Using GPS for establishing frequency traceability in a Time and Frequency Laboratory

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1 Introduction

It is a requirement for laboratories accredited to ISO standard 17025 to have a regular calibration programme whereby their laboratory standards are calibrated, verified or validated. In most cases, this requires that the laboratory standard be removed from the laboratory and transported to a calibration facility.

In the Time and Frequency field, this creates a problem, since switching the laboratory standard off and transporting it can significantly change the value of the oscillator.

This document will describe a method that enables a laboratory to use satellite systems as a common-view timing source, thereby transferring frequency traceability to the laboratory, without the need to take their standard to another location.

2 Time and Frequency Transfer

A Time and/or Frequency Transfer method is a technique to transfer the accuracy of one clock to another clock or oscillator. It can be shown that time error is the accumulation of all the preceding frequency errors. As such, regularly performing a time transfer will yield information about the frequency accuracy and stability of the oscillator as well.

One such transfer method, popular for high accuracy frequency transfers, relies on tracking the phase difference between two clocks. Assume that a measurement is set up to measure the time difference between two clocks (clock 1 and clock 2). If clock 1 is used to start the time difference measurement and clock 2 is used to stop the time interval measurement, the difference between any two such measurements gives an indication of the average period difference and thus the average frequency difference between the two clocks.

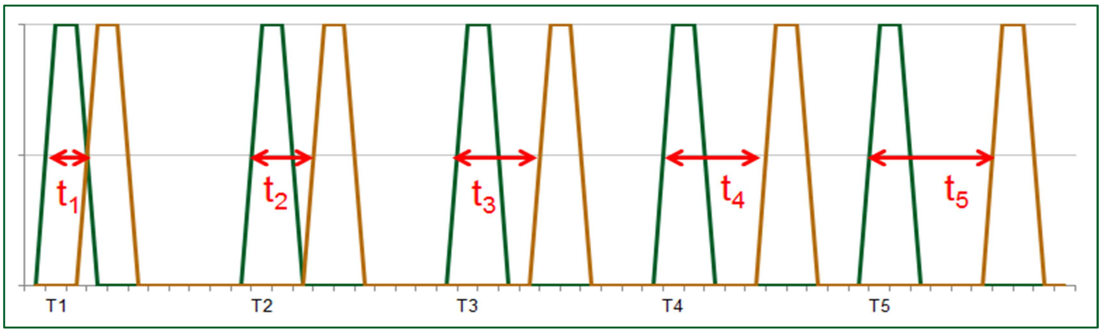

Figure 1 - Illustration of a time difference measurement between two clocks

In Figure 1, time markers from two clocks are plotted on the same scale. It can be seen that the time interval between the two signals are increasing. One can deduce that the period of the second clock is longer than the period of the first clock and that the frequency of the second clock must be lower than the first.

The average relative frequency error is related to the relative time error, as shown by equation (1).

$$\frac{\Delta f}{f} = -\frac{\Delta t}{T} = -\frac{t_{i+1} - t_i}{T_{i+1} - T_i} \tag{1}$$

If time information is important, then all the delays leading up to the measurement system must be known and the time of the reference clock must also be known. If only frequency transfer is required, no knowledge of the delays is required, since they will disappear from the difference calculation, provided that the signal paths stay constant.

3 What is a Global Navigation Satellite System?

A Global Navigation Satellite System (GNSS) is a satellite-based system enabling the users to receive accurate positional information on earth.

GNSS are embedded in our every-day lives. We use GNSS systems to navigate while driving. Our mobile phones have GNSS receivers to provide us with location-aware tools and applications.

There are a number of GNSS systems in the world. Of these systems, the Global Positioning System (GPS), operated by the United States of America, is probably the best known and most used system. The Russian Global Navigation Satellite System (GLONASS) has been operational for a number of years and has recently been restored to a full constellation. The Europeans are currently working on their own system called Galileo, while the Chinese are working on a system called Beidou/Compass.

There is also a number of augmentation systems designed to complement the GNSS systems and provide localised improved accuracy. Some of these are listed below. In South Africa, the South African National Space Agency (SANSA) is currently investigating implementing a system similar to EGNOS in South Africa or Southern Africa.

- Wide Area Augmentation System (WAAS), USA
- European Geostationary Navigation Overlay System (EGNOS), Europe
- Multi Transport Satellite Augmentation System (MSAS), Japan
- GPS and Geo-Augmented Navigation System (GAGAN), India
- System of Differential Corrections and Monitoring (SDCM), Russia
- Nationwide Differential GPS System (NDGPS), USA
- Local Area Augmentation System (LAAS), Some airports
- Global Differential GPS System (GDGPS), USA

This paper will focus on the American Global Navigation System (GPS), since it is the most popular system. Most of the principles described in the document are equally applicable to other GNSS systems.

3.1 The Global Navigation System (GPS) Space Segment

GPS consists of 24 satellites in circular orbits, in six orbital planes, at an altitude of 20 200 km. Each satellite repeats the same ground track every 11h58m. There are currently more than the minimum 24 satellites in orbit.

