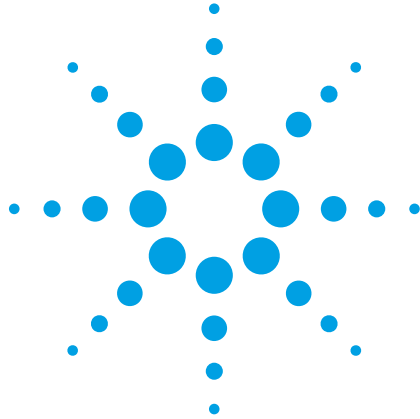


# Characterizing phase-locked-loop signal transition behaviors of Microphonic/Phase-hits

## Application Note



Agilent Technologies

## Introduction

Digital communication systems often have unique carrier synchronization and synthesizer requirements such as rapid carrier acquisition/lock, and stable operation in demanding environments. The performance of these requirements is affected by not only oscillator characteristics themselves but also the design of phase-locked loop circuits interacting with unwanted stimulus such as microphonics. This paper discusses how Agilent's Signal Source Analyzer helps you to identify unwanted phase-locked loop transition "phase-hits", and achieve easy, comprehensive and accurate phase-locked loop characterization in both linear and nonlinear regions.

# Characterizing PLL Linear and Nonlinear Behaviors

Starting with test parameters in characterizing phase locked loop linear and non-linear behaviors; there are three different stages of test usage, component evaluation, oscillator/phase-locked-loop circuit design, and verification/test at operating conditions.

The PLL controls the phase of the output signal to be N times the phase of the reference as shown in figure 1. Similarly, the frequency of the output signal is then N times the reference frequency. Like all linear feedback control systems, PLLs have dynamic behavior characteristics. The linear behavior described by the transfer function method is useful to analyze loop operation in the vicinity of lock. Non-linear effects dominate the behavior of the PLL in unlocked conditions such as when the frequency divider ratio is changed to switch frequencies over a large range.

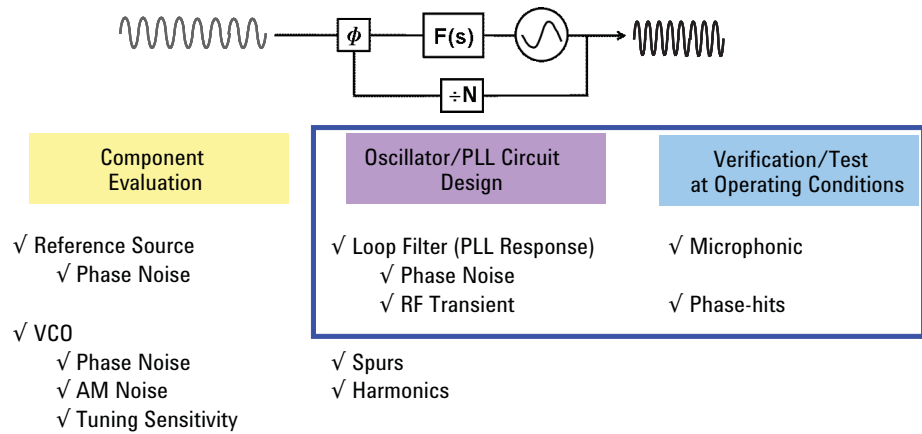


Figure 1. Phase locked loop test parameters and challenges

The building blocks common to most phase locked loops are the phase detector, the loop filter, the voltage controlled oscillator (VCO), and the frequency divider. Each of these building blocks has both linear and non-linear attributes to its operation.

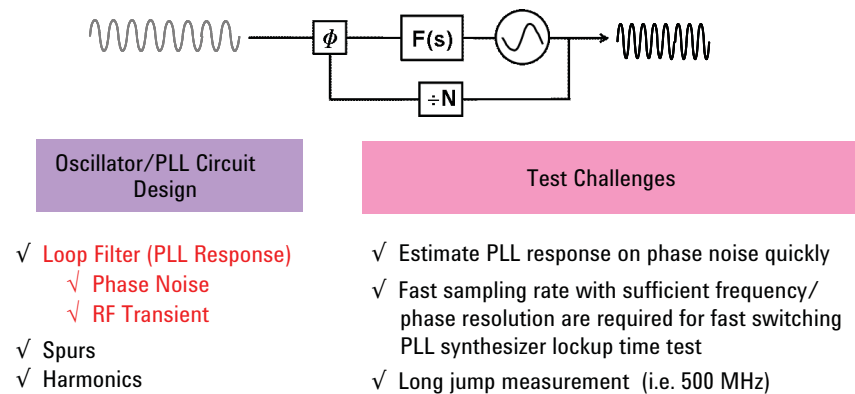


Figure 2. Test parameters and challenges in the circuit design stage

## Characterizing PLL Linear and Nonlinear Behaviors (cont'd.)

PLL response in the PLL linear operating region can be characterized through phase noise measurement. Once both VCO and reference phase noises are known, output phase noise of the PLL can be estimated based on the designed loop filter.

An RF transient characteristic known as lockup time is usually tested with the frequency and phase guard band. Modern digital communication systems often require fast frequency switching synthesizer because the available time slot of the carrier acquisition is getting smaller in order to communicate multiple channels in a very short time period. Typical requirement of lock up time is about 10 ms down to a single micro second order level. So we need faster sampling rate measurement while we need to maintain sufficient frequency or phase resolution.

Also, the frequency synthesizer needs to cover a wider frequency bandwidth due to increasing bandwidth of the communication system. For example, testing of a long jump frequency synthesizer as wide as 500 MHz is needed.

