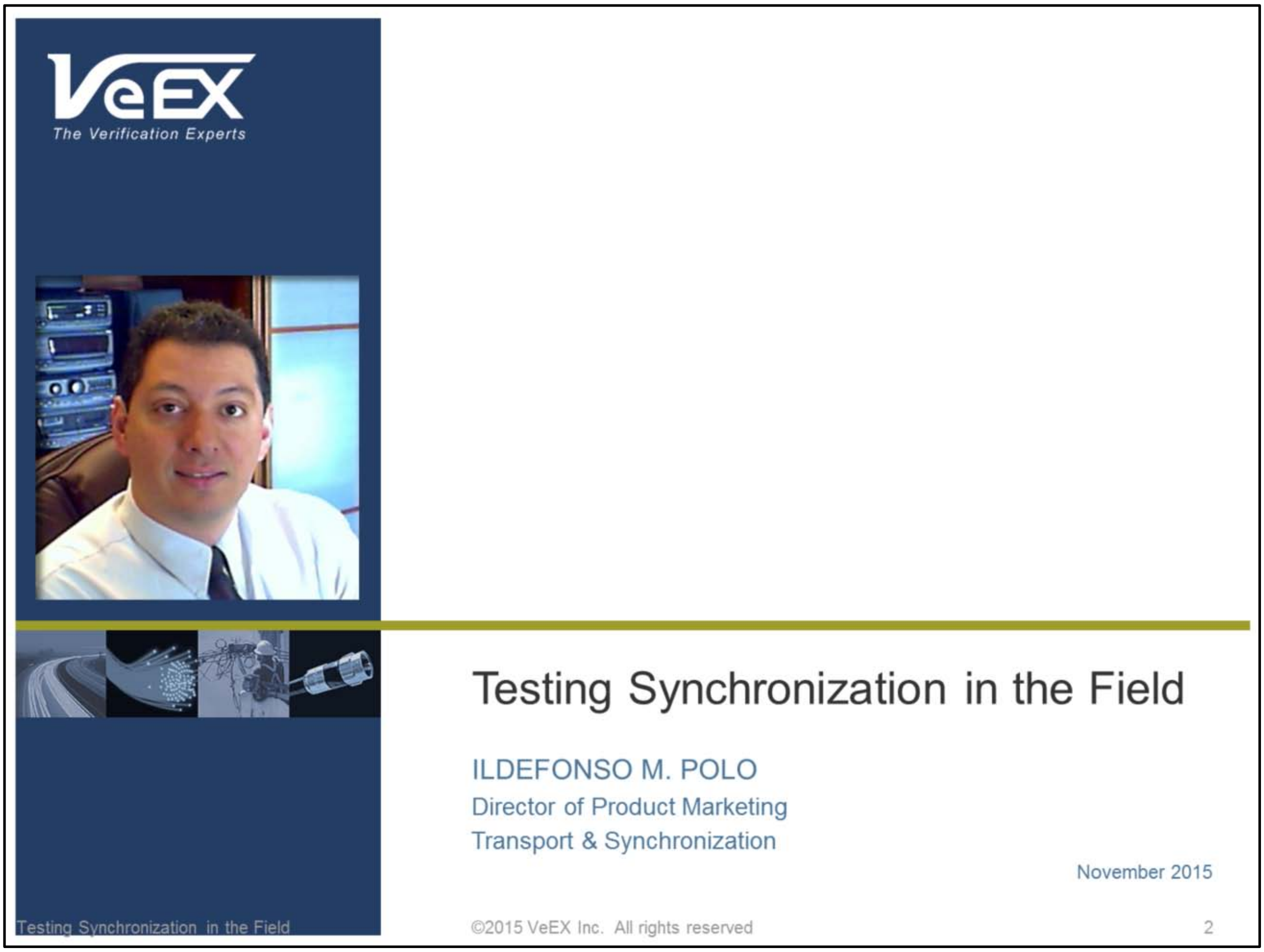
VeEX Inc., a Communications Test & Measurement Equipment Manufacturer was not always a player in the Synchronization verification field, we just offered the regular Jitter and Wander measurements required for bringing new communication links into service.

A few years ago we were approached by a customer with the idea that measuring Absolute Phase Error would become a big issue. We then developed a simple application for them and in the process we figured out that Timing was indeed going to be an important part of test and measurement, as it moved away from central offices to the field.

It has been a very exciting journey, but not without frustration created by the state-of-the-art and certain urban myths. Those same roadblocks have challenged us to look further and create solutions that apply to field testing.



About the Author

Ildefonso M. Polo is a Director of Product Marketing for VeEX Inc., focused on Transport and Synchronization technologies. He has a BSEE degree and more than 20 years of experience in Communications T&M, ranging from installation, field tests and evaluations, product definitions, to his current role. Always with a keen interest in new technologies and attacking new challenges, Ildefonso keeps his feet on the ground and hands-on approach while exploring new techniques and methods applicable to field service testing, to device practical and effective test solutions. (https://www.linkedin.com/in/ildefonsopolo)

VeEX Inc., is a communications test equipment manufacturer headquartered in Fremont, California, U.S.A.

Testing Synchronization in the Field

Introduction

- After meeting with Communication/Service Providers and Network Equipment Manufactures around the world, we realized that although they all know their need to verify phase/timing synchronization, they may still not have a clear "What" or "How".
- Plenty of information has been gathered in controlled environments, through math, simulations, emulations and lab testing.
  - But very little had been adapted for use in uncontrolled environments (Field Testing) and to address the lack of traceable references in the real world.
- To make it worse, there seem to be some misinformation (or assumptions) based on the extension of previous Frequency sync knowledge and lab experiences into Phase testing.
  - We have also seen a lot of mathematical explanations, but very little written about field testing.
- We have come to the conclusion that just refreshing Wander concepts and introducing Phase to end users may not be enough. A discussion needs to be started.
  - The main purpose of this session is to get that conversation going, by bringing the current state-of-the-art into perspective and clarifying some misunderstandings and assumptions, so that each company can come up with their actual needs and define practical Frequency and Phase testing procedures and requirements for field deployment. All within reasonable expectations.

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The Challenges of Testing Synchronization in the Field

Promoting Field Synchronization Testing, through training, seminars, discussions and actual field testing, feels like swimming upstream. Specially when it comes to Phase or Timing Error concepts. It seems like you have to bust a few myths and have to proof everything you are trying to say, before you can engage in a meaningful conversation.

This is not about the technology required to make field synchronization testing possible, because they are available and I'm sure we can continue to improve them as we learn and get access to newer better components.

The main issues are:

- There is not enough guidance or references for testing sync in the field
- Test procedures and requirements are often defined by "the Lab", based on lab tests and experiences. Some could be an overkill for field testing
- Misconceptions and assumptions
- End users training (or the lack of)

Once we resolve these, everything goes smoothly

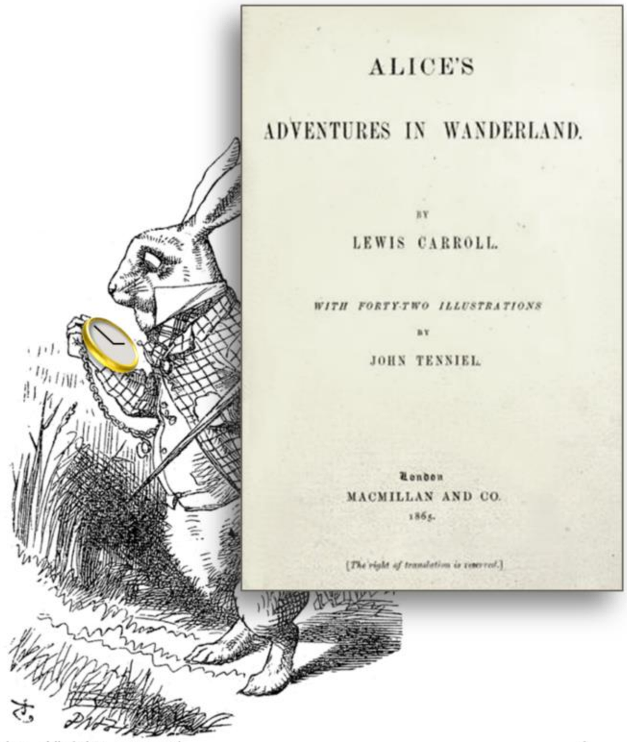
We define "Field" as premises or assets outside the Communication Service Providers' central offices. It includes points of presence such as rented rack spaces, remote aggregation equipment, base stations, antenna sites, customer premises, etc. Those facilities are often serviced by regular installation and maintenance crews.

The Wanderful World of Synchronization

Testing Frequency, Phase/Timing, Time and "Fairy Tales"

Problems that needed to be Solved

- Transition from the Lab to the Field
- Many misconceptions & assumptions
- Frequency Sync vs. Phase Sync
- Lack of local traceable references
- GNSS (GPS) - Myths and Facts
- Indoors Testing
- The Frequency Holdover extrapolation
- The Phase Holdover assumptions
- The challenges in turning long-term tests into "Quick" verification tests
- What and How to test in the field
- Portable Test Equipment availability



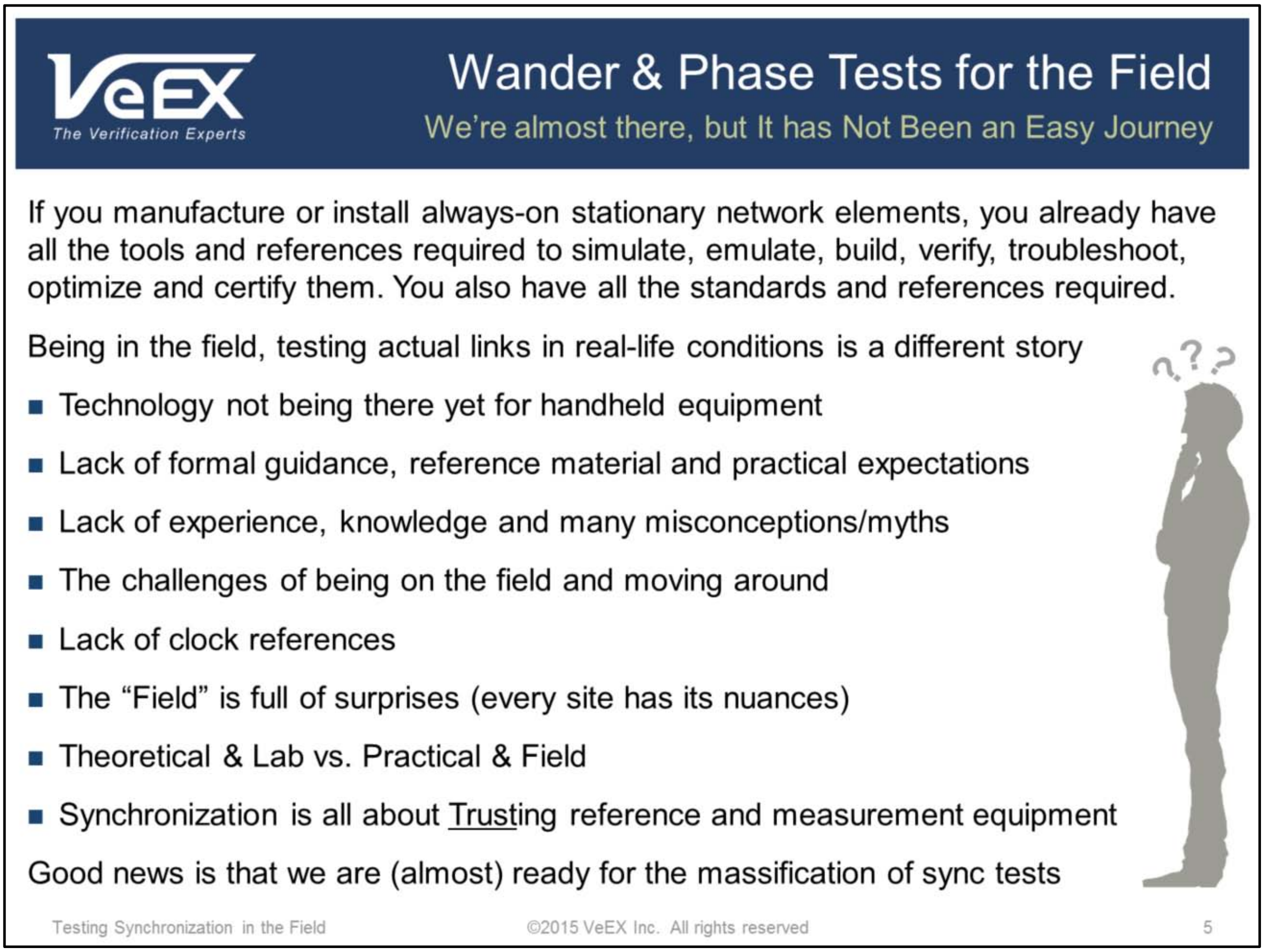
I always start with a fairy-tale analogy because we have seen many experts treating PTP deployment and Phase synchronization just like that. (I have to admit, some of the labs I have visited do look like fairy-land to me ☺, but this is all about testing out in the field.)

This session focuses on issues that are relevant to practical Field Testing and dismissing some of the "virtual" challenges being imposed or assumed.

Let's forget about the lab for a moment. After all, they already have plenty of expensive tools and air-conditioned environments.

- Nonetheless, we can't ignore that most of the expertise and experience are currently with lab people.
- Our message to them is to put all the math, simulations and emulations aside, get a pair of sunglasses, go outside and take a look at the real world. Put all that great amount of gathered knowledge into perspective, to come up with methods and procedures that actually make sense to the people doing it and the places they will be done at.

Keep in mind that methods and procedures may need to be adjusted to fit the local environment, so every service provider, country or region may come up with slightly different solutions. From transporting time in a Tuk-Tuk to state-of-the art Trucks/Vans. Everything matters, even local culture.

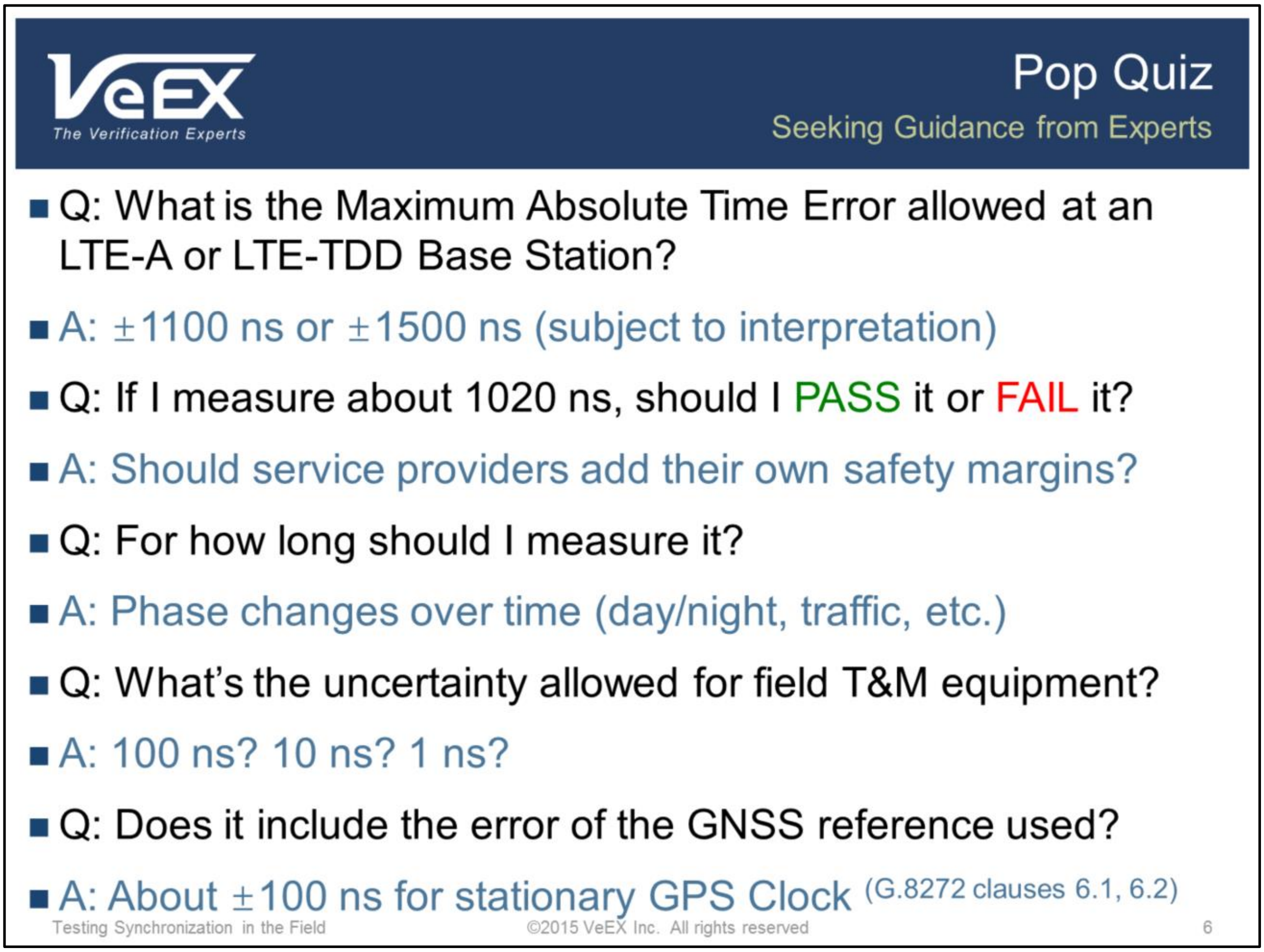


When we first visit a (potential) customer or go through an evaluation process, we deal with "the lab". Besides having to overcome some wishful expectations, the discussions are highly technical and quite fluid due to their experience.