Two navigational frequencies are available from the GPS system:

- L1: 1 575.42 MHz
- L2: 1 227.60 MHz

There are multiple codes transmitted by the satellites. The C/A (course acquisition) code is a civilian code and is only available on L1. It has a pattern that repeats every millisecond. The Y code is a military code available on both L1 and L2 to authorised users only. The Y code consist of a much longer P code (the code could be 266 days long, but only 7 days are used), which is then encrypted with the W code.

Additional civilian codes will be available in the near future. L2C will allow for better ionospheric delay corrections. The implementation of L2C started in 2005 and is expected to be finished in 2016. Implementation of a further code (L1C) to allow more robust applications, and to help with reception under trees and in urban canyons, will start in 2021.

A new frequency, L5, at 1 176.45 MHz, was designed to meet the demanding requirements for transport safety. The implementation of L5 started in 2010 and is expected to be finished by 2018.

3.2 Basic operation of satellite-based navigation systems

Satellite-based navigation systems depend on three principles:

- The transmitter (in this case the satellite) position is known,
- The receiver position is unknown, and
- The transmitter-to-receiver distance can be determined.

The implementation of trilateration relies on the assumption that a time delay measurement (the time delay from time of broadcast of the signal from the satellite to reception at the receiver) can be converted to a distance. This can only be valid when assuming that the signal travels at a known velocity and by modelling the delays caused by atmospheric conditions.

One can see that accurate time keeping becomes fundamental to realising the performance of the system.

If the goal of the navigation system is to achieve one meter positional accuracy, the system must achieve a time accuracy of approximately 3.3 ns. This is the maximum allowable error over the update period. Since one must assume only one update in a 12 hour period, the clock on board each satellite must maintain a relative time accuracy better than $1 \cdot 10^{-13}$.

$$\left|\frac{\Delta f}{f}\right| = \left|\frac{\Delta t}{T}\right| = \frac{3.3ns}{12 \times 60 \times 60} = 7.7 \cdot 10^{-14}$$

The only clocks capable of achieving this accuracy in space conditions are atomic clocks. The satellite clocks are monitored and corrected from ground-based observation and control centres. The GPS system is controlled by the United States Naval Observatory (USNO).

GPS time is steered towards the prediction of Coordinated Universal Time (UTC), as realised by USNO. This time scale is designated UTC(USNO). GPS time is a continuous time scale not corrected for leap seconds. Any time user extracting time information from a GPS receiver must know whether the receiver time output is GPS time or UTC. Most receivers have user selectable options to switch between the two, or can give the difference between the two. Since 1 July 2012, the difference between UTC and GPS is 16 seconds. (The last leap second prior to this publication was on 30 June 2012.)

Since GPS receivers require accurate time information to get an accurate positional fix, a complete solution will also adjust the time of the local oscillator of the receiver. This enables the Time and Frequency community to use GPS as a transfer standard to get precise time and/or frequency standards in their laboratories.

Figure 2 shows the difference between UTC and GPS for a typical month early in 2013, after removing the 16 second offset.

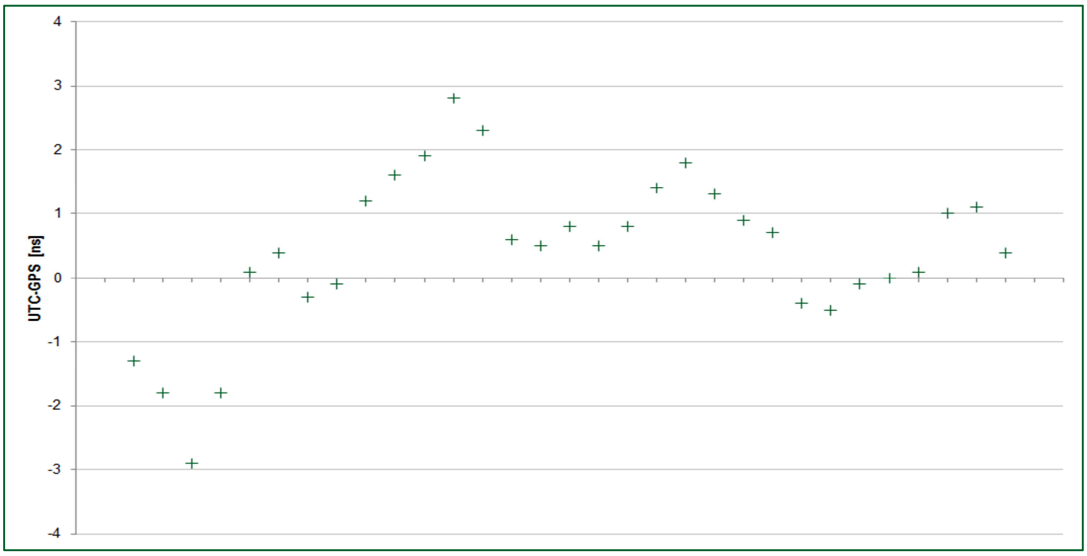

Figure 2 - Difference between UTC and GPS for May 2013

3.3 The fundamentals of GPS

Since it cannot be guaranteed, nor is it expected, that the receiver clock is accurate, GPS relies on four time interval measurements. The four measurements are converted to range measurements (distance measurements).

