

# Generating Eye Diagrams in VectorStar VNA

## Introduction

A feature option available in VectorStar is the ability to calculate an eye diagram representation of what the currently measured RF performance would do to a digital data stream (that can be configured by the user). This is particularly valuable in seeing the data stream signal integrity issues that could occur with a given transmission path and can help with building up subsystem simulation results. Since the eye diagram computation is per-trace, one can configure a single channel having frequency domain, time domain impulse response, TDR-like and eye diagram traces simultaneously and all responding to the same live data.

A generic eye diagram plot shown in Figure 1 illustrates some of the key attributes that will be discussed. A “heat map” type of plotting is used for eye diagram plotting with the color tending to blue for low occurrences and working up through the rainbow to red for very high occurrences.

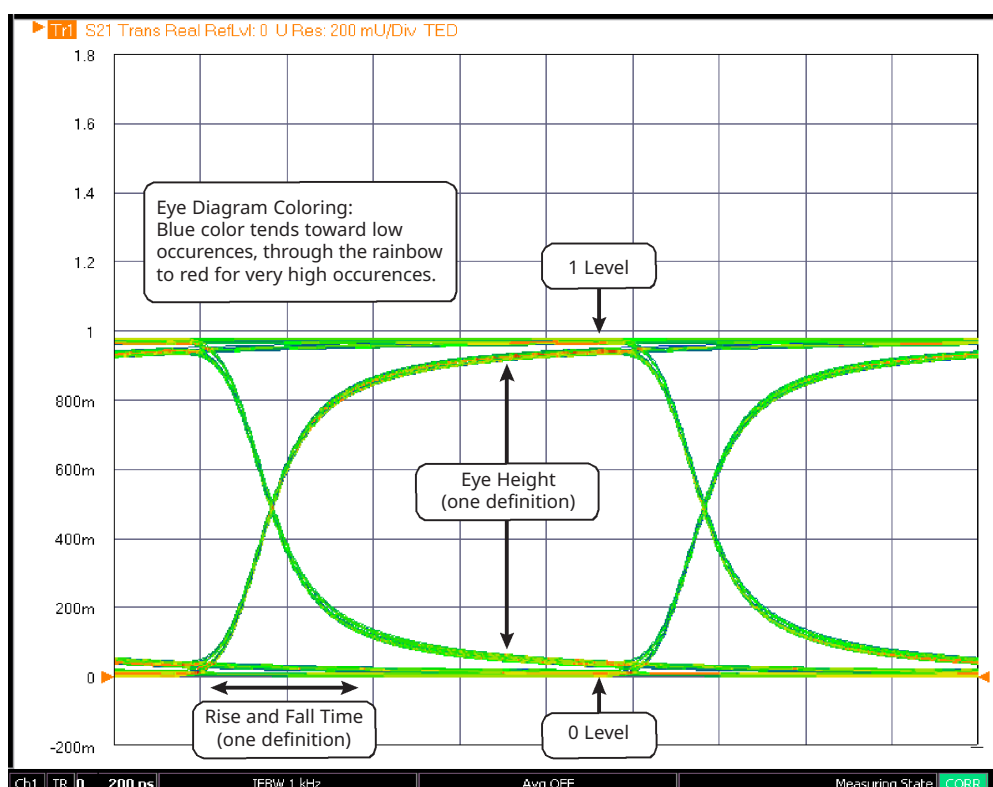


Figure 1. Generic Eye Diagram Plot

There are a few general comments that can be made about the eye structure in Figure 1. The more the insertion loss increases with frequency, the softer the edges will become and the eye will further close in from the sides. Lower frequency defects may create structure throughout the eye, not just the edges. Jitter will cause a general edge broadening while additive white Gaussian noise (AWGN) will cause a more complete line broadening.

## Equipment Requirements:

- VectorStar MS4640B with Options 2 and 47

## Eye Diagram Configuration Dialog

The data stream parameters are configured on the eye diagram calculation setup dialog shown in Figure 2. The type of data stream is the first choice with a Pseudo-Random Binary Sequence (PRBS) being the default. A user fixed pattern (up to 64 bits that then repeats) and the K28.5 standard (ISI maximizer) are also possibilities. The data rate defines the symbol period that will be used for the evaluation. The high and low levels (1 level and 0 level on the input stream) are primarily for scaling and for setup of limit lines later. The pattern length determines the cycle over which the pseudo-random sequence will start to repeat. As the instrument only plots with finite 'persistence' (the number of cycles entered in the dialog which defaults to 200), the pattern length is only important if the persistence level gets very high. Note also that a higher persistence level will slow the processing time and screen update rate.

