UNDERSTANDING PHASE NOISE FUNDAMENTALS

White paper | Version 01.01 | Paul Denisowski

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CONTENTS

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- R&S®FSPN phase noise analyzer and VCO tester

1 OVERVIEW

A stable frequency source is a common requirement for many electronic and most RF devices. Phase noise is the term used to describe measurements of the short-term frequency stability of these sources. This white paper provides a brief technical introduction to phase noise concepts as well as an overview of how phase noise is measured and reported.

2 ABOUT OSCILLATORS

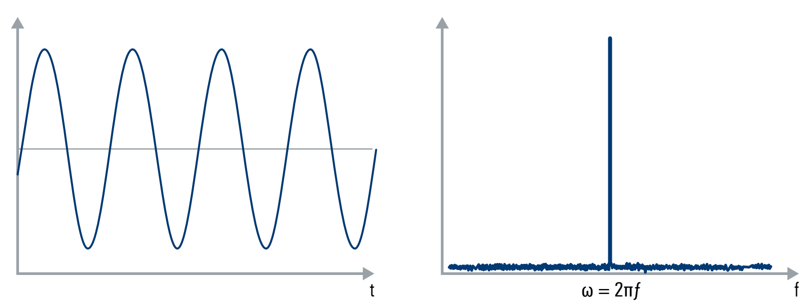
2.1 Oscillators and phase noise

Oscillators are commonly used as frequency references and therefore phase noise is commonly used to quantify oscillator stability. All real-world oscillators exhibit some amount of frequency or phase variation, and although there are ways to minimize this variation, it can never be completely eliminated. As discussed below, excessive frequency instability can create serious problems in many applications, so accurately quantifying or measuring this level of instability is very important.

2.2 Ideal oscillator

The output of an ideal oscillator is usually a purely sinusoidal signal, which can be described mathematically as $V(t) = A \cdot \cos(\omega t + \varphi)$. In this equation, the amplitude (A) of the oscillator output is a constant, the radial frequency (ω) is a constant, and the phase shift or phase offset (φ) is a constant. Viewed in the frequency domain, a pure sinusoid therefore appears as a single narrow spectral line, with all of its power at a single frequency, as shown in Figure 1.

Figure 1: Ideal oscillator

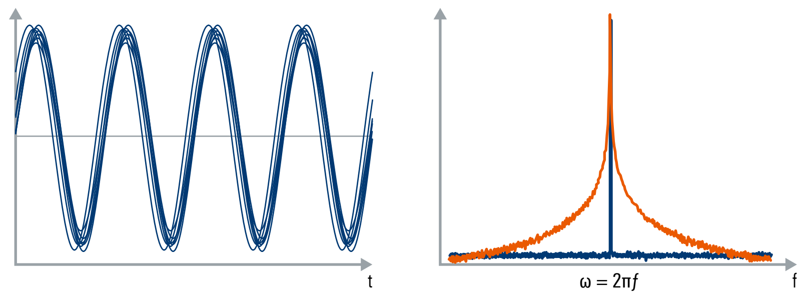


2.3 Non-ideal (real) oscillator

A non-ideal or real-world oscillator signal can be described mathematically as $V(t) = A(t) \cdot \cos(\omega t + \varphi(t))$. Note that this equation differs from the ideal oscillator equation in two ways. The radial frequency (ω) is still a constant, but both the amplitude and the phase offset are now functions of time. In other words, the amplitude and the phase of the signal now vary over time, usually in an unpredictable or random fashion. In the time domain, phase variations cause a shifting of where the sinusoid crosses the x-axis: a phenomenon often referred to as jitter. In the frequency domain, these variations create sidebands extending out from both sides of the carrier. Figure 2 shows the output of a non-ideal, real-world oscillator in both the time and frequency domains.

Unintended or unpredictable changes in the phase and amplitude of an oscillator output are both undesirable, but in most cases the effects of phase variation are much larger and more important than the effects of amplitude variations.

Figure 2: Non-ideal (real) oscillator



3 ABOUT PHASE NOISE

Phase noise is the term used to describe short term variations in phase or frequency stability, with "short term" referring to time intervals on the order of seconds or less. Another way of defining or describing phase noise is as random or unintentional phase modulation. Short term stability or "good phase noise performance" is very important in a wide variety of RF applications, but this short term stability can be difficult to obtain, with a substantial cost and complexity often associated with even modest increases in phase noise performance.

