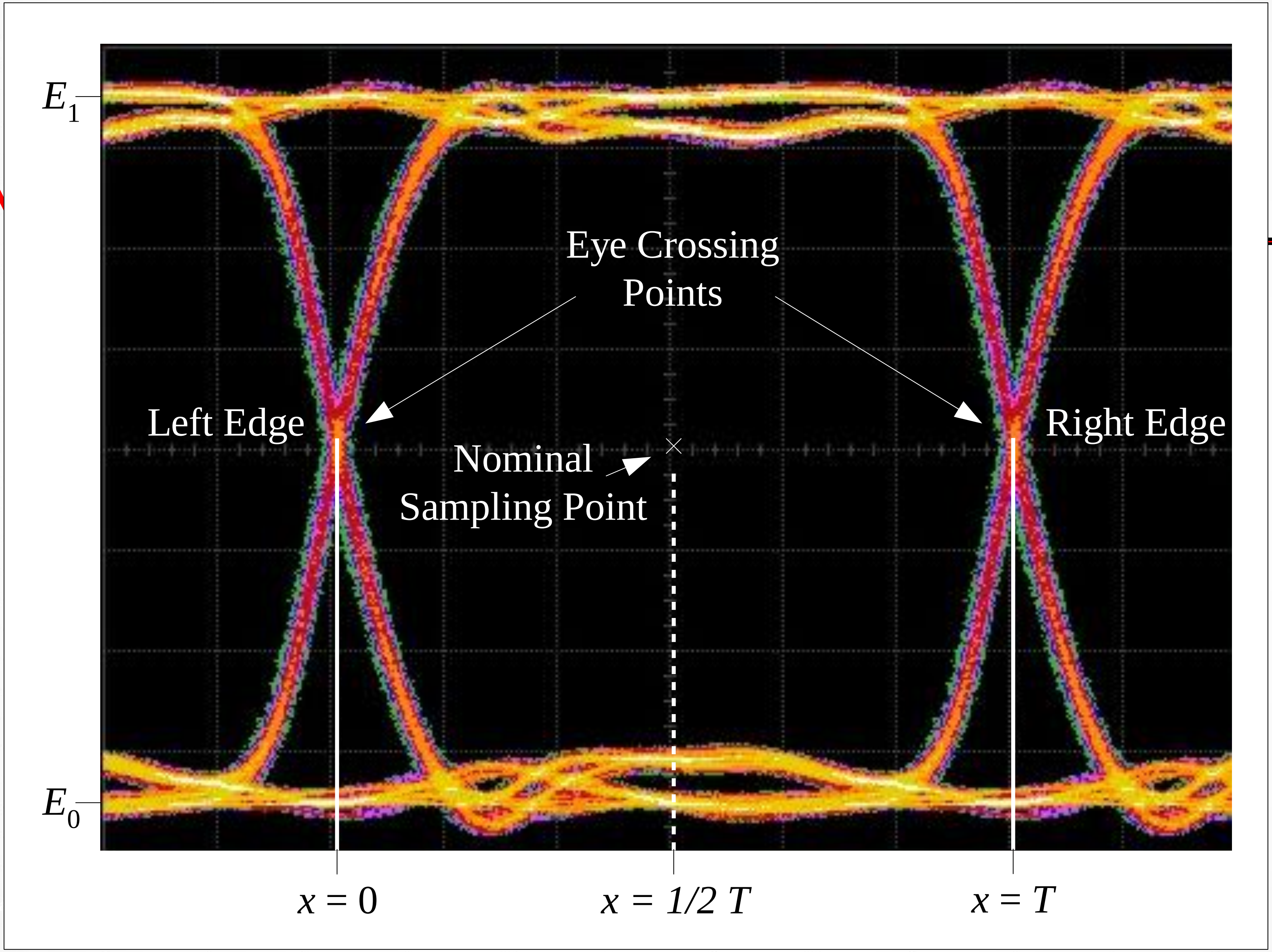
Advanced Jitter and Eye-Diagram Analysis

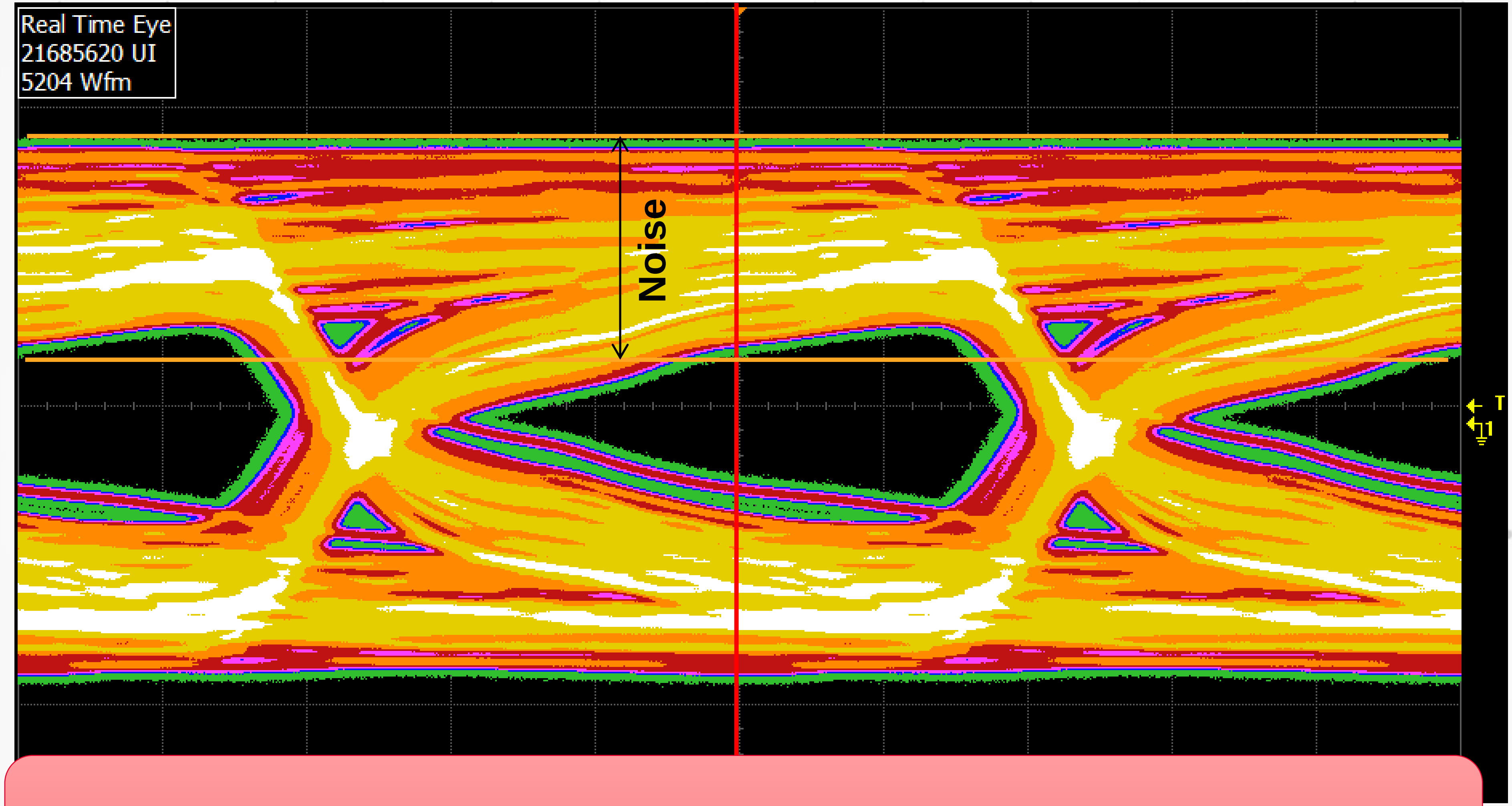
Project Manager / Keysight Taiwan AEO

余宥浚 Jacky Yu

Constructing the Real-Time Eye

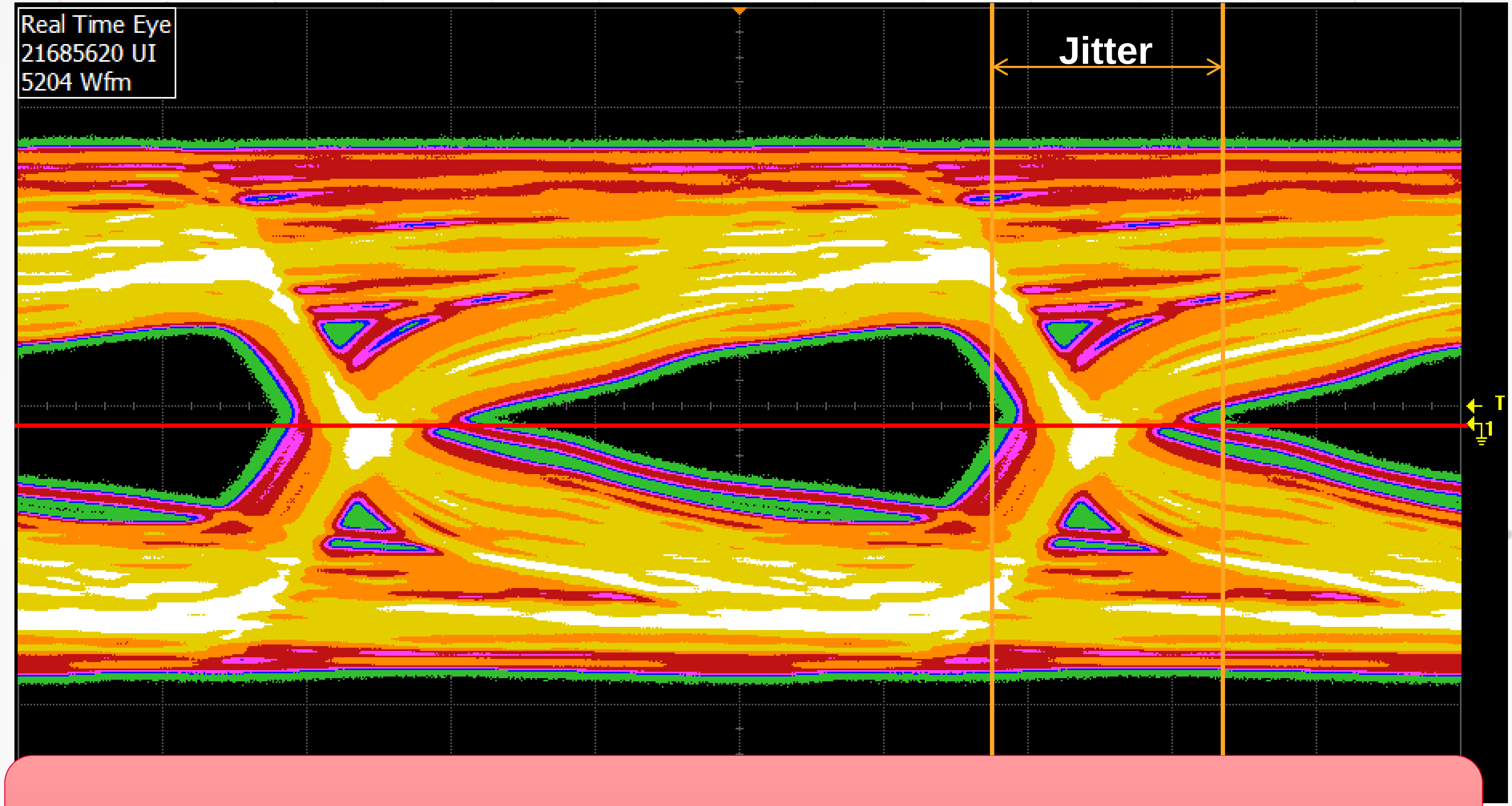


Non-ideal Real-Time Eye



What happened to our eye opening?

Non-ideal Real-Time Eye



What happened to our eye opening?

Pause for definitions

A dictionary definition of the verb "jitter":

To make small, quick, jumpy movements.

In the digital design world, jitter is defined as:

The deviation of the significant instances of a signal from their ideal locations in time.

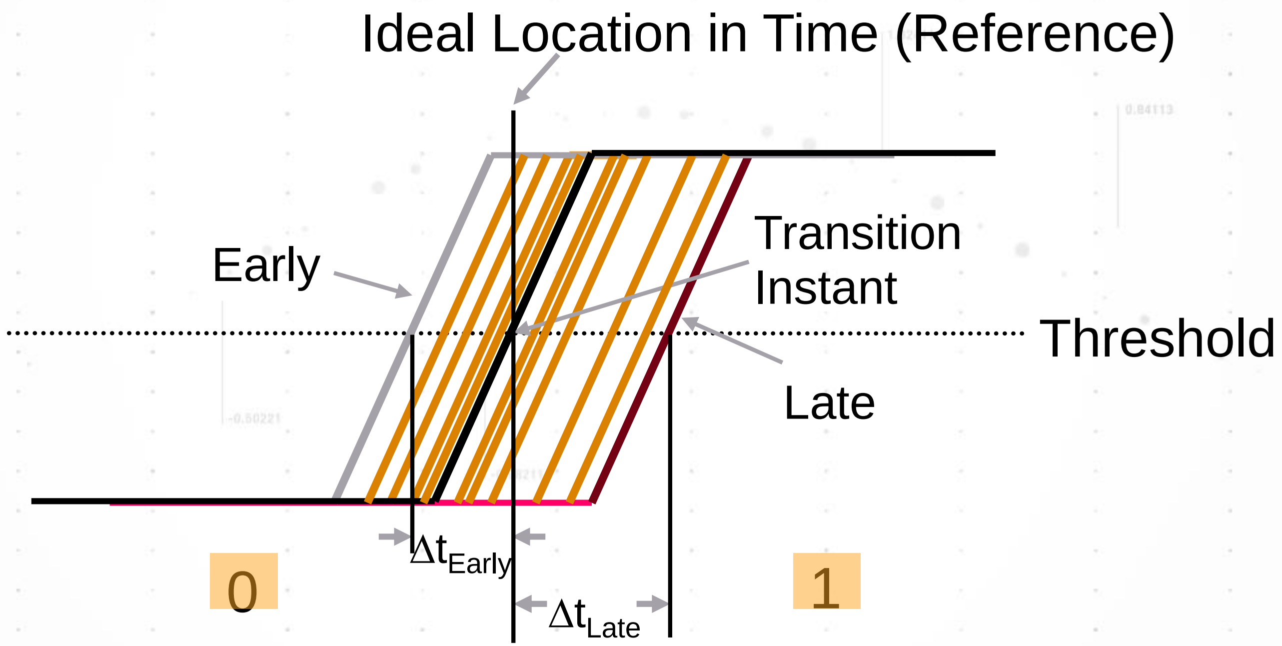
The significant instances for data signals are the transitions (edges)

The ideal locations for the transitions are determined by the time reference (clock)