Eye diagram calculations

This enables the computation of eye diagram based on the current trace parameter for desired data stream configuration.

**Data Stream**

PRBS      Data rate (GBPS) 10      High Level (SE mV) 1000

K28.5      Rise time (ps) 5      Low Level (SE mV) 0

User fixed pattern      Fall time (ps) 5      Pattern length ( $2^n - 1$ ) 511

Selected length is  $2^9 - 1$

**Jitter**

Random RMS (ps) 0

Sinusoidal1 amplitude (ps) 0       Dirac1 offset (ps) 0

Sinusoidal1 frequency (Hz) 1000000       Dirac1 probability 0.1

Sinusoidal2 amplitude (ps) 0       Dirac2 offset (ps) 0

Sinusoidal2 frequency (Hz) 1000000       Dirac2 probability 0.1

**Noise (AWGN)**

RMS amplitude (mV) 10

**Persistence**

Persistence (number of cycles) 200

Done      Cancel

Figure 2. Eye Diagram Calculation Setup Dialog

Other waveform defects can be entered as shown including:

**Rise and Fall Time:**

Note that these values cannot exceed 40% of the symbol period. So for an example data rate of 10 GBPS (100 ps symbol period), the maximum rise and fall times that can be entered are 40 ps.

**AWGN Noise:**

This is pure amplitude noise that is entered in an RMS mV sense. 5 V is the maximum entry.

**Random Jitter:**

An RMS time addition to the transitions.

**Sinusoidal Jitter:**

A deterministic addition to the transitions where the frequency of oscillation of the additive amount can be entered. Two independent sinusoidal jitter mechanisms are allowed. Note that normally the frequency is entered as a substantive portion of the data rate in order for variation to be visible. The amplitude of the jitter cannot exceed 40% of the data rate.

**Dirac Jitter:**

A fixed time error added to the transitions with an entered probability. Two independent Dirac jitter mechanisms are allowed. The probability is evaluated on a per-transition basis. The amplitude of the jitter cannot exceed 40% of the data rate and the sum of the probabilities (if both Dirac entries are used) cannot exceed 1.

**Eye Diagrams Generation**

Following are some points about how the eye diagrams are generated:

- The eye will be based on the data and the parameter in the current trace (eye diagrams are 'per-trace' in the nomenclature used elsewhere in this guide) and will update as the underlying frequency domain data updates. It is possible to have traces in the same channel with frequency domain data, regular time domain results, frequency with time gate results and eye diagrams simultaneously.
- The data waveform is constructed in time domain using the parameters entered and this is convolved with the lowpass time domain representation of the current frequency domain data. Eye diagrams will not be available if the current frequency list does not support lowpass time domain (i.e., the start frequency is not multiple of the step frequency).
- If the bandwidth of the current data is far below the frequency content of the requested data waveform, a very flat, low-amplitude eye diagram will result. If the current data suggests a much larger bandwidth, the eye diagram will approach that of the input data waveform overlaid on itself.
- If the DUT is electrically very long (more than an alias free delay  $\sim 1/(\text{frequency step})$ ), the calculation may have difficulties. Using a reference plane shift to reduce that length can help as can reducing the frequency step size in the measurement.
- Since the output of the calculation is a time domain waveform, the result will always be real. Most graph types are allowed due to some unique application requirements but the Real graph type is the most commonly used. The scale will be labeled in Units but the values are in volts with the results driven by the input signal levels specified by the user.
- Any response parameter can be used for the calculation. S21 is the most common selection in a 2-port system but all transmission parameters are frequently used. Reflection parameters are normally only studied this way in specialty applications.

## Eye Diagram Examples

As an example, consider a long PCB transmission line that has a frequency domain S21 like that shown in Figure 3. A 20 MHz to 40 GHz sweep with 2000 points was used to maintain the harmonic sweep requirement for low pass time domain and eye diagram processing. The loss of this DUT is indeed substantial at high frequencies and there is some additional structure above about 30 GHz. The group delay also shows structure at high frequencies.