- With lab people the major hurdles are usually related to "extreme" expectations or assumptions for field test and measurement equipment.

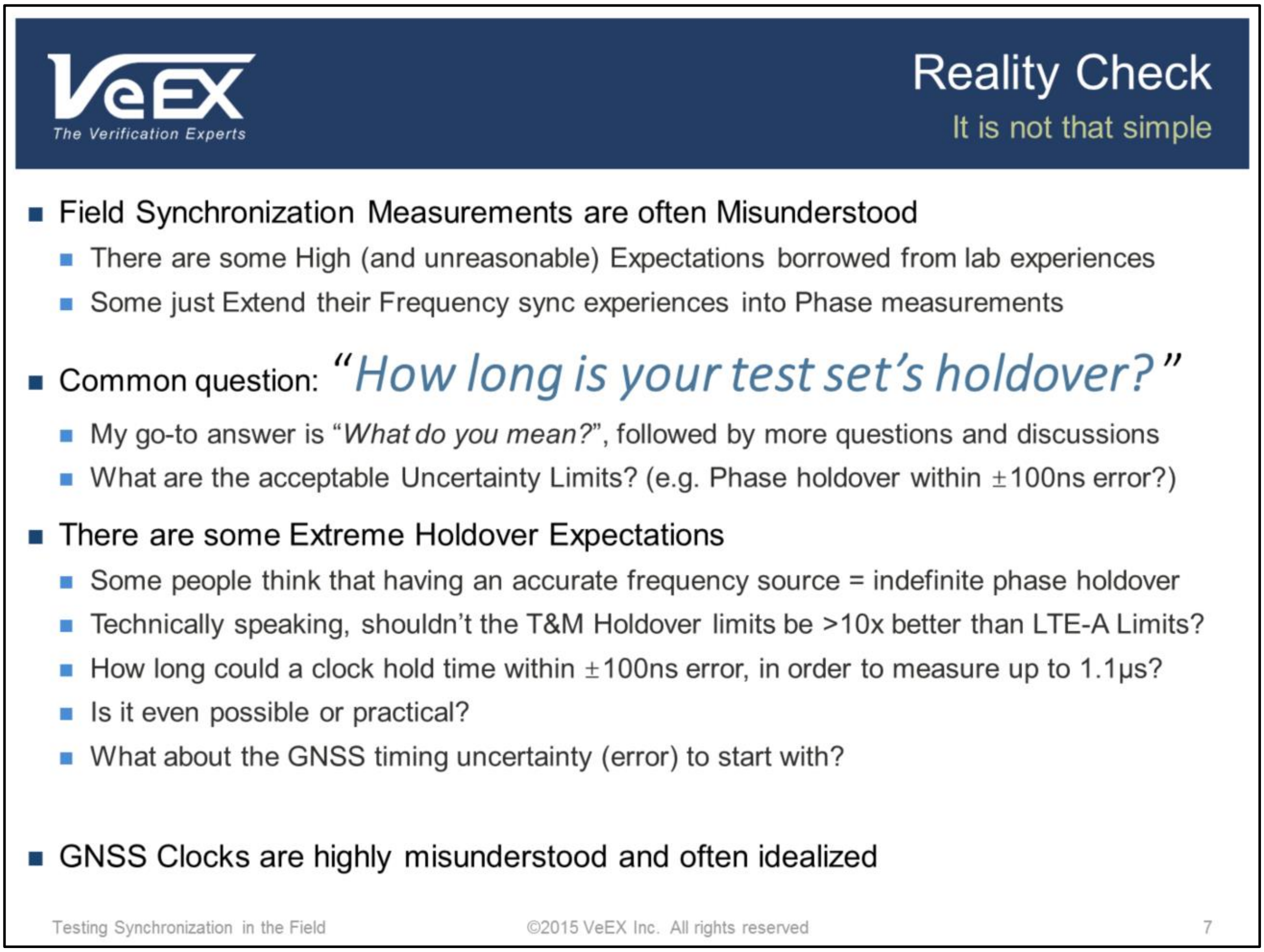
Dealing with end users and their ever-changing environment is a different story. Many of them don't have experience with synchronization. To many of them Synchronization is just another thing to add to the long list of tests they are expected to perform. T&M vendors need to take people and environments into account as practical solutions go beyond technicalities.

- With end users it is all about user friendliness (even to those who don't know or are not expected to learn sync), making the equipment automate as much as the process as possible, provide lots of status information and deal with the environment.
- Having the same test set they use for day-to-day testing to do sync makes it easier to them, bust confidence due to familiarity and may reduce invalid tests or repeat visits.



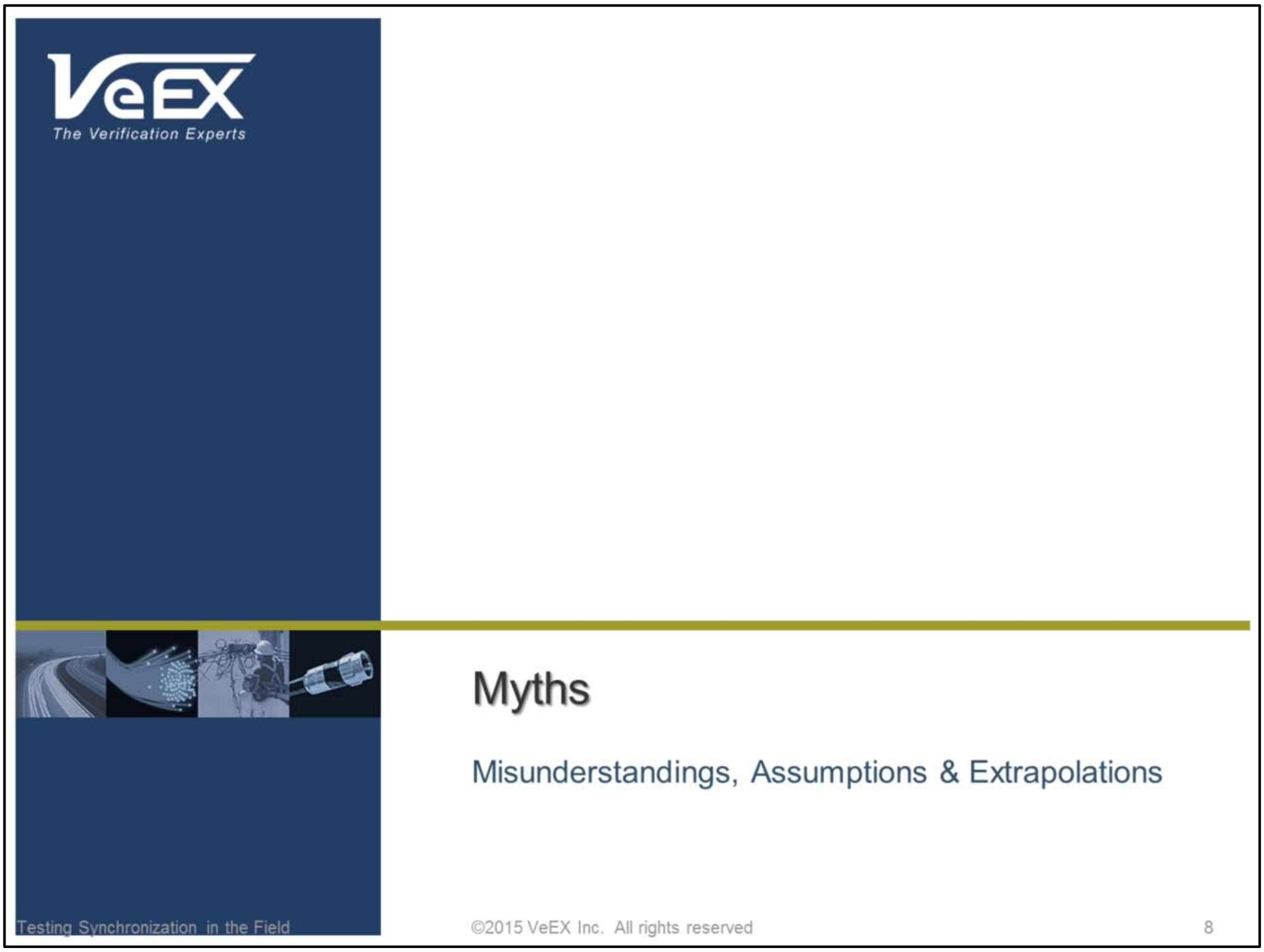
Notes:

- Although the Absolute Time Error requirements or allowance are a bit fuzzy (basically a flat mask that extends forever), the required MTIE wander limits still apply (depending on interface being tested). That helps in defining a bit better the required test time and tightens the phase behavior criteria for Pass/Fail evaluations.
- G.8272 clauses 6.1 and 6.2 define a maximum of 100 ns total error for a properly engineered PRTC (GNSS with calibrated installation, no multipath, controlled interference, no jamming or storms). But, for highly mobile field test applications, some of those factors are unknown or out of users' control. Nonetheless the ±100 ns could still be used as a reference value for discussion purposes.
- If my reference may be 100 ns off, should anything I measure over 1000 ns fail?



Portable GNSS receivers often claim tight accuracies around ±20 or ±50ns but this is stated as RMS.

- In reality they are most likely ±100 to ±150 ns peak-to-peak
- Must also take into account the raise time and shape of the 1PPS waveform and the effects of capacitive load, impedance mismatch, reflections, etc. They also add phase error at the raising edge detection circuitry.
- Note that field users are not very picky about the use of cables and they may select different cables for reference and test signals. At 5ns per meter, cable delay could also be a significant error factor.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Myths
Misunderstandings, Assumptions & Extrapolations
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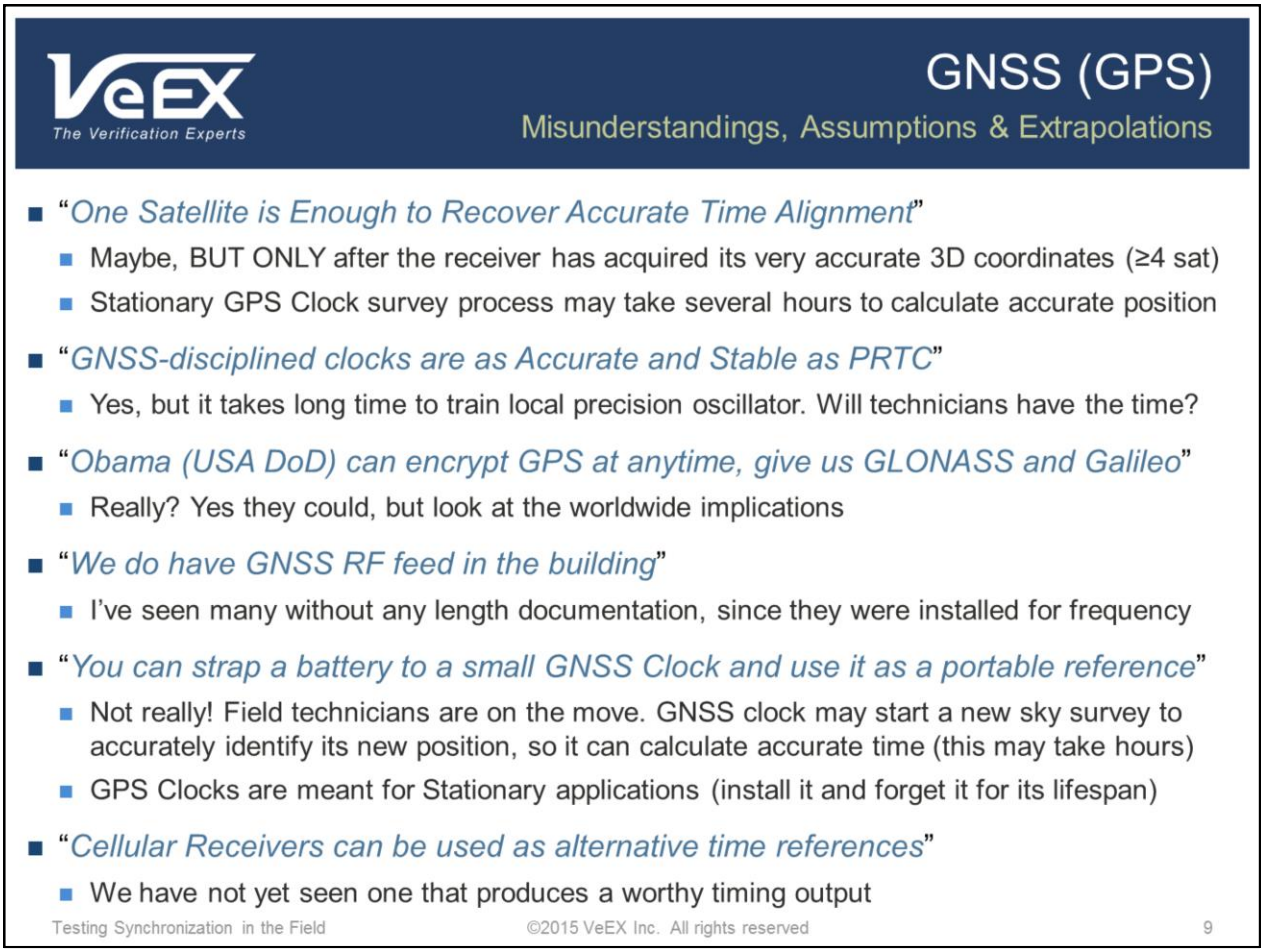

- It always amuses us that customer often use the "Obama" reason to justify their fear, but they seem to be ok trusting "Putin" or Galileo.
- We understand the concern about constant threats of forced GPS outages and all the scary documents that are constantly published, but those are not the right reasons. The decision to block GPS is not that simple as there is too much at stake (airplanes, high-speed trains, ships, autonomous vehicles and even distracted drivers relying on their cars' navigation systems).
- Supporting different GNSS receiver would make sense to avoid jamming, but it would only work if the backup system uses a completely different band. Interference generators are not very selective or follow rules or standards.
- As T&M vendor, we are often "forced" by customers to offer different options, whether they make complete sense or not.

Phase/Timing Holdover

Misunderstandings, Assumptions & Extrapolations

- "*How Long is the Test Set's Phase Holdover?*"
  - Usually no uncertainty limits are given. So, what determines the end of usable holdover?
  - Usable holdover time may be different under different circumstances
  - We need the error tolerance (limit) in order to provide a typical holdover validity time

- "*A Portable Rubidium Provides >24-hour Holdover*" (Some said up to 7 days)
  - They may refer to frequency "soft" calibration (ageing or steer adjustment), not Phase
  - Phase can't be calibrated and Phase holdover has limited validity

- Parts-per-billion (ppb) is not as good as some people tend to think
  - 1 ppb frequency offset is equivalent to 1 ns/s phase drift

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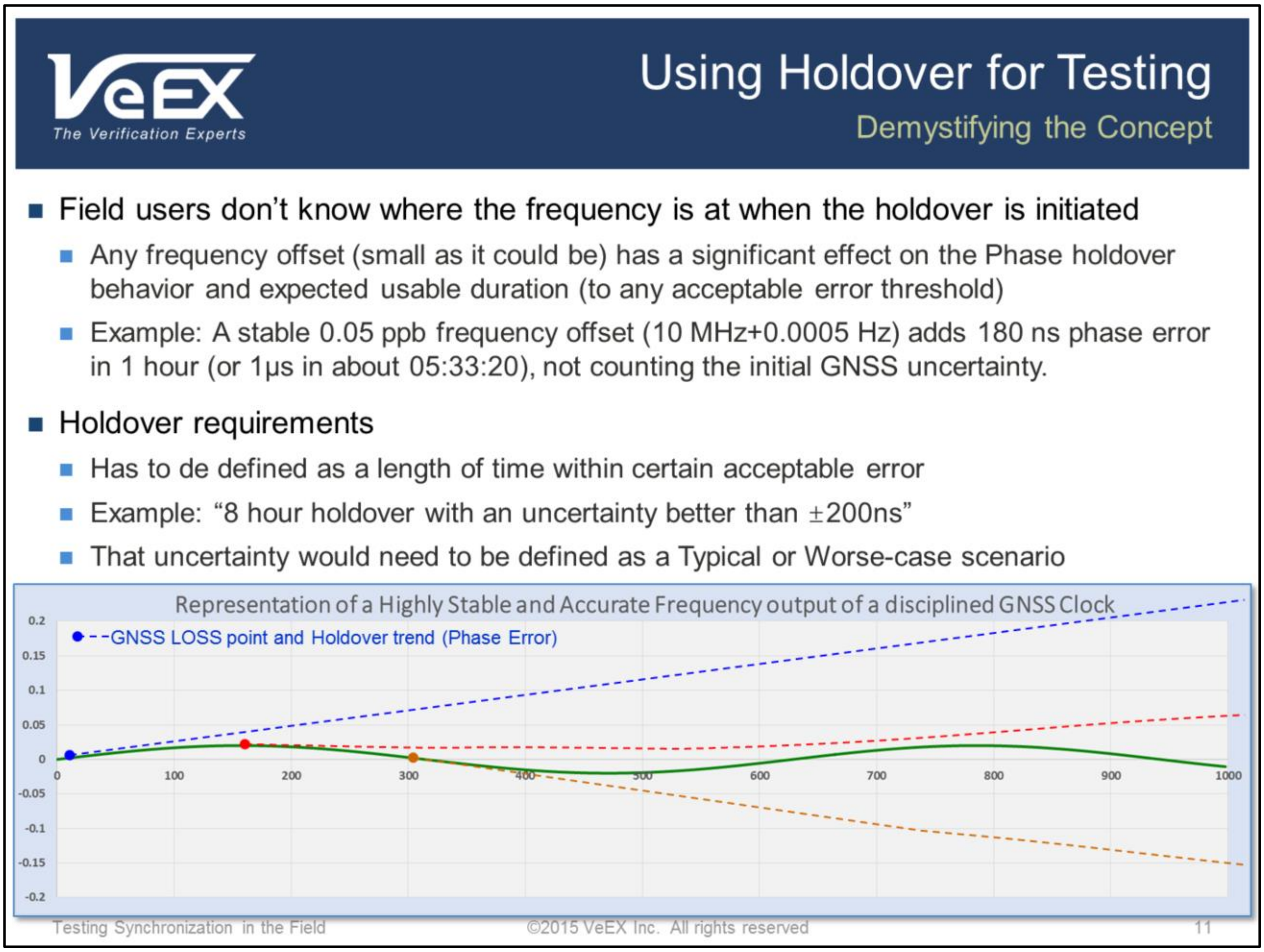