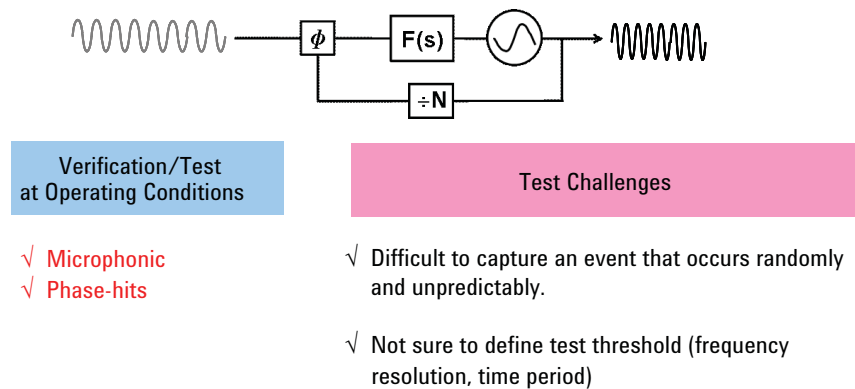


Figure 3. Test parameters and challenges in the verification/operating test stage

When the designed PLL is sensitive to unwanted external physical stimulus, the system may become unstable because the PLL oscillation may be modulating internally. This non-linear behavior is likely to occur at various operating conditions, such as temperature changes, vibration, and shock.

Microphonic and phase-hits are known major problems and stability of the PLL needs to be tested at operating conditions to address sources of unwanted behaviors.

The test challenges here are how to capture such events with an instrument and how to analyze the signal behavior to address sources of these types of modulation, because it is hard to predict when a phase-hit event occurs. Another challenge is how to define the test limit to capture such an event in terms of the frequency or phase variation along with duration of the event.

## PLL Linear Behavior Analysis

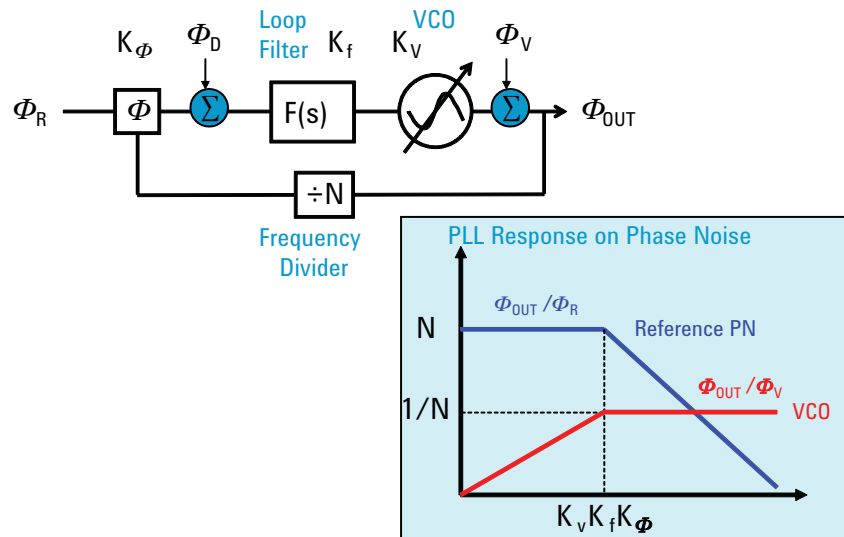


Figure 4. Phase Locked Loop Linear Analysis

The operation of a PLL is easily described using feedback control systems that yield a transfer function in  $S$ , the complex frequency parameter used in Laplace transforms. The transfer function to the various possible stimulus points can be found as shown in figure 4. The responses to phase fluctuate in the reference, the VCO, and to signals injected at the phase detector output are shown here.

$$\frac{\phi_{out}(s)}{\phi_R(s)} = \frac{K_v K_\phi F(s)}{S + \frac{K_v K_\phi K_F}{N}} \quad \text{where let } F(s) = KF \quad \frac{\phi_{out}(s)}{\phi_R(s)} = \frac{K_v K_\phi K_F}{S + \frac{K_v K_\phi K_F}{N}}$$

A response to signals summed at the phase detector output is expressed as,

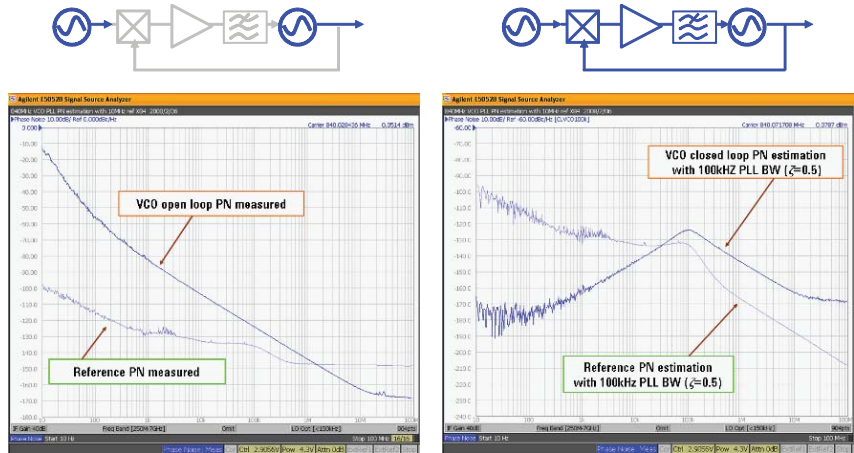
$$\frac{\phi_{out}(s)}{\phi_D(s)} = \frac{K_v K_F}{S + \frac{K_v K_\phi K_F}{N}}$$

