Traceable calibration of time and frequency

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Summary:

Standards for time and frequency can be categorized in *stand-alone standards* (e.g. Cesium, Rubidium and oven-controlled quartz oscillators) and *receiver standards* that get their frequency accuracy via a Cesium controlled radio transmitter. Of these, GPS-controlled frequency standards are dominating the market, leaving no room today for other competing receiver solutions like DCF-77 and Loran-C. A common mis-understanding is that a GPS-receiver automatically is traceable to international standards, since the Cesium oscillators in the GPS satellites are traceable to USNO and NIST. The transmitted GPS signal in itself is a traceable time and frequency standard, but the receiver standard output is only traceable if the unit is correctly designed. The concept of traceability calls for a comparison of the controlled 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 is to build up a measurement system (calibration system) involving the actual GPS-receiver standard, a frequency or phase comparator and an external frequency standard. In February 2000, Wavetek precision measurements launched model 910; the world's first GPS-controlled frequency standard 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. This GPS-controlled frequency standard is the first to be truly traceable on its own merits, 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, 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, NIST took the initiative to propose an additional paragraph to the definition of traceability:

> ”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" or, even worse, once in a lifetime.

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 receiver standards from being traceable to international standards (e.g. NIST) on their own.

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) is defined as 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 never need to calibrate a primary Cesium standard. That is to send it away for comparison 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 comparison with defined GPS-satellite signals.

Commercial Cesium standards have a typical relative frequency uncertainty of 10^{-12} or better. National laboratories that continuously compares with other national standards, can reduce the uncertainty

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 **Rubidium standard** is based on atomic resonance in the Rubidium atom at 6 834 682 613 Hz (6,8..GHz), but contrary to Cesium, Rubidium oscillators have a small ageing of $1x10^{-9}$ or better during a 10-year period.

In an **OCXO (Oven Controlled X-tal Oscillator)**, the oscillator is enclosed in an insulated temperature controlled compartment. Thereby the intrinsic property of the quartz crystal to change its resonance frequency for a change in the ambient temperature, is reduced by 3-4 orders of magnitude. Typical ageing is in the order of 10^{-7} to 10^{-8} per year and typical variation with temperature is in the order of 10^{-8} to 10^{-9}.

Due to this ageing, Rubidium and OCXO standards must be calibrated with shorter (OCXO) or longer (Rubidium) intervals.

Receiver standards have existed for a long time now, e.g. for receiving the DCF-77-transmitter in Mainflingen, Germany, or the navigation system Loran-C. Other local frequency reference transmitters were found in Droitwich, UK and Motala, Sweden. Common for all these systems is that a Cesium standard controls the carrier frequency of the transmitter. The carrier frequency is usually low (Long wave signals) to improve receiving distance. The transmitted signal is thus a *transfer standard*, controlled by the primary Cesium standard. The most important instrument type in the receiver category is the:

GPS-receiver standard, which uses the signals from the GPS satellites as transfer standard. Like all radio-received signals, also the directly received GPS signal has a high amount of jitter and is useless on its own as a frequency reference. The received GPS-signal is however used to monitor and control a local secondary oscillator, that can be anything ranging from the simplest crystal oscillator to a high-end Rubidium oscillator

It is a common mis-understanding 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 Cesium standards in the satellites, which are 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 is called UTC (Coordinated Universal Time) and is a “coordinated” time between a large number of primary standards in the world. UTC is administrated by the BIPM (Bureau International de Poid et Mesure) in Paris. Via UTC various national time standards can be traced to each other.

The Cesium standards of the GPS-satellites are controlled by the USNO (US Naval Observatory) whose master clock is continuously compared to NIST (National Institute of Standards and Technology). Both NIST and USNO contributes to UTC. Due to the continuous comparison between the GPS-satellites and the master clock of USNO, the GPS-satellite signals are traceable transfer standards for time and frequency.

4. GPS-receivers as frequency standards

Using GPS to monitor or control 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
- Stability. Short-term stability is better than long wave systems, where ground and sky waves interfere
- Possible traceability *if properly designed*

A typical commercial GPS-receiver is found in figure 1. 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 due to for example atmospheric variations, multi-path-interference and the jittery SA (Selective Availability) signal, which is applied by the USNO to prevent civilian users to acquire the highest level of positioning precision. The cycle-to-cycle variations of the 1pps signal received from one satellite amounts to hundreds of nanoseconds or even microseconds, which means frequency variations over 1 s in the order of 10^{-7} to 10^{-6}.

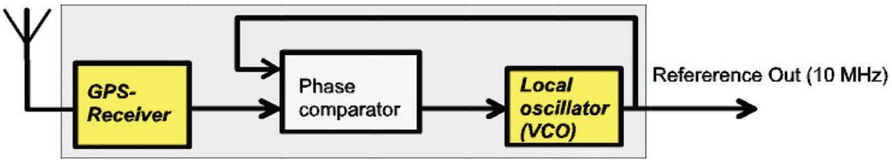

Figure 1: A typical GPS-receiver controls the local oscillator in an undocumented way. What is the actual frequency uncertainty today?

