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Characterizing Jitter Histograms for Clock and DataCom Applications

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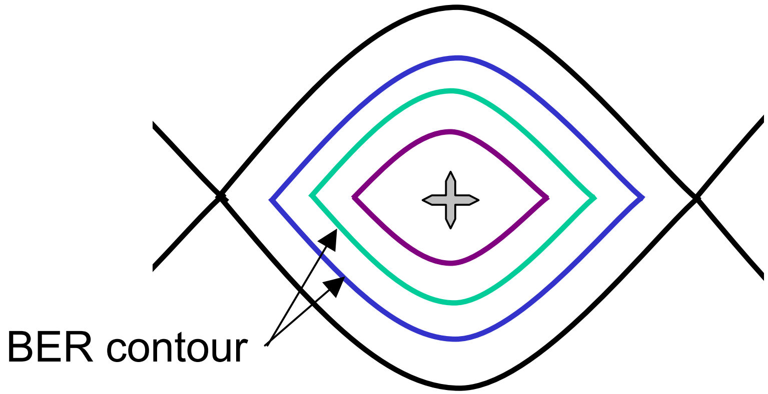
Outline

Motivation

Desire to have a system with the lowest BER



Determining if a system meets your BER specifications, requires an understanding of:

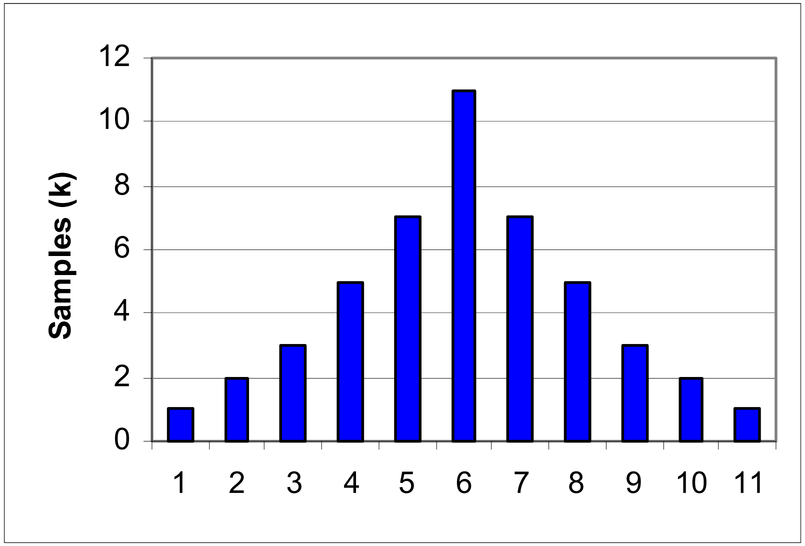
- *Statistics*
- *Jitter and Noise*
- *Types of Measurements*
- *Instrumentation*

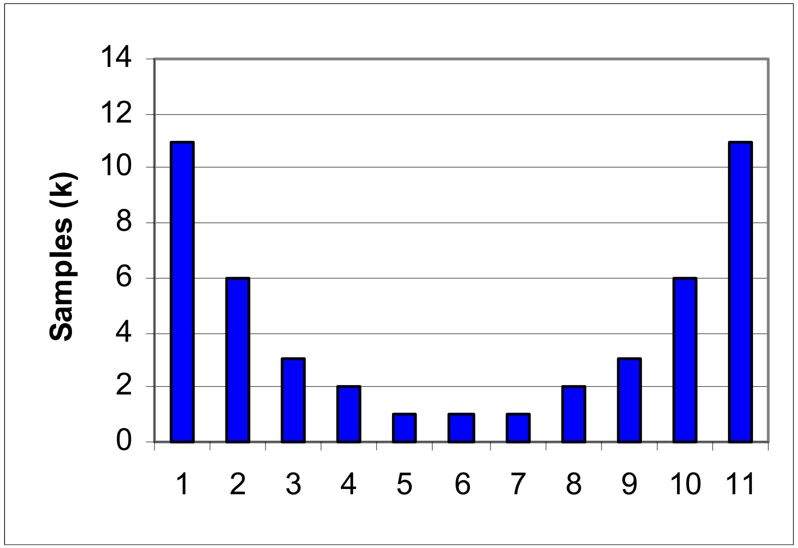
I. Measurement Statistics

- How do you characterize a histogram?
- Is pk-pk a good metric?
- Is the standard deviation a good metric?
- How do different shaped distributions affect the Total Jitter value?
- How do you accurately determine device performance and reliability?

