Jitter Analysis with the R&S®RTO Digital Oscilloscope

Application Note

Products:

- R&S®RTO1002
- R&S®RTO1004
- R&S®RTO1012
- R&S®RTO1014
- R&S®RTO1022
- R&S®RTO1024
- R&S®RTO1044
- R&S®RTO-K12

This application note introduces the Jitter analysis capabilities of the R&S®RTO Digital Oscilloscope and the Jitter option R&S®RTO-K12 for digital signals.

It provides background information on jitter sources and standard jitter measurement tools. Furthermore it demonstrates Period jitter, Cycle jitter and Time Interval Error jitter measurements based on an application example. The benefits of different representations of the measurement results with histogram, track and spectrum display are discussed.

Application Note

Dr. Mathias Hellwig

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ROHDE&SCHWARZ

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1 Introduction

This application note presents the capabilities of the R&S®RTO-K12 Jitter Analysis option for the R&S®RTO Digital Oscilloscope with respect to the jitter analysis of data and clock signals. In the following, the term R&S®RTO Digital Oscilloscope will be abbreviated as RTO and the R&S®RTO-K12 Jitter analysis option as RTO-K12 for simplified reading.

Digital interfaces have become predominant in electronic design with the rise of the digital computer and the associated digital signal processing and digital transmission. Though digital signals are more robust and less susceptible to disturbances than analog signals, the trend to increase the data rate and clock speed reduces the timing margin for these signals. It also requires more detailed analysis and a highly sophisticated test and debug capabilities, if failures occur. As an example of the increase of clock speed over several generations, some well-known digital interface standard families are listed, like PCIe, SATA, USB or DDR.

The analysis of the timing margin is not limited to the data signal itself, it is also applicable to the embedded clock, or the reference clock. Moreover some of the jitter measurements are applicable to different, non-digital areas, like modulated RF signals or timing characterization of analog-to-digital converter (ADC) and digital-to-analog converter (DAC).

In combination with the RTO-K12 option, the RTO is an excellent platform for precise jitter analysis. The RTO's key features for precise signal integrity measurements are a sensitive, wideband, low noise analog front-end, a high precision, single core ADC and a high acquisition and processing rate. The RTO-K12 adds automated measurements for jitter characterization, software based clock data recovery, a track graph of measurements and a wizard tool to ease the use of the jitter analysis option. The RTO®RTO-K13 Clock Data Recovery (CDR) option provides additional capabilities for jitter analysis, which is not further discussed in this application note. It enables a configurable hardware-based CDR for triggering on data signals that contain an embedded clock.

Jitter measurements are possible in the time domain or the frequency domain. Oscilloscopes natively measure signals in the time domain. An example of a dedicated instrument for jitter measurements in frequency domain is the R&S®FSUP Signal Source Analyzer for Phase Noise and VCO test (1). The comparison in Table 1-1 shows that the accuracy is higher for measurements with frequency domain based instruments due to a typically higher dynamic range, longer measurement interval and a dedicated measurement concept for phase noise. Jitter measurements with Phase Noise and Spectrum Analyzers, however, are limited to clock signals only. Jitter Measurements in the time domain allow analysis of digital binary data or to track the phase noise signal over time.

In the first chapter the application note provides some background on jitter, focusing on jitter sources, analysis methods and instrument limitations for jitter analysis. Next, it introduces a signal model, which is used to explain the jitter measurements and the impact on analysis methods. In the last chapter, this application note uses an RTO with the RTO-K12 to analyze a digital clock signal of the Rohde & Schwarz Demo board.

Three widely used jitter measurements are applied to the clock signal, and showcase the Jitter analysis capabilities of the RTO.

Differences of Differences of Time vs. Frequency Domain based Instrument		
	Time Domain	Frequency Domain
Intrinsic measurements	Peak-Peak Jitter Cycle-Cycle Jitter Period Jitter	RMS Phase Jitter Phase Noise Jitter Frequency information
Benefits	Good with low frequency clocks Good with Data-Dependent Jitter Monitor jitter over time	Easy detection of spurs vs. Random Jitter Low Noise Floor

Table 1-1: Differences of Time vs. Frequency Domain based Instruments

A detailed analysis of the impact of a clock data recovery algorithm that is part of the Time Interval Measurement (TIE) is not within the scope of this application note, and the reader may follow the references to obtain more information on this topic.

2 Background on Jitter

2.1 Jitter Definition

The International Telecommunication Union (ITU) provides a widely accepted definition of timing jitter (2): "Jitter is the short-term variations of the significant instants of deviation of timing signal from their ideal positions in time (where short-term implies that these variations are of frequency greater than or equal to 10 Hz)." It is measured with reference to an ideal clock source or to itself.

Due to random jitter components, statistical values like standard deviation or peak-to-peak are used to quantify jitter. Like all statistical measurements, the user should specify a qualitative statement, for example a confidence interval, to ensure repeatable measurements.

The ITU further distinguishes between jitter and wander. In that context, Jitter has frequency components only above 10 Hz, while wander is only below. A further consideration into wander is outside the scope of this application note.

2.2 Jitter Sources

Jitter typically consists of various components that are caused by different jitter sources, see Figure 2-1. For the analysis of jitter it is important to understand these sources and the contributions to the total jitter (TJ). For an analytical approach, a jitter model is frequently used, which splits jitter into the two major categories of Random and Deterministic Jitter.

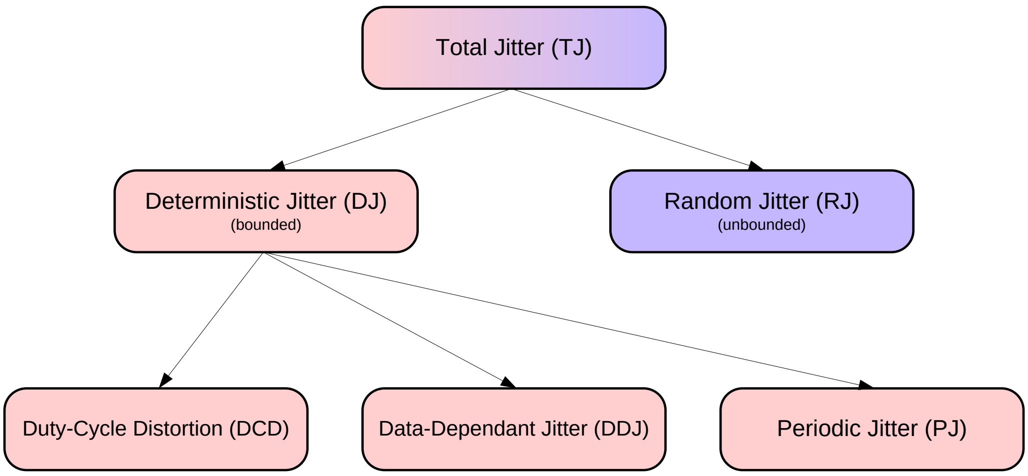


Figure 2-1 Jitter Sources

Deterministic Jitter (DJ), also called systematic jitter, is further broken down into Periodic Jitter (PJ), Data-Dependent Jitter (DDJ) and Duty-Cycle Distortion (DCD). Deterministic jitter is bounded and specified as peak-to-peak value. Random Jitter is unbounded and commonly specified by the standard deviation σ.

It is important for the user to understand and differentiate the jitter sources and the associated probability density function (PDF), because the histogram is a powerful tool for the jitter analysis. However, the interpretation of the histogram can be difficult and requires a good understanding of the underlying effects. The next sections discuss the PDF for all individual jitter sources, because the total jitter is calculated by a convolution of the individual PDFs of each jitter source (3).

2.2.1 Random Jitter

Due to its irregular nature, Random jitter (RJ) is uncorrelated to any other signal and unpredictable in timing behavior. It is described in the time domain and has its equivalent with phase noise in the frequency domain (4). Thermal noise, shot noise, 1/f noise and other physical effects are contributions to random jitter, and a random process is its mathematically representation. The PDF of the random jitter is the well-known Gaussian distribution, see equation (2-1) and Figure 2-2, where the mean value μ is the nominal oscillator period and σ is the standard deviation. With the given PDF, the random jitter turns out to be unbounded, and is usually specified by the standard deviation σ. Sometimes a peak-to-peak measurement over a defined sampling interval is used to describe the random jitter.

$$f_{RJ}(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{2-1}$$

The reason for explicitly referring to the normal distribution of the random jitter is twofold. First, the thermal noise contribution to the random jitter shows already a normal distribution. Secondly, due to the central limit theorem, other contributing physical effects with well-defined distributions converge into the observed normal distribution.

2.2.2 Periodic Jitter

Periodic Jitter (PJ) is caused by a periodic disturbance. Though this signal is not necessarily sinusoidal, it is frequently also named sinusoidal jitter. The amplitude of the periodic signal bounds the jitter. A sinusoidal disturbance signal has a PDF given in equation (2-2) and shown in Figure 2-3.

$$f_{PJ}(x) = \begin{cases} \pi^{-1} \cdot \sqrt{(A^2 - x^2)^{-1}};\ |x| \leq A \\ 0;\ |x| > A \end{cases} \tag{2-2}$$

A strong local RF oscillator, a switch-mode power supply, undesired crosstalk or an unstable, oscillating PLL cause period jitter due to an unintentional coupling into the signal.

2.2.3 Data-Dependent Jitter

Inter Symbol Interference (ISI) causes Data-Dependent Jitter (DDJ). When ISI is present, the signal is disturbed with an attenuated, time-shifted copy of itself or spectral parts of itself.

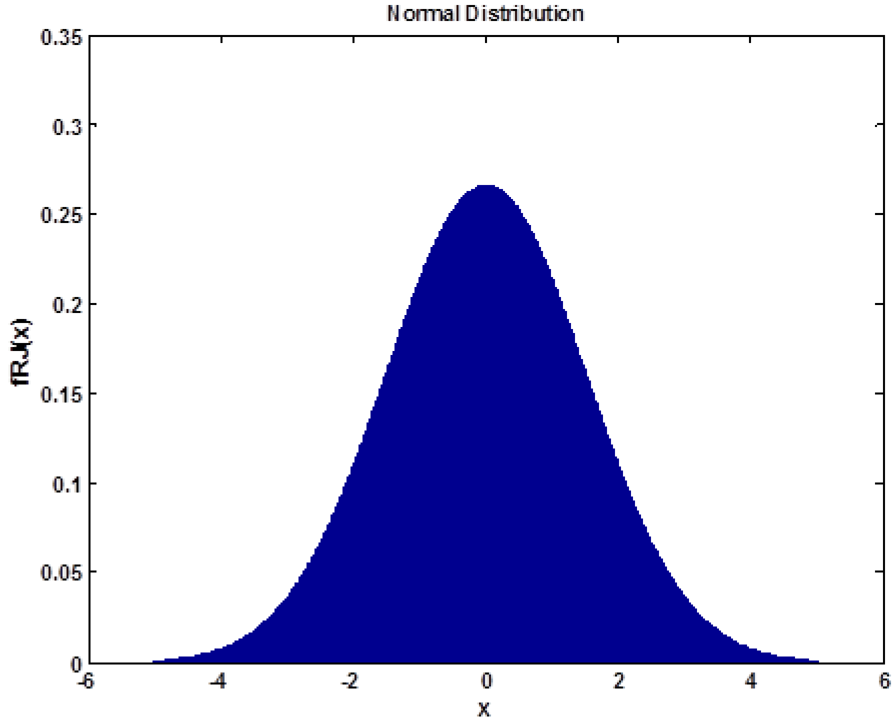


Figure 2-2 Normal Distribution ($\mu = 0, \sigma = 1.5$)

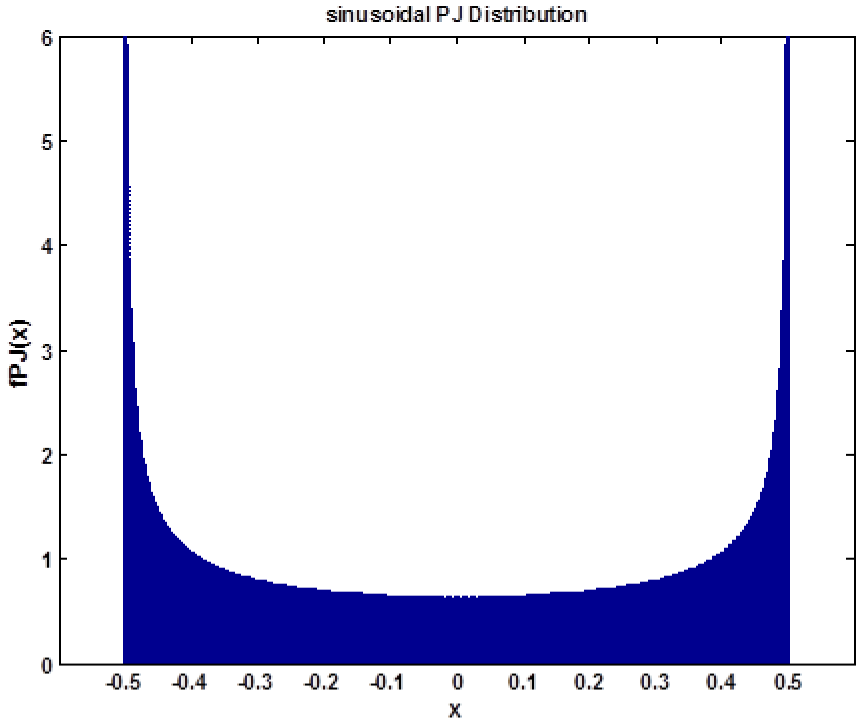


Figure 2-3 Sinusoidal PJ Distribution (A=.5)

In the time domain, ISI is caused by multipath propagation for wireless and reflections for wired transmission that create time-shifted copies of the signal. Reflections, or echoes, occur because of impedance mismatch of the termination as well as physical media discontinuities in the transmission path, like connectors or edges.

