UNDERSTANDING PHASE NOISE MEASUREMENT TECHNIQUES

White paper | Version 01.00 | Paul Denisowski

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- R&S®FSPN phase noise analyzer and VCO tester
- R&S®FSW signal and spectrum analyzer
- R&S®FSV3000 signal and spectrum analyzer

1 OVERVIEW

Phase noise can be measured and analyzed either with traditional spectrum analyzers or with dedicated phase noise analyzers. This educational note explains the differences between these two measurement approaches and provides guidance regarding which instrument is most suitable for a given phase noise measurement application.

This educational note assumes a basic familiarity with phase noise and phase noise measurements. The Rohde & Schwarz white paper "Understanding phase noise fundamentals" provides a general technical introduction to these topics.

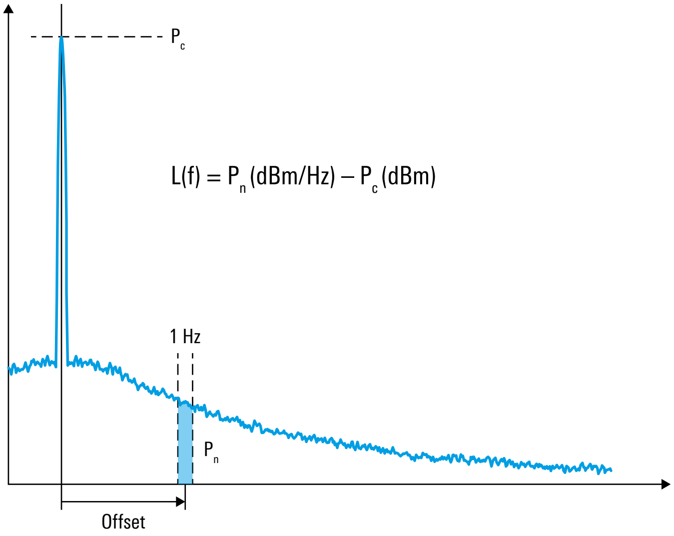
https://www.rohde-schwarz.com/sg/products/test-and-measurement/analyzers/signal-spectrum-analyzers/white-paper-understanding-phase-noise-fundamentals-register_255143.html

2 SPECTRUM ANALYZER METHOD

2.1 Overview of the spectrum analyzer method

The spectrum analyzer method is the oldest, most straightforward, and most widely-used way to measure phase noise. The basic procedure starts with measuring the carrier power (P_c) of the device under test as an absolute value in dBm. The next step is to move to a given frequency offset from the carrier – that is, to a point in the phase noise sideband. The noise power (P_n) contained within a one hertz bandwidth is then measured at this offset. Subtracting the carrier power (P_c) from the noise power (P_n), yields phase noise in units of dBc/Hz at the given offset. This methodology is shown in Figure 1. In almost all cases, this procedure is repeated at different offsets from the carrier, with results presented graphically and/or as individual spot noise values.

Figure 1: Spectrum analyzer method



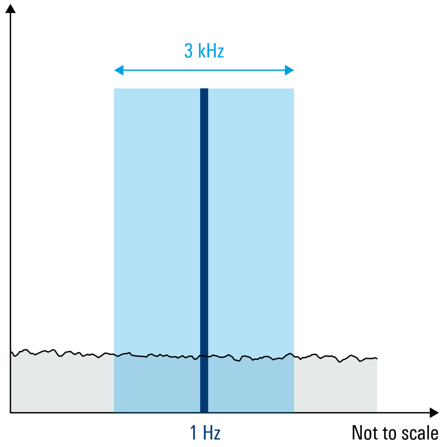
When making phase noise measurements using a spectrum analyzer, there are however two additional steps that must be performed to ensure accurate measurement values: normalization and shape correction.

2.2 Normalization

Phase noise is specified as the noise power contained within a bandwidth of 1 Hz. Spectrum analyzers measure power using a resolution bandwidth (RBW) filter, and in most spectrum analyzers, the filter used for measuring power is more than 1 Hz wide. Therefore, noise power measured by these wider RBW filters must to be normalized to a 1 Hz bandwidth. This normalization is done by reducing the measured noise power value by N dB, where $N = 10 \cdot \log(\text{RBW in Hz})$.