Clock Statistics

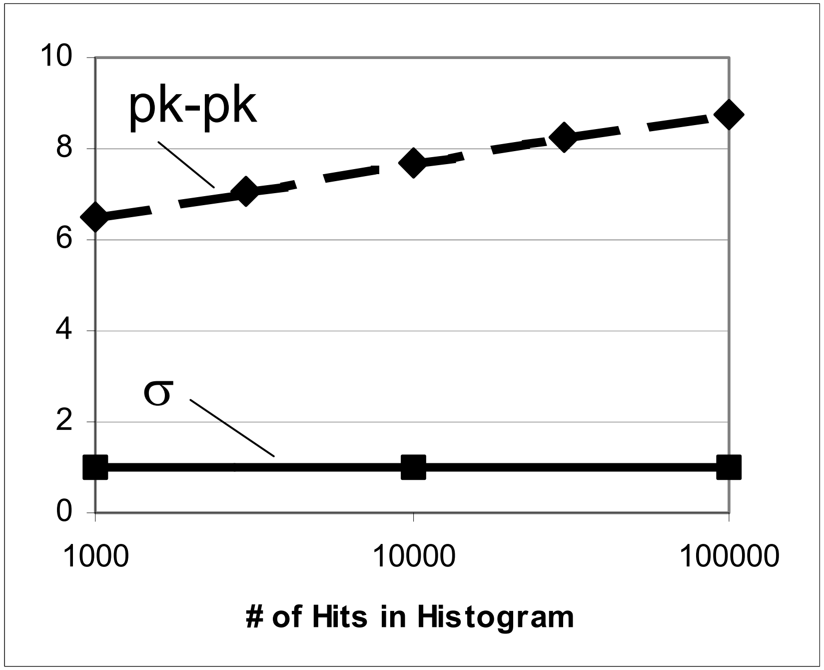
Both histograms have 48,000 hits, mean and a pk-pk of 10

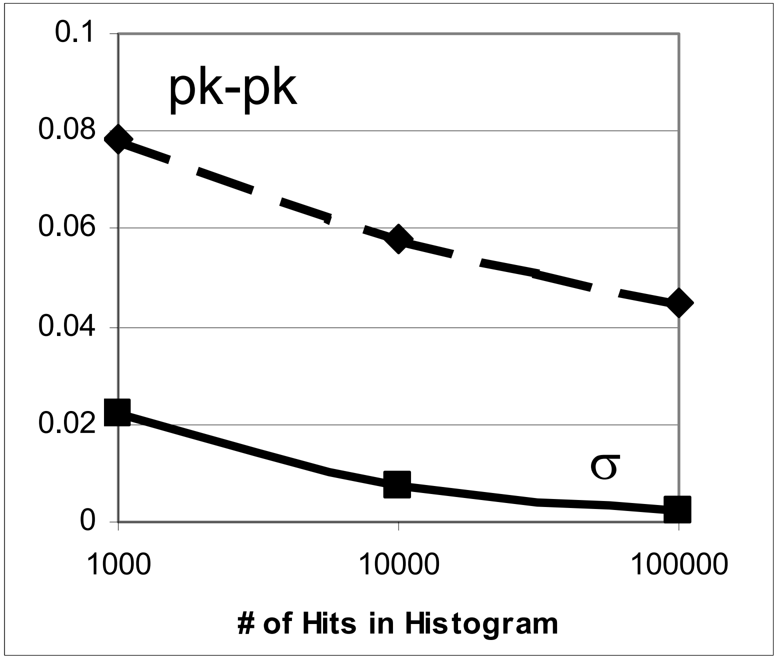




Is pk-pk a good metric for characterizing histograms?

Statistics for a Gaussian variable





pk-pk increases with sample size
σ is stable with sample size

Standard error for pk-pk is larger than standard deviation for all sample sizes (standard error = $\sigma/\sqrt{N}$)

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If the distribution is Gaussian, you can determine TJ for a given BER

BER	TJ Value
1.3×10^{-3}	6σ
3.17×10^{-5}	8σ
2.87×10^{-7}	10σ
9.87×10^{-9}	12σ
1.28×10^{-12}	14σ
1.0×10^{-12}	14.069σ

The standard deviation provides information on the characteristics of the distribution: "width parameter"

