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National Metrology Institute of South Africa

Using GPS for establishing frequency traceability

in a Time & Frequency accredited facility

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Your measure of excellence

Outline

- Global Navigation Satellite Systems (GNSS)
- Time and Frequency Transfer
- Time and Frequency Transfer from GPS to establish traceability in the South African environment
- Conclusion and Discussion

GLOBAL NAVIGATION SATELLITE SYSTEMS (GNSS)

- GNSS introduction
- Satellite Navigation System Fundamentals
- Accuracy

Global Satellite Navigation Systems

- Global Satellite Navigation Systems (GNSS) are embedded in our every-day lives
- There are a number of systems available in the world:
  - GPS (Global Positioning System), USA
  - Galileo, EU
  - GLONASS (Global Navigation Satellite System), Russia
  - Beidou/Compass, China
- Of these, the American GPS system is one most commonly used in SANAS-accredited facilities
  - Most of this talk will be about the GPS system, but the concepts are equally applicable to the other systems

Global Satellite Navigation Systems

- These GNSS systems are also supplemented by Satellite-Based Augmentations Systems (SBAS)
  - WAAS (Wide Area Augmentation System), USA
  - EGNOS (European Geostationary Navigation Overlay System)
  - MSAS (Multi-Transport-Satellite Augmentation System), Japan
  - GAGAN (GPS and Geo-Augmented Navigation System), India
  - SDCM (System of Differential Corrections and Monitoring), Russia
  - NDGPS (Nationwide Differential GPS System), USA
  - LAAS (Local Area Augmentation System), Some Airports
  - GDGPS (Global Differential GPS System), USA
- Although useful information can be obtained from these systems, these systems are typically not available in South Africa

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The GPS space segment

- GPS consists of a 24 satellite constellation
  - Circular orbits at an altitude of 20 200 km
  - Repeating ground tracks every 11h 58m
  - Six orbital planes at 55 degrees – four vehicles per orbit
- A number of frequencies
  - L1: 1575,42 MHz
  - L2: 1227,60 MHz
- Two codes per satellite
  - C/A (Course acquisition) is the civilian code and is only available on the L1 carrier at a one millisecond repeat interval
  - P(Y) code is the military code available on L1 and L2 with a 267 day repeat interval and is only available to authorized users

GPS improvements

- Additional civilian frequencies
  - L2C (implementation started 2005 and is expected to be completed in 2016) will allow for higher accuracy ionospheric delay corrections
  - L5 (implementation started 2010 and is expected to be completed in 2018) was designed to meet demanding requirements for transport safety
  - L1C (implementation scheduled to start in 2021) will allow more robust applications and help with reception under trees and in urban canyons

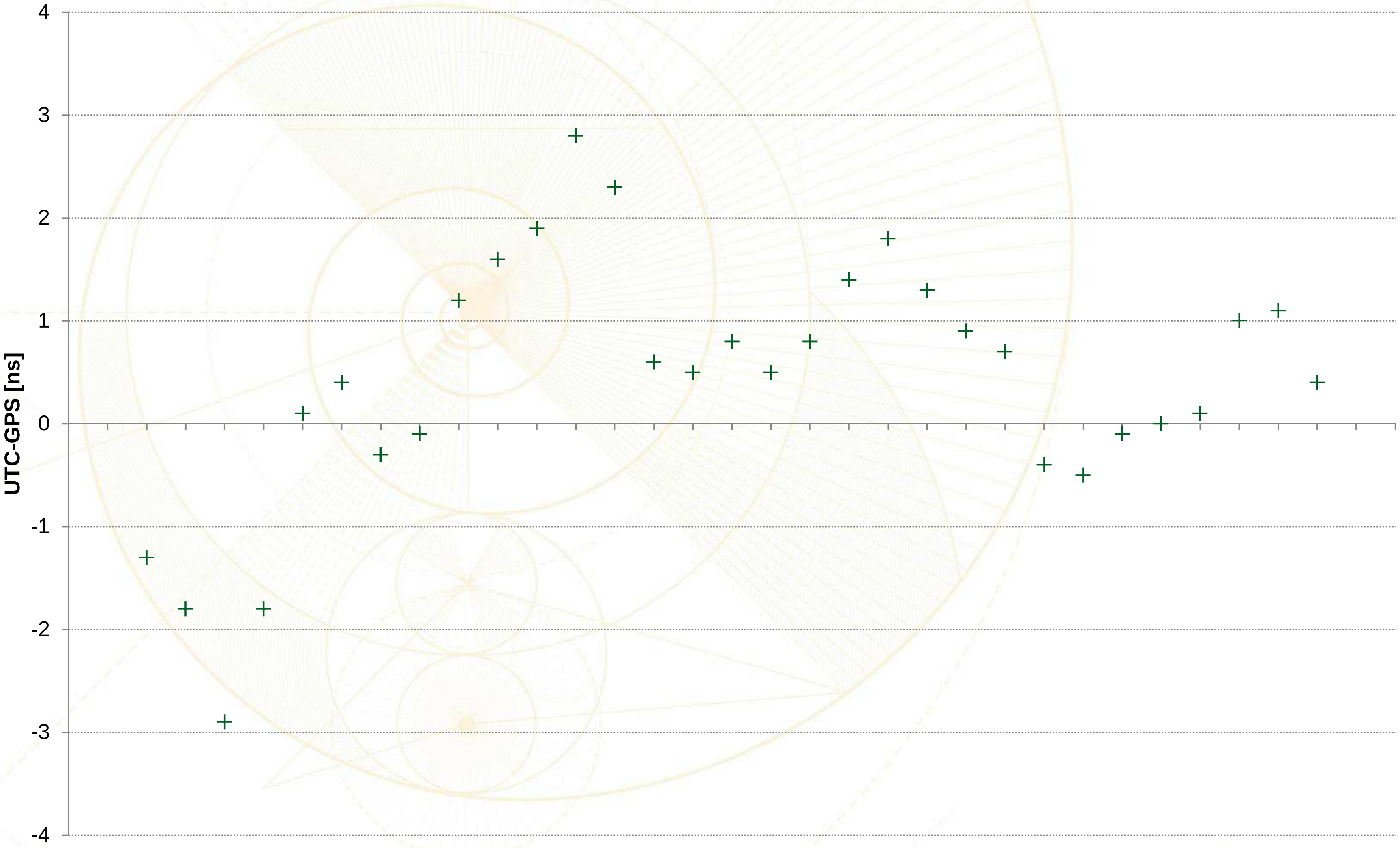
Why use GPS in a TF laboratory?

- Satellite navigation is based on:
  - The transmitter (satellite) position is known
  - The receiver position is unknown
  - The satellite-to-receiver position can be determined using trilateration from time delay measurements and some assumptions for the velocity of the signal
- Precise timing is fundamental to realizing performance from satellite navigation systems
  - An one-meter ranging error is equivalent to approximately 3,3 ns
  - The satellite clock error must be maintained below this level over a 12 hour period (time between updates)
  - This requires a clock accuracy of approximately one part in 10^{13} $(3{,}3\cdot10^{-9}\ \mathrm{s}/43200\ \mathrm{s} = 7{,}7\cdot10^{-14})$

Atomic clocks in space

- To achieve this required clock accuracy, the satellites carry atomic clocks
    - GPS carries redundant rubidium and caesium oscillators
- The clocks on the satellites are steered by ground controllers to be close to UTC
    - GPS are steered by the US Naval Observatory (USNO)
    - GPS time is a continuous time scale, not corrected for leap seconds
    - The difference between GPS time and UTC(USNO) is known and part of the satellite data message
- This enables precise time and frequency transfer on a global scale

