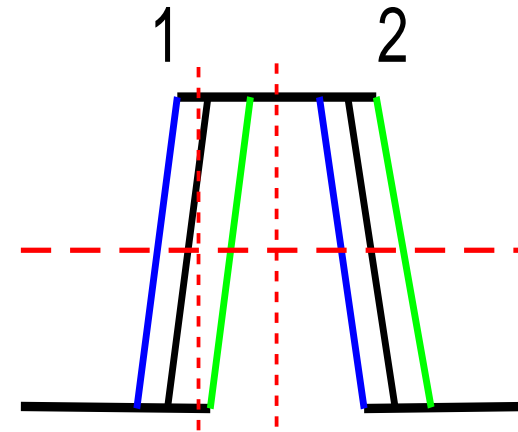# Jitter Basics, Advanced, and Noise Analysis

Mike Tranchemontagne, FAE

Agenda, Part 1

- Jitter Basics
  - What is Jitter?
  - TIE vs. Period Jitter vs. Cycle-to-Cycle
  - Clock Recovery

- Advanced Analysis – Jitter Decomposition
  - Motivation
  - Terminology and Models

- Jitter for Busy People: Hints, Tips & Common Errors

- Q & A

Agenda, Part 2

- Motivations for Jitter & Noise Analysis

- Jitter/Noise Theory

- Jitter/Noise Measurements on Real Time scopes
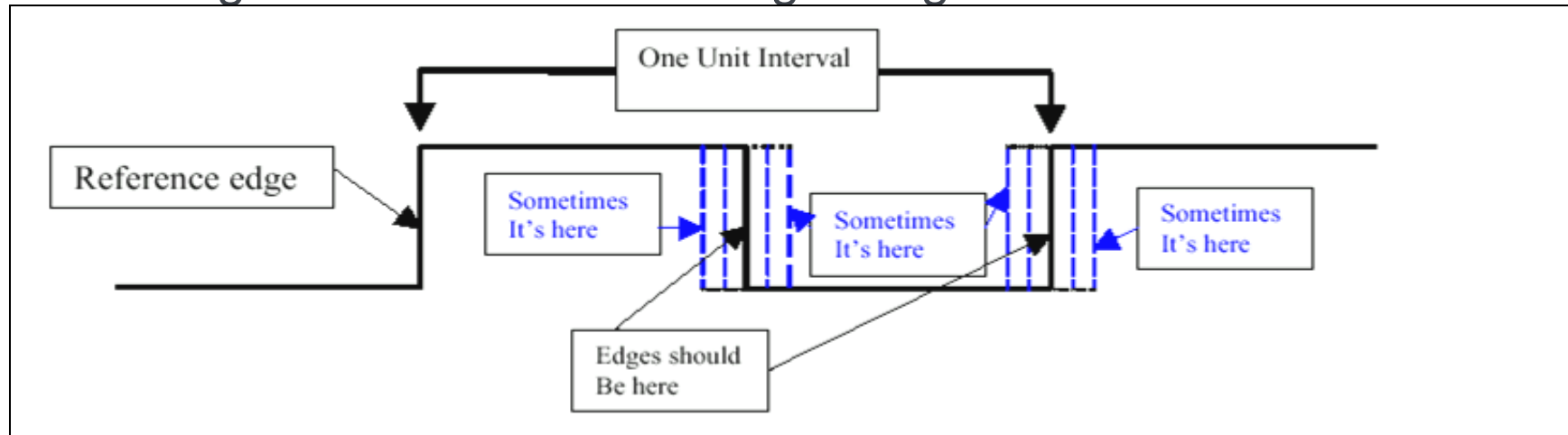
- Q & A

Jitter Basics

## Definitions / Clock-Recovery / Visualization Tools

What is Jitter?

- Definitions
  - "The deviation of an edge from where it should be"

  - ITU Definition of Jitter: "Short-term variations of the significant instants of a digital signal from their ideal
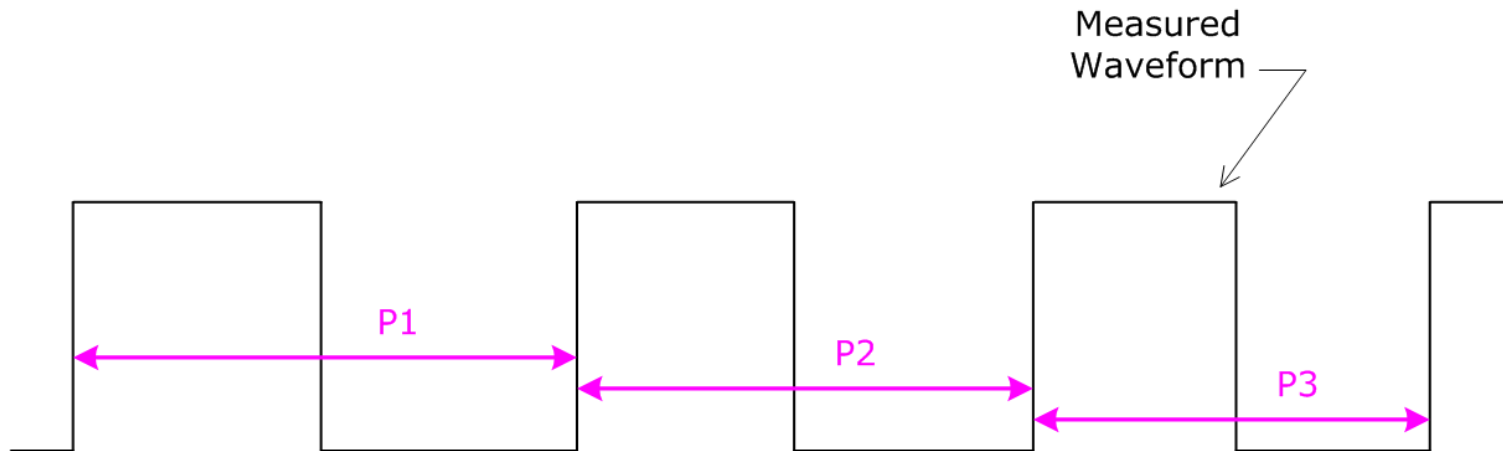
Jitter is caused by many things…

- Causes of Random Jitter
  - Thermal noise
    - Generally Gaussian
    - External radiation sources
    - Like background conversations…random and ever changing

- Causes of Periodic Jitter
  - Injected noise (EMI/RFI) & Circuit instabilities
    - Usually a fixed and identifiable source like power supply and oscillators
    - Will often have harmonic content
    - Transients on adjacent traces
    - Cabling or wiring (crosstalk)

  - PLL's problems
    - Loop bandwidth (tracking & overshoot)
    - Deadband (oscillation / hunting)

- Causes of Data Dependent Jitter

  - Transmission Losses
    - There is no such thing as a perfect conductor
    - Circuit Bandwidth
    - Skin Effect Losses
    - Dielectric Absorption
    - Dispersion – *esp. Optical Fiber*
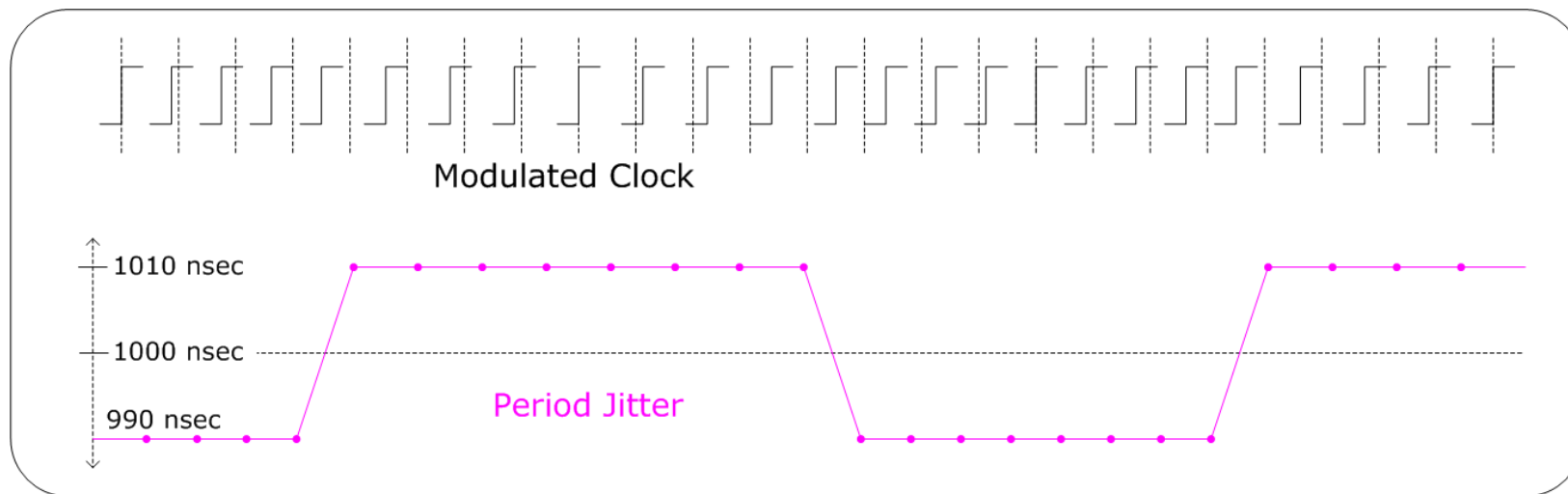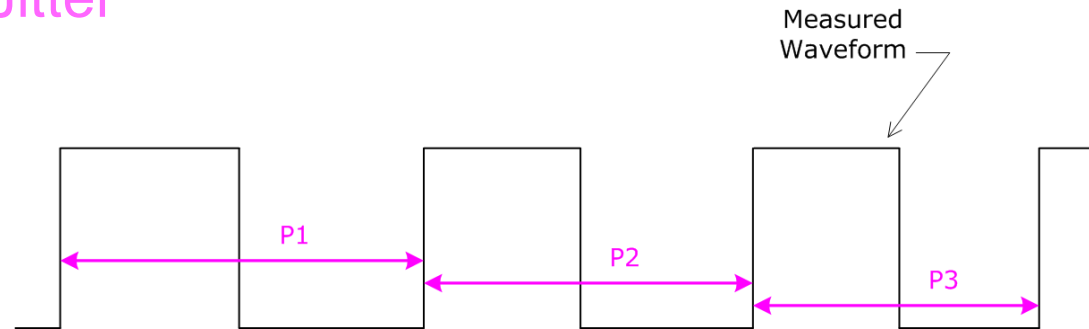   - Reflections, Impedance mismatch, Path discontinuities (connectors)
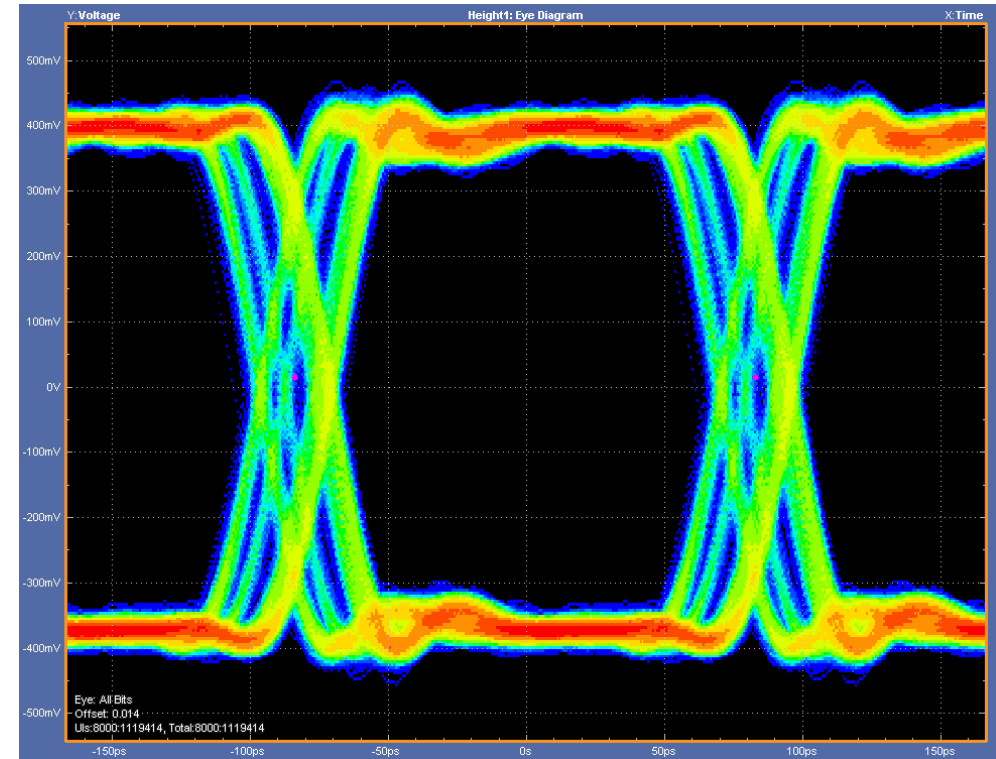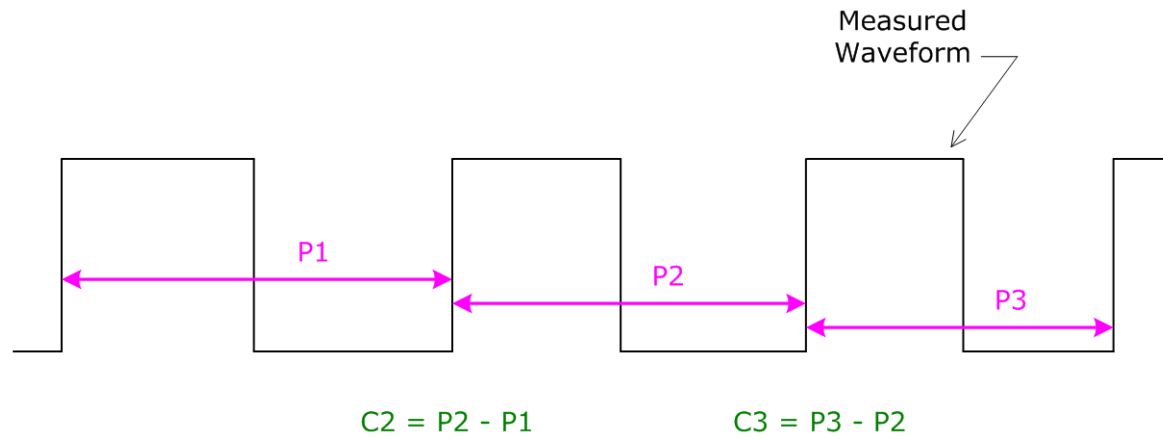
Types of Jitter

- Period Jitter
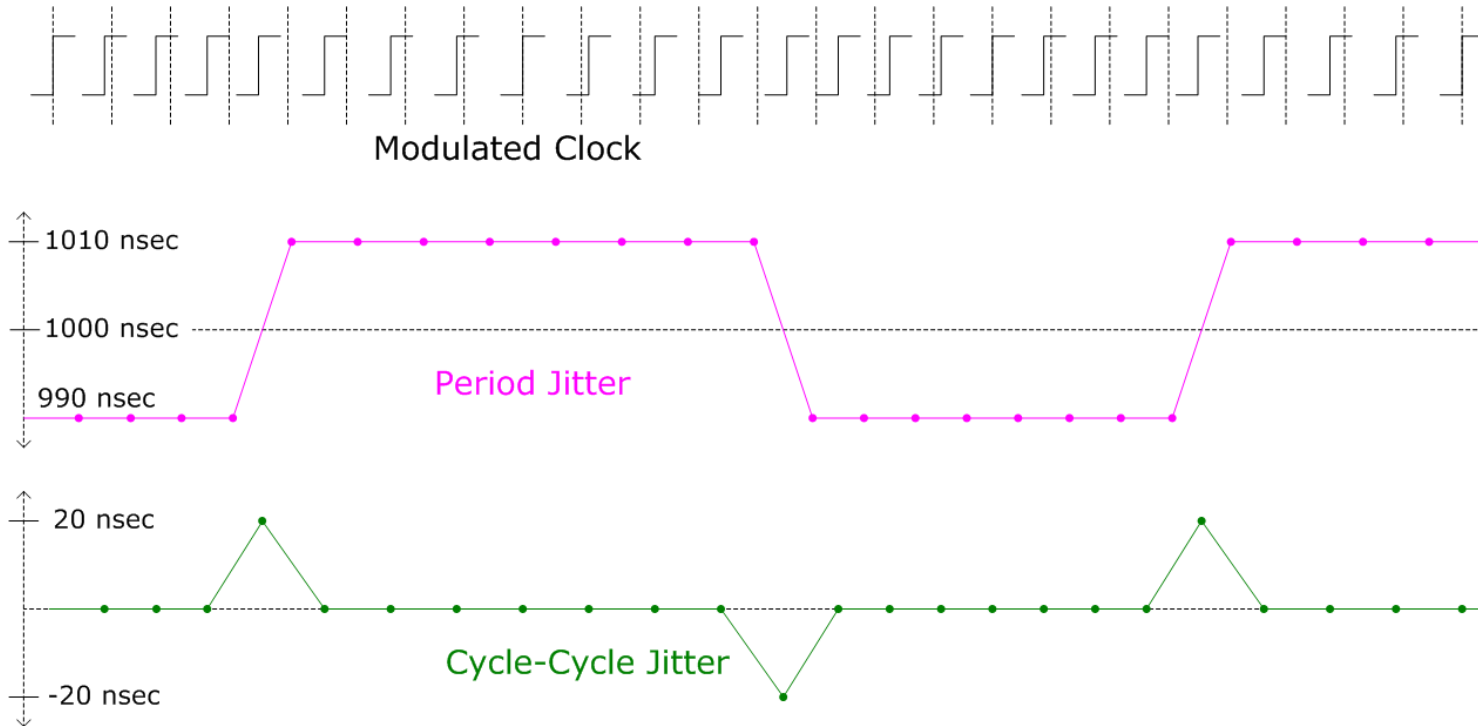
Types of Jitter

- Period Jitter

Measured Waveform

P1   P2   P3

Modulated Clock

1010 nsec

1000 nsec

990 nsec

Period Jitter

Types of Jitter

- Period Jitter
- Cycle-to-Cycle Jitter

Measured
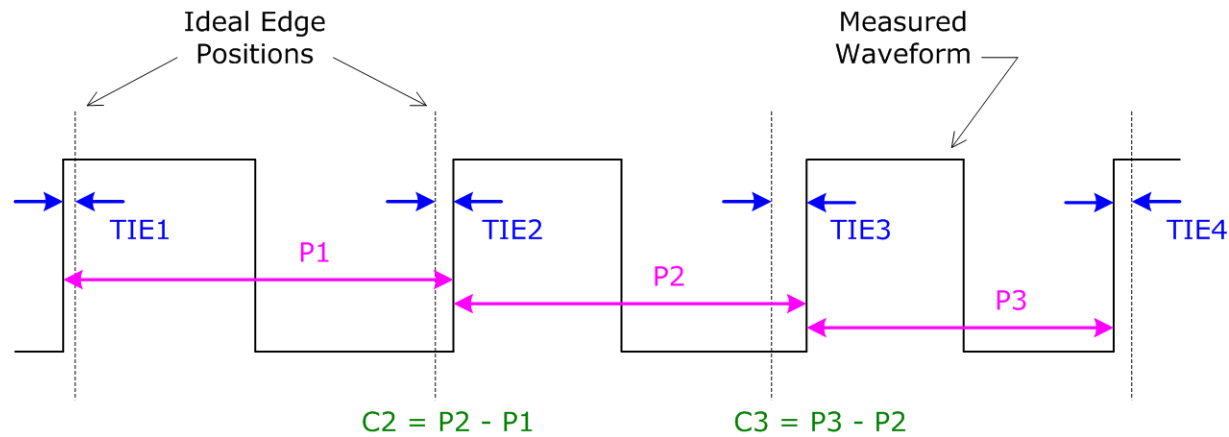Waveform

P1

P2

P3

C2 = P2 - P1   C3 = P3 - P2

- **Cycle-to-Cycle Jitter** is the first-order difference of the Period Jitter

Types of Jitter (Visualization)

Modulated Clock

Period Jitter

Cycle-Cycle Jitter

1010 nsec

1000 nsec

990 nsec

20 nsec

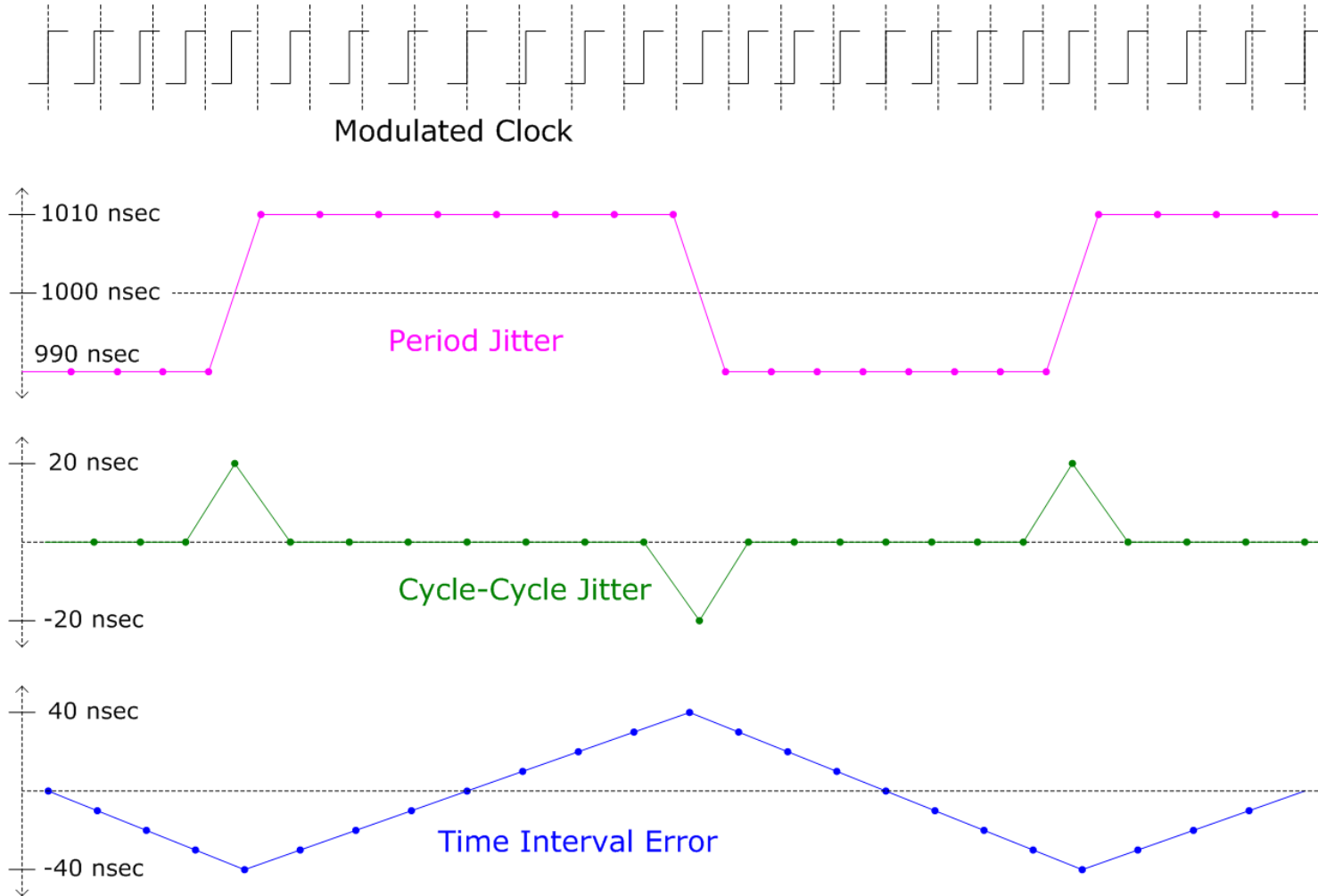-20 nsec

Types of Jitter

- Period Jitter
- Cycle-to-Cycle Jitter
- TIE (Time Interval Error)

– **Period Jitter** is the first-order difference of the **TIE Jitter** (plus a constant)

$$P_n = TIE_n - TIE_{n-1} + K$$

Types of Jitter (Visualization)

Advanced Jitter - Decomposition

Rj / Dj Separation

Motivations for Jitter Decomposition

- **Speed**: Directly measuring error performance at 1e-12 requires directly observing MANY bits (1e14 or more). This is time consuming! Extrapolation from a smaller population can be done in seconds instead of hours.

- **Knowledge**: Jitter decomposition gives great insight into the root causes of eye closure and bit errors, and is therefore invaluable for analysis and debug.