For example, if noise power measured with a 3 kHz resolution bandwidth filter is –90 dBm (Figure 2), the normalized 1 Hz noise power would be –124.77 dBm (–90 – 10 log(3000)).

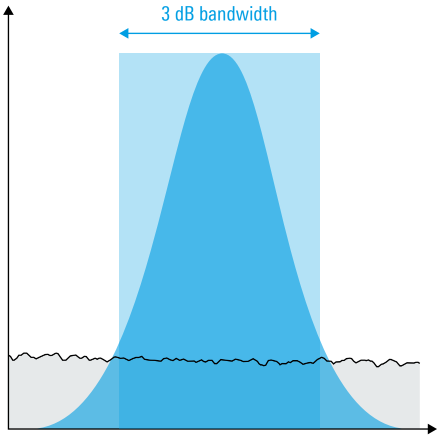
Figure 2: Normalization of noise power to 1 Hz bandwidth



2.3 Shape correction

In Figure 2, resolution bandwidth was shown as a rectangle. However, real-world resolution bandwidth filters are not perfectly rectangular but usually have a Gaussian or similar shape, as shown in Figure 3. Therefore, in additional to normalizing for the bandwidth, corrections must also be made to compensate for the shape of the filter. For a given resolution bandwidth, a Gaussian filter will have a wider noise bandwidth than its nominal (3 dB) bandwidth. Therefore, filter bandwidth must be multiplied by a scaling or correction factor before normalization. This correction factor is implementation-dependent. In other words, the value depends on the specific filter implementation: not all Gaussian resolution bandwidth filters have identical shapes. For example, the shape correction for the 3 kHz filter shown in Figure 3 is 1.165, so when calculating N, the nominal filter width is multiplied by 1.165 before taking the logarithm. Note that most spectrum analyzers automatically apply both types of correction – bandwidth and shape – by means of a special **noise marker** function.

Figure 3: Shape correction



2.4 Measuring phase noise with a spectrum analyzer

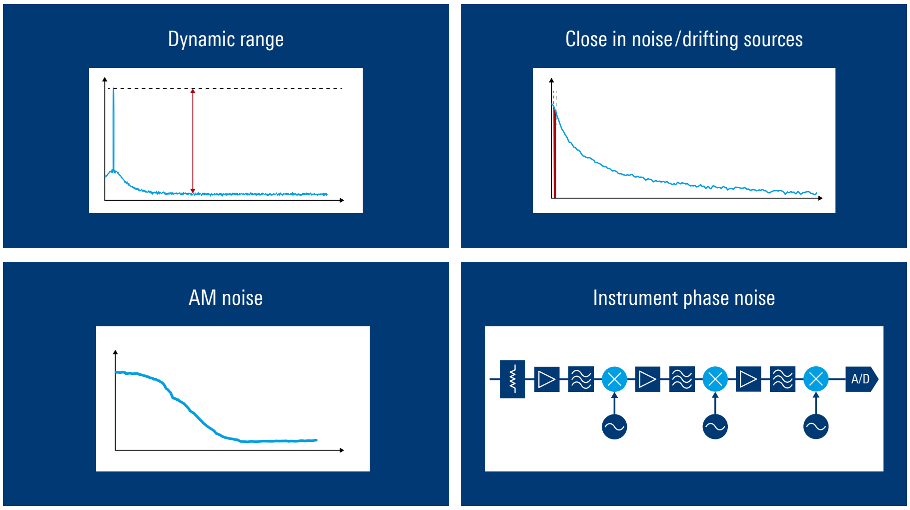
This type of noise marker could be used to manually make phase noise measurements. The marker would simply be placed at the offset of interest in order to obtain the normalized and shape-corrected phase noise value. However, like most other manual processes, measuring phase noise this way is both time-consuming and error-prone. Many modern spectrum analyzers have a phase noise measurement personality that automates the process and repeats the measurement over a user-defined range of frequency offsets.

