APPLICATION NOTE

# Solutions for Using a Frequency Counter to Measure Phase Noise Close to a Carrier Signal

Radar measurement series

KEYSIGHT

# Overview

A local oscillator (LO) produces carrier signals for transmitters and reference signals for receivers—and an LO is the heart of every radar, electronic warfare (EW), or communication system. In communication systems, ever more data is being squeezed into limited bandwidths. In the evolution of radar systems, there is an ongoing need to resolve targets more accurately at greater distances.

To meet the needs of these demanding applications, high stability, and spectral quality in the LO are critical to achieving high-performance transmitter and receiver designs. When verifying stability and spectral quality, an instrument such as a signal (spectrum) analyzer provides informative wide-area views of the noise and spectral content around the LO carrier signal. Unfortunately, this type of instrument may fall short of providing a clear picture of the phase noise extremely close to the carrier. In this context, “close to the carrier” or just “close” refers to the noise within ±200 kHz of the carrier frequency on the x-axis of a frequency-domain plot.

To create a clearer picture of noise close to the carrier, instruments such as the Keysight Technologies, Inc. 53230A universal frequency counter pick up where signal analyzers leave off. The rest of this note describes how the high-resolution and gap-free measurement capabilities of the 53230A can be used to take a closer look at LO signals. It also presents example results in the form of modulation domain analysis plots and Allen deviation plots.[1]

# Problem

Until recently, fully characterizing noise less than 10 Hz from a carrier signal required a complex measurement setup such as the heterodyne method (reference 2, Riley) or an expensive measurement system such as a dedicated phase noise analyzer. Signal analyzers and frequency counters are viable alternatives, but each has limits.

As noted earlier, signal analyzers provide an unmatched wide-area view of spectral content. A typical measurement will clearly show noise around the carrier, and the span and bandwidth can be adjusted to dial in various views of the noise content. However, as measurements get closer to the carrier, the noise content becomes crowded, and it becomes difficult to determine the possible causes of the noise.

A frequency counter can make close-in measurements, but care must be taken to ensure useful results. For example, when working close to the carrier, it is necessary to capture a data set large enough to reveal any gradual changes caused by low-frequency noise. However, when performing a statistical analysis on a large set of timing measurements, traditional methods such as standard deviation won’t suffice because they calculate the cumulative effect of the sample. The consequence: The larger the sample set, the more the standard deviation can grow. Said another way, it can become non-convergent.

[1] When noise caused by oscillator instability is measured in the frequency domain, it is often called phase noise; when measured in the time domain, this noise is often referred to as jitter (reference 1, Button). Even though this note focuses on timing measurements, jitter is referred to as “phase noise” or just “noise” because high-frequency LO signals are typically viewed in the frequency domain.

# Solution

Instruments such as the 53230A counter close to the carrier can provide greater detail than a signal analyzer. Measurement resolution is one important factor—and a key differentiator of modern counters. For example, the 53230A provides a resolution of 20 ps in timing measurements.

The 53230A is also equipped with capabilities that were once found only in advanced and more expensive timing instruments. An example relevant to phase-noise measurements is gap-free or zero-dead-time measurements. As an aside, this feature enabled the creation of an instrument called the modulation domain analyzer (MDA)—and this is relevant because MDA-style plots are useful tools for close-in analysis.

Before describing how these features enable close-in analysis of carrier signals, it will be worthwhile to explain the meaning of gap-free timing measurements briefly.

## Understanding gap-free measurements

A typical timing instrument operates by activating a timer when a “start event,” such as the rising or falling edge of a signal, occurs. The instrument has an internal timer that counts until it detects the stop event, which is the corresponding rising or falling edge representing one full signal period.

All counters have an adjustable sample period or gate time. When making frequency or period measurements, the counter takes timing measurements from edge to edge for the length of the gate time. At the end of the gate time, it averages all the timing measurements, takes the inverse, and returns the measured frequency.

In its “general” mode, the counter goes through a re-arm period after the measurement gate and before it starts the next gate. This is not a gap-free measurement because signal data is being missed while the instrument re-arms.

With the gap-free measurement capability, there is no re-arm time. Signal-edge events are timed continuously — gap-free — based on the specified sample count, which ranges from 1 to 1,000,000 measurements in the 53230A.

A counter’s gap-free measurement rate is based on the speed of its measurement engine. The 53230A universal counter has a gap-free sampling rate of up to 1 MSa/s, which is currently the highest in the industry. If the input signal exceeds the instrument’s sampling rate—whether it’s 10 MHz or 10 GHz — a pre-scaling circuit will divide the input signal down in frequency before sending it to the internal measurement engine. This has a consequence: The counter cannot pick up noise content that is far from the carrier frequency. Even so, this mode can still provide detailed insight into signal content close to the carrier — and this will be discussed in the Results section.