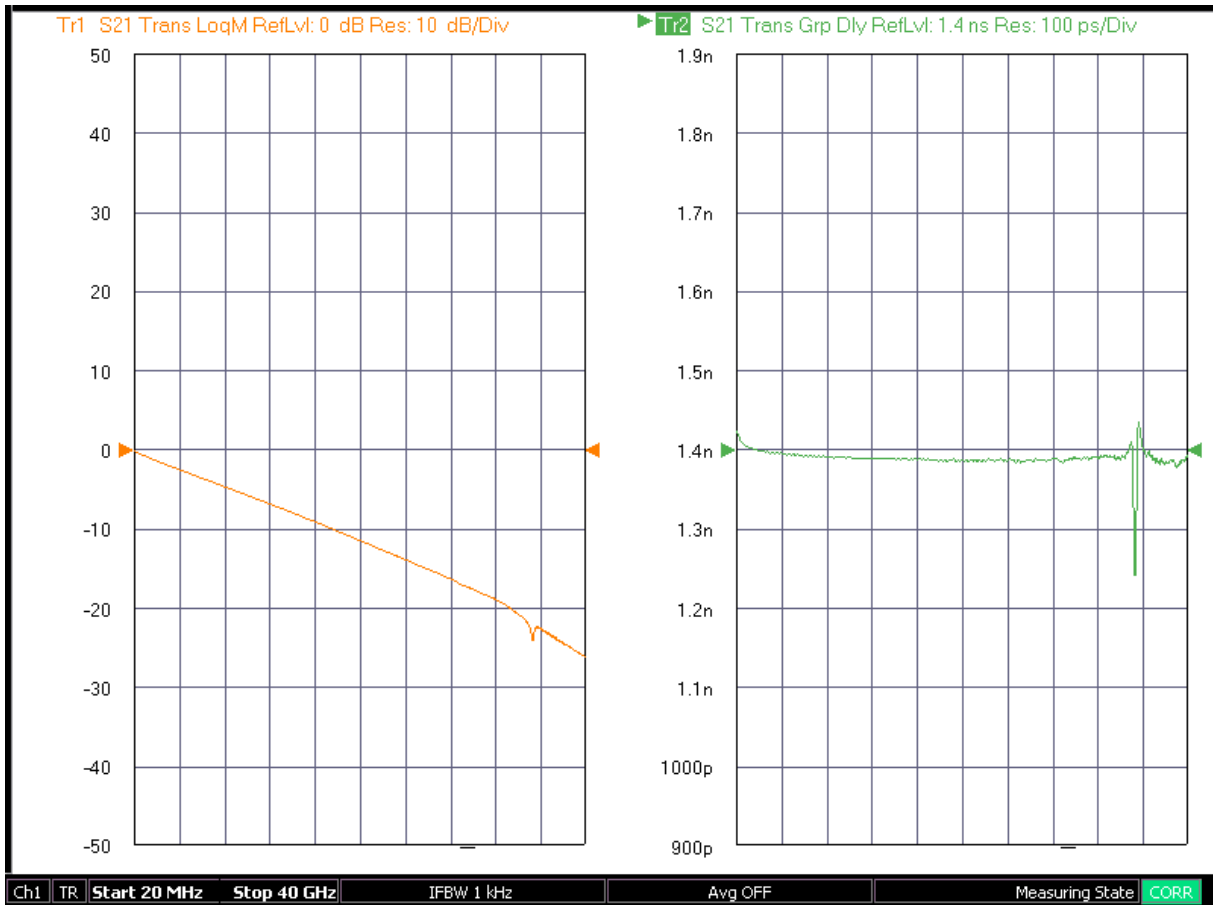


Figure 3. The frequency domain transmission response of the example DUT is shown here.

With a 10 GBPS data rate and no assumed jitter, the eye diagram in Figure 4 is generated. The eye is still quite open at this data rate.