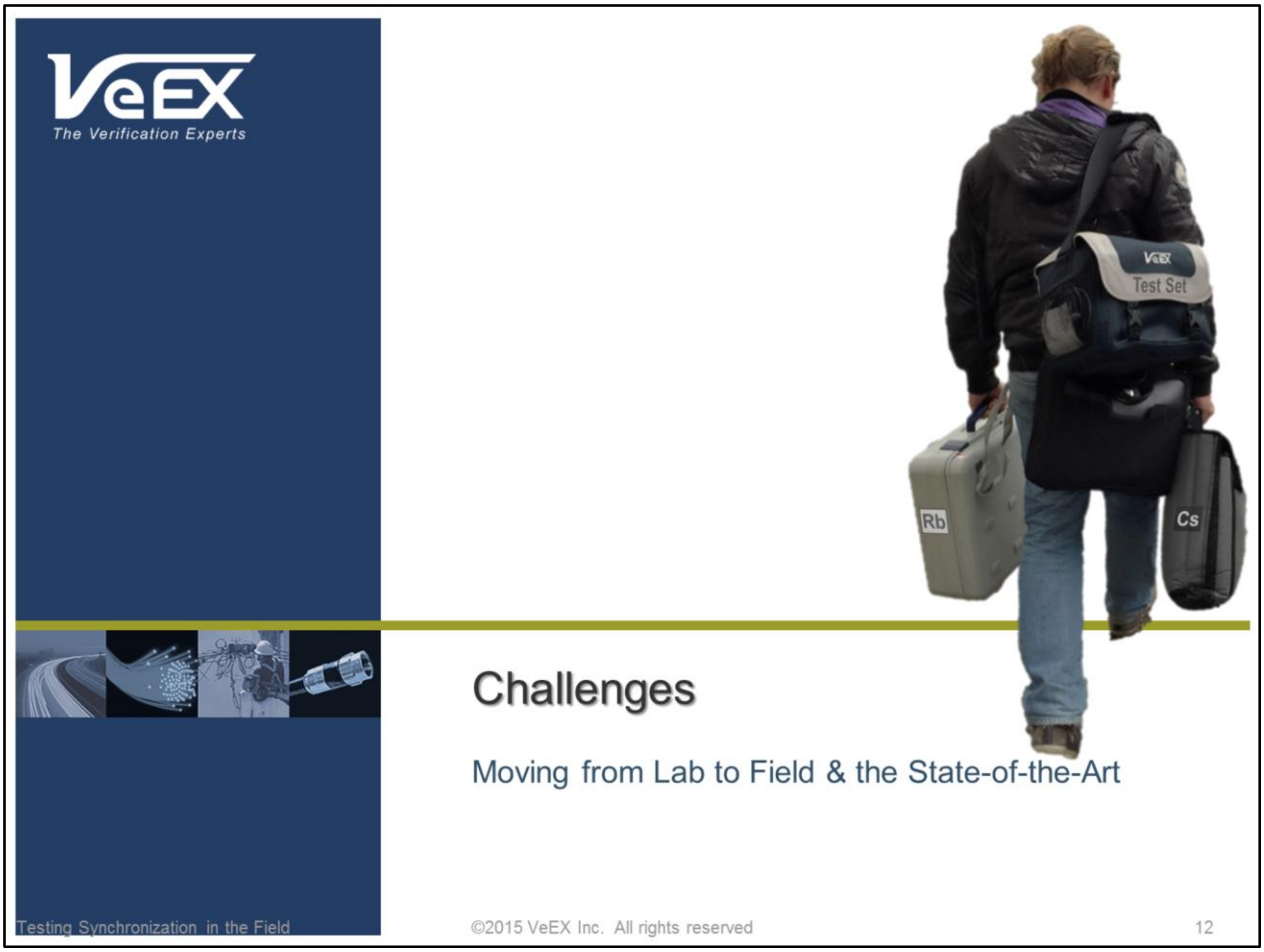
To maintain Phase Alignment, while being disciplined, the oscillator constantly adjusts its frequency to make the necessary phase corrections. The oscillator's frequency will wander around the ideal frequency value, some times slightly slower and sometimes slightly faster than the ideal reference.

Those adjustments are just small fractions of part-per-billion, but they make a difference when the holdover is long (e.g. 0.01 ppb or 1E-11 produces 100 ns cumulative error in less than 3 hours).

The point at which the GNSS reference is lost (or disconnected) defines the subsequent phase holdover behavior

- A lower frequency may cause the phase error to keep on increasing.
- An exact frequency would hold the last known phase for longer.
- A faster frequency may keep increasing the phase error in the negative direction.

The oscillator will try to maintain (hold) the last known frequency for as long as possible, before starting to drift or wander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Rb
Cs
Challenges
Moving from Lab to Field & the State-of-the-Art
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Precision Oscillators

State-of-the-art and Portability

Note: We are still in search for a “perfect” oscillator that fits portable T&M applications

- DOCXO – Good accuracy and stability, but tend to be power hungry and “big”
  - Most are not suitable for battery operation or hand-held form factor
- CSAC – Good accuracy, good stability, low power and fast warm up
  - But, Cesium gas cells work better in always-on applications
  - Storage conditions: End users must learn how to keep the equipment in optimum condition
- Proper Disciplining Time vs. Quick Tests
  - Includes satellite identification, survey, lock and the actual oscillator disciplining time
- Fast and Extreme Temperature Variations
  - Outdoors vs. Indoors (e.g. test sets left in a car, van or truck, during winter nights)
  - You won’t find that kind of information or performance guarantee on a datasheet

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Indoors Testing

What's expected of T&M Equipment

- Availability of test ports
  - Don't assume you will find a Clock Output port on every equipment
- Lack of traceable references
  - Frequency reference are a more common than Phase/Timing reference
  - Excellent free-running accuracy and stability are good alternatives for Frequency reference
  - Phase holdover is proposed as a fair alternative for Phase reference (not for long-term tests)
- Holdover Limitations
  - It has an expiration time (sometimes undefined or unknown)
  - Test sets may need to be turned off to transport (e.g. security or to avoid overheating)
  - There are no other references to verify the holdover claim (users need status indications)
  - Unknown GNSS error (users require status information to assess the quality)
- Environmental
  - Temperature and humidity variations
- The human factor

1588v2 PTP Testing

What's expected of T&M Equipment?

- Protocol emulation is provided as a validation tool only
  - Confirming the provisioning of a link (can it see the GM? Can it negotiate PTP? Can it sync?)
  - Test sets should not be used to benchmark or predict true Slaves' performance
- PTP Slave Emulation Clock Recovery
  - Raw PTP Clock vs. Stabilized ("filtered") Clock
  - Filtering the recovered clock Blinds test equipment as the oscillator removes any anomalies
  - T&M should be able to identify when something has gone wrong or not performing well
  - Customers keep on asking for handhelds to output PRTC and match true slave performance
  - Actual physical TE measurement is recommended with the actual Slave, whenever possible
- Asymmetry (one-way-delay) measurement is still a complex proposition
  - No standard, no interoperability
  - Requires a great deal of coordination (end-to-end test)
  - Includes GNSS and Holdover errors at both ends (most tests are performed indoors)
  - It may require extra time to measure OWD under different traffic conditions
  - Very little guidance from standard bodies

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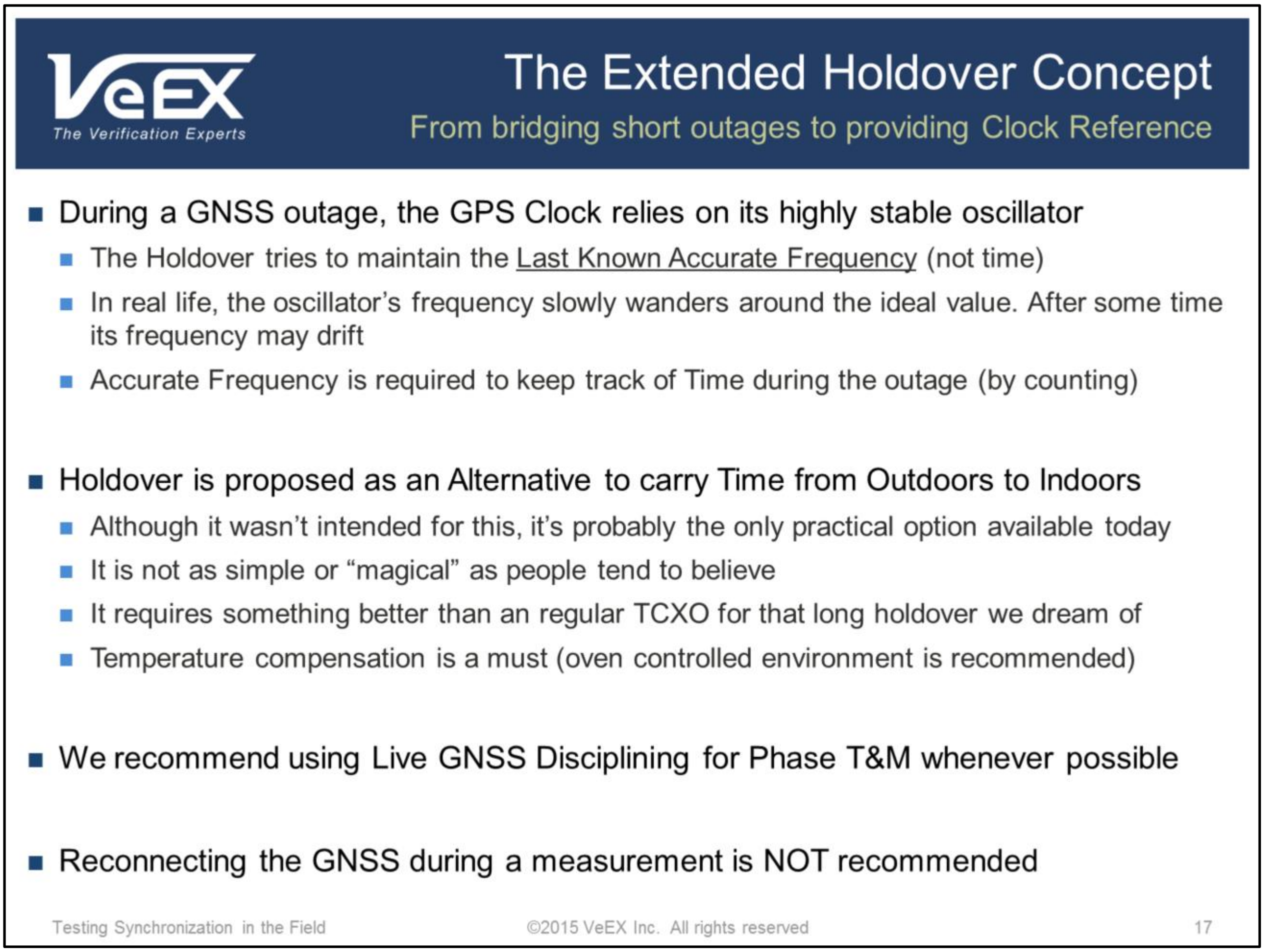
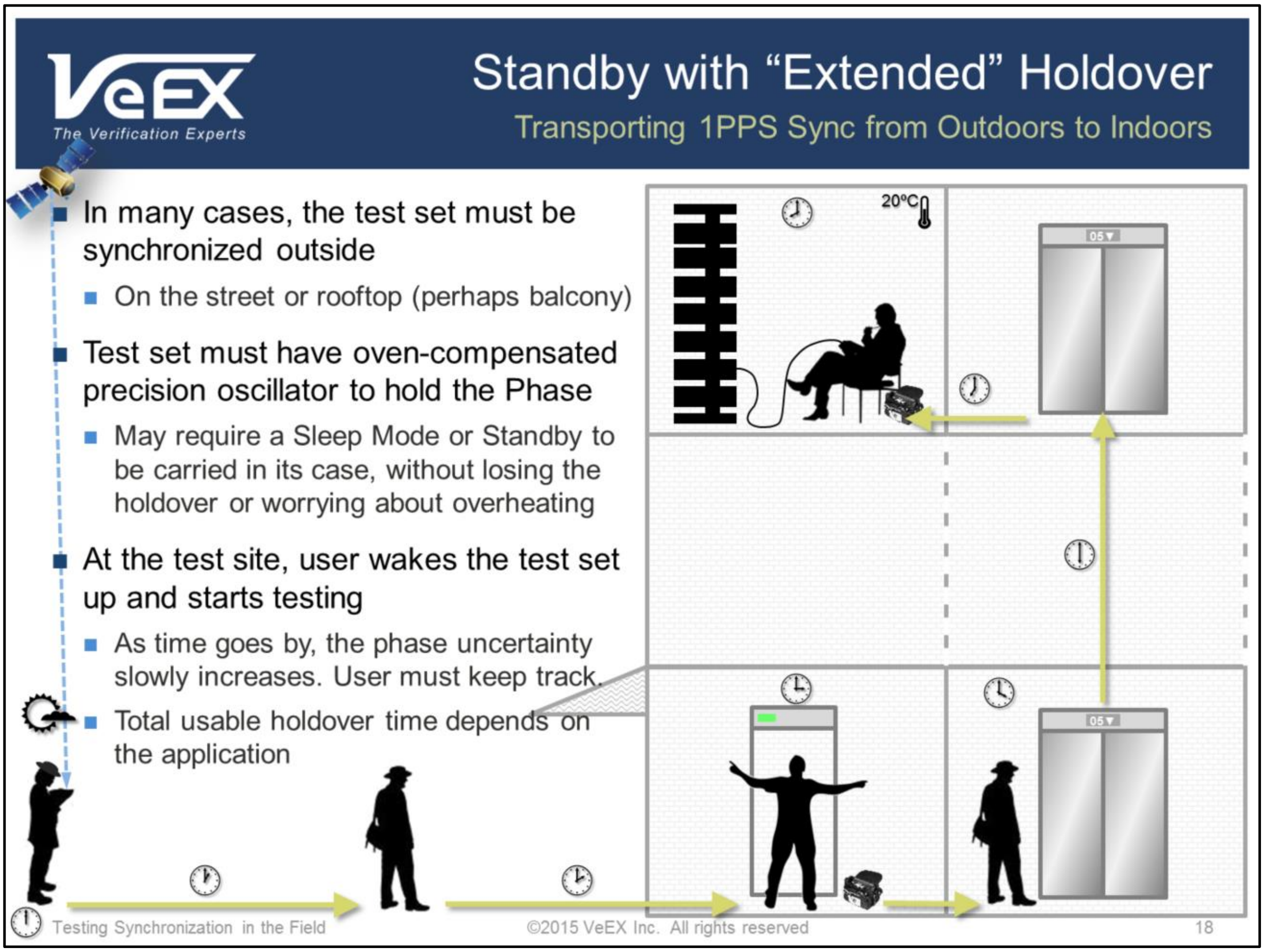


Extended Holdover

- The idea is to use the frequency holdover characteristics of high-stability oscillators to synchronize frequency and time (discipline) to GNSS (outdoors) and then transport that reference indoors to perform Wander, Phase and Latency tests
- The problem with holding Time or Phase, at the nanosecond scale, is that it is not fully repeatable, so the total holdover time to an agreed uncertainty threshold may vary every time, depending on the frequency steer (offset) of the oscillator at the moment the GNSS is disconnected.

Reconnecting the GNSS signal during a test would force the local reference oscillator to make frequency adjustments and it may also realign the 1PPS pulse, making the Wander (TIE) or Time Error (TE) measurements invalid. Needless to say, reconnecting the GNSS is not recommended.