Single Transition Jitter

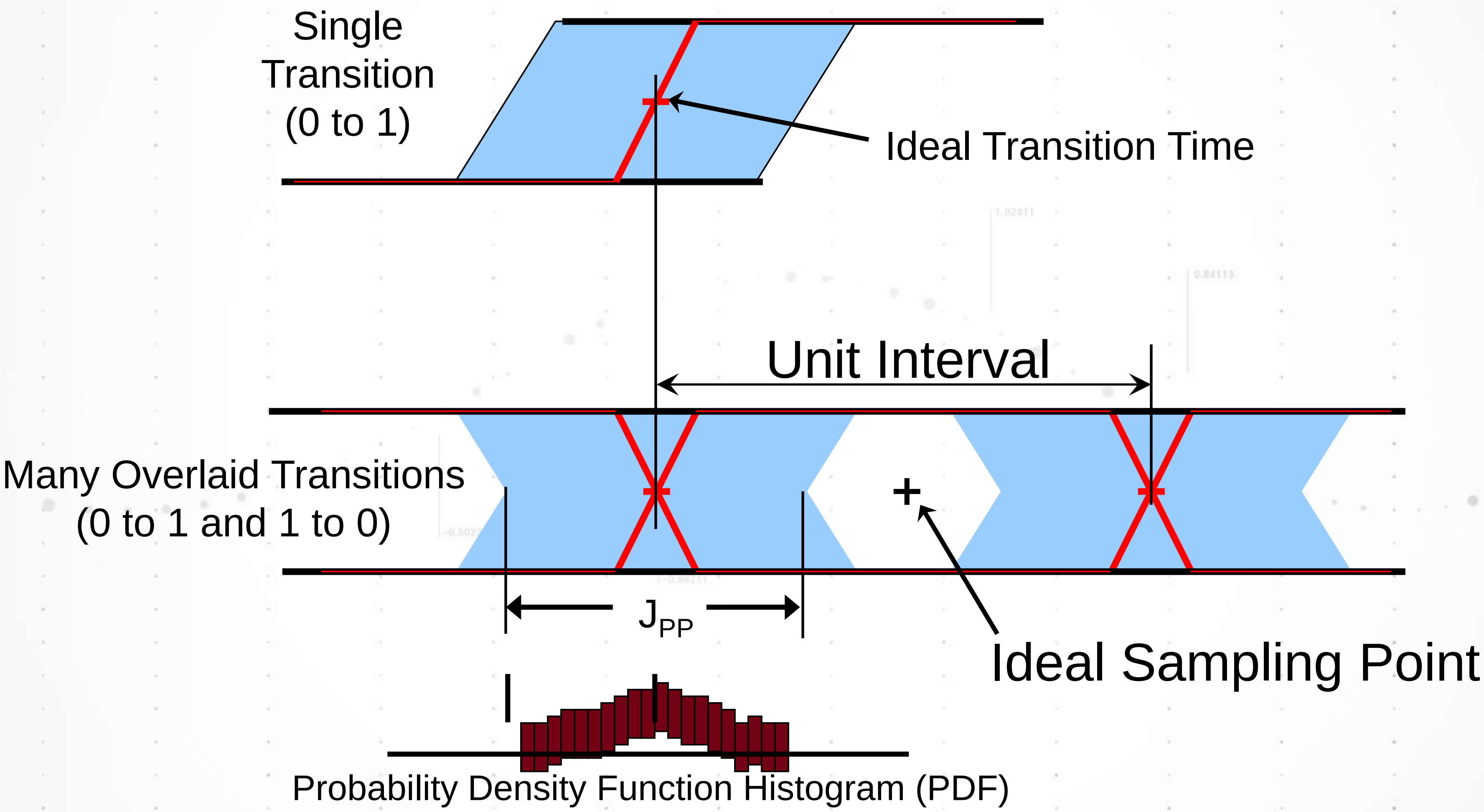
We can see from the eye diagram, jitter effects the transitions of the data stream.

Let's take a closer look at a single transition.



Peak-to-peak jitter = $J_{PP} = \Delta t_{Early\ Pk} + \Delta t_{Late\ Pk}$

Jitter and the Real-Time Eye



It's all about Bit Error Ratio

- Noise and Jitter cause data transmission errors in digital systems
- These errors are characterized by the Bit Error Ratio (BER) of a serial data link
- BER is the primary measure of the *fidelity* of a link

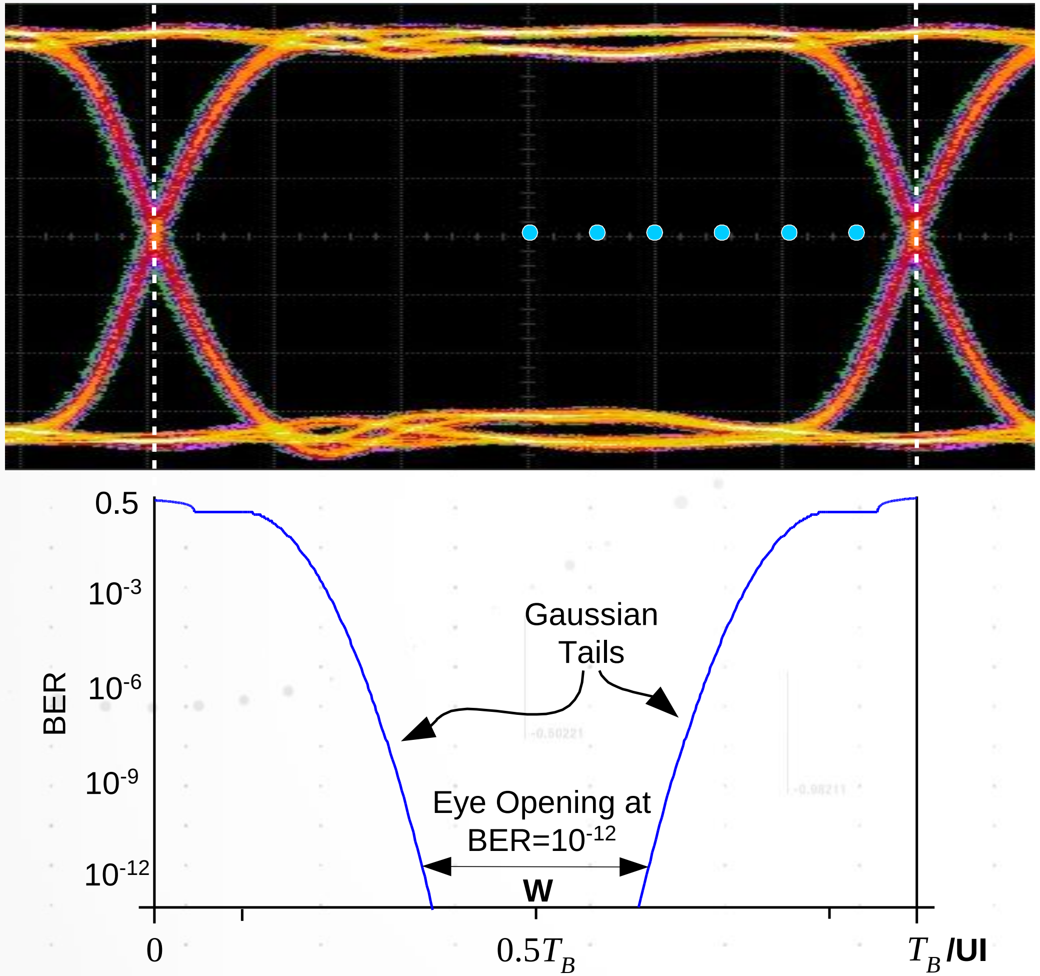
BER = # Transmission Errors / Total # Transitions

When data rates were low, designers were mainly concerned with functionality (1s and 0s)

With rates > 1 Gbps, the analog nature of signals becomes significant

Noise and *jitter* affect system BER and the quality of a data link

Measuring Jitter: Bit Error Ratio (BER) Testing



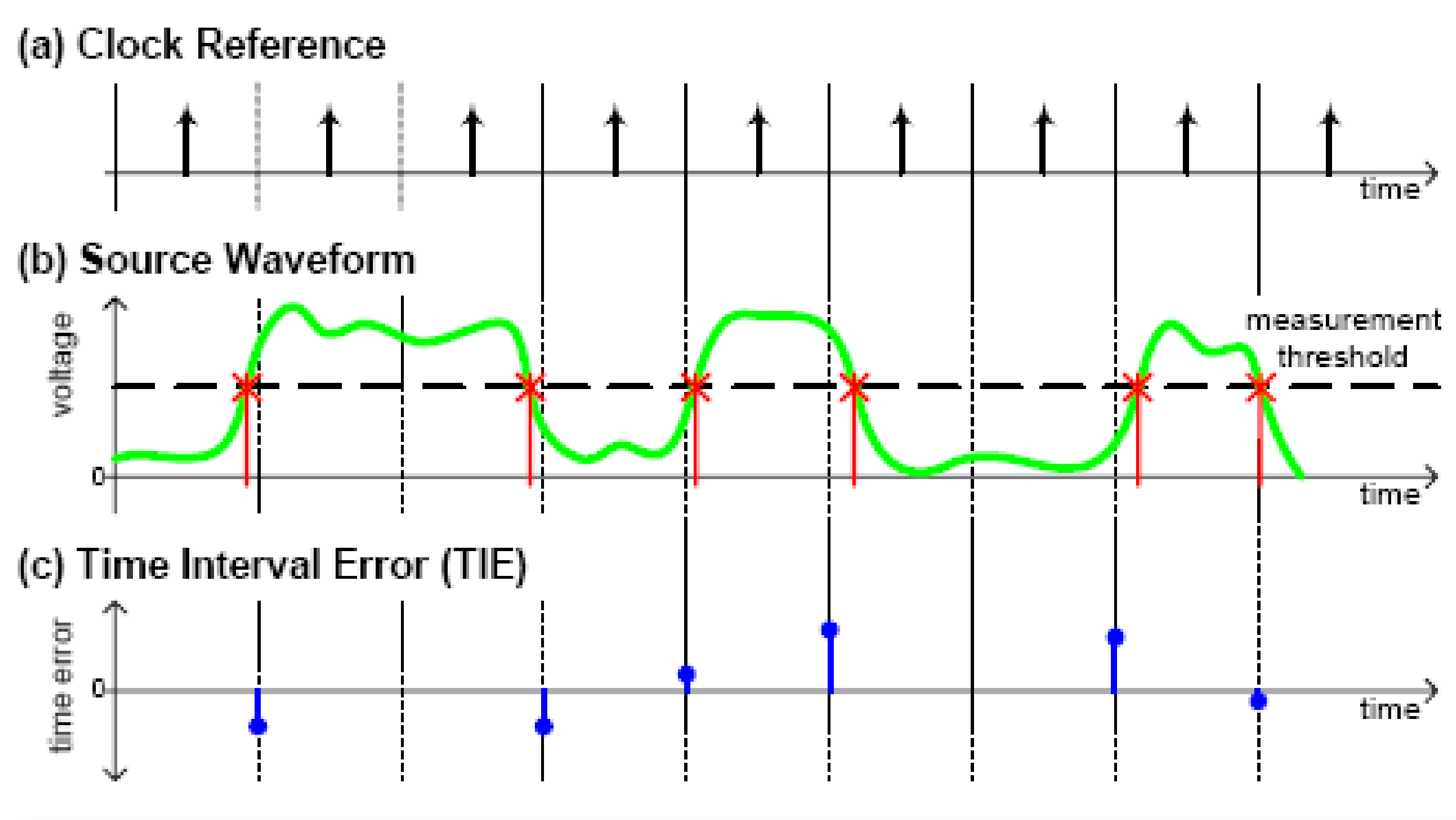
Requires specialized equipment and very slow

- The only way to *directly* measure Total Jitter is with a Bit Error Ratio (BER) test.
- Sample at various points along unit interval, directly measure BER at each point. Plot "bathtub" curve.

TJ(BER) = UI – W

Advanced Jitter Analysis with Real-time Oscilloscopes

JITTER AND TIME INTERVAL ERROR (TIE)



On an oscilloscope we monitor the waveform transitions and note the jitter at each transition point. This is called the Time Interval Error (TIE) record.

Measures total jitter of the *acquisition*. The more transitions you measure, the greater TIE will become.

Waveform transitions deviate from expected transition time

Generate Time Interval Error (TIE) by measuring transitions versus reference clock

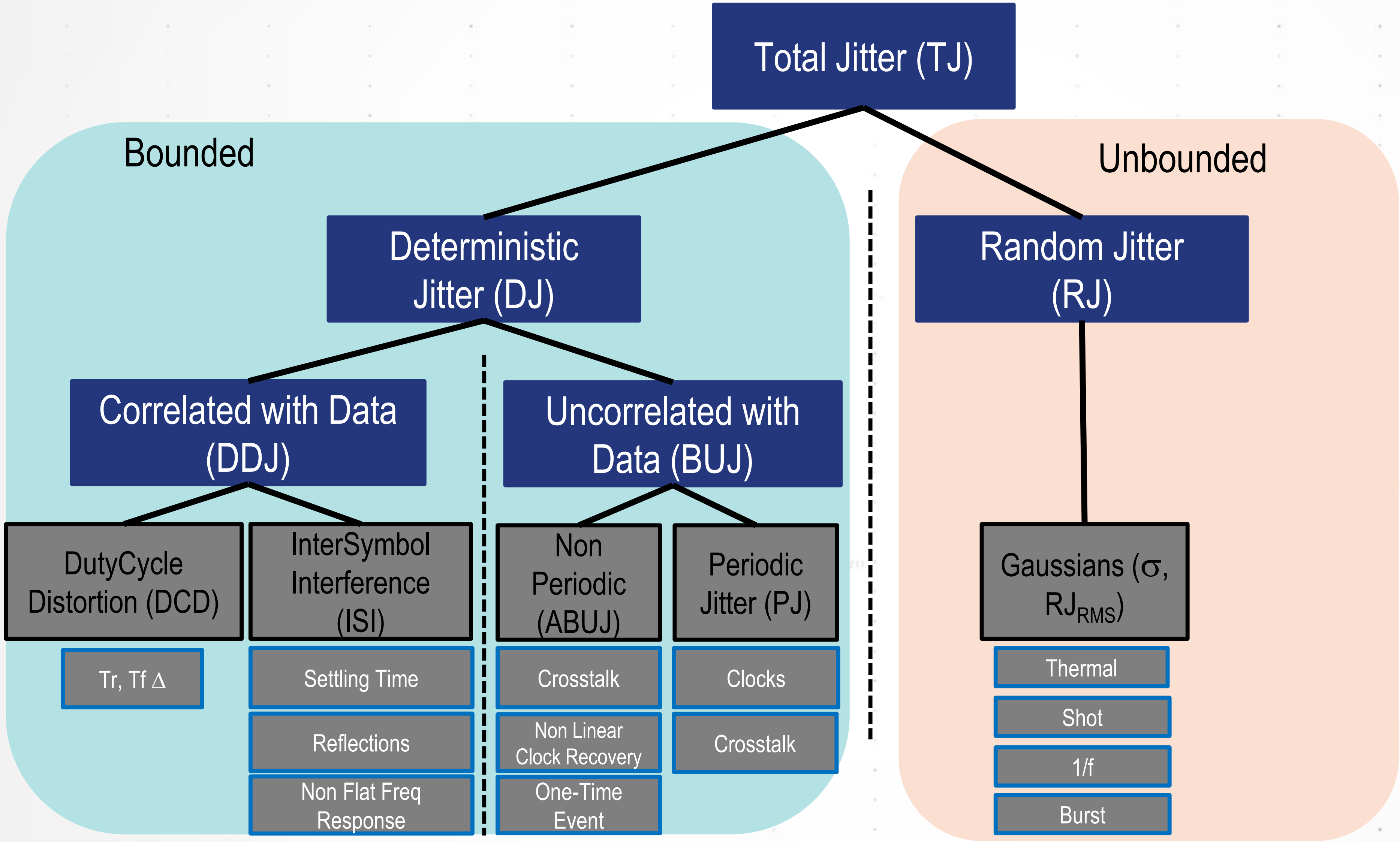
Engineers Never Stop Learning

ADVANCED JITTER ANALYSIS WITH REAL-TIME OSCILLOSCOPES

Agenda

- **Review of Jitter Decomposition**
- Assumptions and Limitations
- Spectral versus Fail Fit Method
- Advanced Jitter Analysis with Crosstalk Removal Tool
- Scope Random Jitter Removal from Jitter Analysis
- Other Tools to consider for Jitter Analysis
- Summary