Typical accuracy of GPS



UTC and GPS currently differ by 16 seconds

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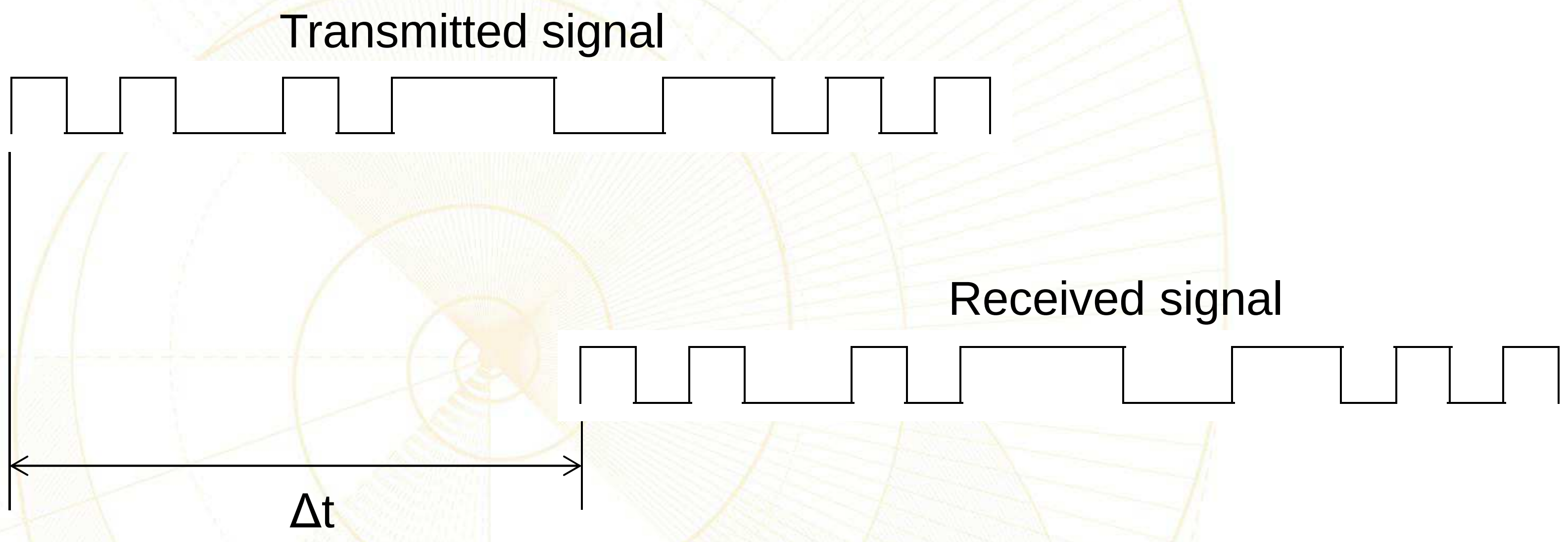
Fundamentals

- GPS relies on trilateration
- To determine the position of the receiver, three range measurements must be made
- Measurement of ranges requires precise knowledge of the time the message was transmitted and received
  - The transmitted time is known, the receiver time is not necessary known accurately
  - To correct the local clock of the receiver, a fourth measurement must be performed, meaning a positional fix requires four satellites to be visible during the track time
- The information available from the satellites contains the precise location of the satellite and the clock corrections

GPS fundamentals

- GPS use spread spectrum communication technology
- All satellites transmit on the same frequency using Code Division Multiple Access (CDMA)
  - Each satellite is assigned a Pseudo-Random Noise (PRN) code
- The received power is below ambient noise levels
- The transmitted signal contains the satellite code and a data message
- To detect the GPS signal and recover the data, the receiver produces a replica of the GPS signal, corrected for time delay and Doppler effects
- The time measurement is performed through a correlation algorithm

GPS pseudo-range fundamentals



- Using “code correlation”, the receiver finds the delay for each satellite and converts this to a range (distance)
- Δt is proportional to the transmitter-to-receiver range
- Four simultaneous measurements allow to solve for the receiver position and to set the receiver clock

Solution accuracy

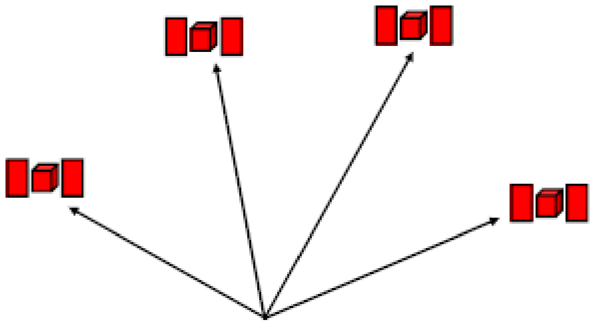
- The position and time accuracy are affected by a number of factors:
  - Ranging error – a function of the quality of the broadcast signal and data
  - Geometry – the distribution of satellites in the sky
  - Receiver errors – design of the receiver, antenna noise levels, modelling errors, algorithm errors, internal time delays, etc.
  - Environmental effects – ionospheric signal delays, tropospheric signal delays, field of view obstructions, multipath reflections, jamming/interference, etc.

Solution accuracy – Range error

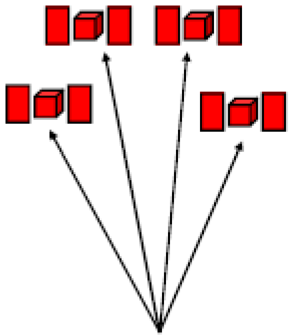
- The User Range Error is the difference between the navigational data received from the satellite and the true line-of-sight distance to the receiver
- This error is composed of several factors outside the control of the user.
  - Stability of the satellite clock
  - Predictability of the satellite orbit

Solution accuracy - Geometry

- Geometric Dilution of Precision (GDOP) is a measure of the quality of the visible satellite geometry
  - Can be calculated for position, horizontal, vertical and time dilution of precision



Good geometry

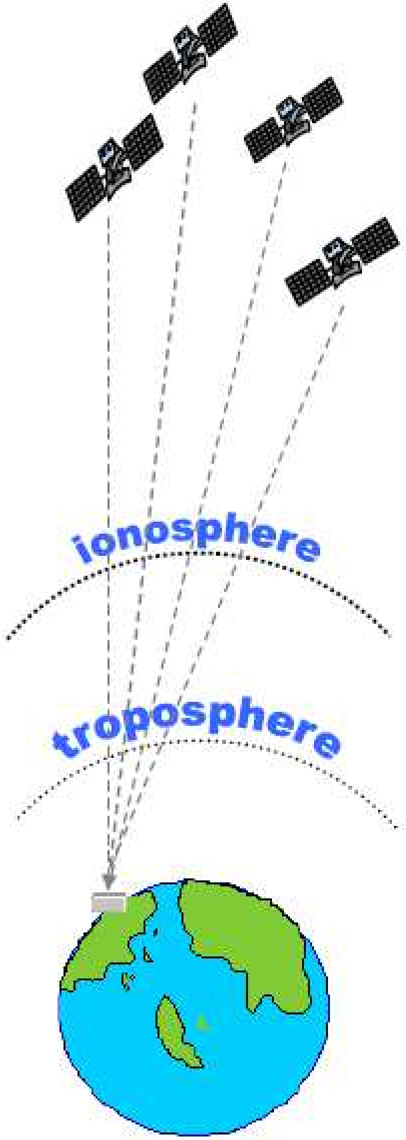


Poor geometry

Solution accuracy – Receiver errors

- The design of the receiver, algorithms and time delays can cause errors both in the reported position and the time of the receiver
- Buying high quality receivers helps to reduce these errors
- Calibration can be used to determine (or estimate) the errors of the receiver
- Internal time delays is one of the biggest uncertainty when GPS is used for time traceability

Solution accuracy – Environment



- The signal from the satellite must pass through the ionosphere and the troposphere before reaching the user
- Both the ionosphere and the troposphere delays the signal
- Receivers typically models this delay, but these models are not perfect
  - Signal frequency receivers has the most inaccurate model
  - Multiple frequency receivers can better estimate the delay
- Multipath reflections degrade the signal quality making it difficult to lock on the correct signal

Typical Error Budget for GPS

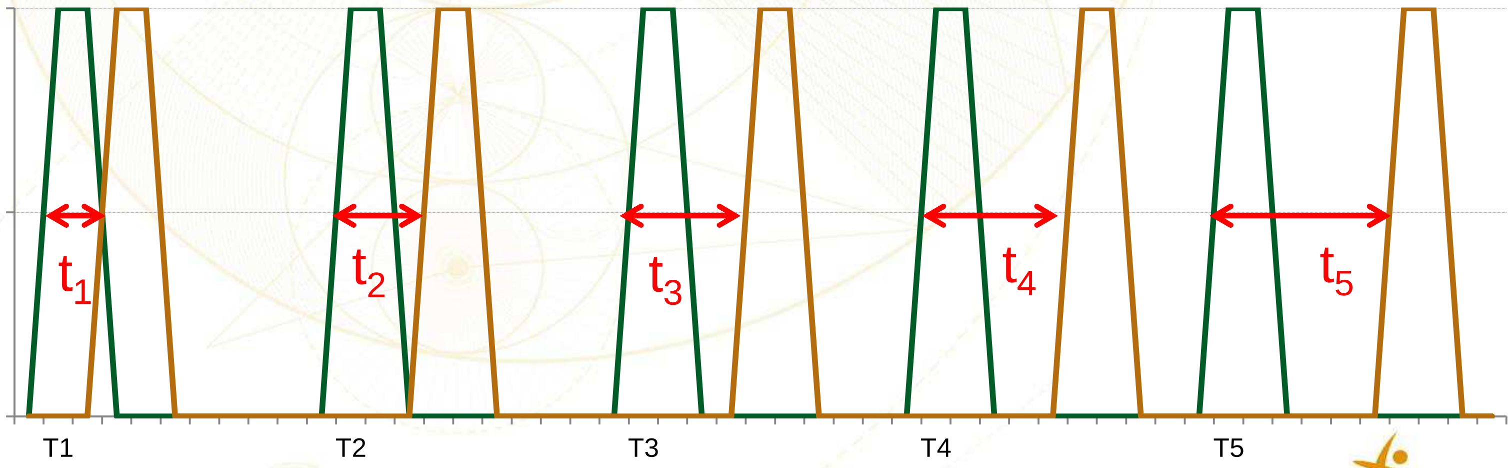
Source / Description	Typical Error
Ionosphere	1 to 5 m (3 to 17 ns)
Troposphere	0,1 to 1 m (0,3 to 3 ns)
GPS orbit accuracy (RMS value)	2 m (7 ns)
GPS clocks (RMS)	2 m (7 ns)
Multipath reflections	0,5 to 1 m (2 to 3 ns)
Receiver noise	0,25 to 0,5 m (1 to 2 ns)
Receiver design – time accuracy	100s of ns (fixed value)

TIME AND FREQUENCY TRANSFER

- The Basics of Time and Frequency Transfer
- GPS Time and Frequency Transfer

Frequency from Time Measurements

- Frequency information can be derived from time measurements
- Assume that clock 1 is used to start a time interval measurement and clock 2 to stop the measurement
- Assume that t_1, t_2, t_3, t_4 and t_5 are the time interval measurements between the two clock signals at times T_1, T_2, T_3, T_4 and T_5.