- **Flexibility**: Already have a scope on your bench? You can do Jitter@BER measurements without acquiring more, perhaps somewhat specialized equipment.
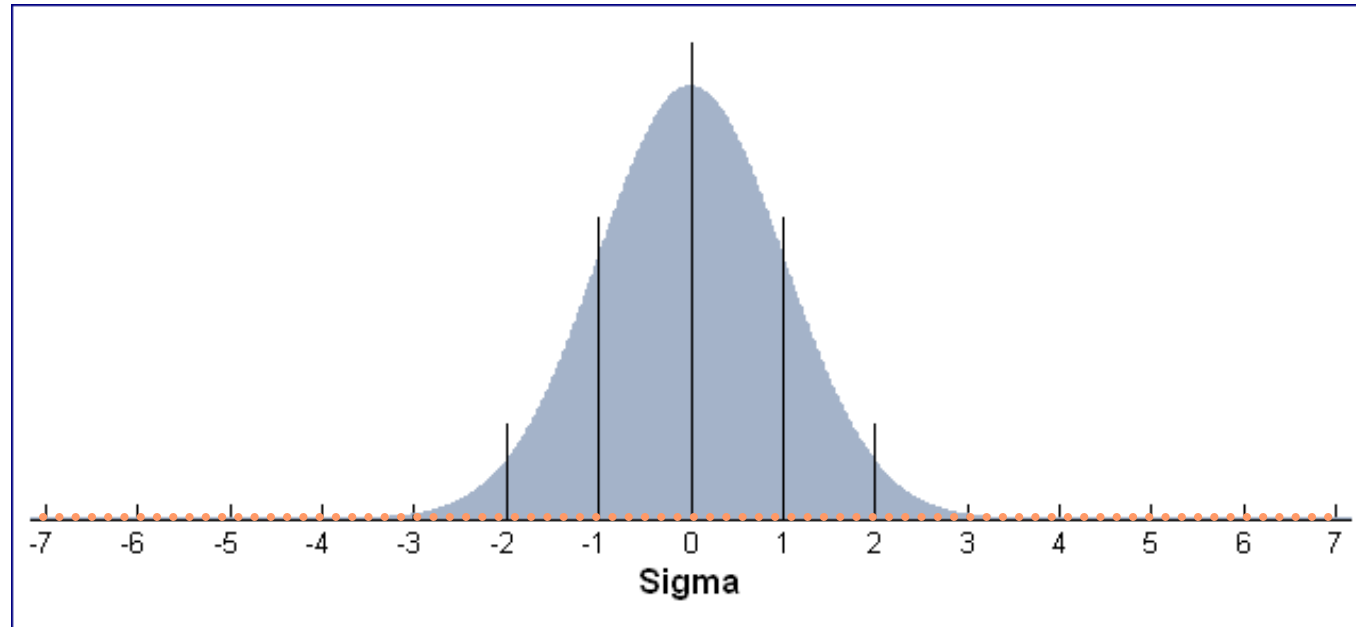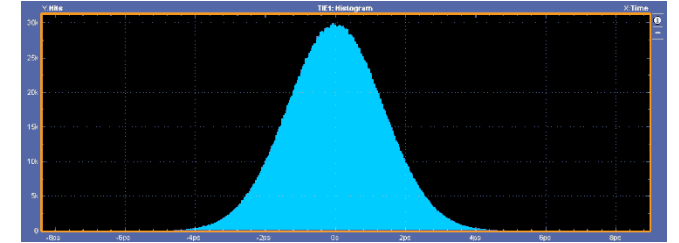
Common Terms

- Random Jitter (RJ)

- Deterministic Jitter (DJ)
  - Periodic Jitter (PJ)
  - Sinusoidal Jitter (SJ)
  - Duty Cycle Distortion (DCD)
  - Data-Dependent Jitter (DDJ)
  - Inter-Symbol Interference (ISI)

- Bit Error Rate (BER)

- Total Jitter ~ (TJ or TJ@BER)

- Eye Width @BER
 - versus Actual or Observed Eye Width

Random Jitter (RJ)

- Jitter of a random nature is assumed to have a Gaussian distribution
  - Central Limit Theorem

- Histogram (estimate) ↔ pdf (mathematical model)

- Peak-to-Peak = … unbounded!

Deterministic Jitter (DJ)

- Deterministic jitter has a bounded distribution: the observed peak-to-peak value will not grow over time

- Histogram = pdf (close enough)

Peak-to-Peak
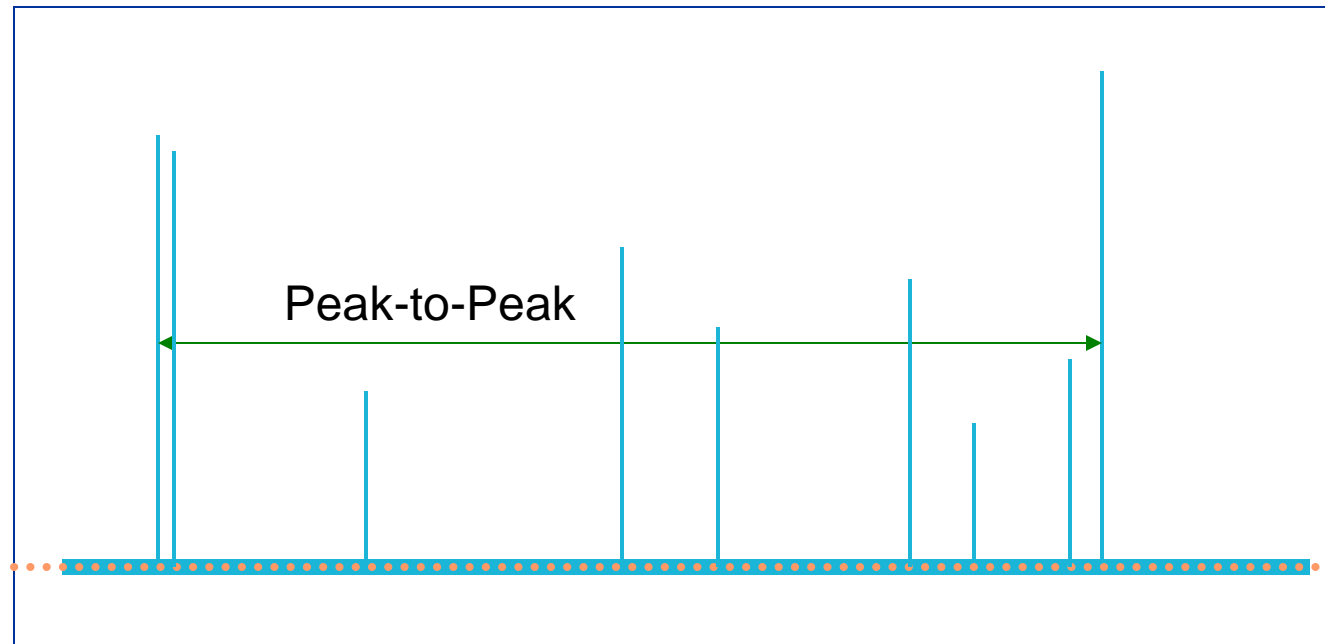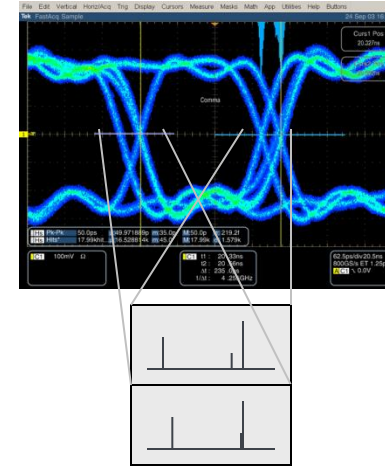
Periodic Jitter (PJ, SJ)

- TIE vs. time is a repetitive waveform

- Assumed to be uncorrelated with the data pattern (if any)

- Sinusoidal jitter is a subset of Periodic Jitter

Peak-to-Peak
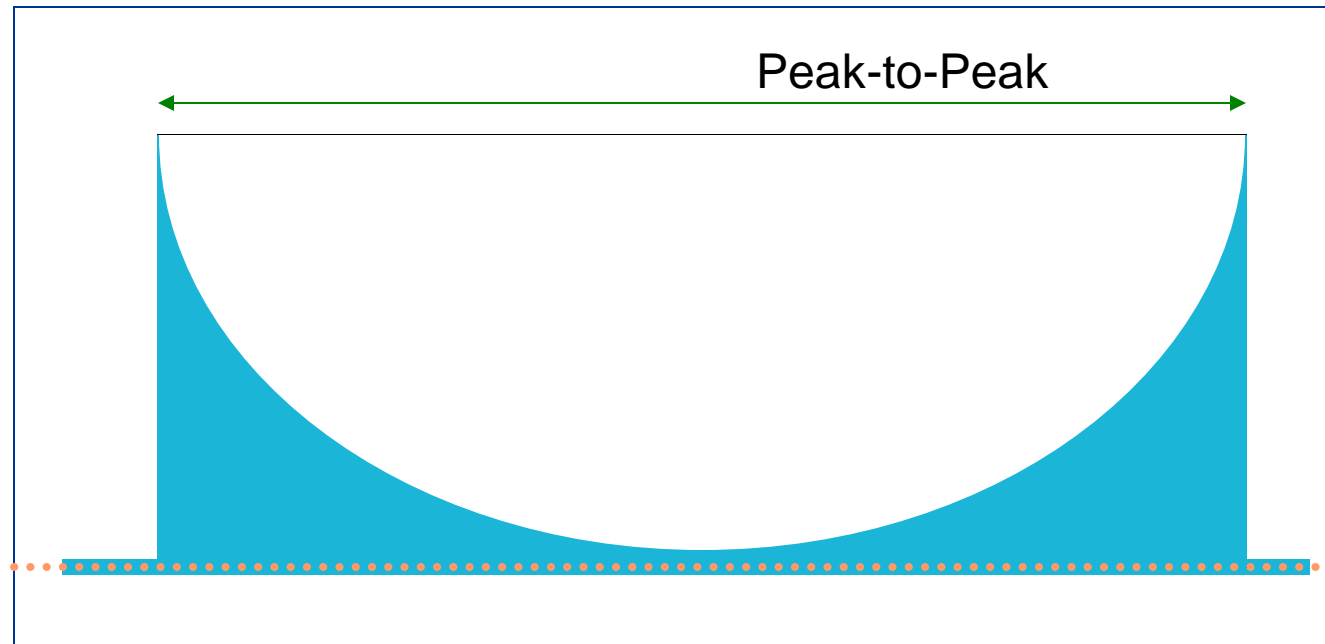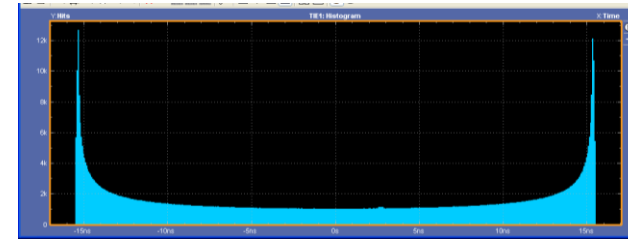
Duty Cycle Distortion (DCD)

- DCD is the difference between mean TIE for rising edges and mean TIE for falling edges

- Causes
  - Asymmetrical rise-time vs. fall-time
  - Non-optimal choice of decision threshold

- For a clock signal, the pdf consists of two impulse

0.0v

-0.1v
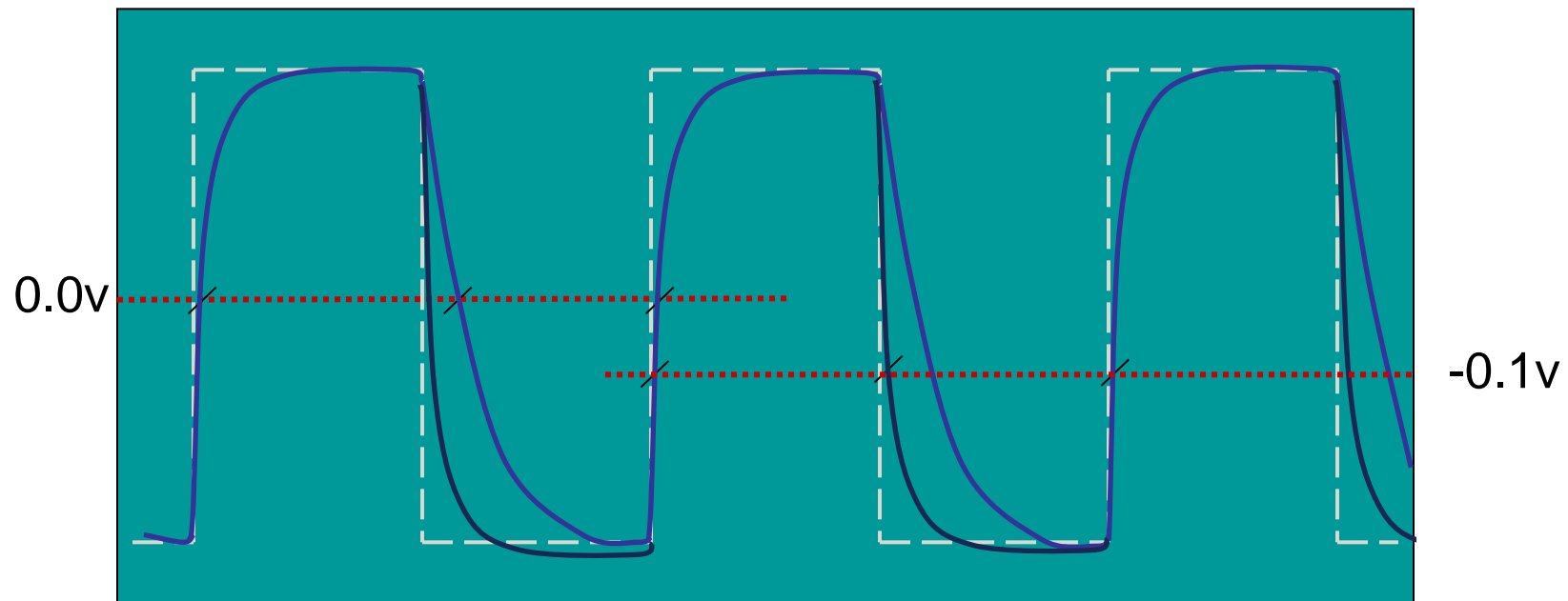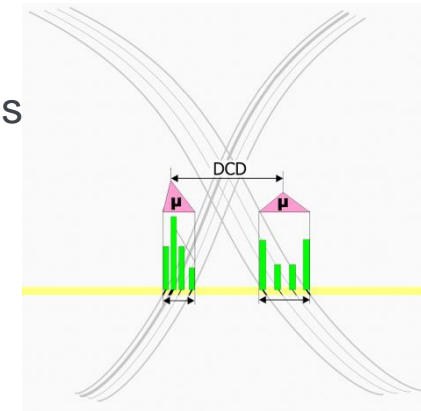
Data-Dependent Jitter

- DDJ or PDJ – used interchangeably

- ISI – usually considered to be the physical/electrical effect that causes DDJ (and DDN)

- Characterizes how the jitter on each transition is correlated with specific patterns of prior bits
  - Due to the step response of the system
  - Due to transmission line effects (e.g. reflections)

24" ISI

" ISI

No ISI
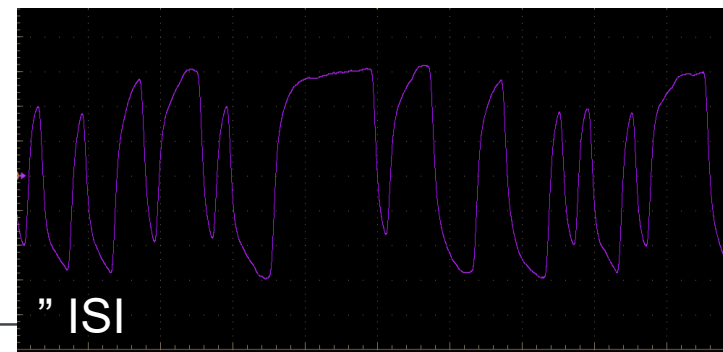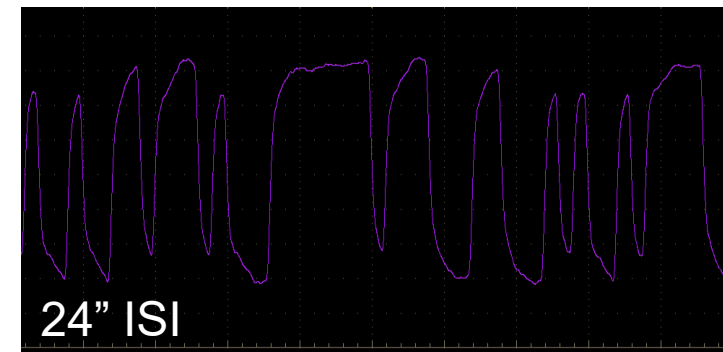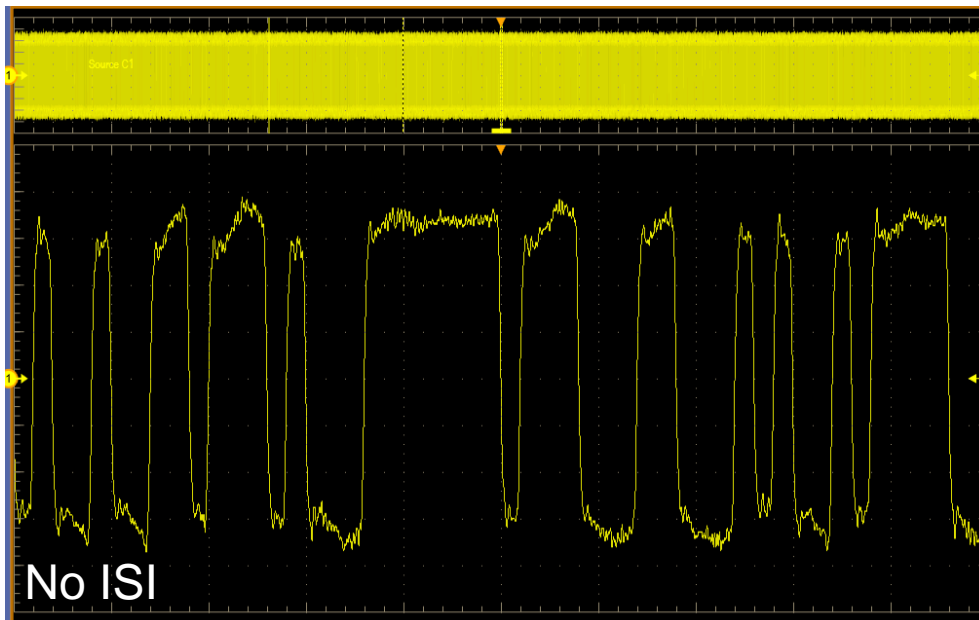
Bounded Uncorrelated Jitter

- Interconnect and board layout technology is advancing and the greatest area of focus is in reducing the insertion loss and Signal-to-Crosstalk ratio.

- The implications of complex channel interaction can be observed and identified by examining the type and amount of Bounded Uncorrelated Jitter or BUJ.

- There is a strong Cause–and-Effect relationship between Crosstalk and BUJ which often gets classified as Random if special steps are not observed.

Table 4-6. Stressed Receiver Conditions

| Symbol	Description
Input swing	Inner eye voltage
AC-CM_rms	AC Common Mode Voltage rms
AC-CM_pk_pk	AC Common Mode Voltage pp
BUJ	Bounded Uncorrelated Jitter
DDJ	Data Dependent Jitter
RJ	Random Jitter
TJ	Total Jitter

Bounded Uncorrelated Jitter (BUJ)
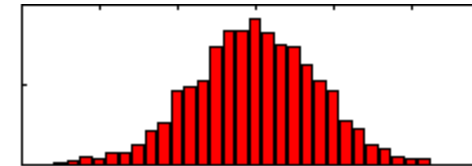
- Definitions of Jitter Properties:

  ○ **Bounded**: Having a PDF (histogram) that does <u>not grow in width</u> as the observation interval increases
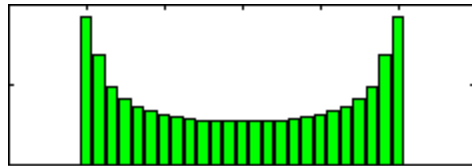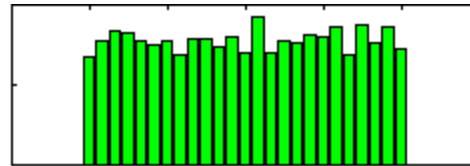
  Bounded   Bounded   Unbounded

  ○ **Uncorrelated**: Specifically, not correlated to the pattern of data bits

    ▪ Note that PJ (Periodic Jitter) is both bounded and uncorrelated → BUJ!

  ○ **Deterministic**: Future behavior can be predicted based on observed past.

    ▪ Deterministic jitter is always bounded

    ▪ But… bounded jitter isn't necessarily deterministic

  ○ **RJ**: By convention, random jitter with a Gaussian histogram

  ○ **NPJ or NP-BUJ**: Non-Periodic (Bounded Uncorrelated) Jitter. This is basically random jitter with a bounded PDF

Jitter Measurement in the Presence of Crosstalk: Problem Summary

- Crosstalk-caused jitter typically is Bounded Uncorrelated Jitter (BUJ); depending on the spectra this should be separated as either

  ◦ PJ (Periodic BUJ)　　　or　　NPJ (Non-Periodic BUJ)

- In traditional oscilloscope-based jitter measurement methodology the more spectrally diffuse BUJ components (i.e. NPJ) are not distinguished from RJ.

  ◦ The inflated RJ is multiplied by a factor, thereby grossly inflating TJ

    Example:　TJ = DJ + **14***RJ　　(at BER = 1e-12)

- This is well known and was documented e.g. in

  "*Method of BER Analysis of High Speed Serial Data Transmission in Presence of Jitter and Noise*", Zivny at all, DesignCon 2007.
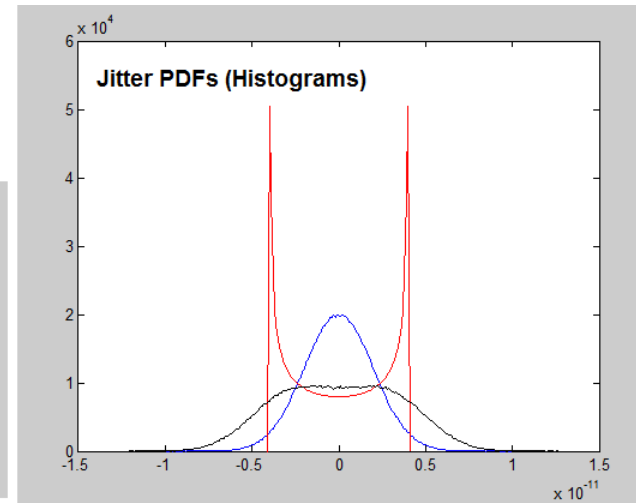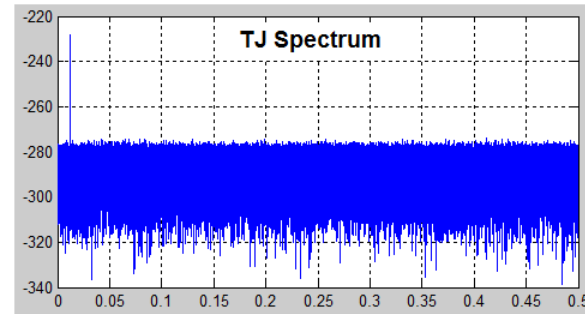
Crosstalk Problem Summary (Graphical Version)

Case 1:
RJ + PJ

Spectral separation works very well

Simulated Jitter, Population = 1e6 observations

Blue = Gaussian RJ, 2 ps rms
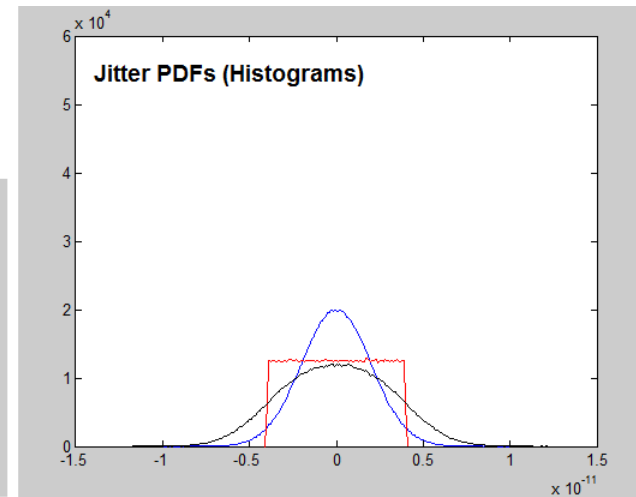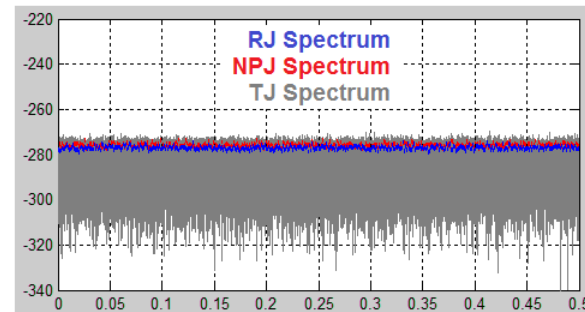Red = Sinusoidal Jitter, 8 ps p-p
Black = RJ + PJ = TJ