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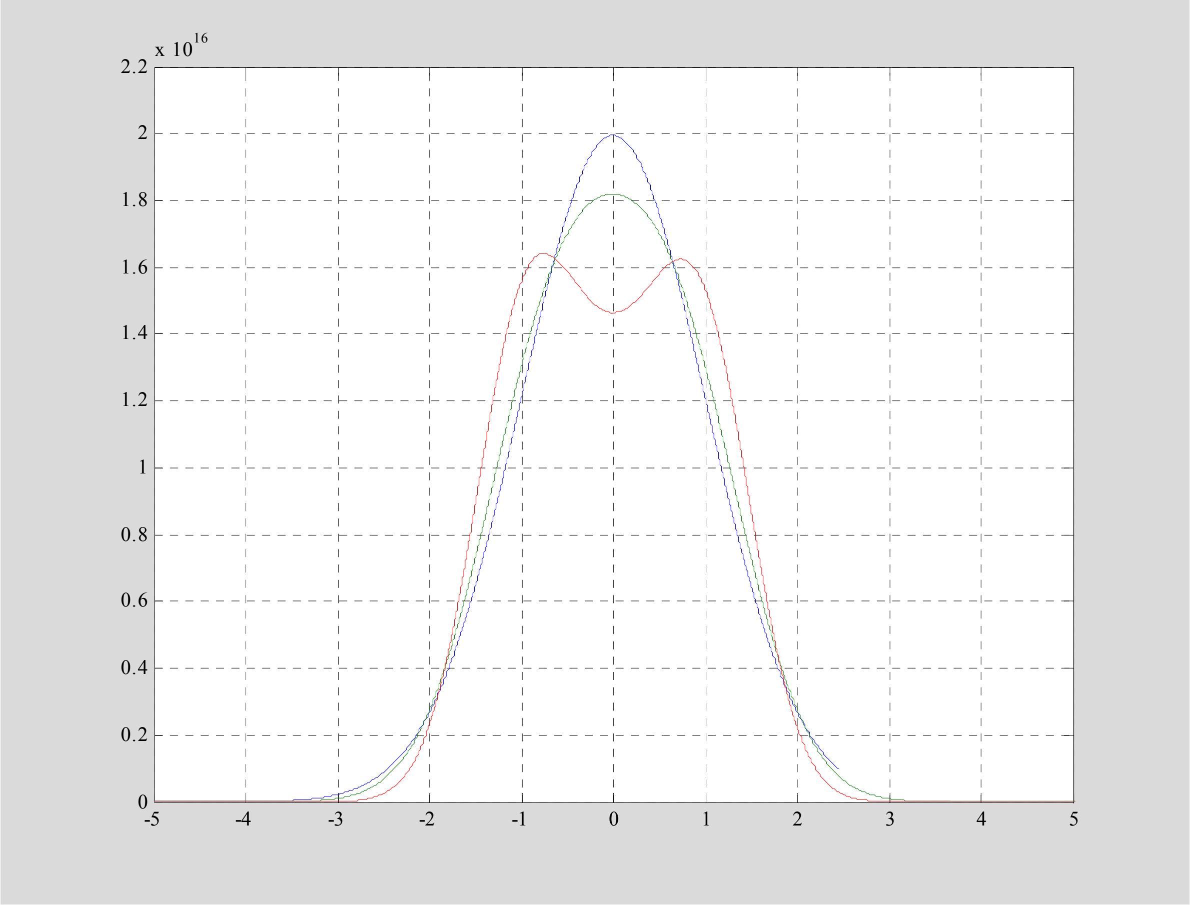
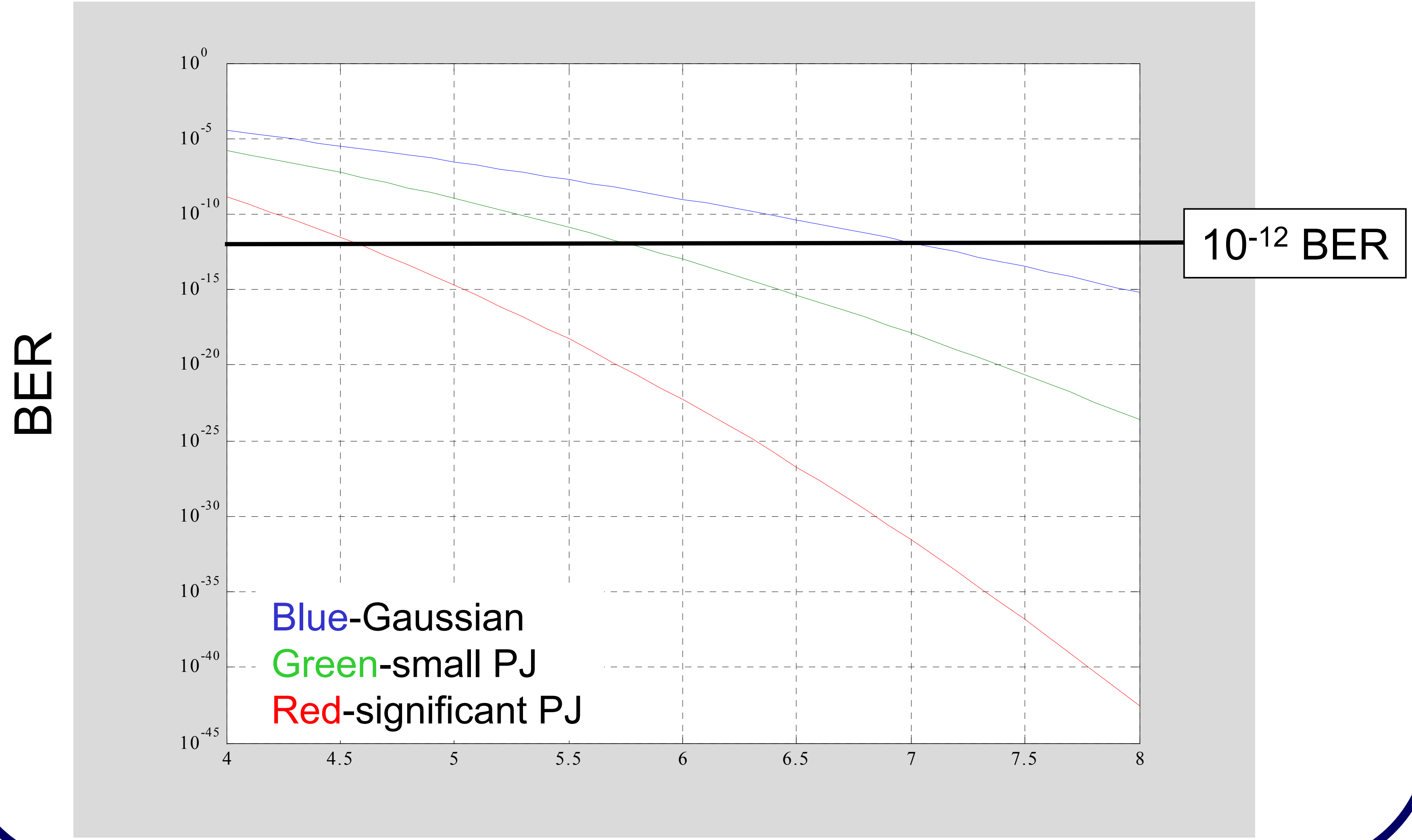
Real life histograms