Frequency from Time Measurements

- Time transfer requires that all delays in both signal paths are known
- It can be shown that the average frequency difference between the clocks can be calculated from the time differences
- It is not required to know the delays in the signal paths for a frequency transfer, as long as the delays in the signal paths stay constant

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

Time and Frequency Transfer using GPS

- A GPS timing receiver has additional outputs to provide the user with time information
    - Typically, a single pulse per second
- Since these receivers are typically in a fixed position, it is possible to lock the receiver position
- A receiver in “position hold” mode can lock onto single satellites and provide information per satellite
- A time interval counter can be used to measure the difference between the laboratory standard and the receiver

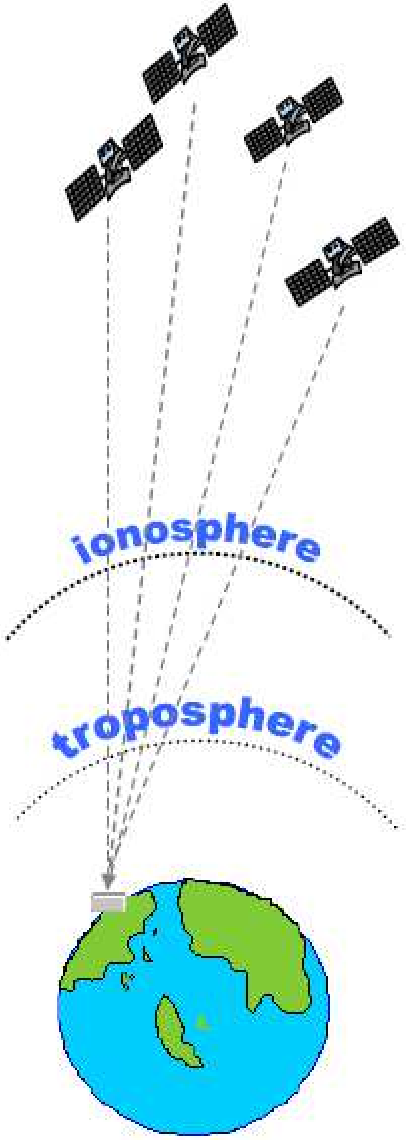
(LAB – GPS)

Using GNSS for traceability

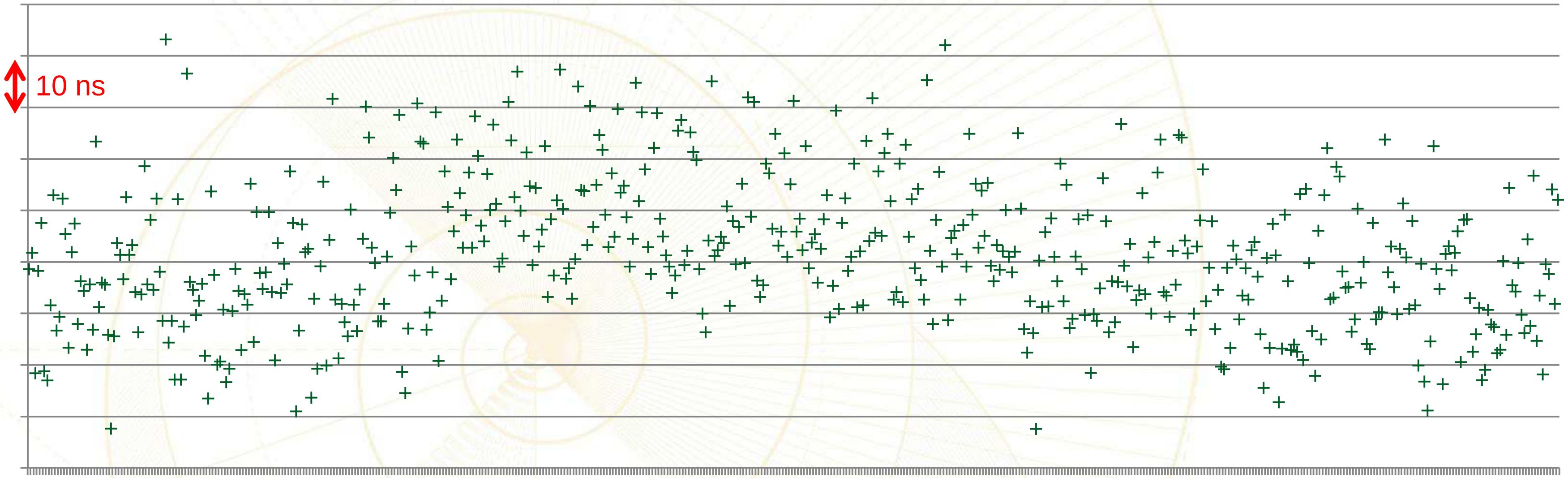
- There are a number of ways how GPS can be used to establish an accurate time and/or frequency source in a laboratory
- This presentation will look at three methods:
  - GPS one way
  - GPS disciplined oscillator
  - GPS common view
- Each of these methods have advantages and disadvantages and require a different amount of work if traceability, complying with the ISO 17025 definition, is required

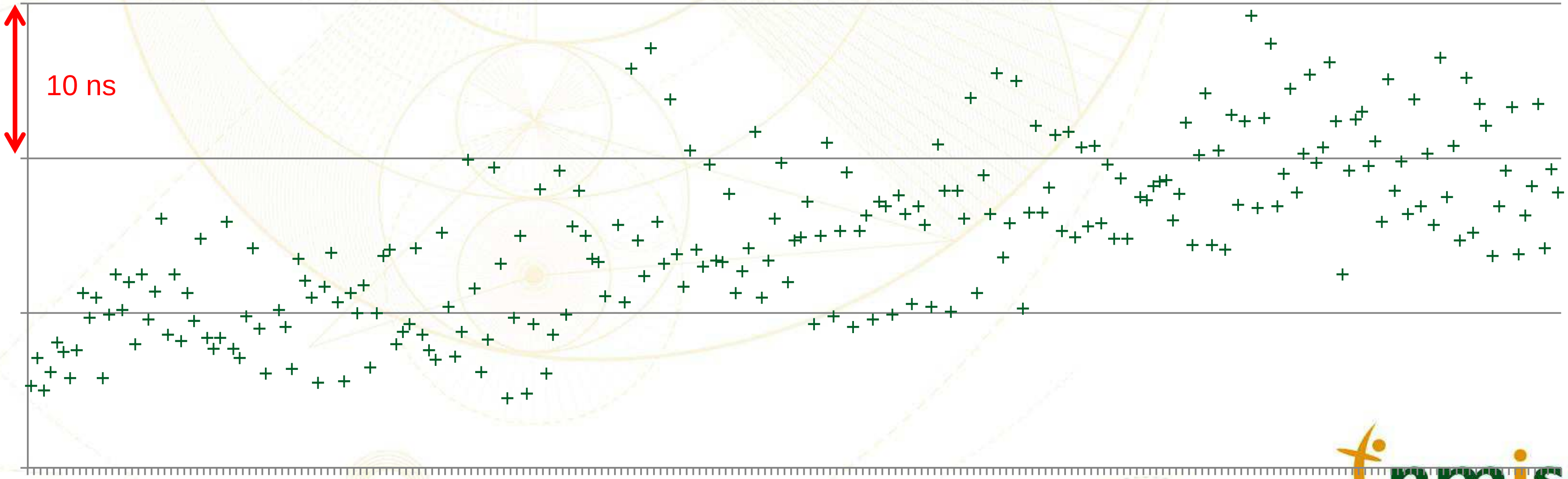
GPS one-way

- The timing receiver should be set to track all available satellites (all-in-view)
- The output is typically a 1PPS signal which can be compared to the laboratory time or frequency standard by measuring (LAB - GPS)
- Main Errors:
  - Satellite clock, ephemeris (orbit) errors, antenna coordinates error, multi-path, ionospheric delays, quality of user equipment
- Traceability is to GPS time which is derived from UTC(USNO)
  - USNO – United States Naval Observatory