Spectrum analyzers are general-purpose instruments, so the greatest advantage of using a spectrum analyzer for measuring phase noise is that it provides additional useful functions for characterizing sources, such as measurements of spurious emissions, settling time measurements, and many others.

2.5 Challenges/limitation of the spectrum analyzer method

For many applications, the traditional spectrum analyzer approach is sufficient for obtaining accurate and repeatable phase noise measurements. It is however important to be aware of some of the challenges or limitations when using the spectrum analyzer method. These are: dynamic range, close-in noise or drifting sources, AM or amplitude noise, and the contribution of instrument phase noise.

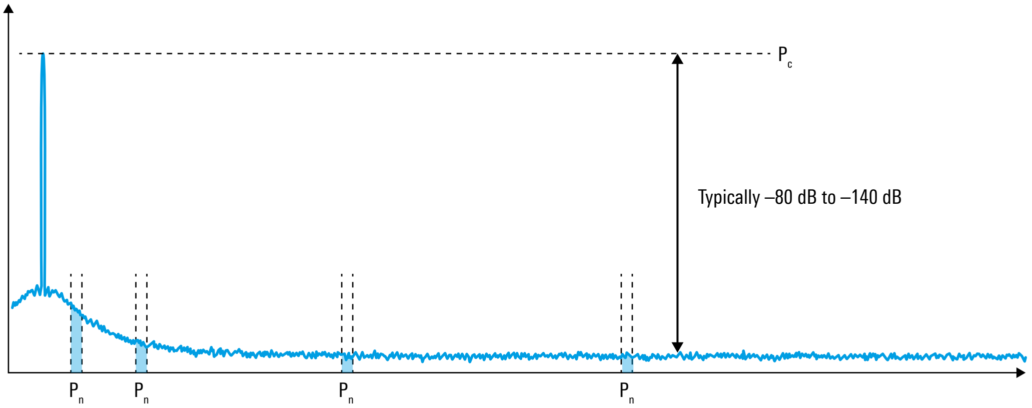
Figure 4: Challenges/limitations of the spectrum analyzer method



2.5.1 Dynamic range

In the spectrum analyzer method, phase noise is calculated by measuring both the power of the carrier as well as noise powers at different offsets from the carrier. The difference between the measured carrier power and the measured noise power is usually quite large, typically from 80 dB to over 140 dB. Therefore, in order to make accurate phase noise measurements, the analyzer must be able to measure both very high and very low powers simultaneously. As a result, dynamic range – the difference between the largest and smaller signals that can be accurately measured – becomes an important consideration when selecting a spectrum analyzer for making phase noise measurements.

Figure 5: Dynamic range and the spectrum analyzer method

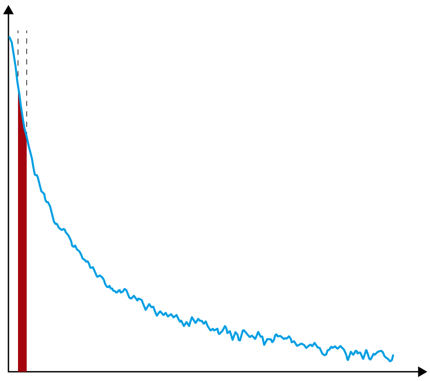


2.5.2 Close-in phase noise/drifting sources

Measuring phase noise at very small offsets from the carrier (“close-in” phase noise) is challenging for two reasons. First, a very narrow resolution bandwidth is required in order to avoid measuring the carrier power as well as the noise power. The fact that resolution bandwidth filters have a Gaussian rather than a perfectly rectangular shape also complicates this issue. An additional challenge is measuring the phase noise of a carrier that drifts slightly in frequency, although some analyzers do have the ability to track a small amount of drift and automatically compensate for it.

Modern spectrum analyzers can avoid some of these issues by measuring phase noise using so-called “I/Q” data. I/Q data is a digital representation of the spectrum and is obtained by means of the fast Fourier transform. Measuring with I/Q data can improve both the stability and the accuracy of phase noise measurements, particularly for close-in or drifting sources.