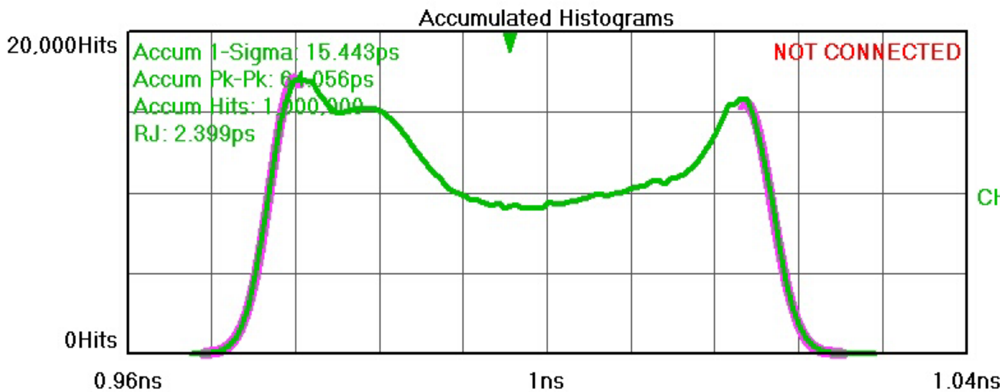
3 histograms with the same standard deviation-what's the TJ for a given BER?