GPS One-Way

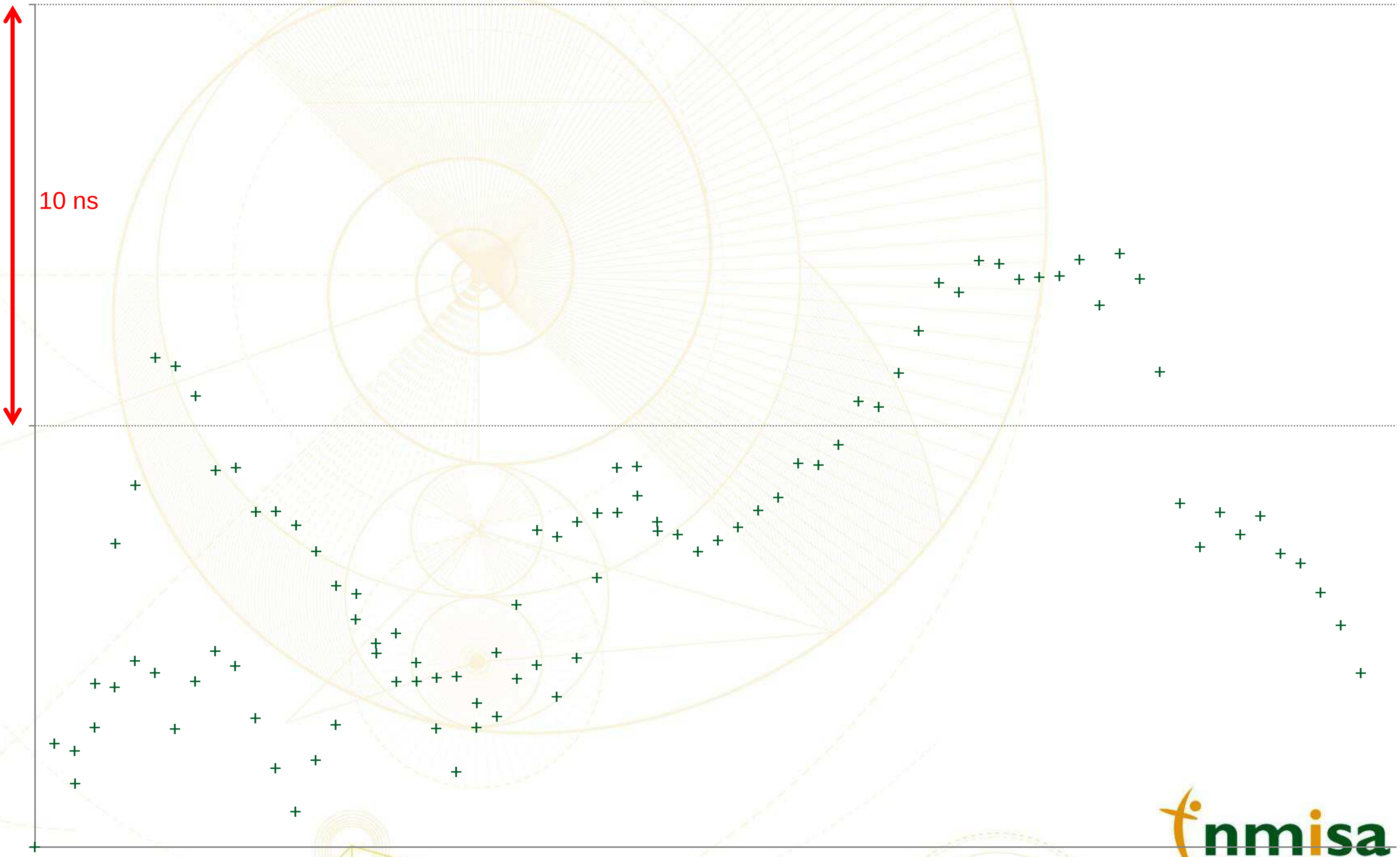




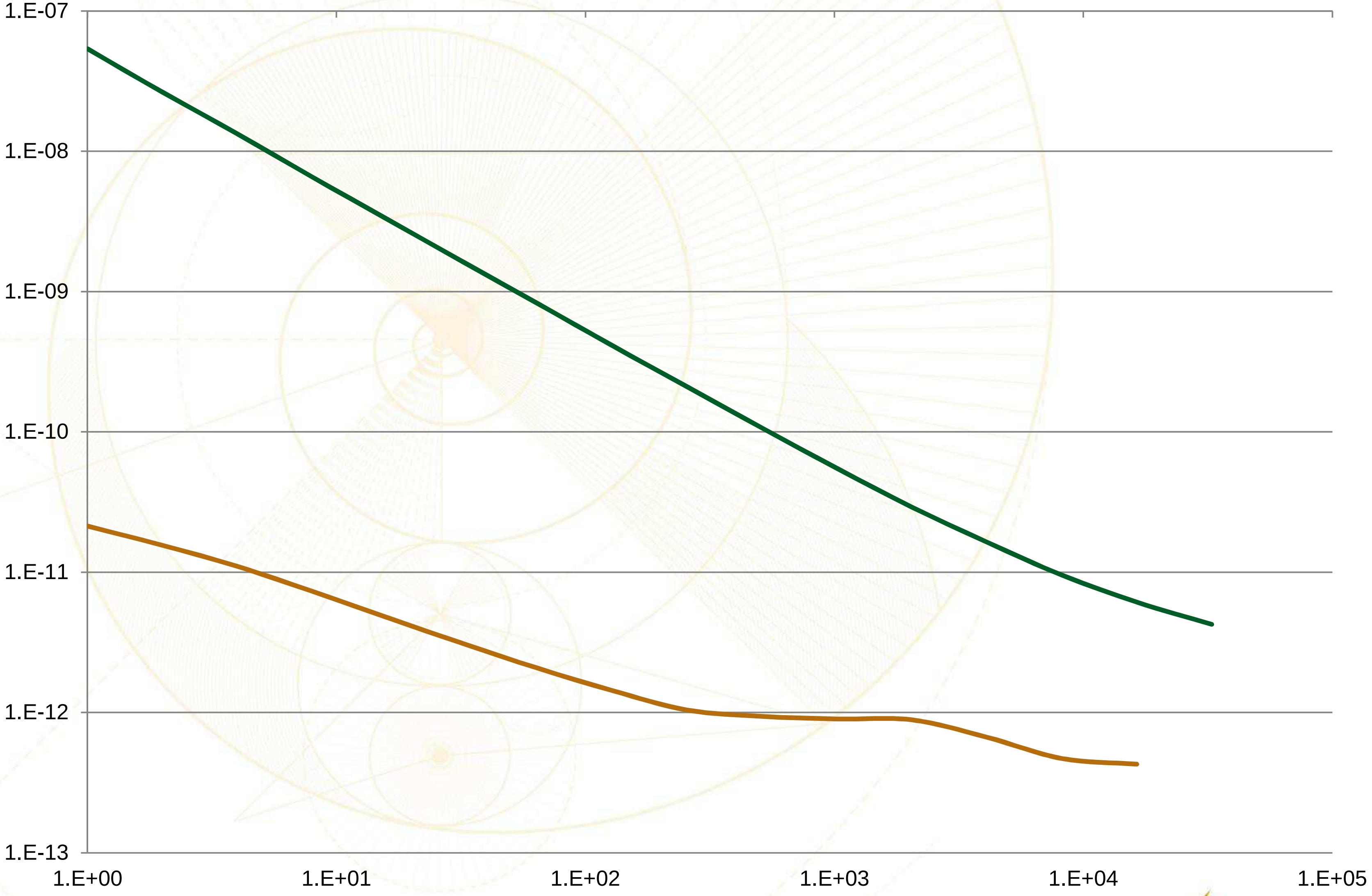
GPS disciplined oscillator

- A GPS disciplined oscillator will internally measure the differences between the GPS time and the time of the local oscillator
- The system will then steer the internal oscillator towards GPS time
- Traceability is to USNO
- The main errors are the same as for GPS one-way, with some additional timing error from the local oscillator
  - Some of the errors are filtered by the electronics and the local oscillator to get smaller variability

