

Time-Domain Jitter Measurement Considerations for Low-Noise Oscillators

Arvind Sridhar and Gabe Ayala

ABSTRACT

Phase Noise and Jitter are important metrics that describe the quality of a low-noise oscillator. Jitter is a time-domain representation of the timing accuracy of a signal and Phase Noise is the frequency domain representation of noise spectrum around the carrier tone. Equipment for measuring jitter in time-domain, such as real-time oscilloscopes, excel in their ability to directly measure period jitter, cycle-to-cycle jitter, TIE and data-dependent jitter which makes them an ideal choice for characterizing high speed serial links. Frequency domain equipment, such as a Phase Noise Analyzer, on the other hand, measures the RMS power of a signal in a frequency band of interest. Phase Noise Analyzers typically have a much lower noise floor than most real-time oscilloscopes making them an ideal choice for characterizing ultra-low jitter oscillators such as LMK61E2.

When measuring jitter performance of oscillators, it is important to understand the limitations of the measurement equipment used. This application note will primarily focus on highlighting some of the limitations of real-time oscilloscopes used for time-domain jitter analysis.

Time-domain jitter specifications of interest are period jitter, cycle-to-cycle jitter, time interval error (TIE) and Total Jitter (TJ).

Per JEDEC Standard JESD65B, period jitter is defined as the deviation in cycle time of a signal with respect to the ideal period over a random number of cycles. The number of cycles selected for this measurement should be significant (1000 to 10,000) to have sufficient confidence in the measurement. Peak-to-peak period jitter is defined as the difference between the largest and the smallest period value from the sample size used for the measurement. Period jitter can also be specified as a root means squared (RMS) value in lieu of peak-to-peak. This jitter specification is primarily used for guaranteeing setup and hold times for logic in CPUs and FPGAs.

Cycle-to-cycle jitter is defined as the variation in cycle time of a signal between adjacent cycles over a random sample of adjacent cycle pairs. Once again, the number of cycles selected for this measurement should be significant (1000 to 10,000) to have sufficient confidence in the measurement. Cycle-to-cycle jitter is typically specified as the greater of the absolute values of the worst case positive or negative variation in cycle time between adjacent cycles. As an example, if the largest positive cycle-to-cycle variation is 62ps and the largest negative cycle-to-cycle variation is -65ps, the overall cycle-to-cycle jitter is commonly specified to be 65ps.

TIE, also known as accumulated jitter is the deviation of a clock period from the ideal clock period measured over a significant number of cycles. It includes jitter contribution due to high and low jitter modulation frequencies. This specification of jitter is commonly used in SONET and Optical Transport Networking (OTN) equipment.

Total Jitter (TJ) is another time-domain jitter specification commonly used in Serial IO applications that is derived from the TIE measurement. It is measured at a specified Bit Error Rate (BER) for the serial IO link and combines the effect of Random and Deterministic jitter components. It predicts a peak-to-peak jitter that will only be exceeded with a probability equal to the BER. Real-time oscilloscopes typically include jitter analysis software tools that decompose TJ into random (RJ) and deterministic jitter (DJ) components. The relationship between TJ, RJ and DJ is shown in [Equation 1](#).

$$TJ_{pk-pk} = DJ_{pk-pk} + n \times RJ \text{ (rms)}$$

where

- n is the application BER multiplier (1)

[Table 1](#) gives a complete list of multipliers for required BER.

Table 1. BER Multipliers

BER	Multiplier
10 ⁻³	6.582
10 ⁻⁴	7.782
10 ⁻⁵	8.834
10 ⁻⁶	9.784
10 ⁻⁷	10.654
10 ⁻⁸	11.462
10 ⁻⁹	12.218
10 ⁻¹⁰	12.934
10 ⁻¹¹	13.614
10 ⁻¹²	14.260
10 ⁻¹³	14.882
10 ⁻¹⁴	15.478
10 ⁻¹⁵	16.028

The jitter specifications described above were measured using a real-time digital phosphor oscilloscope from Tektronix (DPO70804C) on a 312.5 MHz output frequency clock generated using the LMK61E2 high performance programmable oscillator from Texas Instruments. The measurement results are shown in Figure 1.