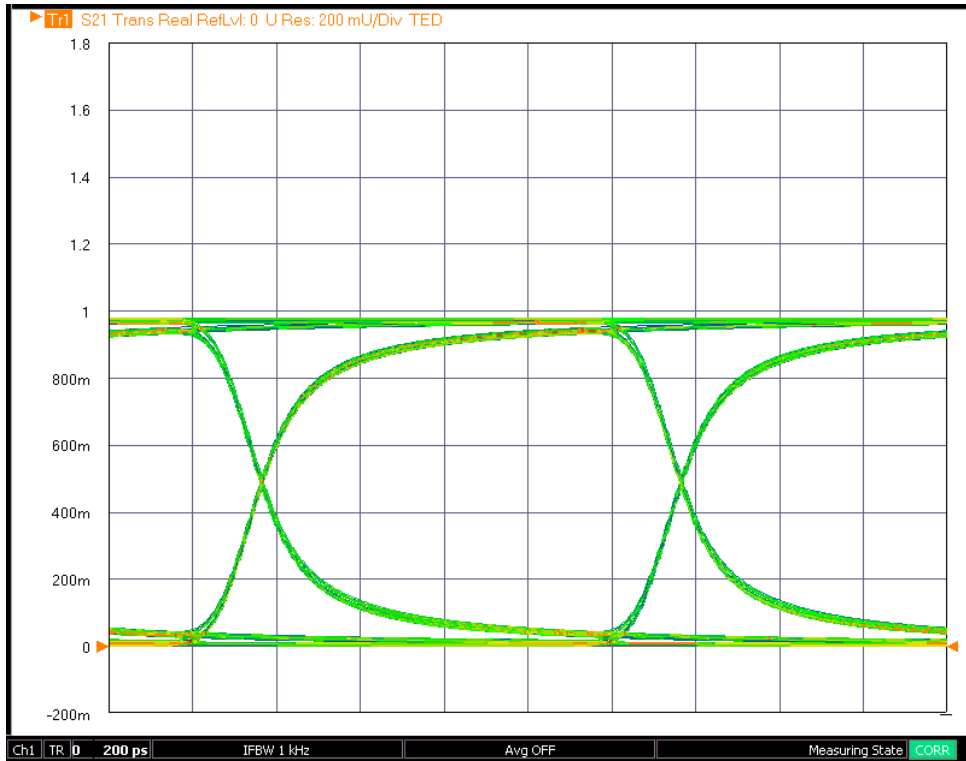


Figure 4. The eye diagram for the DUT of Figure 3 when excited with a 10 GBPS PRBS signal is shown here.

When excited with a 30 GBPS PRBS signal, the eye noticeably degrades further (see Figure 5). The eye height has reduced from nearly 800 mV to perhaps 600 mV and the rise and fall times as a fraction of the UI have increased further.

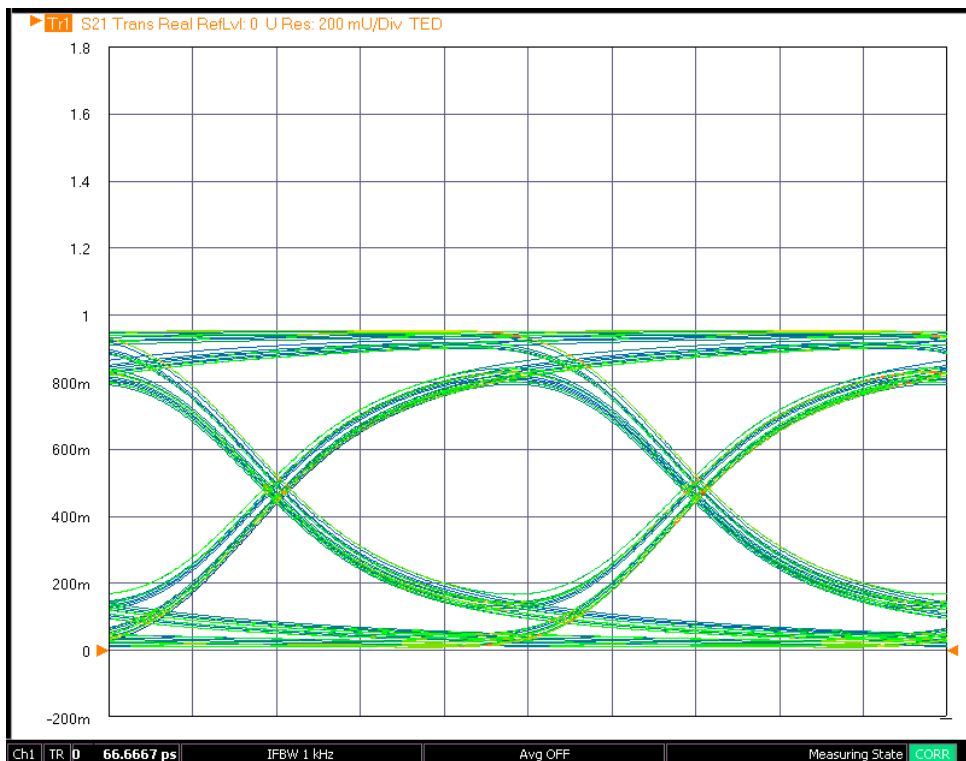


Figure 5. The eye diagram for the DUT of Figure 3 is shown here for a 30 GBPS data rate (PRBS sequence).