And a response to VCO phase fluctuations is also expressed as,

$$\frac{\phi_{out}(s)}{\phi_V(s)} = \frac{S}{S + \frac{K_v K_\phi K_F}{N}}$$

The PLL transfer function that describes its response to reference phase fluctuations has a low-pass shape. The response to signals added at the phase detector has a similar low-pass shape and the output phase becomes independent of the reference for phase components above the PLL bandwidth. The transfer function describing the PLL response to phase fluctuations in the VCO has a high pass shape. The PLL has no effect on the VCO phase for fluctuation components above the loop bandwidth but attenuates lower frequency components that lie inside the loop bandwidth. Thus, the phase noise of the reference and the phase detector noise multiplied by  $N$  dominate low frequencies while the phase noise of the VCO dominates high frequencies.

# PLL Linear Behavior Analysis (cont'd.)



**Figure 5A. Phase noise of both open-loop VCO and Reference**

**Figure 5B. PLL response on phase noise of both VCO and Reference**

Let's review how we estimate the PLL response assuming a PLL transfer function with actual phase noise measurements of both the VCO and the PLL Reference.

In Figure 5A there are two measurements on both the VCO open loop phase noise and reference source phase noise. They are the dominant factor of the PLL output phase noise which is also determined by the designed PLL loop filter.

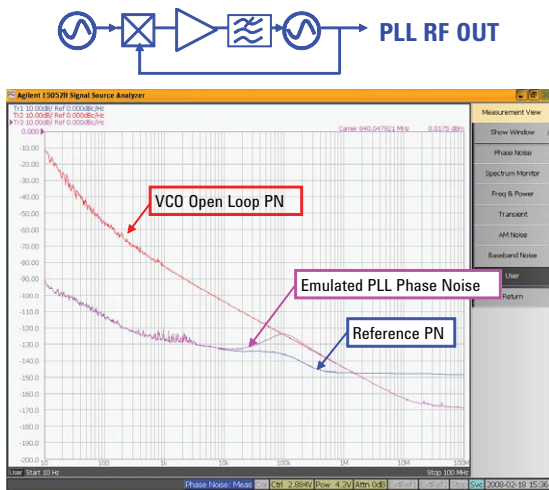
The PLL loop filter response can be defined as gain versus offset frequency, math can be used to estimate the PLL closed loop response based on the phase noise measurement data of both VCO and reference.

In this example, assume that the 2nd order PLL with 100 kHz PLL BW.

*Note the responses of the PLL to phase fluctuations in the reference, signals summed at the phase detector are low-pass functions, and that the PLL to VCO phase fluctuations is a high-pass function.*

Thus, the expected phase noise on VCO closed loop PN exhibits (data trace, bold) and reference phase noise (memory trace, light) are shown in figure 5B.

The final expected phase noise of the PLL can be derived from two estimated phase noise data.



**Figure 6. Estimated Phase Locked Loop Phase Noise**

Based on the measured open loop VCO phase noise and reference oscillator phase noise from Figure 5, estimated total phase noise of the PLL is shown in Figure 6 (pink trace). We assume that the designed PLL has 2nd order PLL with 100 kHz BW and 0.5 damping factor.

Inside the loop bandwidth smaller than 100 kHz offset frequency, the PLL phase noise performance is determined by the reference source. With PLL BW at 100 kHz, the total phase noise performance is determined by VCO closed-loop phase noise or reference source phase noise affected by the PLL loop, whichever is worse. Outside the loop bandwidth, VCO phase noise determines PLL output phase noise as reference source phase noise is lower than that of VCO due to the effect of low pass PLL loop filter.

## PLL Non-linear behavior analysis

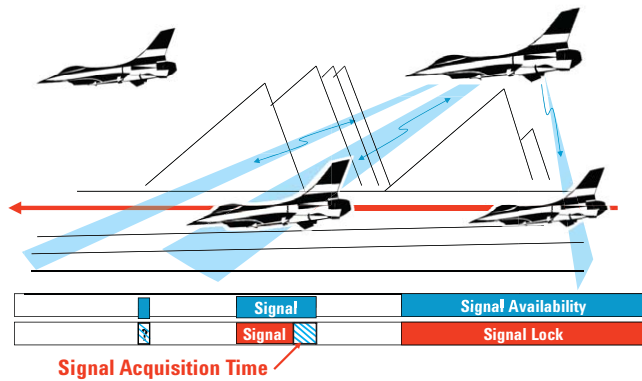


Figure 7. Synchronization issue on carrier acquisition

## Measuring RF transient

The demand of faster carrier acquisition is increasing especially in aerospace and defense communication equipment. A good example is an aircraft flying at high speeds close to the ground. Communications signals may fade in and out very rapidly, so signal availability comes and goes. It often requires that the time to acquire and lock on to the received signal, so the 'acquisition time,' should be very short.