4 COMMON EFFECTS OF PHASE NOISE

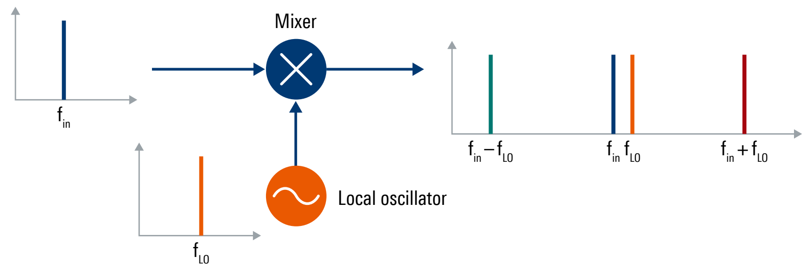
The importance of minimizing phase noise can best be understood by looking at the effects of excessive phase noise. The three most common effects of phase noise are spectral regrowth, decreased sensitivity/selectivity, and increased bit errors.

4.1 Review of mixing

Spectral regrowth and decreased sensitivity/selectivity are both related to mixing. A mixer is a device that can be used to move signals from one frequency to another. It does this by combining an input signal (f_{in}) with a local oscillator (f_{LO}) to produce an output that contains not just the original signals, but also signals at the sum (f_{in} + f_{LO}) and difference (f_{in} – f_{LO}) of these two frequencies (Figure 3).

Mixing is widely used in RF receivers for two main reasons. First, it is generally easier to work with lower frequency signals than higher frequency signals. Second, mixing allows the use of fixed frequency filters, amplifiers, etc. In a receiver, signals can simply be mixed “down” to a convenient frequency for processing. Conversely, a signal may be mixed "up" in frequency, for example, in the case of a transmitter that converts a lower frequency or "baseband" signal into a radio frequency signal.

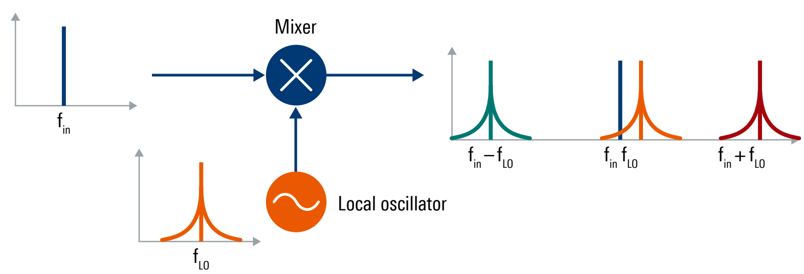
Figure 3: Mixing produces the sum and difference frequency of the input signal and local oscillator



4.2 Phase noise and spectral regrowth

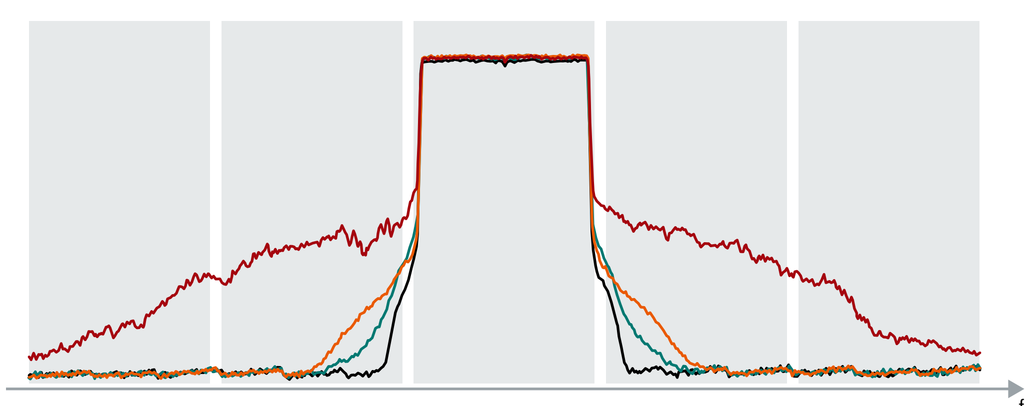
Any phase noise in the local oscillator signal is also mixed with the input signal, leading to an output whose mixing products are distorted and spread in frequency. This is sometimes called "spectral regrowth" and is shown in Figure 4.