In the frequency domain, dispersion creates ISI. Dispersion is a frequency dependent group velocity of the transmission media, introduced by material or modal effects of transmission paths. Bandwidth limitations of the transmission media clearly show frequency dependent group velocity, but ISI in the frequency domain is not restricted to bandwidth limitations.

The most common model of the PDF for DDJ shows two distinct amplitudes, which results in a dual Dirac PDF, see Figure 2-4 and equation (2-3).

$$f_{DDJ}(x) = \frac{1}{2}\left(\delta(x-\mu) + \delta(x+\mu)\right) \tag{2-3}$$

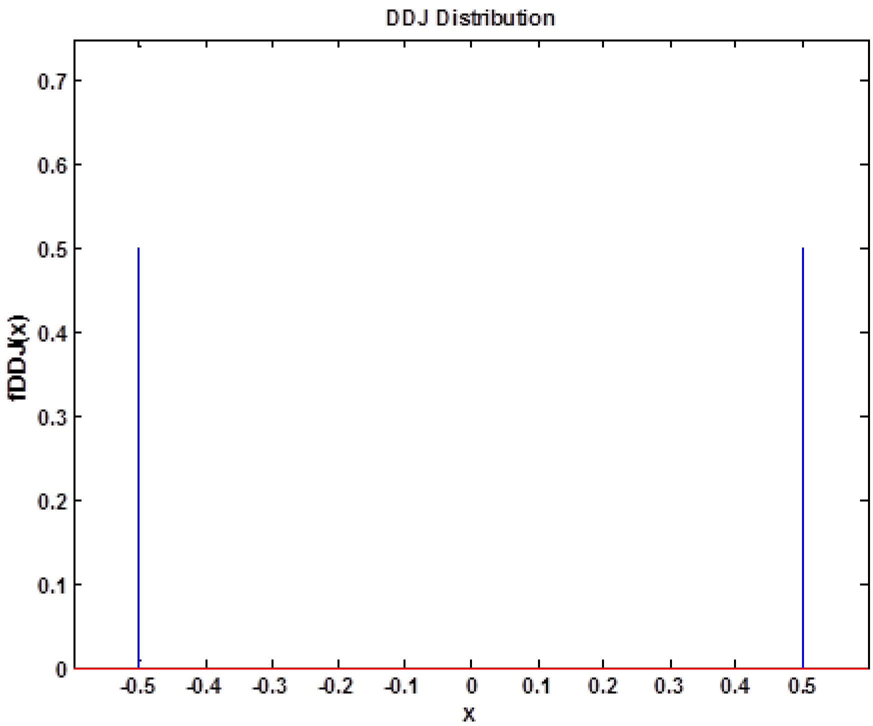


Figure 2-4 Dual-Dirac DDJ Distribution ($\mu = 0.5$)

2.2.4 Duty-Cycle Distortion

Duty-Cycle Distortion (DCD) is the result of two effects. The first effect is caused by the decision level marked with a letter A in Figure 2-5. If the decision level of a signal is altered and not coincident with the optimal decision level, the resulting mismatch introduces DCD. Figure 2-5 shows a raised decision level, which always retards the rising edge at Δt_{ar} and advances the falling edge at Δt_{af}. Usually the standard of a data interface defines the decision level for the specific signal, whereas the crossing of rising and falling edges in the eye diagram determines the optimal decision level.

Similar to the DDJ, the PDF of this jitter histogram becomes a dual Dirac PDF (see Figure 2-4).

Different rise and fall times of a signal cause the second effect, marked with a letter B in Figure 2-5. The duty-cycle error of a high to low transition Δt_{br} of a binary signal will differ from a low to high transition Δt_{bf} proportional to the difference between rise and fall time.

Overall the DCD is bounded like all deterministic jitter sources, though it is difficult to differentiate between DCD and DDJ introduced by ISI. A way to measure these contributions separately is the jitter measurement of a binary, alternating '01' sequence, essentially a binary clock signal. It will eliminate the ISI due to the periodic nature.

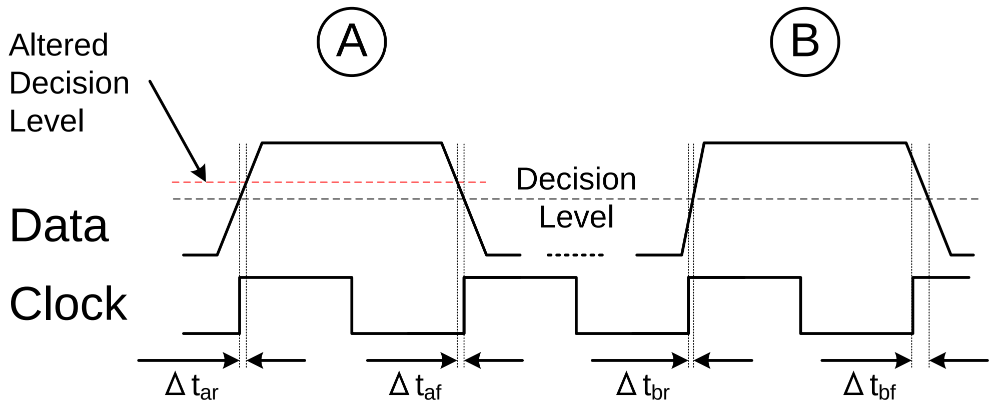


Figure 2-5 Duty-Cycle Distortion (DCD)

2.3 Jitter Analysis Tools

The RTO offers several analysis functions to evaluate signal integrity. The jitter analysis option RTO-K12 extends this set of functions to analyze several types of signals, like digital clock and binary data signals, as well as RF signals,.

As a distinction, digital clock signals are specified in units of Hertz [Hz] as opposed to binary data signals, which are specified in units of bits per seconds [bps]. A digital clock signal can be regarded as a binary data signal of a perpetual sequence of '01's, just that the data rate is double the frequency. The user can analyze clock signals by applying the same measurement and visualization functions as for binary data. Using this analogy, all measurement and analysis tools apply to clock signals. Conversely measurements like frequency, period, cycle-cycle, or N-cycle jitter apply only to periodic digital clock and RF signals.

2.3.1 Statistics

The automatic measurement function of the RTO provides statistical data for any automated measurement. Typical jitter measurements that require statistical evaluation are frequency, period or pulse width measurements. As the measured data contain random components by nature, statistic values are appropriate to describe the signal properties. Well known are mean value and standard deviation as mathematical expressions of the PDF (5).

As previously explained, the user should use the standard deviation if random jitter components are present. In case of Deterministic Jitter, the user can calculate the peak-to-peak jitter by subtracting the '+Peak' from the '-Peak' of the RTO measurement.

The number of measurements is an important point to evaluate the confidence in the measurement results. The high acquisition rate of the RTO is an advantage to gain high measurement confidence in short time. For data with known PDF, the user can verify the confidence of the statistics (5).

Statistics can be enabled in the RTO’s "Meas" menu > "Setup" tab. By default the RTO takes only one measurement per waveform. The user can configure the RTO to take multiple measurements, by defining the number of measurements within one acquisition in the "Meas" menu > "Gate/Display" tab, Figure 2-6.

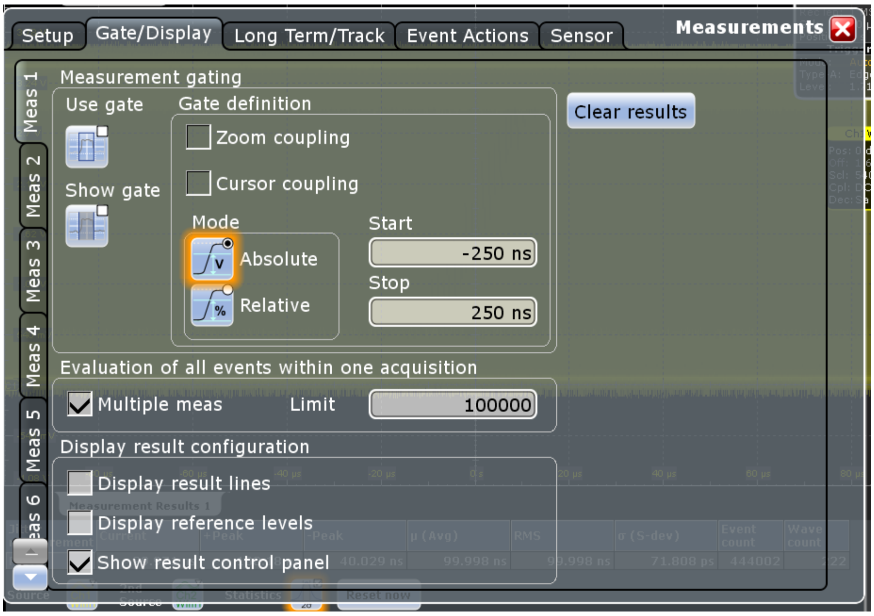


Figure 2-6 Selection of multiple measurements (“Multiple meas”) per waveform

2.3.2 Persistence

A simple way to measure jitter is the use of the display persistence, which emulates the phosphorous screen of an analog oscilloscope ("Display" > "Signal Colors / Persistence"), Figure 2-7 . Once the persistence is set to infinity, the RTO will accumulate the waveforms on the display and the user can, for example, apply cursors to measure the spread of the crossing points of an eye pattern in order to determine the total jitter for a given time or sample size. Figure 2-7 shows an example for persistence and color grading, including a measurement of the total jitter with cursors.

If the user also enables color grading, he will detect variations from a normal distribution in the PDF caused by deterministic jitter. The color grading is turned on in the same menu tab as the persistence.

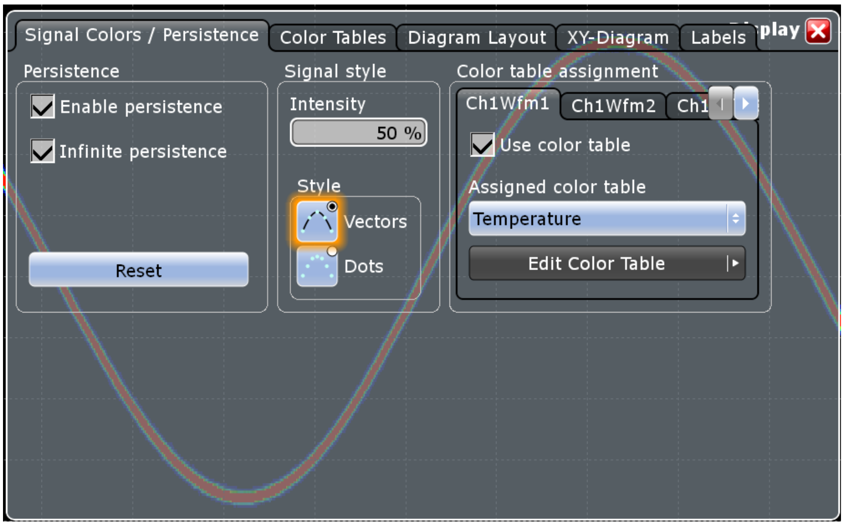


Figure 2-7 Display dialog with "Persistence" and "Color table" setting

2.3.3 Histogram

A histogram, in general, is the graphical representation of the distribution of data. In the context of jitter analysis, histograms support the user in investigating jitter (horizontal histogram on a waveform), noise (vertical histogram on a waveform) and PDF of measurement values (histogram on measurements).

In the case of a horizontal histogram on a waveform, it displays the density of the jitter data and allows a PDF estimate of the underlying jitter variable. It plots a set of jitter data in a group of discrete intervals versus the frequency of occurrence. The discrete interval is called a 'bin'. A histogram for jitter evaluation is typically located at the rising and/or falling edge of a signal. Figure 2-8 presents an example, showing the edge jitter of the clock signal with persistence and color grading enabled. To obtain such a histogram, the trigger point is shifted by one period. With increasing number of jitter data, the density of data displayed by the histogram converges into the PDF of the jitter variable.