Jitter Components

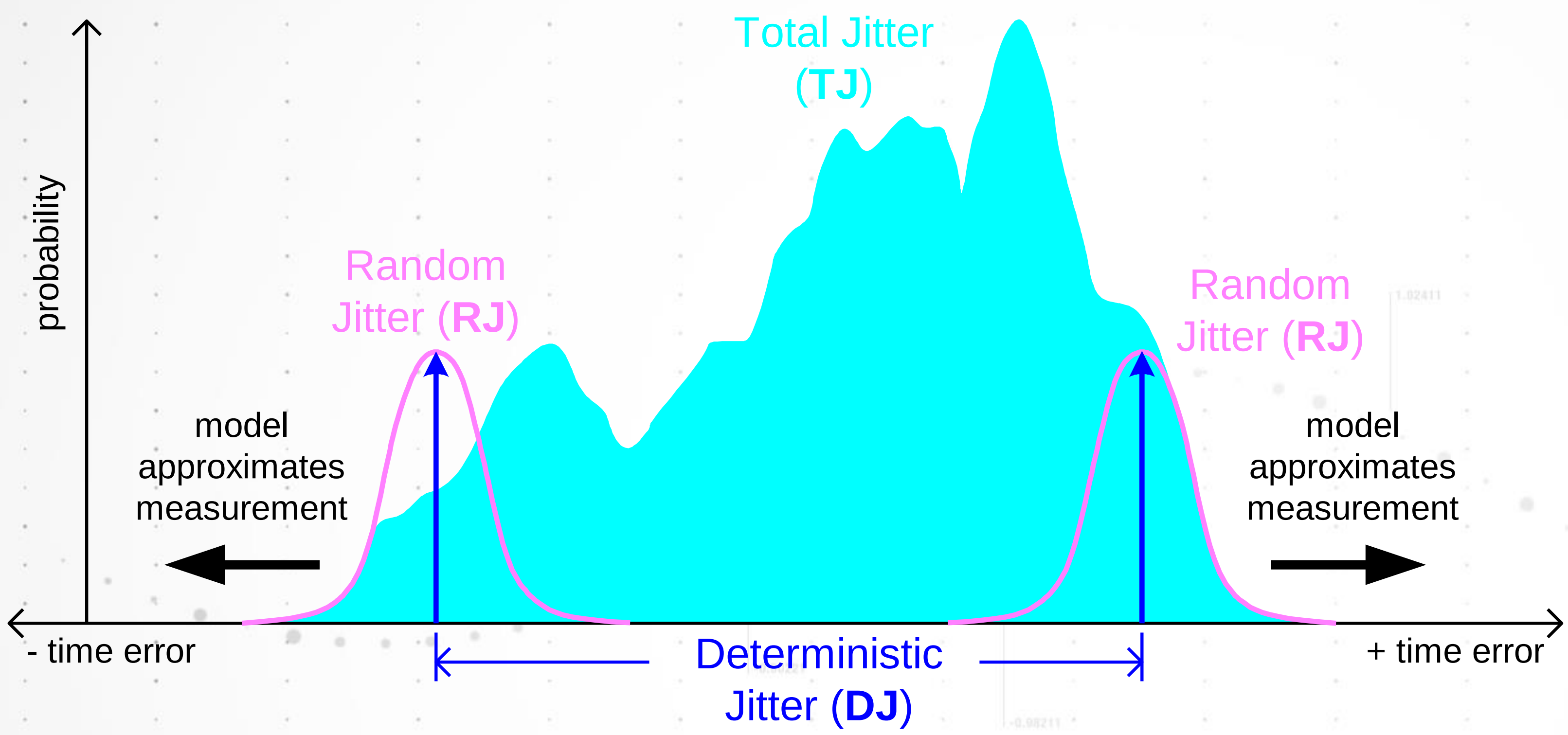


Acronyms

- DDJ : Data Dependent Jitter
- BUJ : Bounded Uncorrelated Jitter

ABUJ : Aperiodic Bounded Uncorrected Jitter

Dual Dirac Model



Key Assumptions

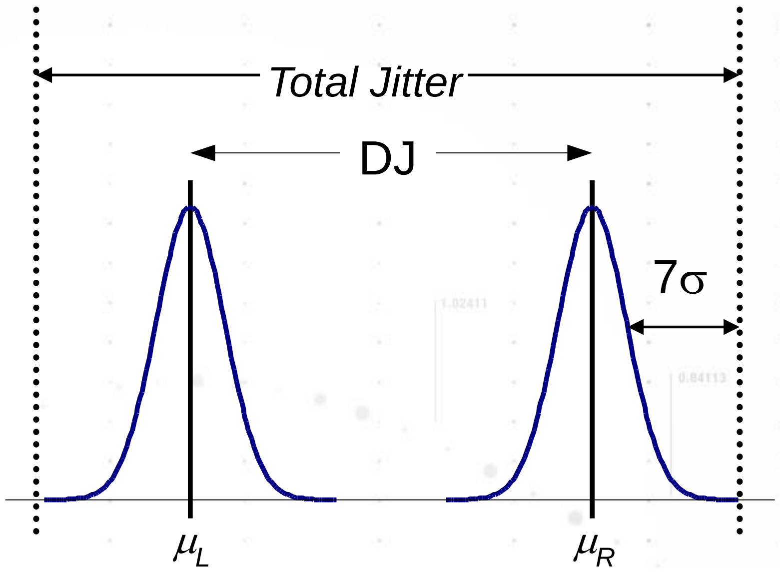
- Total Jitter at a BER can be predicted by a simple model using ‘Deterministic’ and ‘Random’ components.
- Gaussian distribution of random noise
- Stationarity of jitter distribution

Dual Dirac Model – Total Jitter

BER	n
$1x10^{-8}$	5.73
$1x10^{-10}$	6.47
$1x10^{-12}$	7.13
$1x10^{-14}$	7.74

$$n = \frac{RJ_{pp} / 2}{\sigma}$$

$$(\sigma = RJ_{rms})$$



TJ can be measured directly using a BER test

OR

TJ can be calculated using RJ and DJ in the Dual Dirac model

TJ(BER) = UI – W

TJ(BER) = 2n*RJrms + DJ

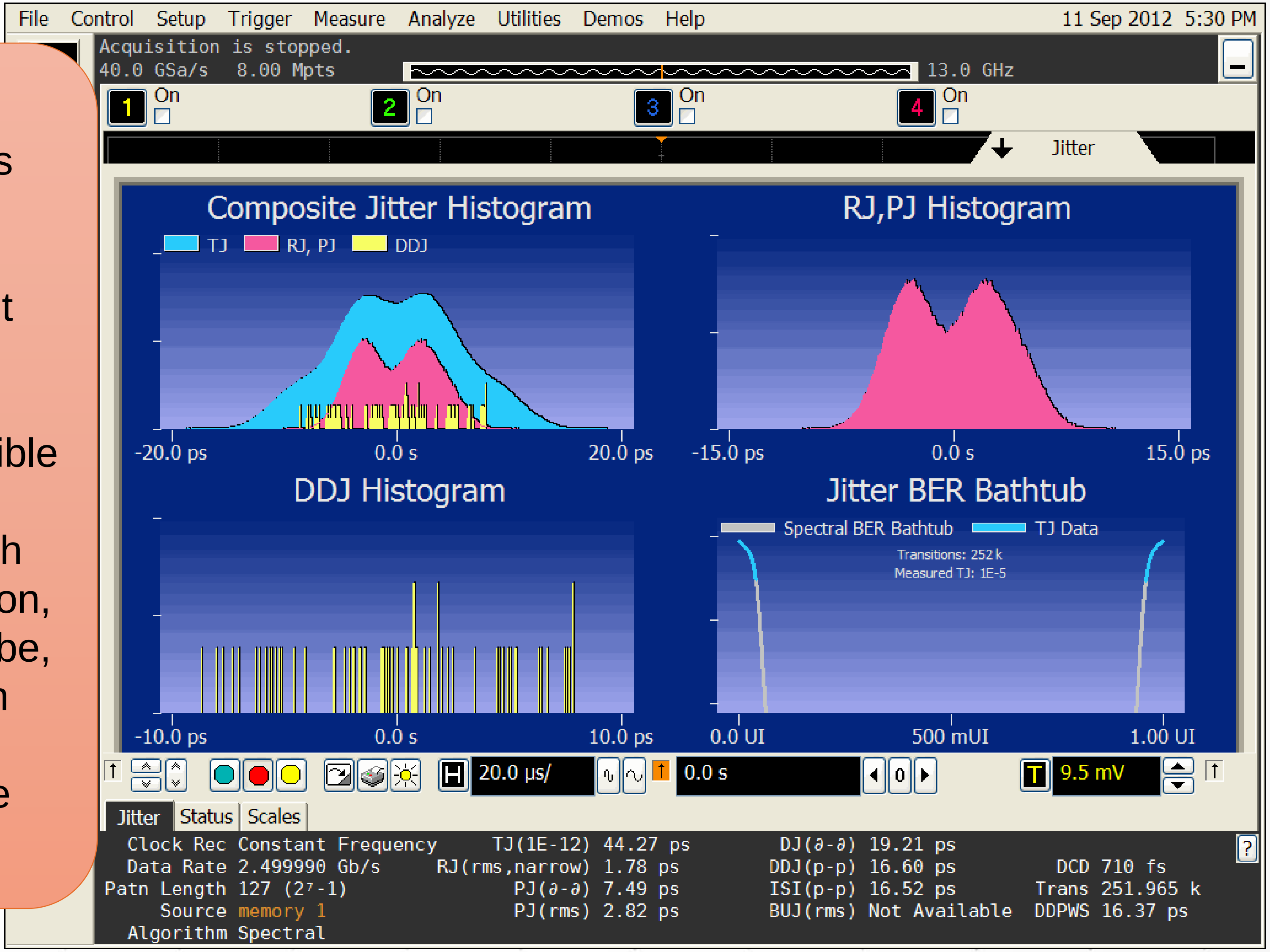
EZJIT Jitter Analysis Suite

For Infiniium Real-Time Oscilloscopes

	Jitter Trend, Histogram, and Timing Measurements	Advanced Jitter Decomposition: RJ/PJ/DDJ/DCD/ISI/ABUJ	Vertical Noise Analysis and Decomposition
EZJIT	✓		
EZJIT Plus	✓	✓	
EZJIT Complete	✓	✓	✓

EZJIT Plus – Advanced Jitter Decomposition

- Easy to use wizard guides you through jitter measurement setup
- Fully compatible with Infiniium Software such as Equalization, PrecisionProbe, and InfiniiSim
- Customizable jitter views



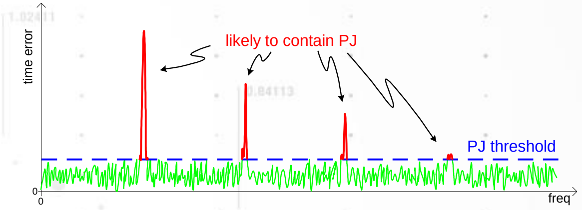
Agenda

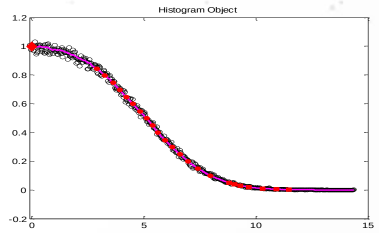
- Review of Jitter Decomposition
- Assumptions and Limitations
- Spectral vs. Tail Fit Method
- Advanced Jitter Analysis with Crosstalk Removal Tool
- Scope Random Jitter Removal from Jitter Analysis
- Other Tools to Consider for Jitter Analysis
- Summary

Spectral vs. Tail Fit Jitter Decomposition

Random Jitter (RJ) Extraction Methods

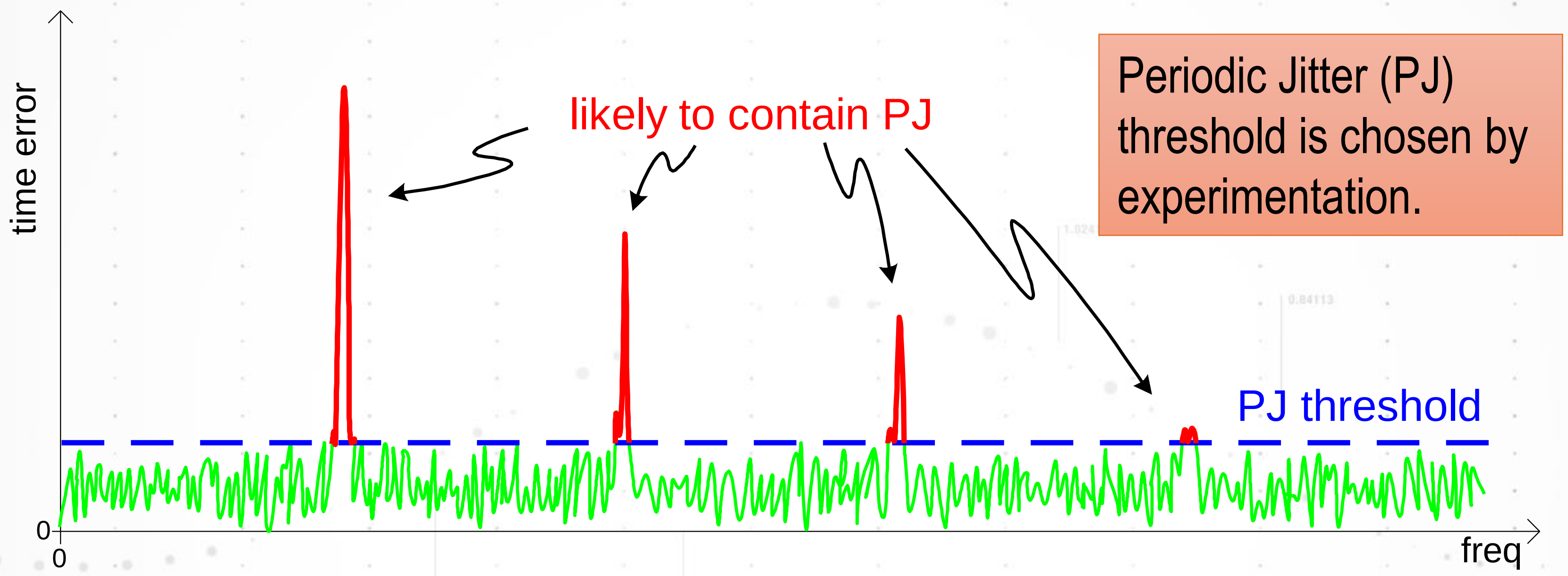
RJ Extraction Methods	Rationale
Spectral	• Speed/Consistency to Past Measurements • Accuracy in low Crosstalk or Aperiodic Bounded Uncorrelated Jitter (ABUJ) conditions
Tail Fit	• General Purpose • Accuracy in high Crosstalk or ABUJ conditions