GPS uses spread spectrum communication technology. All the satellites transmit on the same frequency using code division multiple access (CDMA). Each satellite is assigned its own unique pseudo-random noise (PRN) code. Each transmission contains the satellite code, as well as a data message with information regarding the system. The data message contains, amongst others, the position of each satellite, the accuracy of the clock on each satellite and information regarding the ionospheric model to use. It requires 12.5 minutes to download the entire data message from a single satellite.

The received power is so low that it is below ambient noise levels. The GPS receiver must produce a replica of the transmitted code, correct it for the Doppler Effect and expected time delay, and then use a correlation algorithm to detect the presence of the signal.

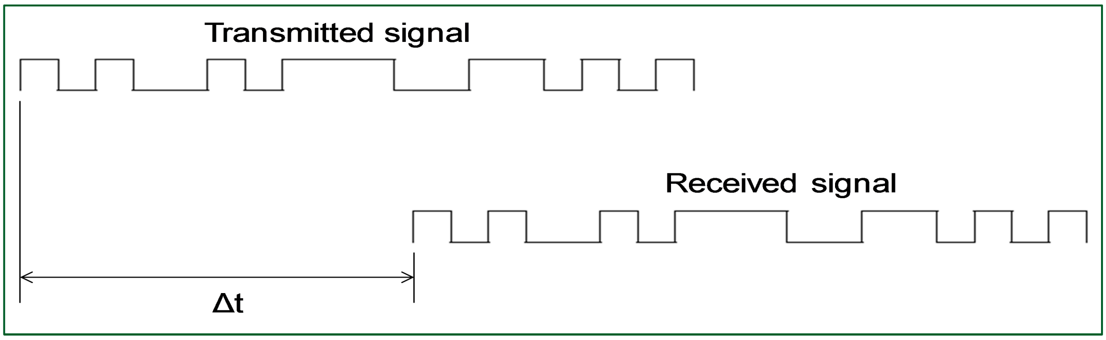

Figure 3 - Graphical representation of a pseudo-range measurement

The delay of the signal is proportional to the transmitter-to-receiver distance and is converted to a range measurement by the receiver. Four simultaneous measurements are performed to solve the four unknowns (three positional variables and the time error of the receiver).

3.4 Solution accuracy

The position and time accuracy are affected by a number of factors, some described below.

3.4.1 Range error

The range error is a function of the quality of the broadcast signal and the data in the broadcast message. The data message contains the satellite orbit and the clock accuracies. The stability of the clocks and predictability of the orbit will influence how accurate the data in the message is. This error is usually referred to as the user range error (URE) and is defined as the difference between the navigational data received from the satellites and the true line-of-sight distance to the receiver. The size of this error is outside the control of the user.

Both GPS orbital accuracy and clock accuracy are typically within 7 ns (rms value) each.

3.4.2 Geometry

The geometry error is a function of the distribution of satellites in the sky. The geometric dilution of precision (GDOP) is a measure of the quality of the visible satellite geometry. It can be further calculated for position, horizontal, vertical and time DOP. The DOP values can be used as a figure-of-merit for the fix.

3.4.3 Receiver errors

The design of the receiver, the antenna position and quality, the models and algorithms used in the receiver and the internal delays all form part of the receiver errors.

High quality receivers will typically use better RF components, algorithms and models to reduce these errors. Calibration can be used to determine (or estimate) the errors of the receiver. If time transfer is required, it will be essential for the delays caused by the receiver, the antenna, the measurement instrumentation and all cables to be calibrated. The internal delay of the receiver can be hundreds of nanoseconds.

The receiver noise will vary from approximately 100 ns for cheap timing receivers down to less than 1 ns for more expensive geodetic receivers.

3.4.4 Environmental effects

The signal must pass through the ionosphere and the troposphere before reaching the user. Delays through the ionosphere and the troposphere must be correctly modelled or the range measurements will be incorrect. The accuracy of these models depends on the type of receiver. A single frequency receiver has the most inaccurate model, while multiple frequency receivers can better estimate the delay.

The ionospheric model is typically accurate to between 3 and 17 ns while the tropospheric delay causes uncertainties between 0.3 and 3 ns.

Field of view obstructions, multipath reflections and signal jamming or interference degrade the quality of the signal and may result in incorrect range measurements from the correlation algorithm. Multipath reflection errors are typically in the 2 to 3 ns range.

4 Time and Frequency Transfer using GPS in the South African context

4.1 GPS timing receivers

A GPS timing receiver differs from a navigational receiver in that the timing receiver will have an output for a time marker and/or frequency. The time marker will typically be a 1 Hz pulse indicating the exact time. Many of these receivers will allow the user to extract more detailed information.

A typical timing receiver will stay in a fixed location. In such a "position hold" mode, the receiver does not have to solve the same navigational algorithm. If the user supplied the position of the antenna, the receiver will be able to provide information about individual satellites. The user can then use an external time interval counter together with data extracted from the receiver to determine the difference between the laboratory reference oscillator and each satellite at all times of the day.

There are a number of ways that a GPS timing receiver can be used to establish an accurate time and/or frequency source for a laboratory. This document will explain three methods. Each of these methods has its own advantages and disadvantages. The effort required to prove traceability, in a way that complies with the ISO 17025, also varies from one method to the next.