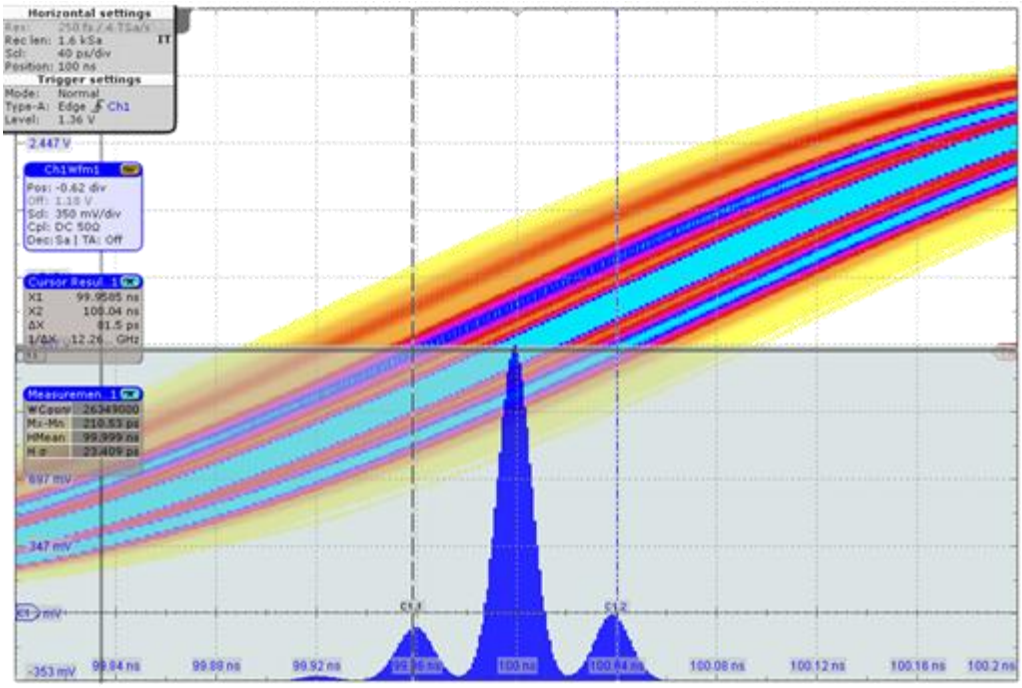


Figure 2-8 Histogram of the rising edge of a clock signal

With the RTO it is also possible to display the histogram of a measurement function for a detailed analysis of the PDF. The user enables it in

"Meas" menu > "Long Term/Track" tab, Figure 2-9. Within this tab, the user has the option to scale the histogram manually, by entering the offset and scale, or let the RTO do this by checking the "Continuous auto scale" box.

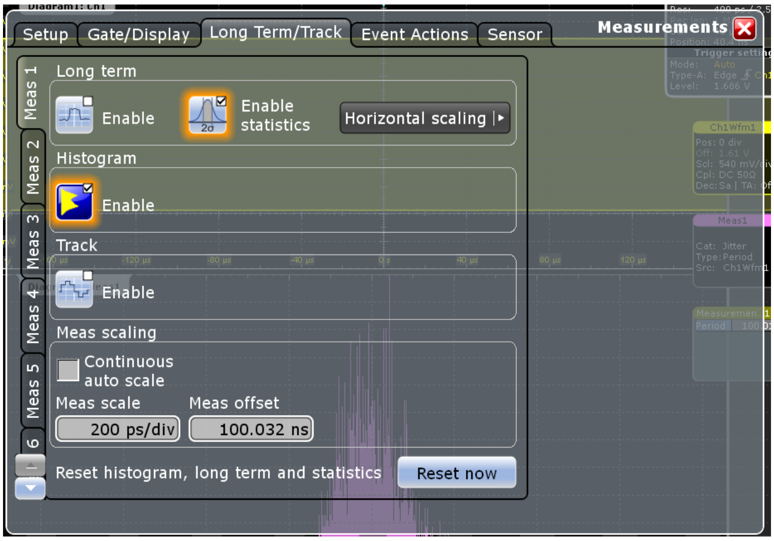


Figure 2-9 Selection of Histogram or Track display for measurement results

2.3.4 Track

The track curve of a jitter measurement displays the measurement results over time for an acquired waveform. Unlike the histogram, it reveals trends of change in the analysis and preserves the timing relationship of the measurement results to the signal. This is, for example, useful for frequency modulated signals, as the track curve of the period measurement of the waveform can reveal the modulating signal. Similarly, the period track might also show unintentional disturbances, due to coupling and cross talk, which are, in the same way, modulating signals. Like the histogram, track is enabled in "Meas" menu > "Long Term/Track". The vertical scaling can be set in the same way as for the histogram.

As a side note, the RTO offers a Long Term function in the same menu. There is a difference between the track and the long term function. The track shows multiple measurements per acquisition and every acquisition displays a new track curve, while the Long Term curve takes one measurement per acquisition and displays it over multiple acquisitions.

2.3.5 Spectrum

The spectrum displays the acquired signal in the frequency domain. The RTO creates the spectrum of the signal waveform by calculating the FFT. The sampling rate determines the maximal frequency of the spectrum, and the ratio between the sampling rate and the number of samples defines the resolution of the spectrum.

Additionally, the introduced track function allows a Fast-Fourier-Transform (FFT) of the track curve due to its timing information. This is a significant benefit of real-time oscilloscope like the RTO over sampling oscilloscopes. Traditionally sampling oscilloscopes have been used for jitter analysis, but their analysis capabilities are limited to histogram data.

If there is no strong modulation on the signal, the jitter track looks like a noise signal. The benefits of the spectrum of a track signal are twofold. First, small signals, which are obscured by the noise in the time domain, become visible in the spectrum. Secondly, the spectrum of the track signal shows the noise floor, which is an equivalent to the signal power, and the spectral shape of the jitter signal gives indications about noise contributions (see chapter 2.2.1).

2.3.6 Eye Diagram

An eye diagram helps to determine the signal quality of digital data signals. Overlaying multiple waveforms of a digital signal creates an eye diagram, Figure 2-10. Usually the eye diagram is displayed over a horizontal range of 1.5 to 2 unit intervals (UI) or bit periods of the digital signal. The user should pay attention to following hints for the creation of an eye diagram of a digital signal:

The timing of the overlay must be related to a reference clock, that can be either an embedded clock signal or an external clock signal. The embedded clock signal must be extracted by hardware or software CDR.

For accurate measurements, all relevant bit pattern of the digital signal should be included in the eye diagram. Memory effects like ISI (see chapter 2.2.3) determine the number of relevant bits for the pattern, it specifies how much one bit of the digital signal influences its neighbors. For example, a standard edge trigger would exclude patterns, which follow just a falling edge. For better results, the trigger should be set at least to both rising and falling edge. The preferred way to generate an eye diagram is based on a clock data recovery (CDR). If a digital signal has an embedded clock, a CDR recovers this clock out of the signal and the oscilloscope may use it for trigger and display. The RTO offers an integrated HW CDR solution (R&S®RTO-K13) to generate an eye diagram.

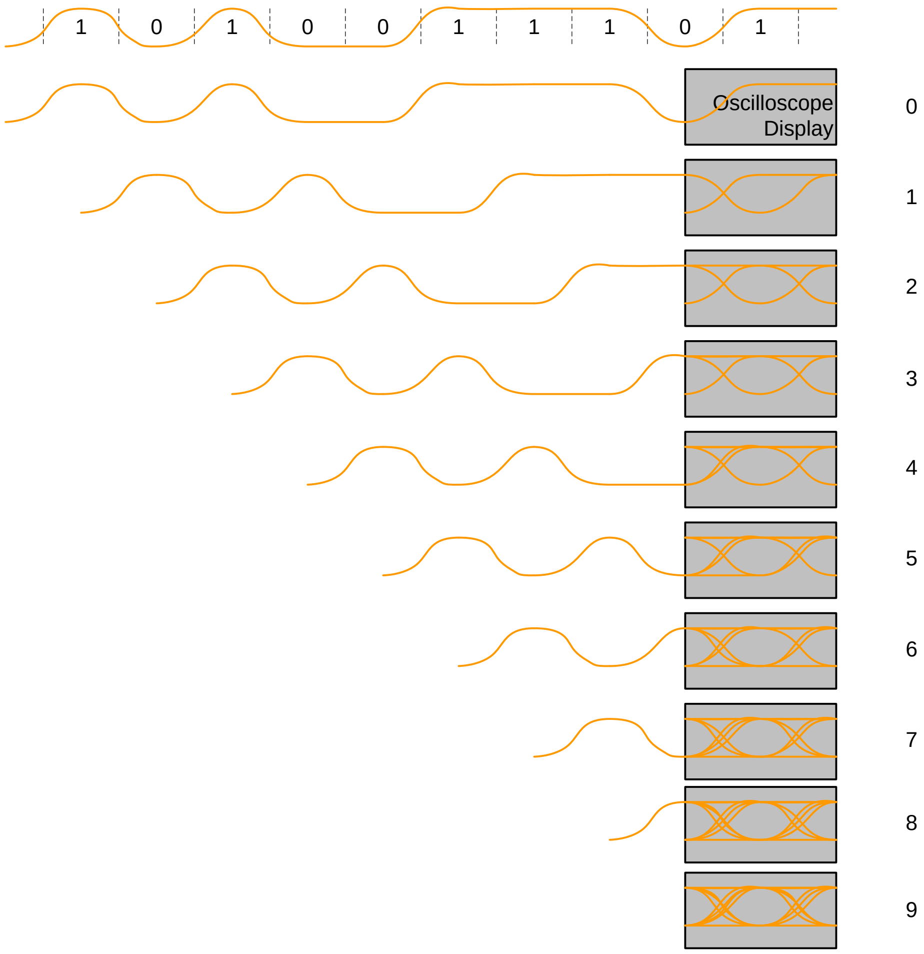


Figure 2-10 Generation of an Eye pattern

2.4 Instrument Limitations for Jitter Analysis

In order to get meaningful results out of a jitter analysis, the user should pay attention to certain aspects of the measurement.

The first and most obvious aspect is the bandwidth of the digital oscilloscope. Based on the frequency of a digital clock signal or the bit period of a digital data signal, the Nyquist criterion must be met. This is necessary but not sufficient. Digital signals can have a low data rate or clock frequency, but still a fast rise or fall time implying high spectral components in the signal. The user can calculate the required bandwidth according to the following rule of thumb $f_{bw} = 0.35/t_{r(10-90)}$. The analog input bandwidth of the oscilloscope shall be bigger than the signal bandwidth. If probes are used, the user must also take the impact of their bandwidth into account, which changes the system bandwidth approximately to a value given in equation (2-4). The sampling rate should be at least twice the signal bandwidth to fulfill the Nyquist criterion. Further resolution can be achieved by interpolation techniques like $\sin x/x$ interpolation.

$$f_{bw\ system} = \frac{1}{\sqrt{{f_{bw\ probe}}^{-2} + {f_{bw\ input}}^{-2}}} \tag{2-4}$$

Another important aspect is the impact of the signal level and transition time (rise or fall). If the signal level is small or the transition time is high, the input noise of the analog front end of the oscilloscope V_N might become a dominant part in the jitter analysis, see Figure 2-11. The influence of the transition time for the sampling accuracy Δt is shown with a fast transition Δt_s and a slow transition Δt_l. A larger amplitude V_A will reduce the transition time. Generally the ratio of vertical scale to the associated RMS noise voltage improves towards larger vertical scales. The interpolation, which is used to determine the signal crossing with the threshold and consequently the accuracy, will greatly benefit from this and an optimal vertical scaling.

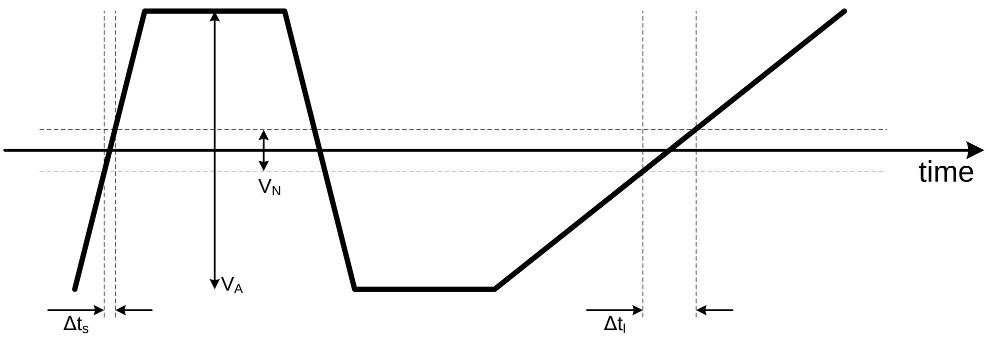


Figure 2-11 Influence of noise on time measurement accuracy

Another aspect is the stability of the time base, long term as well as short term. The variations of the oscilloscope's internal time reference add noise to the acquired signal. The integrated oscillator used as the reference clock causes long term variations. The voltage controlled oscillator (VCO) of the PLL multiplies the reference clock to the sampling frequency, which creates short term variations.

Finally, the noise influence and the time base stability define an intrinsic limit for jitter measurements of an oscilloscope. This limit is the jitter noise floor (JNF), which describes the outermost limit to which the jitter of a signal can be measured under optimal conditions. Equation (2-5) defines the JNF (t_{JNF}), which is frequently named as the time RMS value.

- V_N : input referred noise [V_{RMS}]
- V_A : signal amplitude [V]
- r_{FS} : full scale range
- t_r: rise time 10-90% [s]
- t_j : aperture uncertainty [s_{RMS}]

$$t_{JNF} = \sqrt{\left(\frac{V_N}{V_A \cdot r_{FS}} \cdot t_r\right)^2 + t_j^2} \tag{2-5}$$

Without providing the exact derivation of equation (2-5), a brief rational shall be presented. As described the JNF is caused by noise and slew rate in the threshold point and the short term variation of the sampling clock (see Figure 2-11). The first term represents the noise / slew rate effect, the second term the short term variation of the sampling clock. Both together are random, independent variables, so that the total JNF can be calculated as the square root of the sum of the squares.