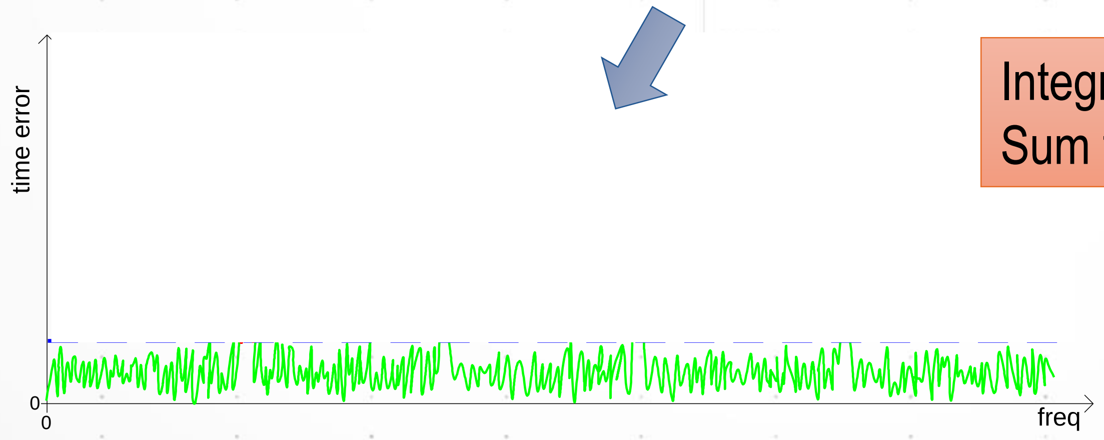


Spectral Method – PJ Threshold

Measurement Details



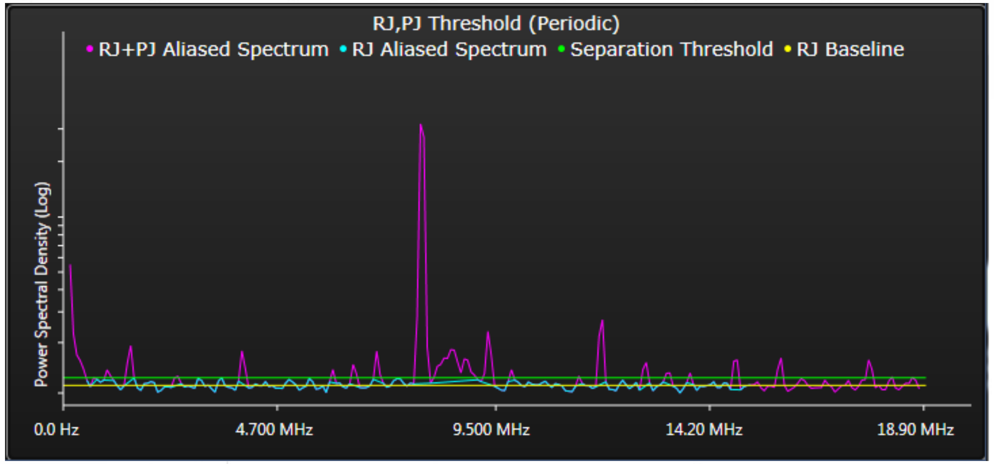
Periodic Jitter (PJ) threshold is chosen by experimentation.



Integrate PSD to derive RJ_{RMS}
Sum the PJ components for PJ_{RMS}

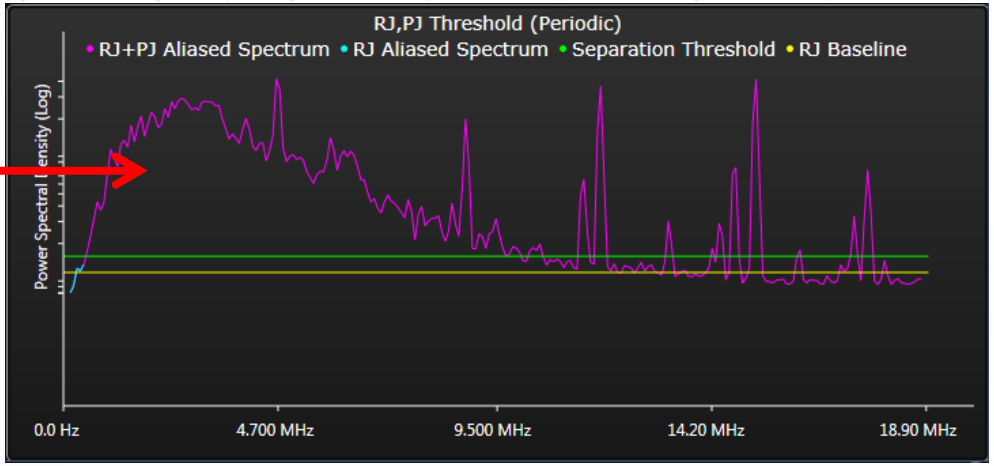
Spectral Method – PJ Threshold

Handling of Different RJ, PJ Spectral Content



Separation occurs as described…

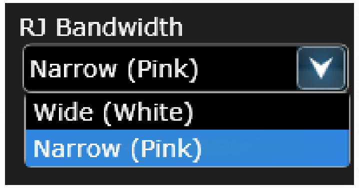
Is it RJ or PJ?



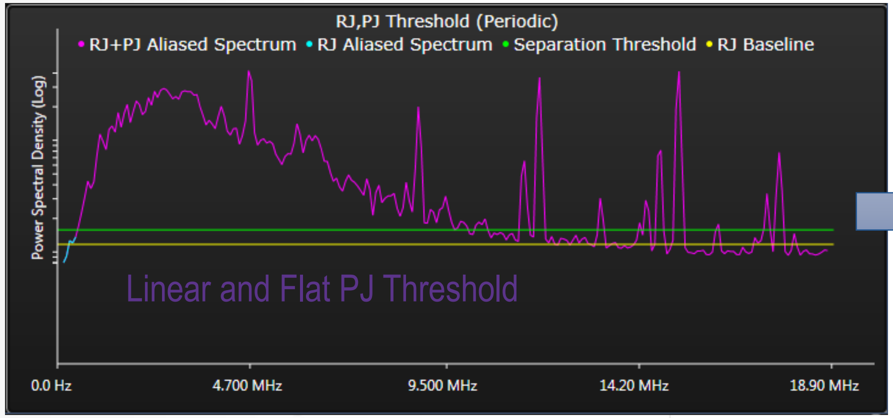
What do you do in this case?

Spectral Method – PJ Threshold

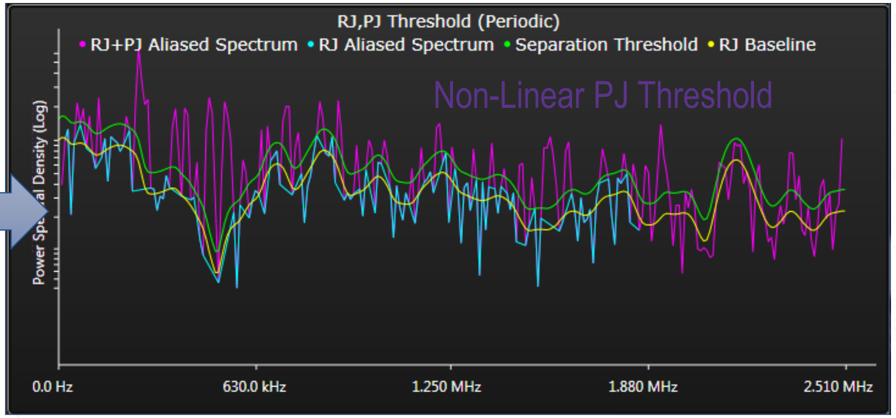
Non-linear Period Jitter (PJ) threshold can help



Wide RJ Bandwidth Analysis



Narrow RJ Bandwidth Analysis



RJ_{RMS} = 1.06ps
PJ_{DD} = 93.17ps

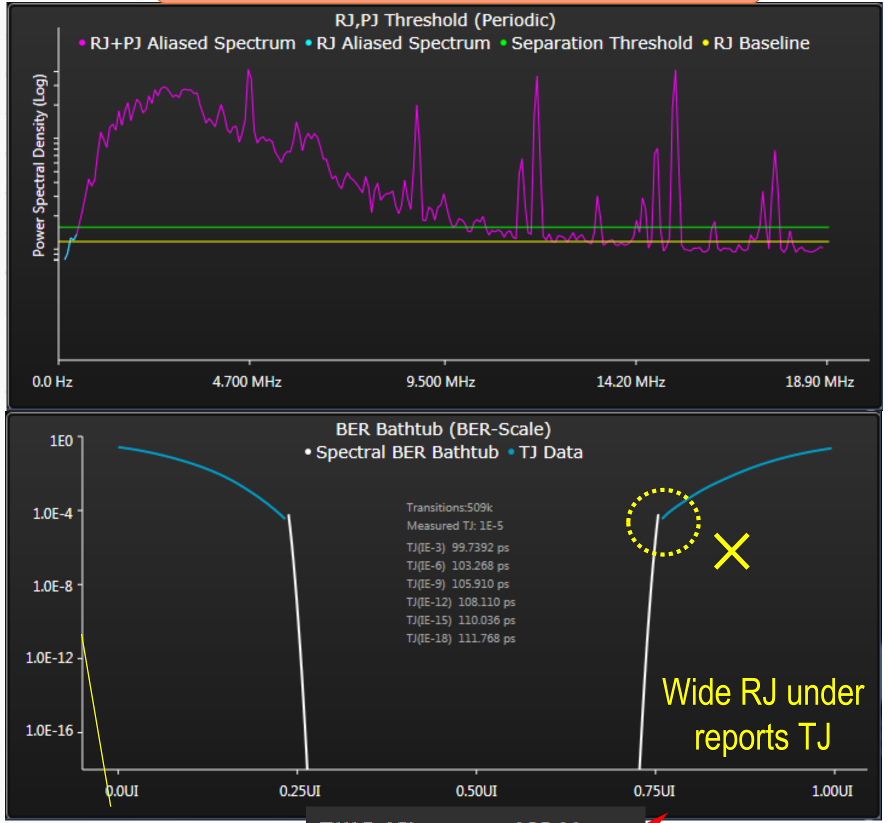
RJ_{RMS} = 9.66ps
PJ_{DD} = 27.18ps

Which PJ Threshold or RJ bandwidth analysis do you choose?

KEYSIGHT TECHNOLOGIES

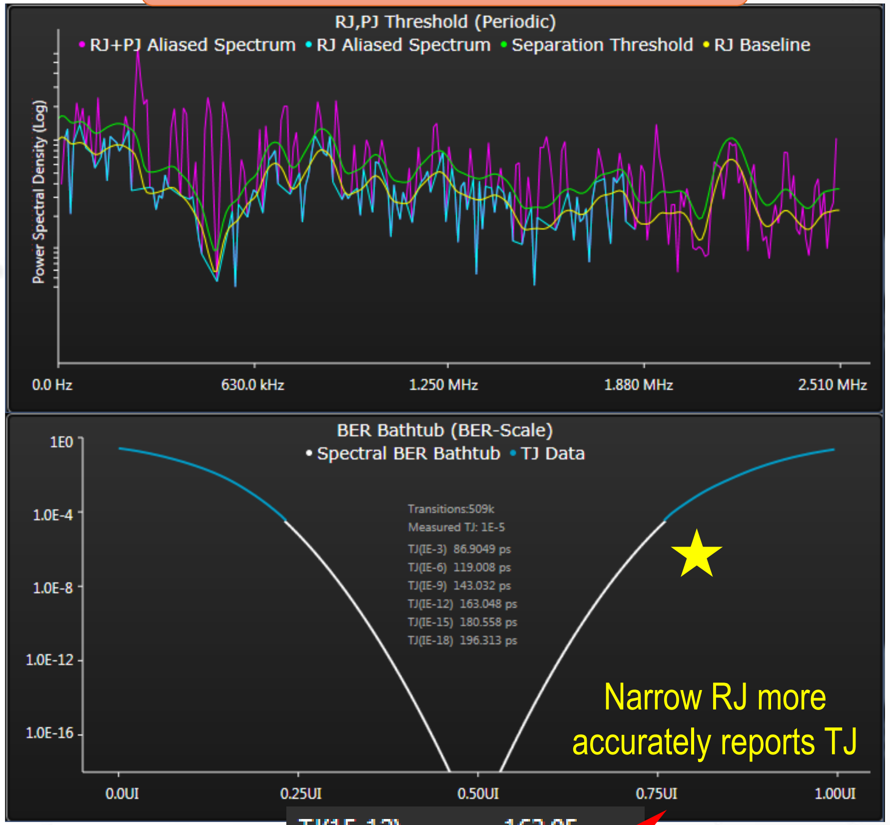
Spectral Method – Wide vs. Narrow

Wide RJ Bandwidth



TJ(1E-12)	108.11 ps
RJrms,wide	1.06 ps
DJδδ	93.17 ps

Narrow RJ Bandwidth

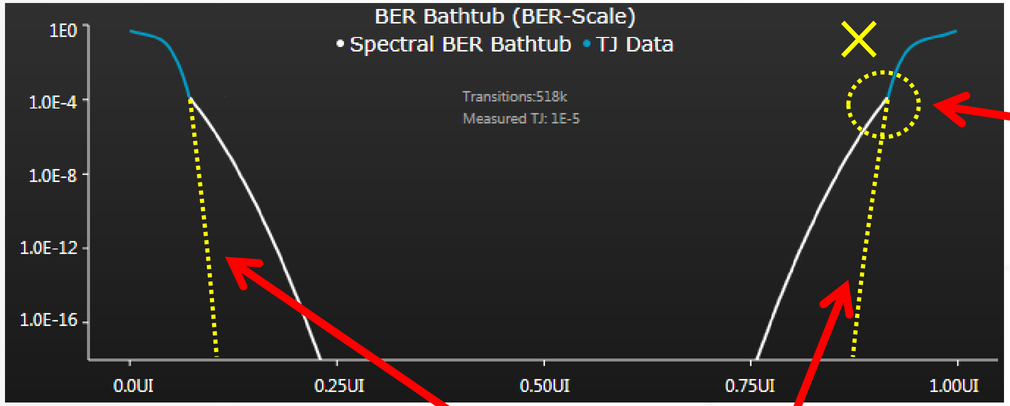


TJ(1E-12)	163.05 ps
RJrms,narrow	9.66 ps
DJδδ	27.18 ps

Smoothness of slope continuity between measured and extrapolated result on the bathtub plot indicates the better PJ threshold (RJ bandwidth) method.

Spectral Method with Presence of Crosstalk or ABUJ

(ABUJ = Aperiodic Bounded Uncorrelated Jitter)



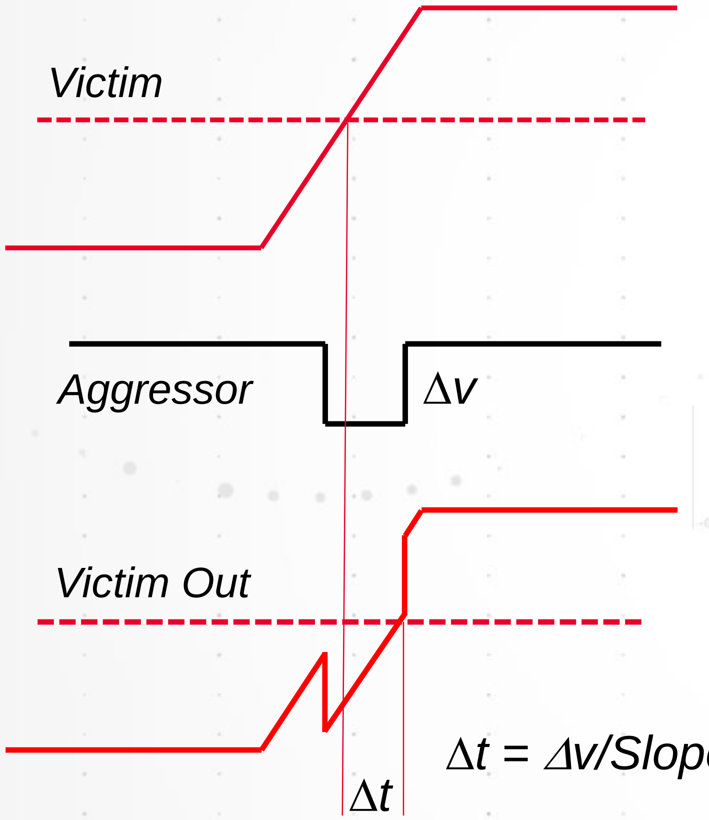
Something is wrong here...