Case 2:
RJ + NPJ

Spectral separation is no help at all

Simulated Jitter, Population = 1e6 observations

Blue = Gaussian RJ, 2 ps rms
Red = Uniformly Distributed NPJ, 8 ps p-p
Black = RJ + NPJ = TJ
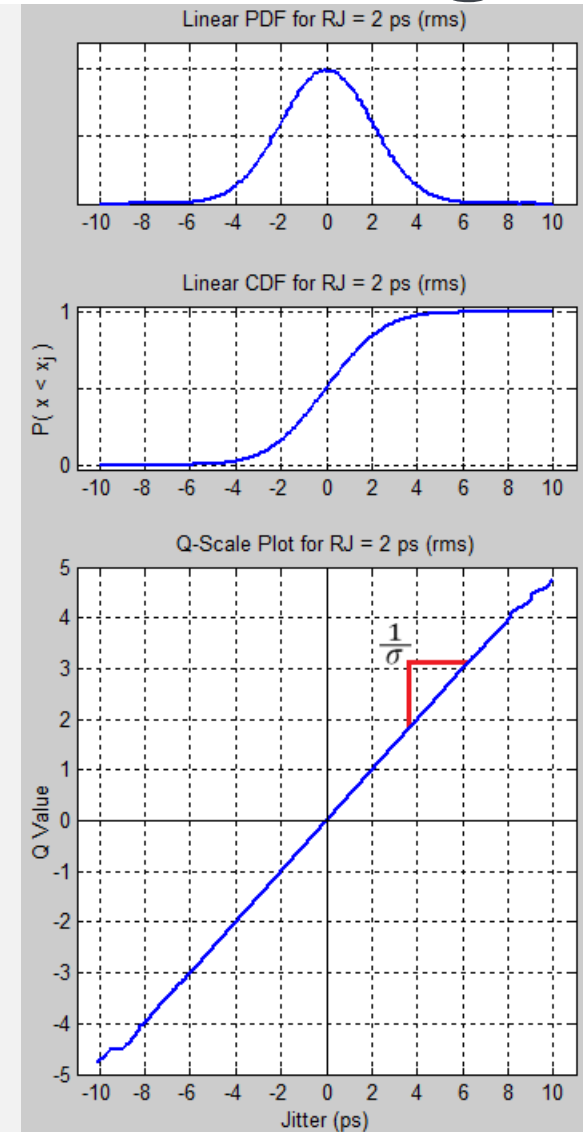
Theory: Q-Scale Analysis for Detecting NPJ

- Cumulative Distribution Function (CDF) for a Gaussian Distribution:

$$CDF(x_{Gaus}) = \frac{1 + erf\left(\frac{x}{\sigma\sqrt{2}}\right)}{2}$$

- Q Sc $Q(x) = \sqrt{2} * erf^{-1}(2CDF(x) - 1)$

$$Q(x_{Gaus}) = \frac{x}{\sigma}$$
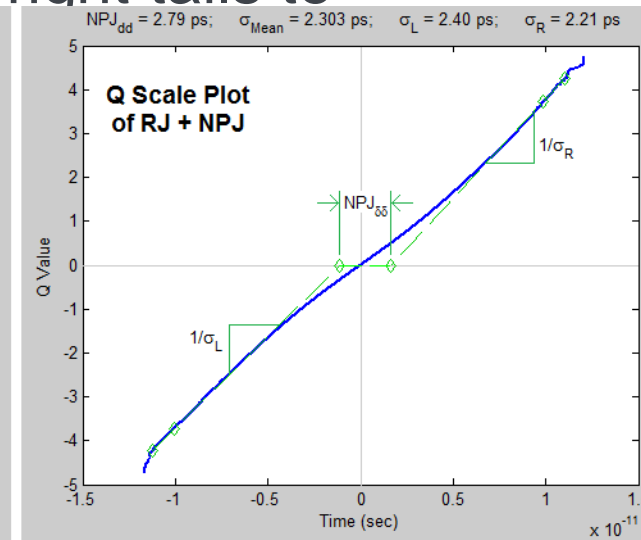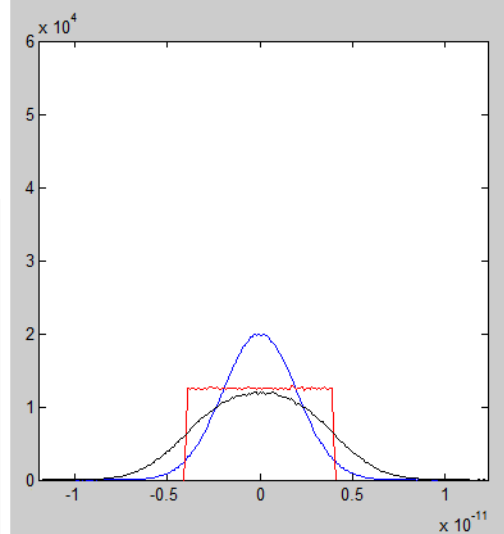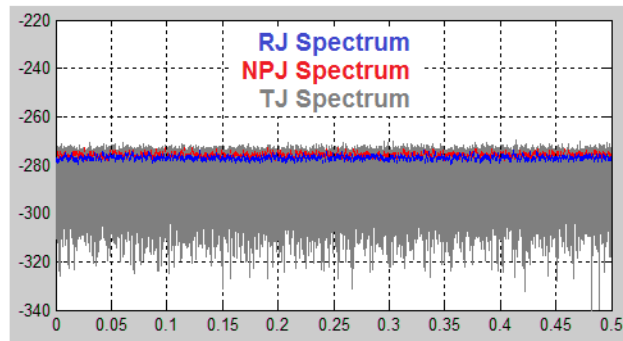
- Q Scale for a Gaussian:

Separation of BUJ and RJ Jitter Components Methodology

- After PJ and DDJ are removed using the spectral approach, RJ + NPJ is converted to a histogram and then plotted using the Q Scale

- Straight lines are fitted to the left and right tails to

Simulated Jitter, Population = 1e6 observations

Blue = Gaussian RJ, 2 ps rms
Red = Uniformly Distributed NPJ, 8 ps p-p
Black = RJ + NPJ = TJ

RJ Spectrum
NPJ Spectrum
TJ Spectrum

NPJ_{dd} = 2.79 ps; σ_{Mean} = 2.303 ps; σ_L = 2.40 ps; σ_R = 2.21 ps

Q Scale Plot
of RJ + NPJ

$1/\sigma_R$
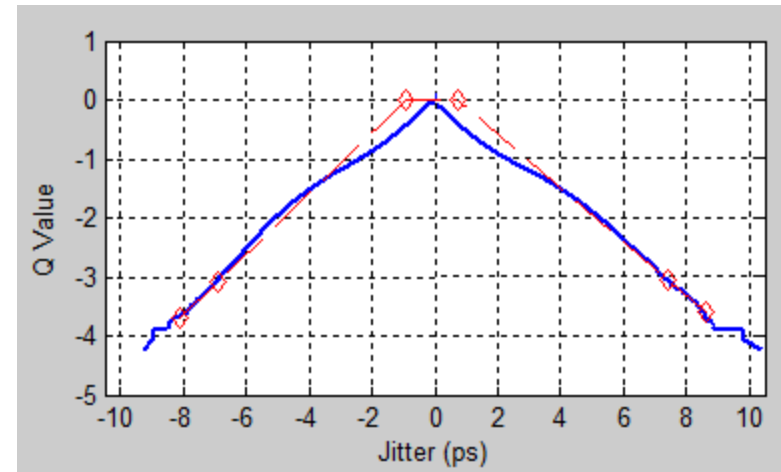
$NPJ_{\delta\delta}$

$1/\sigma_L$

BUJ Separation Example

- Victim: PRBS7, 8 Gbps
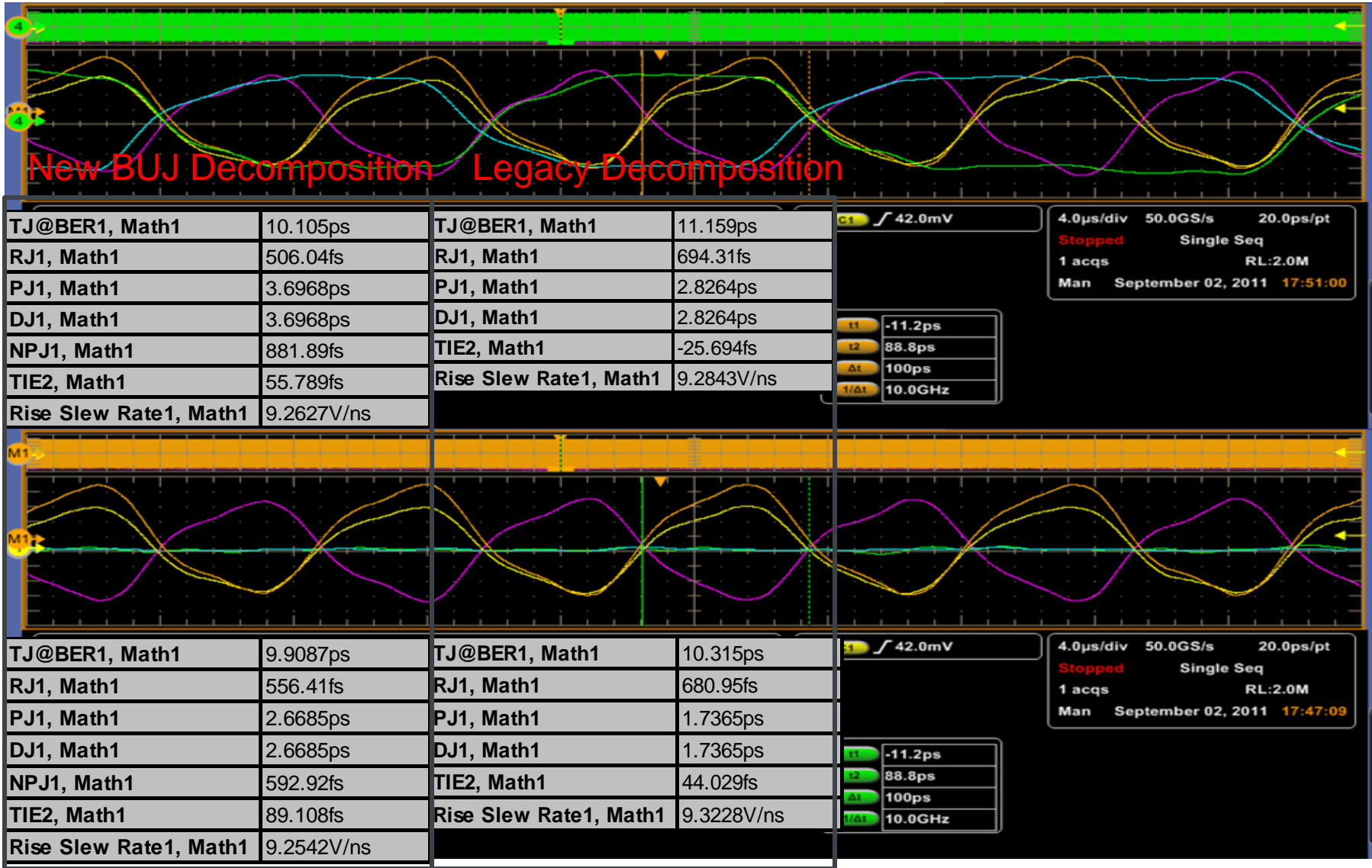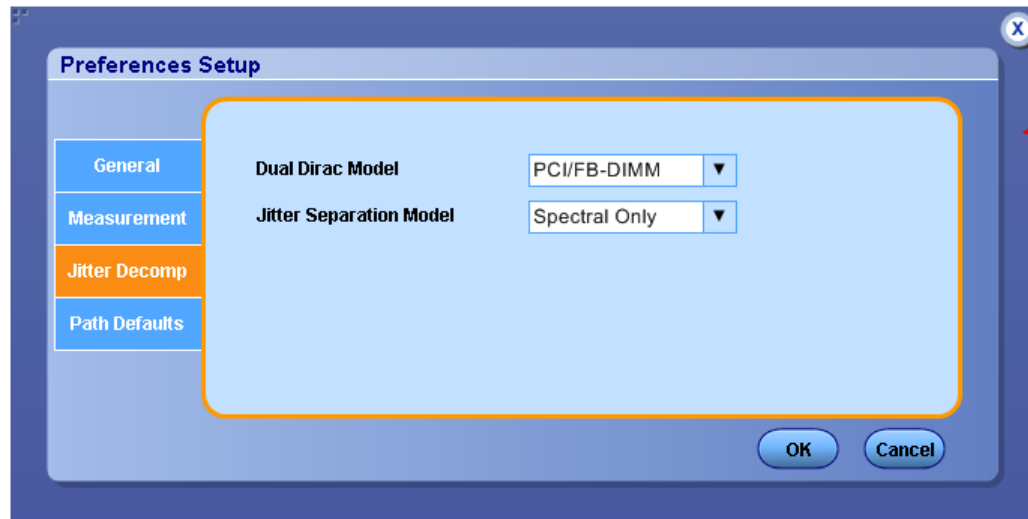
- Aggressor: PRBS31, 10 Gbps

Raw View
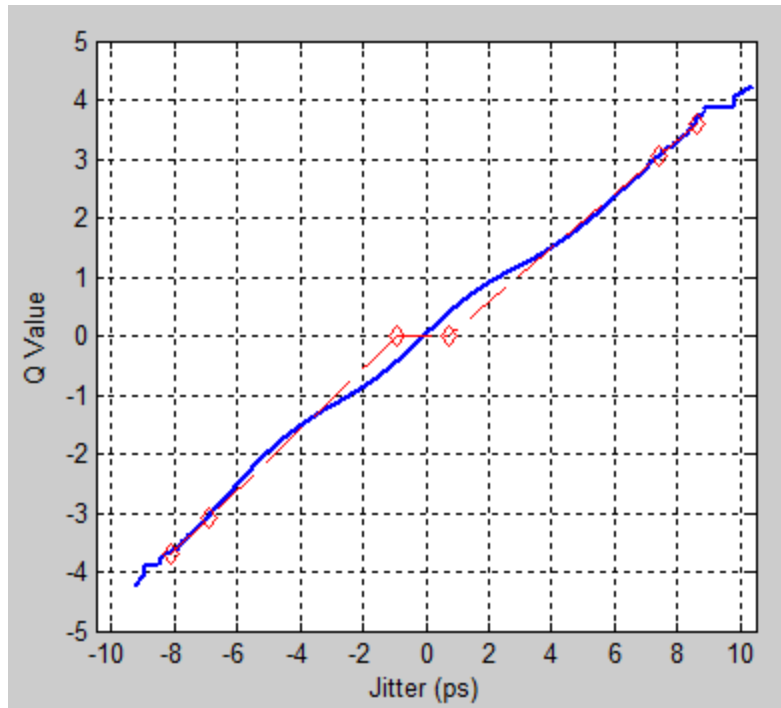
Folded View

BUJ vs. Legacy Jitter Decomposition Results

DPOJET Setup for BUJ / NPJ Measurements

- **Enable** Spectral+BUJ either through the Preferences Setup or the Jitter Map

- **Minimum # of UI** control is only available via Preferences Setup

  ◦ Default is 1M but it can be reduced as low as 10k.

Default
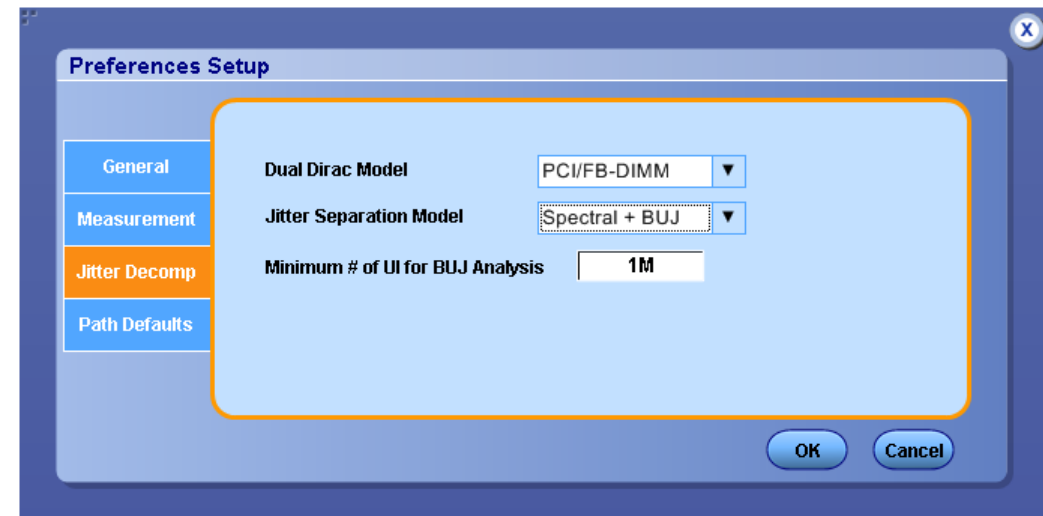
DPOJET Results for BUJ / NPJ Measurements

- Until the population requirement has been met, dependent measurements say "< Min # of UI"

- Clock NPJ measurement shows actual progress toward the population requirement

Jitter Visualization

Gaussian Random Noise

Sinusoidal Jitter

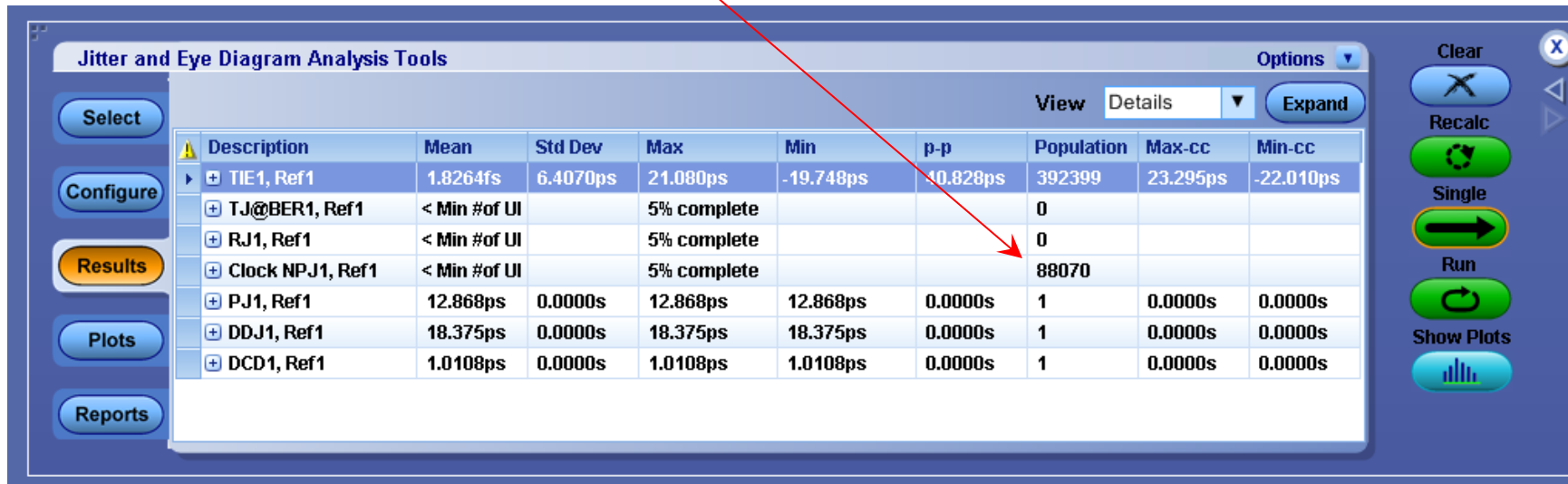# Jitter Visualization - Histogram

- Shows the measurement values in a data set against the frequency of occurrence
  - Data sets with a large number of measurements provide a good estimate of the probability density function (pdf) of the set

- Useful for identifying bi-modal distributions

- Shape of the histogram can identify source of jitter
  - Random jitter has a Gaussian shape
  - Period jitter is a saddle shape
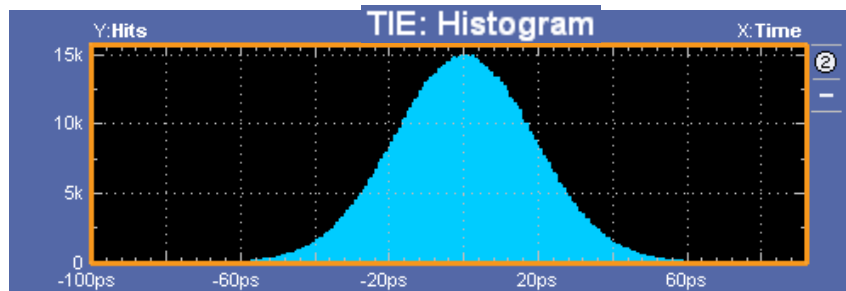
Gaussian Random Noise
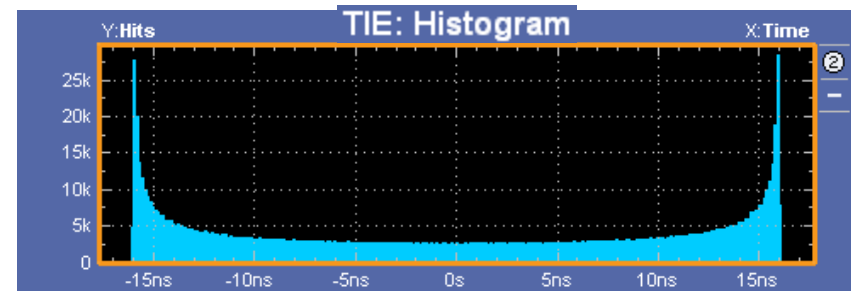
Sinusoidal Jitter

Jitter Visualization – Bathtub Plot

- Shows the Eye Opening at a Specified BER Level
- Note the eye closure of System I vs. System II due to the RJ- RJ is unbounded so the closure increases as BER level increases
    - System I has .053UI of RJ with no PJ
    - System II has .018UI of RJ and .14UI of PJ @ 5 and 10Mhz
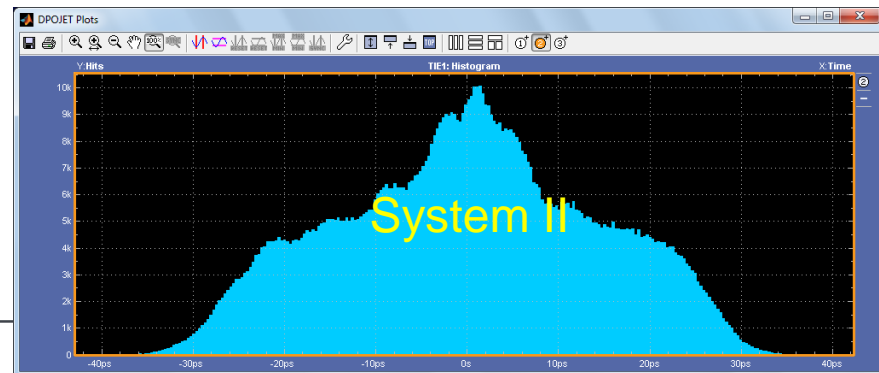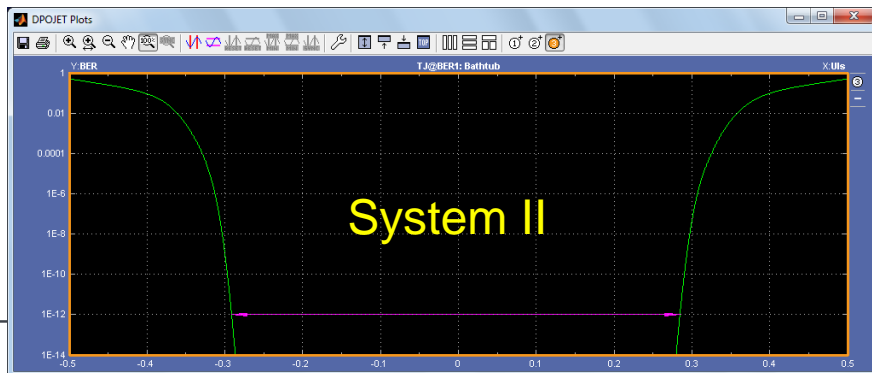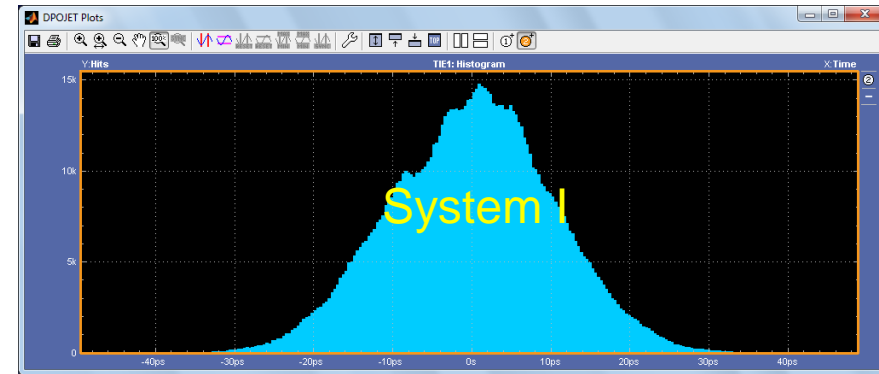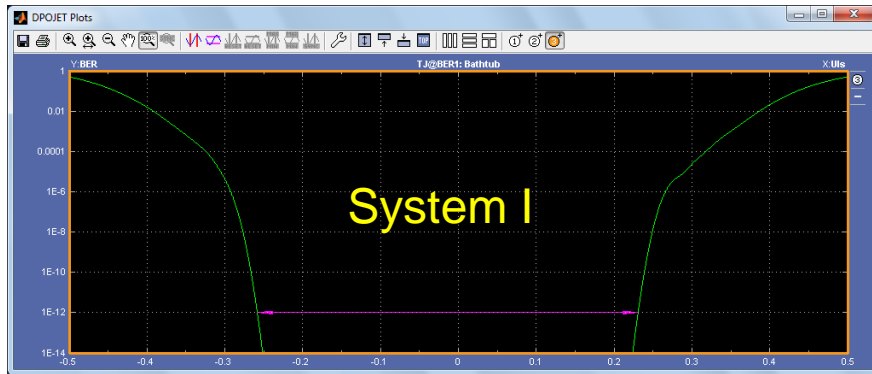
Jitter Visualization – Time Trend