The jitter noise floor for digital real-time oscilloscopes is typically in the region of 1 to 5 ps RMS. It equals the standard deviation of the period jitter, cycle-cycle, or time-interval measurement (TIE). Preferred is the TIE measurement, because it neglects the long term stability of the reference clock due to the ideal estimated clock (explained in chapter 3.3).

Finally it should be mentioned that oscilloscopes typically have a delta time accuracy (DTA) specification, which is a measure for jitter accuracy. It corresponds to the time error between two edges of the same acquisition and channel. This parameter closely relates to the JNF and usually specified as peak-to-peak value, with an additional term for the long term variation.

3 Jitter Measurements

The RTO with the RTO-K12 option supports a wide range of automated jitter measurements that are selected in the measurement dialog, Figure 3-1.

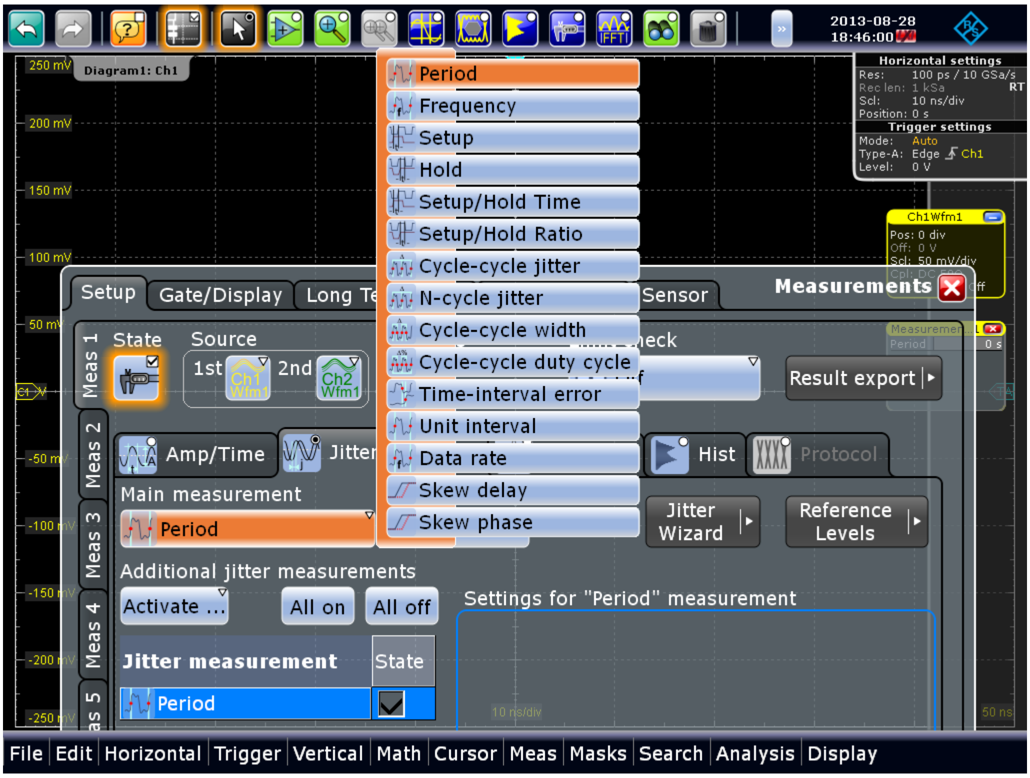


Figure 3-1 RTO measurement dialog with the selection of jitter measurements

This section provides the definition of the most important jitter measurements which are Period / Frequency jitter, Cycle-cycle jitter, Time Interval Error (TIE) and Unit Interval (UI) / Data Rate. Figure 3-2 gives a graphical representation of these jitter measurements with the example of a clock signal.

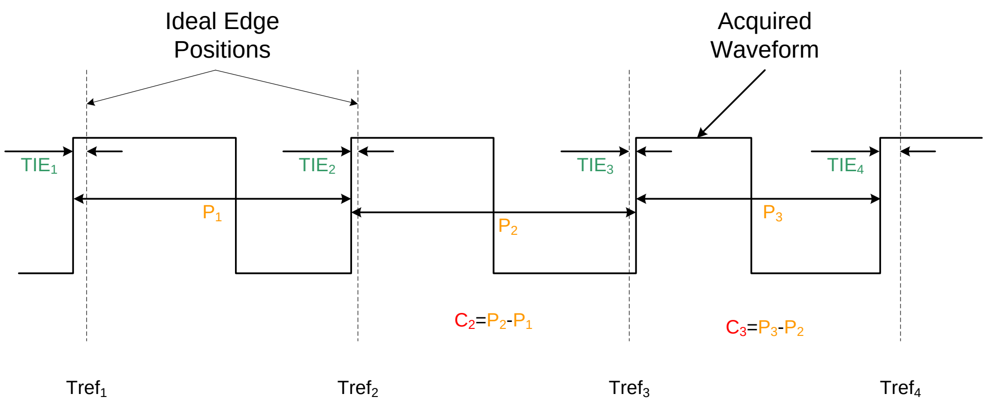


Figure 3-2 Jitter definition of period (P_1), cycle-cycle (C_2) and TIE jitter

3.1 Period Jitter

Period and Frequency jitter can be used interchangeably as they are reciprocal to each other. An oscilloscope is an instrument measuring in the time domain, so the period jitter analysis is preferred over the frequency jitter analysis, because it avoids precision errors in the reciprocal.

Period jitter allows the user to evaluate clock stability. With the help of the track display a modulation signal can be visualized, regardless whether it is intentional or unintentional. It is not applicable for data signals. Period jitter is used to calculate timing margins in digital systems, which rely on a fixed period to meet setup and hold times of the internal flip-flops.

The oscilloscope calculates the period every cycle by the difference of successive edge positions t_n, described in equation (3-1) and shown in Figure 3-2. The period jitter is the deviation of period to the average period, equation (3-2).

$$T_n = t_n - t_{n-1} \tag{3-1}$$

$$j_p(n) = T - T_n \tag{3-2}$$

3.2 Cycle-Cycle Jitter

The cycle-cycle jitter is very similar to the period jitter. It is also only applicable to periodic signals, and there is a generalization from 1st to the Nth difference. Cycle-cycle jitter lets the user evaluate the source stability and the tracking capability of a phase locked loop (PLL).

The oscilloscope determines the cycle-cycle jitter by subtracting the period from the subsequent period, shown in equation (3-3) and in Figure 3-2

$$j_c(n) = (t_n - t_{n-1}) - (t_{n-1} - t_{n-2}) \tag{3-3}$$

This expression can be generalized to an N-cycle jitter with the definition given in equation (3-4).

$$j_n = (t_n - t_{n-N}) - (t_{n-1} - t_{n-N-1}) \tag{3-4}$$

3.3 Time Interval Error Jitter

For oscilloscopes, the TIE calculates the difference of actual edge position t_n from the associated nth ideal edge position t_{REF_n} (see equation (3-5) and Figure 3-2). Precisely, this is the time error not the time interval error as defined by the ITU (2), but a commonly used term for the analysis function in oscilloscopes. For convenience, the term TIE will be used as time error in the remaining part of this application note instead of time interval error.

$$j_{TIE}(n) = \left(t_n - t_{REF_n}\right) \tag{3-5}$$

The TIE is commonly used in communication systems to evaluate the transmission of a digital data stream with an embedded clock. In particular it shows the accumulation of jitter sources. It can be applied to digital clock signals, but preferably it is applied to binary data signals.

For binary data signals, it might be the case that there is no transition for an ideal edge position t_{REF_n}. In this case the oscilloscope assumes the previous value for the TIE jitter $j_{TIE}(n-1)$. With respect to TIE calculation equation (3-5), the oscilloscope must determine the ideal edge position t_{REF_n}. Oscilloscopes have typically two methods to do this.

The first and simplest approach is called the constant frequency approach. Thereby the oscilloscope estimates the value for the interval T of all t_n using a least square estimation (LSE) (5), so that the ideal edge position $t_{REF_n} = n \cdot T$ equals the nth multiple of the estimate and the corresponding TIE jitter is given in equation (3-6).

$$j_{TIE}(n) = (t_n - n \cdot T) = -\frac{\varphi_n}{2\pi f_0} \tag{3-6}$$

The second method uses a phase lock loop (PLL) or CDR to calculate the TIE jitter. This is necessary, because the assumption of the first method, that the frequency of the embedded clock is constant, may not hold true for all signals. The embedded clock may change over time intentionally due to a spread spectrum technique, or unintentionally due to temperature drift or other effects. Spread spectrum techniques are deployed for example in PCIe, and other standard interfaces to reduce electromagnetic interference (EMI).

Oscilloscopes typically implement a CDR in software. The CDR calculates the ideal edge position t_{REF_n} for a single acquisition based on the series of previous edge positions $t_k;\ k \in [1..n]$. Each acquisition requires a new independent calculation of the CDR. Moreover, a CDR shows a memory effect and requires a certain number of transitions preceding the actual edge position t_n to compute a valid ideal edge position t_{REF_n}. This number depends on the configuration parameters, like CDR bandwidth or order of the CDR. The result is that an oscilloscope with a software CDR cannot calculate a valid TIE jitter $j_{TIE}(n)$ for the initial edge positions and as a consequence, the record must be reasonable large for a detailed TIE jitter analysis.

The RTO supports the constant frequency as well as the software CDR method. Additionally the RTO has a built-in hardware CDR, which is unique for this class of oscilloscopes. The hardware CDR runs constantly, even if the oscilloscope does not acquire a waveform, so that, unlike the software CDR, the CDR is able to calculate a valid, ideal edge position t_{REF_n} at the beginning of the acquisition. The hardware CDR is enabled by the R&S®RTO-K13 option.

3.4 Unit Interval and Data Rate

For clock signals, the RTO displays the unit interval (UI) as a time difference of adjacent rising or falling measured transitions, as stated in equation (3-1). If the signal is a binary data signal and transitions are not equidistant in time, the measurement function uses the embedded clock signal, recovered by the CDR to calculate the UI.

The data rate of the signal is the reciprocal of the UI. If the user selects the data rate measurement function, the RTO determines first the UI and then calculates the data rate. As the initial measurement takes place in the time domain and the UI and data rate measurement are mathematically interchangeable the UI measurement function is preferred over the frequency measurement function.

3.5 Eye opening / Mask test

In addition to the jitter measurements discussed so far, the RTO offers also several eye measurements and a specific mask test function, which allow mask tests with eye diagrams. This is helpful for jitter analysis of binary data signals. In the top graph Figure 3-3 displays the color graded eye pattern with the mask test. Mask violations are displayed in the graph in black and recorded in the mask test dialog box of the mask test. At the bottom of the display the eye measurement results are shown. As these are already statistic data, the fields for statistics are left empty.

In order to make use of this feature the use of the hardware CDR is imperative. The explanation is outside the scope of this application note.

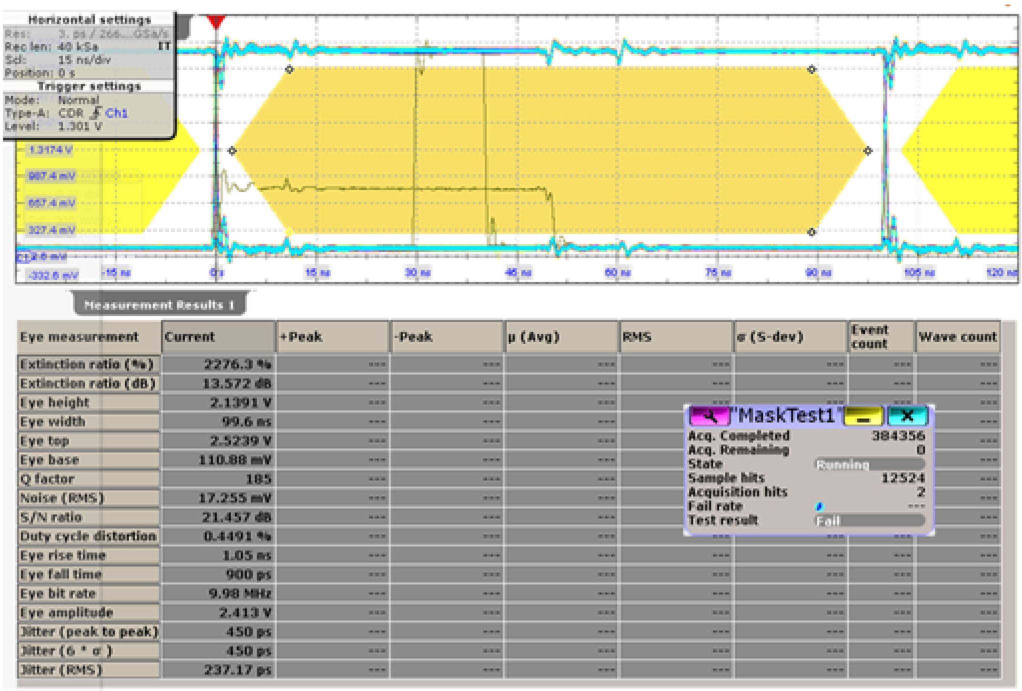


Figure 3-3 Eye measurement and Mask Test for a TTL signal

4 Application Example

This chapter gives a step-by-step example of a typical jitter analysis using the RTO-K12 option. The signal source is provided by the digital clock output of the Rohde & Schwarz Demo board. The TTL clock signal with a nominal frequency of 10 MHz is connected with an active, single-ended 3 GHz probe R&S®RT-ZS30 (Figure 4-1). This digital clock signal allows to focus on the jitter measurements. This digital clock signal is a real world example and shows disturbances, caused by the design of the board.