Combining a counter’s high resolution with its gap-free measurement capability provides two valuable signal analysis capabilities:

- It enables detailed insight into noise around the carrier to help better diagnose its source
- Measurements can be made closer to the LO than with any other type of instrument

Examples of these capabilities are presented in the Results section.

## Getting close to the carrier

The Allan variance (or two-sample variance) was developed to analyze stability and low-frequency noise processes in oscillators and clocks (Equation 1). Applying this method to data captured with a frequency counter is a prelude to using the Allan deviation below to understand close-in sources of phase noise.

$$\sigma_y^2(\tau) = \frac{1}{2}\langle(\bar{y}_{n+1} - \bar{y}_n)^2\rangle = \frac{1}{2\tau^2}\langle(x_{n+2} - 2x_{n+1} + x_n)^2\rangle$$

**Equation 1**. The Allan variance (or two-sample variation) can be calculated through fractional frequency measurements (y) or phase or time perturbations (x).

If you'd like to take a closer look at this method, a substantial number of references are available on the Web. Here is a brief overview:

- Allan variance can be calculated two ways: using fractional frequency measurements (y) or phase or time perturbations (x).
- Tau (t) represents the observation time of each "y" or "x" sample. The value chosen for tau determines the target noise frequency range. For instance, choosing a tau value of 1 s will integrate out any 1 Hz noise content.
- The angular brackets represent infinite series. The more readings (n) used in the series, the higher the confidence level of the calculations.

Another related calculation is the Allan deviation, which is just the square root of the Allan variance (Equation 2). When this calculation is applied to a large sample of frequency data and plotted, it can reveal underlying cyclic disturbances that affect phase noise performance. An example of this is shown in the Results section.

$$\sigma_y(\tau) = \sqrt{\sigma_y^2(\tau)}$$

**Equation 2**. The Allan deviation is the square root of the Allan variance.

# Results and Benefits

Two examples will help illustrate the types of results that are possible with a frequency counter, a PC, and a programming environment such as MATLAB, Keysight VEE, or LabVIEW that can easily manipulate vector data. In both cases, an impaired signal was created using a Keysight signal generator, and the RF output was connected to the 53230A.

## Using the MDA plot

For the first example, the input to the 53230A was a 1-GHz carrier frequency-modulated with square wave noise. The counter's gap-free measurement rate was set to 100 kSa/s, and 500 measurements were acquired. The data was transferred to a PC, manipulated with Keysight VEE, and displayed in the MDA-style plot (Figure 1). This type of plot presents the data with time on the x-axis and frequency on the y-axis.

A signal analyzer display would show FM or PM as a clutter of spectral content around the carrier. In contrast, the MDA plot shows the time-domain shape of the underlying noise source. In this case, the MDA plot reveals the FM square wave noise that was added to the 1-GHz carrier. This can be very useful when searching for spurious coupled noise that may be produced by power supplies, transformers, or mechatronic components.

This data can also be viewed in a more "frequency domain-like" format by plotting it as a histogram. Displaying the gap-free samples as a histogram plot is comparable to viewing the data on a signal analyzer with poor overall bandwidth but great resolution bandwidth.

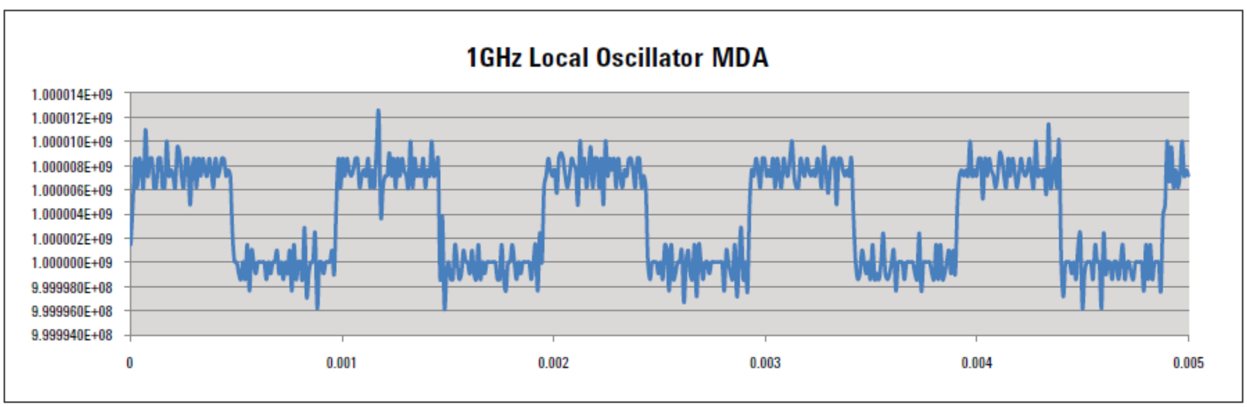


**Figure 1**. This MDA-style plot shows frequency (y-axis) versus time (x-axis) and reveals the modulating signal that was applied to the 1-GHz carrier

# Applying the Allan deviation

The second example uses the Allan deviation to analyze a 3-GHz LO signal. To represent cyclic noise, the test signal was frequency modulated with a 1-Hz sine wave at a 3 Hz deviation. The 53230A was set for a gap-free measurement rate of 100 ms and made 1,200 measurements, yielding 12 s of data.