The jitter can be somewhat reduced by receiving signals from several GPS satellites simultaneously and averaging the time information. But averaged over 24h, the frequency uncertainty of the 1 pps signal is excellent, in the order of 10^{-12}.

To combine the long-term stability of the signal from the GPS-engine with an acceptable short-term stability, a GPS-controlled frequency standard always contains a built-in voltage controlled local oscillator, which is continuously compared to the 1pps-signal from the receiver module.

A control system adjusts the local oscillator with a suitable (long) time constant. This control process is also known as *disciplining*, and sometimes you can see the acronym GPSDO, that stands for GPS-Disciplined Oscillator. 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.

What is the frequency uncertainty of a GPSDO? That depends on the time during which the average frequency is measured. Averaged over 24h, almost all GPSDO:s are stable with an uncertainty in the order of 10^{-12}, except simple designs which have uncertainties in the order of 10^{-11}. 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 the Rubidium oscillator is still in the order of 10^{-12}, but is between 10^{-10} and 10^{-11} for the OCXO. See fig. 2 and 3.

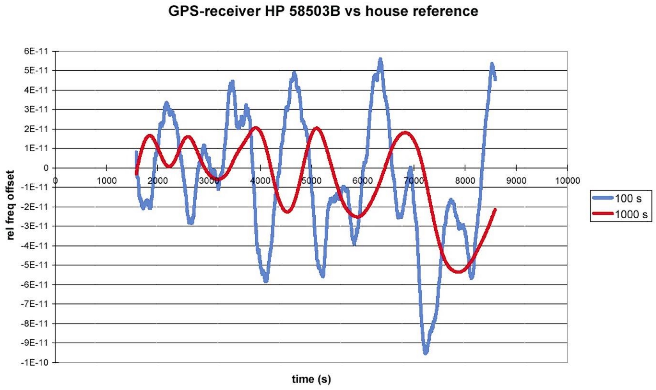

Figure 2: Frequency variations of a GPS-disciplined OCXO over an observation period of some hours. The average output frequency over 100s intervals varies from $-1*10^{-10}$ *till* $+6*10^{-11}$.

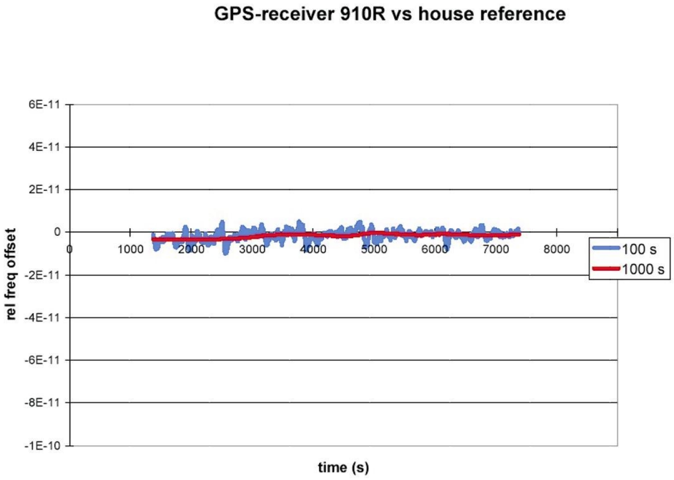

Figure 3: Frequency variations of a GPS-disciplined Rubidium oscillator over an observation period of some hours. The average output frequency over 100s intervals varies from $-9*10^{-12}$ *till* $+4*10^{-12}$*. Note that the same graph scale as in Figure 2 is used. A Rubidium oscillator gives a superior stability over 100s compared to a OCXO.*

5. Traceability for a GPSDO

What about the traceability of a GPSDO? It contains a GPS-receiver that receives a traceable transfer standard and a local oscillator that in one way or another is controlled by this transfer standard.

But, 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 almost all commercially available frequency standards. These are from the user's perspective "black boxes" with an antenna input and a frequency output. Look back on fig. 1. To be able to claim traceability with such a common design, the GPSDO must be phase compared to another frequency standard, by means of e.g. a time interval counter.

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), which gives the phase change between the signals over time, see fig. 4. Since frequency is the time derivative of phase, the frequency difference between the signals is equal to the slope of the TIE-curve. Lets give an example: We measure the time interval between the two signals at the zero crossings on the positive slope of the signals. If the time interval in 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 = $5*10^{-11}$.