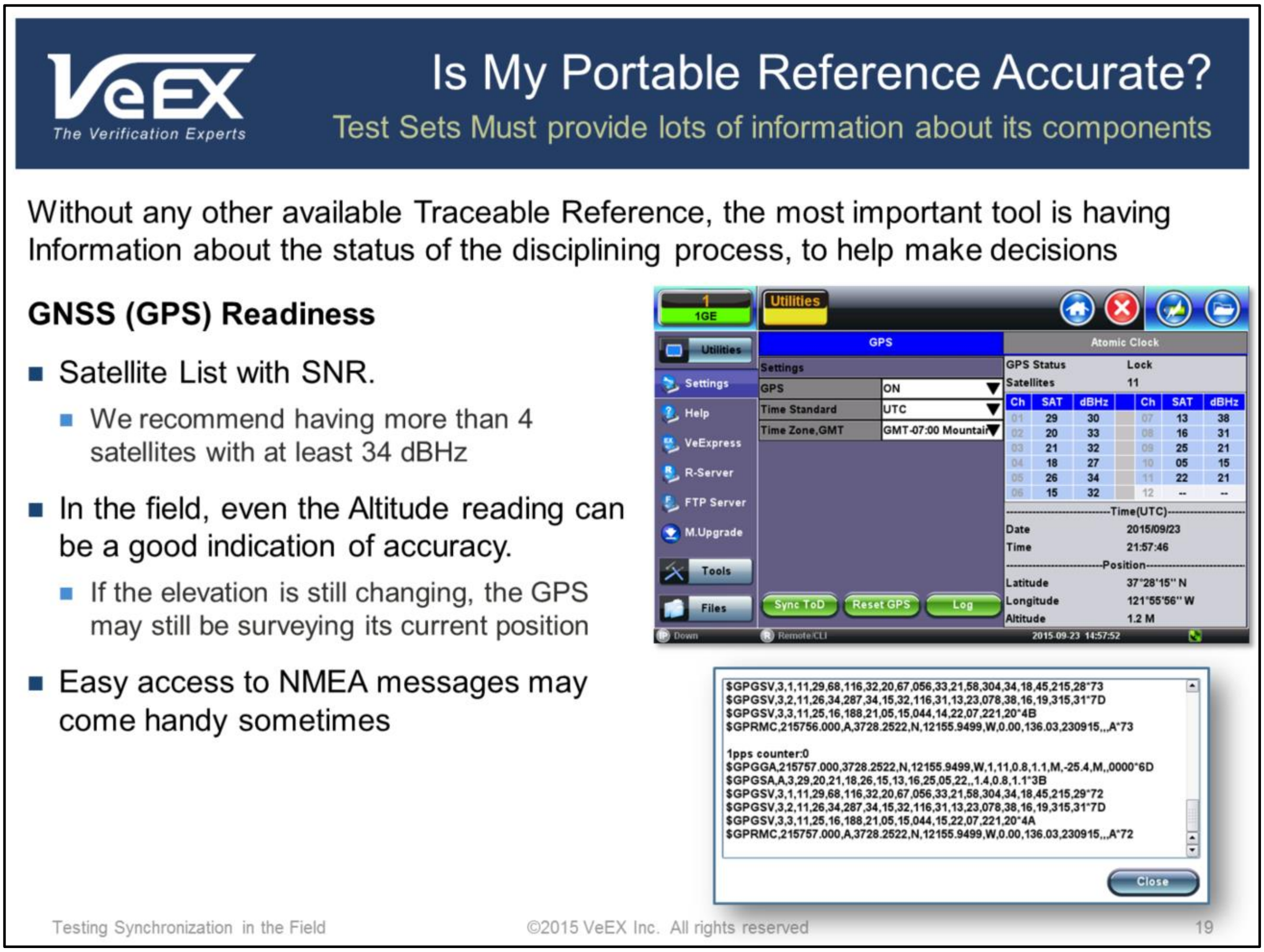
Note: Standing next to glass windows to get GNSS signal is not always a good idea

- Some may suggest a window facing South, other say North, but in reality GNSS satellites are not stationary and they have fast orbits in all directions. So facing UP is the best suggestion.
- Energy efficient glass is now common in most modern buildings and they could contain a reflective metal coating that may also reflect the satellites' RF signals. Neighboring glass buildings could also create a multi-path effect.

Attention! If there is a GNSS antenna feed in the premises, you have two choices:

a) Do not use it and stay in holdover. Because the cable length is different to the one used to discipline the test set outside, there would be a phase difference. Connecting it to the test set's GNSS will cause it to make a phase correction by changing its frequency. You will have to wait for it to discipline again!

b) Use it from the beginning and give it enough time to discipline. Be aware that many GNSS antenna feeds are not properly documented, so the cable length and its delay may not be available to make the necessary corrections.



After performing ride-along with a few synchronization engineers, in different parts of the world, one thing I noticed is that those frequency-oriented professionals had to trust their instruments and references (Rb and Cs). They rely on one or two LEDs to know whether the equipment is ready or not and believe in it. I'm sure that trust comes after a lot of time spent with their gear.

When GNSS, Disciplining, Phase and Holdover are factored in, the situation changes. It is not just about trusting the reference and the instrument, but the process and environmental conditions. They may not be constant or fully predictable. So, the equipment must provide enough information for users to assess the current synchronization status and worthiness. Things like:

- Satellite reception quality
- Precision Oscillator status
- Disciplining process and phase alignment status
- Lock time
- Holdover time

Remember, outside of the lab or central office there may not be any other reference to perform an accuracy check. It is more like a "Trust but Verify" approach.

Is My Portable Reference Accurate?

Test Sets Must provide lots of information about its components

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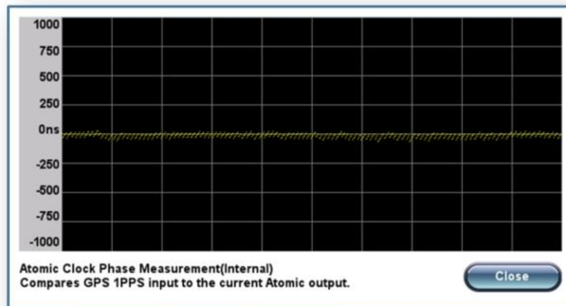
Precision Oscillator Readiness

- Make sure the test set has a temp-compensated oscillator
- Wait for the recommended warm up time
- Have a look at the oscillator status
  - Make sure it is Locked to its calibrated frequency
- Check internal phase alignment
  - verify disciplining status before forcing the test set into holdover
- Easy access to telemetry data (log)

Standby Mode

- Helps keep the oscillator ready and improves frequency retrace



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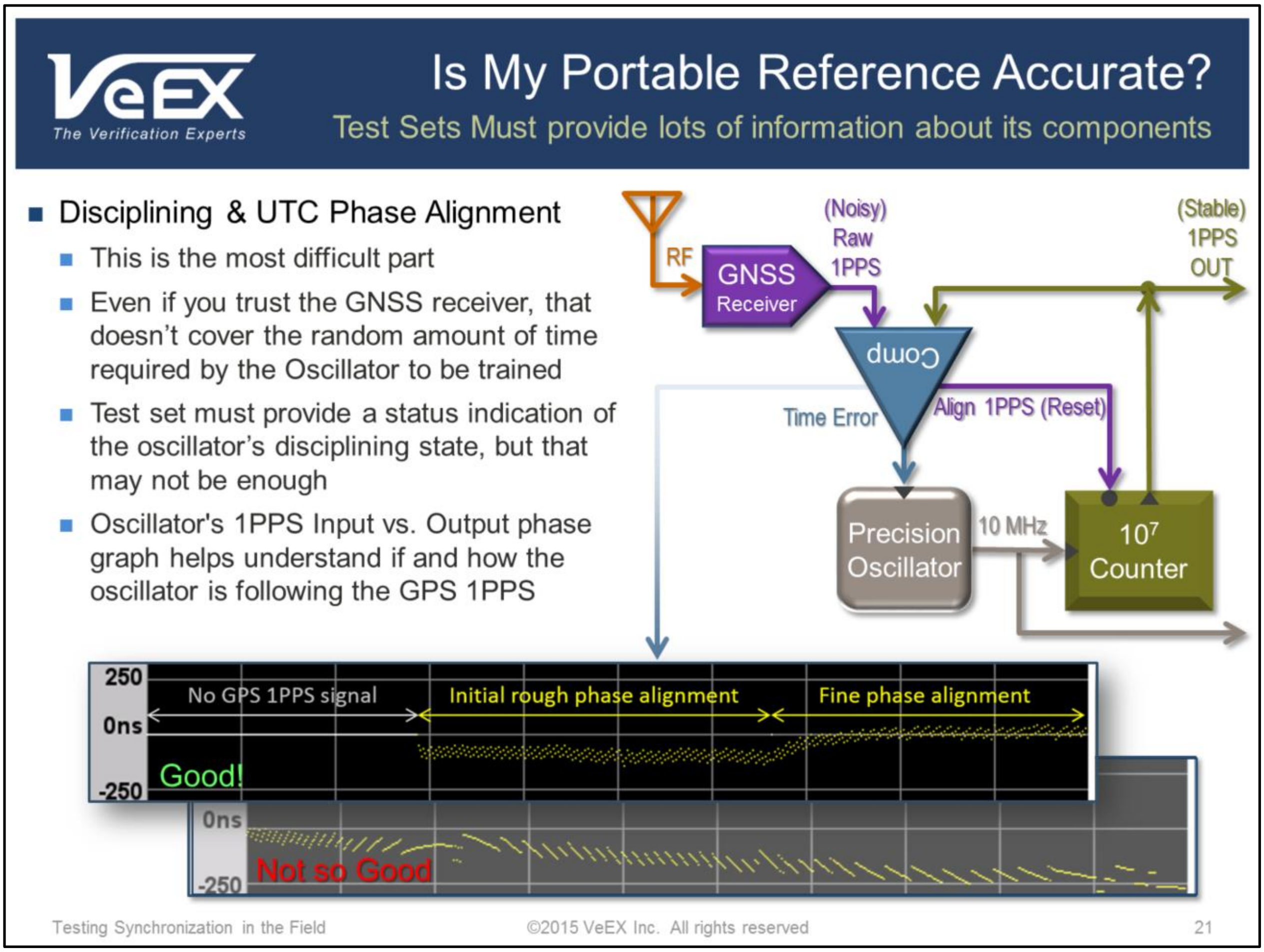
Depending on the oscillator technology used, end users also need to learn how to take care of sync test equipment (or portable references) to keep them in top condition

- Storage requirements
- Handling (shock, vibration, temperature range, etc.)
- Required warm up and ready-to-test times
- Any calibration requirements

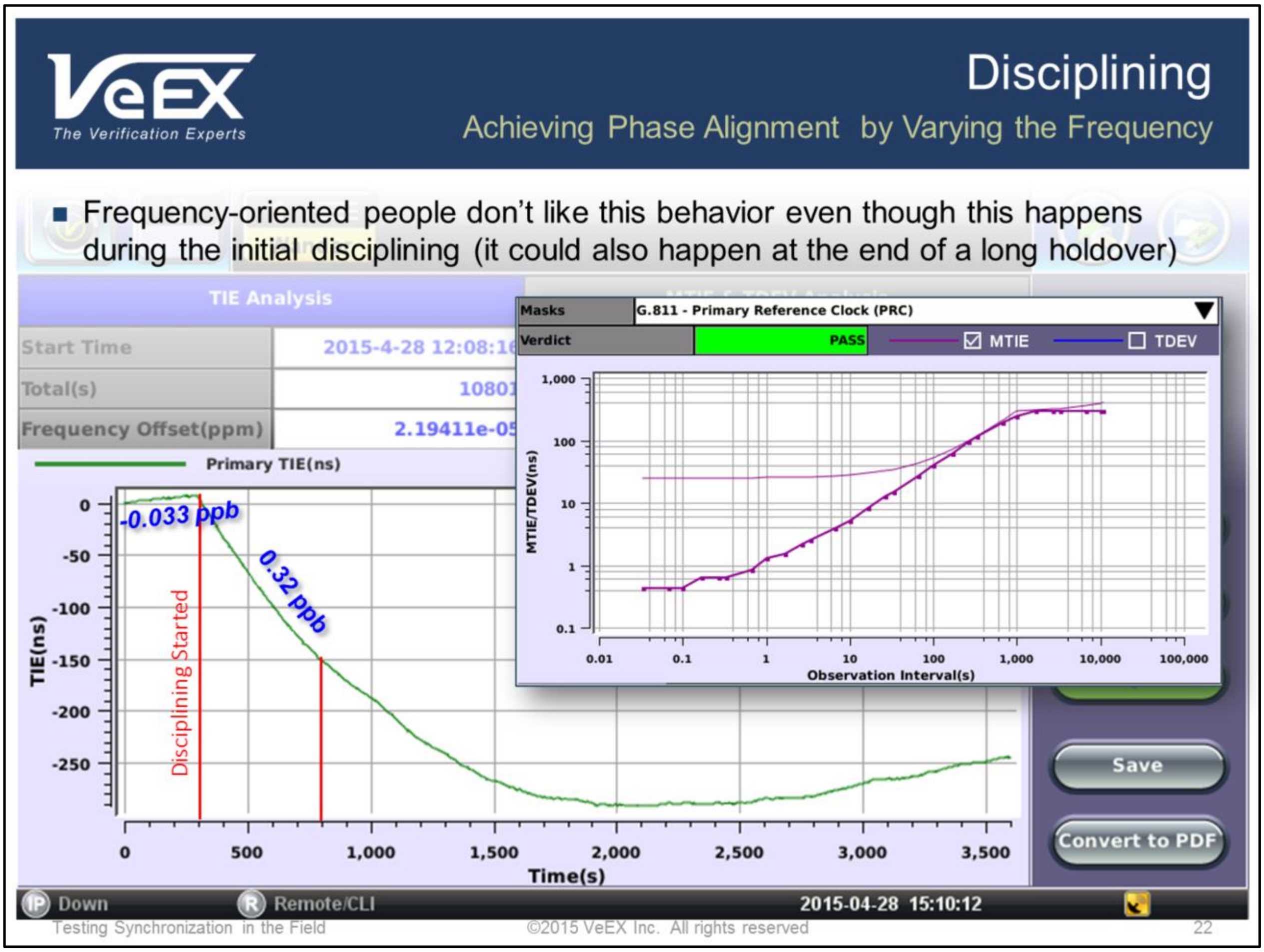


The diagram depicts a simplified version of the disciplining loop

- Let's assume we start with a perfect oscillator with exactly 10MHz frequency
- The counter will count one million cycles and produce an overflow pulse every second (phase is still arbitrary).
- When disciplining is started, the first pulse from the GNSS is used to reset the counter, performing a Rough Phase Alignment of the pulses, within one 10MHz cycle (100ns).
- Followed by the Fine Phase Alignment, which requires the oscillator to modify (steer) its frequency (faster and/or slower) to align its phase to the GNSS 1PPS, until the comparator outputs zero correction.
- At that point the 10MHz and 1PPS are aligned to the GNSS UTC.

Note that changes in the oscillator frequency are required to keep the phase aligned. We have found that this may upset frequency purists.

- Neither 1PPS nor 10MHz outputs should be used for testing during the initial disciplining process



This slide documents the discussion in the previous slide. It shows how the frequency is initially abruptly changed when disciplining is turned on and then slowly steered to align the 1PPS output to the GNSS UTC reference.

- Although this is all done within the PRC requirements, it would affect the results of any Frequency or Phase measurement. This is why users must wait for full disciplining before running any Wander of Time Error tests.
- Similar behavior (phase realignment) may occur if the GNSS is reconnected (ore comes back) after a long holdover, due to the cumulative phase error that needs to be corrected.

Some users have asked if the initial frequency change can be smoothed out, so it doesn't affect measurements much. There are two parts to the answer:

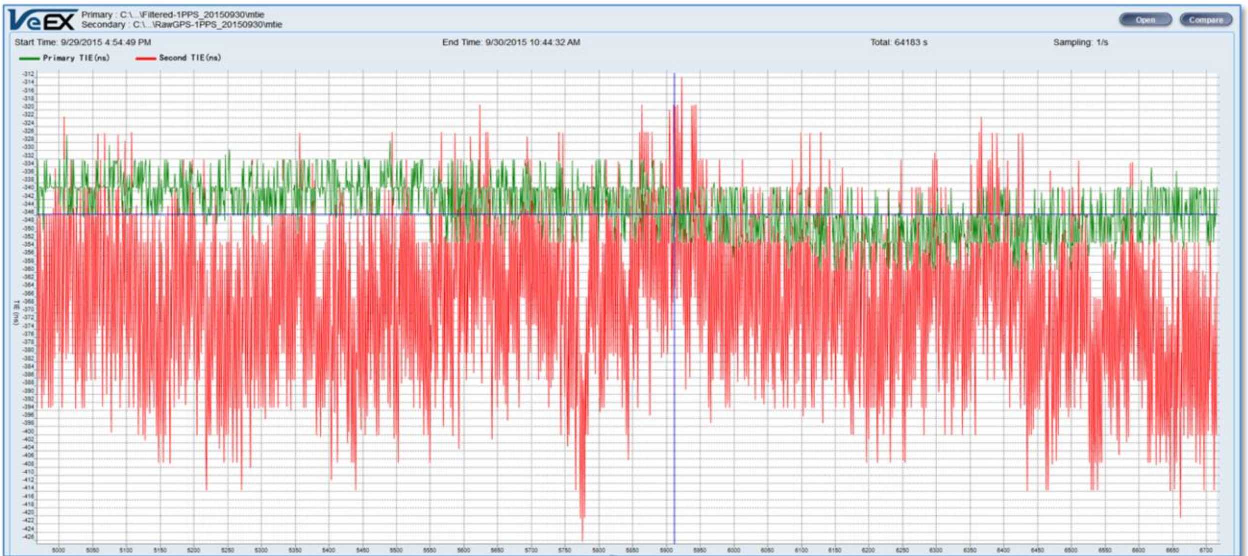
i. This behavior comes from the oscillator component and its disciplining circuitry, so it is vendor dependent

ii. Even if the initial change is made smoother, the frequency and phase of the reference will still change, adding unwanted wander to any measurement. So, there is no improvements. No measurements shall take place until all the equipment involved has warm up, lock and ready.

