Determine the Dominant Source of Phase Noise, by Inspection

Contents

1 Abstract

A novel procedure[1] is presented to determine, by inspection, the location in a phase noise curve that dominates its integral. This location contributes more to an integrated phase noise result than elsewhere in the curve. The procedure can be used to help understand the dominant source(s) of noise present in a signal, as well as simplify the integration process by reducing the amount of data to analyze. A mathematical basis for the procedure is provided, which extends its application beyond phase noise to include logarithmic plots of other quantities for power (e.g., dBm) and fields (e.g., nV/√Hz). Refer to application note *AN10062 Phase Noise Measurement Guide for Oscillators* [1] for a theoretical overview of phase noise and methods and recommendations of phase noise measurement.

2 Introduction

One of the most common tasks working with phase noise is to integrate it over a range of offset frequencies to compute a number for RMS noise. To identify the dominant source of phase noise in this number, apply the following steps:

Step 1. In a phase noise plot, locate the appropriate offset-frequency range for an application of interest.

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[1] This procedure was developed by Dr. Giust at JitterLabs LLC, and taught in a class titled "Jitter Essentials" since 2006. To our knowledge, this is the first publication of this procedure.

Step 2. Draw a −10 dB/decade reference line above the phase-noise curve in this range.

Step 3. Lower the line until it intersects the curve.

The point of intersection identifies the region of the curve contributing most to the RMS noise number. Reducing the phase noise here will reduce the RMS noise number more than any other region in the curve.

For example, suppose the offset-frequency range of interest extends from f_1 to f_3 in Figure 1(a). Draw a −10 dB/decade line above this region and lower it until it intersects the phase noise curve. Line A in Figure 1(a) shows the point of intersection occurs at offset frequency f_1. Integrating the phase noise curve from f_1 to f_3 is therefore dominated by flicker frequency modulation (FFM) associated with the timing reference. If the integration range of interest for the application had started at f_2 instead of f_1, then Line B would be drawn instead, which intersects the curve near the loop bandwidth f_{loop} of the phase-locked loop (PLL) and identifies the PLL as the dominant noise source. Further investigation can narrow this down further, for example, whether the VCO noise is dominant, or if there is insufficient phase margin (e.g., causing peaking) in the PLL closed-loop transfer function, or something else.

As a third example, suppose a clock signal generated without a PLL has the phase noise shown in Figure 1(b). An application using this signal over an offset frequency range of f_4 to f_5 would be dominated (considering only the clock) by broadband noise, typically from the output buffer. Switching to a lower near-in phase noise timing reference would simply raise the cost without improving the RMS noise.