4.1.1 GPS one-way

In the GPS one-way method, the receiver is set to track all satellites in view and to output GPS time or UTC from the timing output. The laboratory can then use a time transfer technique to compare a laboratory standard to the GPS system. Some timing receivers will also make a frequency output available, based on the internal oscillator of the receiver. If the frequency is of a suitable value, it can be used as the laboratory reference, or the laboratory reference can be derived from this output using phase-lock-loop or heterodyning techniques.

The main errors of this method will be errors in the satellite clocks, ephemeris (orbit) errors, antenna coordinate errors, multi-path reflections, ionospheric model inaccuracies and the quality of the user equipment.

With this method, traceability is achieved directly to GPS time, as derived from UTC(USNO). As an institute, USNO is competent and their results are credible. The USNO clock ensemble also contributes a significant amount to UTC. However, USNO is neither a national metrology institute (NMI), nor a designated institute (DI), and thus they do not have calibration and measurement capabilities (CMCs) in the BIPM's key comparison database (KCDB). In the United States of America, the National Institute of Standards and Technology (NIST) performs the task of that country's NMI.

The quality of the user equipment will be very important when using this method – especially if the frequency output is used directly as the laboratory standard.

This method is a viable option for a user who needs a medium to high accuracy time and/or frequency standard without the requirement of "legal traceability."

Below, Figure 4 and Figure 5 show the differences between GPS and two different atomic clocks using two different types of GPS receivers. The data has been plotted for the same day. In both cases, the grid lines on the vertical axes are spaced 10 ns apart. In Figure 4, the drift rate of the clock appears to be better than the clock in Figure 5, but the peak-to-peak noise is approximately four times worse.

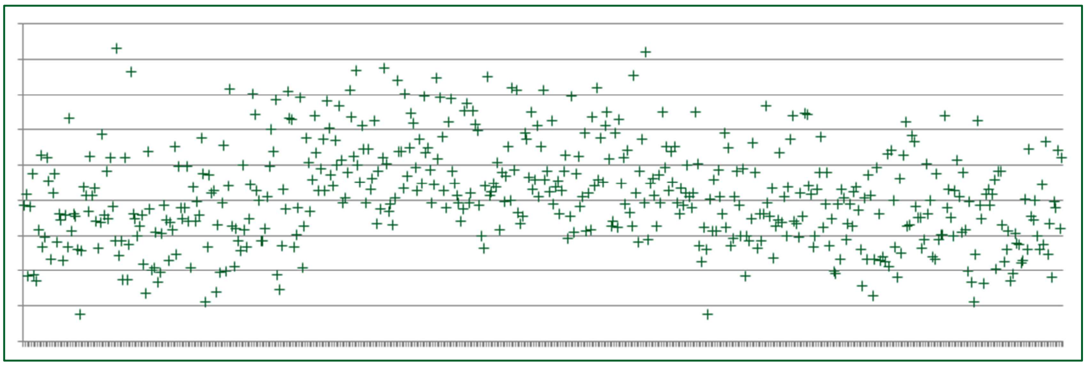

Figure 4 - The difference between GPS and a local clock for a 24 hour period
(Each grid line is 10 ns apart)

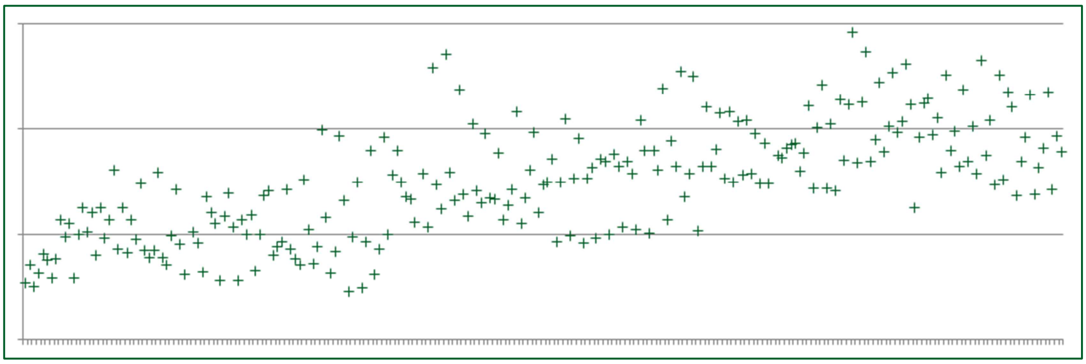

Figure 5 - The difference between GPS and a local clock for a 24 hour period
(Each grid line is 10 ns apart)

4.1.2 GPS disciplined oscillator

By using an oscillator with good short term stability and steering that oscillator according to the input from the GPS system, a user ends up with a system that has good short term stability as well as good long term accuracy. In such a system, the instrument will internally measure the difference between GPS and the additional oscillator, and adjust the oscillator to follow GPS. If the additional oscillator is a rubidium atomic clock, the user gets a clock with very good stability and long term accuracy at an affordable price.

Traceability is still to USNO. The main errors of this method are the same as for GPS one-way, but the additional oscillator filters the influence of the random components to improve the stability of the output frequency.