Disciplining

Stabilizing and Filtering GNSS or PTP Raw Clock

- Disciplining uses the short-term stability of the high precision oscillator and long-term accuracy of the GNSS to provide the best of both worlds
  - The precision oscillator acts as a filter to stabilize the "noisy" GNSS clock phase.
  - After long disciplining, the oscillator will find the "true" time and will try to hold it.

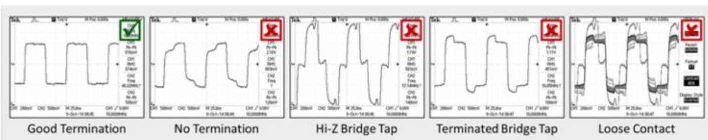


Note: The red behavior is not usually visible to (or affects) users, because it is part of the "magic" that happens inside telecom-grade GNSS-disciplined Clocks or PTP Slaves.

Sync Test Sets for the Field

Required features and functions

- Battery-operated Multi-Purpose Test Set with
  - Portable (built-in) GNSS-disciplined Clock with high-quality temperature-compensated oscillator as a reference (it may need a stand-by mode, if asked to turn the device off)
  - Long-term Wander and Time Error Measurements and Analysis (at least 72 hours)
    - *Measure recovered clock (from data link or protocol) and physical (external) signals*
  - Support for 1PPS, 1.544MHz, 2.048MHz, 10MHz, 1,5Mbit/s, 2Mbit/s,…
    - *Square and sinusoidal clock signals. High sensitivity*
  - Ethernet, SyncE, 1588v2, SDH/SONET, PDH/DSn synchronization testing
    - *Ethernet BERT, Throughput, RFC2544, Y.1564 SAM*
    - *PTP Emulation, Packet Delay Variation measurements, protocol capture and decode*
    - *Traffic Generation with mixed traffic profiles to stress networks, links and protocols*
    - *SyncE, E1 and STM-1 testing with ESMC/SSM QL encoding and decoding*
  - GNSS-assisted One-Way-Delay measurements for symmetry verification
  - Sleep/Standby Mode with Extended Holdover to transport 1PPS synchronization
  - CPRI/OBSAI (FTTA/DAS) for cellular
  - Pulse Shape Analysis
    - *Is this a 2MHz or 2Mbit/s signal?*
    - *Reflections or bad terminations?*



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Why "Multi-Purpose" test sets?

- Unless the NEMs, Contractors or Service Providers have dedicated "Synchronization Crews", most likely the same technicians would be the ones turning up and troubleshooting other links and services. At the very least, Ethernet, SyncE, CPRI/OBSAI could be required in the cellular market. So, having a dedicated synchronization tester may not always be the best choice.

The need for Pulse Shape Analysis

- You would be surprised about the number of times users are unsure about whether the clock signal is 2.048 MHz or 2.048 Mbit/s. User can either carry an oscilloscope or use the built-in Pulse Shape tool to quickly confirm whether is an E1 signal or not.
- Sometimes test signals or reference clocks are branched (e.g. using a simple T to split the signal) and not properly terminated. This can create reflections, distortion and/or smoothing of the pulse's shape. Sometimes other equipment are connected and disconnected in one of the branches, during a wander test, causing the signal to change its shape and rendering the measurement invalid.

- Which sync tests do we want field technicians/engineers to perform during Acceptance or Bringing-into-Service tests?
- What type of results should they be able handle in order to issue a Pass/Fail assessment?
- How long would the battery of tests is expected to take?

Installers and communication service providers (and the industry in general) need to have these discussions to come up with practical solutions and set the right expectations.

It is not that test equipment are not ready for testing sync in the field, because there are a few options already. The question is: how would they be used to achieve the desired goals?


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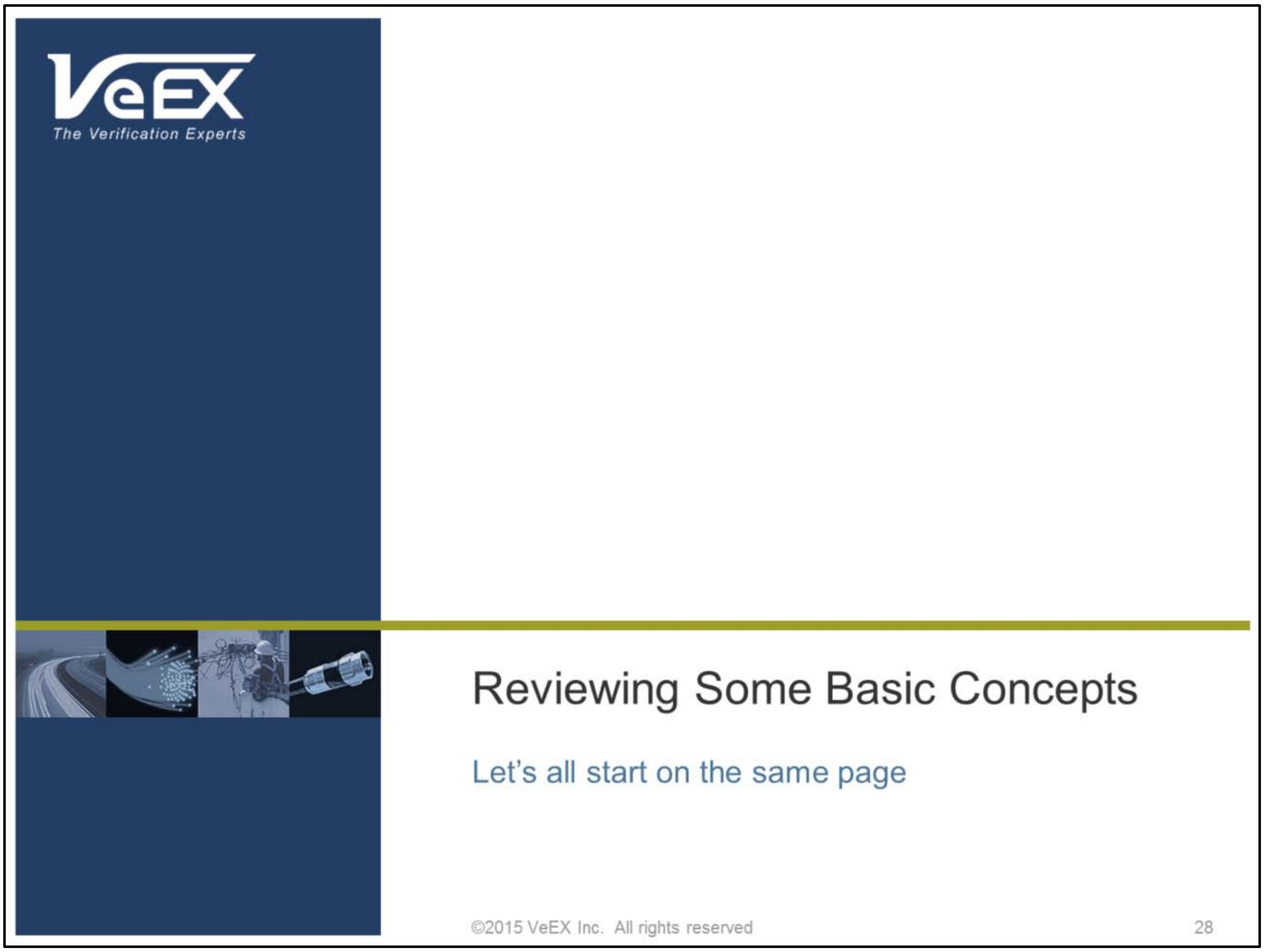
Additional Information…

Extra reading material



Just so we all speak the same language and agree on the same terms. Otherwise we could spend hours disagreeing on the same thing.

Example: What is a Clock?

- A Frequency source (e.g. 10 MHz)
- A Timing source (e.g. 10PPS)
- A Phase or Time alignment source (e.g. 1PPS)
- A Time (as a length) source (e.g. to measure time, as in “the event lasted 1.2 seconds)
- A Time (as an instant) source (e.g. UTC, as in it is exactly 09:35:24)

Specially important is to differentiate Frequency accuracy from Phase or Timing accuracy. Many people think they have the correlation figured all out, but you may be surprised how often we get the “Oh! That’s right”

It is NOT that Simple

How to Verify Synchronization Accuracy & Stability?

- Most Specifications and Recommendations have been written based on lab tests
- Most recommendations are geared towards network elements and links, not T&M
- At Synchronization workshops you may often hear something like this:
  - "*I had a dream the other night, so I went to my office, ran some simulations under certain arbitrary conditions and here are my recommendations…*"
  - "*We used our expensive controlled-environment lab, with a calibrated Cesium reference, network elements and impairment emulators, and here is what we found…*"
  - There are very few references of true field tests, under the conditions to which field engineers and technicians would be facing.
- How to get a reliable, accurate and stable reference in the field?
  - Often the only traceable clock you have is the one that needs to be measured/verified
- What to do if there is no GNSS coverage (indoors)?
- The intention of this presentation is to bring synchronization testing down to earth
  - Start a discussion for all parties to agree on what needs to be tested and what to expect

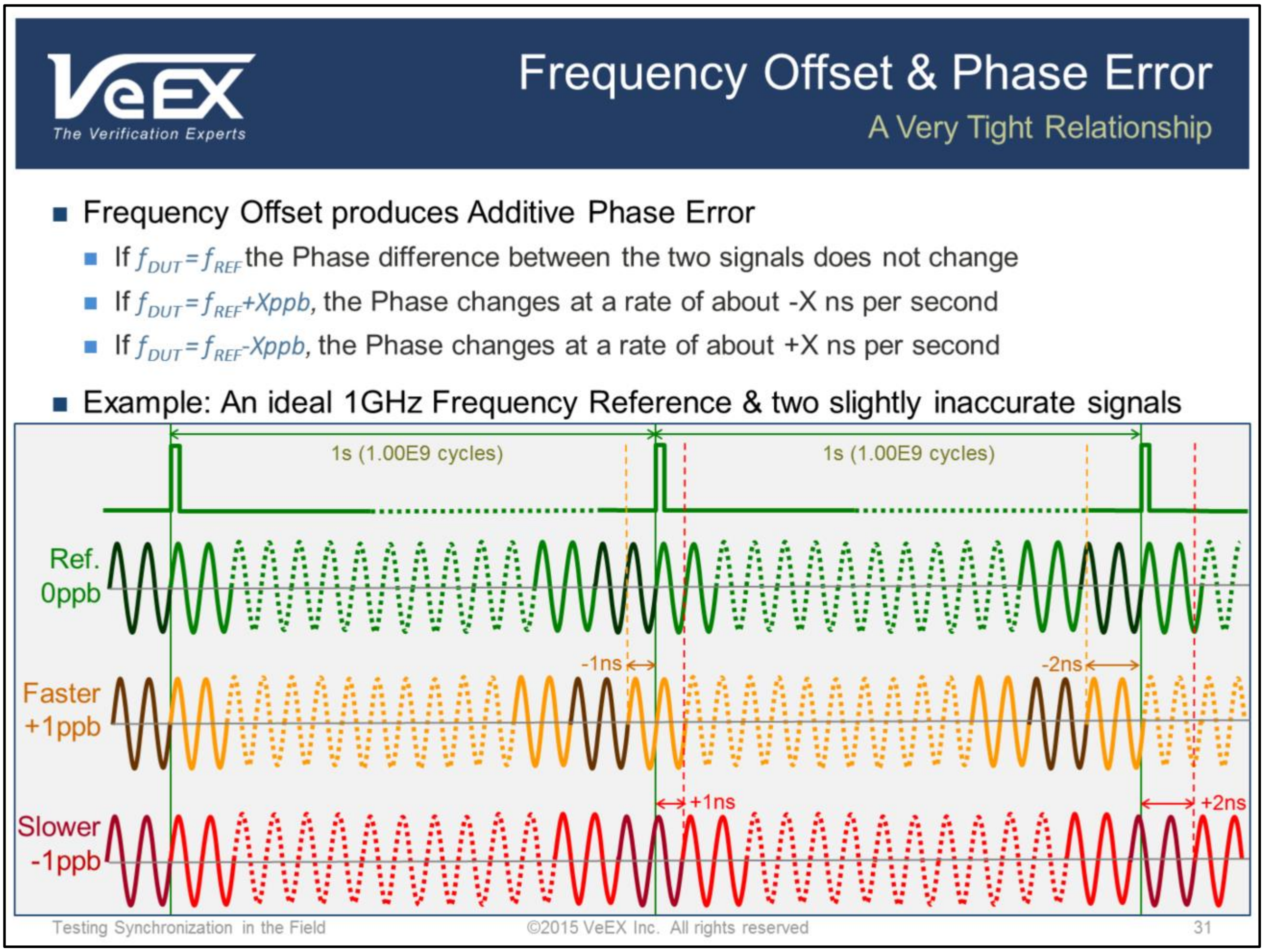
There are solutions for all those issues, but people need to adjust their idealistic (lab-centric) expectations and bring them down to earth. Then, it becomes simpler, without having to compromising on portability, accuracy or autonomy. Just keep it real!

Frequency and Phase Measurements

Long-Term Stability and Accuracy

- Wander Measurements
  - Measures long-term Frequency stability
  - TIE data discards the initial absolute phase error between the two signals (starts at 0ns)
  - Frequency Offset can be calculated (and mathematically removed from analysis)
  - MTIE gives you an idea of the maximum phase variations over different time intervals
  - TDEV measures the expected time variation of a signal as a function of integration time. It provides information about the spectral content of the phase noise of a signal. (Often ignored because the information provided is not obvious or useful in the field.)

- Phase Measurements (Absolute Time Error)
  - Measures the short and long-term accuracy and stability of a timing signal (1PPS)
  - TE records all the actual Phase Differences between test signal and reference pulses
  - Still contains all the frequency stability (wander) information
  - Frequency Offset can be calculated (and mathematically removed from analysis)
  - MTIE and TDEV analysis still apply



Note: The 1000000000Hz example is juts used for convenience, to simplify the math and make it more obvious. The use of 10MHz ±0.01Hz could be more practical but would not be that easy to visualize.

Without thinking too much, some people arrive to the wrong conclusion that having the perfect frequency guarantees phase alignment, but this example shows that Phase Error is cumulative and any small fractions of ppb can make a big difference in short time.

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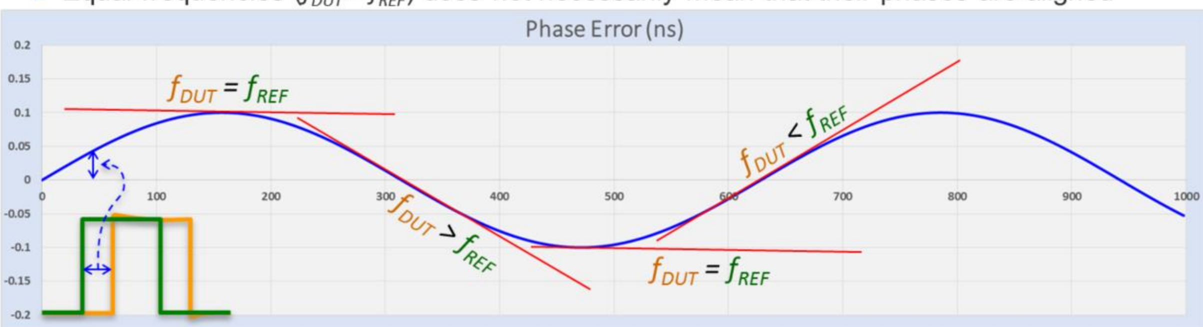
Phase Graphs

Reading TIE or TE Traces

- Wander or Phase Measurements record the phase difference, in time (ns), between a Signal or Device Under Test (DUT) and a Reference Clock
  - Wander (TIE) or Phase (TE) measurements are taken periodically and their results are plotted over time, to identify short and long term behaviors of the test signal.
  - If both frequencies are exactly the same, the phase between them should not change. This is equivalent to a straight horizontal line in the Wander of Phase Error graph.
  - If the frequencies are different, one of the signals would have more or less cycles than the other within each second that passes, which is represented as a slope.
  - Precision oscillators keep on adjusting their frequencies over time to maintain accuracy.
  - Equal frequencies ($f_{DUT} = f_{REF}$) does not necessarily mean that their phases are aligned