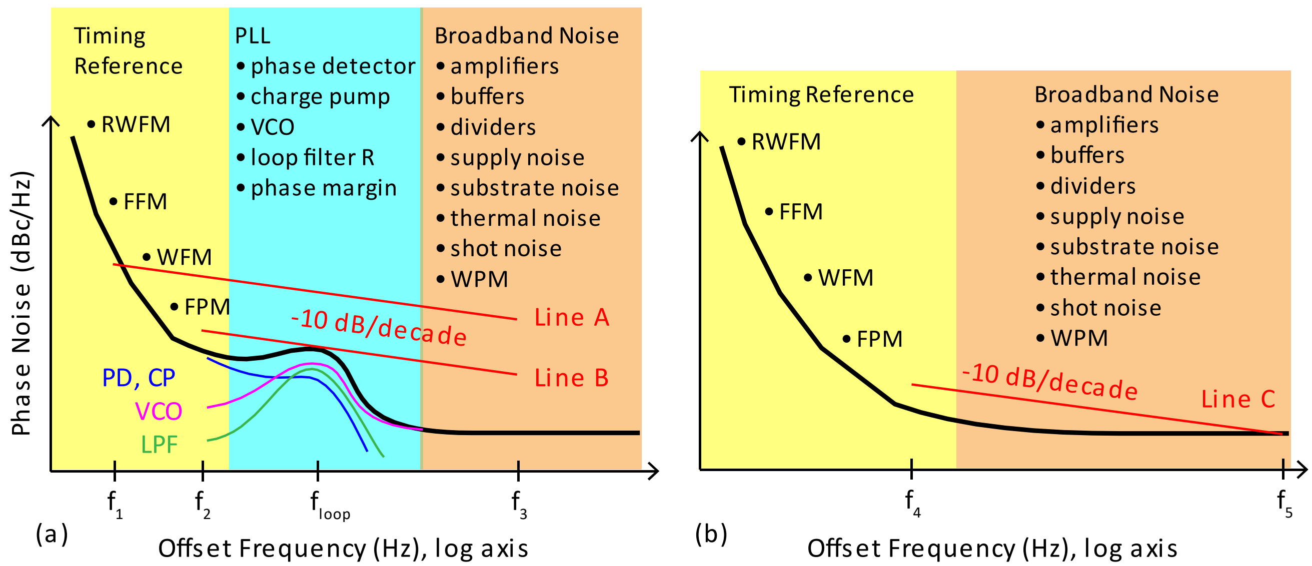

Figure 1: Example phase noise plots (a) with and (b) without a PLL, divided into regions based on the location of common sources of noise

This article explores using the above three-step procedure to determine, by visual inspection of the phase noise curve, the dominant source of RMS noise in a clock signal. For those interested, the Appendix derives the mathematics behind this procedure for plots of logarithmic quantities in general, extending this procedure beyond phase noise to include measurements of power (e.g., dBc), fields (e.g., nV/$\sqrt{\text{Hz}}$), and more.

For reference, RMS noise is computed from phase noise according to [2],

$$RMS\ noise\ (radians) = \sqrt{2\int_{f_a}^{f_b} 10^{L(f)/10} df} \qquad \text{Eq. 1}$$

where f_a to f_b define the offset-frequency region of interest to an application, and L(f) is phase noise in dBc/Hz, which is defined by the IEEE as one half of the double sideband power spectral density of a signal's phase deviation. RMS noise is usually an intermediate step along the way to computing a more appropriate application-specific quantity. For example, phase jitter, residual FM, and error vector magnitude (EVM) may each be computed from RMS noise, and applied to different applications.

3 Applying the 3-step Procedure

In some sense, a phase noise plot can be considered a log-log plot since the y-axis plots a logarithmic quantity (in units of dBc/Hz). However, it's usually easier and more intuitive to perform integration using linear-linear scales. So one of the first steps when integrating a phase noise plot is to apply an inverse log to the phase noise data before integrating it. Small steps along either axis in the phase noise plot result in large changes in the underlying data to be integrated. This makes it difficult, if not impossible, to eyeball whether one region of the phase noise curve has more integrable area below it than another region.

Here's a quick test. Which decade along the x-axis in Figure 2 contains the most integrable area? On one hand, the decade from 1 to 10 Hz spans few frequencies, but has relatively large phase noise. On the other hand, the decade from 100 kHz to 1 MHz spans a wide frequency range, but has relatively low phase noise. Give up? By drawing a –10 dB/decade line as shown in Figure 2 and lowering it, it is easy to see that this line would first intersect the phase noise curve at an offset frequency of 1 Hz. Therefore, the phase noise in the decade from 1 to 10 Hz has more integrable area below it than any other decade.