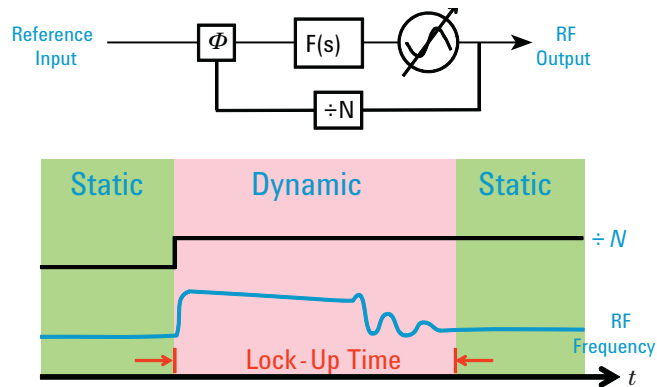


Figure 8. Phase-locked-loop lock-up time

Though there are many factors that determine the speed a synthesizer can change frequency, often a critical element is how fast a tracking loop can lock up on the new channel frequency. Synthesizers have a finite lock up time composed of dynamic control loop tracking and "lock-up time" is the parameter to be tested.

Normally the timing the PLL starts changing its oscillation frequency is the timing that the PLL changes the dividing number  $N$ . The control signal is usually generated by the PLL-IC. The control signal can be used as a trigger signal for an instrument to synchronize the measurement with proper signal conditioning.

Whether the PLL oscillation frequency settles to the desired (target) frequency or not is often judged by the frequency and/or phase guard band. The final phase is referenced to the desired frequency.

So the measuring instrument should provide both sufficient time resolution and frequency/phase resolution to meet the test requirement.

## Measuring RF transient (cont'd.)

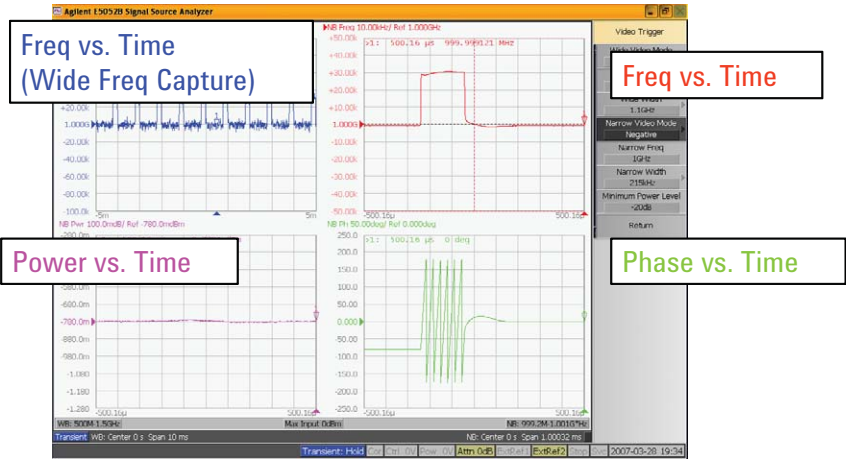


Figure 9. Measuring LO lock-up time

Here's an example of PLL lock-up time measurement with the E5052B.

Seen in this measurement screen, the phase locked loop synthesizer hops between two frequencies as shown in the left upper trace, frequency versus time in the wide frequency capture mode of the analyzer.

Evaluation of the detail response of phase locked loop during the frequency transition from one to another is needed. Frequency and phase versus time characteristics (shown in the right upper trace and right bottom trace respectively) give more precise information on frequency transition to settle to the final (target) frequency.

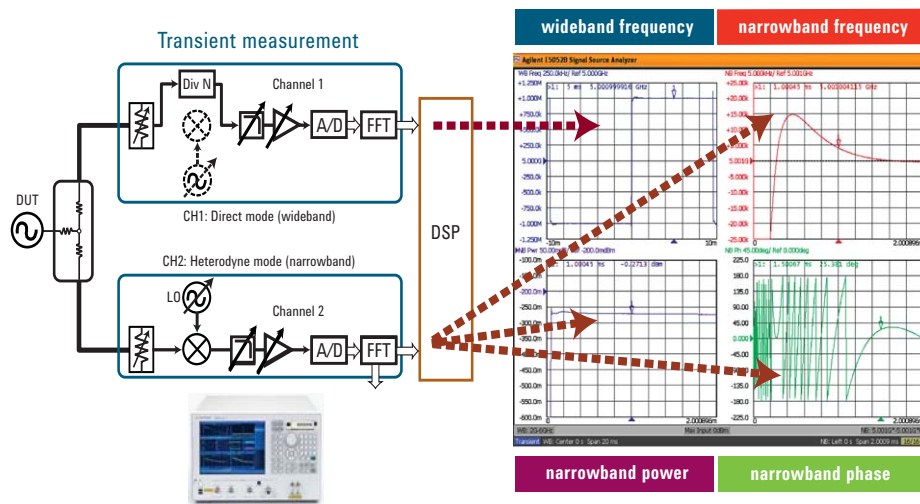


Figure 10. E5052B dual-channel measurements for frequency/phase/power transition phenomena

The signal source analyzer offers a major breakthrough in transient measurements for synthesized signal sources. It has two independent measurement channels and each channel takes a different method for measuring a signal's frequency simultaneously.

The E5052B's wideband mode, called "direct division mode" contains a frequency divider at the very front end of the instrument and offers wider frequency hopping analysis range (maximum 4.8 GHz span) up to 7 GHz of carrier signal.

The narrowband mode (heterodyne mode) shown in this slide, provides significantly fine resolution in frequency or phase transient measurement with reasonably wide frequency hopping range such as 80 MHz, 25.6 MHz, 1.6 MHz or smaller.

Both wideband and narrowband modes operate completely in parallel, the E5052B enables observation of the entire picture of frequency changes and detailed transient response in frequency, phase, and power at the same time.