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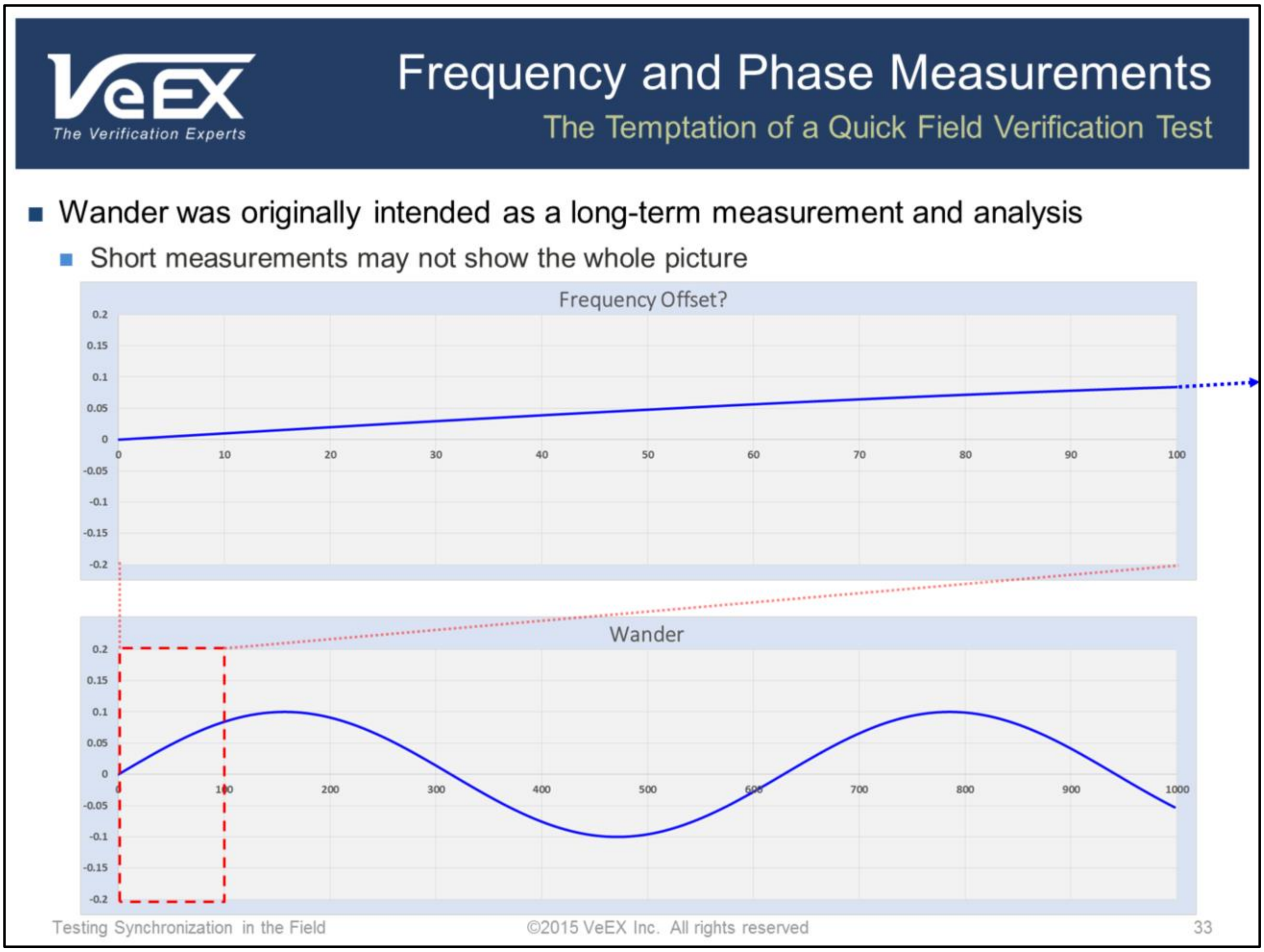
Time Interval Error (TIE) and Phase/Time Error (TE) are both phase measurements, but TIE is a relative measurement (to the fist sample) while TE is absolute.

Phase and Frequency are tied to each other, so on phase variation graphs we can see the frequency variations. The frequency offset at any given point can also be accurately calculated.

- You can read the Phase Error at any instant by looking a any given dot (data point) in the TE graph.
- You can calculate the Frequency Offset by looking at the slope of any line between two different data points in the TE graph.

Sometimes, when people refer to the “frequency” of the TIE or TE behavior, they are usually refereeing to the Rate at which Phase is changing.



1. First graph is a quick (short term) wander test – If the test is stopped here, it would seem like there is a frequency offset (represented by a phase ramp)
2. If the test is allowed to run longer, then you may find that the oscillator makes a correction and the phase comes back. So, it is not offset but wander around the ideal value.

Demystifying GPS (or GNSS)

- “GPS” or “GPS Receiver” ≠ “GPS Clock”
- GPS Clock = GPS Receiver + High-Stability Oscillator (OCXO or better)
  - “GPS Disciplined Oscillator” or “GPS Disciplined Clock” are better terms for it
- GPS Clocks are meant for Stationary applications (install it and forget it)
  - If it takes days to stabilize and reach its highest accuracy, that is not a big problem
  - For portable field applications a quick solution is required as the geographical position changes with every job (perhaps many times a day).
- You can’t just strap a battery to a small GPS Clock to use as a portable reference
  - If its geographical position changes, it may start a new sky survey to accurately identify its new position, so it can calculate accurate time (this may take hours or days)
- What about other Augmented GNSS Technologies
  - A-GPS (Assisted) – Uses cellular triangulation and known Wi-Fi spots to speed up the initial time-to-first-fix (position). But, it requires cellular radio and internet connection.
  - DGPS (Differential) – Uses ground-based RF reference stations to improve position accuracy. Not applicable because of its size, cost and limited availability

GNSS: Global Navigation Satellite Systems

- GPS: Global Positioning System (US Dept. of Defense)
- GLONASS: Global'naya Navigatsionnaya Sputnikovaya Sistema (Russia)
- BeiDou: (China)
- IRNSS: Indian Regional Navigation Satellite System (India) – “Under Construction”
- Galileo: “Under construction” (European Union)

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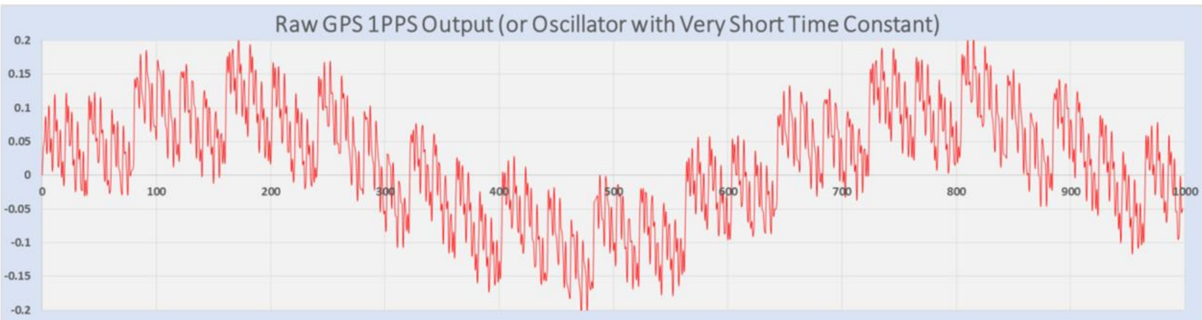
Demystifying GPS or GNSS

Poor Short-term Stability with Long-term Accuracy

- The example below depicts the Absolute Phase or Time Error of a clock signal, measured against an ideal 1PPS reference (aligned to standard UTC second)
  - This could represent the RAW 1PPS output of a GNSS receiver
- There are a lot of rapid phase changes (poor short term stability)
- Although very unstable, overall, the signal can be considered quite accurate as its average (long-term trend) seems to be a zero horizontal line
  - If only you could average it in real-time to extract the accurate timing → Disciplining



You may have never seen something like this simulated waveform, because usually there is no access to the GPS receiver's raw output (internal). What you get at the output of the GPS-disciplined Clock is a filtered and stabilized version of this.

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Demystifying Disciplining
What is the Time Constant (TC)?

- It is a time window used by the oscillator's dynamic steering algorithm, as a "filtering" mechanism to remove the effects of poor GNSS short term stability
  - It could be compared to averaging all the phase values over certain period of time
- Shorter TCs make the oscillator's frequency steer (change) faster
  - The oscillator output follows the source (reference) very close
  - Often used when disciplining the oscillator to a more precise and stable reference
- Longer TCs make the oscillator's frequency harder to steer (change)
  - The oscillator output "ignores" any rapid changes present at the input and slowly adjusts to new values, creating a filtering effect
  - Often used when the input has lower short term stability than the oscillator itself, but better long-term accuracy, such as GNSS sources
- Disciplining is all about "calibrating" the oscillator's Frequency
  - Timing or Phase alignment comes second
- Short-term Disciplining (for field applications) is not an exact science
  - Depends on oscillator's current frequency & phase states and parameters (e.g. TC)

You may not have heard about Time Constant because there may not be a need to change it in stationary GNSS Clock applications, and it may be pre-set to a long value due to their intended long-term installation.

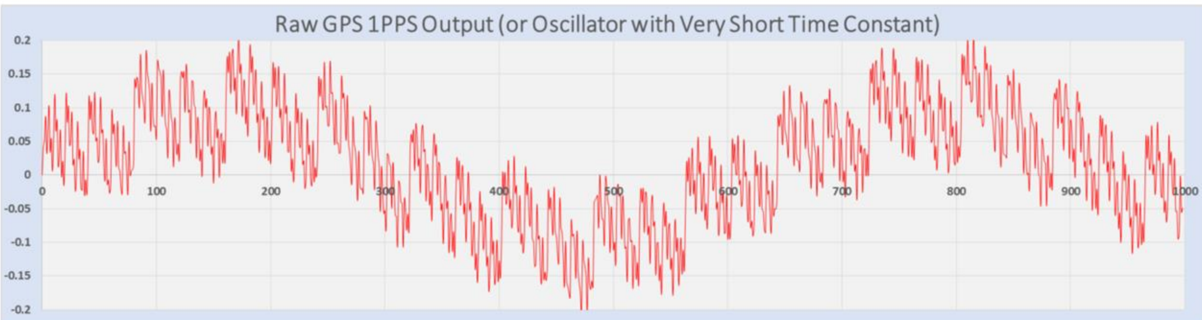
Now, moving the equipment around brings the TC into play, because users' may need to experiment with different values before settling on the one that best fit their test procedures and environments.

- TC values are not standard. They depend on vendor-specific steering algorithm implementations
- For VeEX products with CSAC, we currently suggest using TC=1800s for "quick" field tests

Disciplining Time Constant

Example: "Filtering" with a Very Short Time Constant

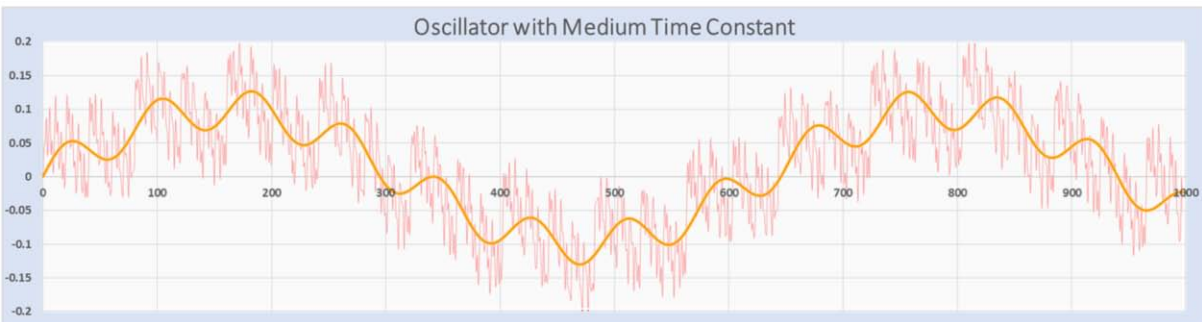
- The original signal is fed to and oscillator with very high short-term stability (DOCXO or Atomic Clock)
- If the Time Constant is very short, the oscillator would be very easy to steer and its output would most likely follow all instantaneous changes at its input.
- Overall, this behavior is not desirable.



Disciplining Time Constant

Example: “Filtering” with a Medium Time Constant

- If the Time Constant is increased to a “Medium” length, then the oscillator would be a bit difficult to steer
  - Its output frequency would be a bit hard to change
  - It would “ignore” fast changes at its input, filtering them out at its output
- The oscillator removes the fast phase changes, but continues to follow its input trend
- Disciplining can be achieved very quickly (tempting for field testing), but long term accuracy or stability can’t be guaranteed



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Disciplining Time Constant

Example: "Filtering" with a Long Time Constant

- If the Time Constant is increased to a "Long" length, then the oscillator would be more difficult to steer
  - Its output frequency would be harder to change
  - It would "ignore" short and medium term changes at its input, filtering them out at its output
  - It would also take more time to correct and settle, before it can be used
- The oscillator successfully removes most of the phase "noise" and isolates the main trend
  - Only the long-term wander can be noticed

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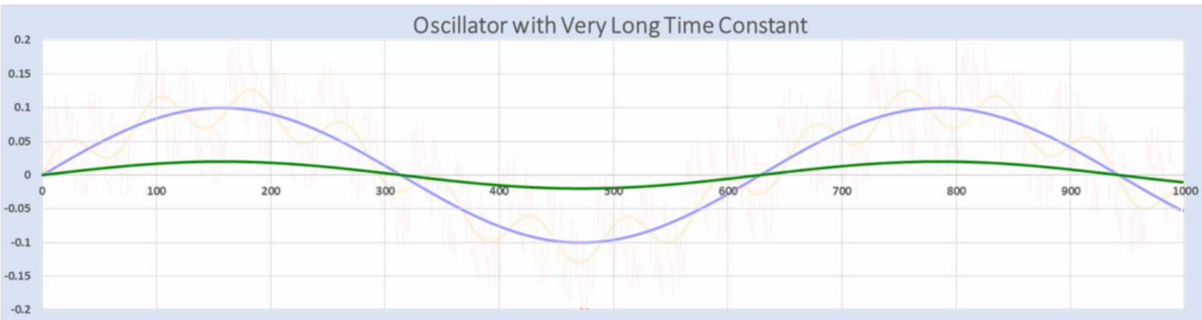
Disciplining Time Constant

Example: "Filtering" with a Very Long Time Constant

- If the Time Constant is increased to a "Very Long" window, then the oscillator would be extremely difficult to steer
  - Its output frequency would be much harder to change
  - It would "ignore" most changes at its input, filtering them out at its output to slowly find the "true" long term accuracy of the source
- The oscillator successfully removes most of the phase "noise"
- The problem: This process will take long time to discipline
  - This may be ideal for stationary equipment, but not for "quick" field tests



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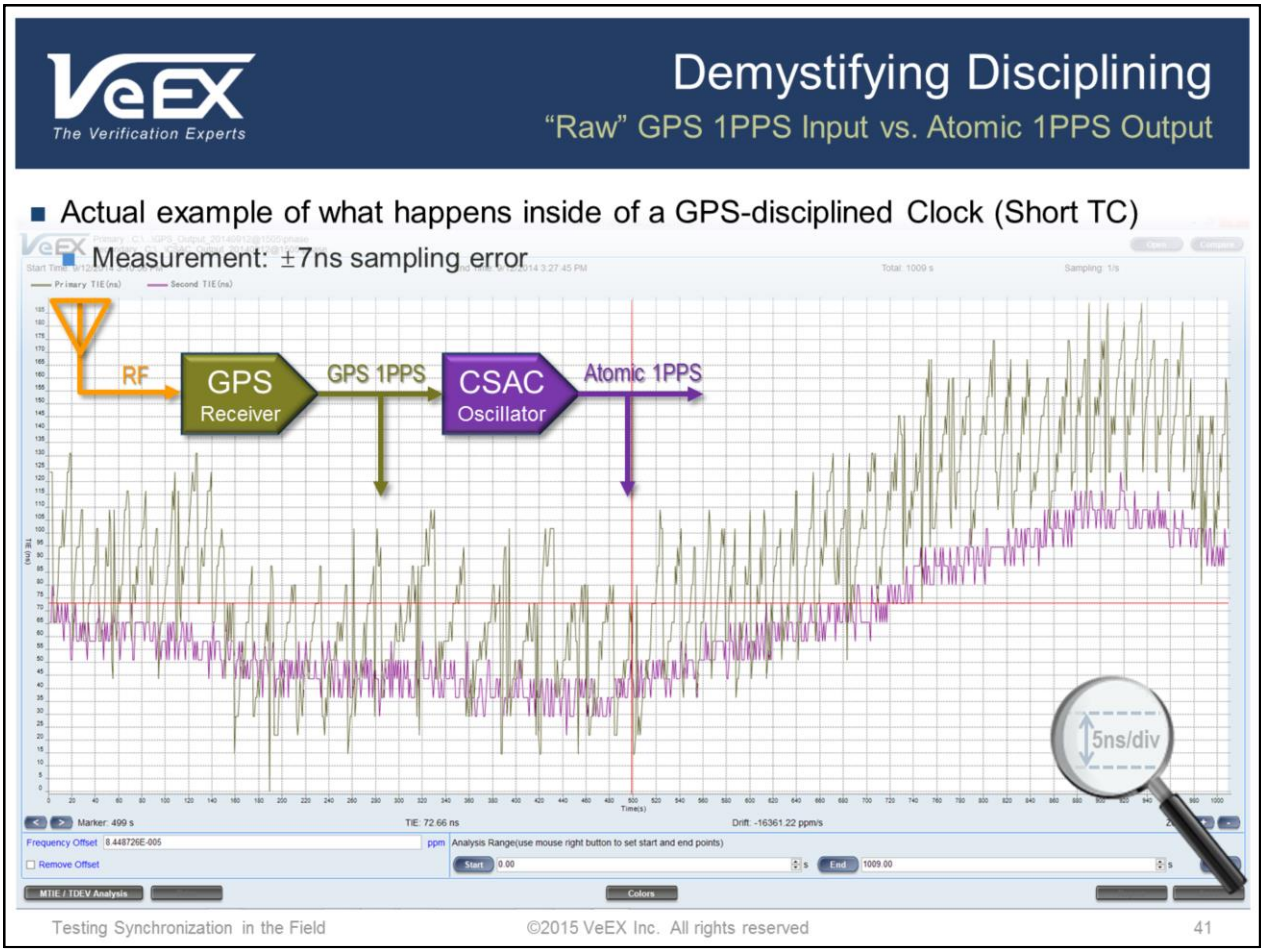
If the GNSS signal is always available, Very Long TC are often recommended for long-term tests, as it would offer the most stable output.