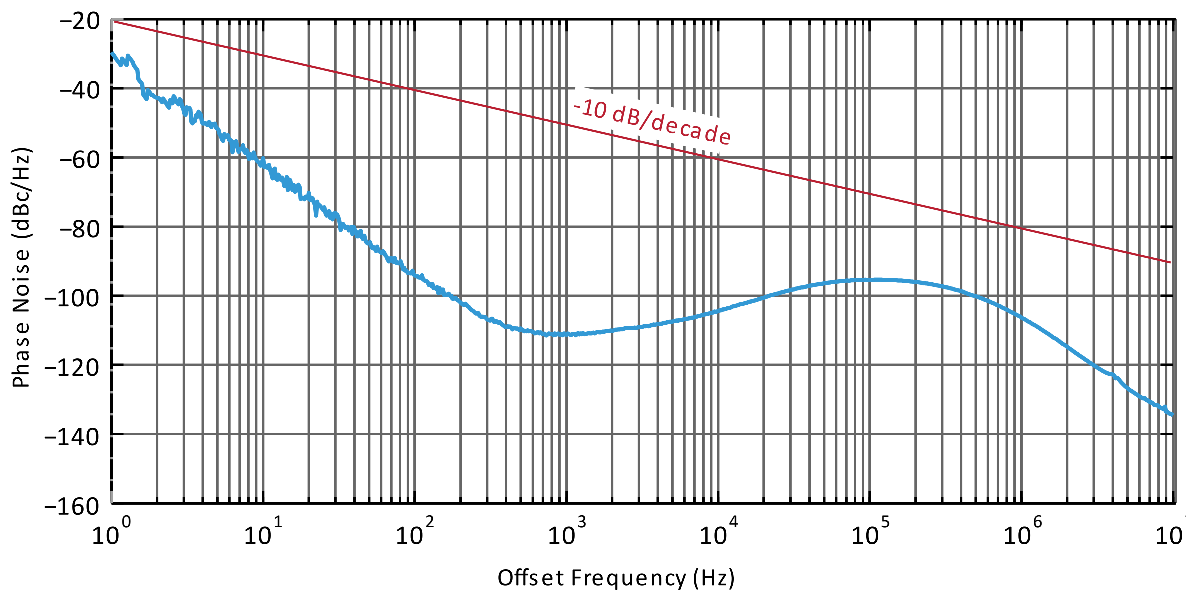

Figure 2: Phase noise plot for a 133 MHz LVCMOS oscillator

What's so special about a –10 dB/decade line? Figure 3(a) illustrates, for a 1 GHz clock frequency, that if this –10 dB/decade line were to represent a –10 dBc/Hz per decade phase noise curve, then regions of phase noise defined by equal log-spaced widths of offset frequency would all integrate to the same RMS noise (e.g., 4.3 rad RMS). The math behind this observation is provided in the Appendix. Although it is convenient to visualize regions with decade widths as shown in Figure 3(a), the exact width of these regions can be set arbitrarily, if the width of each region is the same along the log x-axis. For example, Figure 3(b) illustrates that if 4 decades are divided into 3 regions, the RMS noise for each region is still constant (at 0.555 rad RMS).