- Histogram does not have any context of time
- Time Trend can reveal repeating patterns that may indicate modulation on the signal
  - For example 5 cycle of SSC @ 30khz as shown below
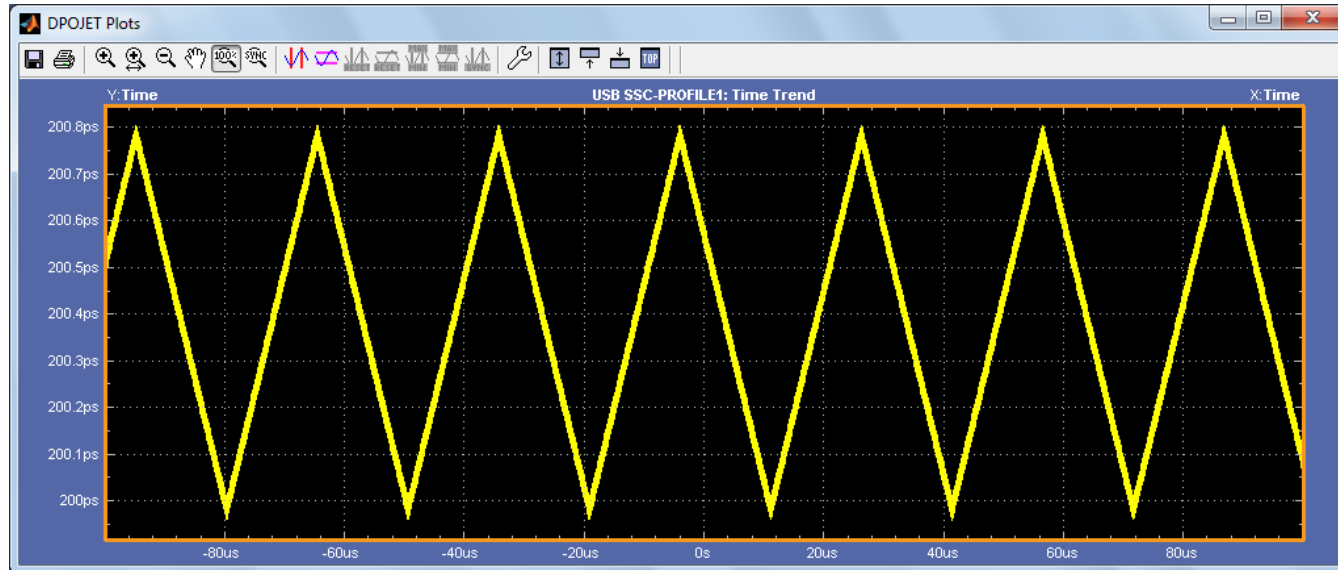
Jitter Visualization – Spectral Plot

- Frequency domain view of the signal content
- Deterministic components show as lines above the noise
  - DDJ is at frequencies of the bit rate / pattern length (example below is 5Gb/s PRBS7) Note the spikes at intervals of 40Mhz in the plot.
  - Constant Clock CR was used
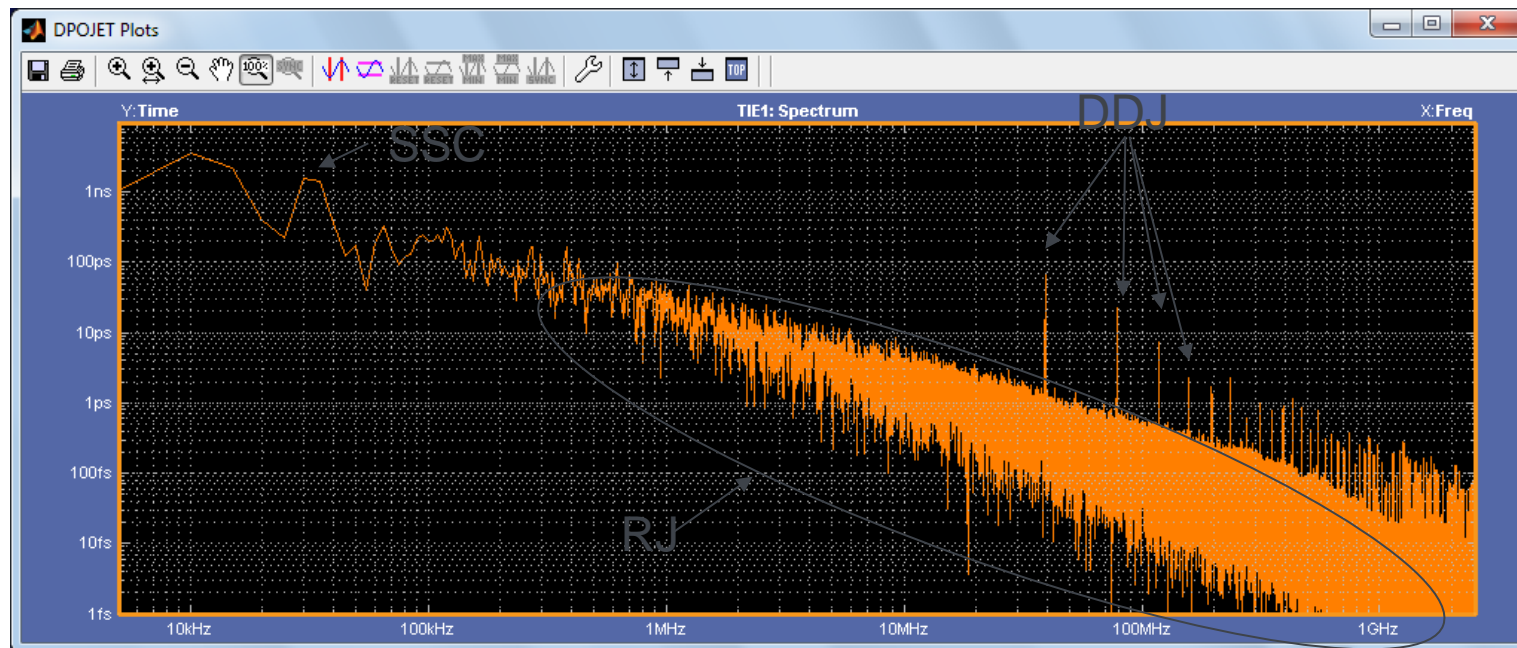
TIE Jitter needs a Reference Clock

- The process of identifying the reference clock is called Clock Recovery.

- There are several ways to define the reference clock:
  - Constant Clock with Minimum Mean Squared Error
    - This is the mathematically "ideal" clock
    - But, only applicable when post-processing a finite-length waveform
    - Best for showing very-low-frequency effects
    - Also shows very-low-frequency effects of scope's timebase
  - Phase Locked Loop (e.g. Golden PLL)
    - Tracks low-frequency jitter (e.g. clock drift)
    - Models "real world" clock recovery circuits very well
  - Explicit Clock
    - The clock is not recovered, but is directly probed
  - Explicit Clock (Subrate)
    - The clock is directly probed, but must be multiplied up by some integral factor

Importance of Clock Recovery

- From spec, "*The jitter measurement device shall comply with the JTF*".

- How do I verify JTF?
  - JTF is difference between input clock (ref) and input clock (unfiltered)
  - Use 1100b or 0011b pattern (proper 50% transition density)
  - Check 1) LF attenuation, 2) -3 dB corner frequency, and 3) slope

Characteristic	Untrained		Trained without SSC support				Trained with SSC support			
	1.5 Gbps	3 Gbps	1.5 Gbps	3 Gbps	6 Gbps	12 Gbps	1.5 Gbps	3 Gbps	6 Gbps	12 Gbps
JTF -3 dB point (kHz) [a] [b]	900 ± 500	1 800 ± 500	900 ± 500	1 800 ± 500	3 600 ± 500	3 600 ± 500	1 300 ± 500	1 838 ± 500	2 600 ± 500	2 600 ± 500
JTF slope (dB/decade)	20	20	20	20	20	20	40	40	40	40
Attenuation at 30 kHz ± 1 % (dB) [c]	N/A	N/A	N/A	N/A	N/A	N/A	61.5 ± 1.5	67.5 ± 1.5	73.5 ± 1.5	73.5 ± 1.5
Maximum Peaking (dB)	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5

JTF vs PLL Loop Bandwidth

- Configuring the correct PLL settings is key to correct measurements

- Most standards have a reference/defined CR setup
  - For example, USB 3.0 uses a Type II with JTF of 4.9Mhz

- Type I PLL
  - Type I PLL has 20dB of roll off per decade
  - JTF and PLL Loop Bandwidth are Equal

- Type 2 PLL
  - Type II PLL has 40dB of roll off per decade
  - JTF and PLL Loop Bandwidth are not Equal
    - For example, USB 3.0 uses a Type 2 PLL with a JTF of 4.9Mhz. The corresponding loop bandwidth is 10.126 Mhz
    - Be careful not to confuse or swap Loop Bandwidth with JTF!

PLL Loop Bandwidth vs. Jitter Transfer Function (JTF)
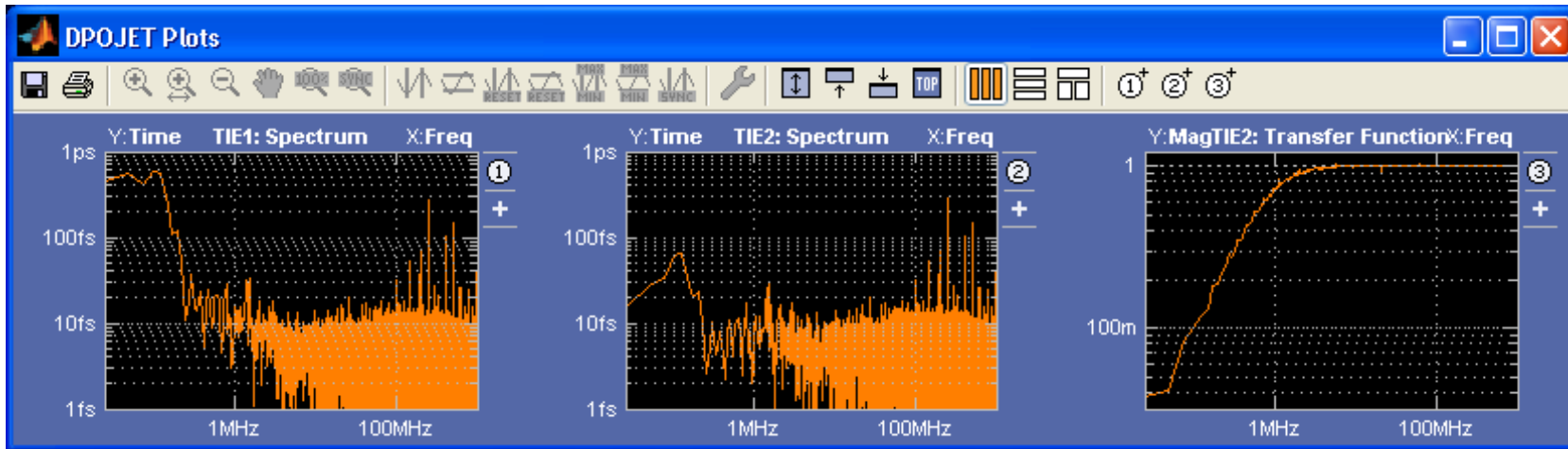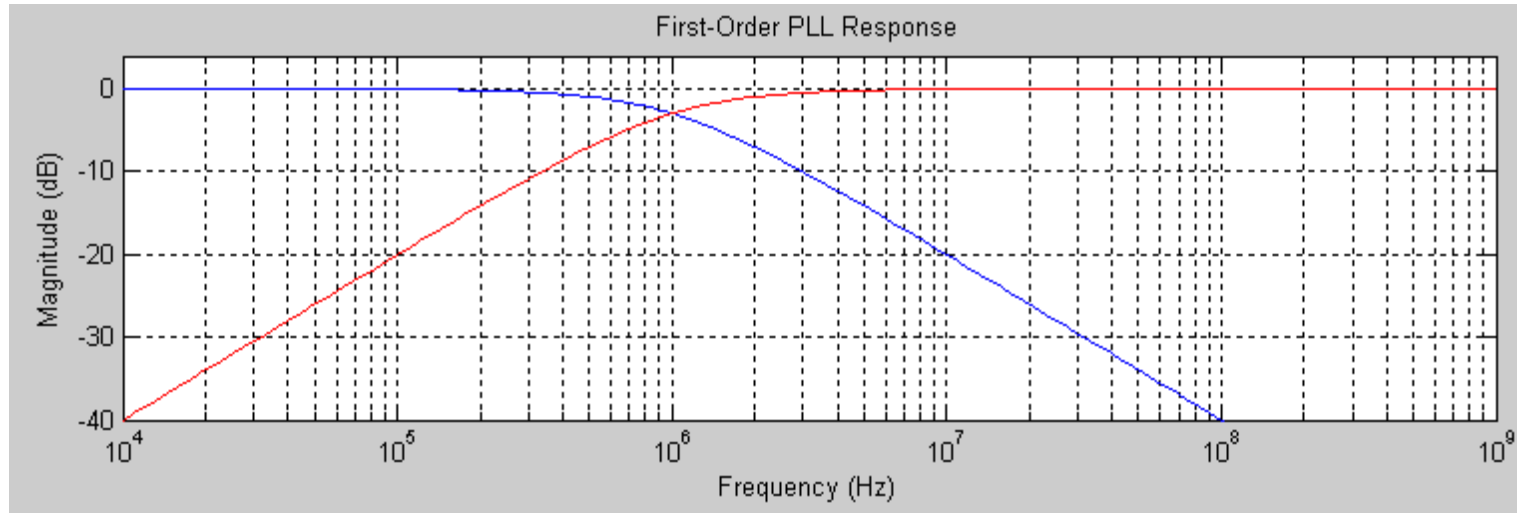
A: Constant Clock Recovery   B: PLL Clock Recovery   Ratio of B/A

Results depend on CR Settings USB 3.0 Example

- The example below shows the effects of using a JTF set to 4.9Mhz vs. Loop Bandwidth set to 4.9Mhz for a Type II PLL

- Note the difference in the jitter that is tracked
  - The results on the left are correct as the JTF was properly set to 4.9Mhz, as opposed to the loop bandwidth
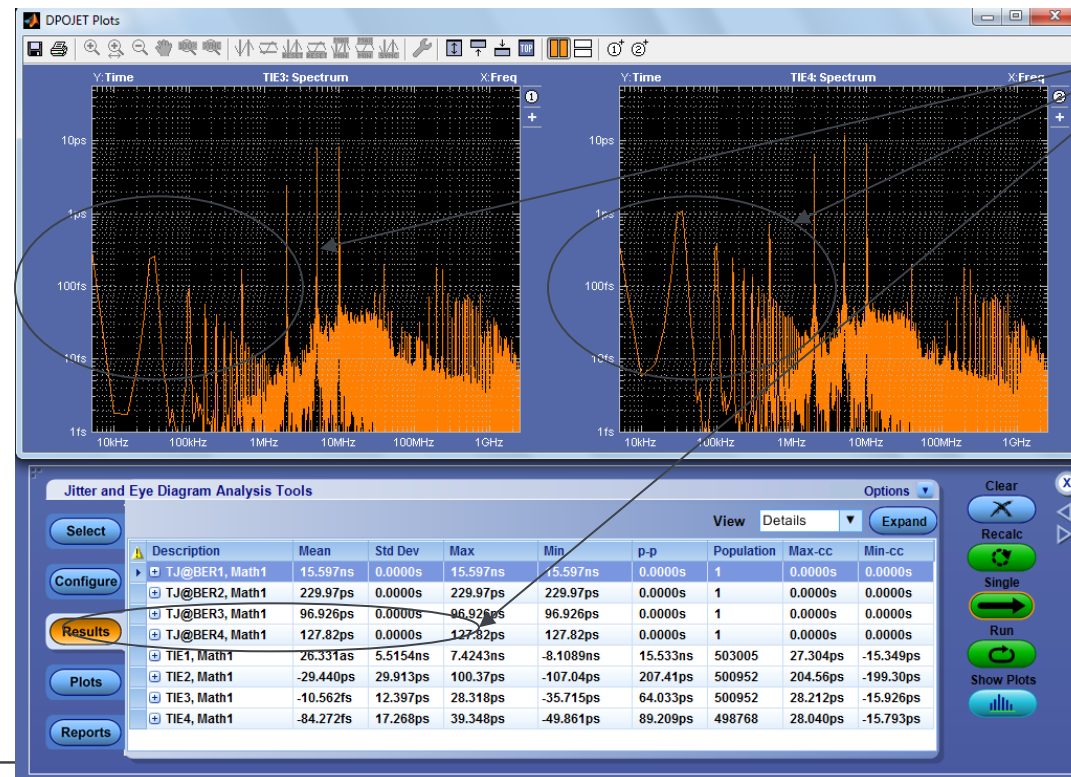
Note: More LF Attenuation for case where JTF set to 4.9Mhz and lower TJ

Further Comparison of PLL Types using Spectrum Plots

Constant Clock
All Jitter Passes Through

Type II
40 dB roll off per decade @ 4.9Mhz
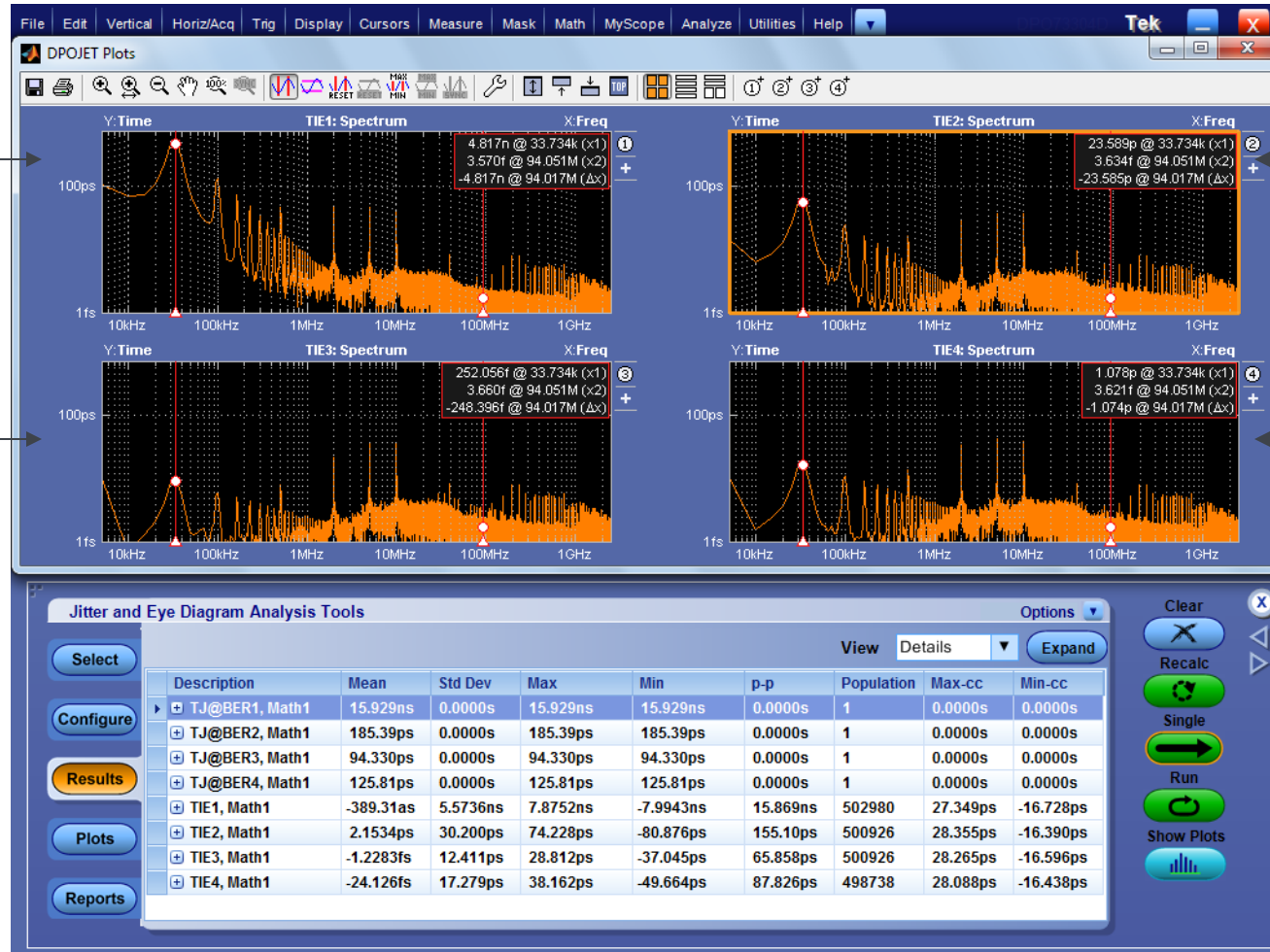
Type I
20 dB roll off per decade @ 4.9Mhz

Type II
40 dB roll off per decade @ 2.3Mhz (JTF to illustrate JTF ! = Loop Bandwidth

First Cursor in each plot is @ 33Khz to illustrate effect on SSC

Further Comparison of PLL Types using Transfer Function Plots

Type II
40 dB roll off per decade @ 4.9Mhz

Type I
20 dB roll off per decade @ 4.9Mhz

Type II
40 dB roll off per decade @ 2.3Mhz (JTF to illustrate JTF ! = Loop Bandwidth)
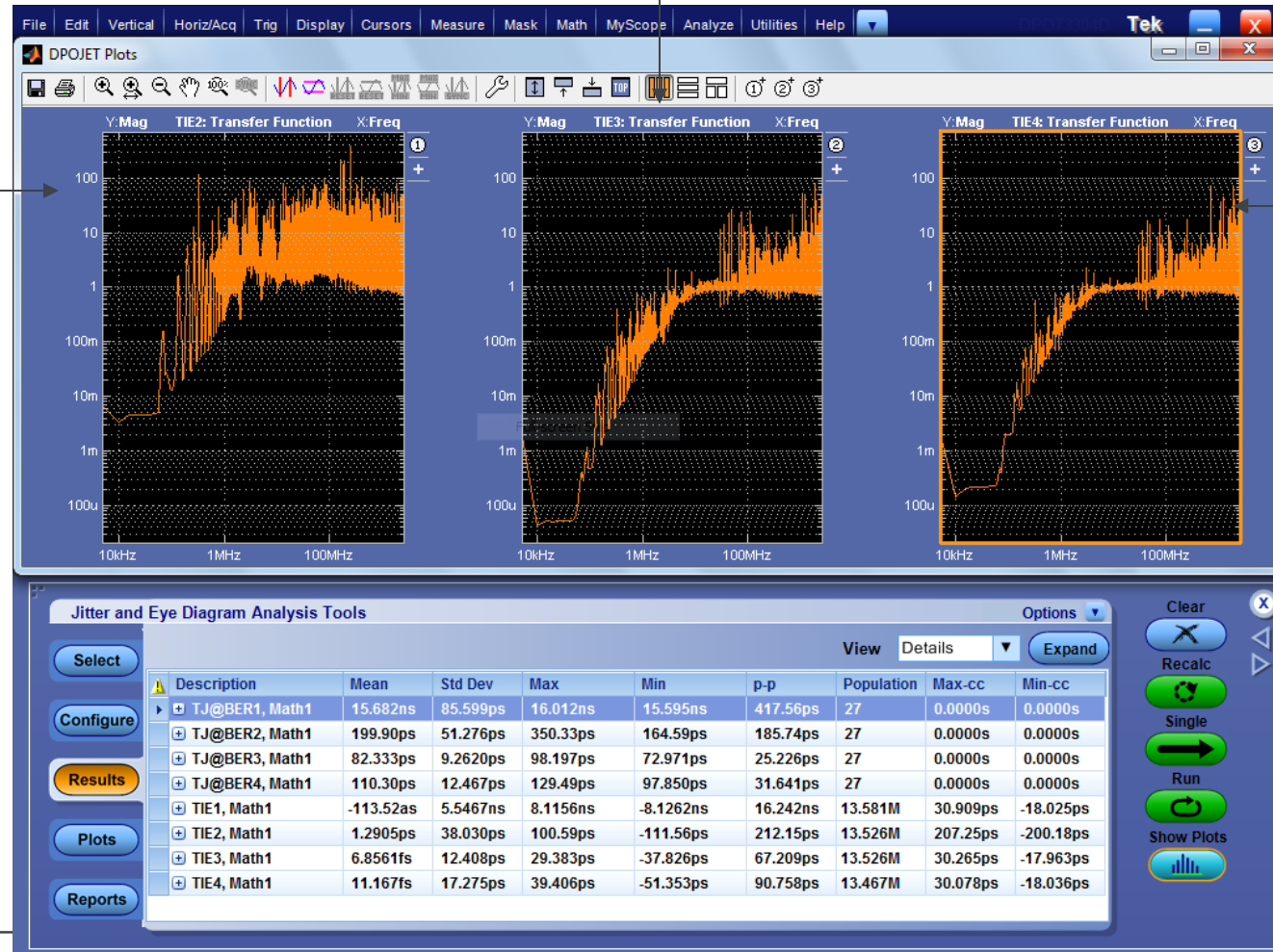
JTF Filtering Effects based on different PLL bandwidths

f_{3dB} = 30 kHz f_{3dB} = 300 kHz f_{3dB} = 3 MHz

How do I know my JTF is compliant?

- **Using DPOJET Transfer Function Plot the JTF can be validated (SAS Example)**

- **Step 1:** Capture 1100b (MFTP) pattern, with SSC on

- **Step 2:** Add TIE (TIE1) measurement and Configure DPOJET PLL settings to match JTF requirements

- **Step 3:** Add TIE(TIE2) measurement and Configure DPOJET Clock Recovery to Constant Clock

- **Step 4:** Add Transfer Function Plot to the TIE1

- **Step 5:** Configure Plot Numerator to TIE1 and Denominator to TIE2

- **Step 6:** Place cursor on plot, the JTF BW should be 3dB point

Jitter for Busy People

Hints, Tips and Common Errors

Using the Jitter Analysis Tools

- Issues manifested in different layers of the protocol stack
  - Crosstalk, jitter, reflections, skew
  - Disparity, encoding or CRC errors

- Where do I start debugging?