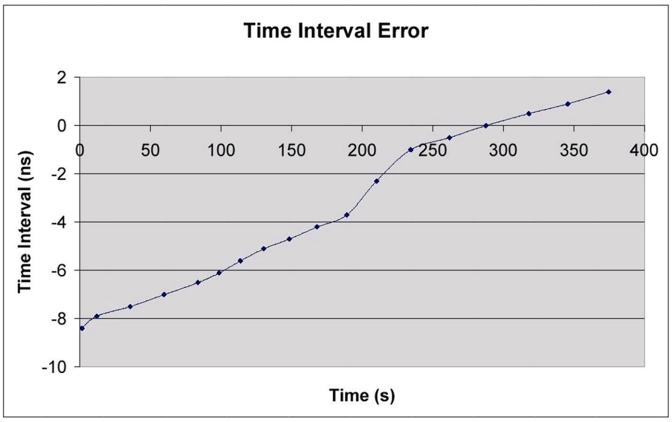

Figure 4: Time Interval Error (TIE) gives the change in phase over time. The slope of the curve equals the frequency difference between the compared signals.

6. The first traceable GPS-frequency standard

Wavetek Precision Measurements introduced in February 2000 a GPSDO, called model 910 or 910R depending on the local oscillator used. The local oscillator can be either an OCXO (model 910) or rubidium (910R). See figure 5. The instruments are developed by the Swedish company Pendulum Instruments AB (former Philips Kistaindustrier AB). These units have a built-in calibration system, which fulfills all possible traceability demands.

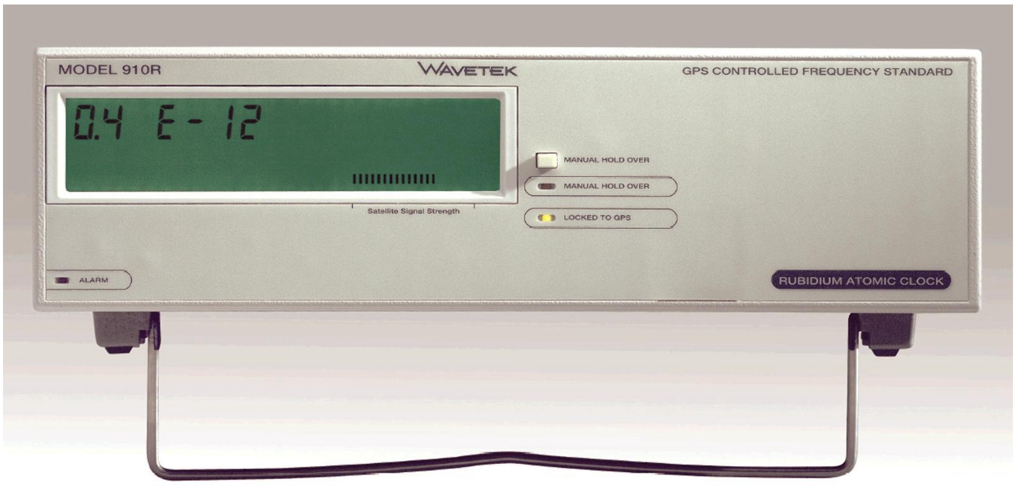

Figure 5: Photo of Wavetek 910R

Since Pendulum Instruments is Europe's leading manufacturer of high precision frequency counters, it is no coincidence that the new products contain a measuring kernel originally developed for the latest frequency counter family from Pendulum Instruments. This measurement kernel performs a continuous TIE-measurement between the signals from the local oscillator and the GPS-engine. See fig. 6.

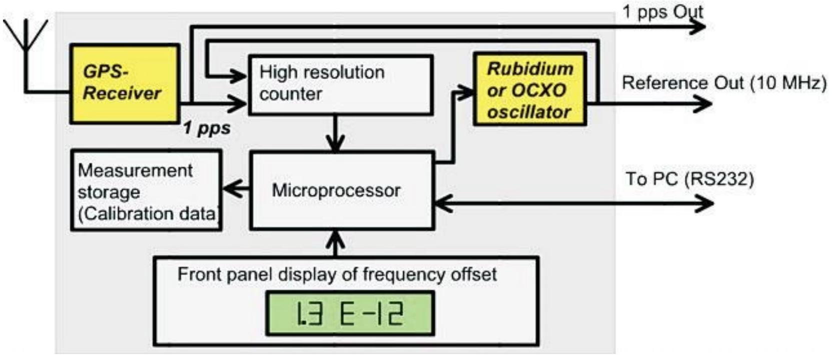

Figure 6: Block diagram of model 910R. Note the built-in measurement system and the non-volatile storage of calibration data.

The result of the TIE-measurement is available on a RS232-port and is updated every 30 seconds, together with the current mean frequency offset over the last 24 h. This value is shown on the numeric display on the front panel. Once a day the 24h frequency offset is internally stored in a non-volatile memory.

By the *continuous* and documented calibration the demands for traceability is fulfilled for the first time ever in a commercially available GPSDO, without the need for external instruments. You can also continuously follow the actual satellites used by the GPS-receiver and their status.

The non-volatile storage contains calibration and adjustment data to cover at least a period of two years. So at any time within a two-year period, the user can connect a PC, run the bundled PC-SW "GPS-View" and print a day-by-day calibration protocol of frequency uncertainty and the adjustment data, covering a period of up to two years. By storing both calibration and adjustment data, the user gets full access to the disciplining process. Not only can he view how accurate his (adjusted) timebase is or was. He can also 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.