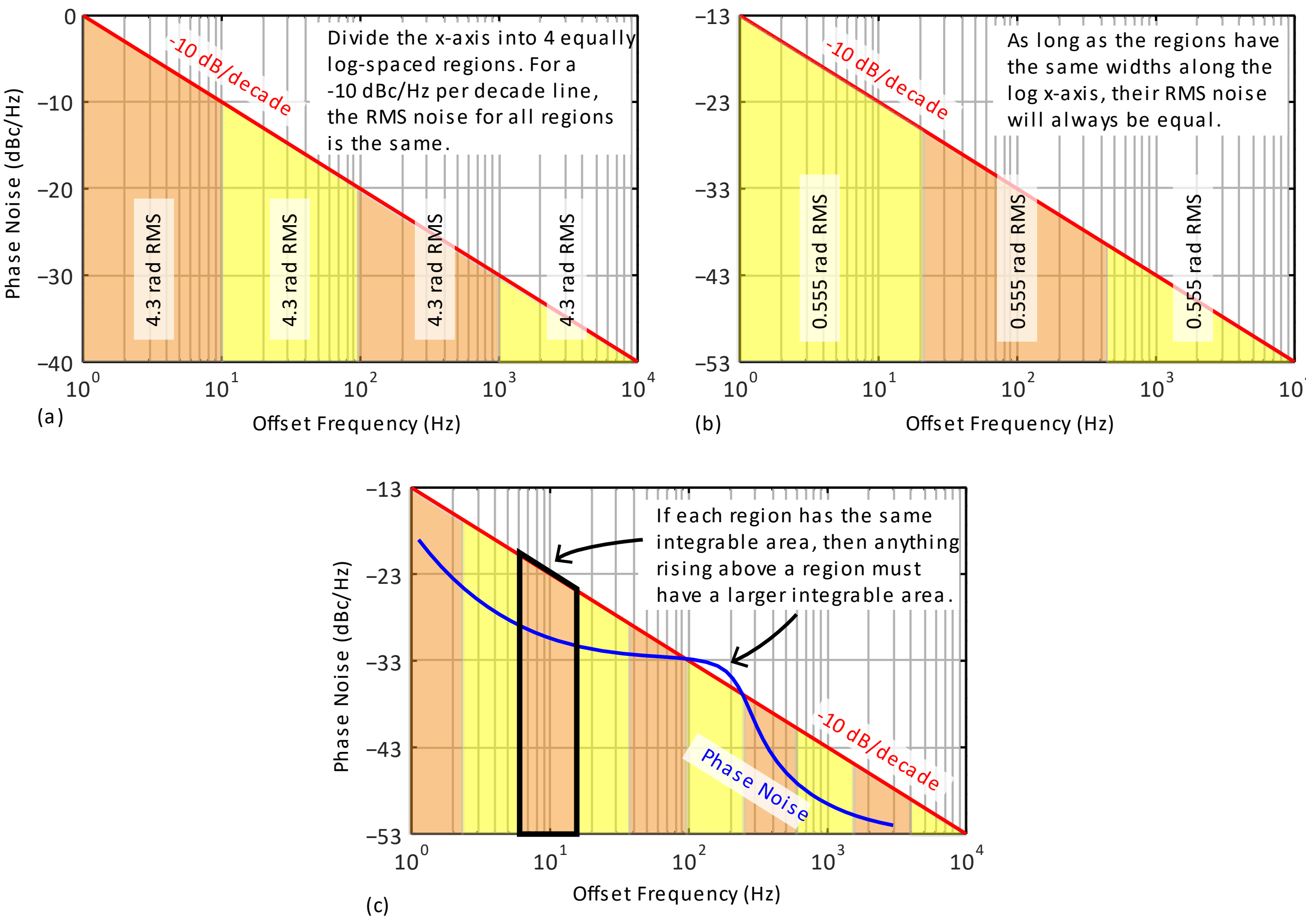

Figure 3: Illustrations to explain why a –10 dB/decade reference line can be used to pinpoint the location in a phase noise curve that dominates its integral. The RMS noise values shown here (in blue) are computed for a 1 GHz clock frequency

When evaluating actual phase noise data, it's useful to define the width of these regions sufficiently small to make it obvious that any portion of the curve popping above the –10 dB/decade line must include more integrable area than elsewhere along the curve. Figure 3(c) illustrates this point using an optimally-sized width. Here, if every region below the phase noise data has equal integrable areas, then the region whose phase noise data extends above the –10 dB/decade reference line must have more integrable area (and therefore more RMS noise) than the other regions. After understanding this, there is no need to go through the mental exercise of visualizing regions anymore. Instead, simply draw a –10 dB/decade line above the phase noise curve and lower it to identify the location where it first intersects the curve.

The –10 dB/decade reference line can be used to advantage in a couple ways. As mentioned in the introduction, any phase noise curve can be compared with this reference line to locate the point in the curve that dominates the RMS noise number. Typically this process only requires a few seconds to visually scan the plot. This location can then be used to help identify the underlying physical source of that noise, which can be an important step in determining how to eliminate that noise. Of course, this requires cross-referencing a point in the phase noise curve with potential noise source(s) appearing at that point. Figure 1 in conjunction with the "Sources of Noise" section below can be used for this purpose.

Additionally, the –10 dB/decade reference line can be used to simplify the integration process. A common approach to integrating phase noise data is to use an online calculator. If the raw data file is available, the easiest solution is simply to import the data into an online calculator [3]. The RMS noise obtained this way for Figure 2 is 0.0336 rad RMS. Unfortunately, the raw data is not always available in file format. Often, it's obtained from published figures. In this case, the phase noise data can be approximated using piecewise linear segments that can be entered into the calculator. Depending on the fit, this can provide accurate results. However, it can be tedious to segment an entire curve. Figure 2, for example, may require a dozen or more such segments to represent it faithfully. A faster approach is to segment only that portion of the curve that dominates the integral.