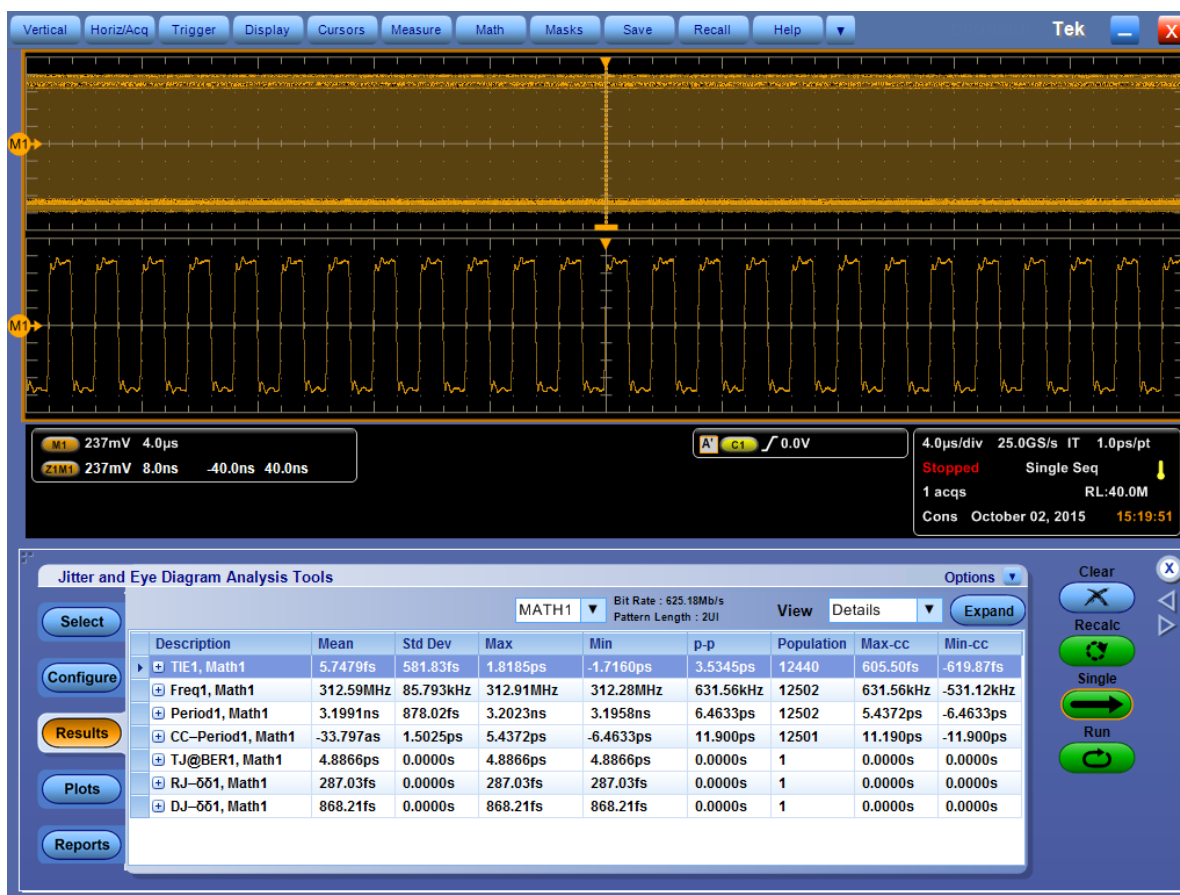


Figure 1. Time-Domain Jitter Measurement Results

The sample size for the above measurements was > 10000 samples and the sampling rate was set to 25GS/s (maximum allowable sampling rate for the oscilloscope). The acquisition interval for the measurement was 40us. A Bit Error rate of 1E-12 was selected for the Total Jitter (TJ) measurement and a 20 MHz low pass filter was applied to the TIE, TJ, RJ, and DJ measurements.

Jitter measurements on real-time oscilloscopes are affected by factors inherent to the oscilloscope. The major sources of noise within the oscilloscope are sampling jitter, vertical noise, timing stability and signal interpolation error.

Signal interpolation error due to linearly interpolating between voltage samples can be minimized by using $\sin(x)/x$ (or sinc) interpolation setting on the oscilloscope (if available) and by maximizing signal amplitude to input full scale.

Vertical noise in an oscilloscope is intrinsic to the input attenuators, preamplifiers and A/D converters. This noise varies with the front-end attenuator and amplifier settings, bandwidth limiting on the scope and sample size used for the measurement. Oscilloscope user manuals specify the vertical noise at a particular V/div setting or as a percentage of the V/div setting.

Timebase stability is another potential source of error in real-time oscilloscopes. The timebase stability is usually specified in the oscilloscope datasheets. ADC aperture uncertainty and quantization error are other sources of error in the oscilloscope that manifest as amplitude and timing noise.