- Jitter and Eye Diagram Tools
  - Oscilloscope-based for quick results
    - Fast jitter measurements with
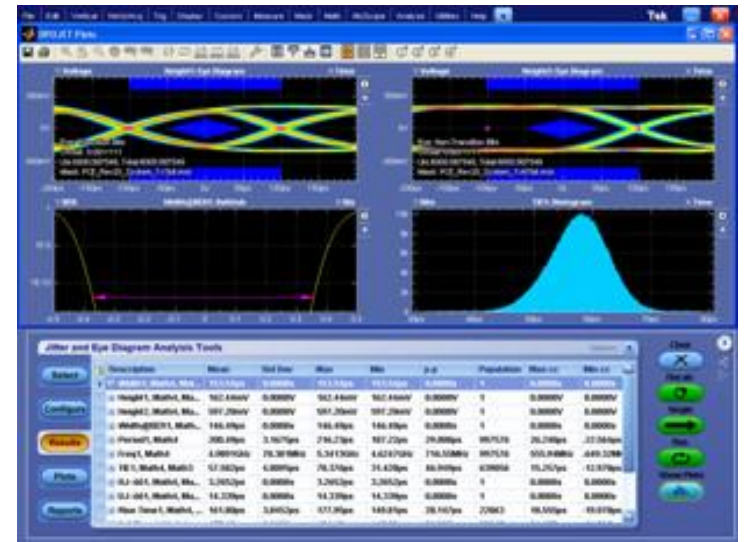   - 'One Button' Jitter Wizard
    - Compare timing, jitter, eye, amplitude measurements
    - User-definable clock recovery, filters, pass/fail limits, and reference levels
  - BERTScope-based for deeper analysis
    - Use stressed pattern modification to determine jitter sensitivity
    - Evaluation with BER results and/or Eye Diagram

Hints for Successful Jitter Analysis

- Verify that signal integrity (i.e. probing) is reasonable
  - Reflections due to mid-bus probing can cause "duplicate" edges

- Check (and consider overriding) your autosets
  - Reference levels are appropriate to the signal
    - If the input signal is differential, consider locking the mid ref to 0 V.
    - A strongly bi-modal histogram often signals a reference level problem.
    - Is the signal noisy enough to require more hysteresis?
  - Explicitly set the signal type to Clock or Data

- Use only the bandwidth you need
  - If the scope BW exceeds the BW of the device being tested, you are adding some scope noise to the measurement results

- Check your RJ/DJ settings
  - Prefer repeating-pattern method over arbitrary-pattern, when practical
    - The "One-Touch Jitter" wizard uses arbitrary-pattern
  - Check that your pattern length is correct

More Hints for Successful Jitter Analysis

- Clock Recovery has a great deal of influence on jitter results. Think about what you're trying to accomplish.
    - Constant-Clock is the most "unbiased"
        - Often best if you're trying to see very-low-frequency effects
        - But it can also show wander in the scope's timebase
    - PLL recovery can model what a real data receiver will see
        - It can track and remove low-frequency effects, allowing you to "see through" to the jitter that really contributes to eye closure
    - Explicit-Clock is appropriate if your design uses a forwarded clock
        - Make sure your probes are deskewed

Hints for looking at Spread-Spectrum Clock

- If you <u>don't</u> want to see the SSC effects, use **TIE** and PLL clock recovery with a bandwidth of at least 1 MHz. A Type-II (2nd-order) PLL will track out the SSC more effectively than a Type-I PLL.

- If you <u>do</u> want to observe the SSC profile:
  - Use a **Period** measurement and turn on a 3rd-order **low-pass filter** (in DPOJET) with a bandwidth of 200 kHz
    - Because Period trends accentuate high frequency noise, the low-frequency SSC trend will be obscured if you don't use a filter
    - You can't use a Frequency measurement directly. The combination of filtering and the reciprocal operation (Freq = 1/Per) cause distortion in the resulting waveshape. (This is a mathematical fact, not a DPOJET defect.)
  - If you use a TIE measurement, you'll see modulation that looks like a sine wave. This is normal. It's because TIE measures phase modulation, which is the integral of frequency. It turns out that the integral of a triangle wave looks very much like a sine wave.

Fast Isolation of Jitter Issues

- **Deep memory capture**
  - Long records needed for low frequency events (SSC, periodic jitter, low speed clocks)
  - Frequency window related to time capture
    - 1 SSC cycle (33kHz) => Need 30us time record

- **Eye Diagram Analysis**
  - Quick visual indicator of voltage and timing performance
  - Related to Bit Error Rate (BER)

- **Debugging Jitter**
  - Knowledge of jitter types and sources aids in debug
  - Common jitter sources
    - Power supply coupling
    - PLL (tracking or overshoot)
    - Limited channel bandwidth and reflections (ISI)
    - Driver imbalance (Rise/fall time asymmetry)

2016-06-17
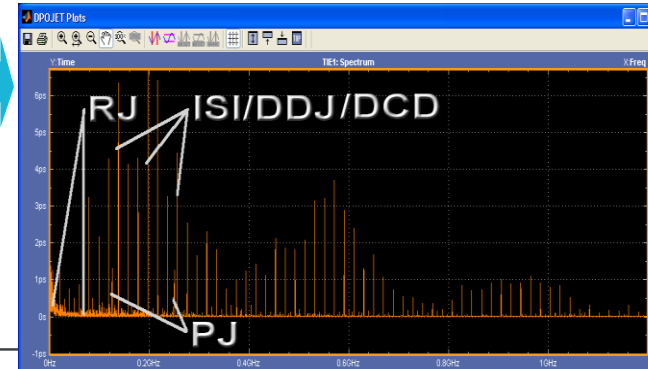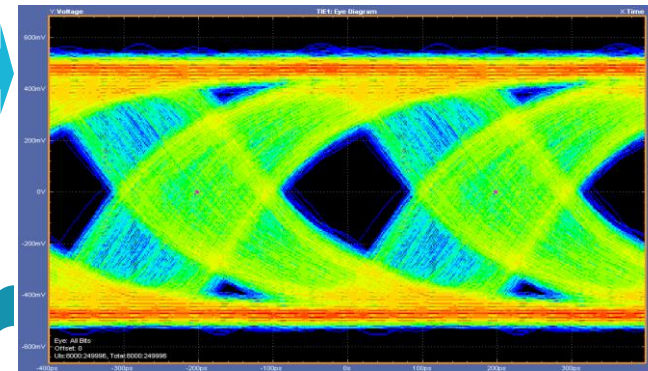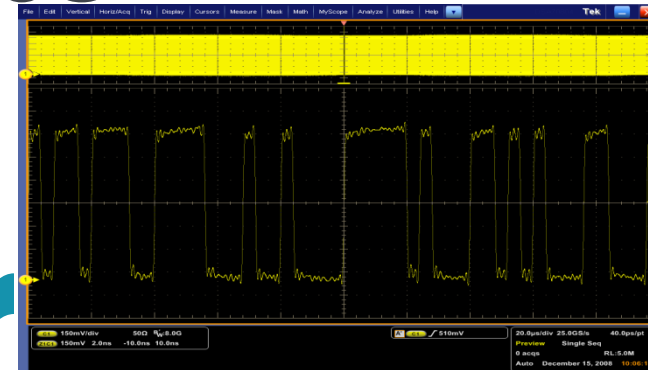
Key Points

- In order to define edges within real signals, we must first identify one or more **reference levels**.
  - Reference levels have a great deal of influence over jitter measurements.
  - Improper choice of reference levels can cause clock recovery problems

- Different type of jitter measurement (TIE, Period, Cy-Cy) are mathematically related but
  - Emphasize (or hide) different parts of the frequency spectrum
  - Can distort modulation shapes due to integration or differentiation

- For TIE measurements, **clock recovery** is used to establish "ideal" clock locations. Choice of clock recovery method and its parameters can greatly influence how jitter is revealed.

Agenda, Part 2

- Motivations for Jitter & Noise Analysis

- Jitter/Noise Theory

- Jitter/Noise Measurements on Real Time scopes

- Q & A

Anatomy of a Serial Data Link
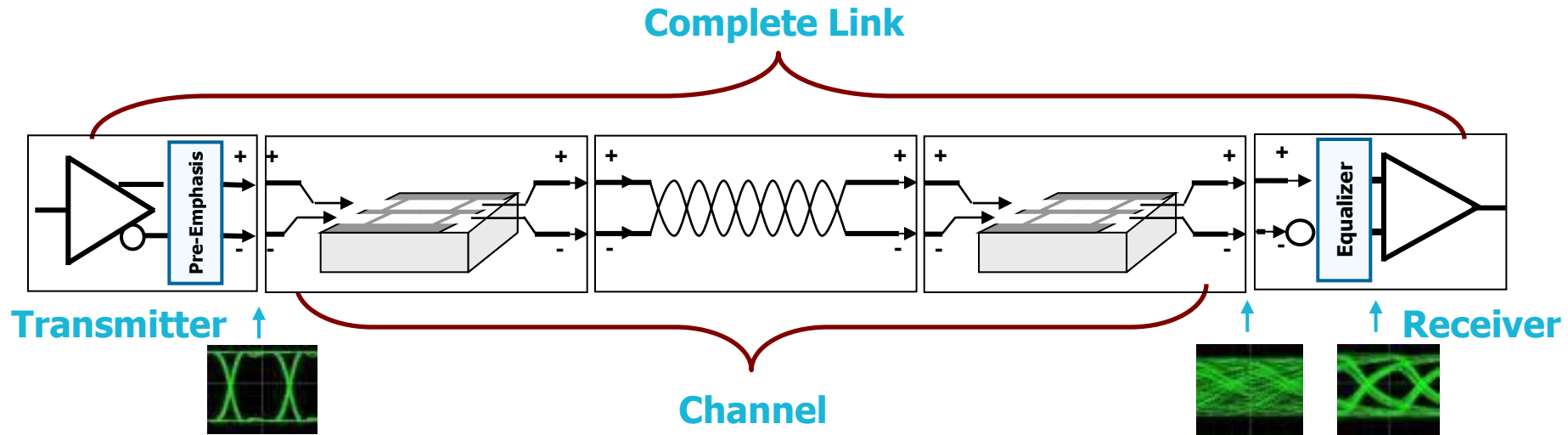
Design Goal: 0 errors

Practical Goal: Bit Error Rate < Target BER

- Since BER is the ultimate goal, why not measure it directly?

Serial Data Link Integrity = Bit Error Rate

- Bit Error Ratio Testers (BERTs) are the tools for measuring BER directly

- Why not use **ONLY** BERTs for Serial Data Link Analysis?
  - Difficult to model/emulate equalizer
  - Measurements could take a very long time
  - Instruments are more expensive and less flexible
  - Less analysis of the **root causes** of link impairments

- Alternative approach: use a scope and advanced analysis tools
  - Easily move from Compliance to Debug
  - Better equipped to identify root causes of eye closure
  - Equalizer can easily be modeled
  - More cost effective
  - Faster throughput

Characteristic	Units	Minimum	Nominal	Maximum	Reference
Tx RJ [b] [c] [d]	UI	0.135 [e]	0.150 [f]	0.165 [g]	5.8.4.6.1
Tx SJ [c]	UI	See figure 129 and figure 130			5.8.5.7.4.5
WDP at 6 Gbps [b] [h]	dB	13		14.5	
NEXT offset frequency [i] [j] [k]	ppm	2 500			
Total crosstalk amplitude [i] [k]	mV_{rms}	4			
Receiver device configuration [l]					

[a] For a characteristic with only a nominal value, the test setup shall be configured to be as close to that value as possible while still complying with other characteristics in this table.
[b] For characteristics with minimum and maximum values, the test setup shall be configured to be within the range specified by the minimum and maximum values. The range shall not be used to define corner test conditions required for compliance.

- BER requirements have been translated to Jitter and Noise budgets

Why Measure Jitter *and* Noise?

- Link Model: Transmitter + Channel + Receiver

- Transmitter generates a stream of symbols

- Receiver uses a slicer to make a decision on the transmitted symbol

- The **Bit Decision** is made by **sampling (t)** within the symbol interval and comparing the sliced data to the **decision threshold (v)**

- **Jitter** impairs the time slicing position

- **Noise** impairs the decision threshold
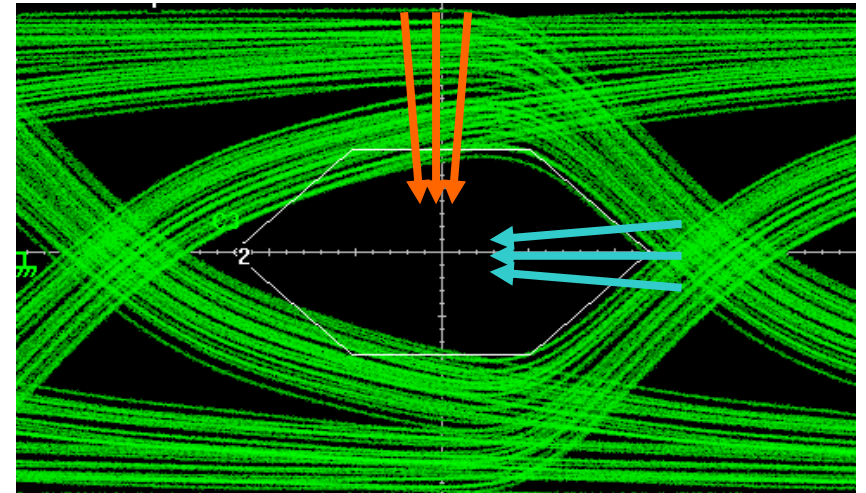
Jitter combined with Noise Analysis is a better predictor of BER performance!

A Quick Look at Jitter and Noise Duality

- Jitter analysis evaluates a waveform in the horizontal dimension based on when the waveform crosses a horizontal reference line.

- **Jitter decomposition** based on spectral analysis of Time Interval Error
  - Individual jitter components can be separated (i.e. PJ, RJ, DDJ, etc.)
 - TJ can then be estimated at a target BER level

- Noise analysis evaluates along a vertical dimension on the basis of crossings of a vertical reference line, typically in the center of the eye.

- **Noise decomposition** based on spectral analysis of voltage error
  - Individual noise components can be separated (i.e. PN, RN, DDN, etc.)
  - TN can then be estimated at a target BER level

Jitter and Noise Decomposition

- Jitter and Noise Decomposition provide deep insight into BER
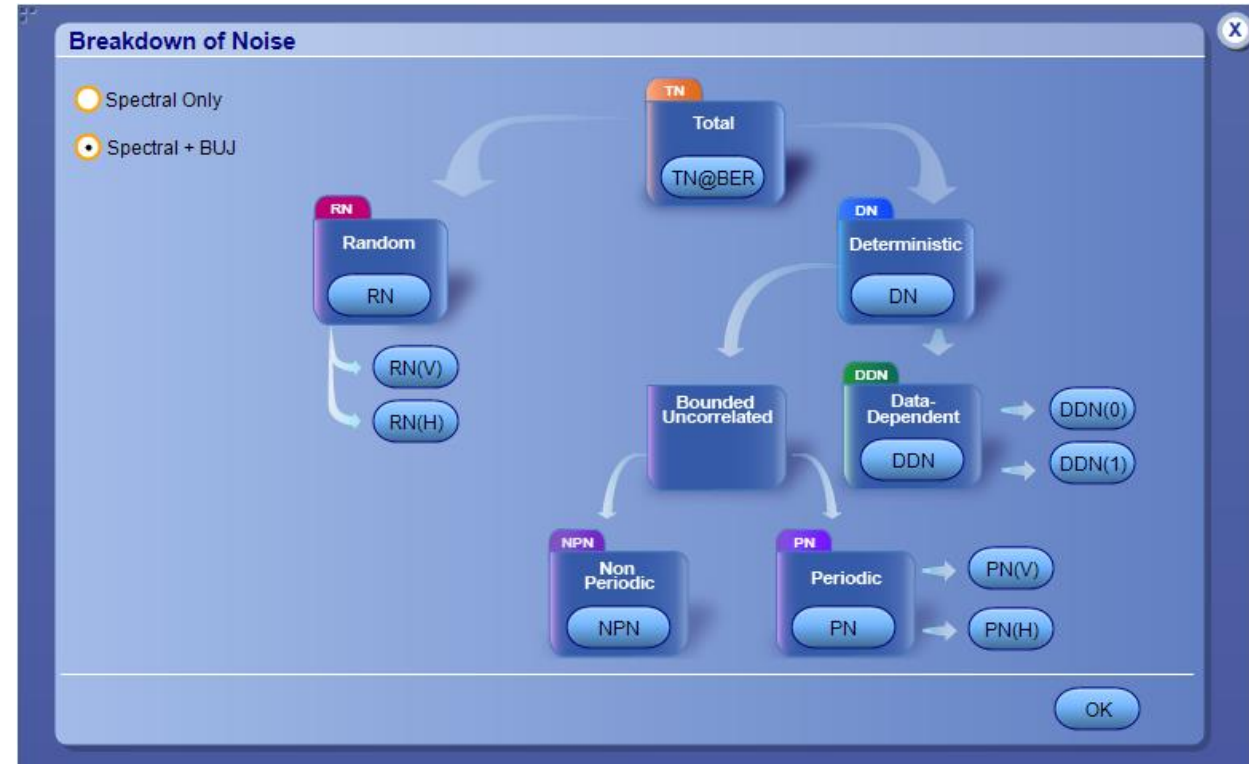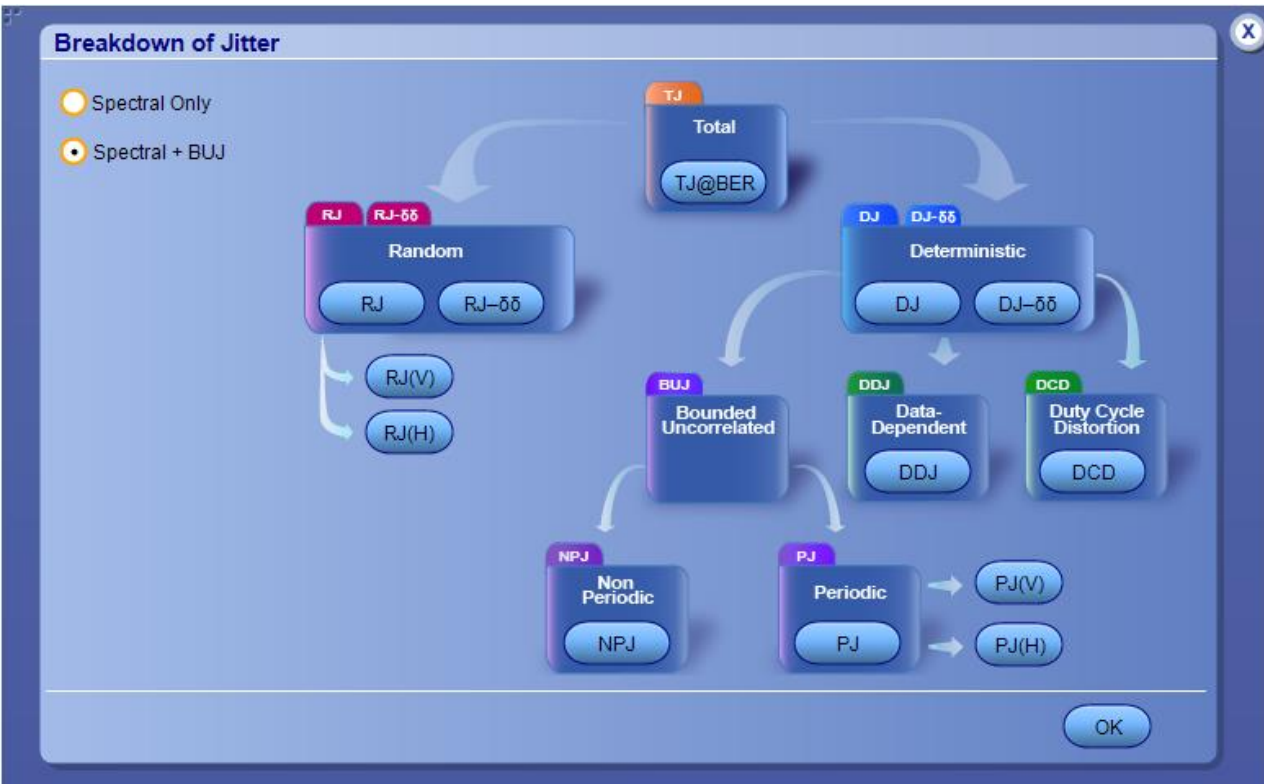
Full Jitter Analysis vs. Mask Testing

- Jitter separation analysis is able to extrapolate total jitter or eye closure at various Bit Error Rates at a specific voltage threshold ▬ but it doesn't reveal the statistical eye closure at any other voltage.

- Conventional mask testing considers both time and voltage ⬡ but cannot extrapolate eye closure at low BER.
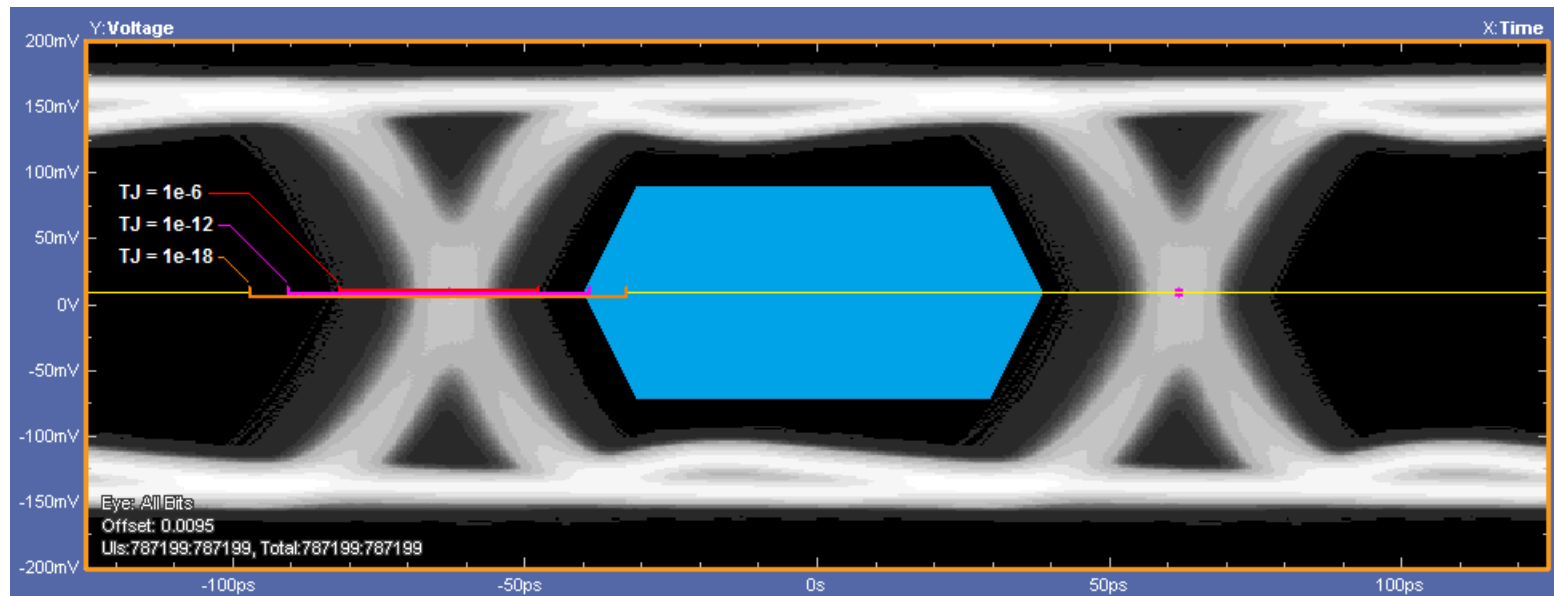
Can we combine the best of both?