Adding 5 ps RMS random jitter, 100 mV RMS AWGN noise and 5 ps rise/fall times (staying at 30 GBPS) further reduces the eye opening but may come closer to predicting a practical environment (see Figure 6). Because the slewing of the DUT is already so severe, the added rise/fall time effects appear more minor than if the DUT had a less dramatic frequency response.

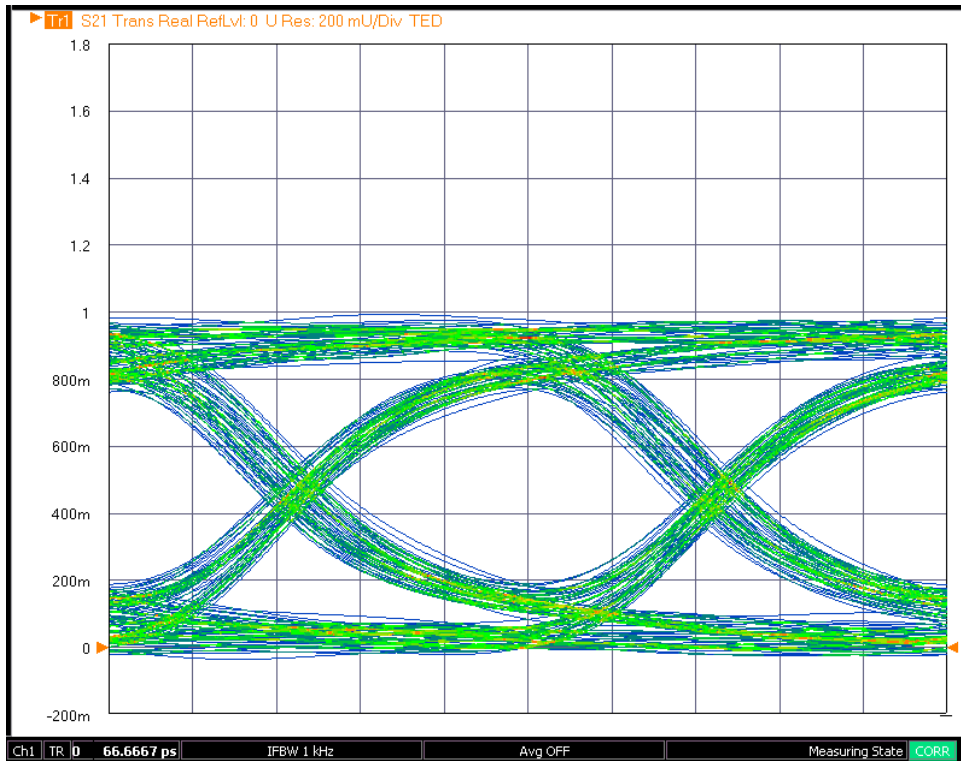


Figure 6. The 30 GBPS example is repeated but with higher AWGN noise and higher incident rise and fall times.