The slew rate of the signal being measured affects the jitter. If the edge rate of the signal measured is slow relative to the system bandwidth, any amplitude noise at the threshold crossing of the signal can result in increased jitter. Slew rate amplifiers can potentially be used to increase the slew rate of the signal before it is connected to the oscilloscope. In general, the faster the edge rate of the signal being measured, the lower will be the impact of any amplitude noise. The use of a limiting amplifier (ONET1191P) for total jitter measurement has been covered in detail in the applications note SCAA120A from Texas Instruments. It should be noted that any limiting amplifier or slew rate amplifier device will contribute some additive jitter to the signal being measured. Also, for measuring signals with fast slew rates, an oscilloscope with adequate sampling rate should be used. The measurements in this application note were not made using any limiting amplifiers or slew rate amplifiers.

The above sources of error are factored in a parameter called JNF for the Tektronix DPO70804C real-time oscilloscope. Jitter Noise Floor is defined as the intrinsic noise portion of a jitter measurement. This sets the lower limit on the amount of jitter that the oscilloscope can detect. If the input signal has jitter lower than the jitter noise floor of the oscilloscope, the measured jitter on the oscilloscope will not accurately represent the true jitter of the input signal.

JNF is described in [Equation 2](#) (referred from Tektronix application note 61W_18786_2).

$$JNF = \sqrt{\left[\frac{N}{FS \times A} \times t_{rm} \right]^2 + t_j^2}$$

where

- A = input signal amplitude (volts)
- t_{rm} = 10% to 90% measured rise time (sec)
- FS = full scale range of input
- t_j = short/medium term aperture uncertainty (sec rms)
- N = input-referred noise (volts rms)

(2)

The details of this specification are beyond the scope of this application note.

Tektronix uses time interval error to measure JNF. The typical value of JNF reported in the oscilloscope datasheets from Tektronix correspond to the longest record length and maximum sample rate setting. The typical Jitter Noise Floor (RMS TIE) for DPO70804C is 450fs.

The unfiltered TIE measurement result for LMK61E2 using DPO70804C oscilloscope is shown in [Figure 2](#)