Statistical Jitter + Noise Analysis

- By jointly analyzing Jitter and Noise, behavior at <u>all</u> points in the eye can be extrapolated at low BER

- The methodology is analogous to current jitter analysis, but is performed across both dimensions of the eye
    - Jitter and noise are separated into components (Random, Periodic, Data-Dependent,…)
    - The components are reassembled into a model that allows accurate extrapolation.
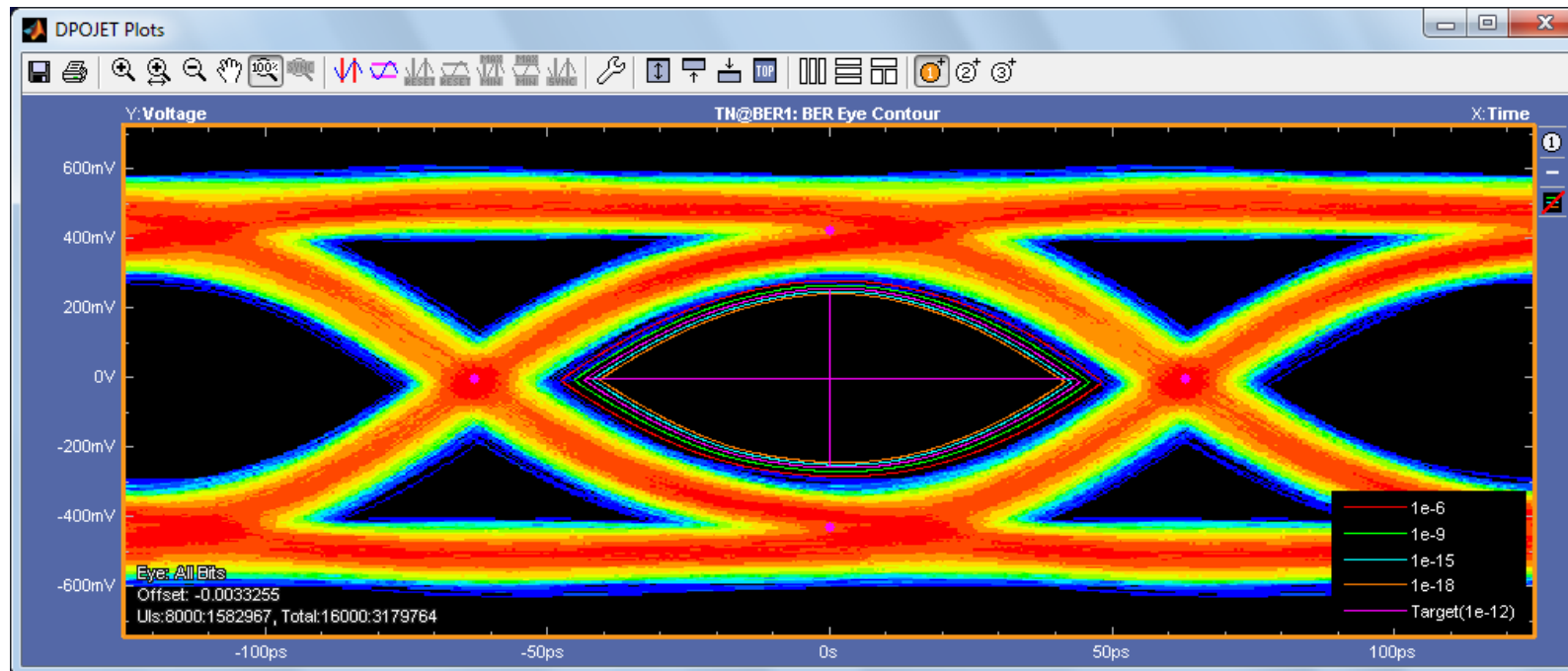
Timing-Induced Jitter

- Since jitter is defined as a shift in an edge's time relative to its expected position, it is easy to think of jitter as being <u>caused</u> by horizontal (chronological) displacement.

- Note that the displaced edge (green) has not moved vertically in this example.
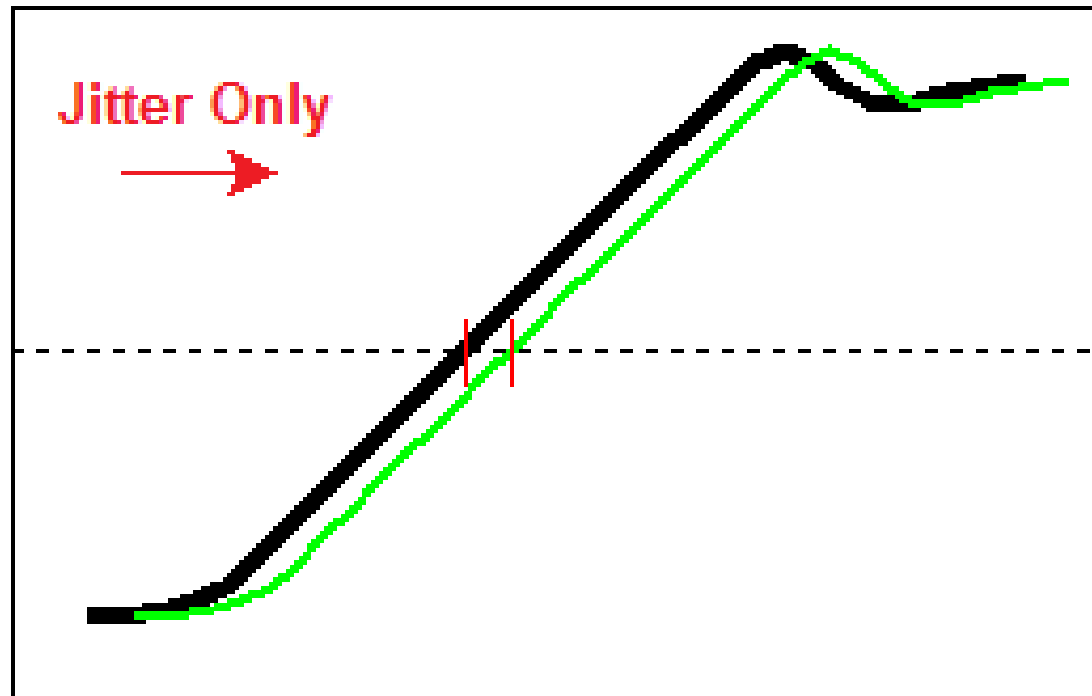
Noise-Induced Jitter

- Consider a burst of voltage noise (right) that displaces a waveform vertically.
  - In this case, the displaced edge (green) has not moved horizontally.
- The jitter as measured at the chosen reference voltage is identical in these cases!
  - So, why should we care?
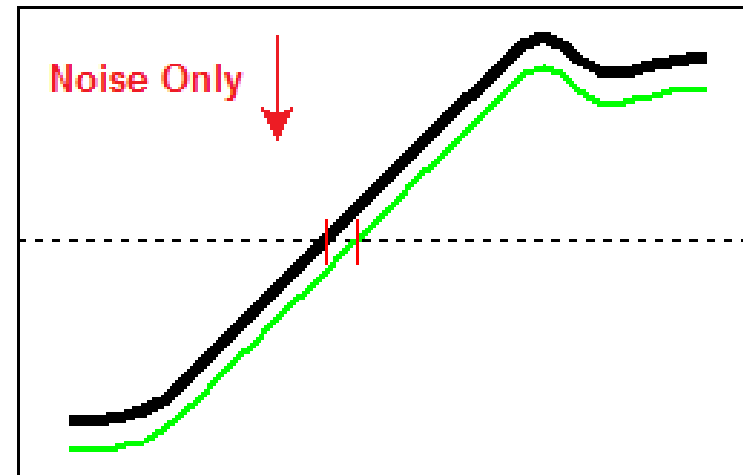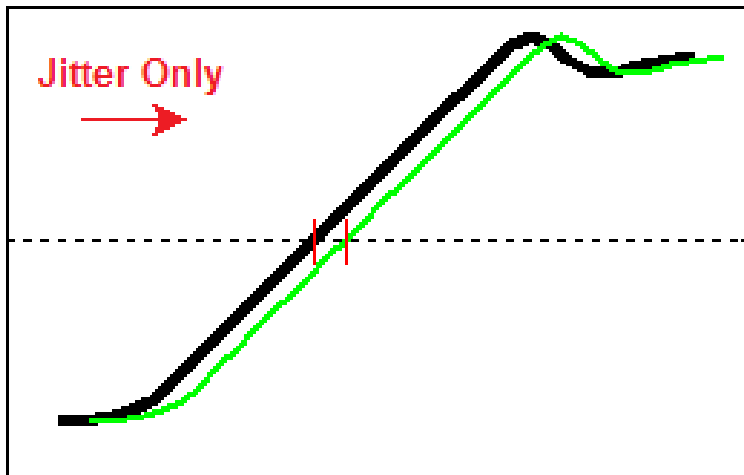
- Two fundamentally different effects have caused the same amount of jitter, and either one will close the eye by the same amount <u>at this reference voltage</u>, but:
  - They will have different effects at other voltages where the slew rate is different.
  - Their differences give insight to root cause

Noise-to-Jitter (AM-to-PM) Conversion

- Since waveform transitions are never instantaneous, the slope (slew rate) of the edge acts as a gain constant that controls how effectively noise is converted to "observed jitter".

Actual Impairment = Noise
Observed Jitter = Noise / Slew Rate

Slew Rate (volts/ns)

Example:

Noise = 10 mV
Slew Rate = 4 V/ns

Jitter = (10e-3 V) / (4 V / 1e-9 s)

= 2.5e-12 = 2.5 ps
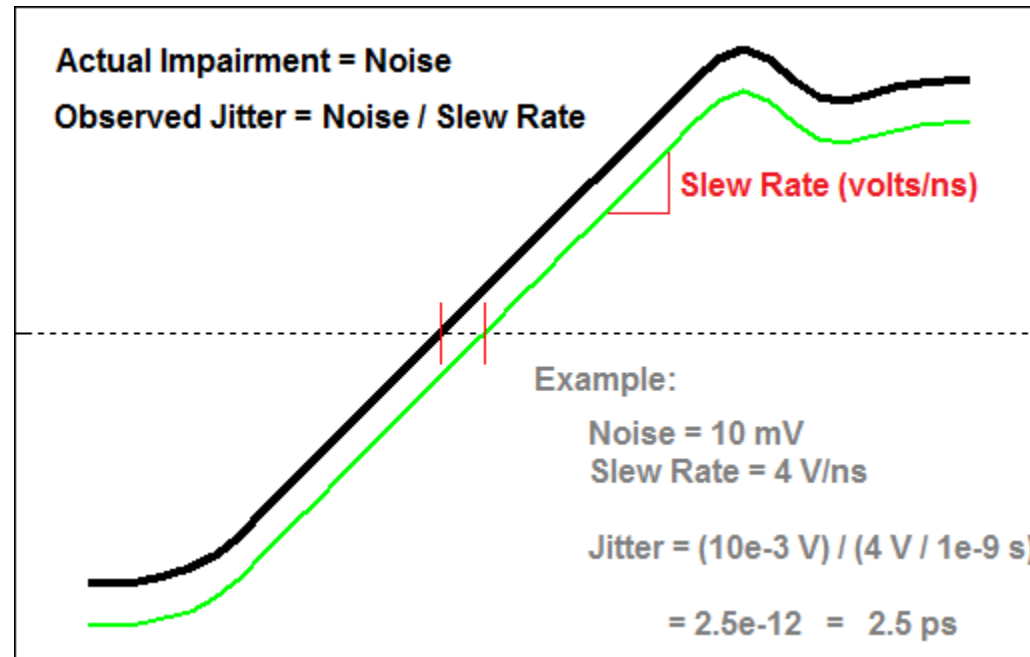
- An analogous effect occurs when voltage is measured at the center of the bit interval: If the slew rate is not zero, then jitter will cause PM-to-AM conversion and appear as noise!

Horizontal and Vertical Components of RJ

- We can think of RJ as being composed of two components.

  ◦ Horizontally induced: RJ(h)

  ◦ Vertically induced: RJ(v)
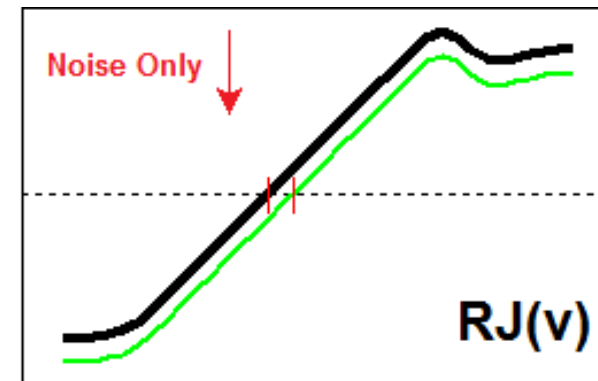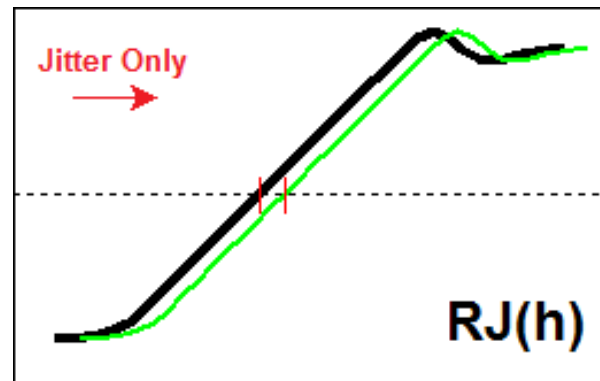
- Since these two components are uncorrelated with each other, they add in the RSS sense:

$$RJ = \sqrt{RJ(h)^2 + RJ(v)^2}$$

- Similarly, PJ can be decomposed into PJ(h) and PJ(v) based on root cause

Horizontal and Vertical Components of RN

- We measure noise at a reference point in the bit interval (usually 50%)
- If slew rate isn't zero, jitter (horizontal displacement) causes observed noise
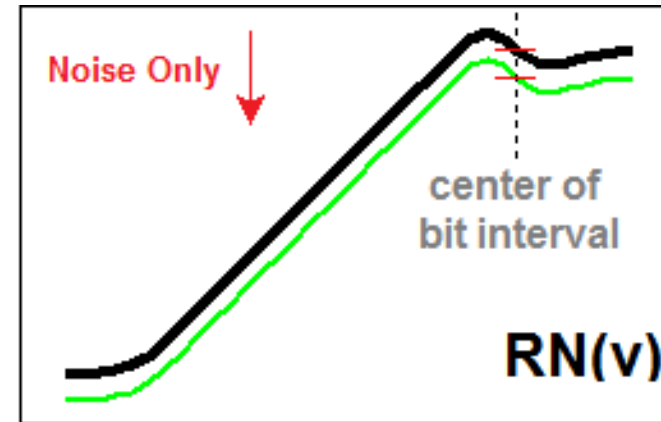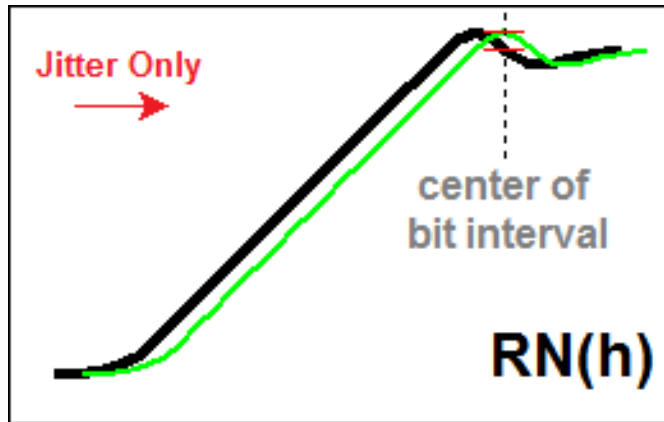
- So as with RJ, RN can be decomposed into components:
  - Horizontally induced: RN(h)
  - Vertically induced: RN(v)
- Similarly, PN can be decomposed into PN(h) and PN(v) based on root cause

Noise to Jitter and Jitter to Noise Conversion

We can separate the noise contribution of jitter for diagnostic purposes by breaking RJ into RJ(v) and RJ(h)

Consider: an "ideal" edge in a pattern actually has two impairments:

- Jitter(h) (see the blue trace)

- and Noise
  (note that both of Jitter *and Noise*
  result in jitter on edge)

The Combined response (bottom right) includes the jitter caused by noise

Non-impaired bit edge
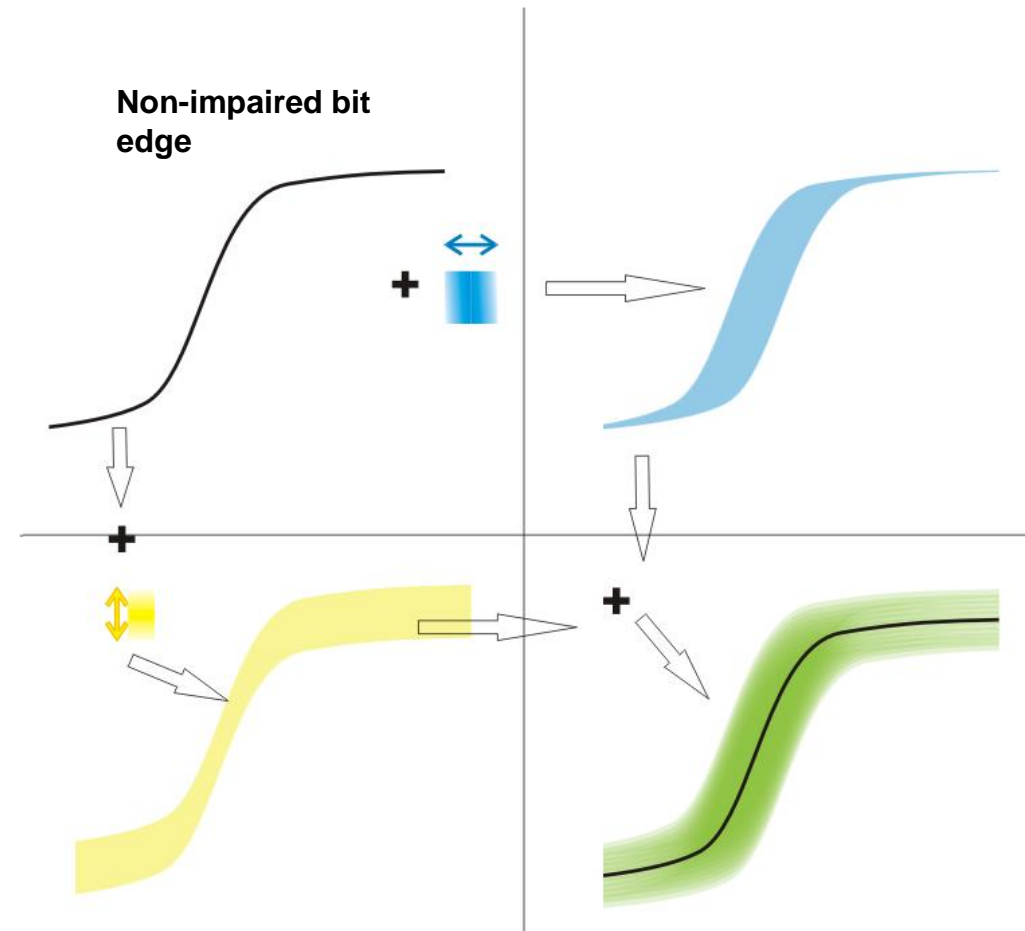
DPOJET and 80SJNB are the *only* tools that will show you this separation, and thus give you an important troubleshooting hint: e.g. is it *crosstalk* causing trouble, or the clocks?

Construction of the BER Eye

- Consider a very simple pattern: 7 bit repeating
- Overlay multiple segments of the 7-bit pattern. Each one has noise and jitter, so although the bit pattern is clear, they follow many slightly different paths:
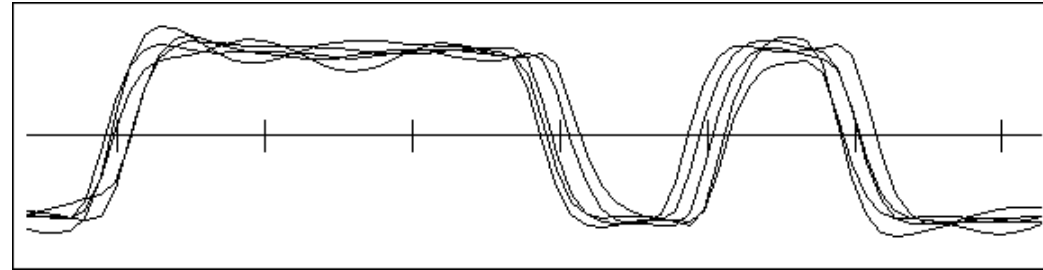
- Average many pattern repeats together. Everything that is uncorrelated with the pattern averages out. What remains is called the '**correlated waveform**'.
  - This waveform fully characterizes DDJ, DCD, DDN, ISI – all data dependent effects
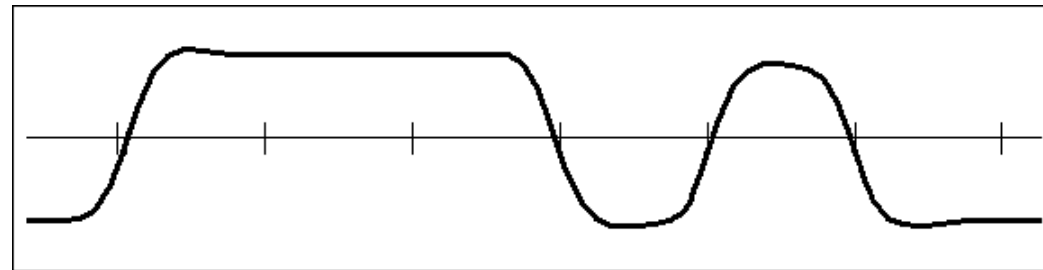
Construction of the BER Eye – Part 2

- The correlated waveform can be snipped into individual bits and overlaid to form an eye diagram, using the recovered clock as the alignment reference. This forms the '**correlated eye**':
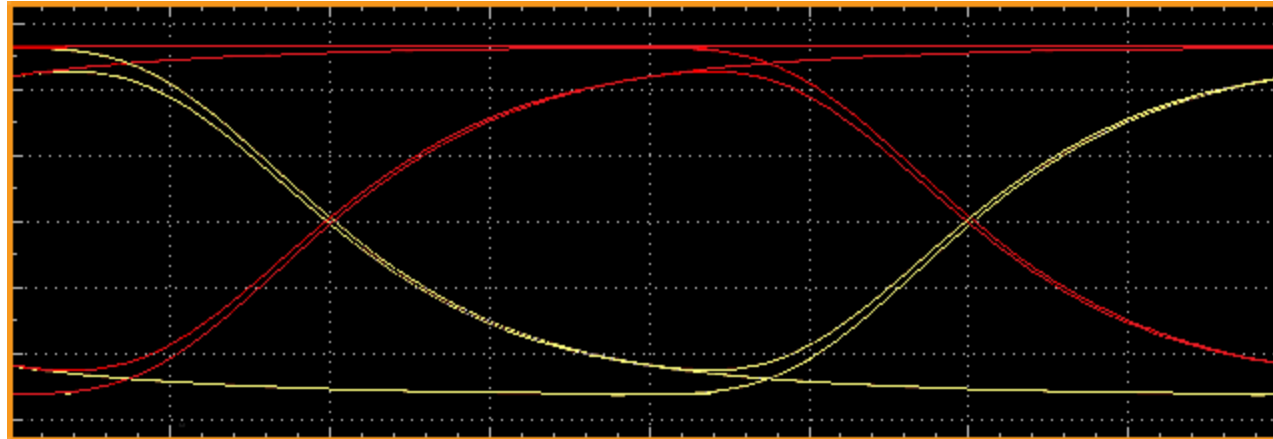
- ◦ There is one waveform trajectory for each bit in the pattern

- ◦ Here we have shown the '1' bits in red, and the '0' bits in yellow

- ◦ This is how your eye would look if there were absolutely no RJ, PJ, RN, PN, or crosstalk

Construction of the BER Eye – Part 3

- Spectral jitter separation is used to find PDFs of the random and periodic jitter.

- The RJ and PJ PDFs are convolved to find the **uncorrelated jitter PDF** (red)

- A similar analysis of the noise yields the **uncorrelated noise PDF** (blue)

  ◦ Care must be taken to properly account for AM-to-PM and PM-to-AM conversion in these steps; otherwise some noise or jitter would be 'double-counted'.