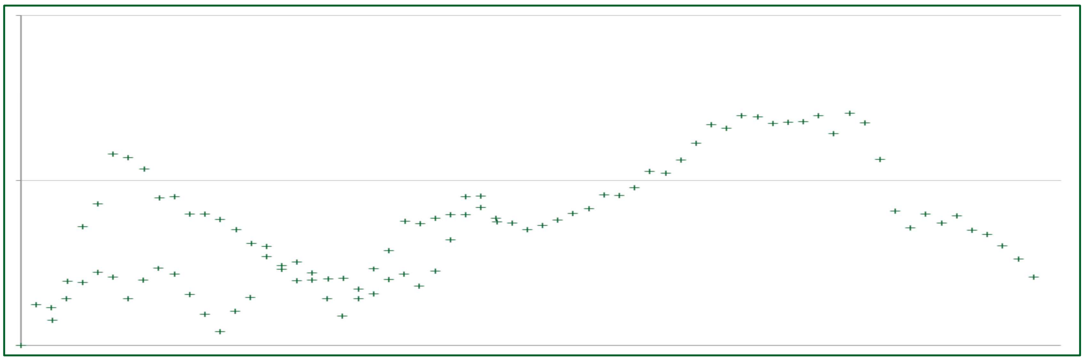

Figure 6 - The time error of a GPS disciplined Rubidium oscillator
(The grid lines are 10 ns apart)

Figure 6 shows how much the output from the same receiver used in Figure 4 can be reduced when filtering the output through a rubidium atomic oscillator. The data is for a 24 hour period and the vertical grid lines are 10 ns apart. (Please note that this is not the same data as in Figure 4, but data obtained from the same type of receiver, operating under similar conditions.)

4.1.3 GPS common-view

The GPS common-view method, as for any common-view method, relies on two laboratories viewing the same event at the same time and exchanging information.

When GPS is used as the common-view source, both laboratories must measure the difference between their laboratory oscillator and any GPS satellite that both can see, at the same time, for the same length of time, using the same protocol and similar data reduction techniques.

When the two laboratories exchange information, data pairs can be identified that will allow the laboratories to calculate the time difference between the two laboratories.

$$(LAB_1 - GPS_k) - (LAB_2 - GPS_k) = (LAB_1 - LAB_2) \qquad (2)$$

Using equation (1), the frequency difference can be calculated by tracking the time difference between the two laboratories, $(LAB_1 - LAB_2)$, as obtained from equation (2), over a period of time. If the absolute frequency of one of the laboratory oscillators is known, the absolute frequency of the second can be calculated. GPS becomes a transfer standard and traceability is to the other laboratory.

With common view, many of the errors disappear, provided that conditions remain similar between measurements. The degree to which ionospheric delays cancel out will depend on the distance between the laboratories. When the laboratories are relatively close together, they will observe the satellites under similar conditions. As the laboratories are located further apart, the angle of the satellites will become lower, localised weather will be different and the ionospheric conditions will differ.

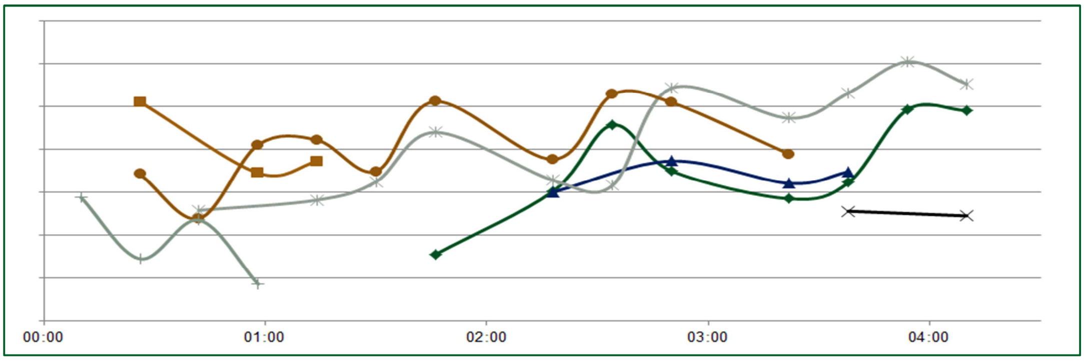

Figure 7 - GPS common-view data for two clocks (Each grid line is 10 ns)

In Figure 7, the data from Figure 4 and Figure 5 were used to calculate the difference between the two clocks. (Only the first four hours of the 24 hour period is shown.) The vertical grid is still 10 ns. This data show that differences from individual satellites can be calculated and that the stability is better than the combined stability of the two systems.

4.2 Requirements from ISO 17025

There are a number of clauses in ISO 17025 dealing with equipment and traceability. If accreditation to ISO 17025 is needed, the laboratory will have to comply with these requirements.

Clause 5.5.2 states that "*before being placed into service, equipment shall be calibrated or checked to establish that it meets the laboratory's specification requirements*".

Clause 5.6.1 states that "*all equipment used for test and/or calibration having a significant effect on the accuracy or validity of the result shall be calibrated before being put into service*".

Clause 5.6.2 of ISO 17025 states that calibration laboratories must "*ensure that calibrations and measurements made by the laboratory are traceable to the International Systems of Units (SI) by means of an unbroken chain of calibrations or comparisons linking them to relevant primary standards of the SI units of measurement*".