Using this approach with Figure 2, lowering the –10 dB/decade reference first intersects the phase noise data around 1 Hz. The entire phase noise curve may therefore be represented by one piecewise linear segment defined by two points: (1 Hz, –29 dBc/Hz) and (100 Hz, –94 dBc/Hz). Inserting these points into an online phase noise calculator returns an RMS noise of 0.0335 rad RMS, virtually identical to the result computed above using the raw data.

However, it's important to note that an online calculator's results are only as accurate as the data it is given. Any noise in the original data, for example, that makes it difficult to estimate phase noise points, can be a significant source of error. For example, had a visual inspection of Figure 2 at 1 Hz estimated a phase noise value of –31 dBc/Hz instead of –29 dBc/Hz, the computed RMS noise would have be 0.0272 rad RMS (about a 20% error). Ultimately, the accuracy is limited by not having access to the raw data. Visually estimating piecewise linear segments will always introduce some error, regardless of the number of segments used to represent the data. The key point here is that only the phase noise near the –10 dB/decade reference line has a significant impact on the RMS noise. Therefore, only this portion of the curve requires integration.

4 Offset Frequency Range

So far the discussion has considered the entire phase noise plot. In reality, applications have bandwidths that "view" only some portion of this plot. To account for this bandwidth, the phase noise data should first be subjected to one or more system filters before being integrated. Assuming these filters get applied over the entire offset range, integration of the filtered phase noise data would occur over this same range. For example, if the phase noise data in Figure 2 were filtered from 1 Hz to 10 MHz, then the integral to compute RMS noise would set f_a and f_b to 1 Hz and 10 MHz, respectively. The exact offset frequencies bounding this range are not critical if the system filters include roll-offs that reduce the phase noise near the edges of this range to insignificant levels.

Certain applications can be represented by applying a brick wall bandpass filter to the phase noise data. This leads to a much easier visual inspection of the filtered phase noise data. Imagine the data in Figure 2 is subjected to a brick wall filter with a passband from 100 Hz to 1 MHz. In this case, analysis of the filtered data using the –10 dB/decade reference line would only examine phase noise data between 100 Hz and 1 MHz. Lowering this reference line would then intersect the phase noise curve (in this passband) around 300 kHz. The RMS noise after filtering reduces to 0.0156 rad RMS.

System filters can therefore dramatically change the resulting RMS noise, and should therefore be accounted for in any phase noise analysis. However, the characteristics of these filters require some knowledge of the system, which can be difficult to obtain. When no system information is available, the industry default is to use a brick wall integration bandwidth from 12 kHz to 20 MHz. In practice, this default filter is more useful for comparing datasheet parameters than device performance because markets are fragmented with respect to the system bandwidth (and therefore filter) requirements. Therefore, the appropriate system filters need to be applied for a meaningful analysis.

5 Spurious Noise

Spurious noise (i.e. spurs) appear as sharp spikes popping out of a relatively smooth slowly-varying phase noise curve. Spurious noise is deterministic in nature. The original (e.g., raw) phase noise data, as measured by an instrument, has units of dBc/Hz. The instrument can apply an algorithm to detect spurs in this data, and convert spur magnitudes to units of dBc. After spurs are detected, the user may view the phase noise in one of three ways shown in Figure 4: (a) raw phase noise data, (b) phase noise data with spurs (with spurs in units of dBc), and (c) phase noise data with spurs omitted.

If phase noise is integrated with the intention of computing RMS noise due only to random phase noise, then perform the above three-step procedure with spurs omitted (e.g., Figure 4(c)). Alternatively, if the RMS noise is intended to represent RMS power (as measured from an RMS hardware detector, which measures both random and deterministic components of phase noise), then perform the above procedure on the raw phase noise data (e.g., Figure 4(a)). In general, if phase noise data with spurs in dBc (e.g., Figure 4(b)) is the only data available, then simply ignore the spurs (since RMS noise should not be computed from data that includes spurs in dBc).