## Eye Diagram Readouts

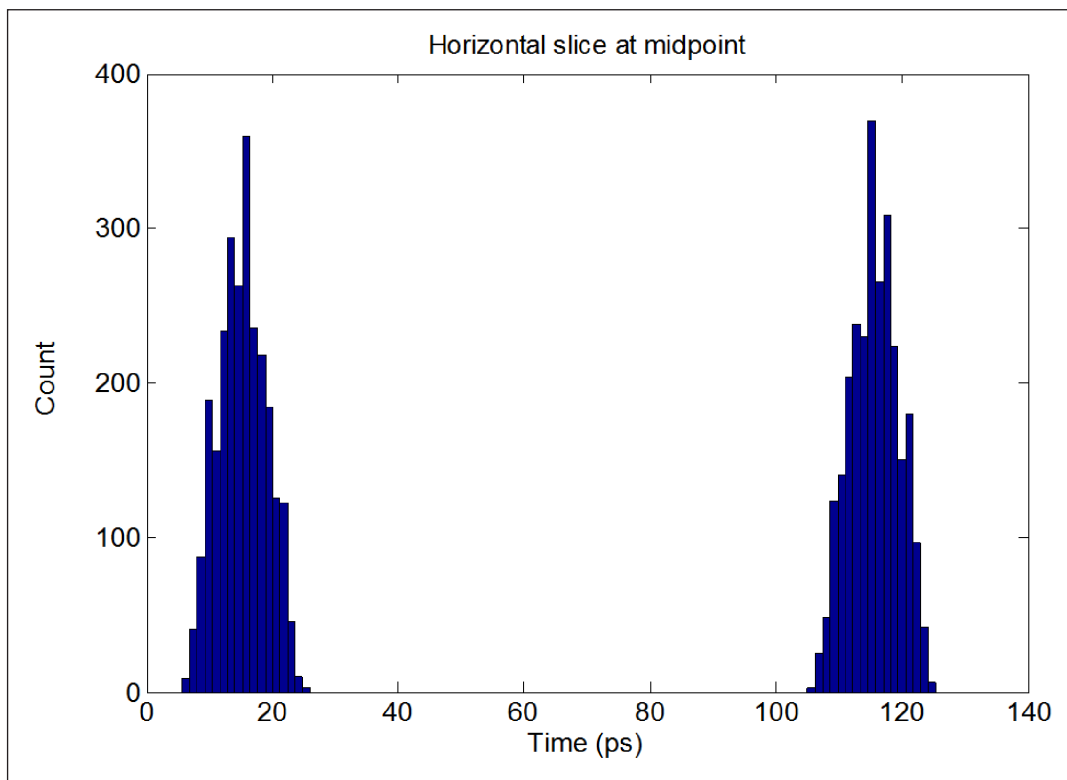
There are a wide variety of readout values (or eye statistics) that are available. These parameters can be enabled in two groups (vertical-based and horizontal-based) and will appear on the trace graticule much like certain marker search parameters (e.g., resonator Q) discussed elsewhere. These parameters are

- **Vertical-based**
  - 0 Level
  - 1 Level
  - Level mean
  - Amplitude
  - Height
  - Signal to noise
  - Rise time
  - Fall time
  - Duty cycle distortion
- **Horizontal-based**
  - Width
  - Opening factor
  - Jitter (pk-pk and RMS)

As might be gathered from Figure 1, these quantities take on a statistical nature since the data at each point of the eye diagram (in the sense of a slice in the vertical direction or one in the horizontal direction) contains a collection of values. Indeed, the above parameters are evaluated based on histogram-like analyses of the distributions.

Note that this list is separated differently from the amplitude-based and time-based separations in the user interface. The above list is based upon how the parameters are calculated whereas the user interface split is based on how the parameters are typically used. For reference purposes, the user interface items based on amplitude are (0 Level, 1 Level, Level Mean, Amplitude, Height, Opening Factor, and Signal to Noise) and those based on time are (Width, Rise Time, Fall Time, Pk-Pk Jitter, RMS Jitter, and Duty Cycle Distortion).

As an example, consider a horizontal slice in the middle of the vertical scale. The histogram of this slice is shown in Figure 7 and shows two distributions at the transition midpoint; one on each side of the eye. The distance between the mean of the two distributions gives an idea of eye width while the standard deviation of one of the distributions gives a measure of jitter.



*Figure 7. The histogram pertaining to a horizontal slice through the middle of an eye diagram is shown here. Although mainly for illustrative purposes, the distributions shown help visualize how the eye parameters are calculated.*

For the horizontal parameters, these are the definitions used:

- **Width:** (Right distribution mean - 3 \* standard deviation of right distribution) - (left distribution mean + 3 \* standard deviation of left distribution)
- **Pk-Pk Jitter:** Absolute width of the distribution
- **RMS Jitter:** Standard deviation of the distribution
- **Duty Cycle Distortion:** If the rising and falling edge distribution means separate at the mean amplitude point, this difference (in time or in % of the bit period) is the duty cycle distortion.

Similarly, a vertical slice, positioned in the middle of the open eye, is shown in Figure 8. Here the difference between the means of the two distributions gives a measure of eye height while the standard deviation could be used to compute a signal-to-noise ratio. The histogram bins were chosen rather randomly for these plots but is the computed statistics that are used for the readout parameters.