To comply with these clauses while using GPS as a transfer standard, the laboratory should ensure that a number of tasks have been performed.

All GPS receivers must be checked before being placed into operation, to see if each operates within the requirements of the laboratory, and that the intended capability of the laboratory can be achieved.

Since the GPS receiver is used either as the laboratory reference, or to calibrate the laboratory reference, it has a significant effect on the accuracy or validity of the result. It is not really practical to calibrate a GPS receiver. Another method must be used to comply with this clause. One method would be a verification program before the receiver is put in service and regular verification through inter-laboratory comparisons, or using a common-view method.

USNO derives UTC(USNO) from an ensemble of about 80 caesium atomic clocks and 25 hydrogen masers, all of them contributing to the international project to derive UTC. As stated previously, USNO is not a NMI or designated institute. Therefore, traceability cannot be made directly to USNO. Additional checks must be put in place to prove traceability: for example, a common-view method using a NMI as one of the participants.

4.3 Suggested procedure

There are a number of ways to prove traceability for a laboratory clock or oscillator. The normal methods of sending the standard away for calibration, or comparison with a transfer/travelling standard, are also applicable.

The method described below allows the laboratory to calibrate their own standard, in their own laboratory, without interrupting the standard or the normal operation of the laboratory. In addition, the laboratory can perform this task as often as is prescribed by their own risk analysis (based on the required capability and the drift and stability of their standard). This method is slightly easier than the programme followed by NMI's to compare their clocks to one another, since it relies on a GPS daily average and does not use individual satellites at multiple times per day.

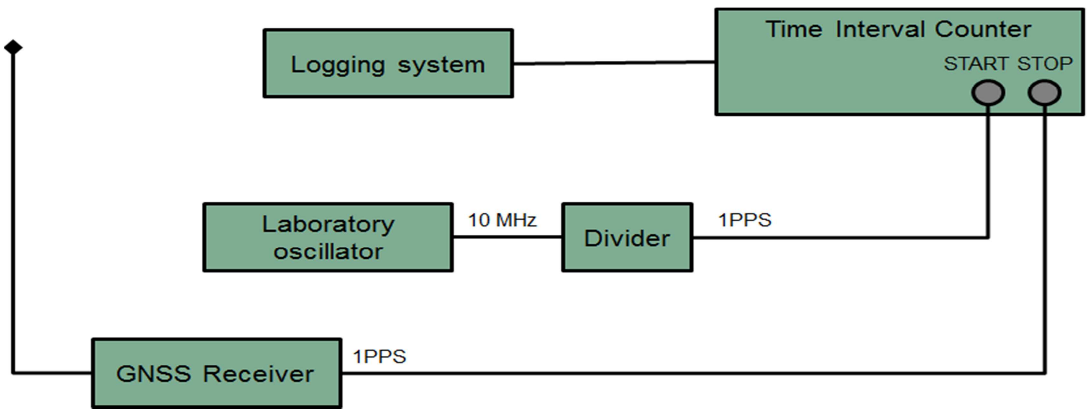

Figure 8 - Block diagram of the proposed measurement setup

4.3.1 Measurement setup

The method proposed in this document requires an external time interval counter to measure the difference between the GPS receiver and the laboratory oscillator. The block diagram of the setup is shown in Figure 8.

The period of a 10 MHz signal is 100 ns. Some of the cheaper GPS receivers will have peak-to-peak noise of 100 ns. It is advisable that the receiver's 10 MHz output not be directly connected to the time interval counter, as this may lead to ambiguities in the data. One can construct a simple divider circuit to divide the 10 MHz down to a lower frequency, or all the way down to a 1 Hz pulse.

Set up the time interval counter as shown in Figure 8. When the laboratory oscillator is connected to the start input, the measurement will be classified as *(LAB - GPS)*. The procedure must be updated for *(GPS - LAB)* if the connection is the other way.

Although the procedure only requires one measurement per day, it is advisable to log at least one measurement per hour. This provides confidence measurements, allows troubleshooting, as well as filtering to remove some of the noise from the GPS.

Disciplined oscillators already have a time interval counter and an additional oscillator included in the instrument. If the software allows the user to extract the time difference information from the instrument, this can be utilised in the procedure described below. If, however, the unit hides this data from the user, additional processes will be required to prove traceability.

4.3.2 Data reduction

Reduce the measurements to a single point per day for 00:00 UTC.

If the actual measurement at 00:00 UTC is used, it will suffer from the large variability of the GPS. Good results are obtained from a fit when the data is arranged in such a manner that midnight of the day in question is in the middle of the data set. This can easily be achieved by using the previous day's data together with the current day's data. If a longer data set it required, one can use data from the previous two days together with the current day and the following day's data.

Atomic clocks and disciplined clocks will typically display a linear phase drift since the frequency is fairly constant over the period of a day. For such clocks, a linear fit to the time difference data is appropriate.

Crystal oscillators will exhibit frequency drift after a much shorter time interval. For crystal oscillators, it may be more appropriate to use a quadratic (or even higher order) fit to the time difference data.

Irrespective of the method used, the uncertainty must be determined. If the fit is set up with the time of interest in the middle of the data set, then the error of the fit should be a good statistic to use.