Blue-Gaussian
Green-small added PJ
Red-significant PJ

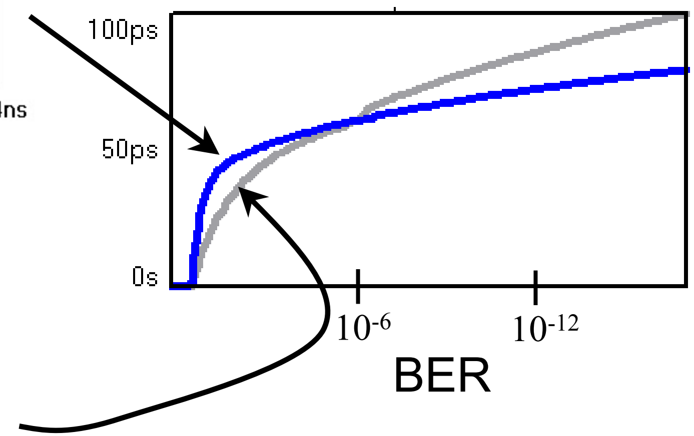
BER vs. standard deviation

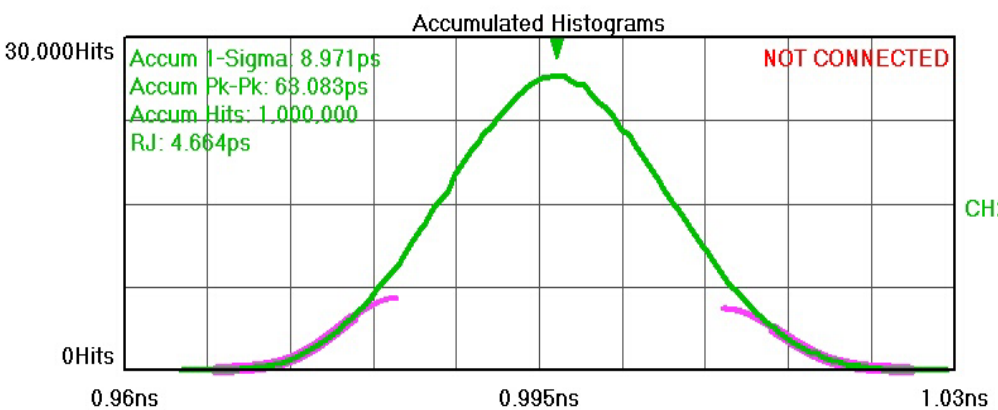


What clock has better performance?



Clock with DJ

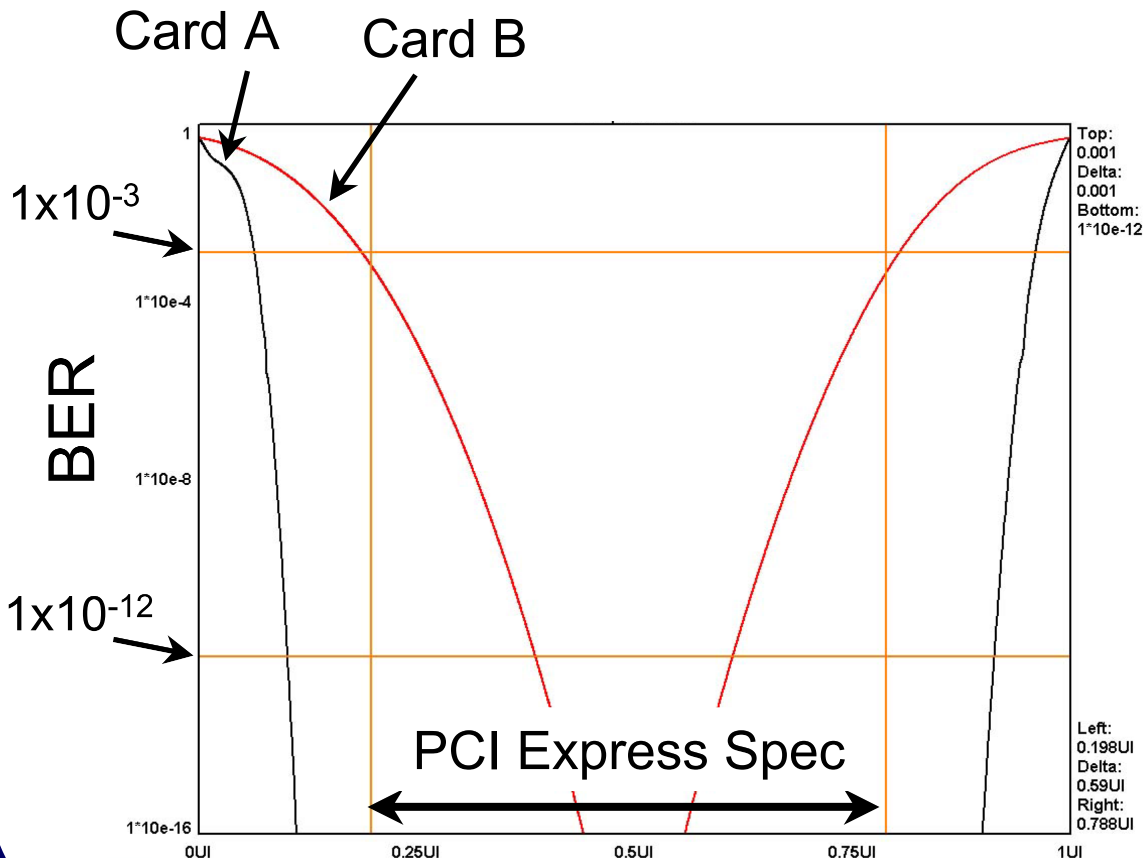




Clock with RJ

PCI EXPRESS™

Why are statistics so important?
Because with insufficient statistics you can pass BAD parts



- Add in card example
- Card B had link training problems
- Sample size of 1000 from software compliance measurement on a real time oscilloscope-**both parts PASS**
- Comprehensive test to actual BER specification indicates part B **FAILS**

Examples of Crystal Oscillator Specifications

RMS Jitter, Output=12.0-77.760 MHz			3		ps

Jitter	Absolute: ±100pSec Maximum One Sigma: ±25pSec Maximum

Jitter *4	t_{DJ}	0.2 ps Typ.	Deterministic Jitter
	t_{RJ}	3 ps Typ.	Random Jitter
	t_{RMS}	3 ps Typ.	σ (RMS of total distribution)
	t_{p-p}	25 ps Typ.	Peak to Peak
	t_{acc}	4 ps Typ.	Accumulated Jitter (σ) n = 2 to 50000 cycles

And some companies do not specify jitter!!!

