIST) can give measurement results with a total frequency uncertainty of 5E-13.

The mean frequency offset per day and the uncertainty of the final link (link 4) according to figure 1 is dependant on the design of the actual Frequency Standard. Important factors are the measurement resolution, disciplining algorithm, local oscillator's ageing and susceptibility to temperature variations. Commercially available GPS-controlled frequency standards hide this process to the user, making it impossible to calculate uncertainty. However, the newly introduced model 910 and 910R from Fluke Precision Measurements employs a new concept, with an integrated calibration system, that performs a continuous phase comparison between the 1 pps signal and the local oscillator, calculates the mean daily frequency offset as a least square fitting of the phase data, and stores the calculated frequency offset result in a non-volatile memory.

By connecting a PC to the frequency standard also actual phase deviation data are available to the user. A Calibration report can be printed at any time showing the frequency offset and the associated uncertainty.

4. GPSDO's as frequency standards

Using a GPSDO as a local frequency standard has become the prime choice for companies, institutes and laboratories. There are several reasons, e.g.

- Access to GPS satellites all over the globe
- Continuous reception of GPS-signals 24h a day
- Security/redundancy. There are 24 satellites in orbit, so it doesn't matter if one or two would fail
- Frequency uncertainty. GPS has lower uncertainty than other radio systems
- Possible traceability *if properly designed*

A typical commercial GPS-receiver is found in figure 3. It contains a receiver module, a local oscillator and a control system. The receiver module – or "GPS-engine" – consist of a radio receiver, demodulator and a micro-controller that interprets the received information on satellite position and timing and controls a pacing oscillator, that generates exactly 1 pulse per second (1 pps). This 1pps-signal has a high amount of jitter and short-term variations mainly due to the jittery SA (Selective Availability) signal. The cycle-to-cycle variations of the 1pps signal received from one satellite amounts to hundreds of nanoseconds, which means frequency variations over 1 s in the order of 10^{-7}. Receiving signals from several GPS satellites simultaneously and averaging the time information can reduce the jitter.

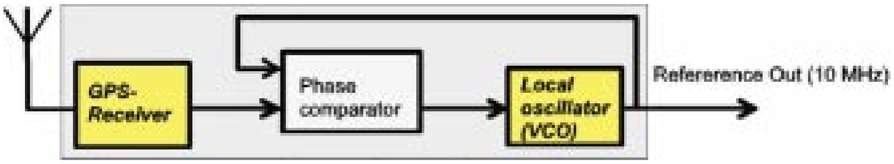

Figure 3: A typical GPS-receiver controls the local oscillator in an undocumented way. What is the actual frequency uncertainty today?

As mentioned above, the average frequency offset per 24h, of a good receiver, with good signal reception has an uncertainty of below 10^{-12}. To combine this long-term stability of the signal from the GPS-engine with an acceptable short-term stability, a GPSDO always contains a built-in voltage controlled local oscillator, which is continuously compared to the 1pps-signal. A control system adjusts the local oscillator with a suitable (long) time constant. The more stable the local oscillator is, the longer time constant can be used. With a local Rubidium oscillator, time constants in the order of hours is adequate, whereas the control loop must be approx 100 times faster for crystal oscillators. This difference between GPS-disciplined Rubidium and crystal oscillators is most noticeable when comparing frequency stability values over 100 to 1000 seconds averaging times. This behavior was also noted by J.A. Davis and J.M. Furlong at NPL, UK in the NPL report no CTM 1. [5]

What is the frequency uncertainty of the reference output from a GPSDO? That depends on the time over which the average frequency is measured. Averaged over 24h, most GPSDO's have an uncertainty in the order of 10^{-12}. Frequency variations over shorter times depend on the disciplining algorithm and the quality of the local oscillator. For e.g. 100s measuring time, the stability of a Rubidium oscillator is still in the order of 10^{-12}, but is between 10^{-10} and 10^{-11} for an OCXO (Oven Controlled Xtal Oscillator). See fig. 4 and 5, showing laboratory measurements at Pendulum Instruments AB, Stockholm, Sweden. Note that the same graph scale is used both in Figure 4 and 5. This measurement illustrates that a local Rubidium oscillator gives a much higher frequency stability over 100s compared to an OCXO, when compared to the in-house frequency standard.

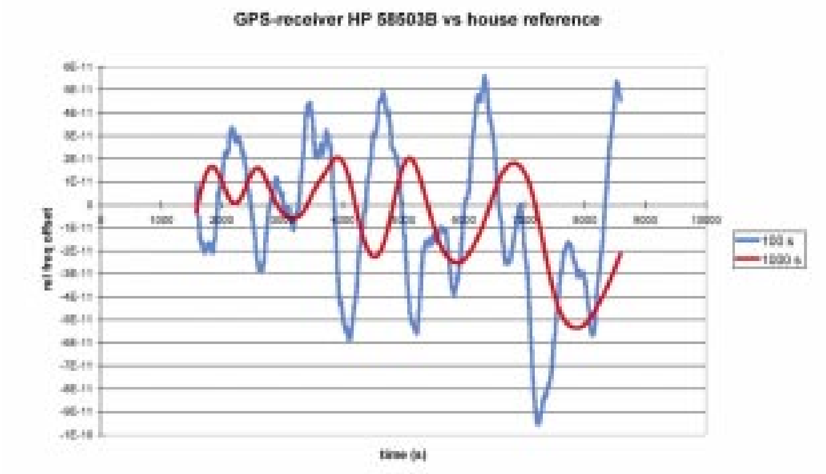

Figure 4: Frequency variation of a GPS-disciplined OCXO over an observation period of some hours. The average output frequency over 100s intervals varies from $-1*10^{-10}$ *till* $+6*10^{-11}$. *Measurements performed at Pendulum Instruments AB*