4.3.3 Compare to NMI

Once a month, collate all the reduced data and obtain the corresponding data from the NMI. Extract *(NMI - GPS)* from the data for all the days of the month. Record the frequency of the NMI clock, the uncertainty of the NMI clock frequency and the uncertainty of the GPS data provided by the NMI.

NMISA publishes a monthly bulletin containing their data. The bulletin only contains *(NMISA - GPS)*, but *(NMISA - GLONASS)* can be made available if required. The bulletin can be downloaded from *http://time.nmisa.org*.

The data in the bulletin cannot be used for time transfer, only for frequency transfer, since not all the delays are known. As such, NMISA only provides the statistical uncertainty of the data and not the systematic uncertainty components.

4.3.4 Analyse the data

Use the *(LAB - GPS)* data and the *(NMI - GPS)* data to calculate *(NMI - LAB)*.

$$\begin{aligned}(NMI - LAB) &= (NMI - GPS) - (LAB - GPS) \\ &= (NMI - GPS) + (GPS - LAB)\end{aligned} \tag{3}$$

From the data, the average frequency of the laboratory oscillator can be calculated. The laboratory can also use the data to predict the performance of their oscillator for the next month. The prediction will require that a suitable prediction model be found. Similar to the discussion above, for atomic oscillators, a linear model is good enough for predicting one month into the future. A quadratic model (or one of a higher order) may be required for crystal oscillators. Each laboratory must analyse their data to determine the best model to use.

The stability of the oscillator for a one day observation time can be calculated from the data using statistical analysis. Oscillators are typically not dominated by stationary noise, but exhibit flicker noise as well as random-walk noise. The data is also time correlated. These factors mean that the standard deviation is not the ideal statistic to use and can lead to errors in the estimation of the variability of the laboratory oscillator. If the dominant noise factor is stationary white noise, standard deviation will give the correct answer, but if the dominating noise is different, standard deviation will give a different answer. A better statistic to use is Allan Deviation.

4.3.5 Uncertainty calculations

This part will only look at the frequency uncertainty. Time transfer uncertainty is not yet a requirement in South Africa.

For frequency uncertainty, it is not required to know all the time delays in the system, as these will cancel out when the difference is calculated.

The following uncertainty components should be considered.

<u>Accuracy and uncertainty of the NMI clock:</u>

This data will typically be provided by the NMI. The uncertainty of the drift rate should be treated as described by the uncertainty procedure of the laboratory.

Strictly speaking, the laboratory should correct for the drift rate. It is however acceptable to convert the drift rate of the NMI clock to an uncertainty, provided that the laboratory keeps in mind that they are deviating from the mathematically correct procedure.

For example, in the first half of 2013, the typical frequency drift of the NMISA master clock was between $0.7 \cdot 10^{-13}$ and $1.0 \cdot 10^{-13}$, with a reported uncertainty of $0.5 \cdot 10^{-13}$ on this value. A laboratory may decide that they are not going to correct for the NMISA drift rate, but will be satisfied with a rectangular uncertainty contribution of $\pm 1.5 \cdot 10^{-13}$.

<u>Statistical uncertainty of GPS data:</u>

Both the statistical uncertainty reported by the NMI and the statistical uncertainty in determining *(LAB - GPS)* should be taken into account. The mathematic model of the measurement method has been described in equations (1), (2) and (3). From this, one can deduce that the standard uncertainty for the statistical error is:

$$u(x_i) = \frac{\sqrt{2} \cdot (value)}{86400} \tag{4}$$

(assuming that the difference between two data points is one day, as described above).

The NMISA statistical uncertainty is typically 2 ns, resulting in a relative frequency standard uncertainty of $3.3{\cdot}10^{-14}$. The statistical uncertainty of the laboratory should be treated in the same way.

Variability of the measurement:

It is better to use Allan Deviation for data containing time correlation. The equation for Allan Deviation is given below:

$$\sigma(\tau)^2 = \frac{1}{2(M-1)}\sum_{n=1}^{M-1}(y_{n+1} - y_n)^2 = \frac{1}{2(N-2)\tau^2}\sum_{n=1}^{N-2}(x_{n+2} - 2x_{n+1} + x_n)^2 \quad (5)$$

where:

τ is the observation period,

y_n is the average fractional frequency error over the observation period (τ), and

x_n is the phase difference.

It is easy to calculate Allan Deviation in a spread sheet, but it becomes a lot of work for anything more than the shortest interval. Alternatively, dedicated software can be used to calculate the Allan Deviation. The advantage of dedicated software is that it opens up some of the other algorithms derived from Allan Deviation. The Overlapping Allan Deviation algorithm is useful for supplying more data points and for raising the degrees of freedom of the statistic.

Other factors:

The majority of other factors mentioned earlier in this document will cancel out when the difference calculation is performed, or appear as measurement noise.

For example, changes in the differences in the ionospheric delay for the two laboratories will appear as measurement noise.

There may be a slow variability due to the 4 minute daily difference between mean solar time and the sidereal timescale of the satellites. This effect should be small enough not to be noticeable in a typical laboratory standard.

If multipath reflection is a concern, it should be added to the uncertainty calculations.