GPS disciplined oscillator

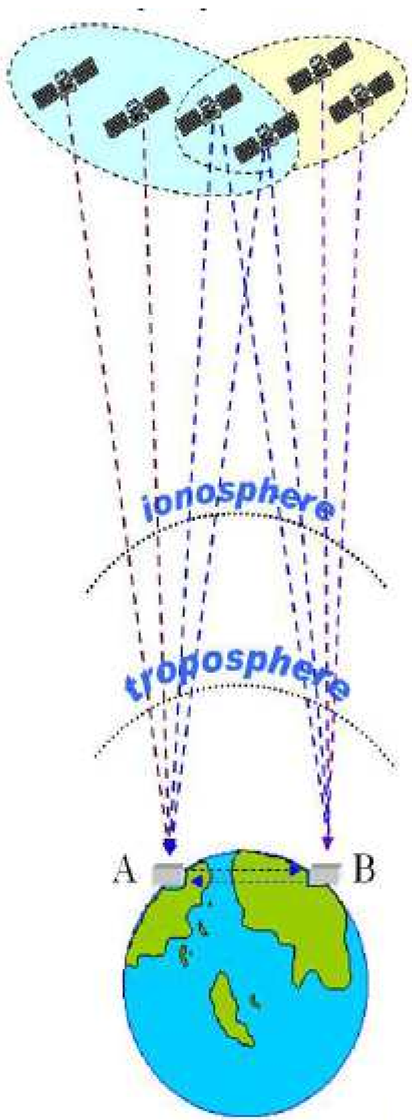


GPS disciplined oscillator - stability



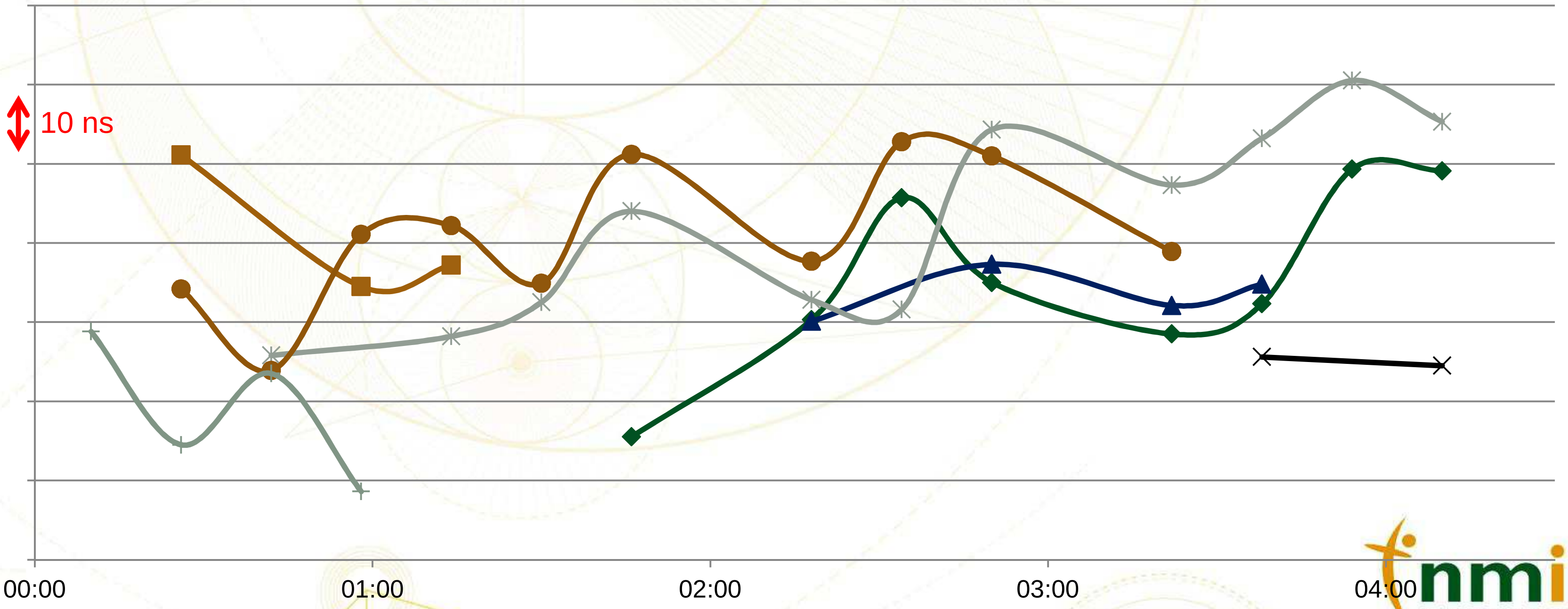
GPS Common-view

- The timing receivers at two or more locations track all available satellites (all-in-view) and measures (LAB - GPS) for each satellite
- Data from the remote locations are exchanged and data pairs where both locations tracked the same satellite at the same time is searched for $(LAB_1\text{-}GPS_k)\text{-}(LAB_2\text{-}GPS_k)=(LAB_1\text{-}LAB_2)$
- Main Errors:
  - Antenna coordinates error, multi-path, residual ionospheric delays and ephemeris data, quality of user equipment, differences in data analysis and changes in parameters during track (e.g. receiver delay)



GPS Common View

- GPS Common View allows the users to calculate the frequency difference between their two clocks
  - If one has traceability, the other can get traceability with this method
- The graph below shows a comparison between two laboratories using the GPS common view transfer method



TIME AND FREQUENCY TRANSFER FROM GPS TO ESTABLISH TRACEABILITY IN THE SOUTH AFRICAN ENVIRONMENT

- ISO 17025
- SANAS Requirements
- Suggested procedure
- Typical uncertainty

What does ISO 17025 say

5.5 Equipment
5.5.2 Equipment and its software used for testing, calibration and sampling shall be capable of achieving the accuracy required and shall comply with specifications relevant to the tests and/or calibrations concerned. Calibration programmes shall be established for key quantities or values of the instruments where these properties have a significant effect on the results. Before being placed into service, equipment (including that used for sampling) shall be calibrated or checked to establish that it meets the laboratory's specification requirements and complies with the relevant standard specifications. It shall be checked and/or calibrated before use (see 5.6).
A GPS receiver must be checked to see that it operates within the requirements of the laboratory and that the intended MC of the laboratory can be achieved

What does ISO 17025 say

5.6 Measurement traceability
5.6.1 All equipment used for tests and/or calibrations, including equipment for subsidiary measurements (e.g. for environmental conditions) having a significant effect on the accuracy or validity of the result of the test, calibration or sampling shall be calibrated before being put into service. The laboratory shall have an established programme and procedure for the calibration of its equipment.
Since it is not practical to get a GPS receiver calibrated, compliance to this clause will have to be met in another way. One method would be a verification program before a receiver is put in service and regular verification through inter-laboratory comparisons.

What does ISO 17025 say

5.6 Measurement traceability

5.6.2 For calibration laboratories, the programme for calibration of equipment shall be designed and operated so as to ensure that calibrations and measurements made by the laboratory are traceable to the International System of Units (SI) (Systme international d'units). A calibration laboratory establishes traceability of its own measurement standards and measuring instruments to the SI by means of an unbroken chain of calibrations or comparisons linking them to relevant primary standards of the SI units of measurement. The link to SI units may be achieved by reference to national measurement standards. National measurement standards may be primary standards, which are primary realizations of the SI units or ……...

USNO derives UTC(USNO) from about 80 caesium atomic clocks and 25 hydrogen masers, all of them part of the international project to derive UTC, and steer GPS time based on their prediction of UTC. But USNO is not a NMI. Traceability can not be directly to them. Additional checks must be put in place to prove traceability.

NMISA operates primary standards and can be used as a traceability provider.