Using the slope continuity concept we expect the extrapolated curve to look like this.

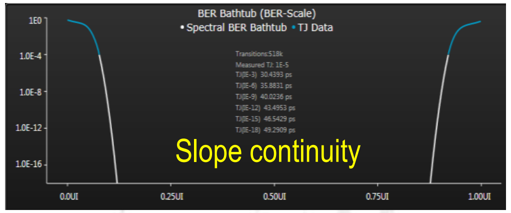
The RJ/PJ spectral extraction does not deal with Crosstalk or ABUJ well. The RJ is overestimated severely.

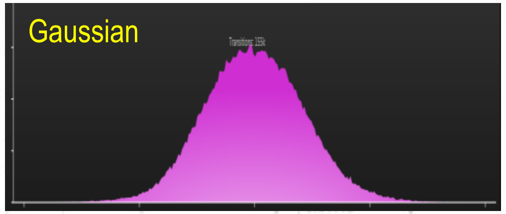
ABUJ: Crosstalk or Ground Bounce

Amplitude interference uncorrelated with data and not periodic in nature.

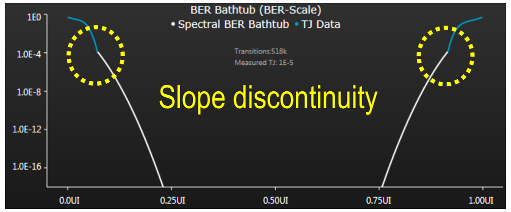


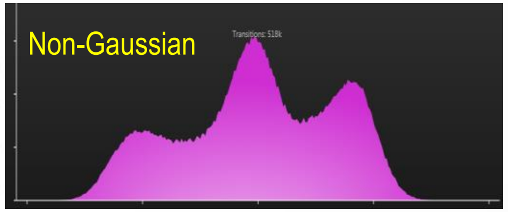
$\Delta t = \Delta v / Slope_{victim}$





No crosstalk
Bathtub and RJ,PJ Histogram

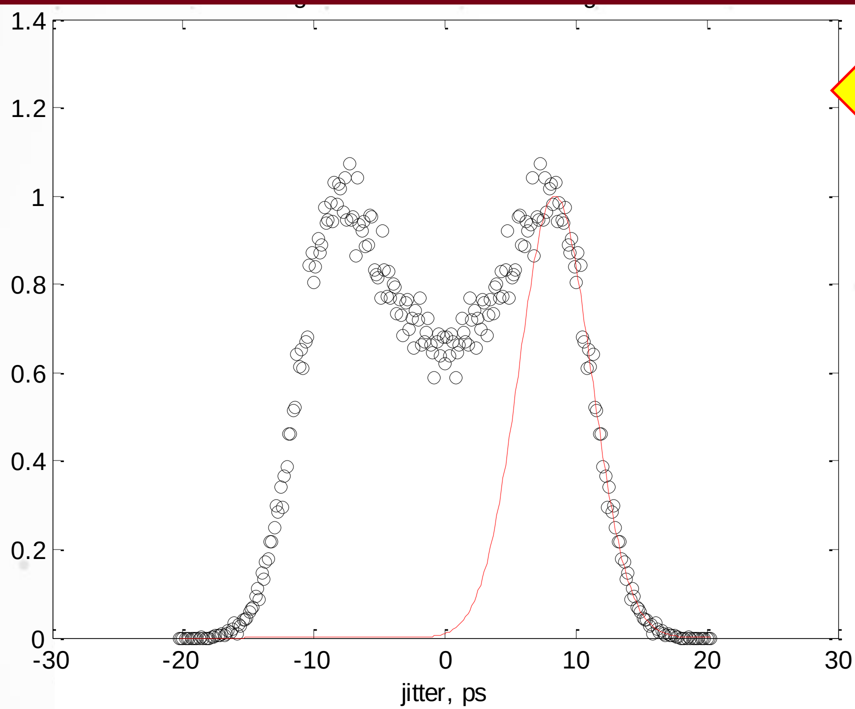




With crosstalk
Bathtub and RJ,PJ Histogram

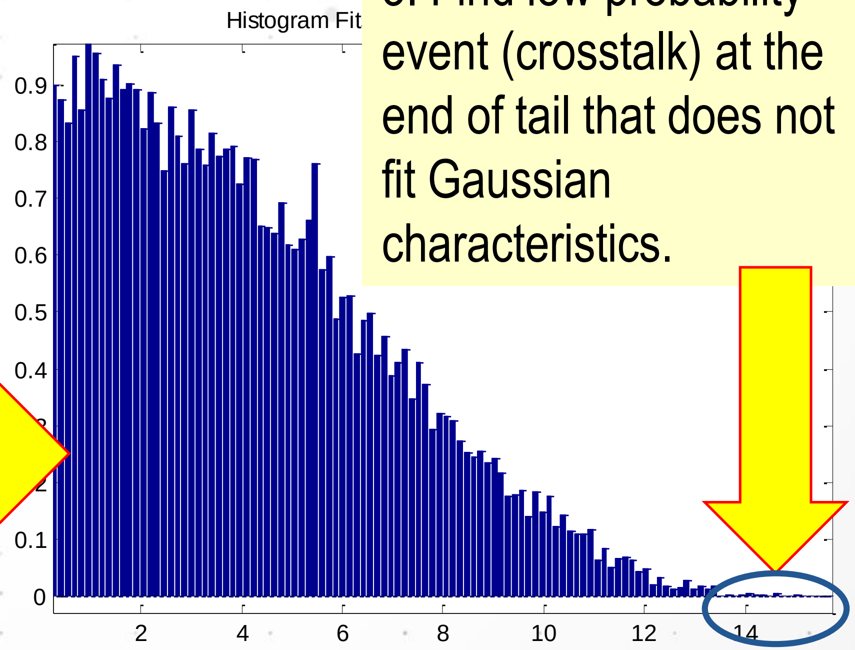
Tail Fit Method – Gaussian Extraction

MEASUREMENT DETAIL



1. Fit a Gaussian characteristic to the right and left extremes of the RJ/PJ histogram distribution.

2. Actual data is never smooth

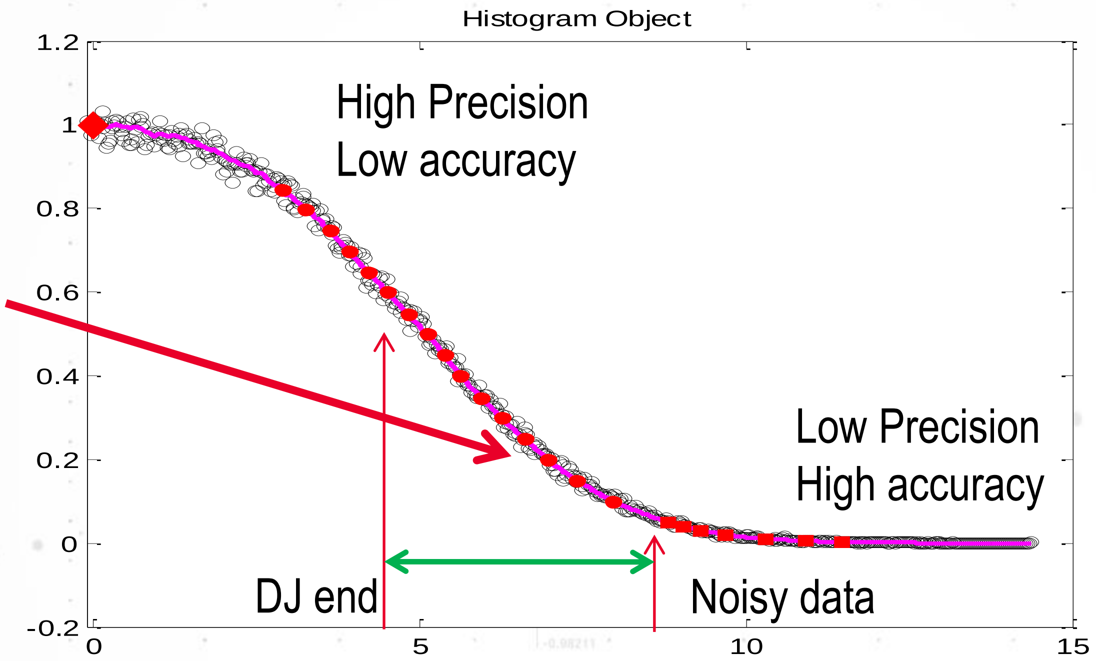


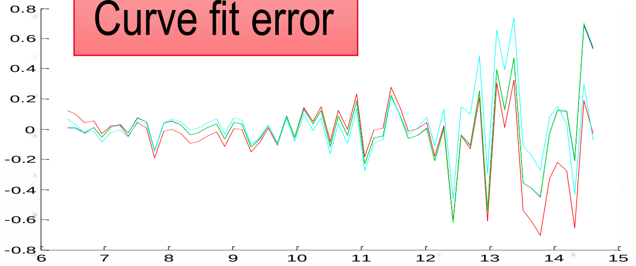
3. Find low probability event (crosstalk) at the end of tail that does not fit Gaussian characteristics.

What Makes Tail Fit Hard

Measurement Detail

Fit Window

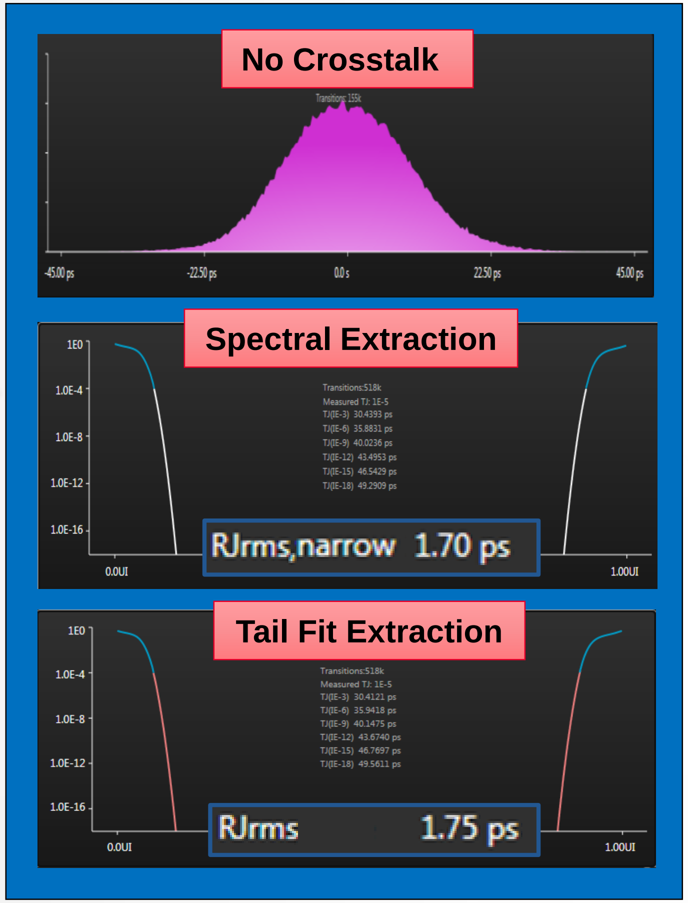


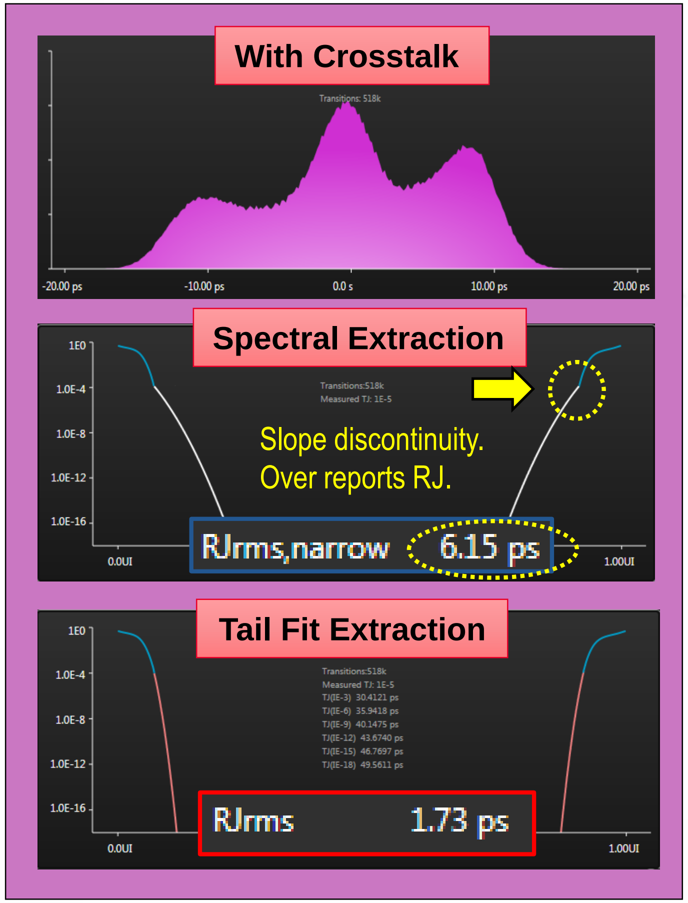


Hard to detect Crosstalk events out in the tail. Might take longer time for Tail Fit results to converge.

RJ Extraction with Presence of Crosstalk (ABUJ)

SPECTRAL VS. TAIL FIT EXTRACTION





Analyze the bathtub plot with both RJ extraction modes to explore the presence of crosstalk or ground bounce.

Agenda

- Review of Jitter Decomposition
- Assumptions and Limitations
- Spectral vs. Tail Fit Method
- Advanced Jitter Analysis with Crosstalk Removal Tool
- Scope Random Jitter Removal from Jitter Analysis
- Other Tools to Consider for Jitter Analysis
- Summary

Jitter Analysis with Crosstalk Removal Tool

Crosstalk Identification

- Which signals are coupling onto your victim?

Crosstalk Quantification

- How much error and jitter do each aggressor add to your victim?