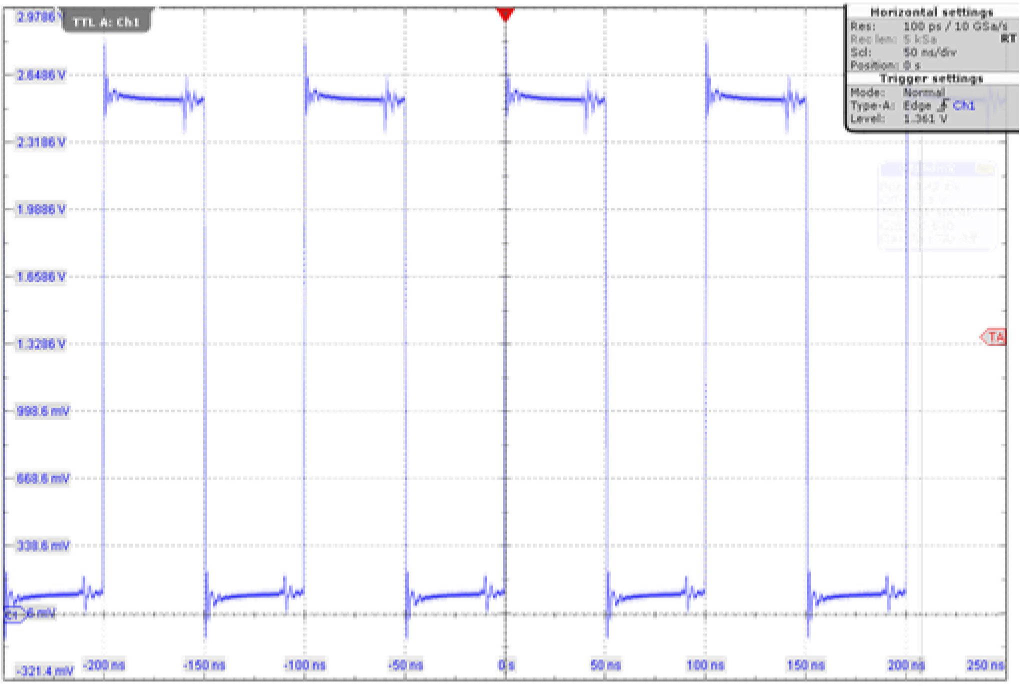


Figure 4-1 TTL clock of the RTO demo board

4.1 Measurement Setup with the Jitter Wizard

For convenience and demonstration purpose the Jitter Wizard of the RTO-K12 option is used to setup the measurements. It is started in the menu "Meas" > "Wizard" > "Jitter Wizard" and brings up the start menu as shown in Figure 4-2. The "period and frequency" measurement is preselected, and the "Next" button gets the user to the "configuration" tab, see Figure 4-3. Channel 1 is preselected, and again pressing the "Next" button brings the user to the "autoset" tab, see Figure 4-4. In order to retain the favorable, vertical settings, the "Retain current settings" in the vertical scaling section is selected. Another "Next" button gets the user to the final "results plot" tab (Figure 4-5). All four analysis options are selected and a click on the "Execute" button will display the period jitter analysis.

The individual measurement results will be presented in the following sub-chapters.

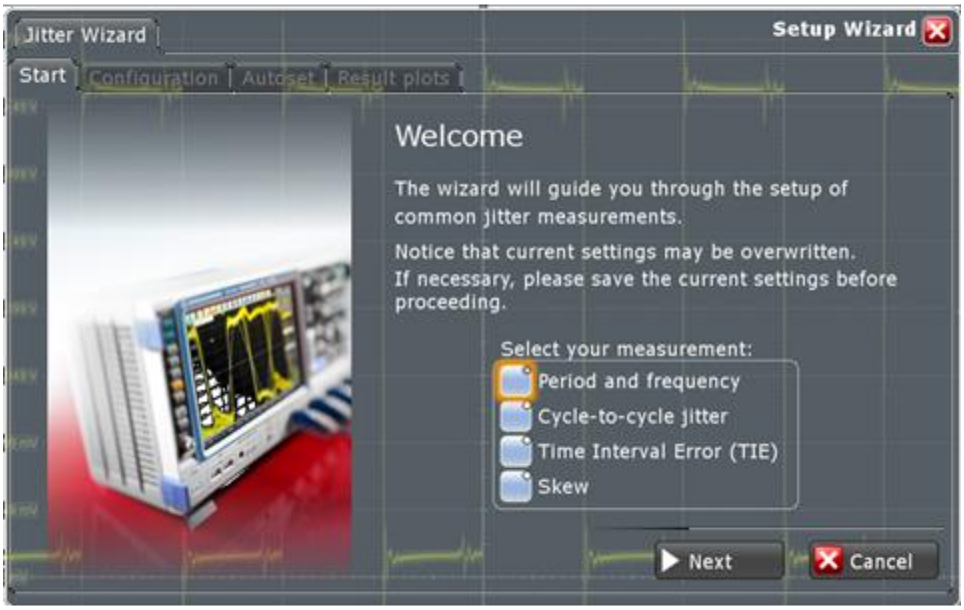


Figure 4-2 Jitter Wizard of the RTO-K12 option - Measurement selection

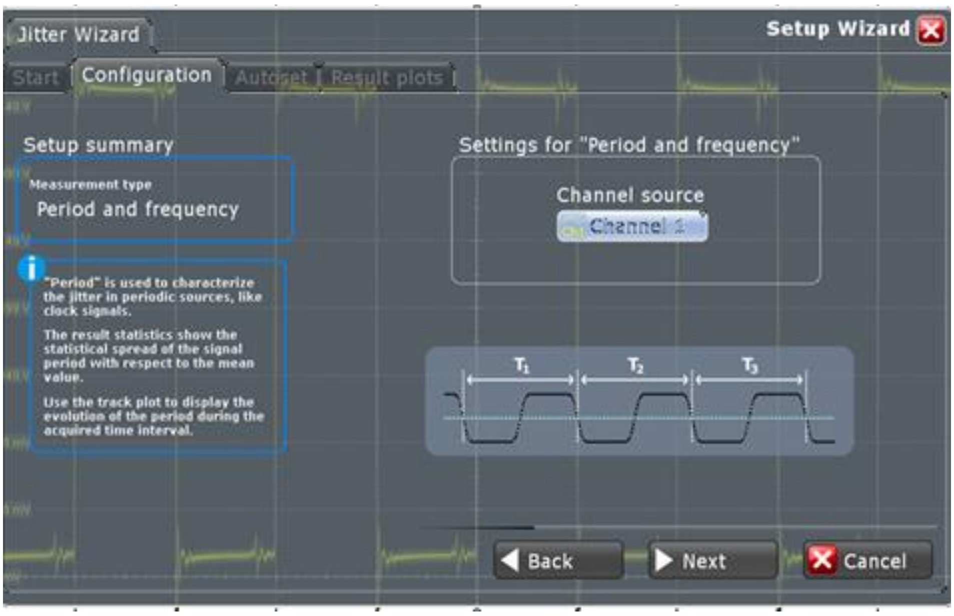


Figure 4-3 Jitter Wizard - Channel Selection

Figure 4-4 Jitter Wizard - Autoset Selection

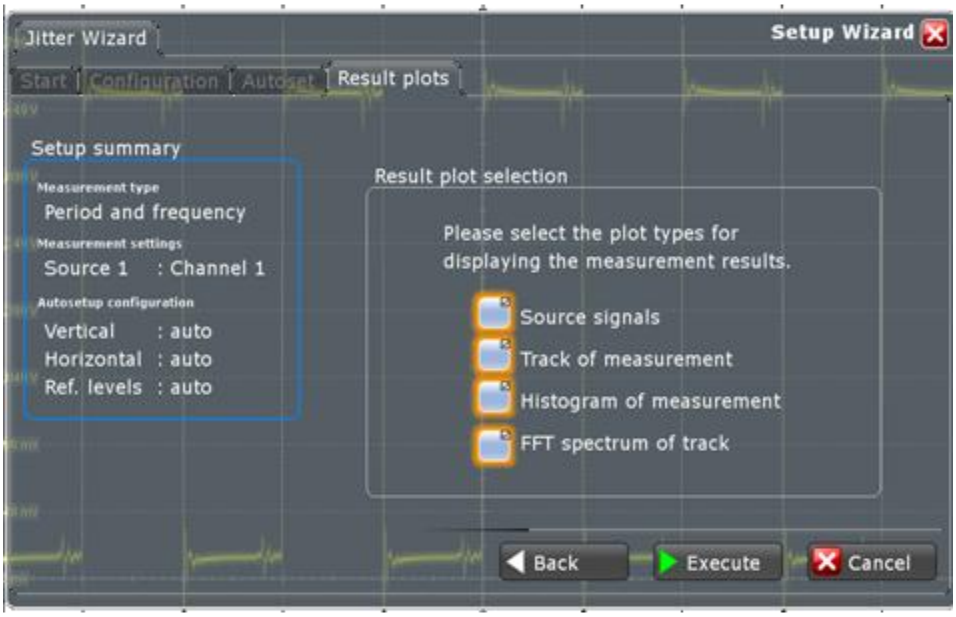


Figure 4-5 Jitter Wizard - Result plot selection

4.2 Period Jitter Measurement

The period jitter measurement was introduced in chapter 3.1. Figure 4-6 shows the result of the Jitter Wizard execution from the previous chapter 4.1. In the top diagram an overlay of the TTL clock waveform (blue) and period jitter track waveform (green) can be seen. This is useful, because the user can immediately associate specific deviations of the nominal period related to the waveform. The diagram in the middle shows the spectrum of the period jitter. The lower diagram displays the period jitter histogram $j_p(n) + T$, which is the PDF of the period jitter and shows a tri-modal

Gaussian distribution. The table at the bottom of the screen shot displays the measurement results for the period and frequency including the statistical data.

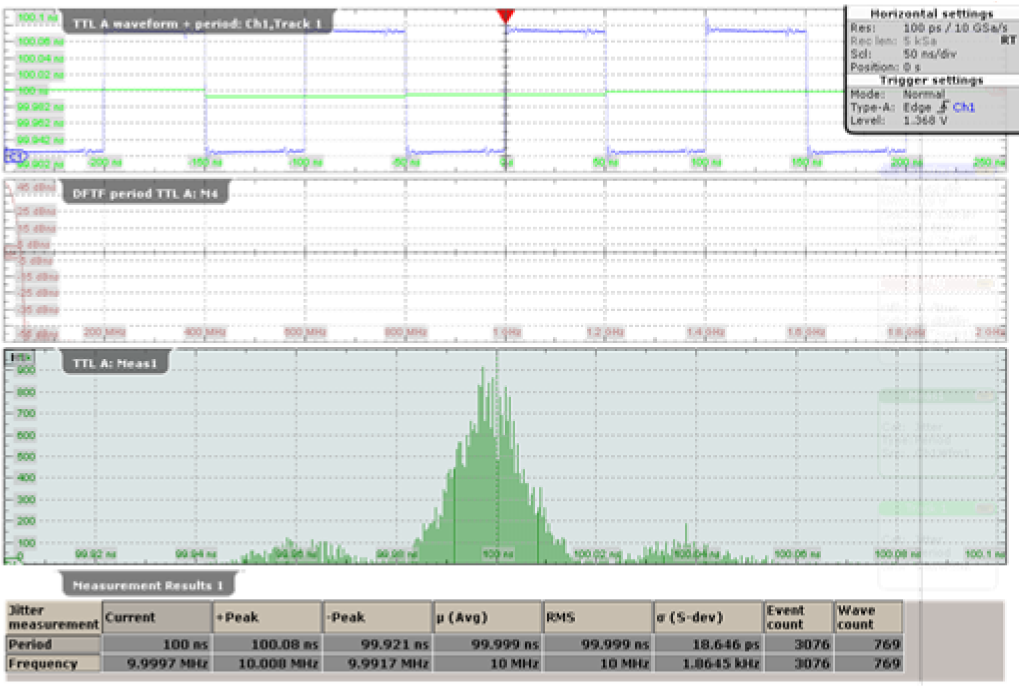


Figure 4-6 Jitter Wizard result for the TTL clock

In a next step, the record length is increased to 4 Msamples, to analyze the PDF in more detail and to get better resolution in the spectrum. Figure 4-7 shows the result of the increase in record length. As a side effect, the number of measurements (event count) is significantly increased and the histogram looks much smoother now.

The track of the period jitter reveals two kinds of disturbances. Around the main line with a period of 100.00 ns, there is a small disturbance in the order of ±40 ps. There is also an occasional disturbance to observe, which has a magnitude of 100 ps. Figure 4-8 shows these disturbances in more detail by applying a Zoom. On the other hand it becomes clear that the disturbance is not prevalent during the entire acquisition time. This gives a strong indication that cross-talk from another digital data signal is causing this disturbance.