SANAS Requirements

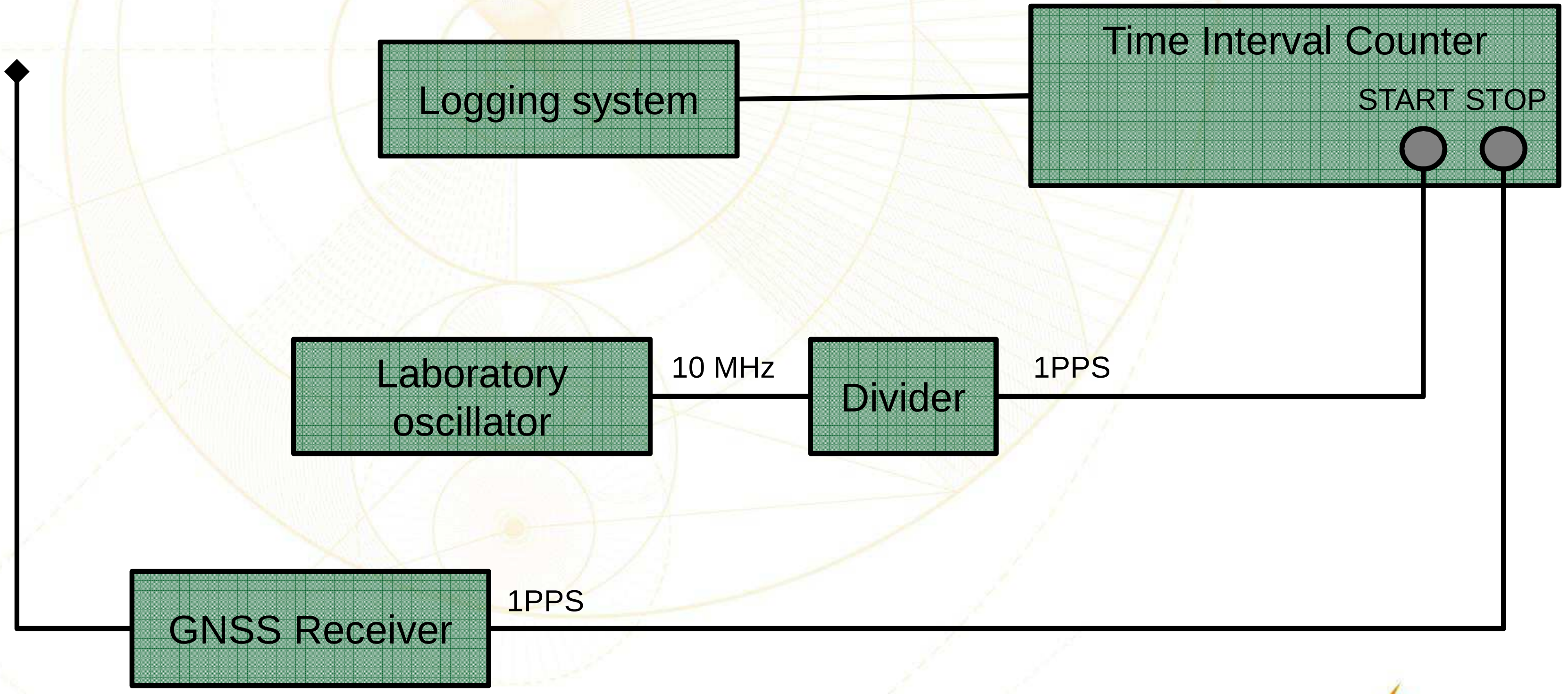
- Document TR20 (Version 01, dated 2008) gives the "Criteria for Laboratory Accreditation in the Field of Time and Frequency Metrology"
  - Nothing is mentioned regarding establishing traceability through the use of GNSS
  - During the 2011 STC meeting, a new version of TR20 was proposed to SANAS (not yet published)
  - This new version specifically discuss what would be accepted when a laboratory wants to use a GNSS for frequency traceability
- Currently, the acceptability of GNSS as a source of traceability, and the procedure for establishing that traceability, are left to the judgement of the technical assessor

Suggested procedure

- The following method is suggested by NMISA:
  - Set up a time interval counter to measure the difference between the 1PPS signal from the GPS and a 1PPS signal derived from the laboratory oscillator
  - Record at least one measurement per hour for (LAB-GPS)
  - Use curve fitting to fit a line through the daily GPS data to determine (LAB-GPS) for 00:00 UTC
  - For each month, obtain the TF Bulletin from NMISA (or similar data from another NMI participating in CCTF-K001.UTC) and extract (NMI-GPS) from the bulletin
  - Using the data from the NMI, calculate (NMI-LAB)
  - Use this data to determine the drift rate and stability of the laboratory oscillator and make a prediction of what the oscillator will be doing the next month

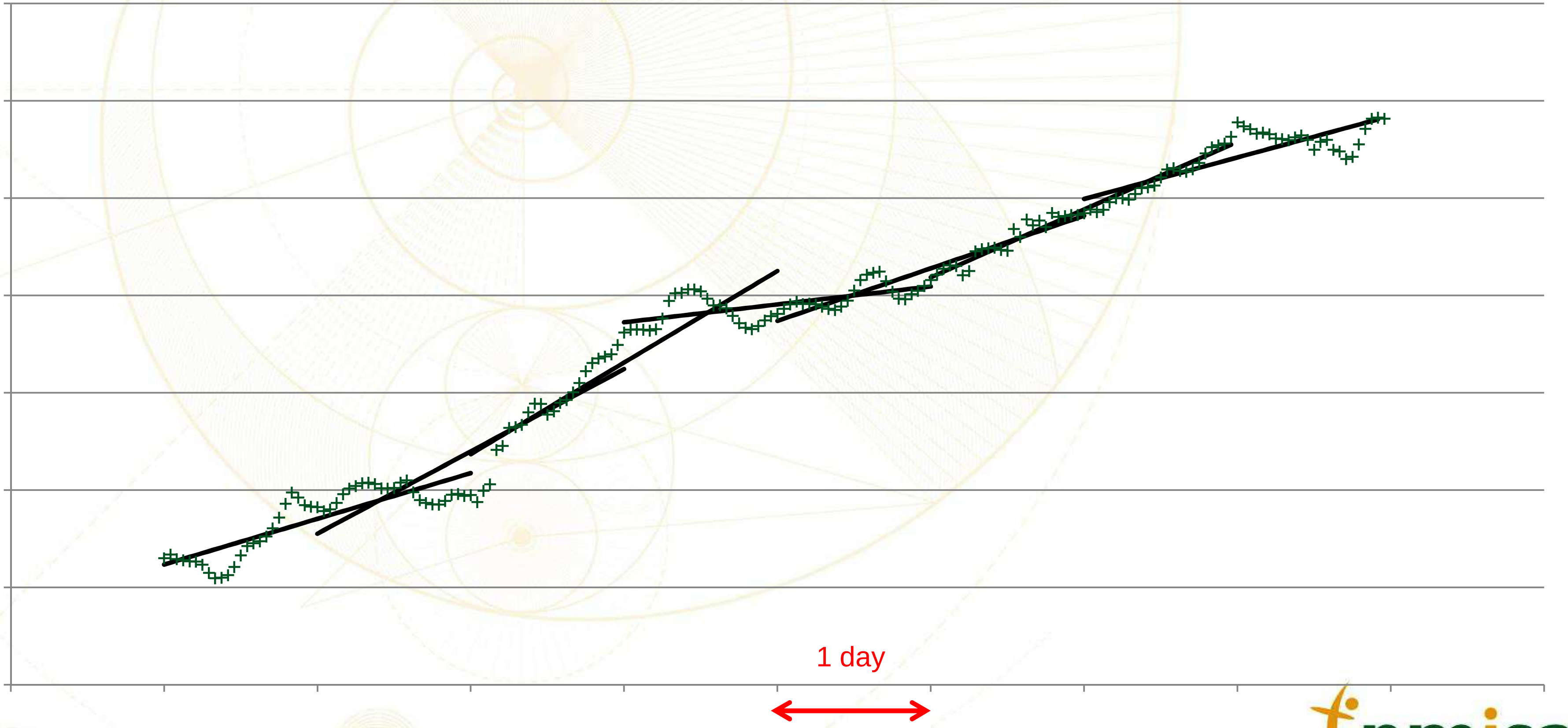
Suggested procedure

- Set up a time interval counter to measure the difference between the 1PPS signal from the GPS and a 1PPS signal derived from the laboratory oscillator



Suggested procedure

- Use curve fitting to fit a line through the daily GPS data to determine (LAB-GPS) for 00:00 UTC



Suggested procedure

- For each month, obtain the TF Bulletin from NMISA (or similar data from another NMI participating in CCTF-K001.UTC) and extract (NMISA-GPS) from the bulletin
  - NMISA publishes a monthly bulletin available from http://time.nmisa.org
  - Table 1 contains values for (NMISA-GPS)