- But, it would take long time to find the most accurate time.

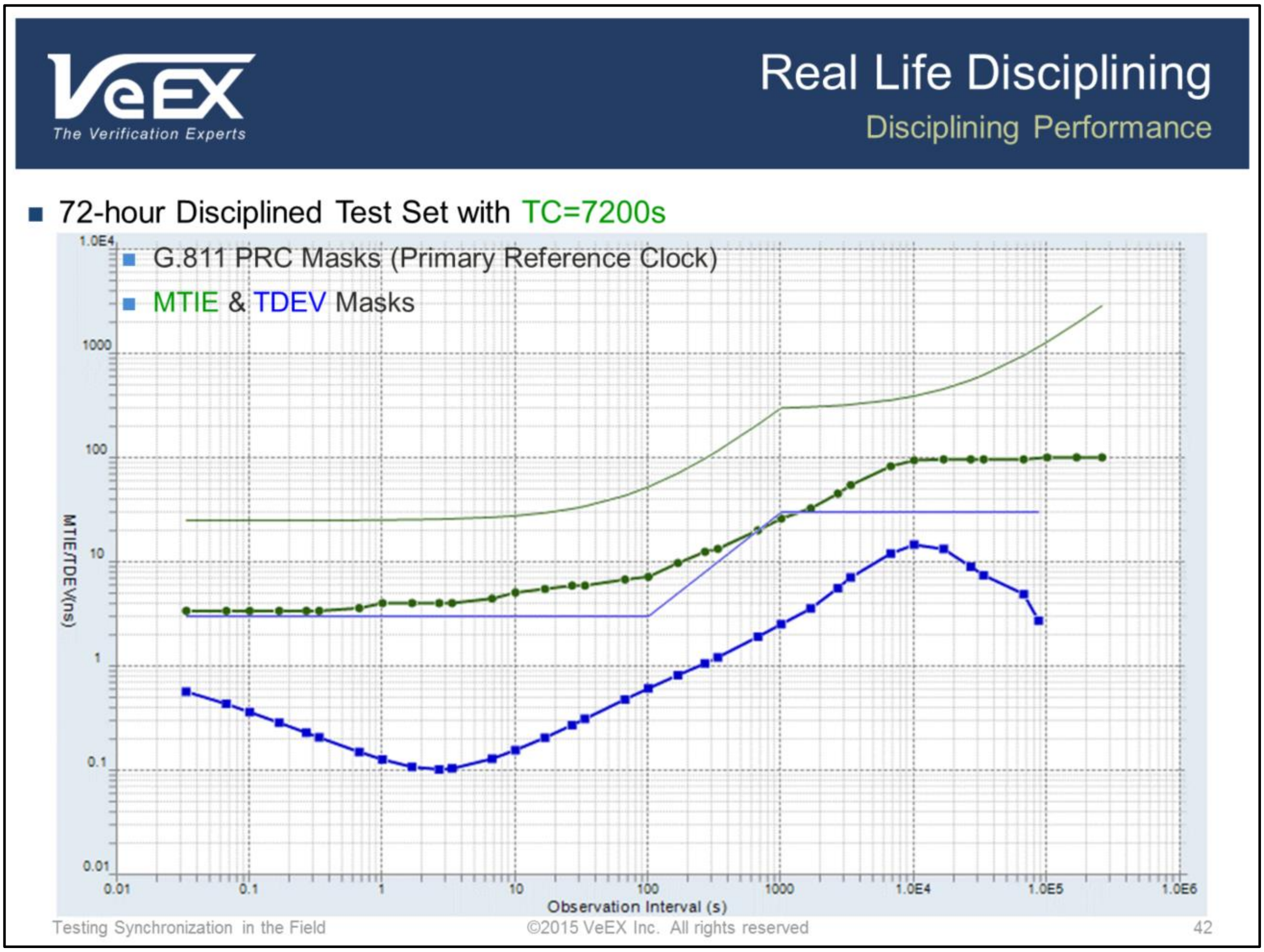
Changing the TC often is not recommended as the oscillator may display unintended behaviors,

- Users experimenting with TC values are encouraged to reset the oscillator every time (in some cases, power cycling the device) so it "forgets" previous training or disciplining



You may wonder why there is so much "noise" on the purple signal, instead of being a very smooth (ideal) line.

- First, you have to keep in mind that the vertical scale is just 5ns/division. We are still not used to see data this "close"
- Second, the test set used to measure the phase has a resolution of ±7ns, so a 0ns phase would be read as either +7, 0 or -7 ns.
- Time constant (TC) used was very short, so the oscillator follows the main phase trend, while filtering the short-term noise.



Disciplined CSAC's MTIE and TDEV performance under G.811 PRC masks

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Precision Oscillators

Comparison of Typical Characteristics

- High Quality frequency oscillators are required for Field Synchronization measurements and Extended Holdover
  - Cost, power consumption, size are important for field equipment
  - Temperature compensation is key for field measurements (e.g. outside vs. inside)

Type	Frequency Accuracy	Stability (1s)	Warm Up	Power	Comments
Cesium	< 0.001 ppb	$\sim10^{-11}$	30 min	High	Cost, size, weight, not rugged, etc.
Rubidium	< 0.05 ppb	$\sim10^{-11}$	N/A	High	Cost, size, weight, not rugged, etc.
CSAC (Chip Scale Atomic Clock)	< 0.1 ppb	$2.5\text{x}\ 10^{-10}$	~2 min	120 mW	Sealed physics package (optical VCSEL atomic vapor resonance cell). Oven controlled environment.
High Qual. OCXO	<10 ppb (up to 1 ppm)	$\sim10^{-10}$	~10 min	Watts	Oven-controlled Quartz oscillator.
XO, TCXO	>1000.00 ppb	$\sim10^{-9}$	N/A	Low	Not Applicable - Quartz, Inaccurate, unstable, no Temp. compensation.

Field Stability and Accuracy T&M

Challenges and Solutions

Limitations of Legacy Portable Test Sets

It may NOT just be a Firmware Upgrade promise

- They may have been designed to handle common data link clock interfaces only
  - No support for standard Sinusoidal (1.544, 2.048, 10 MHz) or 1PPS clock references
- Lack of precise internal Frequency sources
  - Use of regular Quartz oscillators with no temperature compensation
  - 4.5 and 3 ppm are the typical accuracies (OK for BERT but not for synchronization)
- May have been designed for quick acceptance and verification tests
  - Long-term software stability may be an issue
- May be able to accept external GNSS Time Stamp via RS232 or USB-converter, but would require direct 1PPS support for accurate timing
  - There are limitations in using stationary (long-term) receivers for nomad applications
- There was a Jitter and Wander Measurement “vendor blackout” for several years
  - Sunrise Telecom may have been one of the few vendor of freq. sync test sets for a while
- VeEX redefined its Sync strategy in 2011, foreseeing future LTE-A/TDD wander and phase needs. Fully redesigned test gear with added GPS-receiver and chip-scale Atomic Clock

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Lack of Traceable References

The Biggest Challenge for Field Measurements

- Finding a portable Wander and Phase Measurement Test Set is not the hard part

The Problem

- The challenge is to find a Frequency and/or Phase reference in the premises
  - The clock output recovered from the DUT is often the only clock signal available
  - GNSS disciplined clocks don't work indoors or in L1 obscured areas ("urban canyons")
- Free-running highly-stable calibrated oscillators (e.g. Rb, Cs) are technically good Frequency references for relative Wander measurements
  - In practice, customers often disagree
  - They expect to see a flat horizontal wander line, without any mathematical "magic"

Proposed Solution

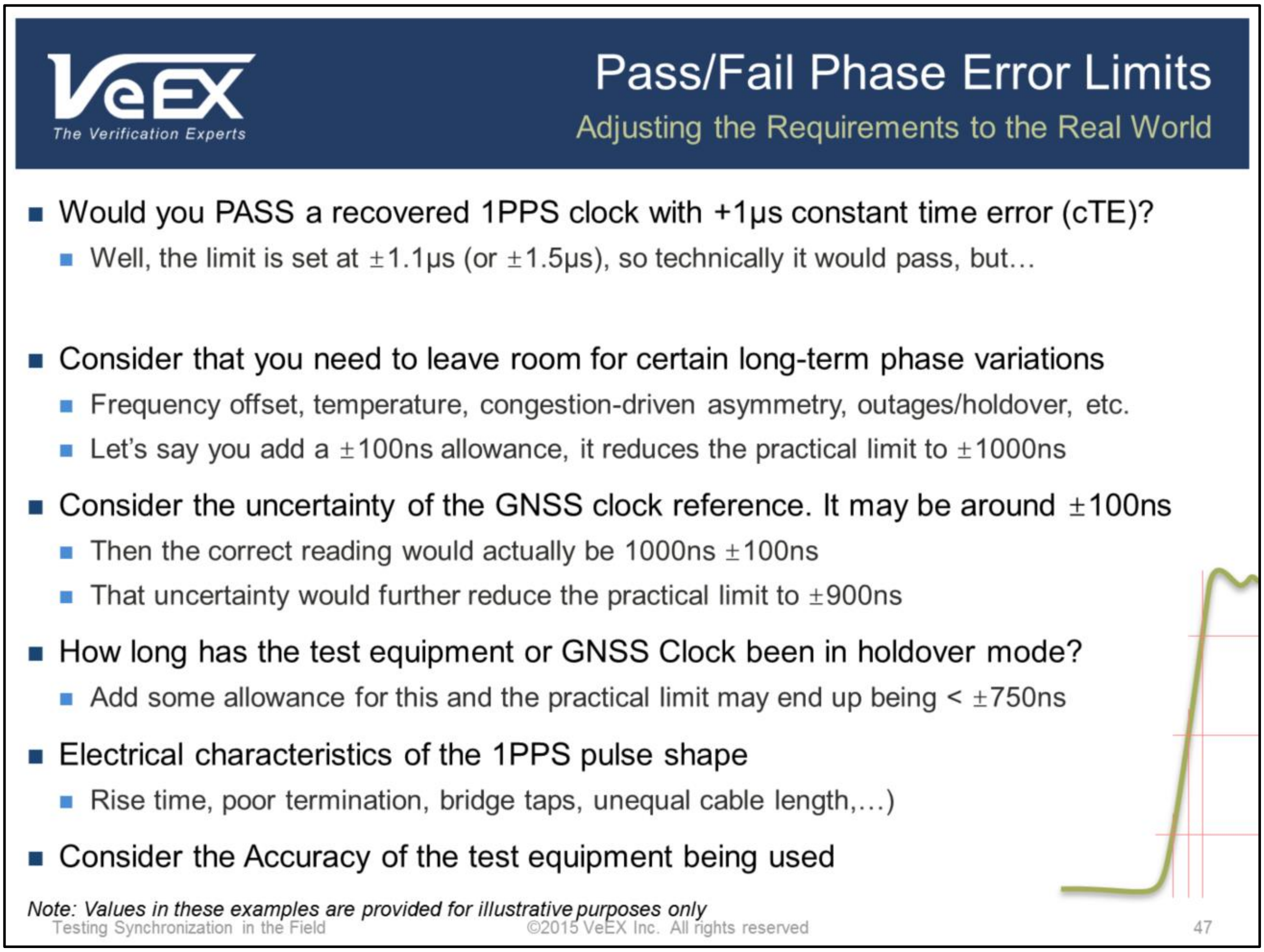
- Use the Holdover characteristics of a precision oscillators to provide temporary Frequency and Phase/Timing references for short-term verification tests
  - Discipline outside and bring inside for Time Error (Phase) sync test
  - They can provide a few hours of accurate and stable reference
  - Requires high-quality temperature-compensated precision oscillator (e.g. OCXO, CSAC)

High-quality high-stability calibrated oscillators can be used, in free-running mode, to measure Wander (frequency stability), because the frequency its offset (compared to the ideal frequency) can be accurately calculated and mathematically removed, isolating the DUT wander as if it was measured against an ideal clock.

The same does not apply to absolute Phase, Timing or Time error measurements. The reference's phase always has to be aligned to the standard timing reference.

- Time itself doesn't exist as an absolute natural reference. It is a concept we humans agree on and constantly coordinate through observation.
- How something that doesn't exist became so important? To the point of being the core definition for "everything" else we know. A fundamental part of the structure of the universe or a way for us to explain it.
- The "arbitrary" Cesium definition of a second links the length of a second to a physical characteristic (it actually defines the period of 1Hz). But what defines time? When should that second start?

We "believe" in UTC (Coordinated Universal Time) as the definition of time as an instant, an event (not as a "length")



To many end users it is not quite clear how the Absolute Time Error at the edge device should be assessed as a Pass or Fail. The limit is set at ±1.1µs as an infinite flat mask, but:

- If the recovered clock's is unstable and its phase quickly wanders between +500ns and -500ns, which is still within the mask. Would it pass? No, because it would surely fail the wander requirements for the clock interface in question.
- Over time the frequency and phase are expected to move around a bit, do we have leave a safety margin? Who defines it?

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1588v2 PTP Emulation

Grandmaster and Slave Emulation

- Truth: A test set may never be as good a true Grandmaster or Slave
  - Clock recovery has a lot of proprietary "magic" that differentiate vendors' performance
  - An emulation WOULD NOT reflect or predict the final performance of the actual link
- Grandmaster and Slave emulation
  - Must support Unicast & Multicast, Layer 2 & 3, up to 64pkts/s (128 optional)
  - Raw Clock recovery (no filtering) and clock translation
- Emulation may come handy in the following scenarios
  - Run a quick Feasibility test on a link, before the GM or Slave are installed
  - Verify that GMs can be "seen", are reachable from the far end, PTP session can be initiated, basic synchronization can be attained and have a look at the link's PDV.
  - As a troubleshooting tool to quickly check or evaluate Slaves under different traffic profile conditions and configurations (Much faster than carrying or configuring a GM and extra Ethernet test set)
  - Run wander measurements on the RAW recovered 1PPS clock (no filtering)
  - Identify any potential Phase/Timing offset before the approved Slave is installed
  - Training sessions

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Grandmaster and Slave emulation is more of a convenience than a true representation of the expected network performance when all is set and done.

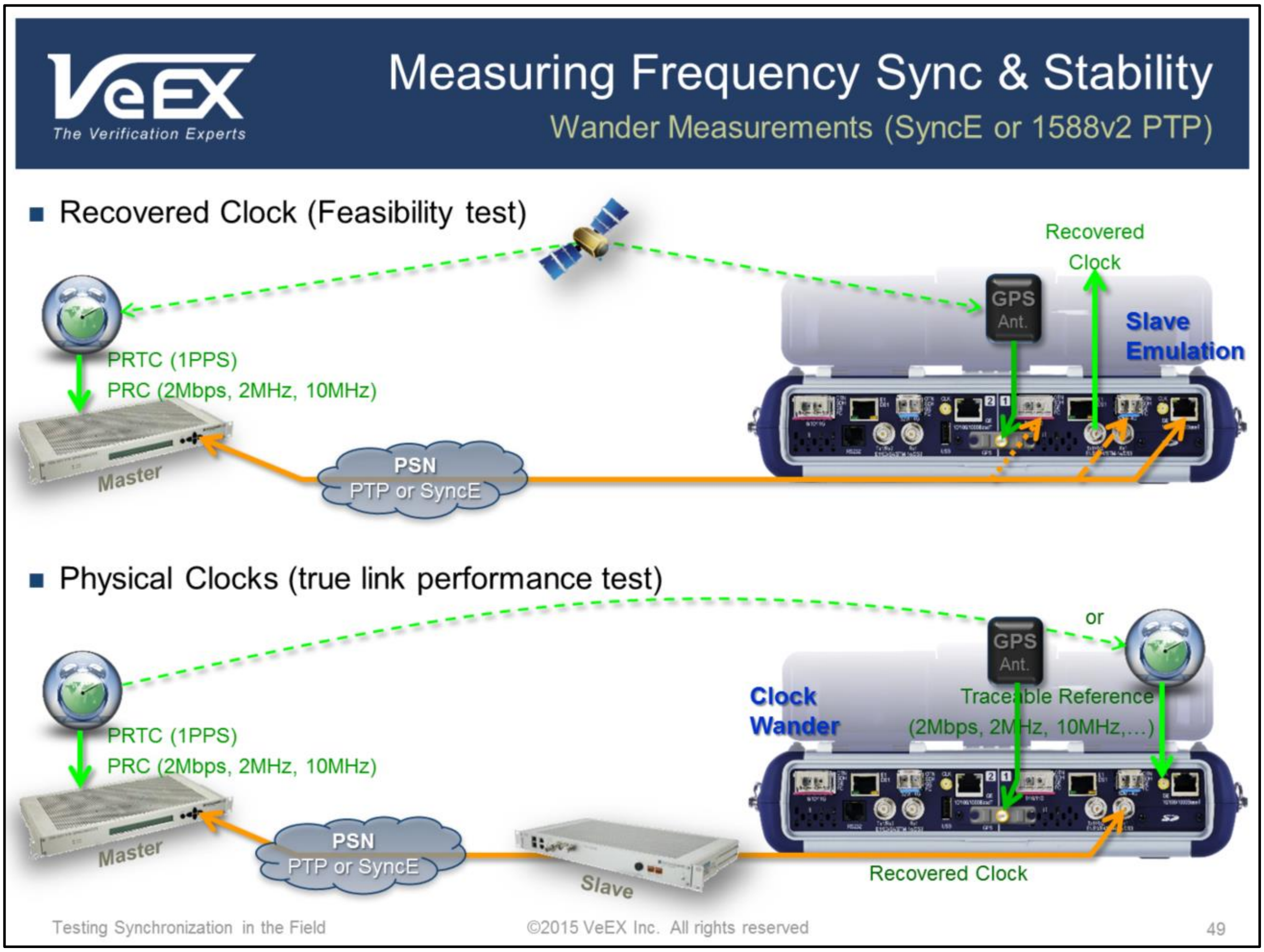
What is RAW Clock?