The E5052B takes 125 MHz sampling ADC (analog to digital converter) and the minimum time resolution is 8 ns in the narrowband mode while maintaining finer frequency resolution than any other instrument. It also covers long term observation up to 1,000 seconds (or 10,000 measurement points of the time resolution set).



## Capturing and Analyzing Microphonic and Phase-hits

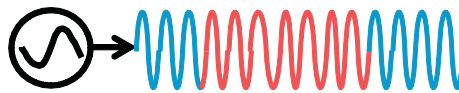


Figure 11. Modulated RF signal behavior by external mechanical stresses

## Common sources of unwanted stimulus

One of the critical concerns for the aerospace and defense engineer is the operating environment of their microwave system. Aerospace and military equipment is usually expected to operate in an environment where the shock and vibration levels are very high. Rockets produce extremely high levels of vibration, jets produce high 'G' loading, cannons and high-speed land vehicles produce pounding shock.

Microwave systems can be affected by shock and vibration. A common problem caused by shock and vibration is the unwanted modulation of signals such as microphonic. Temperature stress affects the microwave systems operation and can generate sudden unwanted oscillation frequency changes. Some of materials and components are likely to be affected by the temperature changes and generate unwanted frequency modulation in a short time period.

Frequently these undesirable effects can be mitigated or eliminated by proper design of phase lock loops, and final testing of products in manufacturing is often required.

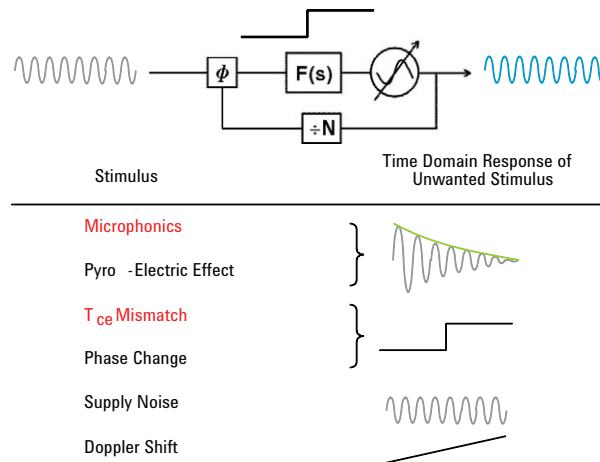


Figure 12. Common sources of unwanted stimulus.

Here are the common sources of unwanted stimulus on phase locked loop components.

These are causes of a sudden frequency and phase change of the controlled signal of the synthesizer. This phenomenon is often called 'phase-hit'.

Phase hits are infrequent but damaging causes of signal degradation in high-performance telecommunications systems, and their effect increases with data rate. As a result, the continuing increase in data rates dictated by dramatic increases in network traffic are making phase-hits a prime target for elimination.

## Microphonic

Phase-hits can be defined as sudden, uncontrolled changes in the phase of a transmitted signal that occurs randomly, and generally lasts for fractions of a second. It can be caused by temperature changes from dissimilar metals expanding and contracting at different rates, as well as from vibration or impact.

In addition, detecting and measuring phase-hits generally requires test equipment either designed for the purpose or modified to meet the stringent demands of not only measuring but also characterizing transition events that last a few tens of microseconds at most.

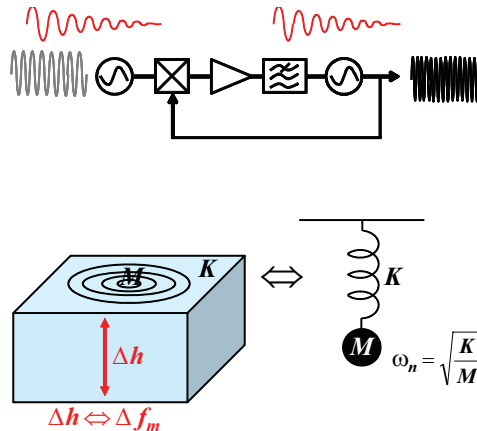


Figure 13. Microphonics

Microphonics is the phenomenon where certain components in electronic devices transform mechanical vibrations into an undesired electrical signal (noise).

Microwave components are often susceptible to mechanical modulation of the electrical wavelength. This can create a microphonic sensitivity if the amount of mechanical movement becomes significant relative to the electrical wavelength. As frequency goes higher, the electrical length shortens, and then mechanical stability becomes more critical.

Direct mechanical modulation of electrical length is usually found to be a problem only in extreme vibration environments, but microphonic phenomena are generally repeatable and can be simulated with physical methods.

## Phase-hits due to TCE Mismatch

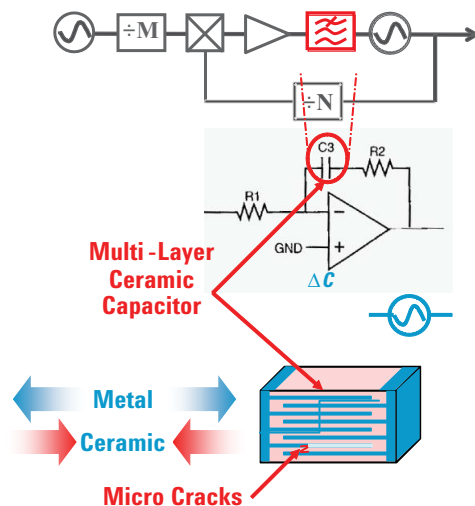


Figure 14. TCE mismatch in ceramic capacitors

The coefficient of thermal expansion (CTE) referring to the thermal or temperature coefficient of expansion (TCE) is an important material property when it comes to avoiding phase-hit problems.