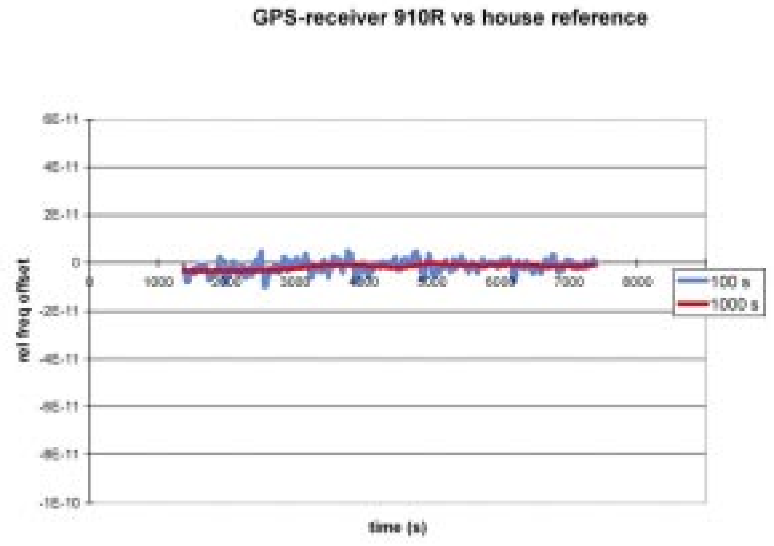

Figure 5: Frequency variation of a GPS-disciplined Rubidium oscillator over an observation period of some hours. The average output frequency over 100s intervals varies from $-9*10^{-12}$ *till* $+4*10^{-12}$. *Measurements performed at Pendulum Instruments AB*

5. Calibrating frequency offset

Do all GPSDO's deliver a frequency standard that is traceable to NIST or other national standards?
The answer is NO.

As stated in the first part of this paper, traceability demands a comparison between the local oscillator and the GPS signal using a documented process, that produces documented measurement results. Comparison data (calibration data) must be available to the user, which is not the case in commercially available frequency standards. These are from the user's perspective "black boxes" with an antenna input and a frequency output. See fig. 3. To be able to claim traceability with such a design, the GPSDO must be phase compared to another frequency standard, by means of e.g. a time interval counter.

How is this external comparison best made? Frequency offset between two stable frequency sources of the same nominal frequency is best measured by a so-called TIE measurement (TIE=Time Interval Error), using a high-resolution time interval counter. A time interval measurement gives the phase difference between the signals and repeating the measurement gives the phase drift between the signals over time, see fig. 6. Since frequency is the time derivative of phase, the frequency difference between the signals is equal to the slope of the TIE-curve, between the start and the stop point.

Let's give an example: We measure the time interval between the two stable signals at the zero crossing on the positive slope of the signals. If the time interval at a certain moment is 30 ns and 100s later is 35 ns, the phase drift during the observation interval is 5 ns. Over this 100s interval the mean frequency difference is 5ns/100s = $5*10^{-11}$.

When averaged over 24h, the best estimate of the frequency difference is a least square line fitting to the individual TIE-points during the 24h period. This calculation can be performed in a computer.

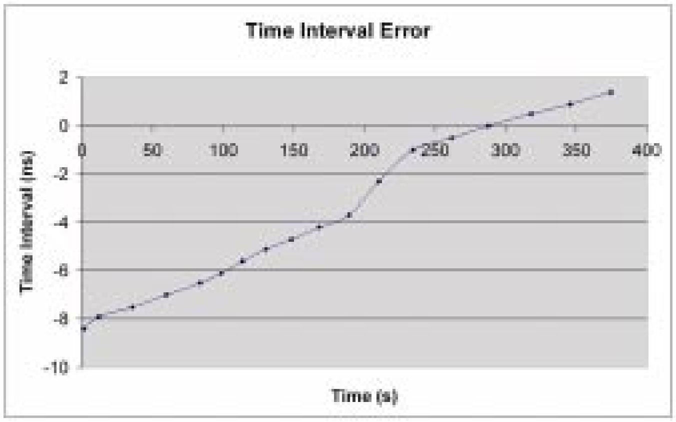

Figure 6: Time Interval Error (TIE) gives the change in phase over time. The slope of the curve equals the frequency difference between the compared signals.