Figure 4: Local oscillator phase noise and distorted/spread mixing products



The consequences of spectral regrowth are easily seen in wider bandwidth signals, such as those found in LTE, 5G NR, Wi-Fi, etc. If the local oscillator has low phase noise, the resulting signal will be mostly contained within its assigned channel (Figure 5) with very little power leaking into the adjacent channels. But as the level of phase noise increases, the signal will become wider and will spread further into these adjacent channels. At high levels of phase noise (the red trace), this regrowth or "adjacent channel leakage" can become quite severe, causing significant interference.

Figure 5: Spectral regrowth (adjacent channel leakage) in a wideband signal

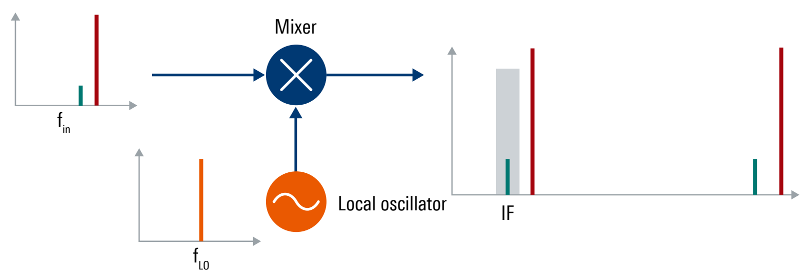


4.3 Phase noise and reciprocal mixing

Phase noise can also cause problems due to reciprocal mixing. Reciprocal mixing arises in situations where a small wanted signal (green in Figure 6) is adjacent to a large unwanted signal (red).

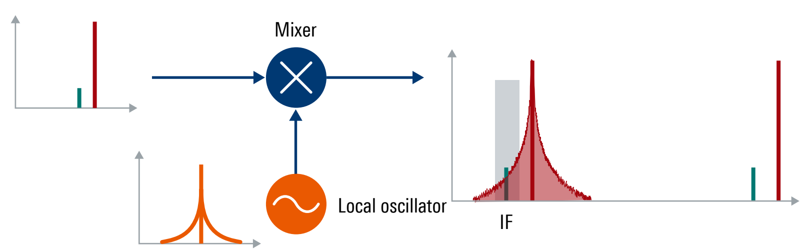
A local oscillator and mixer can be used to move the signals down to an IF (intermediate frequency) for processing. The IF filter (gray) only selects the desired signal and rejects the larger unwanted adjacent signal.

Figure 6: Large adjacent interferer rejected by IF filter



However, if the local oscillator has excessive amounts of phase noise, energy will spread from the adjacent unwanted signal into the IF filter, making it difficult or impossible to recover the smaller signal (Figure 7). Local oscillator phase noise therefore should be kept as low as possible, since this phase noise reduces both the sensitivity and selectivity of a receiver.

Figure 7: LO phase noise reduces sensitivity when interferer power spills into IF



4.4 Phase noise and communications systems

Phase noise can also create problems for communications systems that use some form of phase modulation. Most modern high-data rate wireless technologies use modulation schemes that are based on phase and amplitude modulation, for example, APSK (amplitude and phase shift keying) or QAM (quadrature amplitude modulation). These modulation schemes are often represented using polar **constellation diagrams**, where each point in the constellation is a "symbol" composed of a unique amplitude and phase (Figure 8).

Phase noise causes a rotation of the constellation, with higher levels of phase noise causing greater rotation of the points (Figure 9). If this rotation becomes high enough, symbols can be interpreted incorrectly, leading to bit errors or a higher bit error rate.