To capture such rare events the measurement limits are very helpful. The user may set the measurement limit slightly above the -Peak or below +Peak, and select “Stop on violation” as an action in the measurement menu. The acquisition stops, if such an events occurs. Figure 4-8 shows an example where both conditions occur. In this display the spectrum diagram is switched off and the focus is on the zoom diagram that contains signal waveform and period track. A singular event of a 100 ps jitter pulse is marked with an oval. The other disturbance with a magnitude of ±40 ps appears to be almost periodic. Red arrows mark the period between two successive disturbances for the same polarity with a periodicity of $12 \cdot T$.

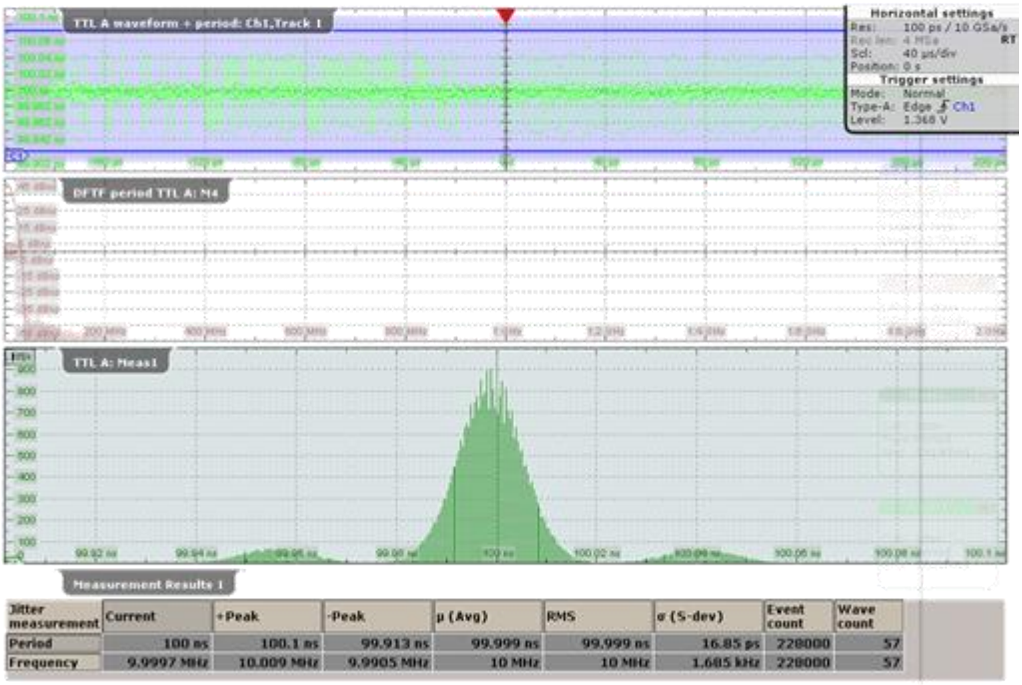


Figure 4-7 Jitter Wizard result with increased record length (Figure 4-6)

The disturbance with the magnitude of ±40 ps causes the observed tri-modal PDF of the period jitter. An undisturbed signal would show a mono-modal Gaussian PDF. The disturbance, induced by internal crosstalk, creates a periodic jitter, but only the aggressor signal's rising and falling edges disturb the oscillator signal. Using the periodicity of $12 \cdot T$ the PDF for this periodic jitter has three Dirac functions at -40 ps, 0 ps and +40 ps, with an amplitude relation of 1:10:1. The convolution with the Gaussian PDF of the random jitter yields the tri-modal distribution. The measured variance σ for the random jitter is 16 ps.

Figure 4-8 Jitter Wizard result period jitter zoom

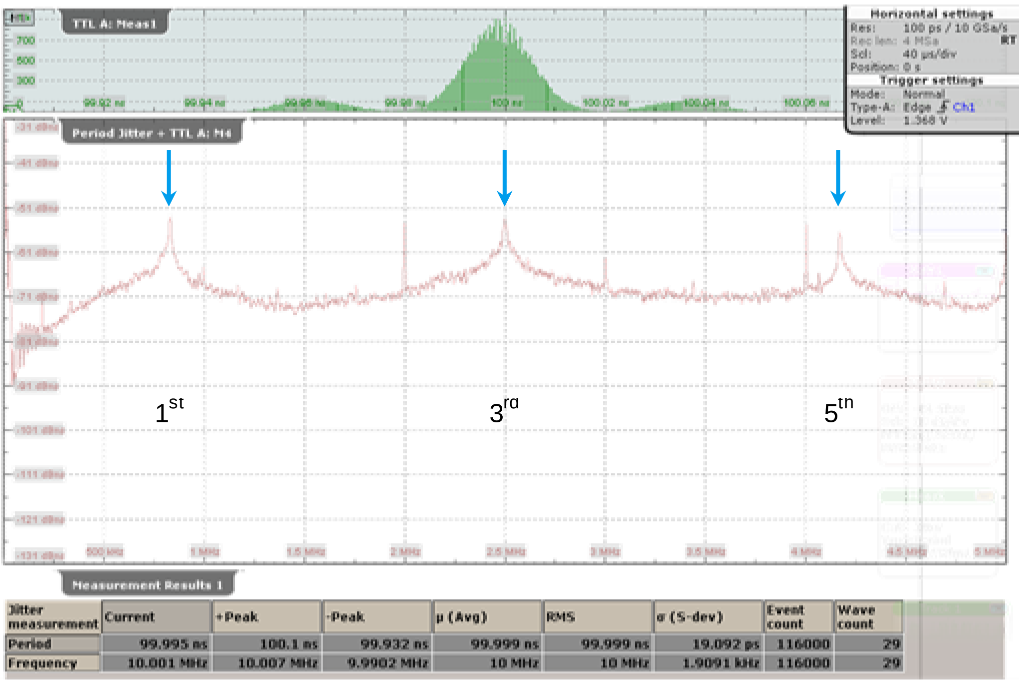
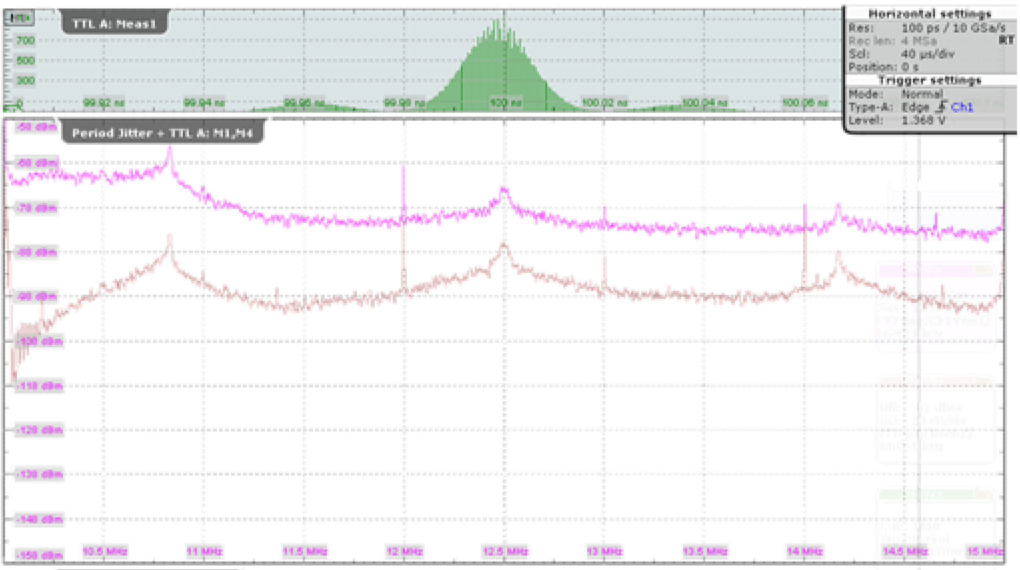


Figure 4-9 Jitter Wizard result period jitter spectrum

For the further analysis of the spectrum, the waveform and the track curve is minimized and not visible in the screen shot (Figure 4-9). The spectrum setup is reconfigured to a center frequency of 2.5 MHz with a frequency span of 5 MHz and a span/RBW ratio of 1000. To reduce the noise of the spectrum display the waveform averaging is enabled with an average count of 25. The findings are as follows: besides some sub harmonics of the 10 MHz clock signal at 2 and 4 MHz also disturbing signals at 0.833, 2.50, and

4.17 MHz are visible. These frequencies match perfectly to the 1st, 3rd and 5th harmonics of the discovered crosstalk signal. Again this signal was found with a period of $12 \cdot T$ of the clock signal, which confirms the measurement of the track in the time domain. In this application example, the analysis in the frequency domain provides the benefit that the almost periodic disturbance signal was easier to find, even though this signal is not active during the entire acquisition.

For reference Figure 4-10 compares the period jitter spectrum with the spectrum of the original waveform with the same scale but at different offset. The waveform spectrum is plotted in magenta and the spectrum of the period jitter measurements in brown. In order to make the spectra comparable, the user must recall the fact, that the period jitter is just the right-hand-sided spectrum of the original spectrum of the waveform. So the waveform spectrum is set to a center frequency of 12.5 MHz with a frequency span of 5 MHz and a span/RBW ratio of 1000. The congruence between both spectra is remarkable and the user can recognize the squared sinusoidal transfer function of the period jitter.



Jitter measurement	Current	+Peak	-Peak	µ (Avg)	RMS	σ (S-dev)	Event count	Wave count
Period	100 ns	100.1 ns	99.913 ns	99.999 ns	99.999 ns	16.232 ps	264000	66
Frequency	9.9997 MHz	10.009 MHz	9.99 MHz	10 MHz	10 MHz	1.6232 kHz	264000	66

Figure 4-10 Jitter Wizard result period jitter and waveform spectra

4.3 N-cycle Jitter Measurement

The cycle-cycle jitter and, in the generalized form, the N-cycle jitter was introduced in chapter 3.2. For the following analysis, the N-cycle jitter is selected, as the RTO offers a convenient way to select cycle-cycle jitter by setting N to 1.

By using the measurement configuration of the previous section, it is easy to switch from the period jitter measurement to an N-cycle jitter measurement. In the "Meas" menu > "Setup" tab the user can select "N-cycle jitter" under "Main measurement". To start with the cycle-cycle jitter, the user should set the "Cycle offset" to 1 and the "Cycle begin" to "Positive".

The track curve of the cycle-cycle jitter measurement does not reveal any different information as the track curve of the period jitter measurement. Therefore the following discussion focuses on the histogram and the spectrum of the N-cycle jitter measurements. In the top diagram Figure 4-11 displays the PDF of the cycle-cycle jitter of the digital clock signal. As a difference to the histogram of the period measurements it is now centered on the origin of the diagram, because the cycle-cycle jitter only displays the variance of the period. Moreover the standard deviation of the Gaussian distribution is doubled due to the difference of the two stochastic variables (5).

As for the period jitter, the second diagram compares also the spectra of the cycle-cycle jitter (brown) and the digital clock signal (magenta). Similarly to the pervious section, there is a coincident between both spectra. However for the N-cycle jitter spectrum there is larger decay towards the origin compared to the period jitter.

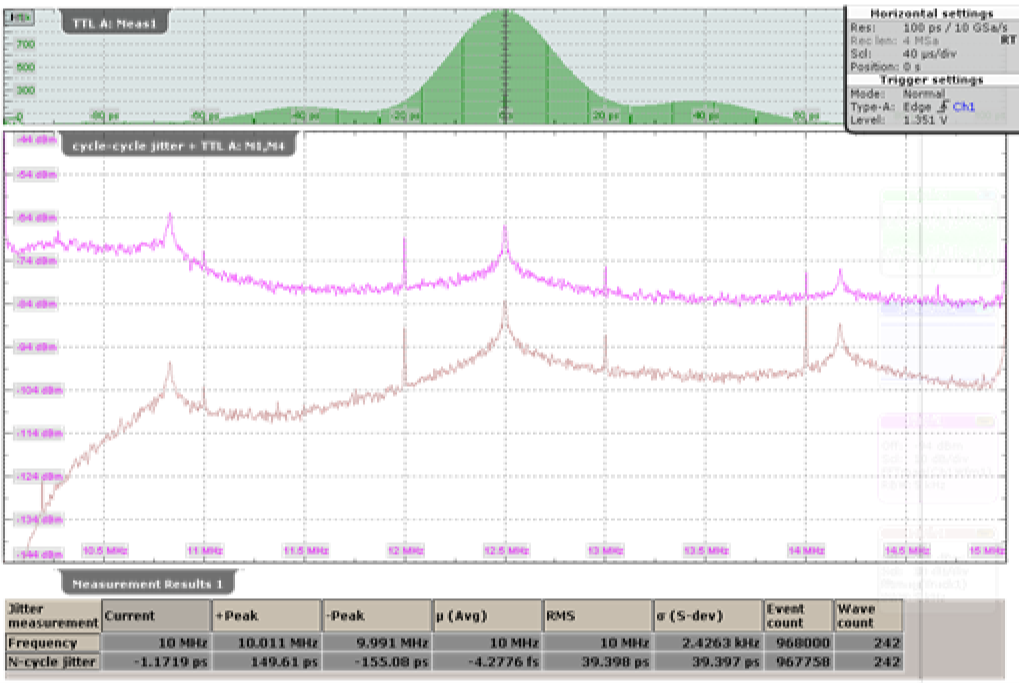


Figure 4-11 Cycle-cycle jitter and waveform spectra

The comparison of both spectra demonstrates the benefit of a jitter spectrum. Looking more closely into the spectra (see Figure 4-12) by using the zoom function of the RTO, a spurious signal close to zero can be detected at 194 kHz within the jitter spectrum. This spur is not visible within the waveform spectrum.