When most materials are heated, they expand. If we use materials with different TCE's, the mismatch can build up large mechanical stresses inside the radio. If that energy is released suddenly, it can result in a phase-hit.

Multi-layer ceramic capacitor (MLCC) is commonly used in radio circuits. If a capacitor with a micro-crack is used as part of the loop filter in a PLL integrator circuit, the capacitance value can change suddenly. To the phase lock loop, a sudden change in capacitance will cause a sudden shift in phase of the output oscillator. Phase steps greater than 90 degree or 180 degree can cause a momentary loss of lock as the phase detector goes nonlinear.

## E5052B frequency boundary trigger to capture micro-phononic/phase-hits events

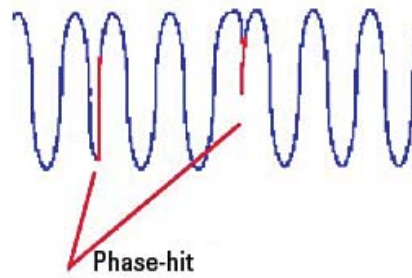


Figure 15. Capturing unexpected signal transition

Phase-hit is an unintentional signal transition behavior that may cause unlock of carrier synchronization and/or affect bit-error in the communication system. It is natural that the test limits are defined by a guard band of phase along with its lasting period.

A phase-hit limit could be specified as such, greater than 45 degrees lasting longer than 4 milliseconds and may occur in a 60 second period.

Phase transition can be interpreted to frequency transition so that we can capture this phenomenon if we have a dedicated trigger function based on the frequency over time measurement data.

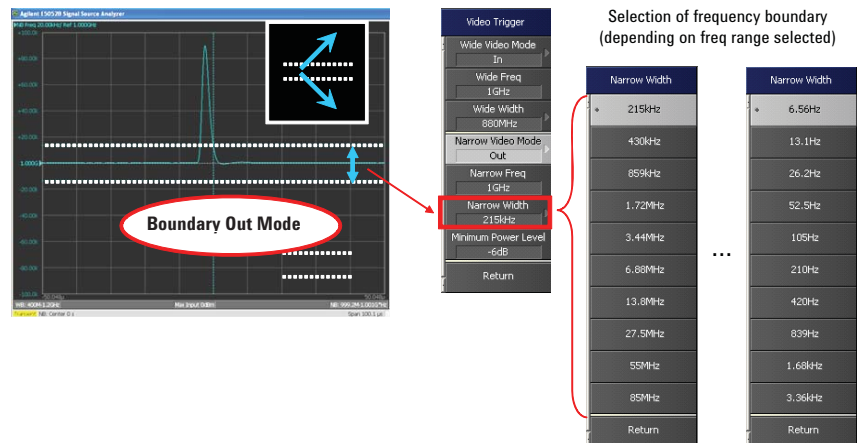


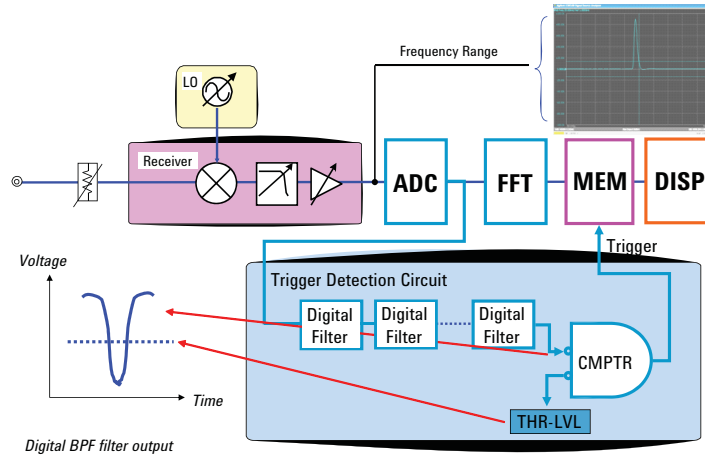
Figure 16. E5052B SSA frequency boundary trigger function (video out mode)

The E5052B SSA provides frequency boundary trigger function to be able to capture such signal transition events.

You can set frequency boundary in the frequency over time measurement screen. The boundary trigger works as trigger off mode. When a measured frequency goes out of the frequency boundary you set, the SSA automatically triggers and then stops the recording until it has reached the end of memory. The recording length is the time span you set in the SSA.

The SSA frequency boundary trigger provides ten frequency boundary selections depending on the frequency range, that is the IF bandwidth of the analyzer up to 80 MHz. First you need to have some information about what kind of frequency transition you want to capture, but you can select from the list provided.

**Capturing and Analyzing E5052B frequency boundary trigger to capture micro-phonics/phase-hits events (cont'd.)**



**Figure 17. E5052B frequency boundary trigger (video out) circuit diagram**

This is a simplified block diagram of the SSA transient measurement mode as well as the frequency boundary trigger detection circuit.

The RF signal is coming out of the receiver section, which is downconverted to IF, and goes into the AD converter. The digitized incoming data with available sampling rate of the AD converter, with a maximum rate of 125 MSa/s. The data is fed into the FFT section to obtain frequency data and then recorded in the internal memory. The data is recorded continuously similar to an endless tape recorder if there is no trigger signal present.

The digitized data is also fed into the trigger detection circuit. The circuit consists of several stages of digital filter and a digital comparator. The digitized voltage data coming out of the trigger detection circuit is compared to the threshold level for triggering. In the frequency boundary out mode, the output signal of the digital filter stage is shown in Figure 17. When the frequency goes out of the frequency boundary, the voltage of the digitized data drops accordingly.