- Two-dimensional convolution is used to create a joint PDF of uncorrelated jitter
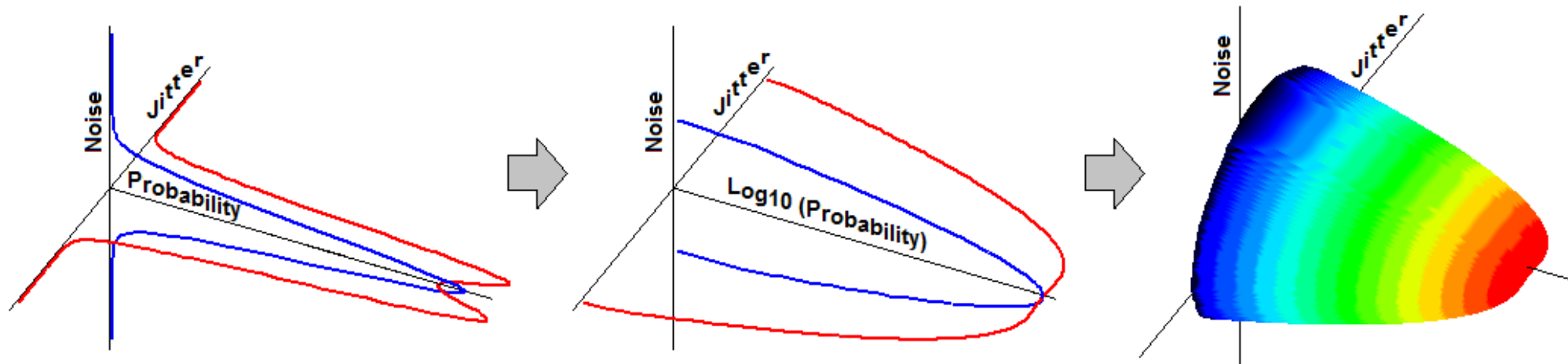
Construction of the BER Eye – Part 4
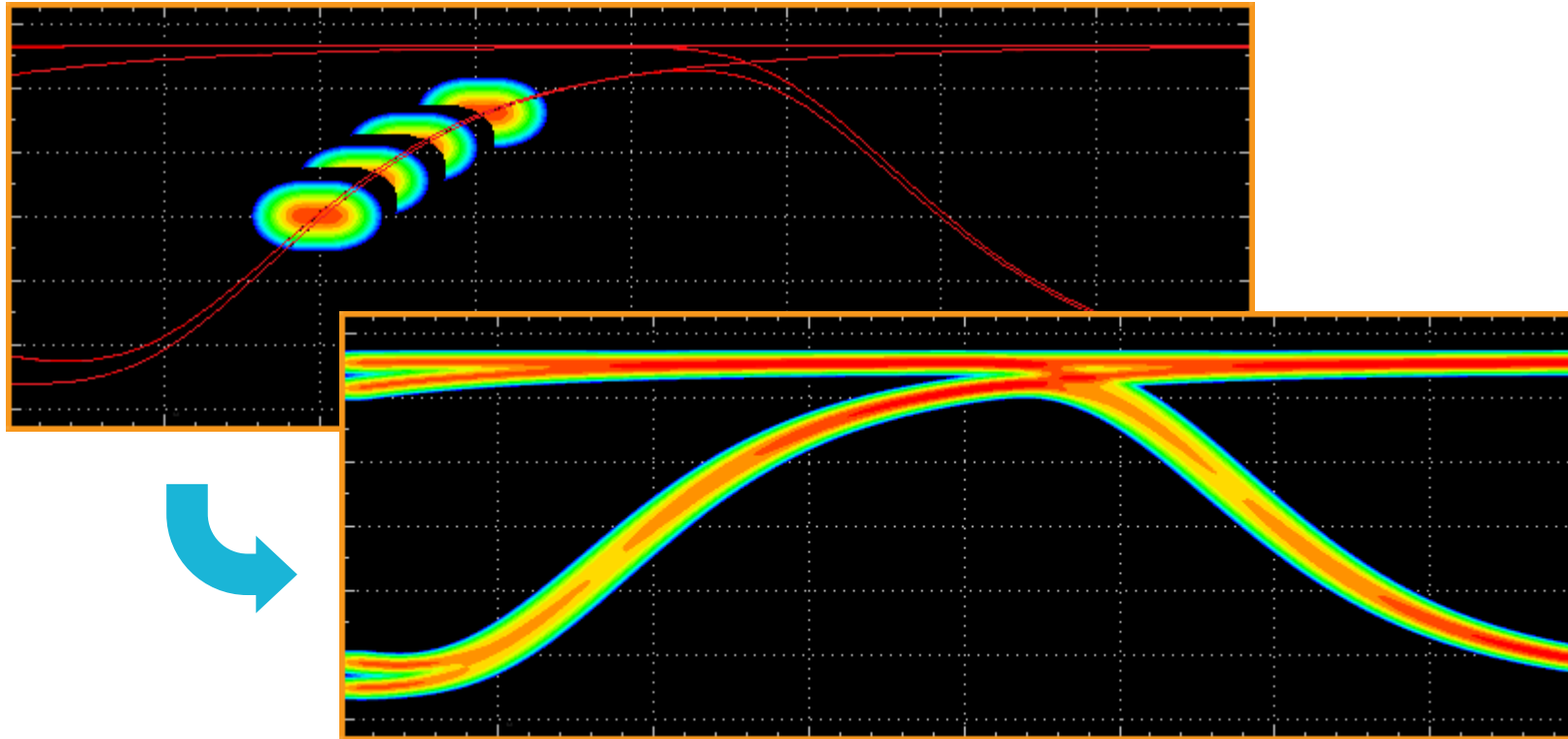
- The jitter/noise set is convolved (two-dimensionally) with the correlated eye for the '1' bits to get the **overall** (correlated + uncorrelated) PDF for '1' bits

Construction of the BER Eye – Part 5
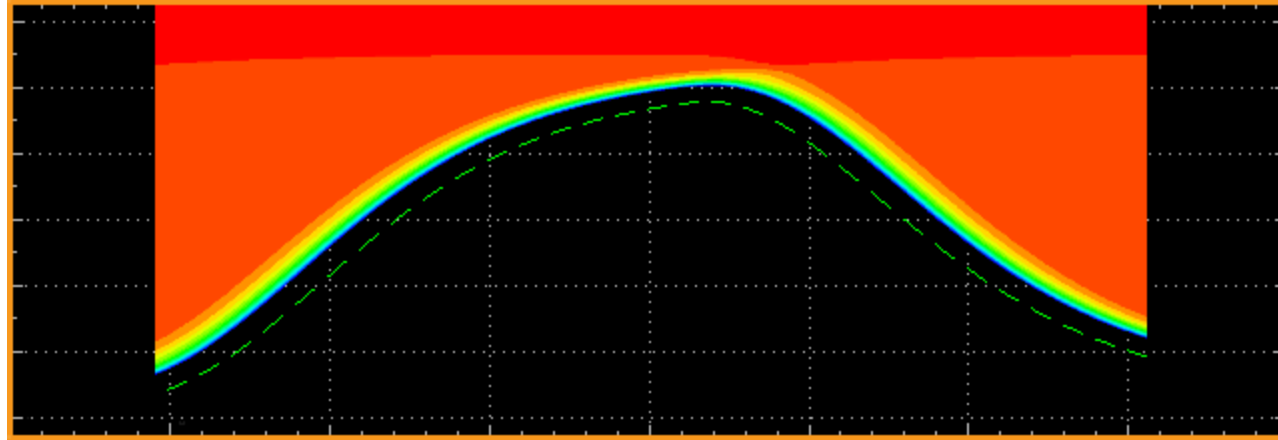
- The '1' bit PDF is integrated vertically (from bottom to top) to get the '1' bit CDF (Cumulative Distribution Function)

  ◦ In this color-graded view, each color represents a particular BER level

Construction of the BER Eye – Part 6
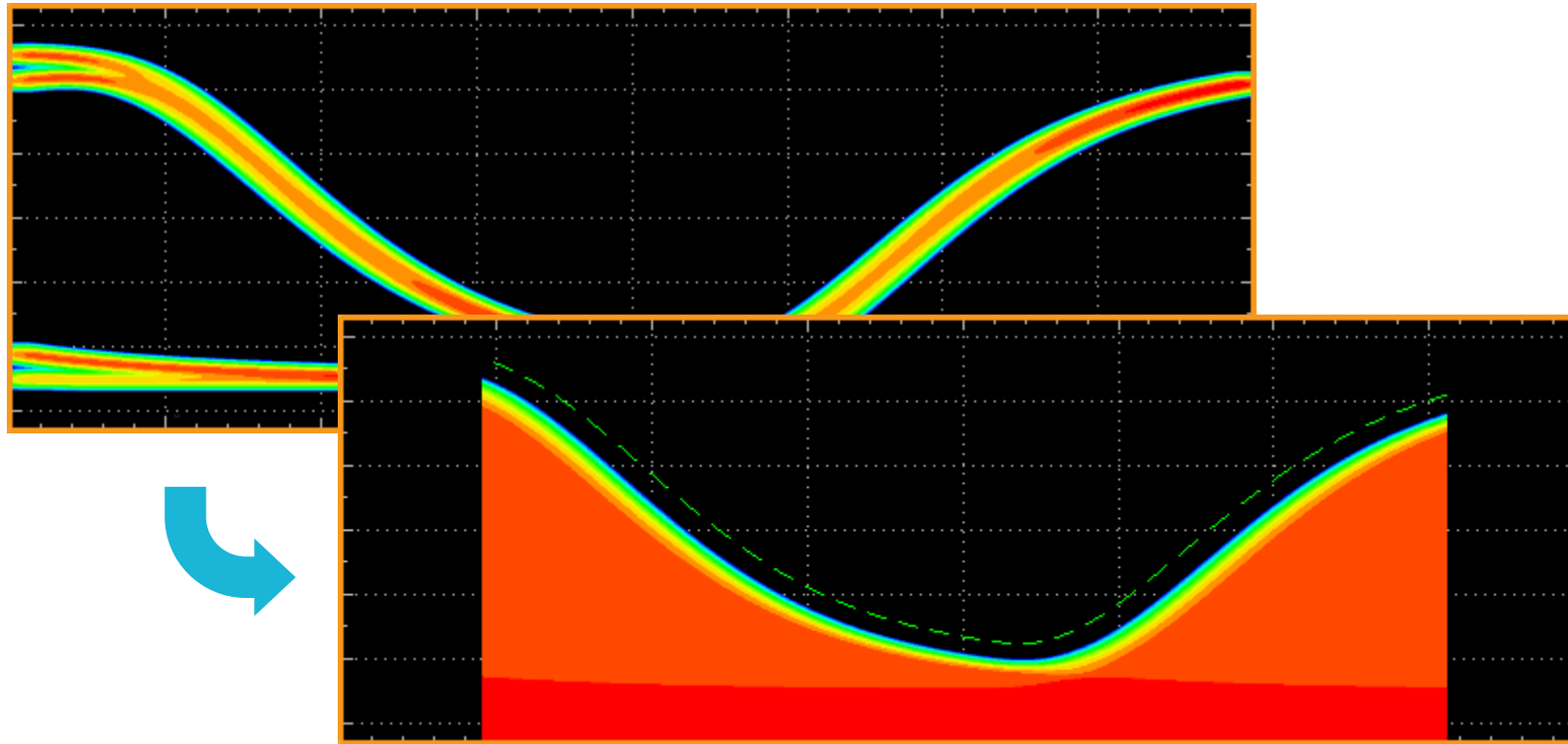
- A similar treatment for '0' bits yields the '0' bit CDF

Construction of the BER Eye – Conclusion
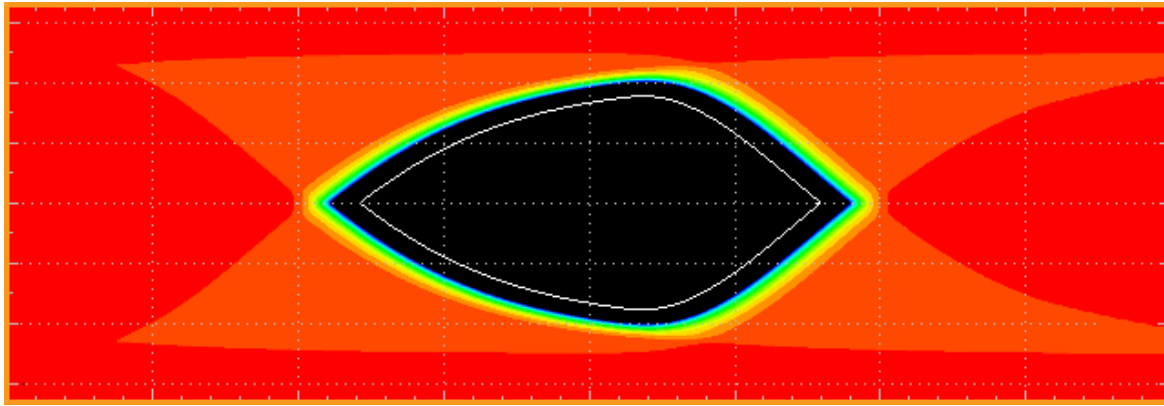
Color-Graded View
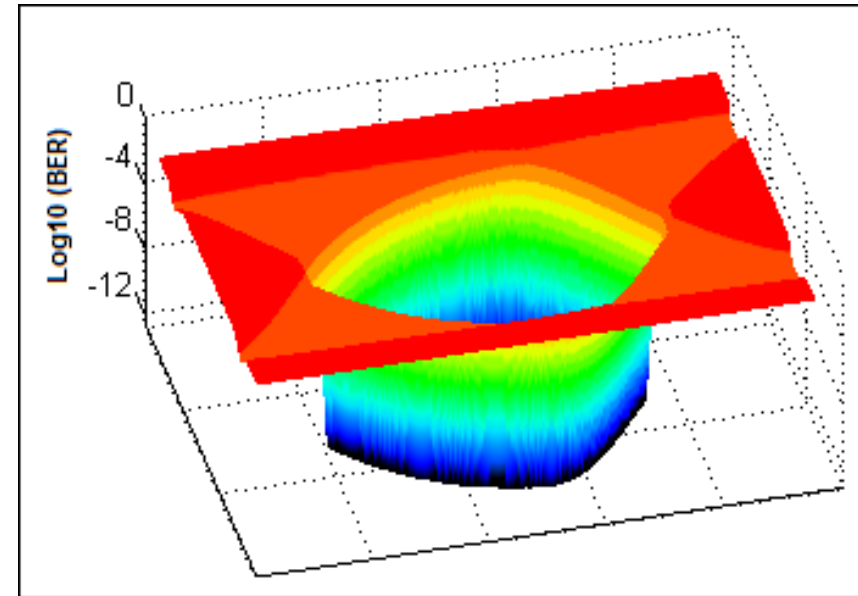
3D View

- The '1' bit and '0' bit CDFs are added to get the overall "BER Eye"
  - A particular BER contour can be found in the 3D version of this plot by slicing it horizontally, or by extracting a specific color on either version
  - Since this 'eye' looks rather unconventional, DPOJET extracts the BER contours and then overlays them with the rendered eye.

Benefits of Noise Analysis

- Jitter combined with noise analysis enables us to quickly determine the eye opening at a target bit ratio

- BER contour plots provide a quick multi-dimensional view of the progression of eye closure as bit error rate increases

- But, that is not the complete story. Understanding and decomposing the effects conversion of jitter to noise and vice versa provides insight into the root cause of eye closure

What Scope Platform for Jitter and Noise Analysis?

System

Add-In
Cards

Chip
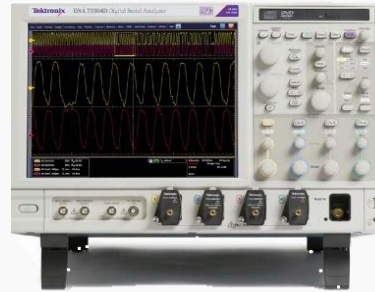
Real-time Scopes

The most versatile tool for all areas of high-speed digital and analog applications

✓ Single shot acquisition ideal for post processing
✓ Most advanced trigger system to identify unique events
✓ Most flexible software-based clock recovery
✓ Debugging and Troubleshooting
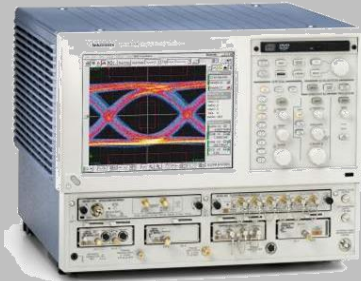
Sampling Scopes

For applications that place top priority on waveform precision

✓ Over 60dB of dynamic range, ideal for PAM
✓ High BW to 100Ghz
✓ Repetitive waveforms
✓ Very Low Jitter Noise Floor

R&D   Verification/Compliance   Manufacturing

Noise and Jitter Measurements with DPOJET

- Model system performance at a target bit error ratio

- Understand the sources of jitter and noise and the conversion of jitter to noise and noise to jitter

- Quickly determine the bit error rate at multiple levels using contours

- Correlated Eye provides insight into the effects of channels and equalization
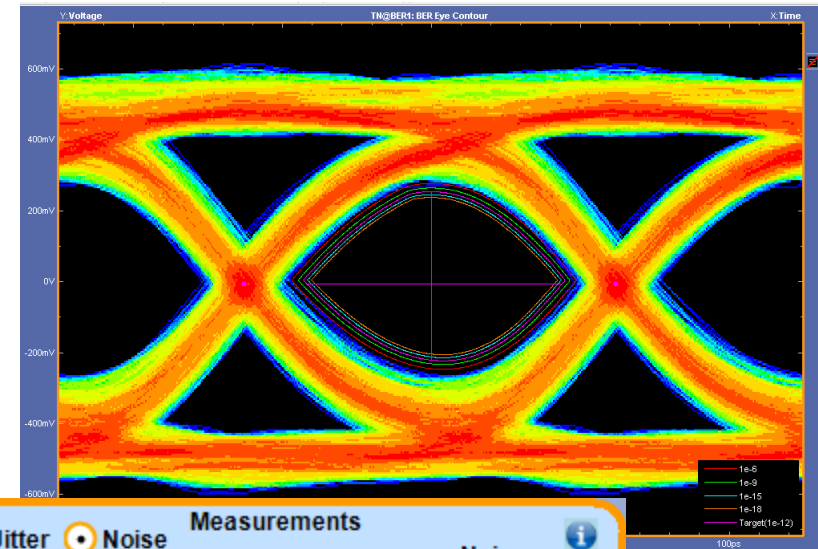
Jitter and Noise Analysis with DPOJET

- Complete decomposition of both Jitter and Noise
  - Jitter: TJ@BER, RJ, DJ, RJdd, RJ(v), RJ(h), DJdd, PJ, PJ(h), PJ(v), NPJ, DCD, DDJ, J2, J9, F/n, Subrate
  - Noise: TN@BER, RN, RN(v), RN(h), DN, DDN, DDN(0), DDN(1), PN, PN(v), PN(h), Unit Amplitude
- Data Visualization
  - Histogram, Time Trend, Data Array, Spectrum, Phase Noise, Transfer Curve, Eye Diagram, Bathtub, Waveform Database for Mask Hit Violations, Bathtub, Composite Histogram
  - NEW: Composite Noise Histogram, Noise Bathtub, BER Eye Contour, PDF Eye, BER Eye, Correlated Eye
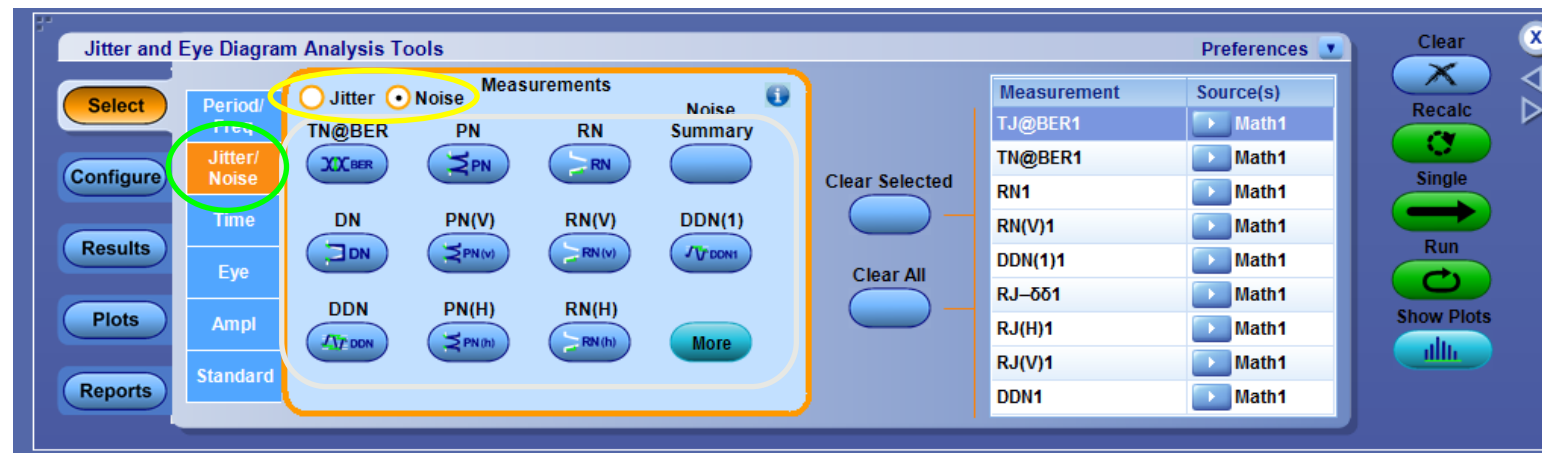
Visualization of Eye Closure

- Noise Bathtub shows the vertical eye closure

- Traditional bathtub shows the horizontal eye closure
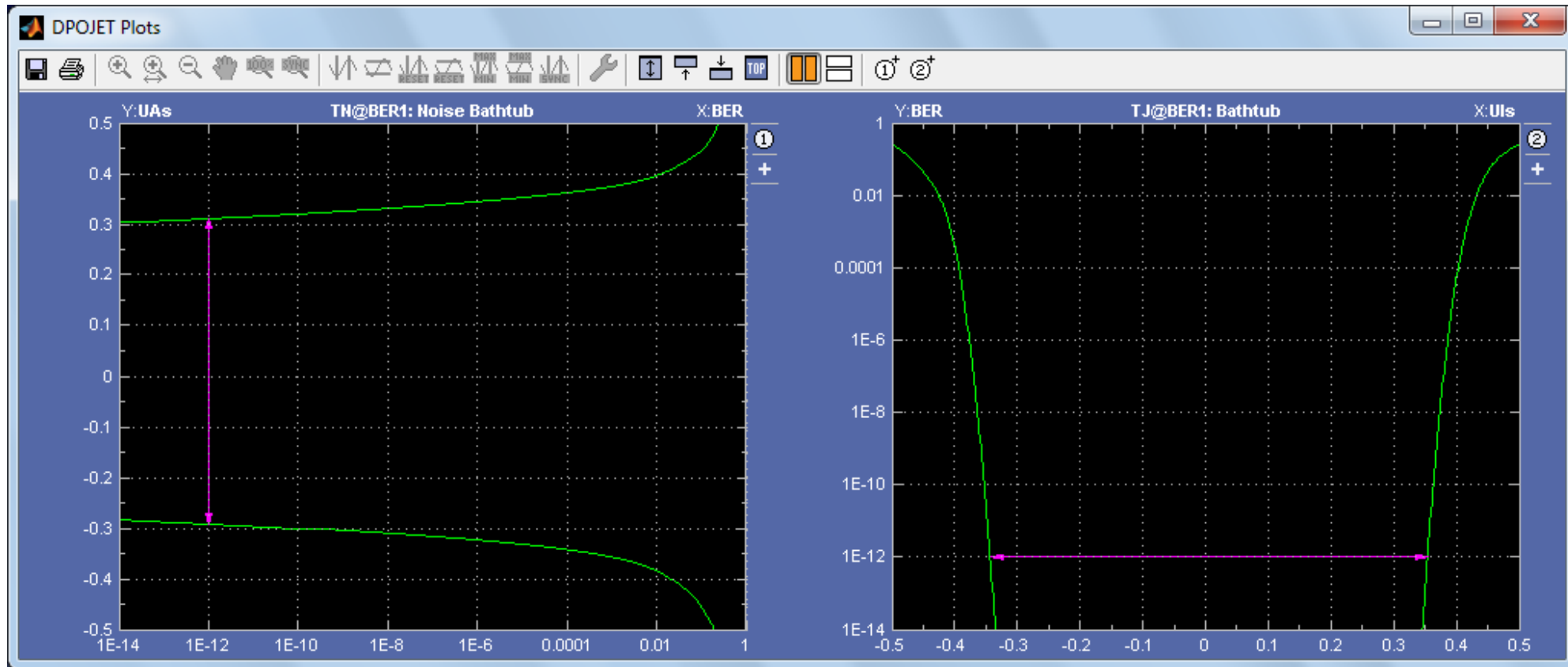
Jitter and Noise Distribution