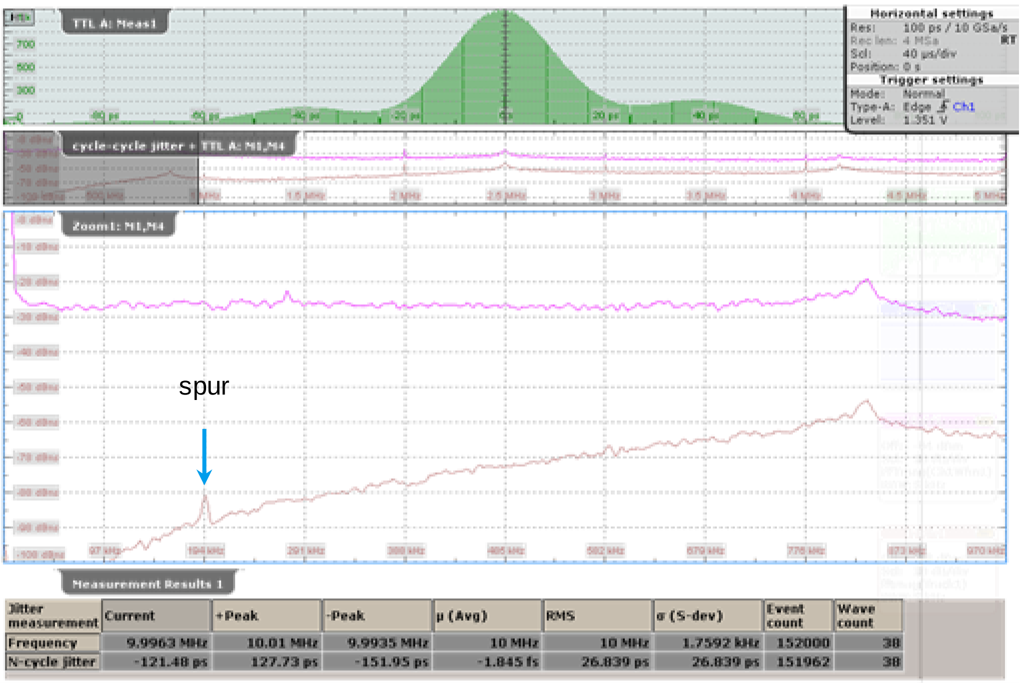


Figure 4-12 Zoom into cycle-cycle jitter and waveform spectra

The existence of this spurious signal at 194 kHz is confirmed by using an R&S®FSV signal and spectrum analyzer. The settings for span and center frequency of the FSV are identically to the RTO. The measured spectrum in Figure 4-13 confirms the existence of this spurious signal (M2) with a similar accuracy to the RTO.

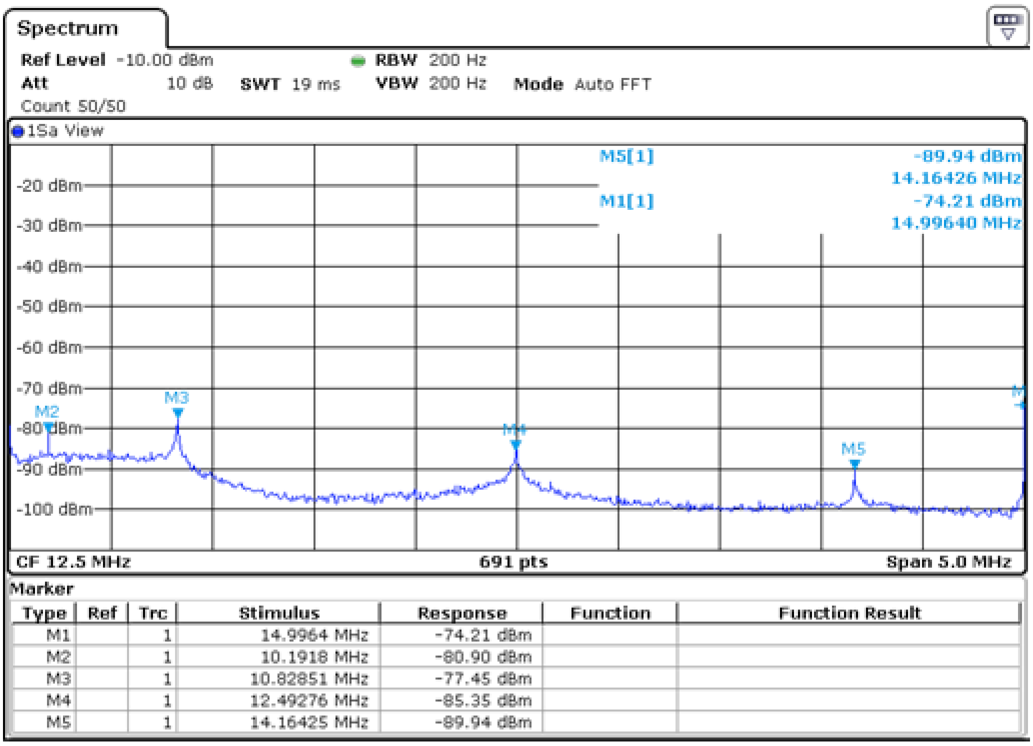


Figure 4-13 Spectrum of the digital clock signal, measured with an R&S FSV

The RTO's cycle-cycle jitter spectrum has a specific advantage over the RTO's associated spectrum of the waveform. This spectrum is able to resolve spurious signals close to the carrier, which a spectrum of the waveform cannot display. The jitter spectrum gives a good qualitative result, though the user should be careful using the results for a quantitative analysis.

For completeness, Figure 4-14 presents an example with a N-cycle jitter measurement. In the "Meas" menu > "Setup" tab, the user can change the "Cycle offset" to 4 from the existing configuration. As a result, the PDF and track do not change, and the spectrum looks similar to the one for the cycle-cycle jitter measurement. However, the zeros in the spectrum are noticeable changed, which is caused by the transfer function of the N-cycle jitter.

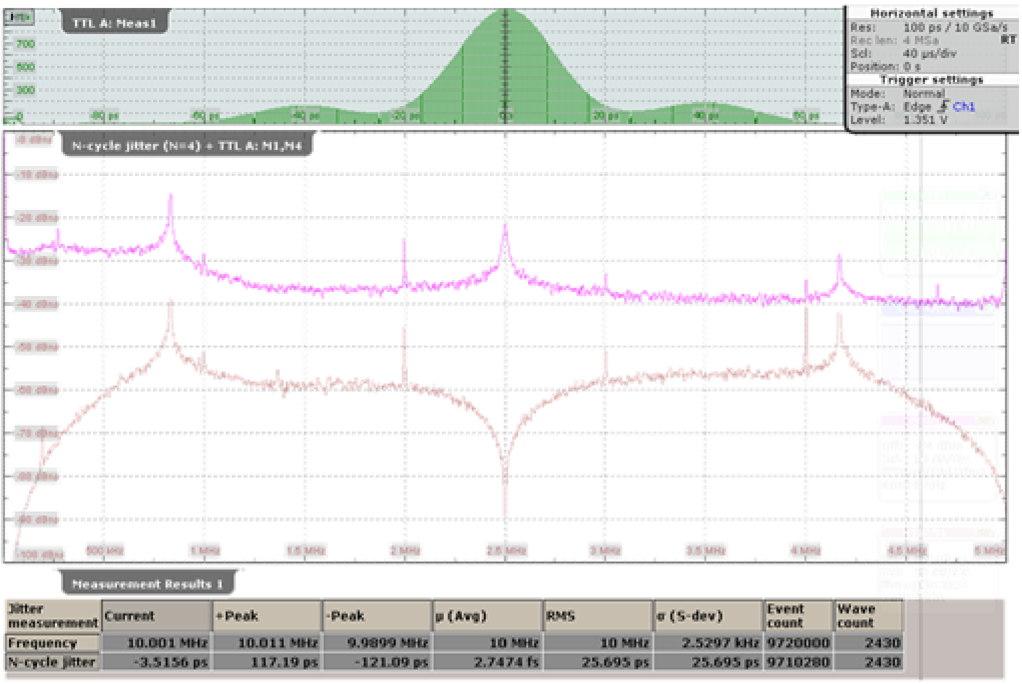


Figure 4-14 N-cycle jitter (N=4)

4.4 TIE Jitter Measurement

Chapter 3.3 introduced the TIE jitter and the respective measurement algorithm. The TIE jitter measurement requires the configuration of the CDR in addition to the configuration of the measurement. The following section explains both configurations.

Starting from the previous configuration, the user finds the TIE measurement in the "Meas" menu > "Setup" tab > "Main measurement". Once the user has selected TIE measurement, more user settings appear in the tab, Figure 4-15. A digital clock signal usually strobes on the rising edge, so the "Data slope" field is set to "Positive". As the TIE measurement requires a clock signal, the clock mode is set to "Software CDR". The "CDR setup" button will get the user to the CDR configuration. Alternatively, the user might select the configuration menu from the "Protocol" menu > "CDR Setup" > "SW".

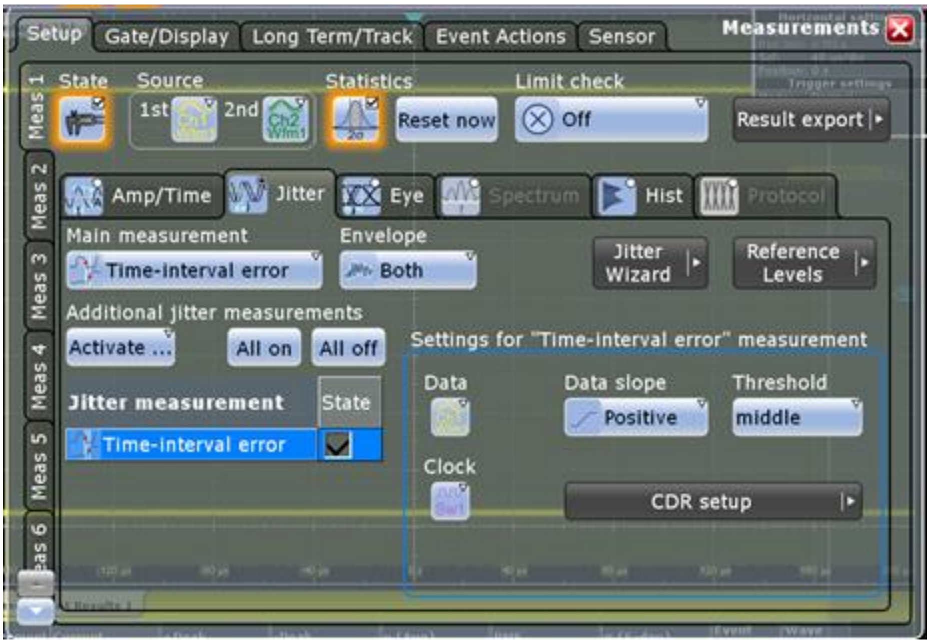


Figure 4-15 TIE Jitter measurement configuration

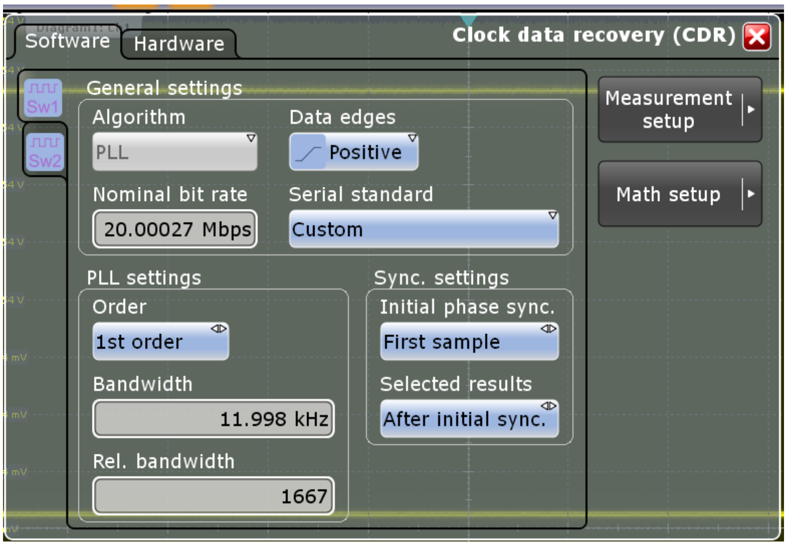


Figure 4-16 Software CDR configuration

Two software based CDRs configurations are available, separated by two tabs labeled with "SW1" and "SW2". "SW1" CDR is used in this example, Figure 4-16. Because the TIE measurement references to the rising edge of the clock signal, the field "Data edges" is set in a consistent manner to "Positive". To set the correct value for the "Nominal bit rate" field, the user must pay attention to the type of signal (chapter 2.3). The applied digital clock signal with a frequency of 10 MHz has a nominal bit rate of 20 Mbps, if it is interpreted as an alternating '01' bit sequence. The remaining fields are left as suggested by the RTO.