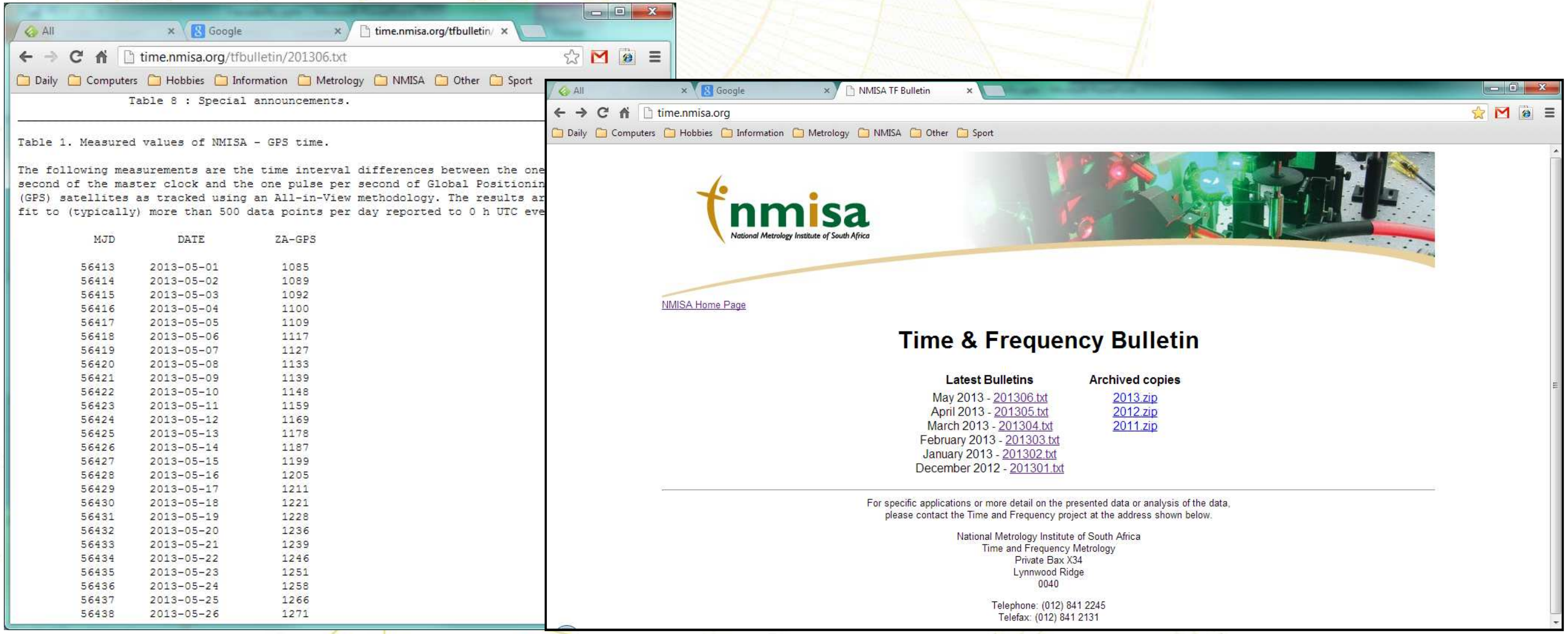


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                    Table 8 : Special announcements.

_____________________________________________________________________

Table 1. Measured values of NMISA - GPS time.

The following measurements are the time interval differences between the one
second of the master clock and the one pulse per second of Global Positionin
(GPS) satellites as tracked using an All-in-View methodology. The results ar
fit to (typically) more than 500 data points per day reported to 0 h UTC eve

            MJD          DATE             ZA-GPS

           56413      2013-05-01           1085
           56414      2013-05-02           1089
           56415      2013-05-03           1092
           56416      2013-05-04           1100
           56417      2013-05-05           1109
           56418      2013-05-06           1117
           56419      2013-05-07           1127
           56420      2013-05-08           1133
           56421      2013-05-09           1139
           56422      2013-05-10           1148
           56423      2013-05-11           1159
           56424      2013-05-12           1169
           56425      2013-05-13           1178
           56426      2013-05-14           1187
           56427      2013-05-15           1199
           56428      2013-05-16           1205
           56429      2013-05-17           1211
           56430      2013-05-18           1221
           56431      2013-05-19           1228
           56432      2013-05-20           1236
           56433      2013-05-21           1239
           56434      2013-05-22           1246
           56435      2013-05-23           1251
           56436      2013-05-24           1258
           56437      2013-05-25           1266
           56438      2013-05-26           1271
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NMISA Home Page

Time & Frequency Bulletin

Latest Bulletins	Archived copies
May 2013 - 201306.txt	2013.zip
April 2013 - 201305.txt	2012.zip
March 2013 - 201304.txt	2011.zip
February 2013 - 201303.txt	
January 2013 - 201302.txt	
December 2012 - 201301.txt	

For specific applications or more detail on the presented data or analysis of the data, please contact the Time and Frequency project at the address shown below.

National Metrology Institute of South Africa
Time and Frequency Metrology
Private Bax X34
Lynnwood Ridge
0040

Telephone: (012) 841 2245
Telefax: (012) 841 2131

Suggested procedure

- Using the data from the NMI, calculate (NMI-LAB)

MJD	NMI-GPS [ns]	LAB-GPS [ns]	NMI-LAB [ns]	$\Delta f/f = -\Delta t/T$ $(\mathrm{x}10^{-11})$
54420	1133	47978	-46845	-----
54421	1139	47189	-46050	-0,92
54422	1148	46306	-45158	-1,03
54423	1159	45396	-44237	-1,07
54424	1169	44571	-43402	-0,97
54425	1178	43690	-42512	-1,03
54426	1187	42793	-41606	-1,05
54427	1199	41971	-40772	-0,97
54428	1205	41124	-39919	-0,99
54429	1211	40268	-39057	-1,00
			Average:	**-1,00**

Suggested procedure

- Use this data to determine the drift rate and stability of the laboratory oscillator
  - The average fractional frequency error for the days shown in the previous slide is $-1{,}00 \cdot 10^{-11}$
  - The stability can typically not be calculated using standard deviation, since there is time correlation in the data
  - Real oscillators have frequency drift, flicker noise and random walk noise
  - Allan Deviation is a better statistic for determining the stability/variability of our oscillators
- Predicting the drift rate of the oscillator for the next month will require data from previous months to determine the best model for the local laboratory oscillator

Uncertainties – time traceability

- For time traceability, all the systematic uncertainties and all the delays on both sides must be known
  - This includes receiver delays, antenna cable delays, oscillator to counter delays, receiver to counter delays, etc.
  - It also includes the errors in the model used to estimate the delay through the ionosphere and the troposhere
- NMISA does not publish the systematic uncertainty of the TF Bulletin data
- The TF Bulletin can not be used to obtain time traceability

Uncertainties – frequency

- For frequency traceability, most of the systematic uncertainty components are cancelled out and only the residual and random uncertainty components remain
- It is not required to know any of the delays in the system, as long as the delays stays constant
- NMISA published the statistical uncertainty of (ZA-GPS), the predicted frequency of UTC(ZA) and the uncertainty of that prediction

Uncertainties – frequency

- Remaining uncertainty components:
  - NMISA uncertainty in data fit – available on TF Bulletin – typically one or two nanoseconds
  - Drift rate and uncertainty of NMISA clock prediction
  - Laboratory uncertainty in data fit – can be determined by calculating the standard error of the fit when reducing the GPS data to one point per day – typical values will depend on the quality of the receiver, but can be as high as 100 nanoseconds
  - Laboratory oscillator stability – will be part of the (NMI-LAB) stability analysis
  - Laboratory time interval counter – systematic components cancel out – random components will be part of the previous statistical analysis

Uncertainties - frequency

- (NMISA-GPS) values from the TF Bulletin
  - The uncertainty reported in the TF Bulletin is the statistical error of the fit and is reported at one sigma (k=1)
  - When using the average method explained earlier, the effect on the final uncertainty is √2 times the reported value divided by then number of seconds in one day
  - For our example, assume that the reported uncertainty was 2 ns
  - The standard uncertainty for our budget would be:

$$u(x_i) = \frac{\sqrt{2}\cdot\left(2\cdot 10^{-9}\right)}{86400} = 3{,}3\cdot 10^{-14}$$

- The uncertainty for determining (LAB-GPS) should be treated in the same way

Uncertainties - frequency

- Accuracy and uncertainty of NMISA clock
  - The drift rate of UTC(ZA) is currently between $0{,}7 \cdot 10^{-13}$ and $1 \cdot 10^{-13}$ with a reported uncertainty of $0{,}5 \cdot 10^{-13}$
  - Strictly speaking, the laboratory should correct for the published drift rate of UTC(ZA) and add the reported uncertainty to their budget
  - One may also decide to add a rectangular uncertainty contributor with limits of $\pm 1{,}5 \cdot 10^{-13}$ to the uncertainty budget resulting in a standard uncertainty of $0{,}866 \cdot 10^{-13}$

Uncertainty – frequency stability

- The best method to calculate frequency stability is to calculate the Allan Deviation
  - Standard deviation can not handle time correlated data
- The equation for calculating Allan Variance is:

$$\sigma(\tau)^2 = \frac{1}{2(M-1)} \sum_{n=1}^{M-1} \left(y_{n+1} - y_n\right)^2$$

$$= \frac{1}{2(N-2)\tau^2} \sum_{n=1}^{N-2} \left(x_{n+2} - 2x_{n+1} + x_n\right)^2$$

  - τ is the observation period, y_n the average fraction frequency over the observation period and x_n the phase difference

Uncertainty – frequency stability

- It is easy in a spreadsheet to calculate the Allan deviation, but becomes a lot of work for anything more than the shortest time interval

MJD	NMI-GPS [ns]	LAB-GPS [ns]	NMI-LAB [ns]	$\Delta f/f=-\Delta t/T$ $(\times 10^{-11})$	$y_{n+1}-y_n$ $(\times 10^{-13})$
54420	1133	47978	-46845	-----	-----
54421	1139	47189	-46050	-0,92	-----
54422	1148	46306	-45158	-1,03	-11,23
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54424	1169	44571	-43402	-0,97	9,95
54425	1178	43690	-42512	-1,03	-6,37
54426	1187	42793	-41606	-1,05	-1,85
54427	1199	41971	-40772	-0,97	8,33
54428	1205	41124	-39919	-0,99	-2,20
54429	1211	40268	-39057	-1,00	-1,04
sqrt(sumsq(values)/2/count(values))					**4,715**