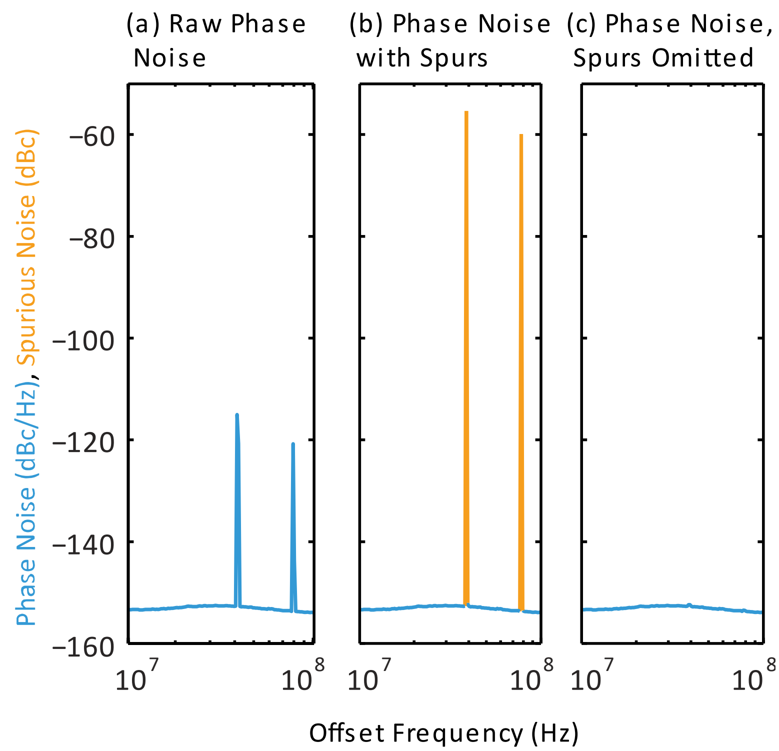

Figure 4: A phase noise plot may display (a) raw phase noise data, (b) phase noise data with spurs detected and displayed in dBc units, and (c) phase noise data with spurs omitted

6 Sources of Noise

A phase noise curve is shaped by the noise sources present in the signal [4-6], which can be either broadband or concentrated in specific offset regions. Figure 1 shows example curves (a) with (b) without a PLL in the signal path. In addition, noise sources are grouped into three regions based on their location in the curve. Note that the noise sources listed in Figure 1 are not necessarily present in every signal. Furthermore, some sources, when present, may be sufficiently low and be ignored. Once a region is identified as dominant using the above three-step procedure, considerable effort may need to be spent troubleshooting to pinpoint the exact root cause for the noise.

The Timing Reference region of the phase noise curve in Figure 1 typically includes noise created by the timing reference's oscillator hardware and clock resonance mechanisms [6]. A power-law model is used to represent five common noise types: (1) random walk frequency modulation (RWFM), (2) flicker frequency modulation (FFM), (3) white frequency modulation (WFM), (4) flicker phase modulation (FPM) and (5) white phase modulation (WPM). The power spectrum for WPM is spectrally flat, whereas FPM, WFM, FFM, RWFM increase as f^{-1}, f^{-2}, f^{-3}, f^{-4}, respectively. Spurious noise sources that can appear in this region include interference from AC power lines (50/60 Hz hum), diurnal and seasonal temperature variations, vibrations, and control algorithms with feedback. Many system bandwidths are designed to filter near-in phase noise, thereby leading to cost savings and flexibility in choice of the timing reference.

The PLL region in the phase noise curve in Figure 1 includes noise introduced by each of its loop components: phase detector (PD), charge pump (CP), voltage controlled oscillator (VCO), and loop filter

(LP). These noise source can be simulated using behavioral models. Insufficient phase margin in the PLL closed-loop transfer function can lead to excessive peaking, which increases the PLL's characteristic hump centered near the loop bandwidth in the phase noise curve. Charge pump current, closed loop bandwidth, and other potential adjustments can tune the shape and location of this hump. Often, VCO phase noise and loop filter thermal noise are dominant sources of noise introduced by PLLs.