Figure 8: 16QAM constellation diagram

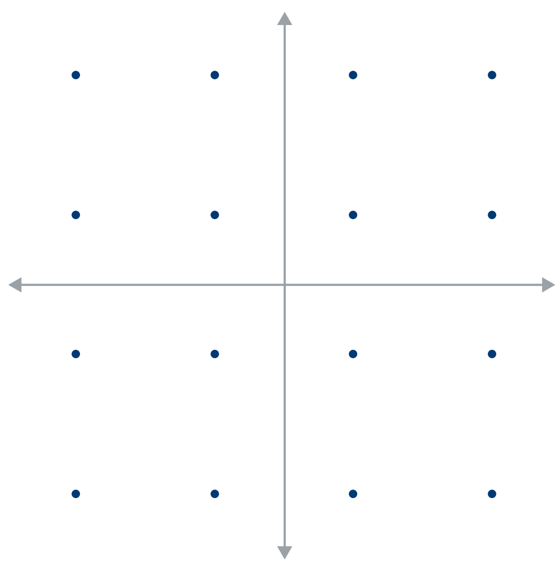
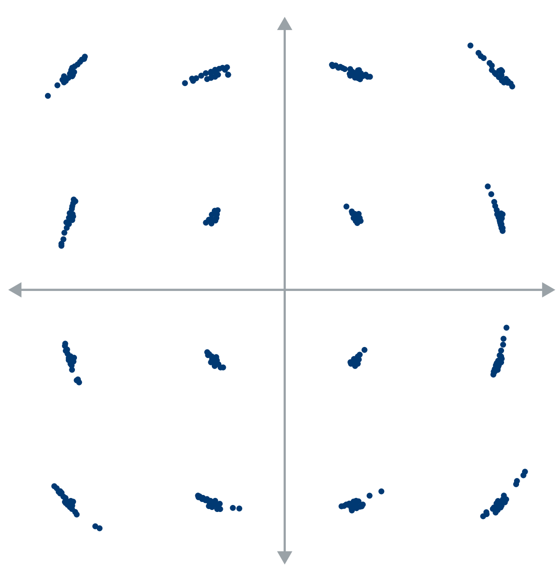


Figure 9: 16QAM with phase noise



5 MEASURING AND ANALYZING PHASE NOISE

There are two types of RF test and measurement instruments that can be used to measure or analyze phase noise: spectrum analyzers and phase noise analyzers. Outwardly, these instruments are often very similar in appearance and display results in similar ways, but there are important differences between them.

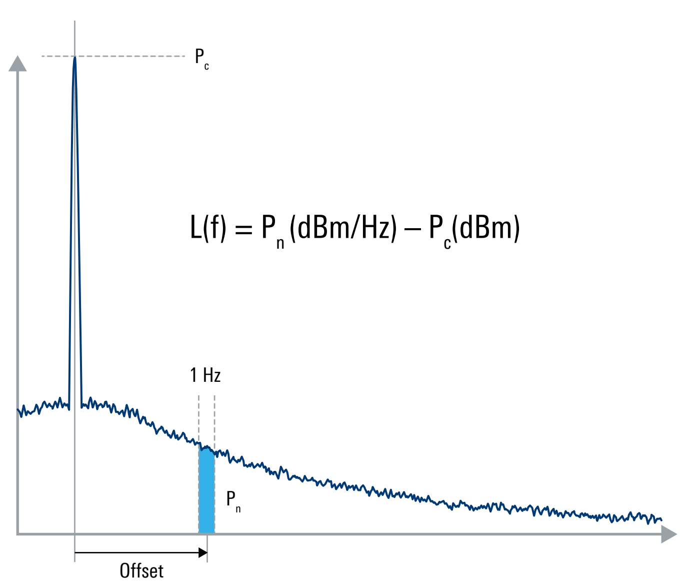
Spectrum analyzers are general-purpose instruments and are the traditional tool used for measuring phase noise. In almost all cases phase noise measurements using spectrum analyzers are performed by means of an automated phase noise measurement application. The greatest advantage of using a spectrum analyzer for phase noise measurements is that a spectrum analyzer is a flexible, general-purpose instrument that can be used for a wide range of other measurements as well.

A **phase noise analyzer**, as the name implies, is an instrument containing specialized hardware specifically designed for making phase noise measurements. Phase noise analyzers usually have higher speed and higher sensitivity than traditional spectrum analyzers, the increased sensitivity primarily being a result of the cross correlation method implemented in many phase noise analyzers – this will be covered in chapter 5.5. In addition, many modern phase noise analyzers also have other functionality used in testing oscillators, such as the ability to measure amplitude noise and spurious emissions or the ability to characterize voltage controlled oscillators.