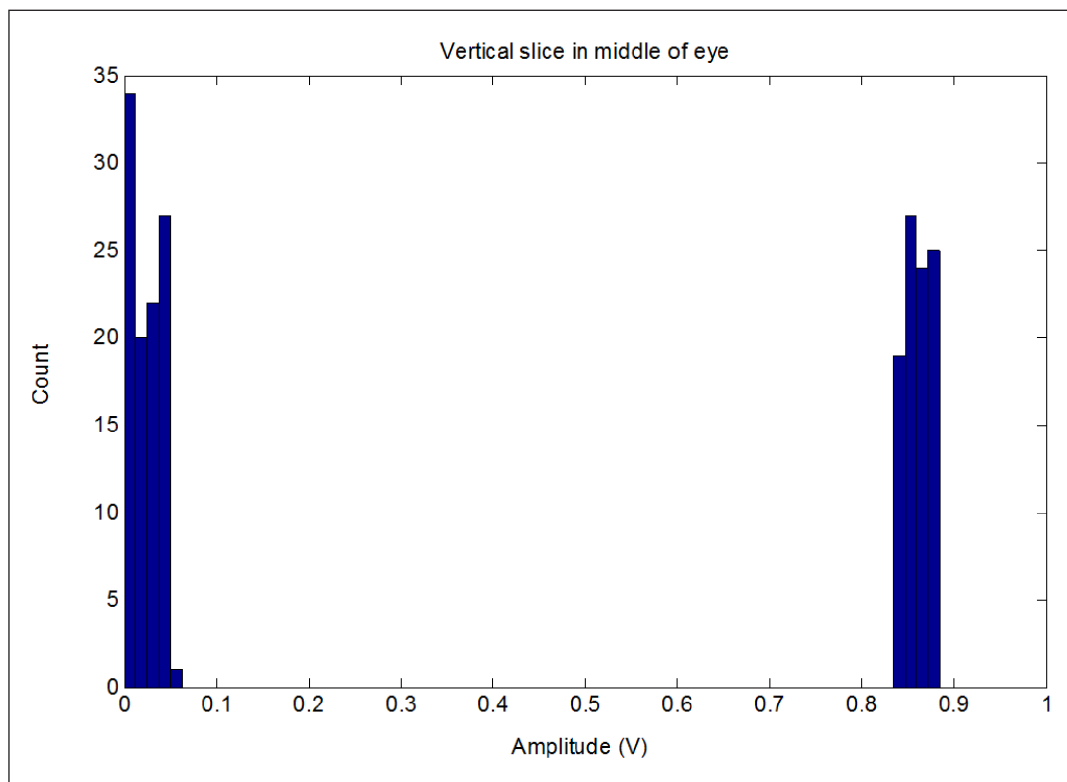


Figure 8. A histogram corresponding to a vertical slice through the middle of an open eye is shown here.

For the vertical parameters, these are the definitions used where a slice in the middle of the eye is used:

- **0 level:** Mean value of left distribution
- **1 level:** Mean value of right distribution
- **Level Mean:** Mean of all data
- **Amplitude:** Mean of right distribution – mean of left distribution
- **Height:** (Mean of right distribution – 3 \* standard deviation of right distribution) – (mean of left distribution + 3 \* standard deviation of left distribution)
- **Opening Factor:** Ratio of eye height to eye amplitude
- **Signal to Noise Ratio:** (Eye level 1 – Eye level 0) / (sigma of left distribution + sigma of right distribution)

Rise and fall time need a sweep through some vertical slices:

- **Rise Time:** Time from when the mean of the left distribution reaches 10% of the eye amplitude above the eye level 0 (starting from a mean at eye level 0) to the time (after a crossing) when the mean of the right distribution reaches 90% of the eye amplitude above the eye level 0.
- **Fall Time:** This is the same as above except starting from eye level 1 on the right distribution and working down.



## Eye Diagram Limit Lines and Their Configuration

Limit lines are of value in eye diagram measurements just as in other VNA measurements although the topology of those limit lines is somewhat different due to the nature of the data. While traditional 'upper' and 'lower' limits still are useful and serve to demark limits of overshoot and undershoot, there is now an additional concept of a 'polygonal' limit line to constrain the amount of eye closure to be allowed. An example of all three types of allowed limit lines are shown in Figure 9.