Uncertainty - frequency

Description	Value	$u(x_i)$ $(\times 10^{-13})$	ν_i
NMISA-GPS	2 ns	0,327	500
LAB-GPS (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**

- The average fractional frequency error of the laboratory standard, for an one day observation time, was found to be:

$$(-100{,}2 \pm 6{,}8) \cdot 10^{-13} \text{ @ } 68{,}27\% \text{ LoC}$$

$$(-10{,}0 \pm 1{,}5) \cdot 10^{-12} \text{ @ } 95{,}45\% \text{ LoC}$$

Uncertainty - frequency

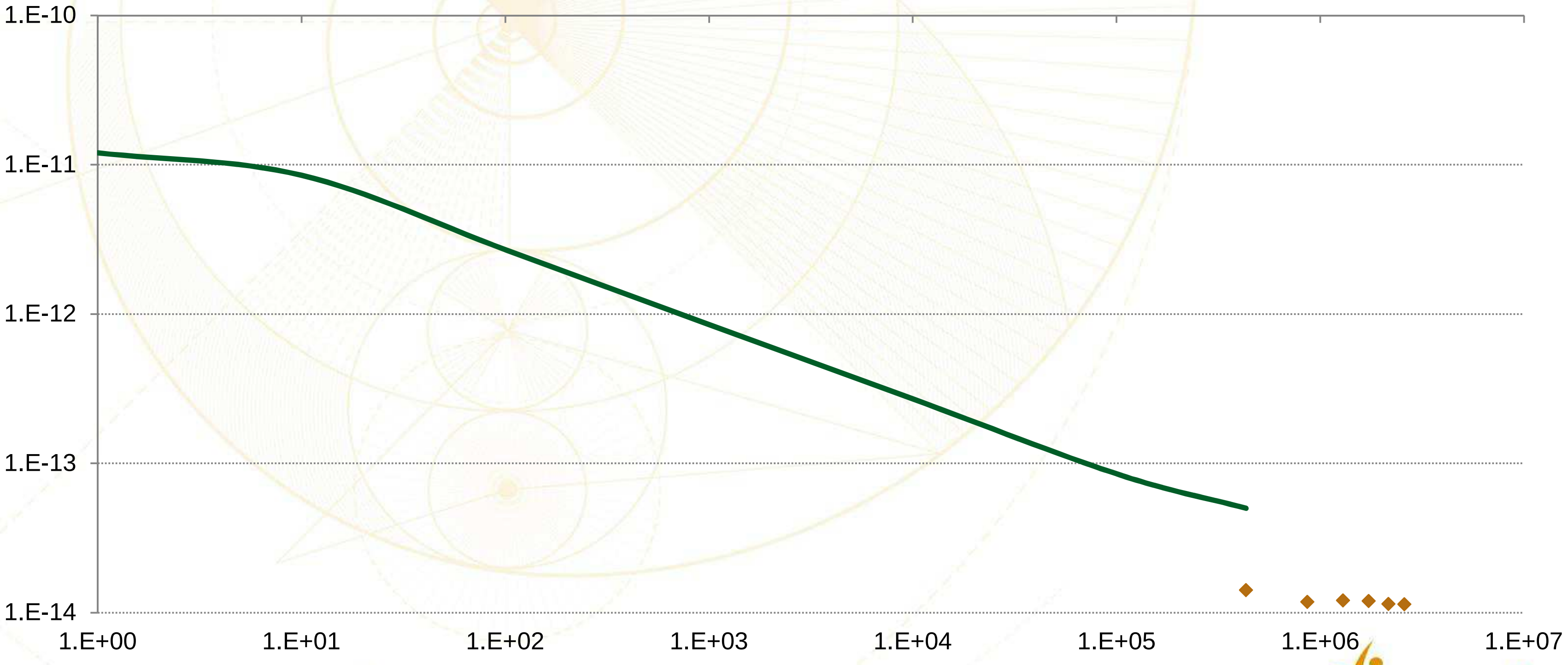
- The frequency calculated in the example was the average over one full day
- Is this average frequency valid for shorter intervals?
- How can one convert the one day uncertainty to the observation times we typically use for measurements?
  - What would be the uncertainty for 10 second or 100 second measurements?

Uncertainty - frequency

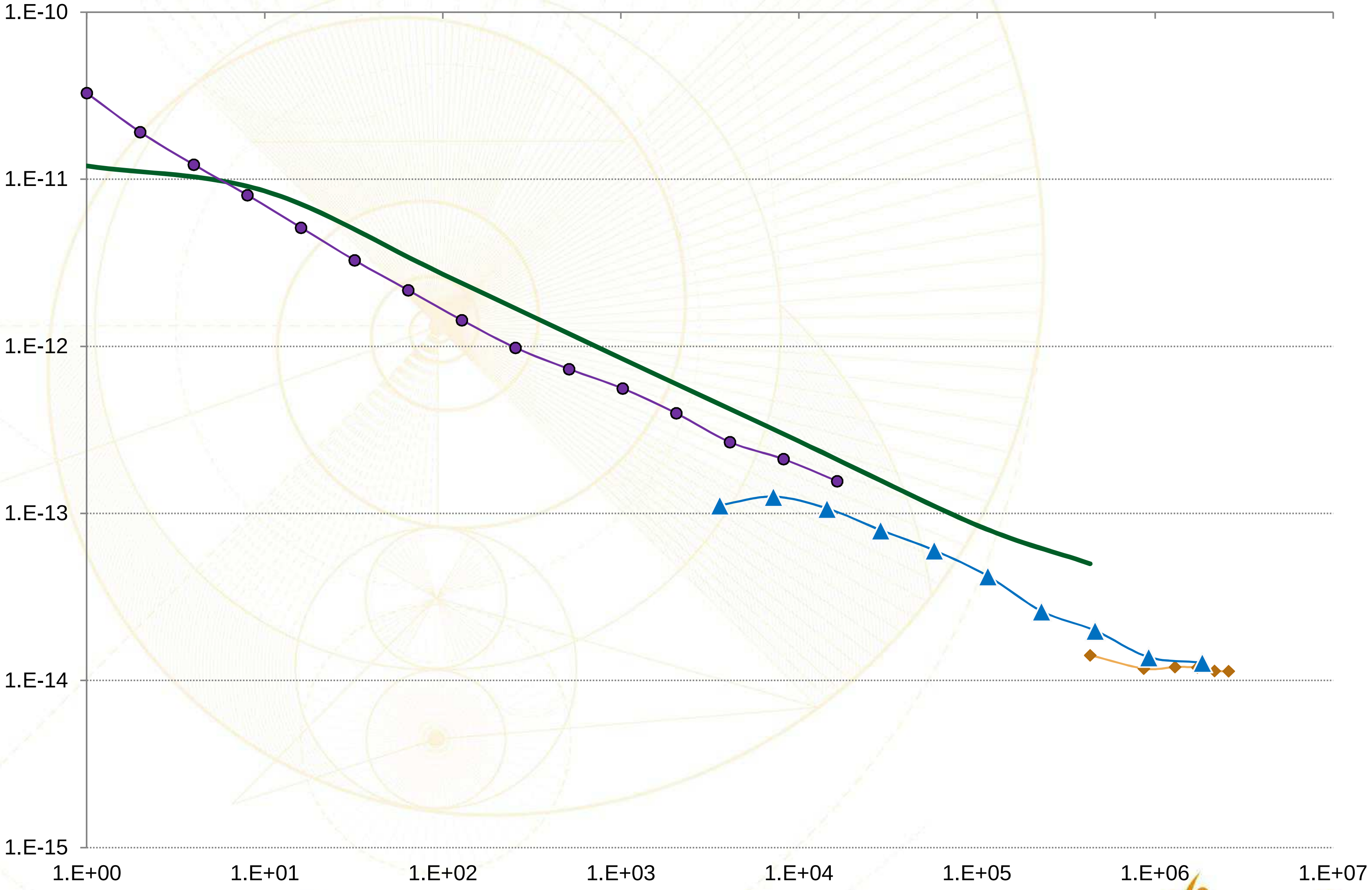
- The correct method to determine the frequency stability for shorter intervals is to have a second oscillator and then to track the relative stability of the two oscillators at that shorter observation times
  - The absolute stability of any one is equal or better than the combined stability of the two

Uncertainty - frequency

- The CCTF has accepted a method where one may use the information from the manufacturer to identify the dominant noise and then extrapolate from there
  - For example, a caesium is dominated by white frequency noise for observation times up to 90 days



Stability of UTC(ZA) in 2013



Conclusion

- GNSS allows a T&F laboratory to prove traceability at their site without the need to transport their standard for calibration, or for transfer standards
- To satisfy accreditation and legal requirements, some work is required
  - Record data comparing the local oscillator to the GNSS
  - Obtain similar data from a participant in CCTF.K001-UTC
  - Perform analysis on the data to prove that the local standard is operating within specifications fit for the purpose of the laboratory