The Broadband Noise region in Figure 1 contains spectrally flat noise sources. It's drawn as a distinct region only because it establishes the noise floor of the device (ignoring instrument noise). WPM, mentioned above, is a general term categorizing noise from broadband sources. Typically, output buffers are a dominant source of noise in this region. Divider, amplifier, supply, and substrate noise can also be present in various levels. Quantization error in digital PLLs also appears as broadband noise.

7 Conclusion

A novel procedure is presented to pinpoint the location in a phase noise curve that contributes the most to RMS noise, which is derived by integrating phase noise over a region of offset frequencies. RMS noise is an important figure of merit for phase noise and can be used to derive other useful metrics, such as phase jitter, residual FM, and EVM. The procedure is simple and can be applied by inspection: imagine a –10 dB/decade line above the phase noise curve, then lower this line until it intersects the curve. The phase noise at the point of intersection dominates the integral used to compute RMS noise. This procedure can be used to (1) quickly identify dominant sources of noise present in the signal, and (2) simplify the integration process by reducing the amount of data needed to analyze.

8 References

[1] Application Note, "AN10062 Phase Noise Measurement Guide for Oscillators," SiTime, https://www.sitime.com/support/resource-library/an10062-phase-noise-measurement-guide-oscillators

[2] E5052B Signal Source Analyzer Web Help, User Manual, http://ena.support.keysight.com/e5052b/manuals/webhelp/eng/measurement/phase_noise_measurement/confirming_result_of_phase_noise_measurement.html

[3] "Desktop Phase-noise Calculator", https://www.jitterlabs.com/support/calculators

[4] A. Hajimiri, "Noise in phase-locked loops," Southwest Symposium on Mixed-Signal Design, 2001. pp. 1-6.

[5] U.L. Rohde, A. K. Poddar, A. M. Apte, "Phase Noise Measurements and System Comparisons", Microwave Journal, April 2013, pp. 22-46.

[6] S. Bregni, "Synchronization of digital telecommunications networks," John Wiley & Sons, Ltd, 2002, ISBN 0471615501, pp. 246-251.

9 Appendix

Figure 5 establishes a coordinate system containing three example points for discussion. The goal, given equally spaced points X_i, X_{i+1}, and X_{i+2}, is to find slope m such that areas A_i and A_{i+1} are equal. If all such areas are equal, then when the line is lowered until some part of a phase noise curve pokes up above it, this part of the curve must contribute more to the integration than elsewhere in the curve.

A traditional phase-noise plot can be represented by Figure 5(a), using a linear y-axis scale for phase noise in dBc/Hz with M=10, and a logarithmic x-axis scale for offset frequency in Hz. Before integrating, the data is transformed to linear axes as shown in Figure 5(b).