5.1 Overview of the spectrum analyzer method

The spectrum analyzer (or "direct spectrum") method is the traditional method for measuring phase noise and is illustrated in Figure 10. The first step in this method is measuring the power of the carrier (P_c), that is, the nominal oscillator output signal, as an absolute power in dBm. Next, the noise power (P_n) within a 1 Hz bandwidth is measured at a given frequency offset from the carrier. Subtracting the carrier power from the noise power yields phase noise (L(f)) in units of dBc/Hz. Note that these values will always be negative. Phase noise measurements normally involve repeating this process at different frequency offsets from the carrier. Measured phase noise will usually be different at different offsets, generally decreasing the further away measurements are made from the carrier.

Figure 10: Spectrum analyzer method



5.2 Single sideband phase noise

In Figure 10, phase noise was measured at a positive frequency offset from the carrier. Since the "sidebands" created by phase noise are usually symmetrical around the carrier, measured phase noise is normally the same for a given positive or negative offset from the carrier. In Figure 11, phase noise is –70 dBc/Hz at both +10 kHz and –10 kHz offsets from the carrier. Therefore, phase noise is normally only measured on one side of the carrier (Figure 11) and this measurement is called "single sideband phase noise". By convention, positive offsets (the upper sideband) are used when measuring and reporting phase noise.

Figure 11: Symmetrical phase noise

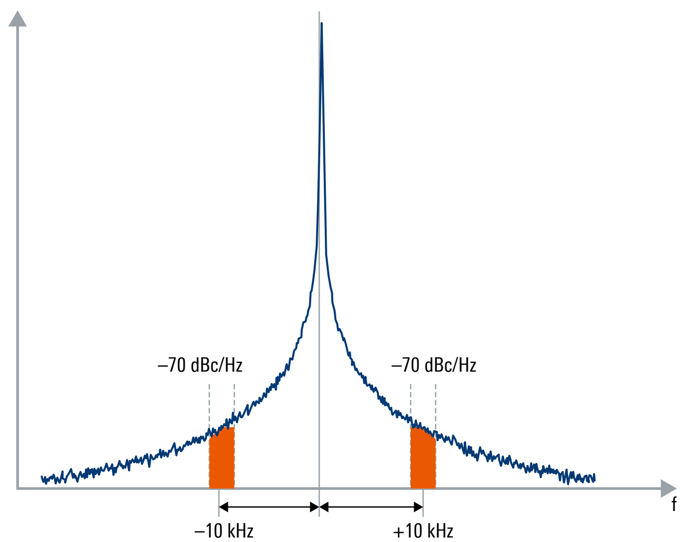
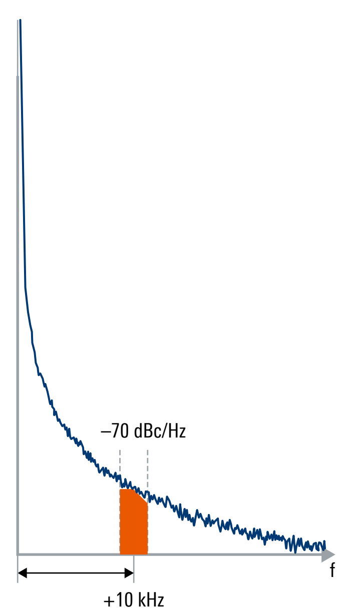