- Is a direct representation of the clock recovered by the PTP engine, without passing it through a disciplined oscillator to "filter" it

Why RAW? Don't all Slaves filter and stabilize their clock outputs?

- **Yes**, for Slaves and BCs. That is their job. Slave manufacturers spend a lot of R&D perfecting their "secret sauce" to best their competitors. Disciplining a local oscillator makes sure that glitches in the network side don't affect the clock output.
- **No**, for Test Equipment. At least that our position at VeEX. If we pass the PTP recovered clock through the CSAC we would be able to present a fairly good clock output, but our users would end up being blindfolded. If PDV goes "crazy", the CSAC would make it look like nothing is happening. One could even disconnect the Ethernet cable and the holdover would mask it all.

In our opinion, the purpose of Test Equipment is to give users visibility. Looking at the unfiltered recovered clock you will see the instantaneous effects of any variations on the network side (PDV, traffic, impairments, outages, etc.)



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Measuring Frequency Sync & Stability
Wander Measurements (SyncE or 1588v2 PTP)
Recovered Clock (Feasibility test)
Recovered
Clock
GPS
Ant.
Slave
Emulation
PRTC (1PPS)
PRC (2Mbps, 2MHz, 10MHz)
Master
PSN
PTP or SyncE
Physical Clocks (true link performance test)
or
GPS
Ant.
Clock
Wander
Traceable Reference
(2Mbps, 2MHz, 10MHz,…)
PRTC (1PPS)
PRC (2Mbps, 2MHz, 10MHz)
Master
PSN
PTP or SyncE
Slave
Recovered Clock
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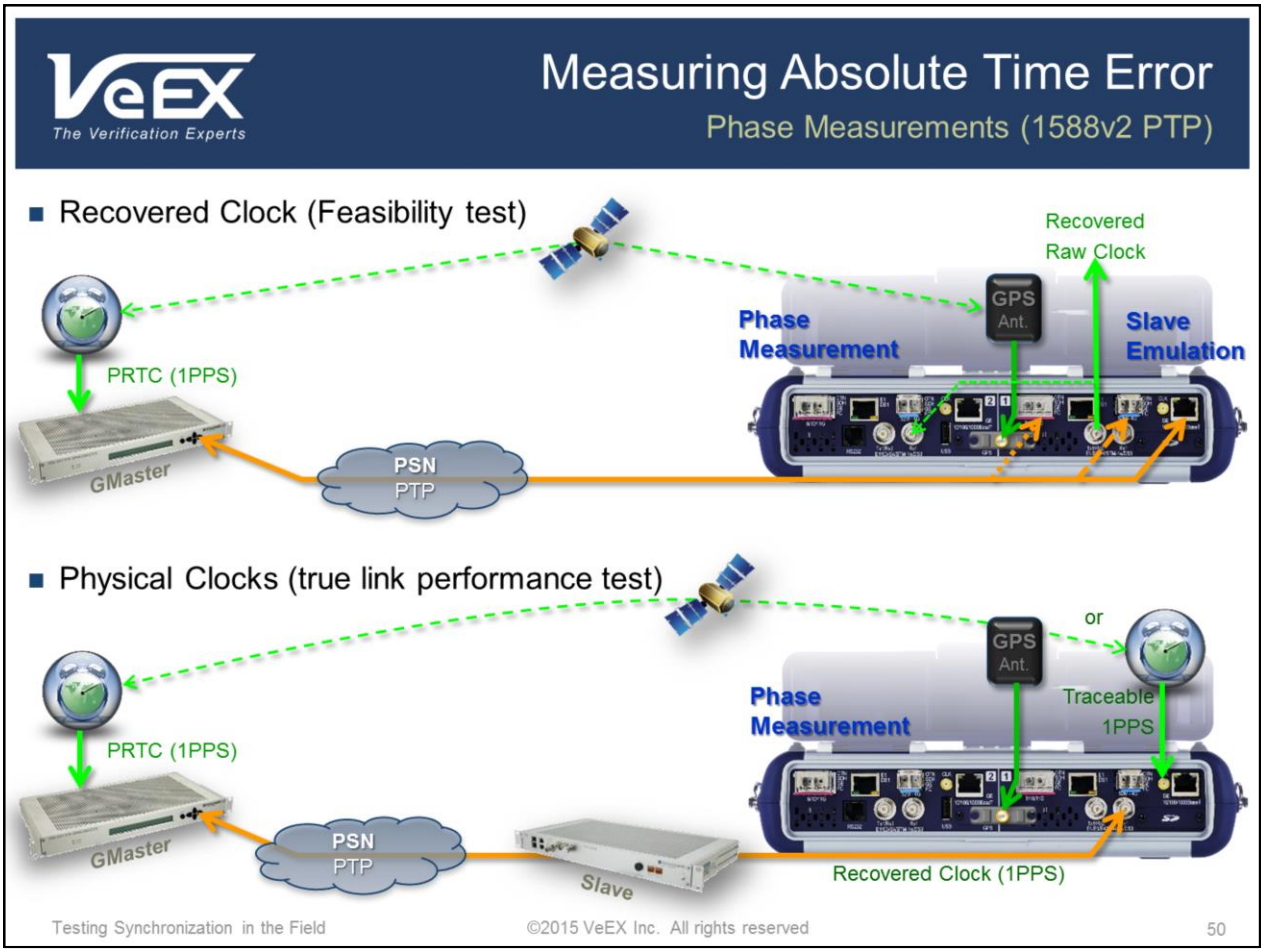

Measuring Absolute Time Error
Phase Measurements (1588v2 PTP)
The Verification Experts
Recovered Clock (Feasibility test)
PRTC (1PPS)
GMaster
PSN
PTP
Phase Measurement
GPS Ant.
Recovered Raw Clock
Slave Emulation
Physical Clocks (true link performance test)
PRTC (1PPS)
GMaster
PSN
PTP
Slave
Phase Measurement
GPS Ant.
or
Traceable 1PPS
Recovered Clock (1PPS)
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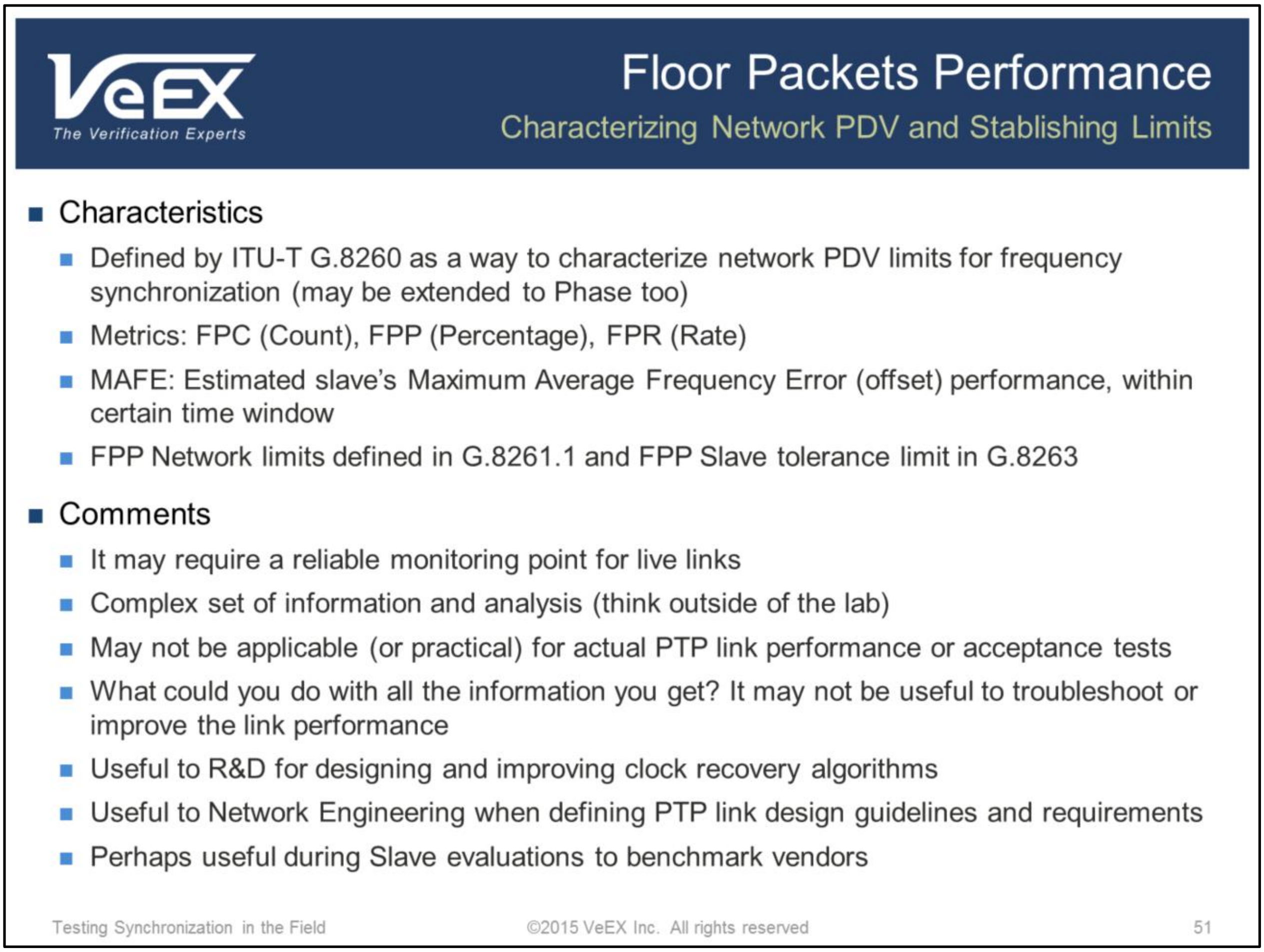

There are plenty of tests and metrics to evaluate an actual link performance, but:

- Would you expect field crews to perform all of them?
- Would you expect field crews to consolidate all the data and come up with a conclusion or diagnostic?

Whether it is needed, useful or not, Floor Packet metrics is currently becoming a requirement in field T&M tenders. Clear explanations on why it is needed have not been given, but that is how the industry seems to be working these days ("test equipment have to support everything that is published, just in case").

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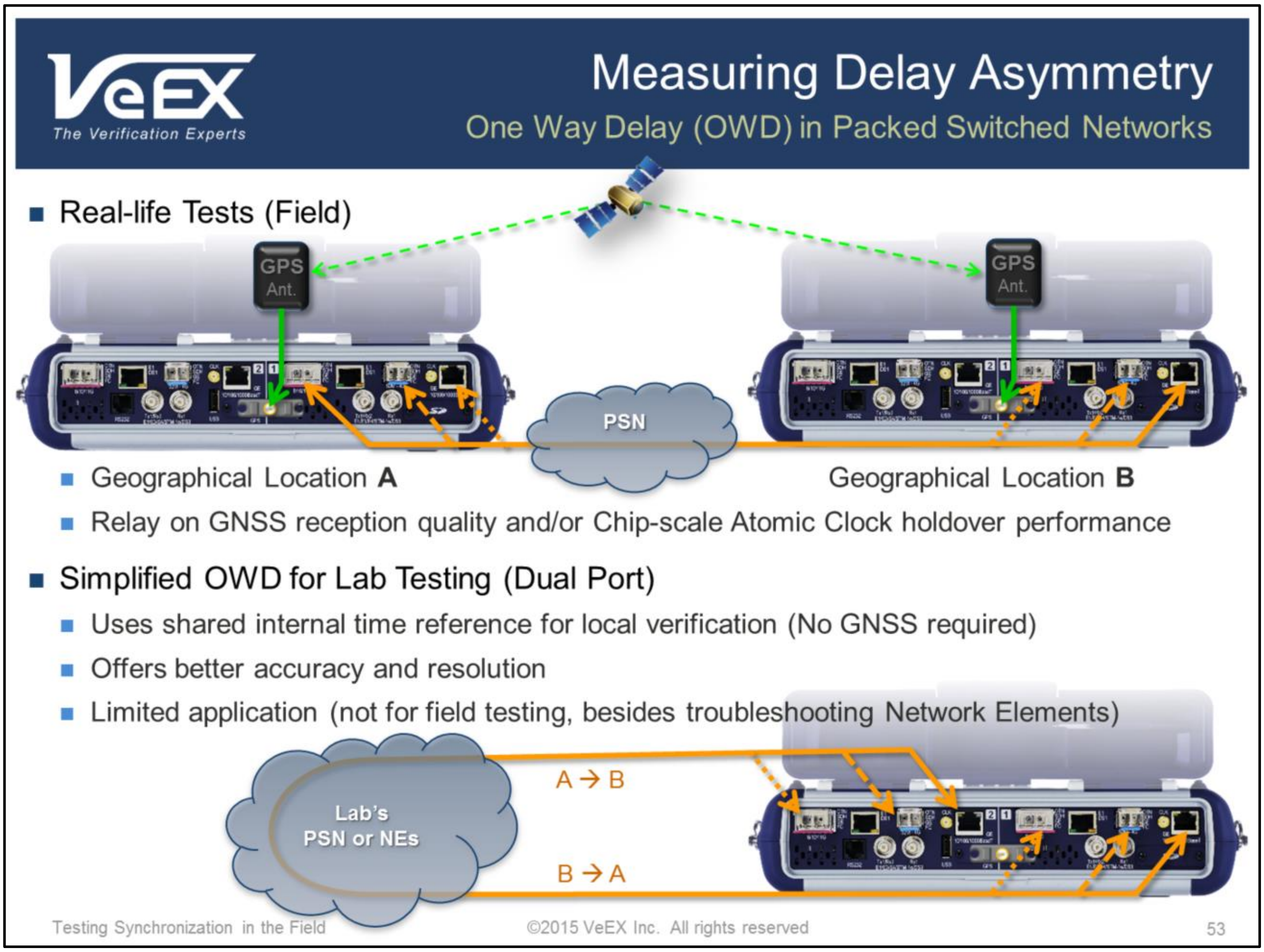
GNSS-Assisted One Way Delay

Quantifying Asymmetry

Phase/Time delivery via PTP does not tolerate latency asymmetry

- One-Way Latency measurements
  - Uses UTC timing (from GNSS) to time-stamp TX packets as they leave the test sets
  - Uses UTC timing to record the packets arrival
  - Each test set uses “simple” math to calculate the delay in the incoming direction
  - Information is exchanged with the far end to identify any asymmetry
- Things to Consider
  - PSN delay times vary over time due to traffic conditions, packet sizes and priorities
  - Proprietary – There are no industry standards for OWD tests (but that is also true for other end-to-end Ethernet tests)
  - Logistics – Requires tight coordination between crews and equipment (usually disciplined and in holdover) at the two geographical ends of the link
  - Uncertainty (accuracy) as both test sets could be in different stages of holdover
  - Achieving better than 1µs accuracy can be challenging (it may not be enough for the granularity being required to fine-tune physical layer asymmetry compensation)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Measuring Delay Asymmetry
One Way Delay (OWD) in Packed Switched Networks
Real-life Tests (Field)
GPS Ant.
GPS Ant.
PSN
Geographical Location A
Geographical Location B
Relay on GNSS reception quality and/or Chip-scale Atomic Clock holdover performance
Simplified OWD for Lab Testing (Dual Port)
Uses shared internal time reference for local verification (No GNSS required)
Offers better accuracy and resolution
Limited application (not for field testing, besides troubleshooting Network Elements)
Lab's PSN or NEs
A → B
B → A
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Build Your Own Portable GNSS Clock?

It may NOT be that Simple

- Some may think that strapping a battery pack to a GPS-disciplined Clock is a good idea or quick solution → It is NOT that simple!
  - Commercial GNSS-disciplined Clocks are meant for Stationary installation (The long time they take to stabilize is usually insignificant, when compared to the lifetime they will spend in one place)
  - The self Survey (find its accurate position) is required to provide accurate time. This takes long time
  - GNSS clocks don't like to be moved. Significant changes in position makes them take longer to acquire satellites or start a new location survey
  - Requires to carry a laptop to monitor its current state
  - Antenna cables are not that flexible
- The DIY Portable GNSS Clock

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Synchronization Test Sets

Portable Test Solutions for the Field

Thank You!

Any Questions?

info@veexinc.com
CustomerCare@veexinc.com
www.veexinc.com
+1 (510) 651-0500

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