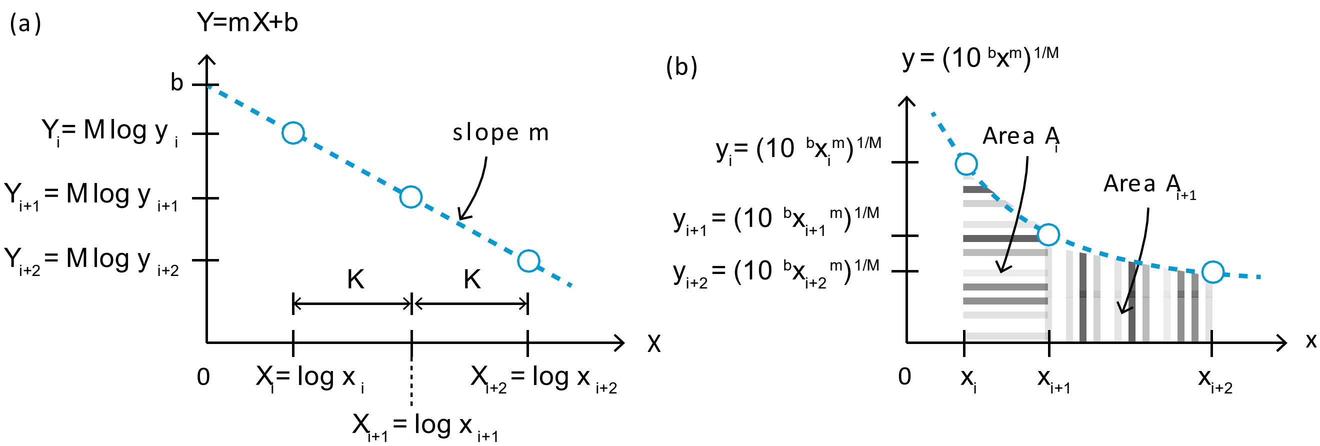

Figure 5: Example data showing (a) the original plotted data in logarithmic y-axis units and logarithmic x-axis scale, and (b) transformation to linear axes for integration

We start by writing the assumption that x-axis points in Figure 5(a) are equally spaced on a log scale, with spacing K,

$$log(x_{i+1}) - log(x_i) = K \qquad \text{Eq. 2}$$

This may also be written as,

$$\frac{x_{i+1}}{x_i} = 10^K \qquad \text{Eq. 3}$$

The area A_i shown in Figure 5(b) may be computed as,

$$A_i = \int_{x_i}^{x_{i+1}} y(x)\, dx = 10^{b/M} \int_{x_i}^{x_{i+1}} x^{m/M}\, dx = \frac{10^{b/M}}{\frac{m}{M}+1}\left(x_{i+1}^{m/M+1} - x_i^{m/M+1}\right) \qquad \text{Eq. 4}$$

which can be rearranged as,

$$A_i = \frac{10^{b/M}}{\frac{m}{M}+1} x_i^{m/M+1}\left(\left(\frac{x_{i+1}}{x_i}\right)^{m/M+1} - 1\right) \qquad \text{Eq. 5}$$

and simplified using the above relationship for K (a constant) as,

$$A_i = \frac{10^{b/M}}{\frac{m}{M}+1} x_i^{m/M+1}\left(10^{K(m/M+1)} - 1\right) \qquad \text{Eq. 6}$$

We can perform a similar analysis for area A_{i+1} to obtain,

$$A_{i+1} = \frac{10^{b/M}}{\frac{m}{M}+1} x_{i+1}^{m/M+1}\left(10^{K(m/M+1)} - 1\right) \qquad \text{Eq. 7}$$

Now if we equate areas A_i and A_{i+1}, most of the terms cancel each other leaving,

$$x_{i+1}^{m/M+1} = x_i^{m/M+1} \qquad \text{Eq. 8}$$

Taking the log of both sides of this equation gives,

$$\left(\frac{m}{M}+1\right) log(x_{i+1}) = \left(\frac{m}{M}+1\right) log(x_i) \qquad \text{Eq. 9}$$

which can be rearranged as,

$$\left(\frac{m}{M}+1\right)\left(log(x_{i+1}) - log(x_i)\right) = 0 \qquad \text{Eq. 10}$$

which also equals,

$$\left(\frac{m}{M}+1\right) K = 0 \qquad \text{Eq. 11}$$

which can be simplified as,

$$\frac{m}{M}+1 = 0 \qquad \text{Eq. 12}$$

which can be solved for slope m as,

$$m = -M \qquad \text{Eq. 13}$$

Since phase noise is plotted on the y-axis in logarithmic units using a 10 log rule (e.g., 10 times the log of a ratio of power quantities), M equals 10. The same discussion applies to other parameters plotted in logarithmic units with a 10 log rule, such as power in dBm. Field quantities plotted in logarithmic units are based on a 20 log rule (e.g., 20 times the log of a ratio of field quantities, such as current or voltage) and the same discussion applies where M equals 20. Finally, for the general case of plotting any y-axis quantity in logarithmic units using a 1 log rule (e.g., simply the log of some quantity), or using a logarithmic y-axis scale, set M equal to 1.

Table 1: Revision History

Version	Release Date	Change Summary
1.0	14-Sep-2016	JitterLabs LLC Initial Release
1.0	30-Mar-2021	SiTime Initial Release

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