The threshold level is also accessed by the user. In the previous softkey menu, there is “minimum power level” entry, which determines the threshold level in dB.

For example, if you set  $-3$  dB as minimum power level, the threshold level is located at the half height of the peak voltage with reference to the ADC converter full scale.

**Table 1. E5052B frequency boundary trigger (video out mode) performance summary.**

Minimum period of event to capture	1 usec for 80 or 25.6 MHz freq range mode 5 usec for 1.6 MHz freq range mode 50 usec for 200 or 25 kHz freq range mode 400 usec for 3.125 kHz freq range mode
Sampling resolution	8 nsec/point (80 or 25.6 MHz freq range) to 10 msec (3.125 kHz freq range), 1-2-5 step
Maximum recording length	1000 second or 10,000 points, whichever smaller time period

Minimum period of an event for the instrument to capture depends on the frequency span you select as sampling rate varies depending on the frequency range. One usec lasting event can be captured when you choose 80 MHz or 25.6 MHz frequency span. The longer the minimum time period to capture, the narrower frequency span you select.

## Microphonic/phase-hits measurement examples

Sampling resolution also depends on the frequency span selected. If you look at the E5052B Signal Source Analyzer Data Sheet (5989-6388EN) in the transient measurement section, there is a table of available frequency resolution and time resolution at time span that can be selected.

Maximum recording length is a function of time resolution as the memory length is physically limited. The hardware limits recording up to 1,000 seconds, also the time resolution is limited by the maximum recording points, up to 10,000.

For instance, if you select 1 usec time resolution, the maximum recording length is 10 msec.

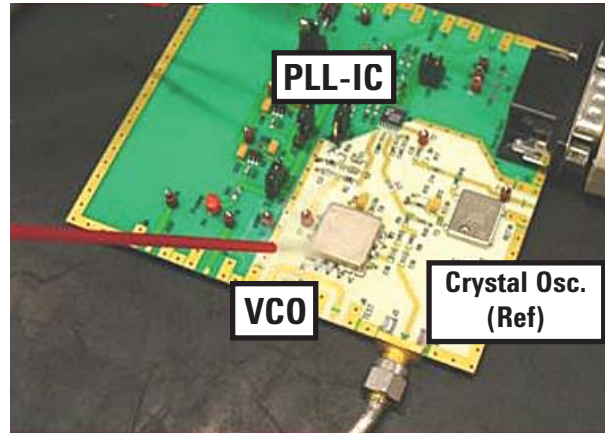


Figure 18. Phase-locked-loop under test

Here are some examples of microphonic and phase-hits measurements of an actual device. The device under test is a PLL circuit that consists of a VCO, crystal oscillator as a reference, PLL-IC, and loop-filter.

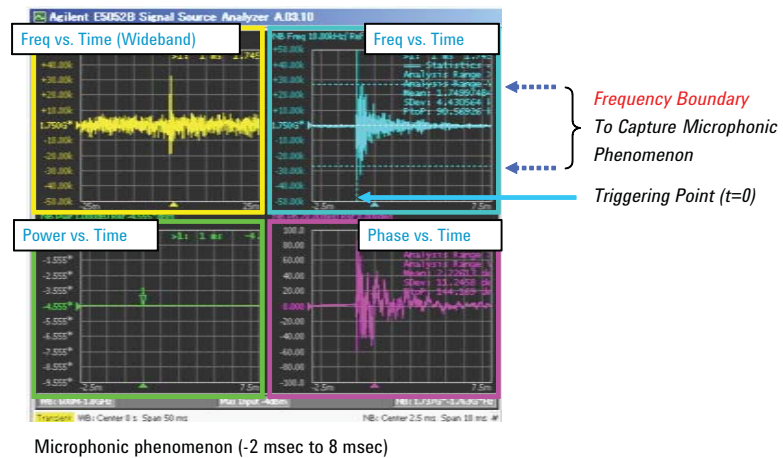


Figure 19. Example of microphonic measurement

The first measurement is a microphonic measurement of the PLL. For microphonic measurement, we gave an mechanical shock to the DUT to observe the DUT's signal transition behavior. In general, you can also put the DUT on a vibrating table or use an impact hammer to give mechanical stresses.

Here's a measurement example of microphonic phenomenon of the PLL.

The measured data was a 10 millisecond recording, which includes 2 milliseconds for a pre-trigger event and 8 milliseconds after the event.