6. A traceable GPS-frequency standard

Fluke Precision Measurements introduced in spring 2000 two GPSDO’s, called model 910 and model 910R. The local oscillator is either an OCXO (model 910) or a Rubidium oscillator (910R). See figure 7. The instruments are developed by the Swedish company Pendulum Instruments AB.

.

Figure 7: Photo of Fluke 910R

These units have a built-in calibration system, which fulfills the traceability demands. Since Pendulum Instruments AB is Europe’s leading manufacturer of high precision frequency counters (sold under the Fluke brand name), it is no coincidence that the new products contain a high-resolution measuring kernel (ASIC) originally developed for its latest frequency counter family. This measurement kernel performs a continuous TIE-measurement between the signals from the local oscillator and the GPS-engine. See fig. 8.

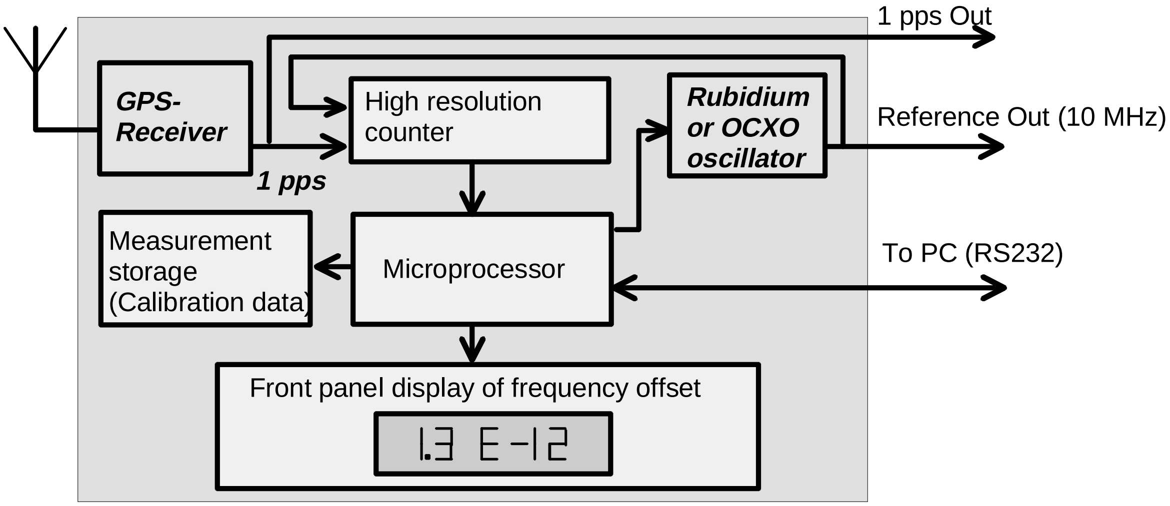

Figure 8: Block diagram of model 910R. Note the built-in measurement system and the non-volatile storage of calibration data.

The result of the TIE-measurement is available on an RS232-port and is updated every 30 seconds. Every 15 minutes the current mean frequency offset over the last 24 h is calculated as a least square line fitting to the TIE-data. This value is shown on the numeric display on the instrument front panel, and is also available on the RS232-port. Once a day the 24h frequency offset is internally stored in the non-volatile memory.

A Windows-based application program (GPSView^{TM}) can collect the phase deviation and frequency-offset data from the instrument. The uncertainty of each frequency-offset value is calculated based on:

a) an assumed uncertainty of 1E-12 (k=2) of the 1pps GPS-signal at the receiver output
b) the measured dispersion of TIE-values over the day
c) The resolution and other known uncertainty parameters of the measuring kernel.

A calibration report can be printed from the GPSView program on the user's request giving day-by-day calibration data for 24h frequency offset and its uncertainty. By the *continuous* and *documented* calibration the demands for traceability is fulfilled in a commercially available GPSDO, without the need for external instruments.

The non-volatile storage contains frequency calibration data and adjustment data to cover at least a period of two years. By storing both calibration and adjustment data, the user gets more insight in the disciplining process. Not only can he view how accurate his (adjusted) timebase is or was. He can also monitor the intrinsic ageing process and check if the local oscillator is or was excessively adjusted at any day, which could indicate e.g. problems with the climate control of the environment of the GPSDO.

References

[1] International Vocabulary of Basic and General Terms in Metrology, BIPM etc., International Organization for Standardization, Geneva, Switzerland (1993)

[2] R.E. Hebner, Calibration Traceability: A summary of NIST's view, Gaithersburg, Maryland, USA, 1996

[3] Michael A Lombardi, "An introduction to frequency calibrations" (reprinted from NIST Frequency Measurement & Analysis System Operator's manual), page 29, NIST Time and Frequency Division

[4] Michael A. Lombardi, Traceability in Time and Frequency Metrology, Cal Lab journal vol. 6 no. 5, September-October 1999

[5] J. A. Davis and J. M. Furlong, NPL, National Physics Laboratory, Report on the study to Determine the Suitability of GPS Disciplined Oscillators as Time and Frequency Standards Traceable to the UK National Time Scale UTC (NPL), Teddingdon, Middlesex, UK, 1997

[6] Proceedings of the IEEE, vol. 79, no 7, page 991 ("GPS-time transfer"), 1991