Parameter	Benefits	Drawbacks
pk-pk measurement of a histogram	•Provides a number	•Measurement must be stated with sample size and setup conditions. •Measurement less repeatable than σ
Standard deviation (σ)	•Measurement parameter is repeatable •Can be used to calculate pk-pk jitter as a function of BER or probability level	•Useful only for Gaussian distributions
Quantifying random and deterministic components	•Can be used to calculate pk-pk jitter as a function of BER or probability level for any shape of histogram. •The magnitude of the components provides diagnostic information	

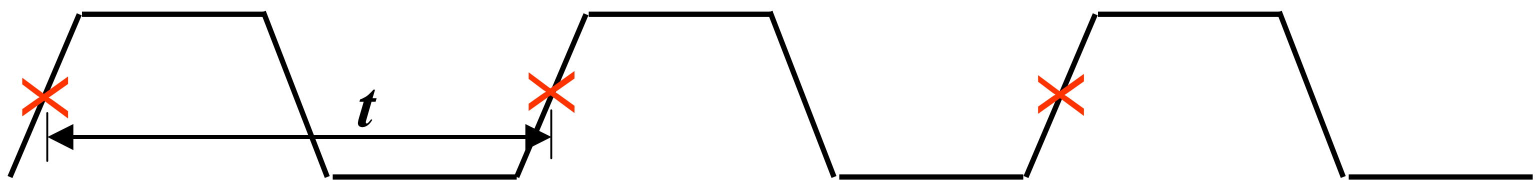
- How do you characterize a histogram? ***By quantifying its components***
- Is pk-pk a good metric? ***In general, No***
- Is the standard deviation a good metric? ***For Gaussian distributions***
- How do different shaped distributions affect the Total Jitter value? ***It depends on the contribution from the jitter components***
- How do you accurately determine device performance and reliability? ***By quantifying its components and calculating long term performance***

II. Types of Jitter measurements

- Should I perform a phase (accumulated jitter), period or cycle-to-cycle jitter measurement?
- Why do these measurements give different numbers for the same signal?
- Does the measurement emulate the device?

Phase, Period and Cycle-to-Cycle Jitter

- Assume test instrument that measures threshold crossings



- A sinusoidal term has been added to the ideal waveform
- 400 ps ideal time intervals (PCI Express)

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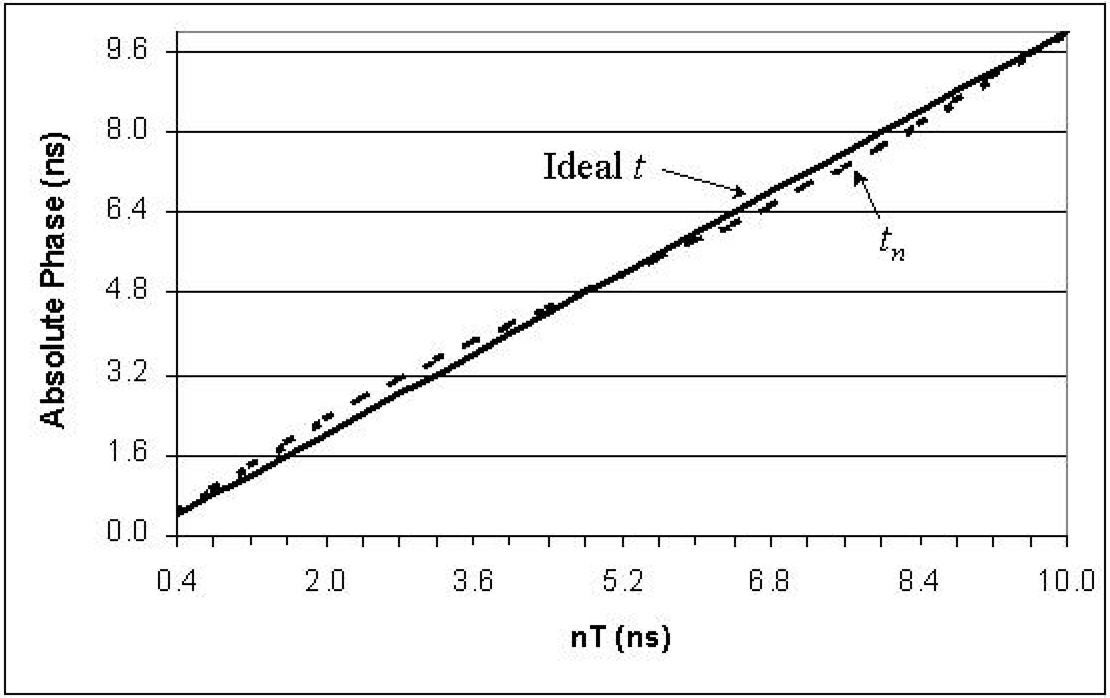
Types of Jitter measurements: Phase Jitter