# Capturing and Analyzing Microphonic/phase-hits measurement examples (cont'd.)

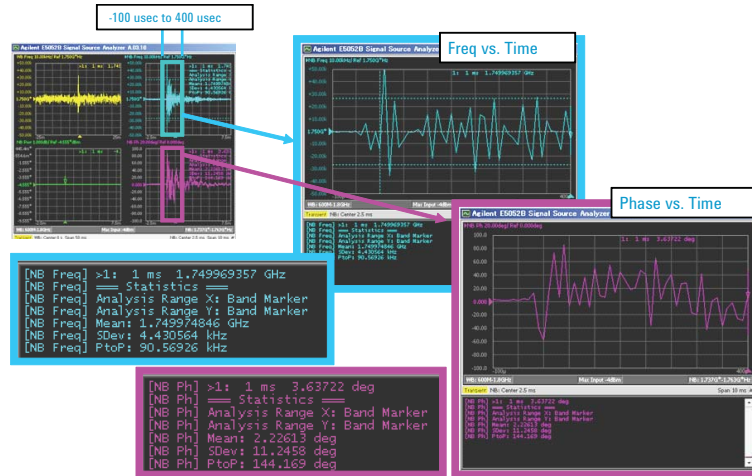
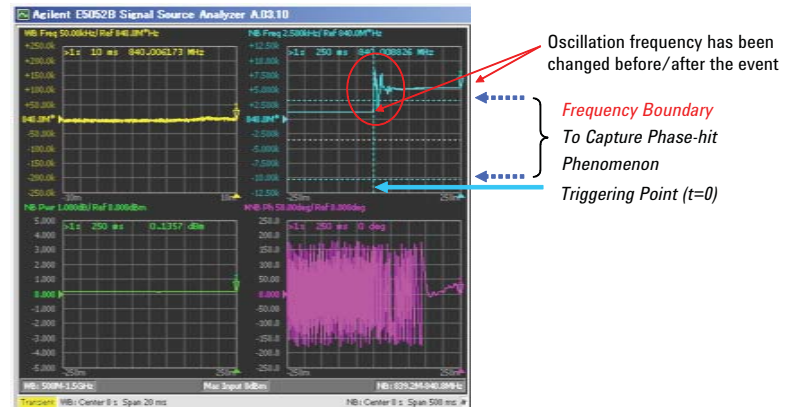


Figure 20. Microphonic measurement—a closer look

The recording data contains 1001 points, so the detailed transition behavior can be observed using the zooming function. It also provides statistical analysis of standard deviation as well as frequency and phase deviation in the time period of interest.

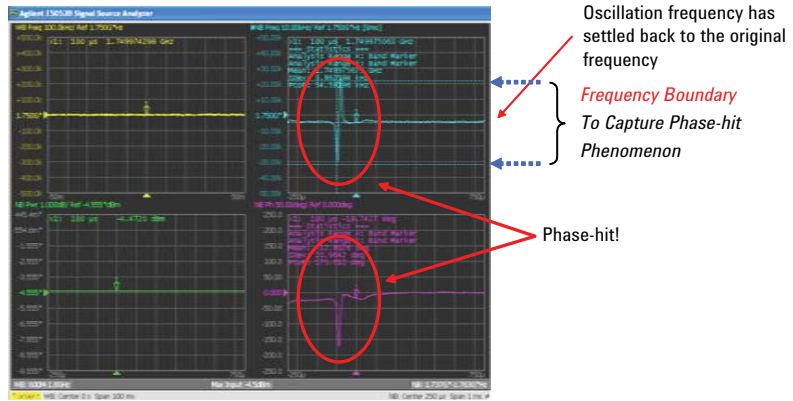


VCO Phase-hit phenomenon (- 250 msec to 250 msec)

Figure 21. Example of Open-Loop VCO Phase-hit Measurements

The second measurement is about phase-hit measurements both on a free-running VCO and locking PLL. Also for phase-hit measurements, temperature stress to the DUT using a temperature controlled chamber. Because the VCO contains ceramic capacitors in the tank-Q circuit the VCO may show temperature stress and generate its oscillation frequency transition in a short period.

*Note that the VCO was operating in free-running mode and the oscillation frequency was changed after the phase-hit event.*

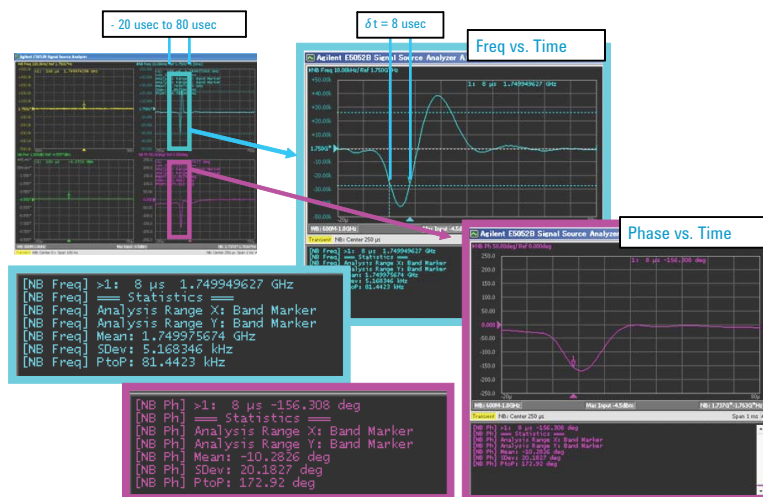


PLL Phase-hit phenomenon ( -250 usec to 750 usec)

**Figure 22. Example of PLL Phase-hit Measurement**

This is another phase-hit measurement example of phase-locked-loop.

Compared to the result of free-running VCO, PLL loses a frequency lock momentarily and tries to set the oscillation frequency back to the original (desired) frequency as soon as the phase-hit events occurs. How fast the oscillation frequency and/or phase settles back to the original one depends on the PLL dynamic response characteristics.



**Figure 23. Phase-hits Measurement – A Closer Look**

In this example, the first frequency transition due to the phase-hit phenomenon occurred in a period of 10 microsecond or more and settled back to the original frequency in the period of 50 microsecond.

The E5052B with the frequency boundary trigger clearly captured the event in the period of 8 microseconds or less and the frequency went out of the boundary.

## Summary and Conclusion

Characterizing both linear and non-linear behaviors of phase locked loop is the key to identify the root cause of unwanted response in the design of your products. The Agilent E5052B Signal Source Analyzer (SSA) provides world class RF transient measurement performance for capturing and analyzing PLL non-linear behaviors such as lock-up time and microphonic/phase-hit phenomena.





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