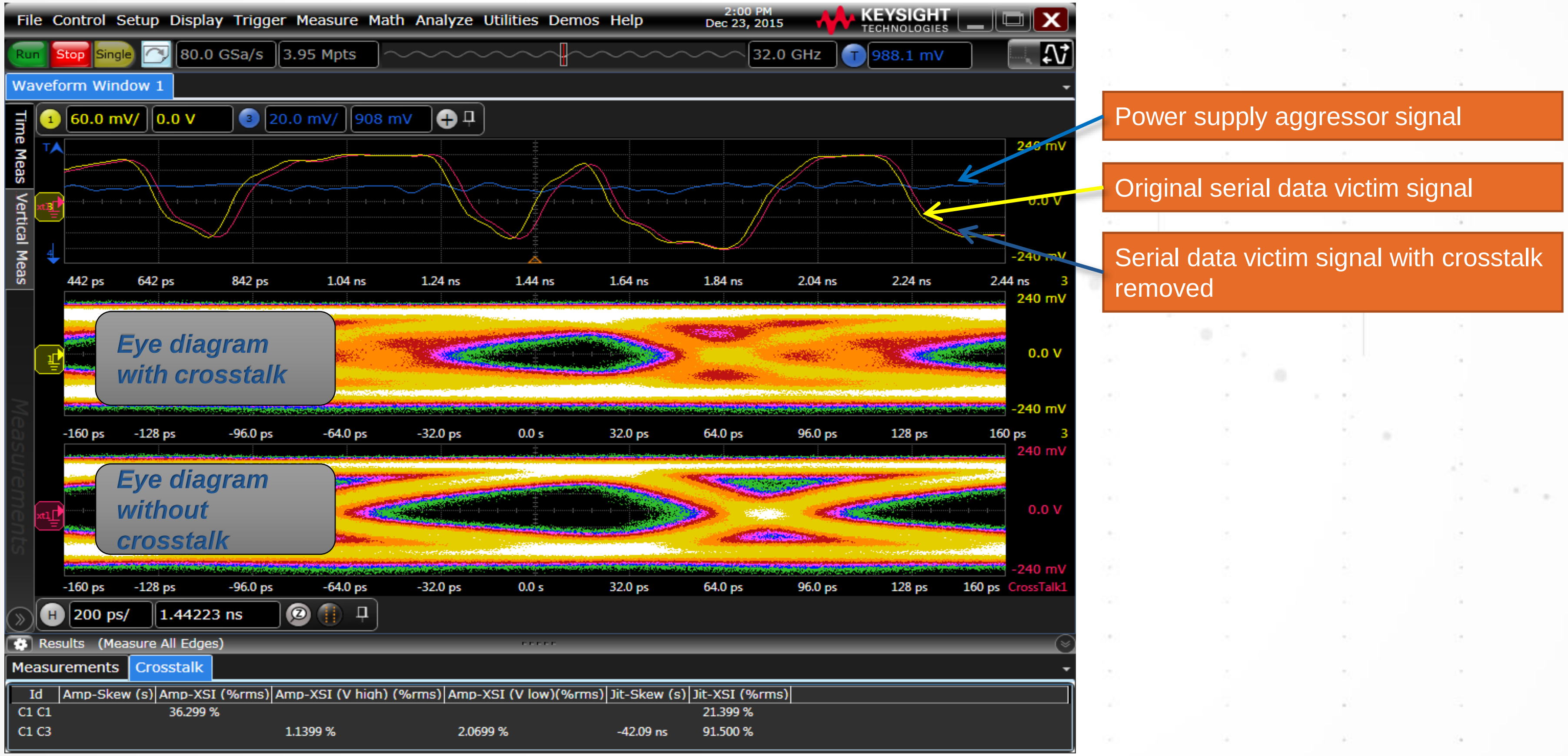
Crosstalk Removal for Jitter Analysis

- What would your signal look without crosstalk present on victim?
- How much jitter margin can be recovered without crosstalk?
- If the signal was failing the jitter spec, can it pass without crosstalk?

Assist in making important design decisions:

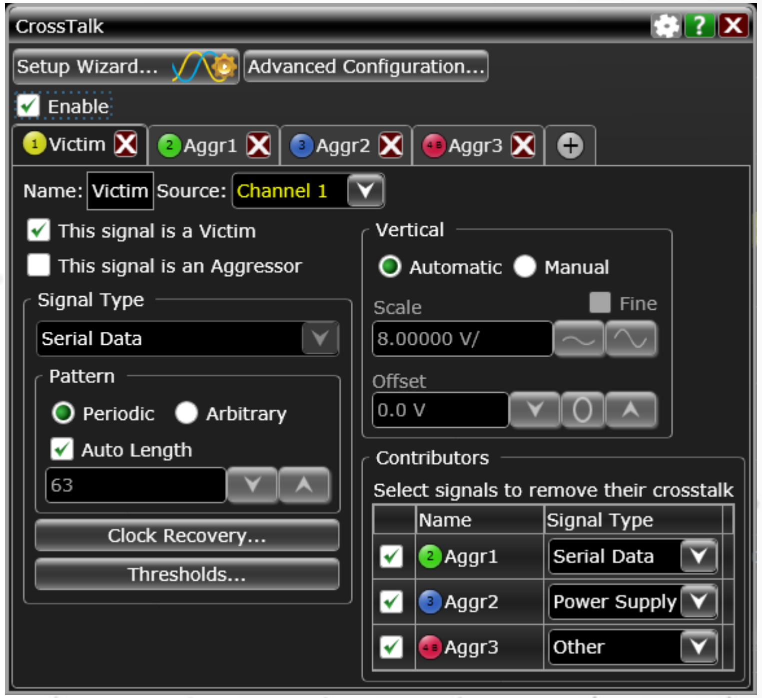
- ***Is it worth reducing crosstalk impact in design?***
- ***Where to improve?***

Remove Crosstalk from Victim Signal



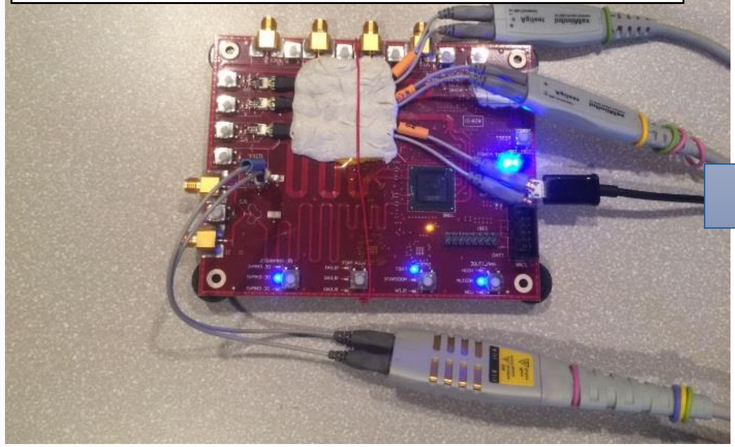
Features of the N8833A Crosstalk Analysis Application

1. Analyze up to four signals (victim or aggressor) at once.
2. Remove Near-End Crosstalk (NEXT), Far-End Crosstalk (FEXT) and Power Supply Crosstalk from Victim signal.
3. Plot waveform without crosstalk on the scope which can be:
   - Used for eye diagram, ***jitter decomposition***, de-embedding, equalization and mask test
   - Saved as a waveform file



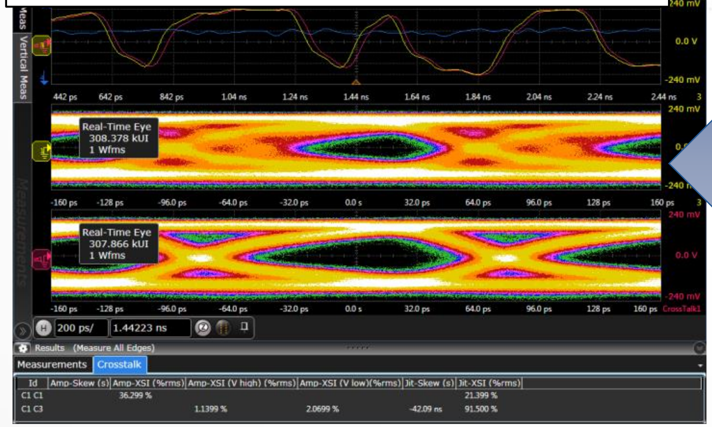
Crosstalk Analysis Setup

1. Probe up to 4 signals (Aggressors or victims). No simulation models or inputs are required.



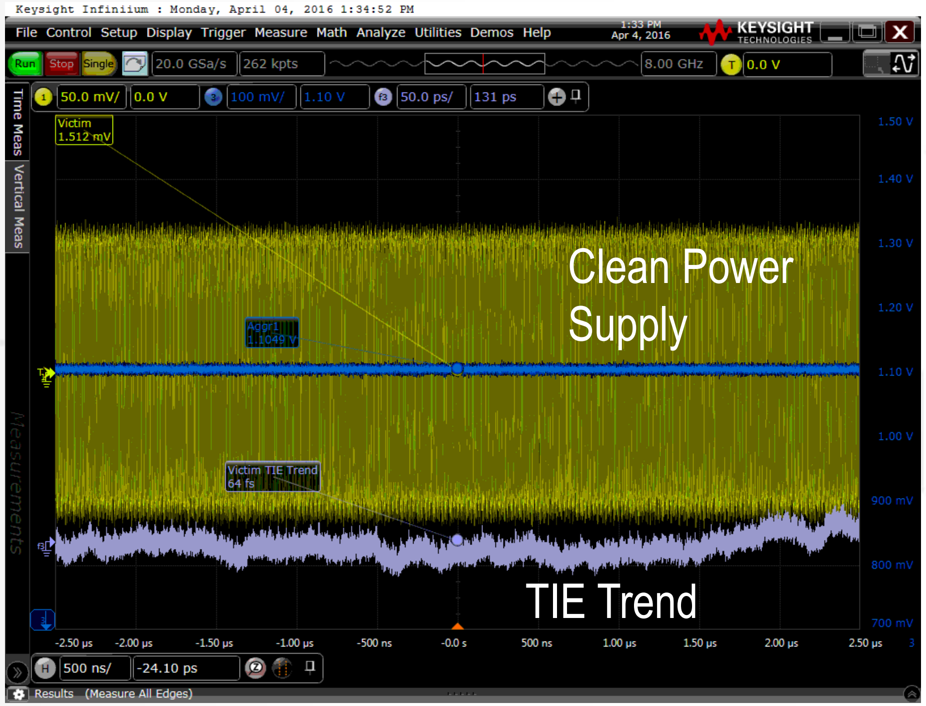
2. Setup the victim signal.

4. The app reports the amount of crosstalk from each aggressors and return a waveform without crosstalk for analysis.

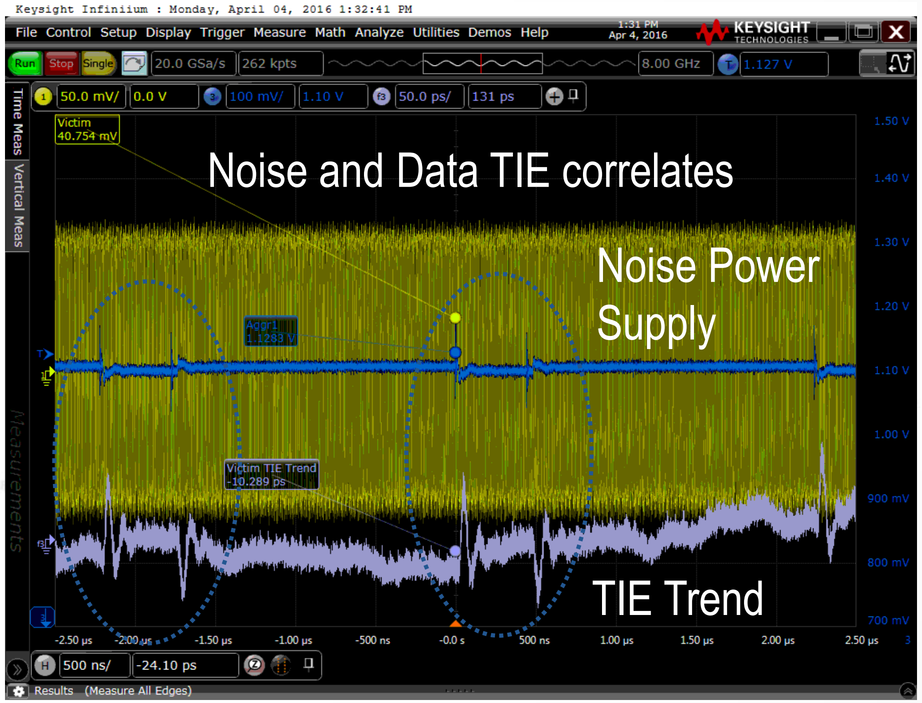


Power Supply Crosstalk on Victim

No Power Supply Aggressor

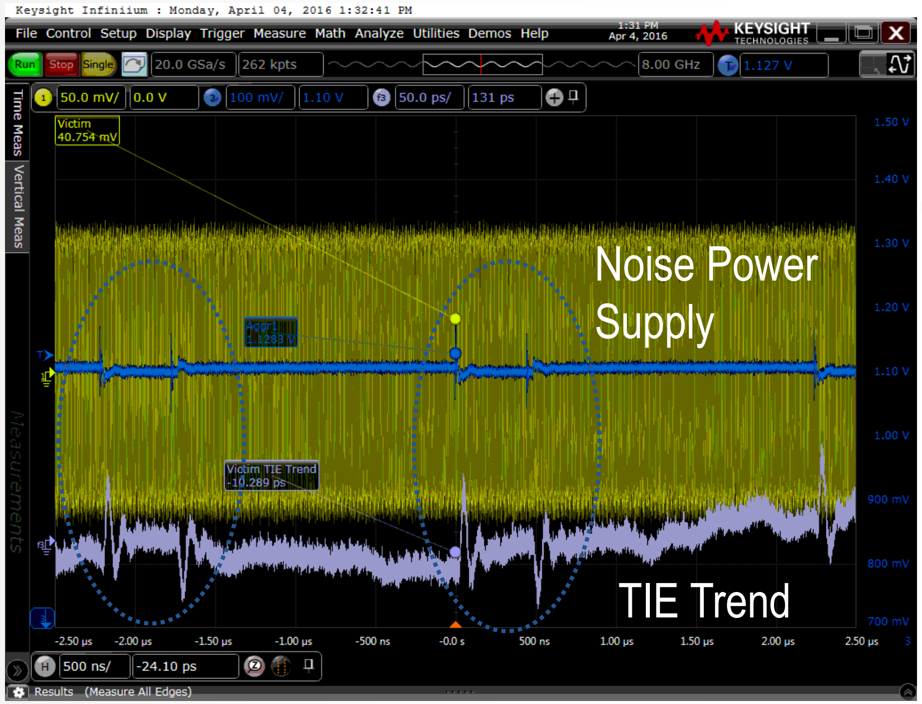


With Power Supply Aggressor on the Transmitter PLL

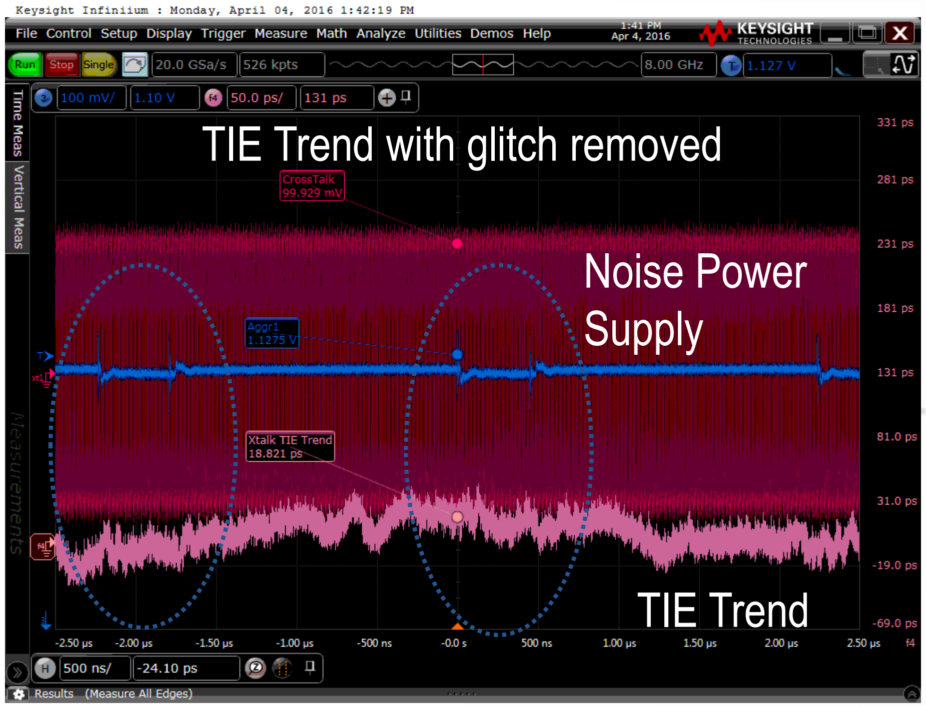


Removing Power Supply Crosstalk from Victim

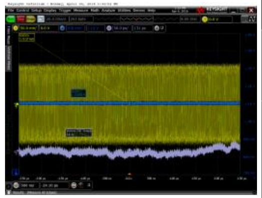
With Power Supply Crosstalk on the Transmitter PLL