Figure 6: Measuring close-in phase noise

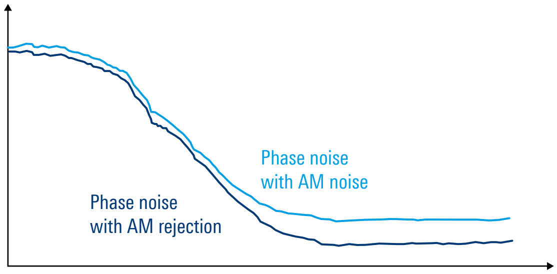


2.5.3 Amplitude noise

This same I/Q mode is also useful when it comes to AM or amplitude noise. When measuring phase noise, it is assumed that the noise sidebands around the carrier are mostly due to phase noise, with some smaller amount of amplitude noise mixed in. In general, this is a valid assumption: the AM noise in real-world devices is usually much less than the phase noise. In some cases, however, this assumption may not be true, and if a relatively large amount of amplitude noise is present, the spectrum analyzer method may not produce accurate results, because this method cannot normally distinguish between AM and phase noise.

Separate measurements of AM and phase noise usually require the use of a different instrument, that is, a dedicated phase noise analyzer, but a traditional spectrum analyzer can reject some AM noise if the measurement is made with I/Q data. It should also be noted that the influence of AM noise is usually greatest at higher frequency offsets from the carrier, so the benefits of using I/Q data become more noticeable as the offset from the carrier increases.

Figure 7: Phase noise with and without AM noise



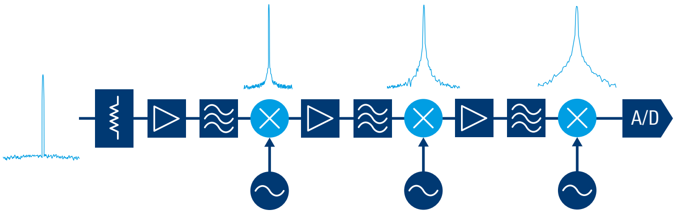
2.5.4 Instrument phase noise

An additional consideration is the phase noise of the analyzer itself. Spectrum analyzers usually contain multiple local oscillators (LO). Like all other oscillators, the local oscillators used in a spectrum analyzer have their own phase noise, and the phase noise of the LOs in the spectrum analyzer is added to the phase noise of the measured signal as it moves through different stages in the analyzer.

One of the limitations of the spectrum analyzer method is therefore the difficulty in separating or distinguishing the phase noise present in the original signal from the phase noise added by the instrument. The easiest and most common way of avoiding this issue is to ensure that the analyzer has a better phase noise specification than the device under test (DUT). At least 10 dB is generally considered the minimum acceptable margin, but generally speaking, a larger margin will provide more accurate phase noise results.

Another method for reducing the influence of instrument phase noise is the **cross-correlation method**, which is discussed in the next section.

Figure 8: Contribution of instrument phase noise



3 CROSS-CORRELATION METHOD

3.1 Phase noise measurement challenges

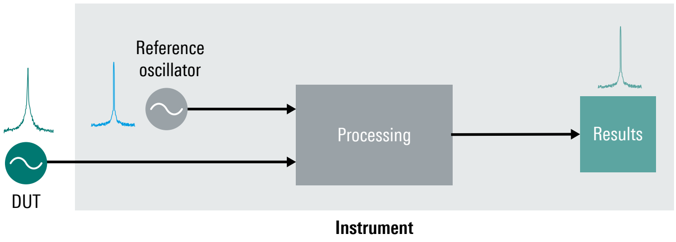
There are many different methods for measuring phase noise. Some of the more common methods are the spectrum analyzer method discussed above, the PLL method, and both phase detector and digital phase demodulator methods. Each of these methods has different strengths and weaknesses but they all share the common limitation that phase noise from the instrument is added to the phase noise from the device under test. Most of this added noise comes from the instrument's local or reference oscillator(s) and this noise is problematic because it makes it difficult to determine how much phase noise is present in the DUT signal and how much is added by the measuring instrument.