- View the distribution of the individual jitter and noise components
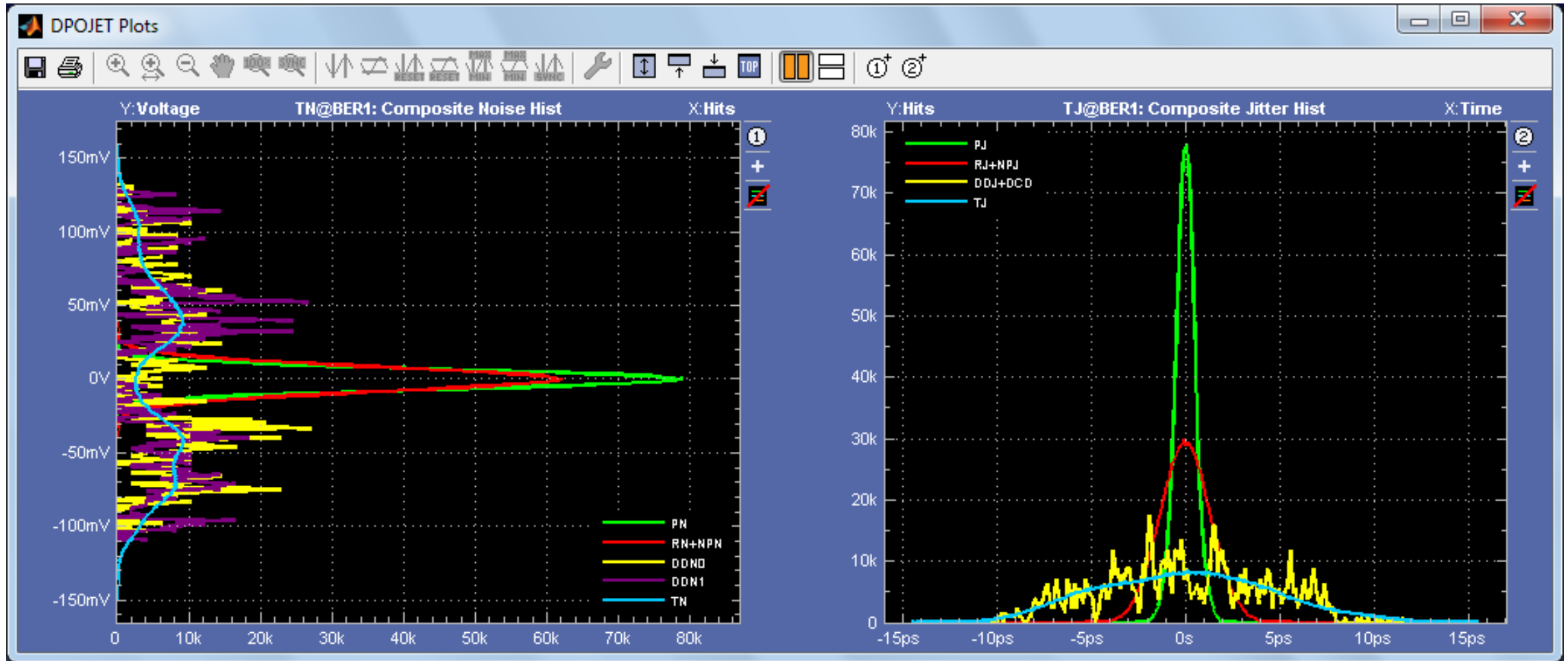
Multiple Views of Eye Diagram
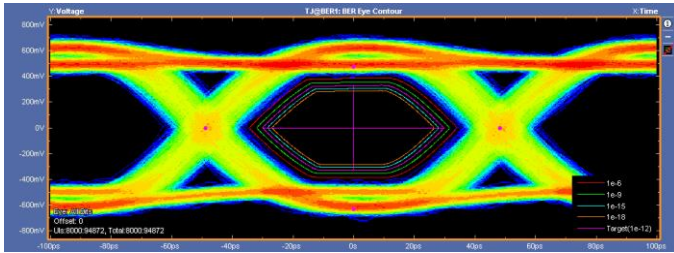
- Acquired Eye with BER Contours
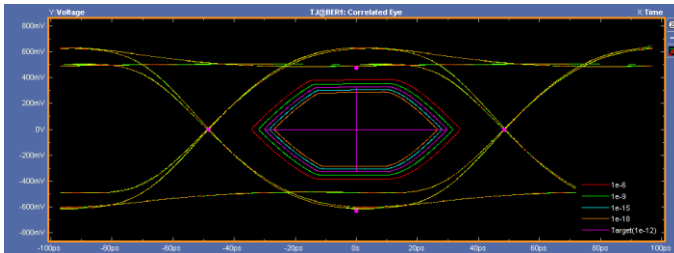
- Correlated Eye
  - Show the data dependent eye with all uncorrelated effects removed
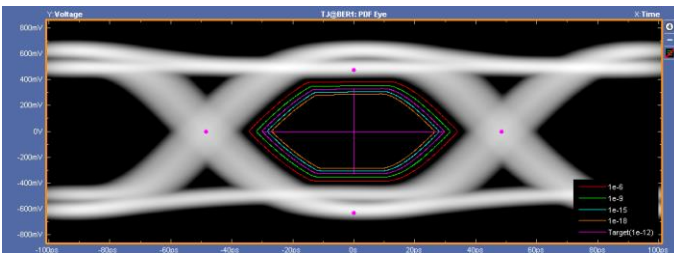
- PDF Eye with BER Contours
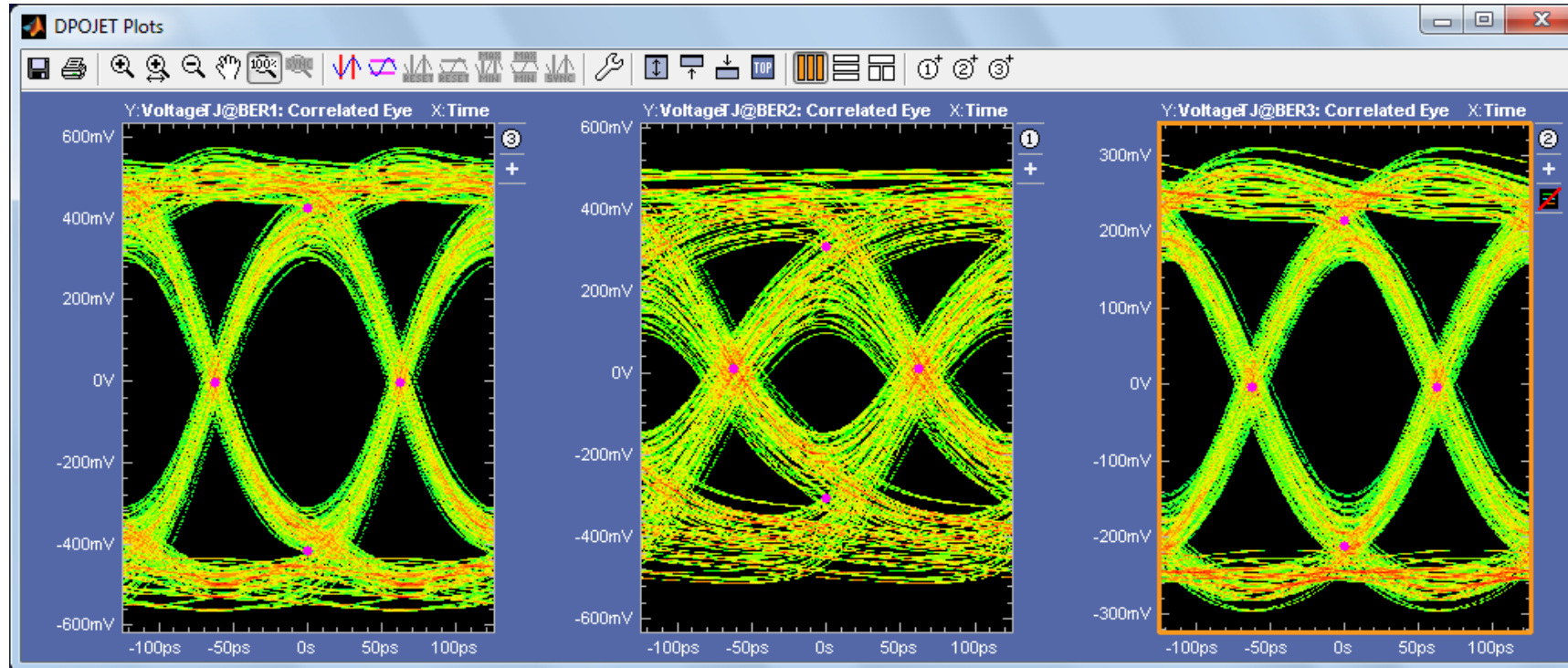 - Shows the underlying statistical model used to generate the BER contours
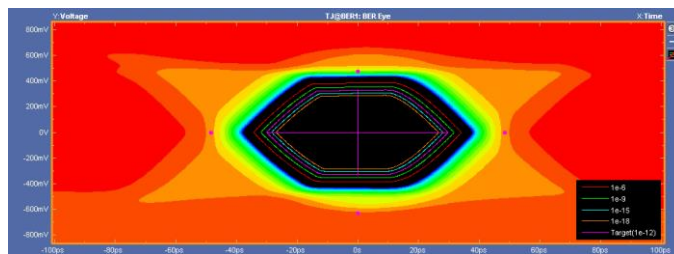
- BER Eye with BER Contours
  - Shows the probability of a hit vs. the location in the eye

Correlated Eye

- Correlated Eye illustrating the impact of equalization on an 8Gb/s PRBS7 signal

- Acquired Eye, Eye after the Channel and Equalization
- Ideally, the equalizer will compensate for the DDJ as in this case. The jitter between the acquired eye and after the equalizer is within 3ps.

BER Eye Contour Plot
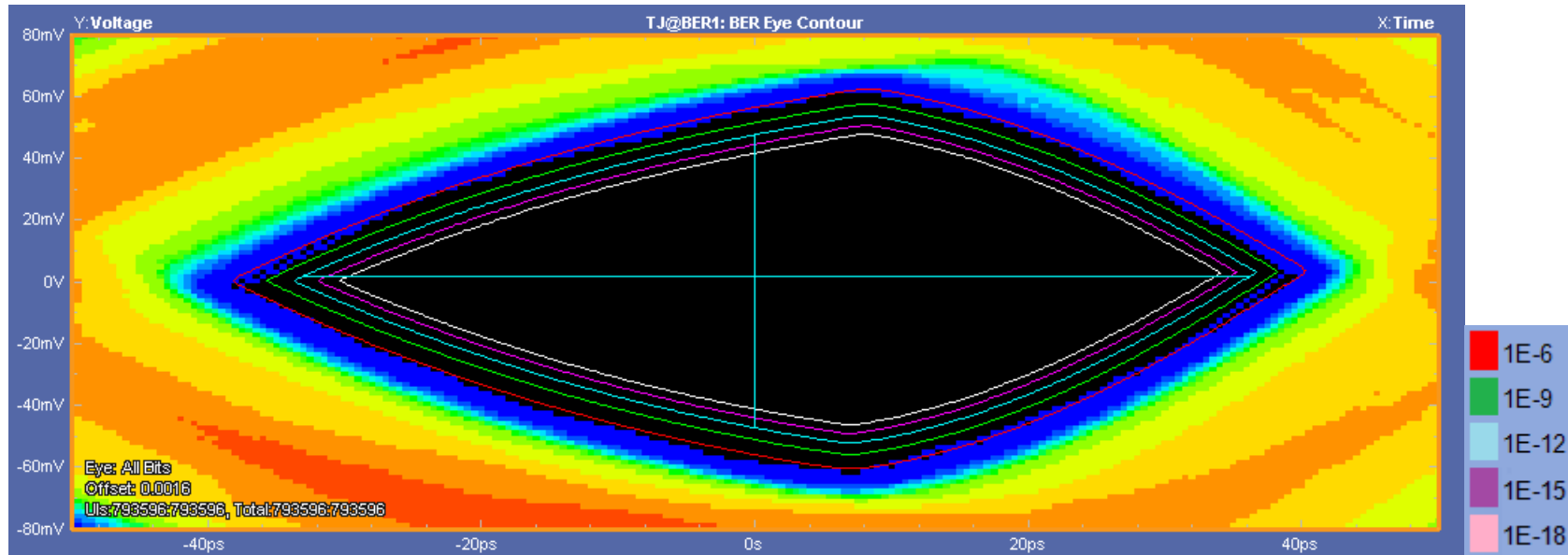
- The BER Eye Contour plot provides the following insight:
  - The horizontal line is positioned at the mid reference level used to make jitter measurements.
  - The vertical line is positioned at the UI percentage (default 50%) used to make noise measurements.
  - Multiple eye contours correspond to different BER levels
  - A mask may be superimposed to check margin against a target BER contour
  - Fully interactive plot (zooming, cursors, export)

Effects of RN and RJ on Eye Closure

- No RN, .15UI of RJ
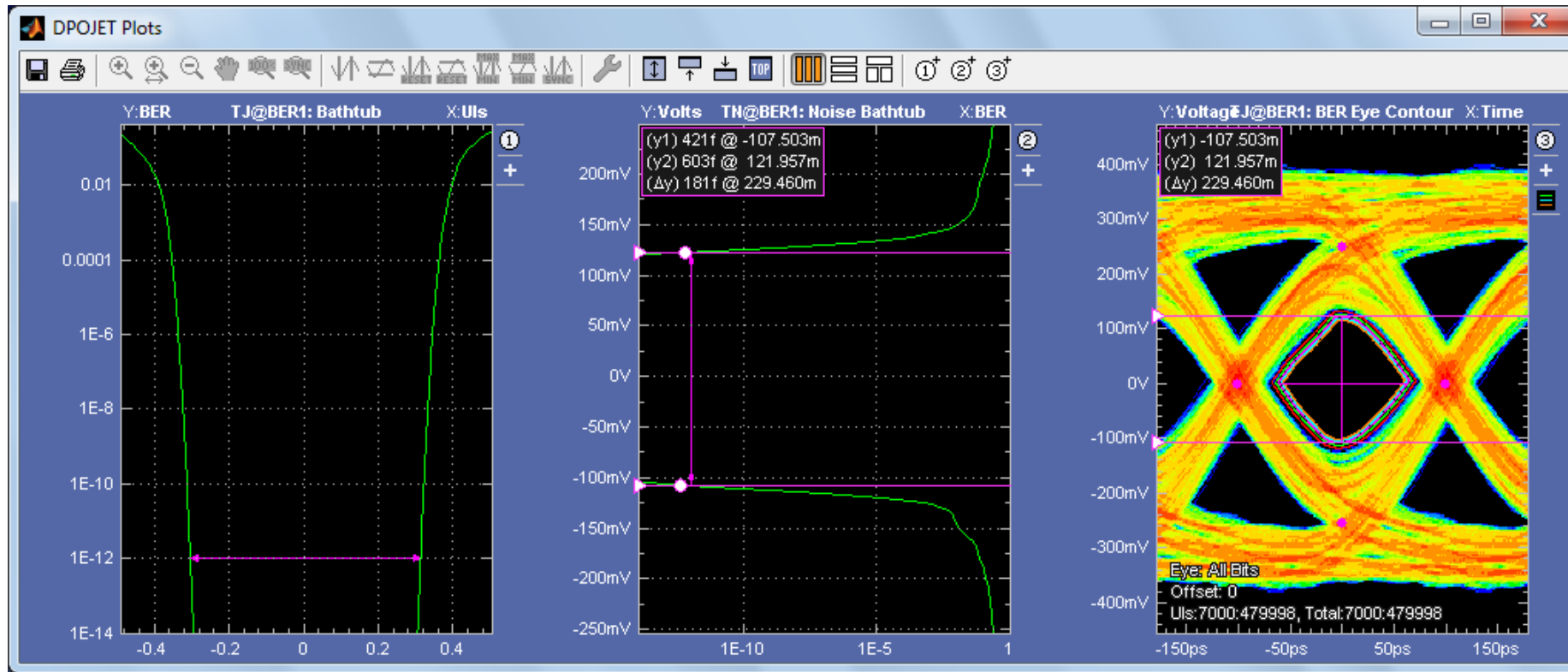
Effects of RN and RJ on Eye Closure

- Baseline RN, .15UI of RJ
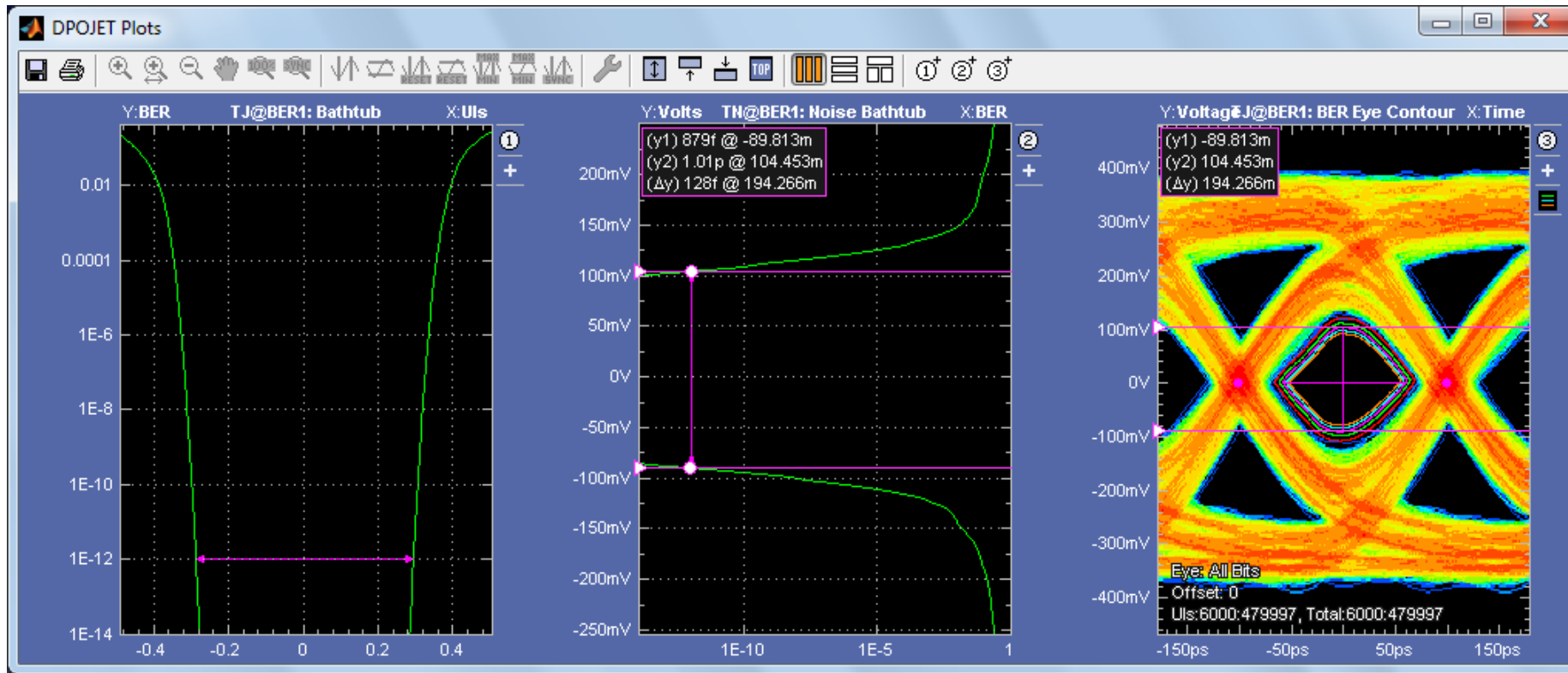
Effects of RN and RJ on Eye Closure

- Increased RN, .15UI of RJ
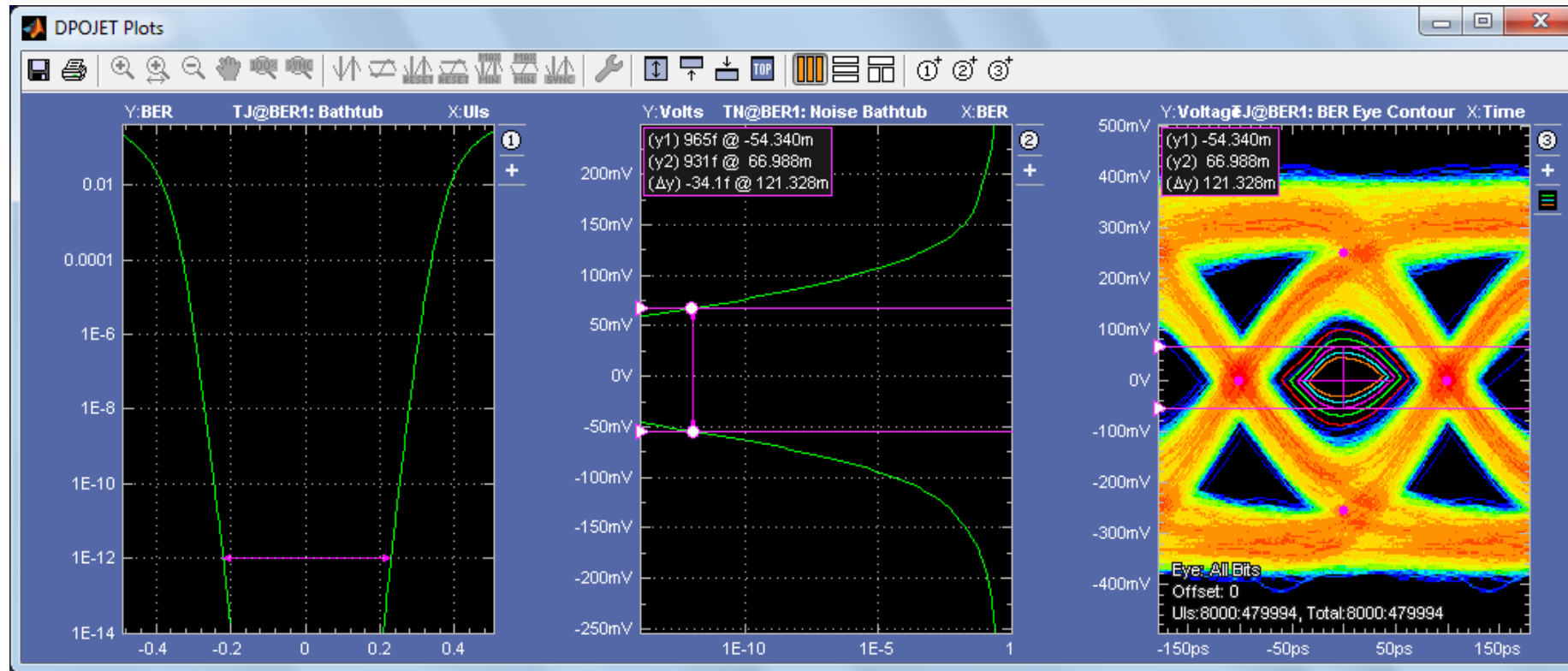
DPOJET Report Generator

- Makes it *easy* to archive and share analysis results: Internet Explorer MHT file
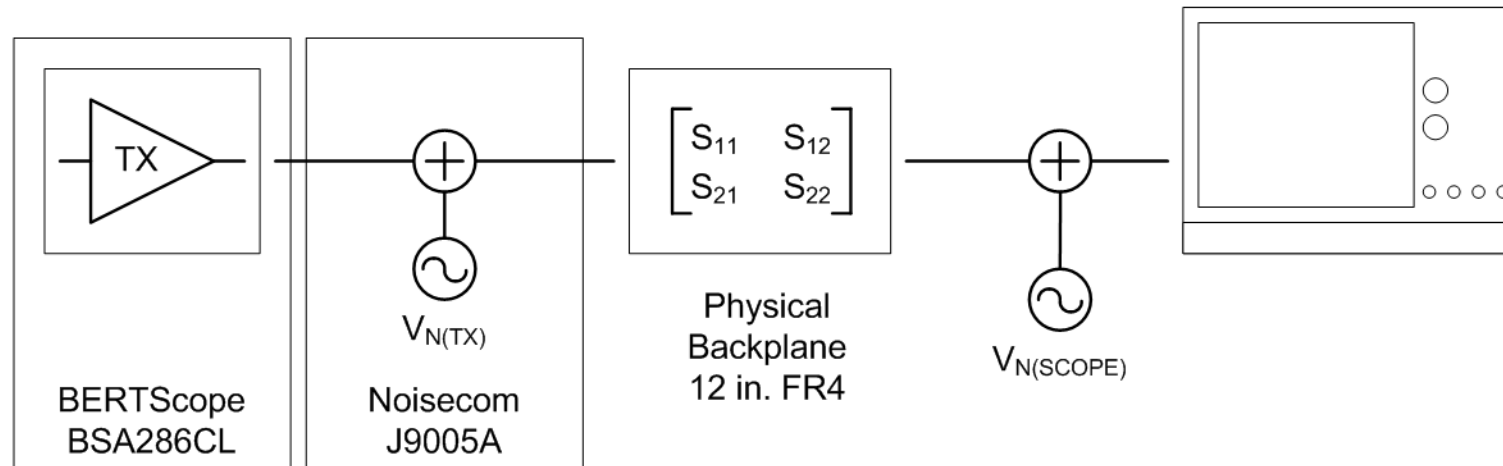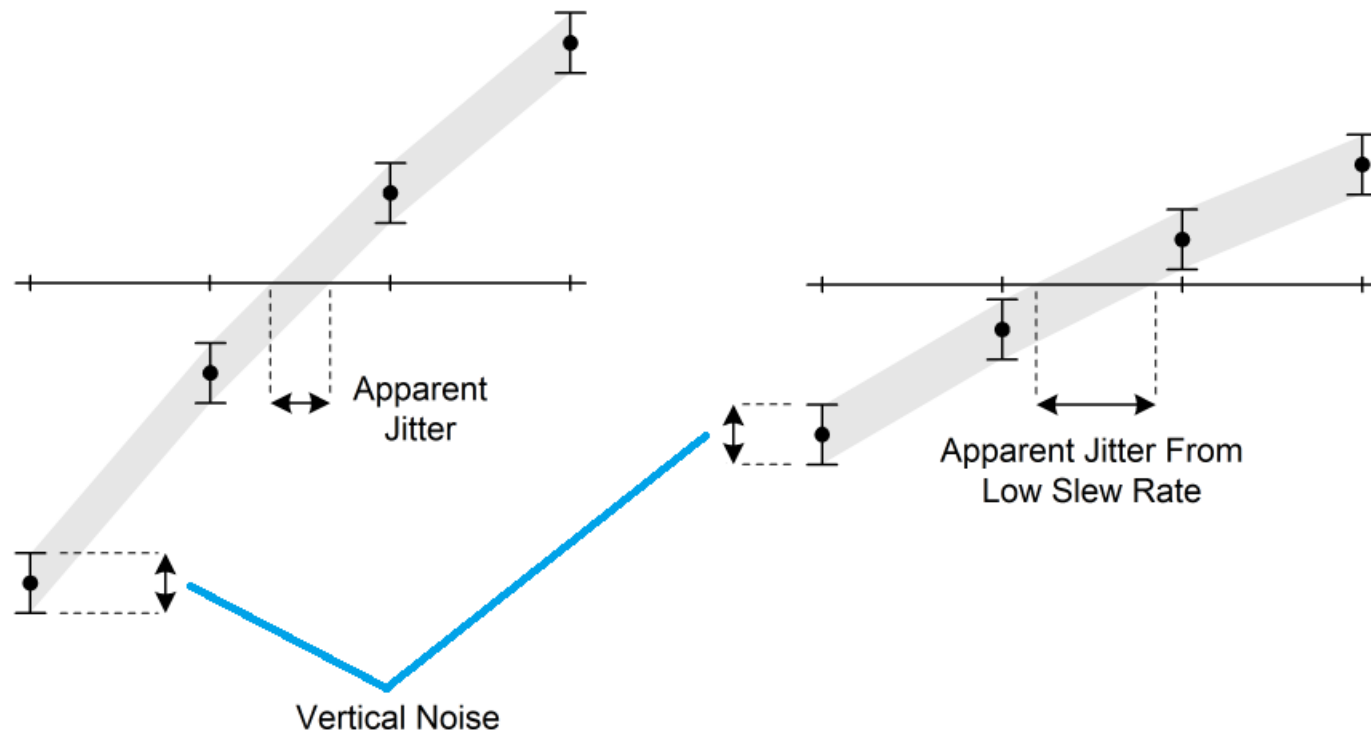
Demo Setup

Demo Setup

As slew rate decreases, slows down, a given amount of vertical (voltage) noise will appear as a greater amount of timing jitter

Summary

- DPOJET can measure the contribution of **noise,** as well as **jitter** to overall system performance

- Provides a breakdown of the sources of noise – analogous to jitter
  - RN, PN, DN, DDN, etc.

- Allows you to visualize overall **eye closure** at various Bit Error Rates without very long measurement runs

- Provides deep insight into the interactions of noise and jitter, which can be crucial for root-cause analysis

- Please visit www.tek.com/jitter for more information and white papers on jitter and noise analysis