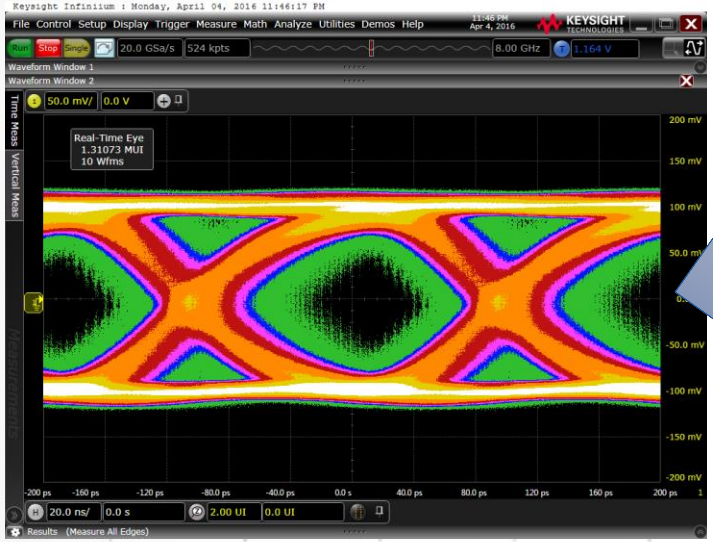
Power Supply Crosstalk Removed with Improvement on Data TIE Trend

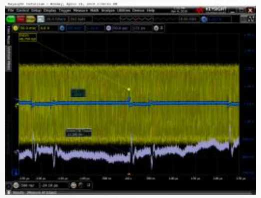


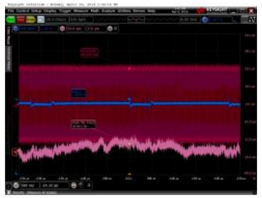
Removing Power Supply Crosstalk from Victim



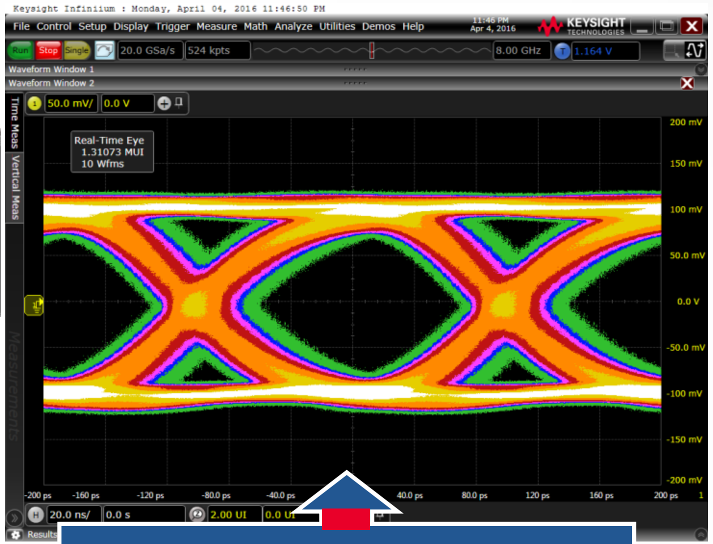
Measured Victim with Power Supply Crosstalk



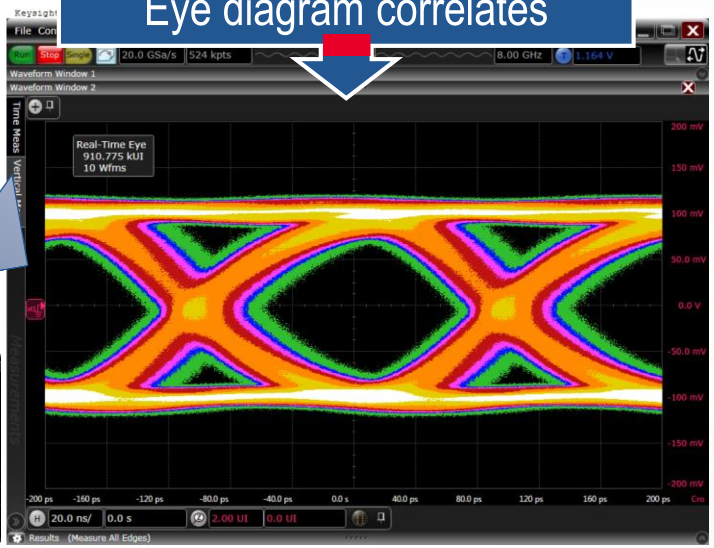




Measured Victim Without Crosstalk



Eye diagram correlates



Victim after Power Supply Crosstalk removed

Jitter Improvement Without Power Supply Crosstalk

Compare jitter results before and after crosstalk removal.

TJ = 158ps
PJdd = 58ps
DJdd = 68ps

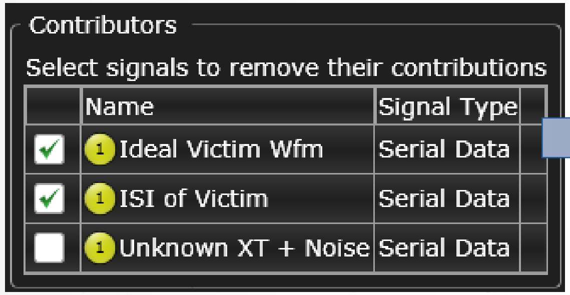
TJ = 124ps
PJdd = 27ps
DJdd = 33ps

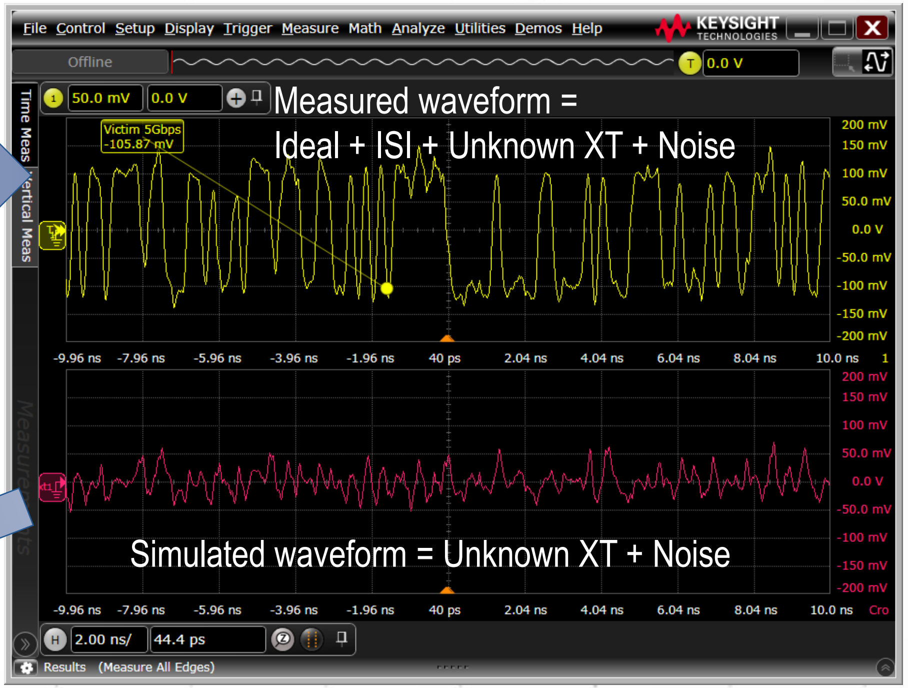
An Improvement of 20% to Total Jitter without Crosstalk.

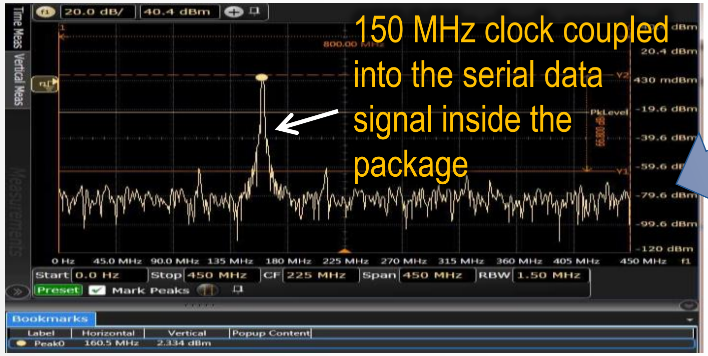
Analyze Crosstalk & Noise that Contributes to Jitter

- The crosstalk application can remove the ideal, ISI and return "Unknown Crosstalk + Noise" (residual) content.
- Perform further analysis on this residual waveform with measurements such as FFT, markers, etc. to root cause the source of aggressor.

Remove: Ideal + ISI of Victim
Show: Only "Unknown Crosstalk + Noise"







FFT on "Unknown Crosstalk + Noise"

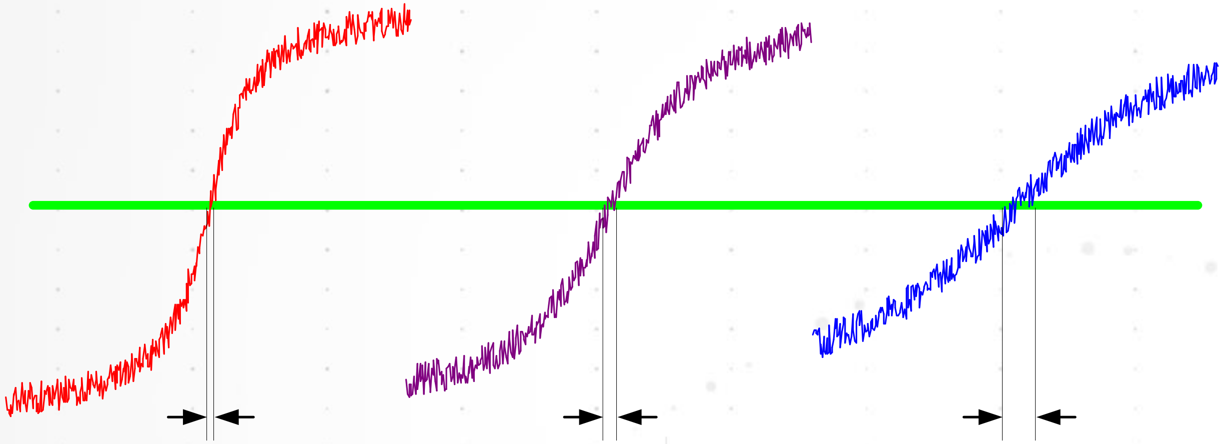
37

Agenda

- Review of Jitter Decomposition
- Assumptions and Limitations
- Spectral vs. Tail Fit Method
- Advanced Jitter Analysis with Crosstalk Removal Tool
- Scope Random Jitter Removal from Jitter Analysis
- Other Tools to Consider for Jitter Analysis
- Summary

Influence of Scope Noise to Jitter Performance

Random jitter will vary with slew rates.



TIE:

$$\sqrt{\left(\frac{Noise}{SlewRate}\right)^2 + SampleClockJitter^2} \quad \text{sec rms}$$

Periodic Jitter:

$$\sqrt{2}\cdot\sqrt{\left(\frac{Noise}{SlewRate}\right)^2 + SampleClockJitter^2} \quad \text{sec rms}$$

Cycle-Cycle:

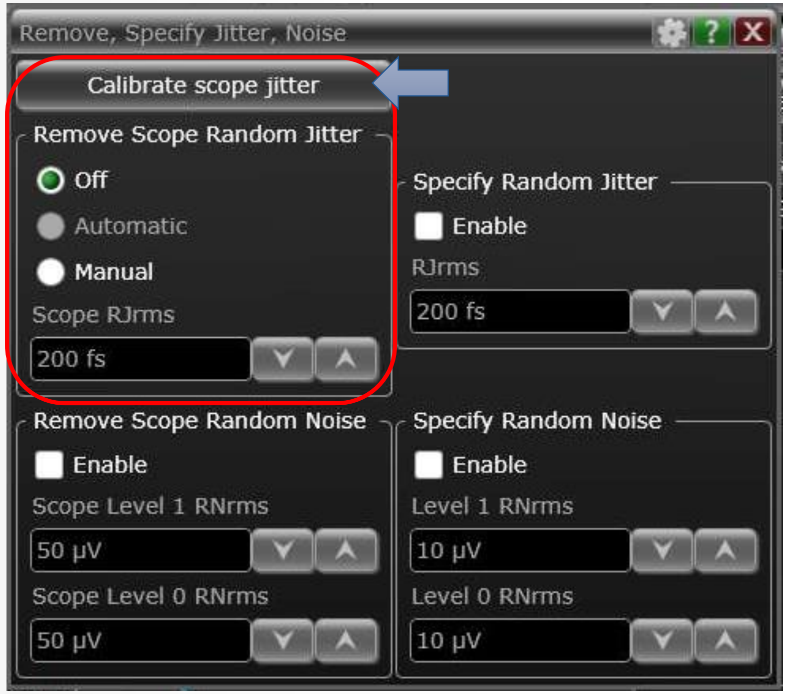
$$\sqrt{3}\cdot\sqrt{\left(\frac{Noise}{SlewRate}\right)^2 + SampleClockJitter^2} \quad \text{sec rms}$$

1. Every scope has intrinsic vertical noise floor. This vertical noise can translate into horizontal jitter.
2. As signal slew rate decreases, vertical noise increases the random jitter.
3. Measured random jitter is a function of signal slew rate, scope noise and scope sample clock jitter.

KEYSIGHT TECHNOLOGIES

Scope Random Jitter Removal

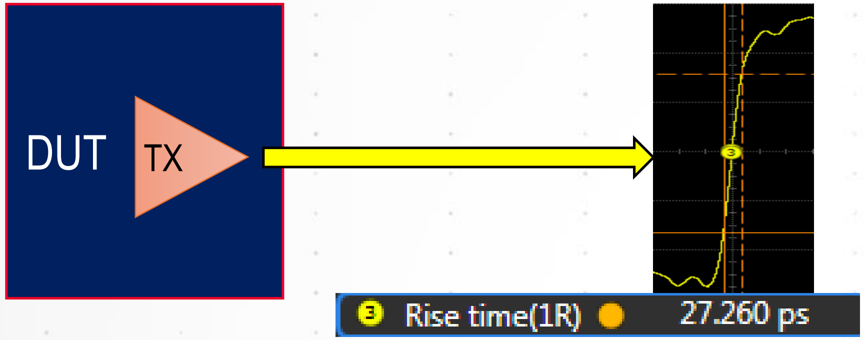
Calibrate and remove scope random jitter contribution

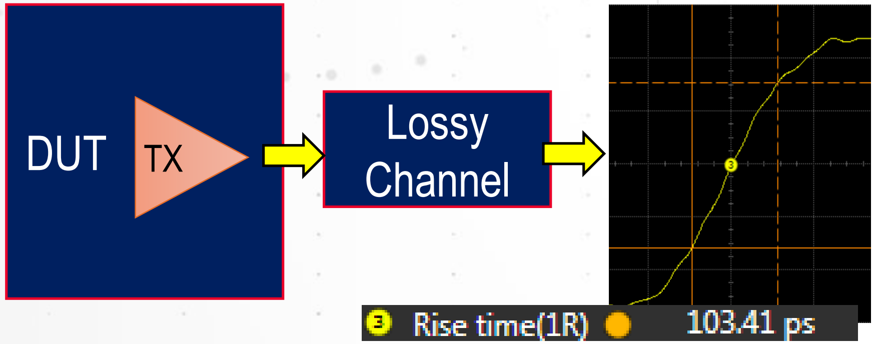


- Scope RJ calibration is available to remove the contribution of scope noise to measured RJ.
- User is asked to disconnect the signal from Channel to measure the ACV_{rms} noise for the current Vertical setting.