Figure 4-17 shows the result of the TIE measurement. In the top diagram the acquired waveform and the track curve of the TIE jitter are displayed. The TIE jitter looks similar to a noise signal, but there is a straight line for the first 170 µs. The reason is, that the software based PLL, which starts over with every acquisition, must settle before it provides a stable reference. During this settling time, the TIE jitter is set to a constant value and therefore appears as a straight line. This behavior can be changed in the CDR setup by setting the "Selected results" field from "After initial sync." to "All". Now the TIE does not show an initial constant value, but the settling of the reference falsifies this part of the track. A hardware based CDR does not start over and would not show this behavior.

The second diagram shows the histogram of the TIE jitter with the PDF of the phase noise function centered on the origin. As opposed to the period jitter the distribution has changed to a bi-modal distribution with two peaks at ±20 ps.

The table at the bottom of the display shows the statistical data, as discussed in chapter 2.3.1, for frequency TIE jitter measurement.

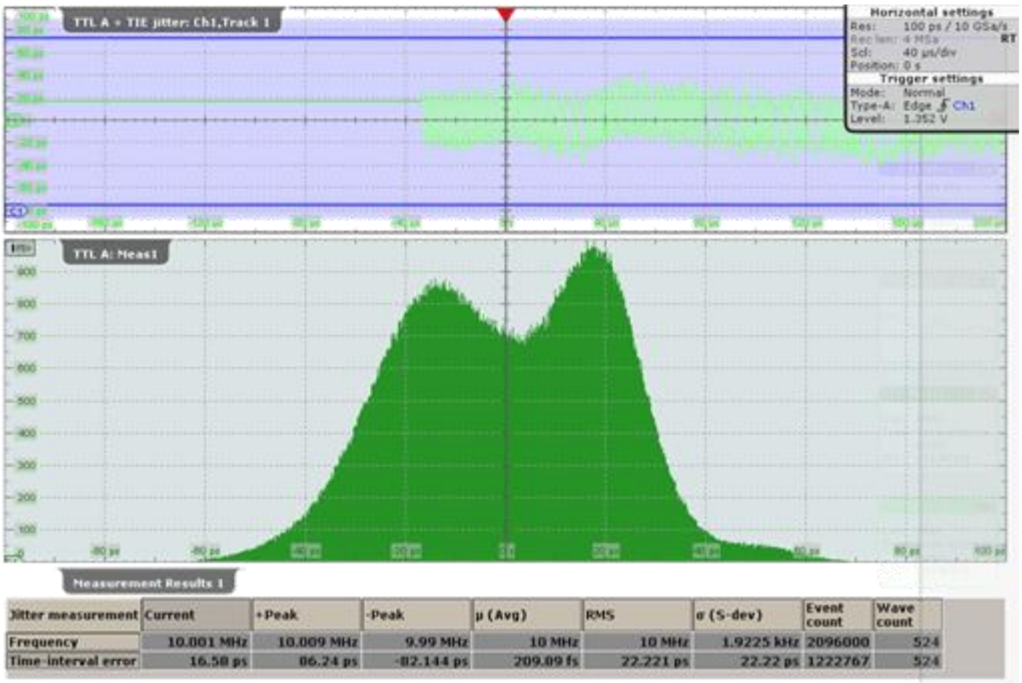


Figure 4-17 TIEjitter

To explore the change in the PDF from the period jitter to TIE jitter, the waveform is minimized and the track curve is zoomed in Figure 4-18. A comparison of this track with the track of the period jitter in Figure 4-8 shows that the disturbing signal is low pass filtered. Without going into the mathematical analysis, a brief explanation shall be provided in the following. The transfer function of a TIE measurement using a 1^{st} order CDR exhibits the behavior of a low pass filter, which attenuates the DC components in the phase noise signal. So the Dirac pulse train visible in the track curve in Figure 4-8, is tuned into a '01' sequence, Figure 4-18, which has still a 40 ps change for the rising and falling edges, but not from the 0 ps level anymore.

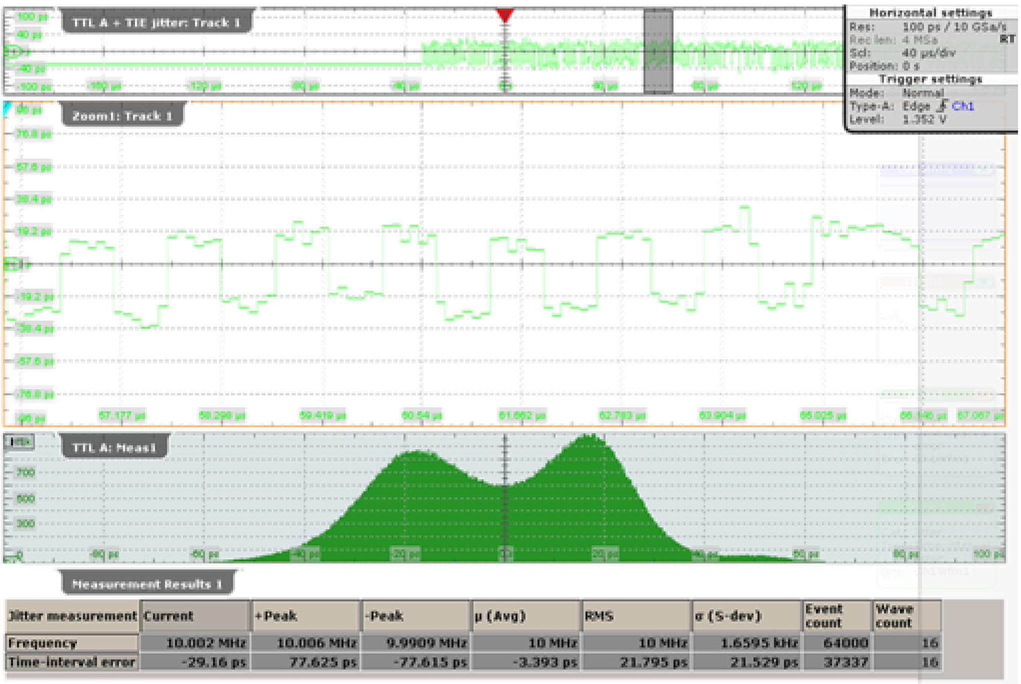


Figure 4-18 TIEjitter zoomed

In the same way as in Figure 4-10, the spectrum is configured for TIE measurement and associated waveform. In the top diagram Figure 4-19 displays the histogram and in the second diagram the spectra of the TIE jitter (brown) and of the waveform (magenta) with the same scale for both spectra. The congruence between both is noticeable. Comparing the spectra of TIE jitter with the period jitter, the TIE jitter does not show the attenuation towards the origin.

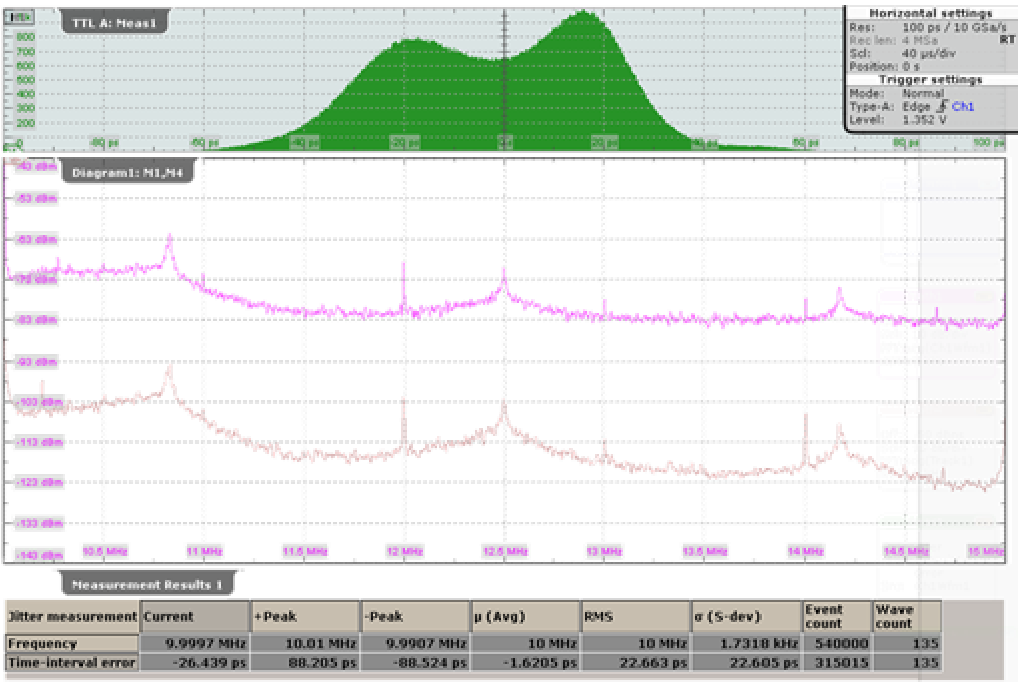


Figure 4-19 TIEjitter spectrum

5 Conclusion

For the transmission of signals, jitter is a significant limitation, which requires analysis and characterization; this applies to system-level, board-level and chip-level. The RTO in combination with the RTO-K12 option is a valuable tool, which offers a comprehensive set of functions for the jitter analysis in design, debug and conformance test of electronic circuits.

This application note discusses the measurement of period, cycle-cycle and TIE jitter based on an application example and compares the impact on track, histogram and spectrum display. It can be concluded that period measurements are most suitable for oscillators, cycle-cycle measurements most applicable for PLLs and TIE measurements most appropriate for transmitted data.

Low intrinsic jitter of the oscilloscope is a key parameter for a precise jitter measurement. The excellent hardware of the RTO and the features of the RTO-K12 greatly support precise jitter analysis and allow remarkable detection capability. An example is the detection of spurious signals close to a carrier.

The Jitter Wizard of the RTO-K12 offers an easy starting point for users of any experience levels.

The R&S®RTO-K13 Clock Data Recovery option provides a unique and powerful solution for eye-pattern analysis of binary data signals with an embedded clock, which gives extra value to the jitter analysis functions discussed in this application note.

6 Literature

1. *R&S®FSUP Signal Source Analyzer Specifications.* 81671 München, Germany : Rohde & Schwarz GmbH & Co. KG, 2011.

2. *Definition and terminology for synchronization networks.* Geneve : ITU-T, 1996. G.810.

3. **Li, Mike Peng.** *Jitter, Noise, and Signal Integrity at High-Speed.* s.l. : Prentice Hall, 2007.

4. *Time Jitter and Phase Noise – Now and in the Future?* **Underhill, Michael J.** Lingfield, UK : IEEE, 2012.

5. **Rice, John A.** *Mathematical Statistics and Data Analysis.* Belmont, CA : Thomson, 2007.

6. *Clock Jitter Estimation based on PM Noise Measurements.* **D. A. Howe; T. N. Tasset.** Boulder, CO 80305 : Proceedings of the 2003 IEEE International Frequency Control Symposium, 2003.

7. *Discrete-time signal processing.* **Alan V. Oppenheim, Ronald W. Schafer.** s.l. : Prentice Hall, 1989.

8. *Spectral Analysis of Time-Domain Phase Jitter Measurements.* **Un-Ku Moon, Karti Mayaram, John T. Stonick.** 5, MAY 2002, IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS—II: ANALOG AND DIGITAL SIGNAL PROCESSING, Bd. 49, S. 321-327.

9. *Definitions Of Jitter Measurement Terms And Relationships.* **Iliya Zamek Steve, Zamek.** s.l. : IEEE, 2005. INTERNATIONAL TEST CONFERENCE.

7 Ordering Information

Naming	Type	Order number
Digital Oscilloscopes		
600 MHz, 2 channels 10 Gsample/s, 20/40 Msample	R&S®RTO1002	1316.1000.02
600 MHz, 4 channels 10 Gsample/s, 20/40 Msample	R&S®RTO1004	1316.1000.04
1 GHz, 2 channels 10 Gsample/s, 20/40 Msample	R&S®RTO1012	1316.1000.12
1 GHz, 4 channels 10 Gsample/s, 20/80 Msample	R&S®RTO1014	1316.1000.14
2 GHz, 2 channels 10 Gsample/s, 20/40 Msample	R&S®RTO1022	1316.1000.22
2 GHz, 4 channels 10 Gsample/s, 20/80 Msample	R&S®RTO1024	1316.1000.24
4 GHz, 4 channels 20 Gsample/s, 20/80 Msample	R&S®RTO1044	1316.1000.44
Software Options		
Jitter analysis option	R&S®RTO-K12	1317.4690.02
CDR option	R&S®RTO-K13	1317.4703.02

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Regional contact

Europe, Africa, Middle East
+49 89 4129 12345
customersupport@rohde-schwarz.com

North America
1-888-TEST-RSA (1-888-837-8772)
customer.support@rsa.rohde-schwarz.com

Latin America
+1-410-910-7988
customersupport.la@rohde-schwarz.com

Asia/Pacific
+65 65 13 04 88
customersupport.asia@rohde-schwarz.com

China
+86-800-810-8228 /+86-400-650-5896
customersupport.china@rohde-schwarz.com

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- Energy-efficient products
- Continuous improvement in environmental sustainability
- ISO 14001-certified environmental management system

Certified Quality System
ISO 9001

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Rohde & Schwarz GmbH & Co. KG
Mühldorfstraße 15 | D - 81671 München
Phone + 49 89 4129 - 0 | Fax + 49 89 4129 – 13777

www.rohde-schwarz.com