As mentioned in the previous section, the traditional way of dealing with this issue is to use an instrument that has "better" phase noise performance than the DUT, with "better" usually being defined as at least 10 dB or more. However, this approach still may not be sufficient when measuring modern DUTs with very low levels of phase nose.

3.2 DUT phase noise versus instrument phase noise

Figure 9 illustrates the issue of instrument phase noise. The device under test has a certain amount of phase noise to be measured. Within the measuring instrument, this signal is processed using one of the different phase noise measurement methods. Regardless of the method used, processing or measuring the signal requires at least one local or reference oscillator, and the phase noise of this oscillator is combined with the DUT phase noise. Depending on the relative levels of the phase noise in the DUT and reference oscillator, the resulting phase noise measurement results may not be an accurate measurement of the DUT phase noise.

Figure 9: Phase noise added by the instrument



3.3 Improving phase noise measurements

Using an instrument whose local oscillators have low phase noise and using a modern phase noise measurement method, such as digital phase demodulation, can greatly improve phase noise results, but this still may not be sufficient for measuring very "quiet" oscillators. In these cases, being able to remove, or at least reduce, the influence of instrument phase noise would be particularly advantageous. This would increase sensitivity, that is, allow measurement of very low levels of phase noise. Since the 1990s, **cross-correlation** has been the primary method for reducing or removing the effect of instrument phase noise.

3.4 About cross-correlation

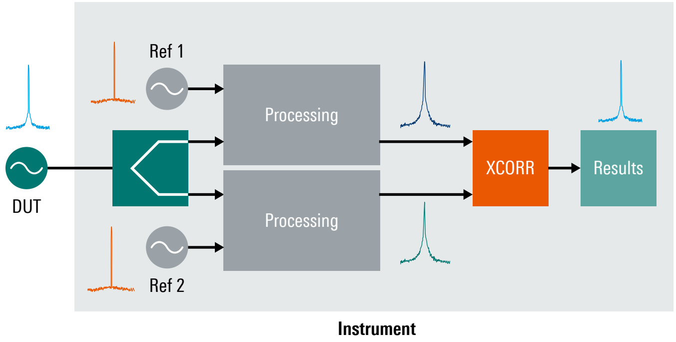
Cross-correlation is a measure of the similarity between two different series or signals, and it can also provide the time delay needed for maximum similarity. Cross-correlation is very widely used in many different signal processing applications, such as radar, direction finding, etc. Because cross-correlation identifies the similarities between two signals, it also can be used reduce or remove the "differences" between sets of data. In other words, cross-correlation can be used to separate data into "correlated" or similar parts and "uncorrelated" or dissimilar parts. In addition, cross-correlation can be performed as an iterative or repeated process: performing repeated cross-correlations more clearly separates the correlated and uncorrelated elements in two sets of data.

3.5 Cross-correlation in phase noise measurements

Because cross-correlation involves measuring the similarity of two different signals, it is implemented by adding a second measurement path to the measuring instrument. The signal from the device under test is split and processed by these two, nominally "identical," paths. Because the DUT signal is simply being split, the DUT phase noise remains the same or "correlated" on each path. However, each path uses its own independent local oscillator for measuring phase noise, and the phase noise introduced by these local oscillators is therefore uncorrelated or "different" on each path. Therefore, the measurement results from each path are a combination of the correlated DUT phase noise and the uncorrelated local oscillator phase noise. When these two paths are fed into a cross-correlation function, the uncorrelated instrument noise is removed or reduced, leaving only the correlated phase noise of the DUT. This process is depicted graphically in Figure 10.

Note that because of the need for two separate paths and the need to compare two sets of data, cross-correlation can only be implemented in dedicated phase noise analyzers, not in traditional single-path spectrum analyzers.

Figure 10: Cross-correlation in phase noise measurements



3.6 About correlation count

Recall that cross-correlation can be performed iteratively or repeatedly. If the number of correlations, N, is increased, this will reduce the level of uncorrelated instrument noise in the measurement results. This in turn provides increased sensitivity or a lower noise floor, allowing the accurate measurement of even very low levels of phase noise. The improvement obtained by increasing the number of correlations is logarithmic and follows the formula $5 \cdot \log10(N)$ dB. Every time the number of correlations is increased by an order of magnitude, sensitivity increases by 5 dB. For example, 10000 correlations will lead to a 20 dB improvement.