Other Jitter Measurement Considerations

Gain Margin by removal of Scope contribution to RJ





Signal with Fast Rise Time

TJ(1E-12)	7.115 ps
RJrms,narrow	347 fs
DJδδ	2.236 ps

With no Scope RJ removal

TJ(1E-12)	26.96 ps
RJrms,narrow	1.28 ps
DJδδ	8.99 ps

After Scope RJ removal

TJ(1E-12)	14.43 ps
RJrms,narrow	340 fs
DJδδ	9.70 ps

Gain margin through scope RJ removal.

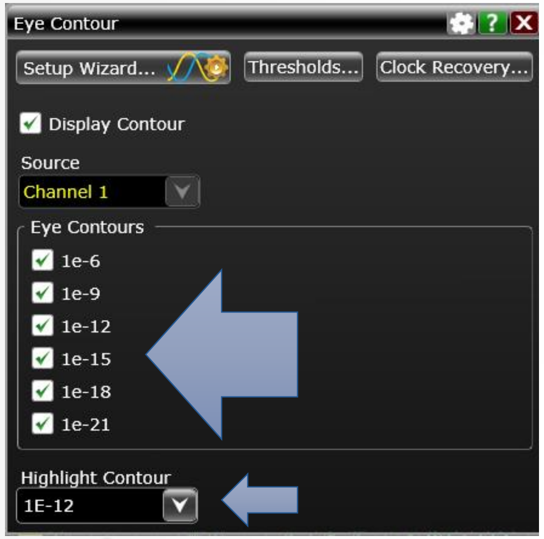
KEYSIGHT TECHNOLOGIES

Agenda

- Review of Jitter Decomposition
- Assumptions and Limitations
- Spectral vs. Tail Fit Method
- Jitter Analysis with Crosstalk Removal Tool
- Scope Random Jitter Removal from Jitter Analysis
- Other Tools to Consider for Jitter Analysis
- Summary

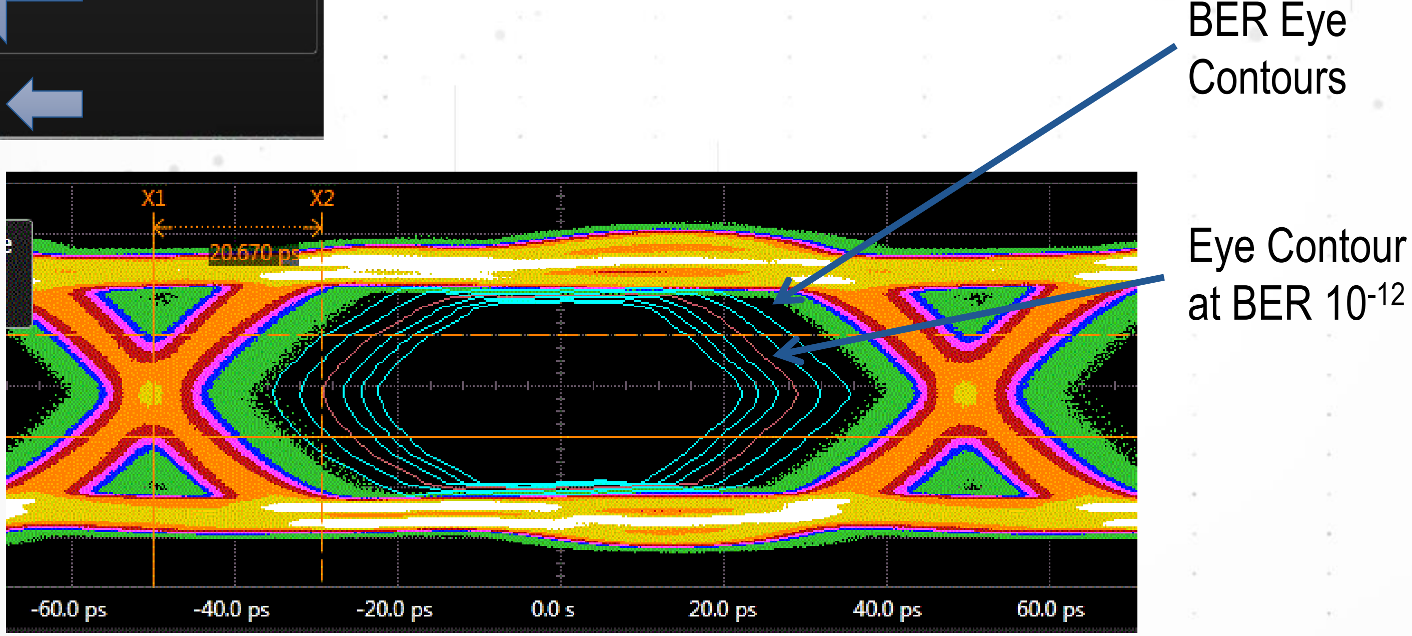
Jitter Analysis with BER Eye Contour

Estimate Jitter and Eye Opening to various BER level



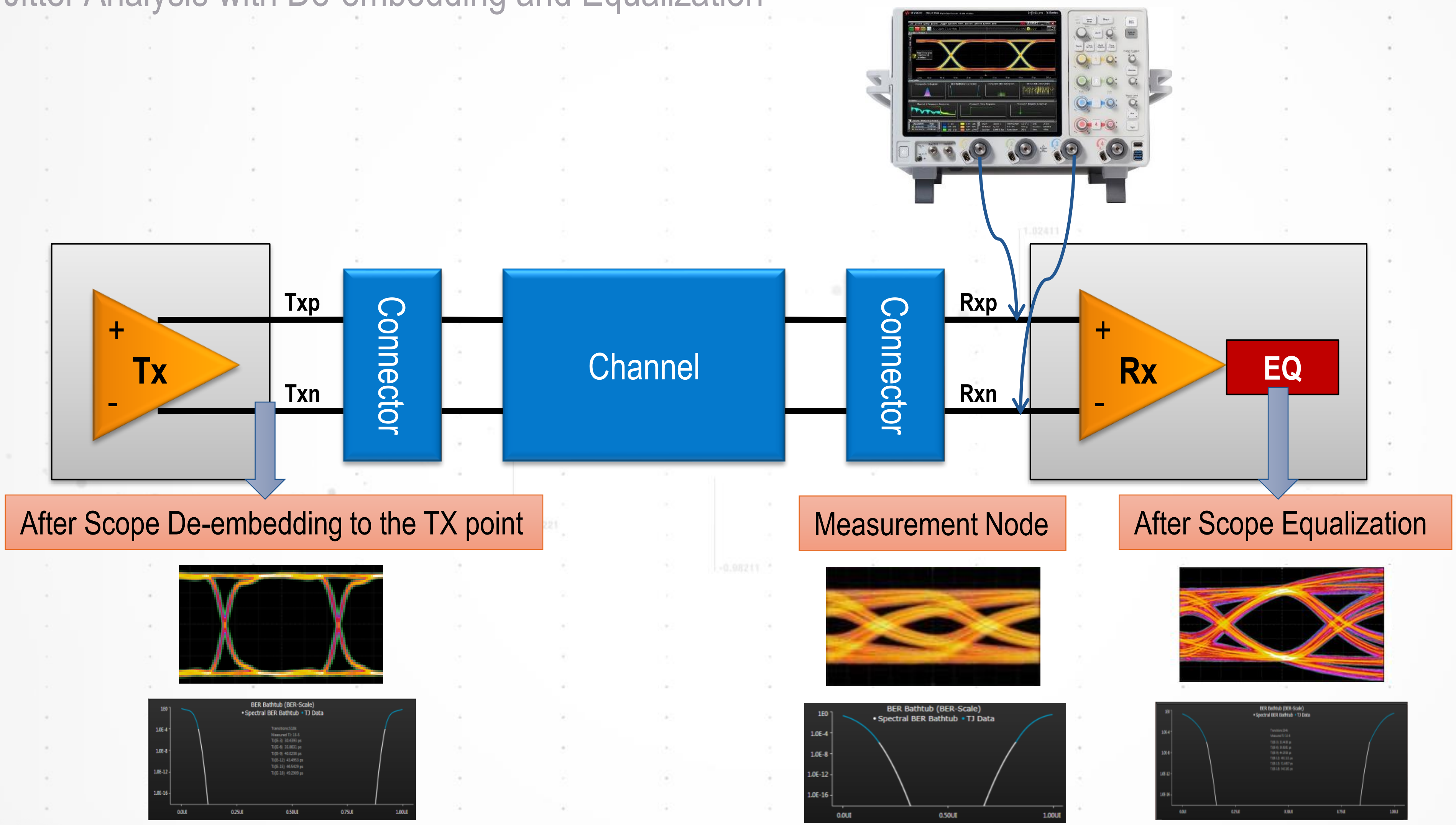
– Specify the BER eye contours you want the scope to plot.

– Specify which BER contour to highlight in red.



Analyze Jitter at Various Test Points

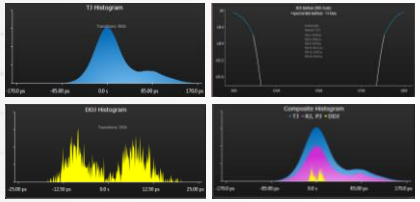
Jitter Analysis with De-embedding and Equalization



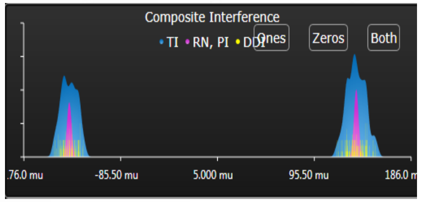
Agenda

- Review of Jitter Decomposition
- Assumptions and Limitations
- Spectral vs. Tail Fit Method
- Jitter Analysis with Crosstalk Removal Tool
- Scope Random Jitter Removal from Jitter Analysis
- Other Tools to Consider for Jitter Analysis
- Summary

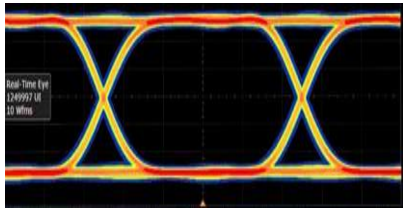
Keysight Real-Time Scope Jitter Analysis Tools



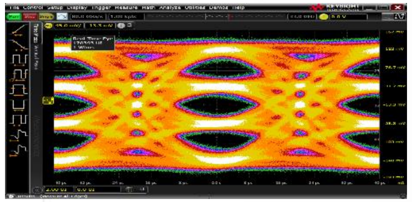
N5400A EZJIT Plus for Jitter Analysis and RJ Scope Removal Calibration



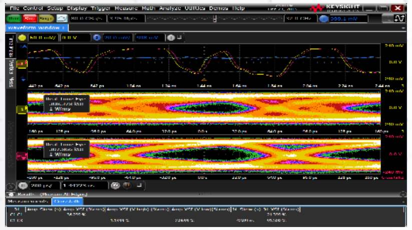
N8823A EZJIT Complete for Vertical Noise Analysis



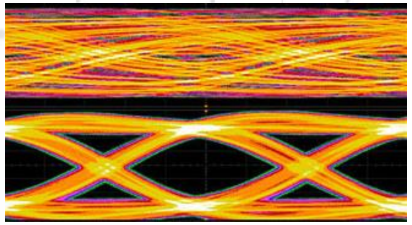
E2688A High-Speed SDA for Reference Clock Recovery and Eye Analysis



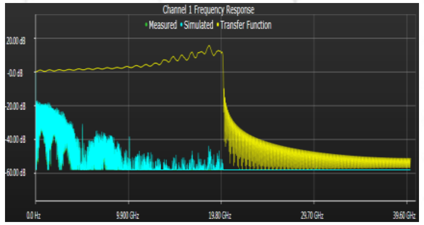
N8827A PAM-4 Clock Recovery



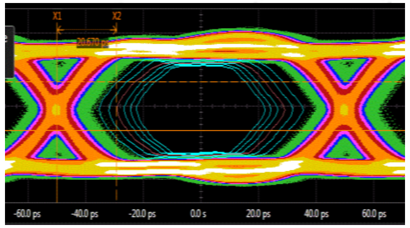
N8833A Crosstalk Analysis and Removal Application



N5461A Serial Data Equalization Software

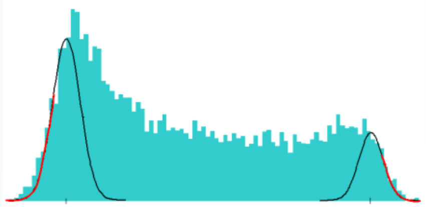


N5465A InfiniiSim De-embedding Software

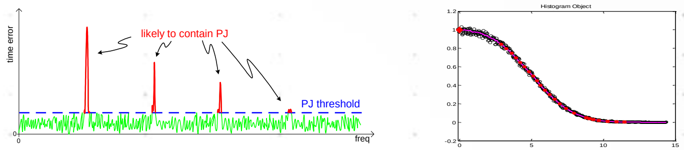


BER Eye Contour Comes standard with E2688A and N8823A

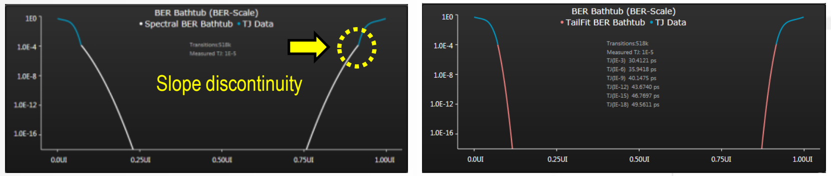
Jitter Analysis Summary



Dual Dirac Model for Jitter Decomposition

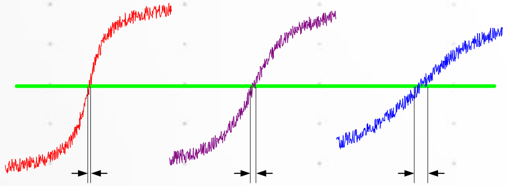


Spectral vs. Tail Fit for ABUJ (Crosstalk) Jitter Analysis

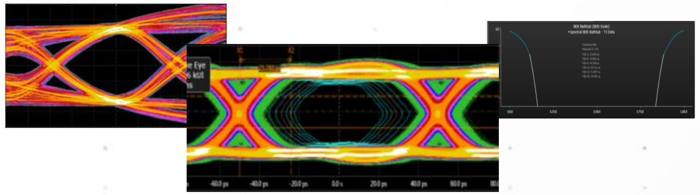


Use Smoothness of Slop Continuity on the Bathtub Curve

Use Crosstalk Removal Tool to Recover Jitter Margins



Scope Random Jitter Removal



BER Eye Contour, De-embedding and Equalization for Jitter Analysis