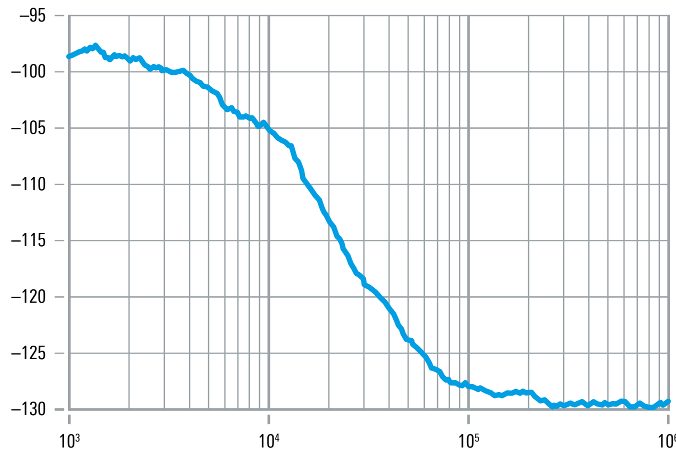
Figure 12: Upper sideband



5.3 Plotting SSB phase noise

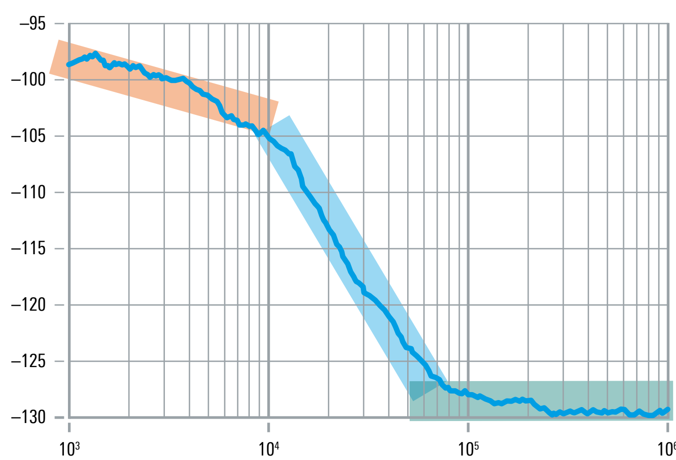
Single sideband phase noise is measured and plotted over a defined range of frequency offsets. In Figure 13, this offset range is 1 kHz to 1 MHz. A logarithmic scale is used because this allows both a wide frequency range as well as finer resolution close to the carrier – smaller offsets or "close in" phase noise are often of greater interest than the phase noise at larger frequency offsets.

Figure 13: Single sideband phase noise plot



Since phase noise is undesirable, lower values in a phase noise plot indicate "better" phase noise performance. Note that many phase noise plots have distinct "regions" in which the phase noise graph has different slopes. These are highlighted in Figure 14. These different regions exist because the causes or sources of phase noise are often different at different offsets from the carrier.

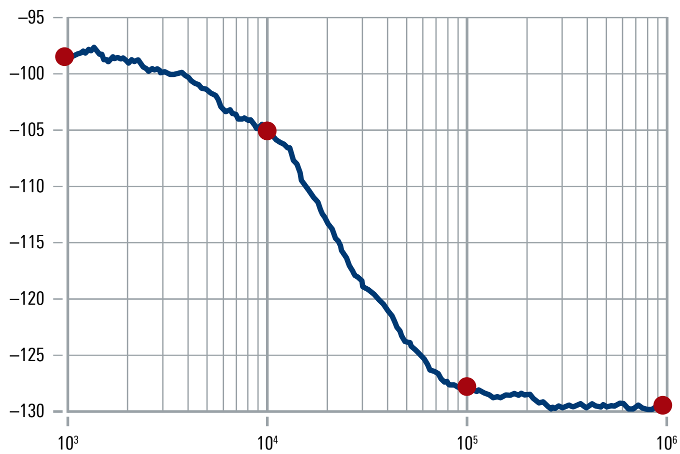
Figure 14: Phase noise "regions"



5.4 Spot noise

In addition to the single sideband phase noise plot, another common way of representing phase noise measurement results is **spot noise**. Spot noise is the numerical phase noise result (in dBc/Hz) at one or more specific frequency offsets. Spot noise is often measured at decade offsets, that is, offsets which are powers of ten, e.g. 1 kHz, 10 kHz, 100 kHz, etc., although it is also possible to measure spot noise at arbitrary, user-defined offsets. Spot noise is commonly reported in table form and is often used to verify that phase noise at a given offset is below a specified threshold or specification value.