Ideal waveform and one with a sinusoidal term added

Types of Jitter measurements: Phase Jitter

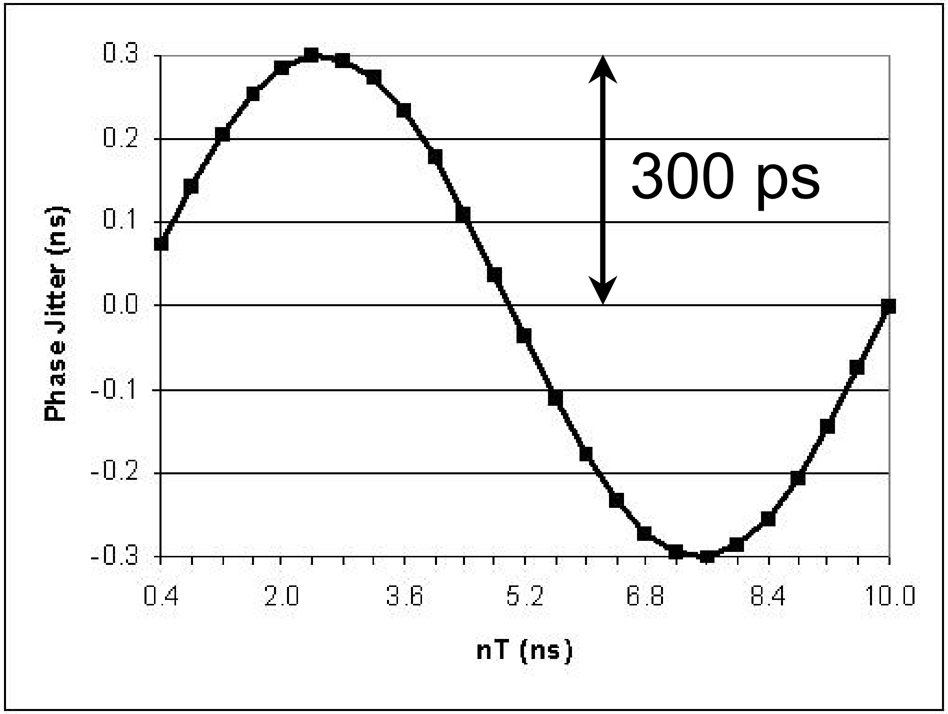
- Phase jitter is the difference between the measured time and the ideal time

$$\Phi_n = t_n - nT, \qquad n = 1,2,3\ldots..$$

- The time error accumulates for increasing bit periods
- Phase jitter is also known as accumulated jitter

Types of Jitter measurements: Phase Jitter

- For example, 100 MHz sinusoidal term a magnitude of 300 ps on a signal with a unit interval of 400 ps