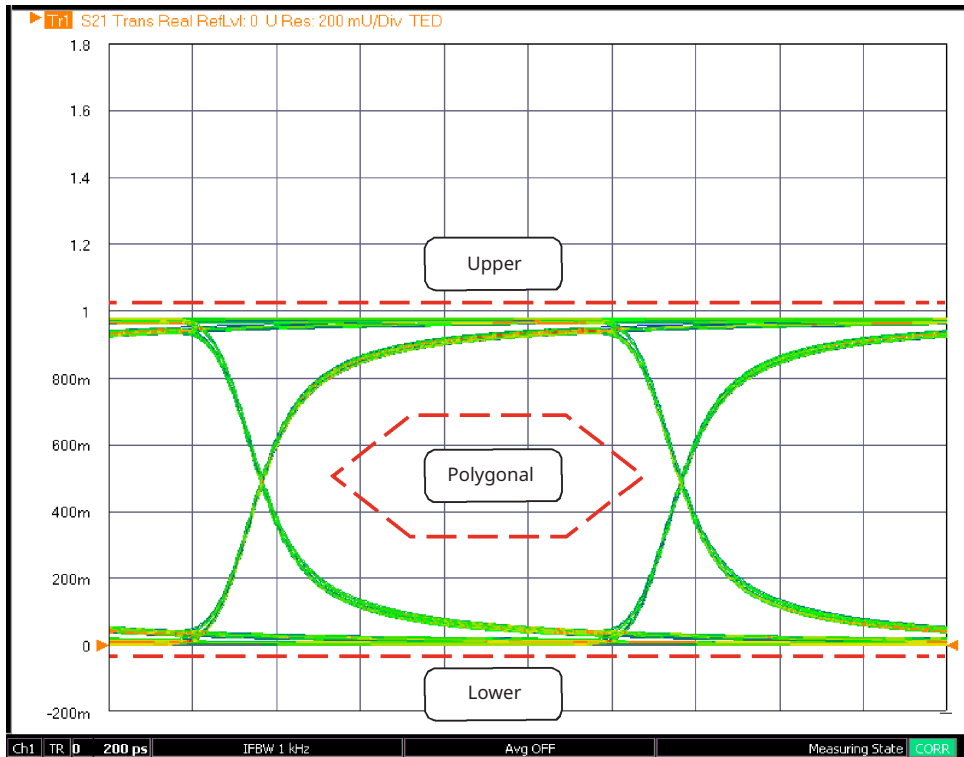


Figure 9. An example eye diagram with the three types of limits sketched in is shown here.

The upper and lower limit lines are covered elsewhere in this application note. The polygonal lines apply only to eye diagrams and that choice in the limit line table only appears in this mode (Figure 10) The polygonal limit line must have at least 3 vertices and must be closed. The system will automatically close the polygon if a complete set of segments have not been entered. The interior of the polygon is always considered the 'Fail' zone.

Type	X1	X2	Y1	Y2	X Offset	Y Offset
1 Upper	-3 ns	4 ns	49.8 dB	9.8 dB		
2 Lower	-6 ns	9 ns	59.8 dB	9.8 dB		
3 Polygon	-1 ns	4 ns	9.8 dB	9.8 dB		

Figure 10. The limit line table in the eye diagram mode is shown here with a polygonal line item shown. Normally three or more polygon segments are used to form a close structure. The polygon will automatically be closed if a complete set of segments have not been entered.

## Eye Diagram Recommendations

As with many time domain-based VNA measurements, using the largest frequency domain sweep range possible where the DUT still has a response and is not radiating severely will lead to the most complete time domain response.

In terms of the calibration quality, cable/connector issues most strongly affect the low frequency and wide-ranging phenomena that have the most time domain impact. Paying more attention to those aspects of the setup and calibration process can pay good dividends. The very low frequency response has less of an effect as the data rate approaches a reasonable fraction of the measurement bandwidth. In these cases, the intrinsic rise/fall time starts to dominate the eye shape.

Depending on the level of mismatch involved, a transmission frequency response calibration (or a simple trace memory normalization) may be an adequate level of calibration. A full port calibration will reduce uncertainty and may be required for reasonable eye diagrams if the mismatch levels are high. Any of the VectorStar's de-embedding tools may be invoked prior to the eye diagram calculation.

When using jitter and rise/fall time entries, keep in mind that the limits on these scale inversely with the bit rate (as they tend to do in practice).

The eye diagram results are effectively simulations based on frequency domain data of the connected DUT. As such, they may not represent an entire system and they rely on relevant entries for noise, jitter, rise/fall times, and amplitudes.

## Summary

The VectorStar Option 47 Eye Diagram combined with Option 2 Time Domain provides design engineers the ability to monitor transmission quality of digitally modulated signals. This important display allows design engineers to observe the likelihood of bit errors due to level compression, jitter, slew and edge distortion as well as other effects. Due to the trace-based nature of the display, VectorStar provides the ability to display all key parameters such as Eye Diagram, Time Domain/ TDR, and S Parameters on the same channel while continuously sweeping.



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