Figure 15: Spot noise



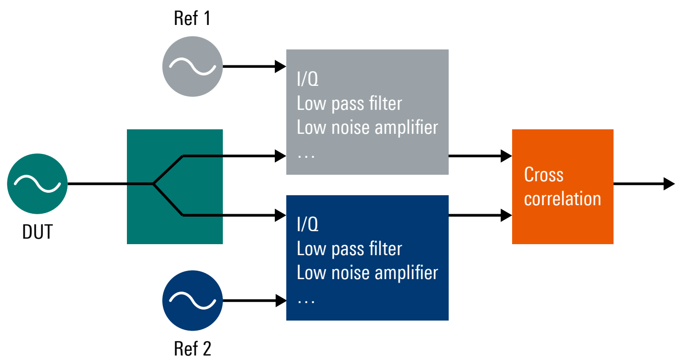
Offset	Phase noise
1.00 kHz	–98.35 dBc/Hz
10.00 kHz	–105.16 dBc/Hz
100.00 kHz	–127.56 dBc/Hz
1.00 MHz	–129.45 dBc/Hz

5.5 Phase noise analyzer/cross correlation method

Although it presents results in the same way, a phase noise analyzer measures phase noise differently than a spectrum analyzer. The first difference is that phase noise analyzers measure phase noise directly, typically using a special digital phase demodulator. The other important difference is related to **the cross correlation method** in modern phase noise analyzers.

All measurement instruments contain local oscillators whose phase noise will be added to the phase noise of the device under test (DUT). In cross correlation, the incoming signal from the device under test (DUT) is routed through two "identical" measurement paths in the instrument. These "identical" paths have independent local oscillators, each of which has slightly different, that is, uncorrelated phase noise. When these two paths are fed into a cross-correlation function, the uncorrelated phase noise generated by the instrument can be minimized or removed, thus allowing a more precise and more sensitive measurement of the phase noise in the signal from the DUT. Increasing the number of cross correlations further increases the sensitivity, allowing the measurement of extremely low levels of phase noise.

Figure 16: Cross correlation method

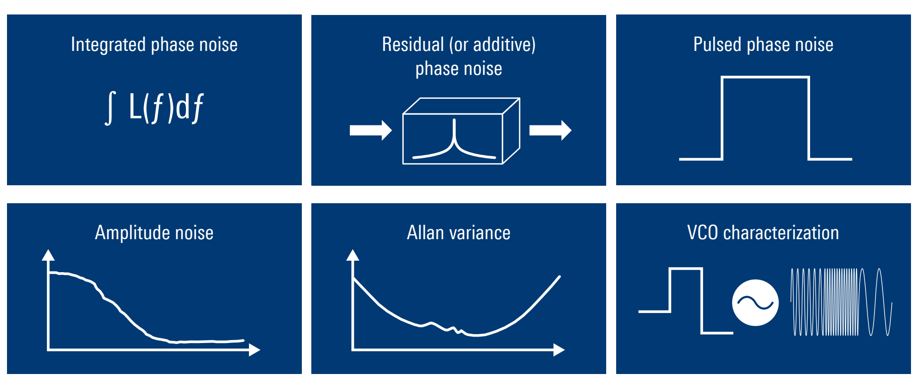


Phase noise analyzers therefore have the advantage of being much faster, especially when measuring close-in offsets, as well as having much greater measurement accuracy and sensitivity when using the cross correlation method.

5.6 Additional phase noise related measurements

This white paper covers the fundamentals of phase noise measurements, but there are many additional types of phase noise related measurements. **Integrated phase noise** measurements involve integrating over some portion of the single sideband phase noise curve. **Additive** (or "residual") phase noise measurements are used to determine how much phase noise is added as a signal moves through a device. Measuring the **phase noise of pulsed signals** such as radar presents special challenges, as does measuring **amplitude noise** separately from phase noise. **Allan variance** is a measure of long-term frequency stability, and **VCO characterization** is used to determine additional key properties of voltage controlled oscillators.

Figure 17: Additional common phase noise related measurements



6 SUMMARY

An ideal oscillator produces a signal whose frequency, amplitude, and phase do not vary over time. Phase noise describes the short-term variations in the frequency or phase of signals produced by real-world oscillators or other devices. Phase noise is undesirable for many reasons and phase noise measurements are used to quantify phase noise performance. Phase noise measurement results are typically given in the form of a single sideband plot, which shows phase noise as a function of carrier offset, and as spot noise, which is a measurement of phase noise at specific offsets. Two types of instruments are used when measuring phase noise. Traditional spectrum analyzers often support automated phase noise measurement personalities in addition to their many other functions. Dedicated phase noise analyzers contain special hardware designed to make very fast and very accurate measurements of phase noise and also frequently incorporate a cross correlation function in order to reduce the influence of instrument phase noise and maximize measurement sensitivity.

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