4.3.6 Example result sheet and uncertainty budget

Table 1 – Extract from monthly clock calculations

MJD	NMI-GPS [ns]	LAB-GPS [ns]	NMI-LAB [ns]	$\Delta f/f$ ($x10^{-12}$)	y_{n+1}-y_n ($x10^{-13}$)
54420	1133	47978	-46845	-----	-----
54421	1139	47189	-46050	-9.20	-11.23
54422	1148	46306	-45158	-10.3	-3.356
54423	1159	45396	-44237	-10.7	9.954
54424	1169	44571	-43402	-9.66	-6.366
54425	1178	43690	-42512	-10.3	-1.852
54426	1187	42793	-41606	-10.5	8.333
54427	1199	41971	-40772	-9.65	-2.199
54428	1205	41124	-39919	-9.87	-1.042
54429	1211	40268	-39057	-9.98	-----
Average fractional frequency & Allan Deviation (calculated for a one-day observation time)				-10.0154	4.715

Table 1 shows an example of how such a spread sheet could look. Table 2 shows an example uncertainty budget.

Table 2 – Example uncertainty budget

Description	Value	$u(x_i)$ $(x10^{-13})$	v_i
NMISA – GPS	2 ns	0.327	500
LAB – GPS (worst case peak-to-peak)	100 ns	4.725	40
NMISA clock frequency	$1.5 \cdot 10^{-13}$	0.866	∞
Measurement variability		4.715	8
Combined standard uncertainty		6.739	≈27

4.4 Extending the result to other measurement intervals

In the examples shown above, the average frequency of the laboratory oscillator was $(1 - 100.2 \cdot 10^{-13} \pm 6.8 \cdot 10^{-13}) \cdot f$ at a level of confidence of 68.27%.

This result is correct for measurements for which the observation period (or averaging period) was one day. Since most measurements are performed with observations times much shorter (from 1 second to about 1 000 seconds), the question must be asked whether this results is valid for shorter time intervals as well.

The correct method to determine frequency stability for shorter intervals, and thus the frequency uncertainty, is to have a second oscillator and to track the relative stability between the two laboratory oscillators at that shorter observation time. Since the calculated stability is the combination of the stability values of the two oscillators, each oscillator's stability will be equal to or better than the calculated value.

The Consultative Committee for Time and Frequency (CCTF) of the International Bureau of Weights and Measures (BIPM) has accepted a method where one may use the information from the manufacturer to identify the dominant noise and then to extrapolate from there.

For example, a caesium atomic clock is dominated by white frequency noise for observation times up to 90 days. As such, one can use the $1/\sqrt{\tau}$ relationship to calculate what the variability would be at a shorter time period, or use the specification of the clock.

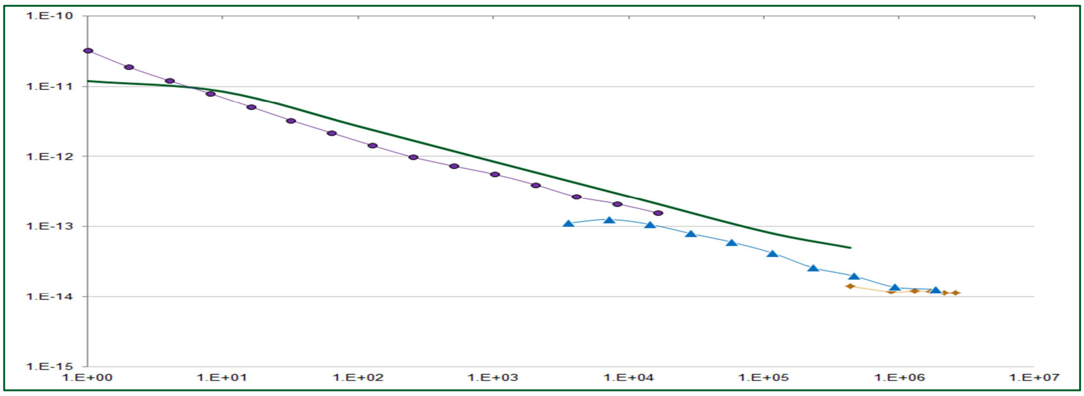

Figure 9 - Stability of a caesium atomic clock

In Figure 9, the line without markers is the specification of a caesium atomic clock and the shortest line on the bottom right is from data obtained using the GPS common-view method described above. The other lines are from different monitoring systems running at different observation times. From this one can see that, even if the additional monitoring systems were not available, it would still be safe to assume that the clock was operating within specification based solely on the GPS common-view measurements and historic data. (The data for observation periods less than 10 seconds appear to be out of specification due to the limitations of the monitoring system, and not the actual clock performance.)

5 Conclusion

It is a requirement from the ISO 17025 standard that laboratories verify all their instruments which can have a significant effect on the accuracy or validity of a result, before the instrument is placed into service, and at regular intervals after that. It is problematic for a Time and Frequency laboratory to power down their oscillator for transportation to a calibration service provider.

A GNSS common-view methodology allows a Time and Frequency laboratory to prove traceability at their own site, without the need to transport their standards for calibration. It also allows the laboratory to run frequency verification checks on their standard, to improve confidence that their laboratory standard is performing within the required limits. This "self-calibration" can be performed to a degree that will satisfy the requirements of ISO 17025 for legal traceability.

6 References

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