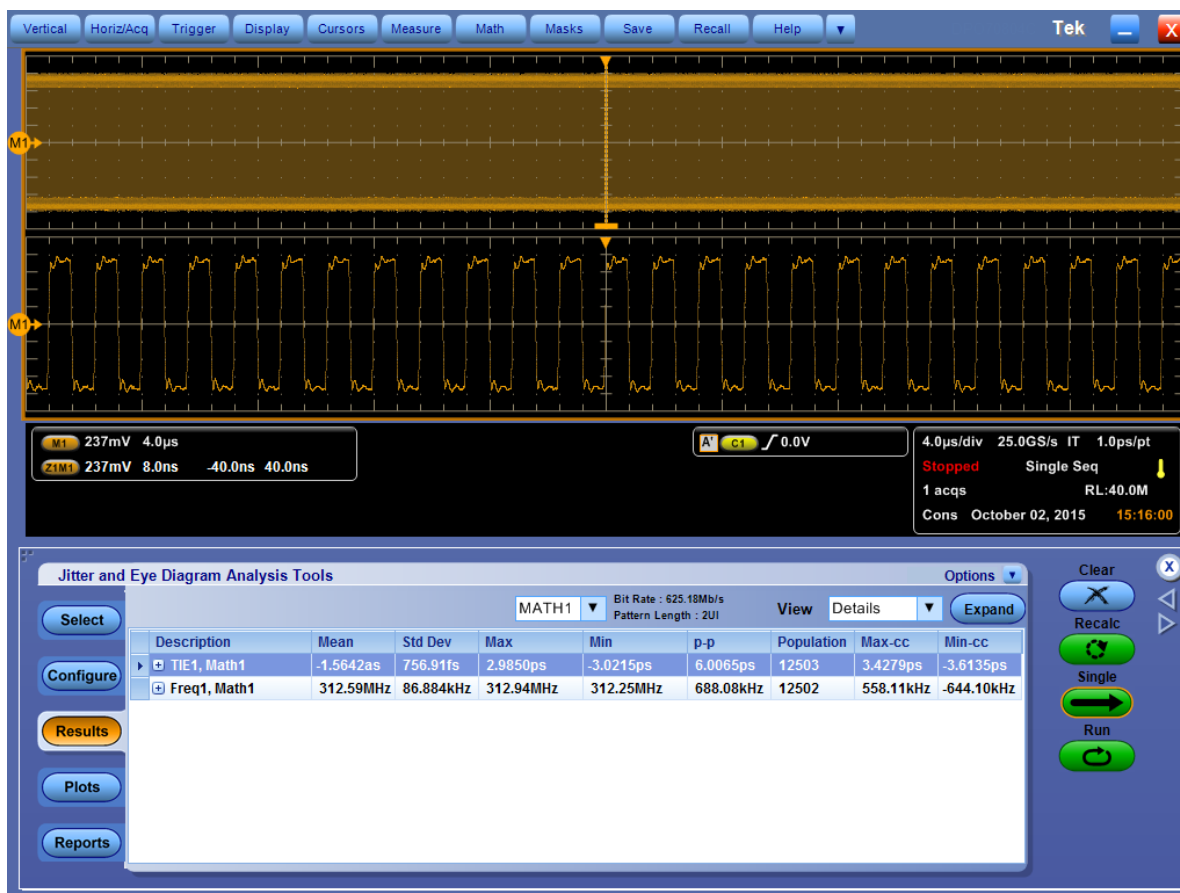


Figure 2. Unfiltered TIE Measurement Results

The total measured RMS TIE is approximately 757 fs RMS. The oscilloscope contributes roughly 450 fs RMS TIE. The RMS TIE due to the device (LMK61E2) can be calculated to be approximately 608 fs RMS.

Please note that the above jitter specification applies to Tektronix real-time oscilloscopes. Agilent lumps all the jitter sources into a similar parameter called Jitter Measurement Floor. From the Agilent 90000 X-Series datasheet, the jitter measurement floor is specified by [Equation 3](#).

$$JMF = \sqrt{\left(\frac{\text{Noise}}{\text{Slew Rate}}\right)^2 + \text{Sample Clock Jitter}^2} \quad (3)$$

The first term in [Equation 3](#) corresponds to the noise influence due to the slew rate of the signal being measured. The second term represents the oscilloscope intrinsic noise. These parameters can be found in the oscilloscope specifications from the manufacturer website. Other scope manufacturers have their own specification that factors in the sources of jitter discussed above.

The impact of the jitter noise floor of the oscilloscope can also be seen in the random jitter measurement result (RJ). The filtered RJ from Figure 1 is ~287fs. A low pass filter of 20 MHz was applied for this measurement. Since the acquisition interval was set to 40us, effect of noise frequencies down to $1/40\mu\text{s} = 25\text{ kHz}$ are included in the measurement. In contrast, the integrated RMS phase jitter (12 kHz – 20 MHz) measured using the Agilent 5052 Phase Noise Analyzer (superior noise floor when compared to real-time oscilloscopes) is ~87fs (as shown in Figure 3). Filtered RJ in time-domain is equivalent to the Integrated RMS phase jitter in frequency domain.