Increasing the number of correlations will also increase the total time required for the measurement, but the benefits of cross-correlation normally far outweigh the relatively minor increase in measurement time. Typically, the number of correlations used in phase noise measurements are in the range of several thousand to one million.

Figure 11: Correlation count and sensitivity improvement

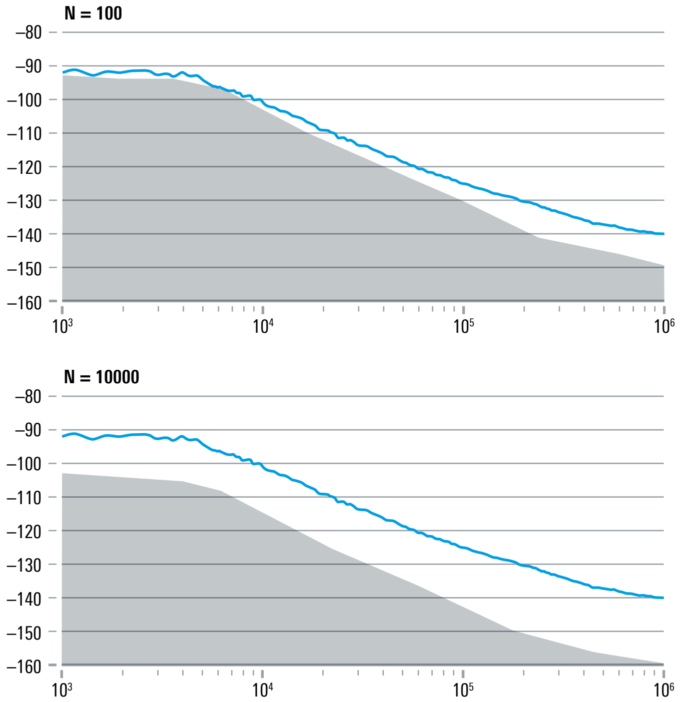
Number of correlations (N)	Sensitivity/noise floor improvement
1	0 dB
10	5 dB
100	10 dB
1000	15 dB
10000	20 dB

3.7 Visualizing cross-correlation gain

The next question is how many cross-correlations to perform. The correlation count should be high enough to lower the instrument noise floor below the level of DUT phase noise, ideally with some margin to spare. This helps ensure that only the DUT phase noise is being measured.

In addition to the measured phase noise trace, some phase noise analyzers can also display the so-called cross-correlation gain, which can be used to visually verify that sufficient measurement margin exists. In Figure 12, the gray area beneath the phase noise trace shows the cross-correlation gain. The higher the trace lies above this region, the more accurately the DUT phase noise can be measured separately from instrument noise. If the trace is too close to or touches this region, the instrument should be configured to perform a higher number of cross-correlations to further lower the measurement floor. In Figure 12, increasing number of correlations from 100 to 10000 clearly improves the measurement margin, particularly for phase noise at close-in offsets.

Figure 12: Visualizing cross-correlation gain



4 SUMMARY

Phase noise can be measured using either traditional spectrum analyzers or dedicated phase noise analyzers. The primary advantage of spectrum analyzers is that they are general-purpose instruments and can be used for a wide variety of other measurements in addition to phase noise. However, the spectrum analyzer method does have certain limitations which can make them unsuitable for measuring very low levels of phase noise or close-in phase noise. Phase noise analyzers use different types of specialized hardware to measure phase noise, but their greatest advantage is the ability to use the cross-correlation method. By using a second measurement path, the cross-correlation method greatly reduces the influence of instrument phase noise and allows accurate measurement of very low levels of phase noise. In some cases, phase noise analyzers may also implement many traditional spectrum analyzer functions, providing both enhanced phase noise measurement sensitivity as well as standard spectrum measurements in a single instrument.

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