The Allan deviation calculation was performed on the data using tau values ranging from 40 ms to 2 s to perform what is known as an “all-tau analysis” of the data (reference 3, NIST). An all-tau analysis on an LO signal makes it easy to spot low-frequency cyclic disturbances such as temperature cycling (reference 2, Riley). An all-tau plot was created using MATLAB (Figure 2).[2]

In Figure 2, the tau value dips at 1 and 2 seconds. This is expected because it is the period of a 1-Hz sine wave. As a result, the added 1-Hz noise was integrated out of the Allan deviation measurements made with tau values of 1 s and 2 s because they are integer multiples of the noise period. In the figure, the Allan deviation also gradually declines at lower tau values. This is the result of moving farther away from the noise source’s frequency range.

The dips at certain tau values and the trend changes in the Allan deviation measurements help reveal the frequency range of parasitic noise that is affecting the LO signal. This insight into the noise processes extremely close to the LO signal helps pinpoint the source and provide information that can be used to reduce or eliminate the noise.

This discussion scratches the surface of using Allan variance and deviation measurements for analyzing noise and stability. For more information, please refer to the NIST handbook (reference 3).

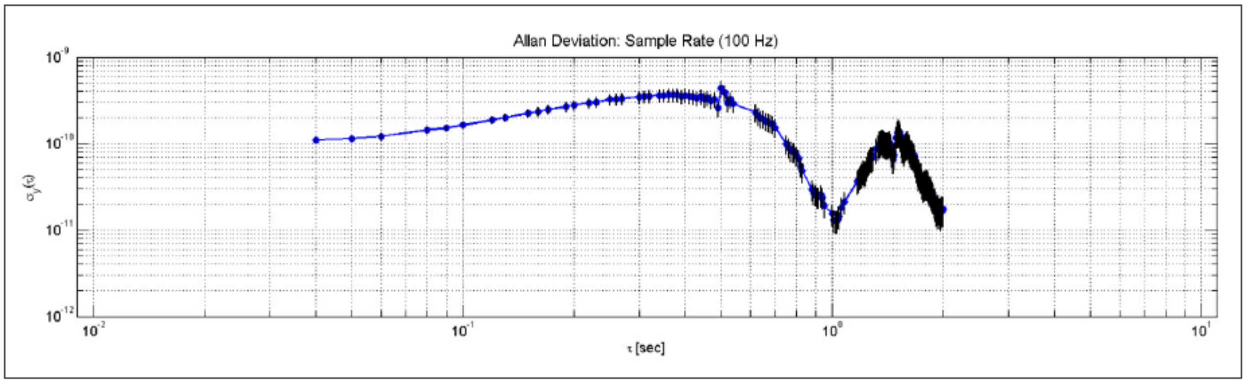


**Figure 2**. An all-tau plot based on calculations of the Allan deviation can reveal low-frequency cyclic disturbances

[2] The MATLAB script that generated the plot in Figure 2 is available at no cost on MATLAB Central, a program- and code-sharing site, under the name “Stability Analyzer 53230A.”

# Conclusion

A frequency counter is a great addition to an RF engineer's toolbox because it complements the information provided by signal analyzers. Two important capabilities are high-resolution and gap-free sampling—and these make it possible to not only capture close-in phase noise but also extract clues about noise sources and identify ways to reduce or eliminate the noise.

# References


1. Button, K.J. (1984). Infrared and Millimeter Waves; Ch 7, Phase Noise and AM Noise Measurements in the Frequency Domain (239-289). Academic Press, Orlando, FL

2. Riley, W. J. (2007). Methodologies for Time-Domain Frequency Stability Measurement and Analysis. Retrieved from website: www.wriley.com/METHODOLOGIES.pdf

3. National Institute of Standards and Technology (NIST Handbook of Frequency Stability Analysis (NIST Special Publication 1065). Retrieved from NIST website: http://tf.nist.gov/general/pdf/2220.pdf


# Related information

- Family Overview: Keysight Technologies 53200 Series of RF and Universal Frequency Counter/Timers, literature number 5990-6339EN
- Data Sheet: Keysight 53200A Series RF/Universal Frequency Counter/Timers, literature number 5990-6283EN
- MATLAB: More information is available from The MathWorks at www.mathworks.com/products/matlab/
- Selection Guide: Keysight's Phase Noise Measurement Solutions, literature number 5990-5729EN

For more information on the Keysight 53200 Series, please visit:
https://www.keysight.com/us/en/products/frequency-counter-products.html