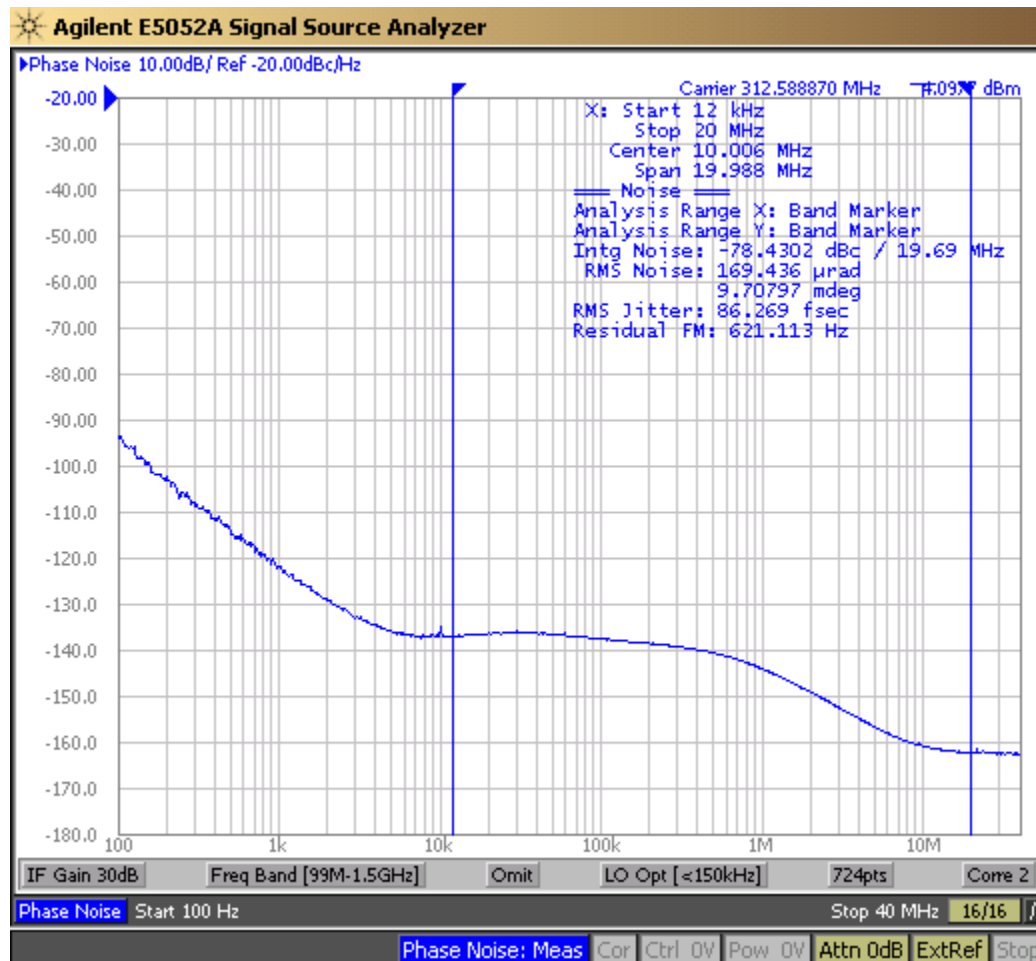


Figure 3. LMK61E2 312.5 MHz Phase Noise

In summary, when performing jitter measurements in time-domain using real time oscilloscopes from different oscilloscope vendors, it is important to consider all the sources of jitter that are intrinsic to the oscilloscope. The impact of some of these errors can be minimized by careful action on part of the operator. Ensuring fast slew rate for the signal being measured, use of the highest sampling rate available on the oscilloscope for the measurement, setting the input signal amplitude to full scale and use of sinc interpolation or enhanced bandwidth setting (if available) on the oscilloscope are some of the steps that the operator can follow to minimize the sources of error in the jitter measurement. The oscilloscope with the lowest jitter noise floor will represent the true jitter of the input signal most accurately.

IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46, latest issue, and to discontinue any product or service per JESD48, latest issue. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All semiconductor products (also referred to herein as "components") are sold subject to TI's terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its components to the specifications applicable at the time of sale, in accordance with the warranty in TI's terms and conditions of sale of semiconductor products. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by applicable law, testing of all parameters of each component is not necessarily performed.

TI assumes no liability for applications assistance or the design of Buyers' products. Buyers are responsible for their products and applications using TI components. To minimize the risks associated with Buyers' products and applications, Buyers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI components or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of significant portions of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI components or services with statements different from or beyond the parameters stated by TI for that component or service voids all express and any implied warranties for the associated TI component or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards which anticipate dangerous consequences of failures, monitor failures and their consequences, lessen the likelihood of failures that might cause harm and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI's goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed a special agreement specifically governing such use.

Only those TI components which TI has specifically designated as military grade or "enhanced plastic" are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components which have **not** been so designated is solely at the Buyer's risk, and that Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949.

Products

Audio	www.ti.com/audio
Amplifiers	amplifier.ti.com
Data Converters	dataconverter.ti.com
DLP® Products	www.dlp.com
DSP	dsp.ti.com
Clocks and Timers	www.ti.com/clocks
Interface	interface.ti.com
Logic	logic.ti.com
Power Mgmt	power.ti.com
Microcontrollers	microcontroller.ti.com
RFID	www.ti-rfid.com
OMAP Applications Processors	www.ti.com/omap
Wireless Connectivity	www.ti.com/wirelessconnectivity

Applications

Automotive and Transportation	www.ti.com/automotive
Communications and Telecom	www.ti.com/communications
Computers and Peripherals	www.ti.com/computers
Consumer Electronics	www.ti.com/consumer-apps
Energy and Lighting	www.ti.com/energy
Industrial	www.ti.com/industrial
Medical	www.ti.com/medical
Security	www.ti.com/security
Space, Avionics and Defense	www.ti.com/space-avionics-defense
Video and Imaging	www.ti.com/video

TI E2E Community

e2e.ti.com