Phase Jitter

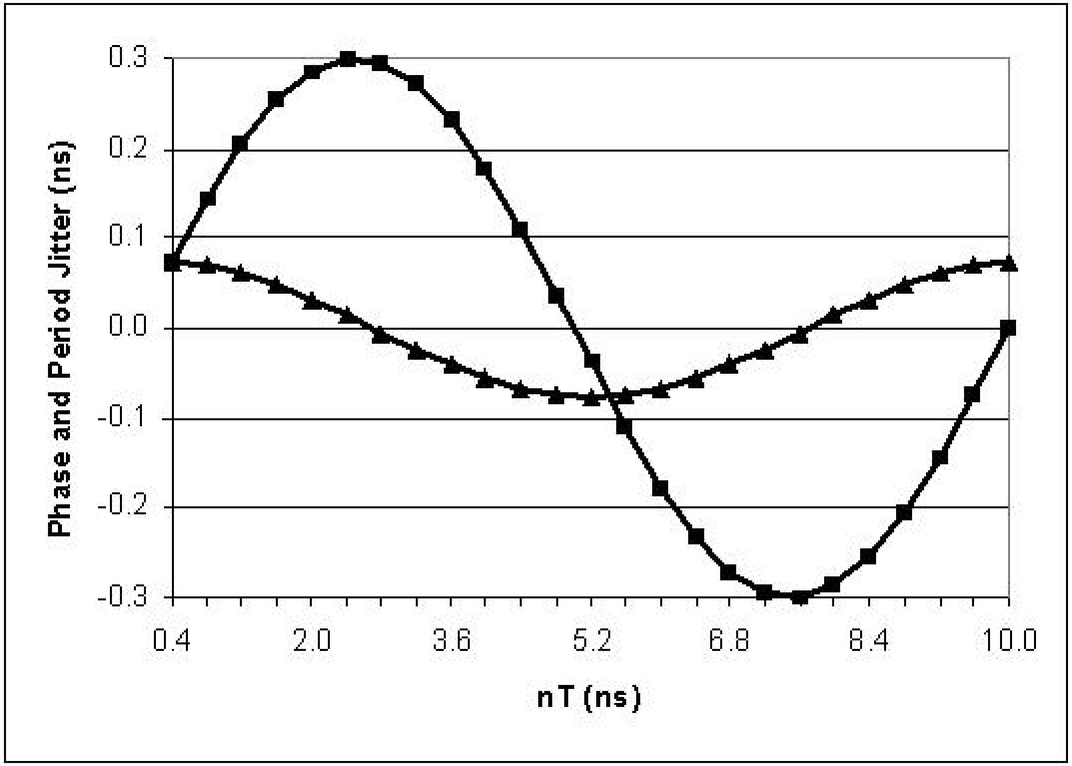
Types of Jitter measurements: Period Jitter

- Period jitter is the difference between the measured period and the ideal Period

$$\Phi'_n = (t_n - t_{n-1}) - \mathrm{T} \qquad n = 1,2,3\ldots.$$

- Period jitter is also the first difference of the phase jitter

Types of Jitter measurements: Period Jitter



Phase (■) and Period Jitter (▲)

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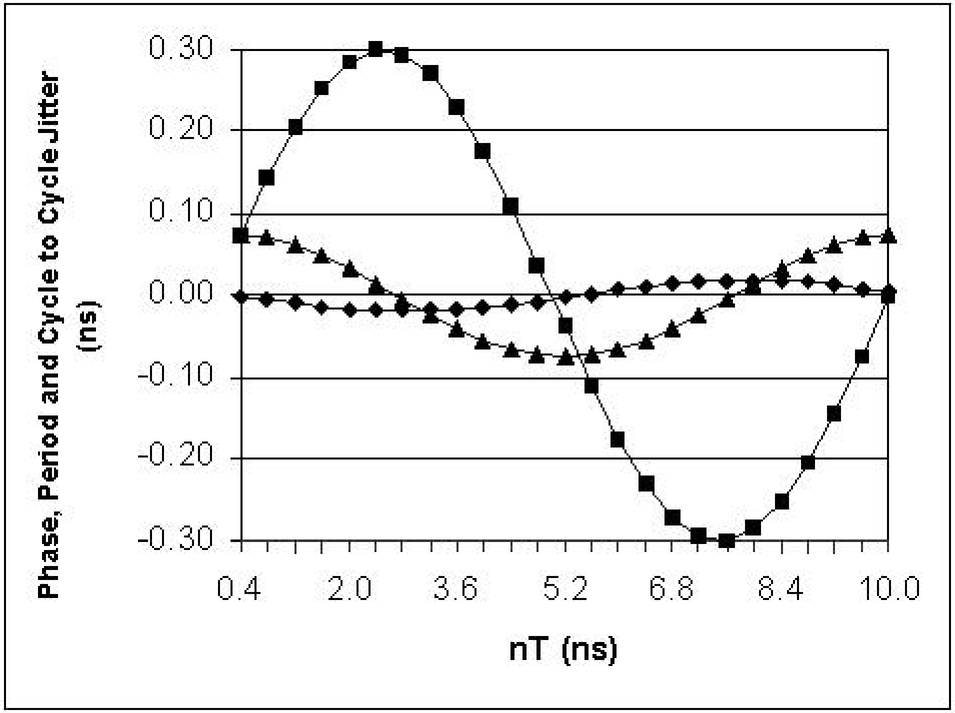
Types of Jitter measurements: Cycle-to-Cycle Jitter

- Cycle-to-cycle jitter is the difference between the consecutive bit periods

$$\Phi''_n = (t_n - t_{n-1}) - (t_{n-1} - t_{n-2}), \quad n = 1,2,3\ldots.$$

- Cycle-to-cycle jitter is also the first difference of period jitter and second difference of phase jitter

Types of Jitter measurements: Cycle-to-Cycle Jitter

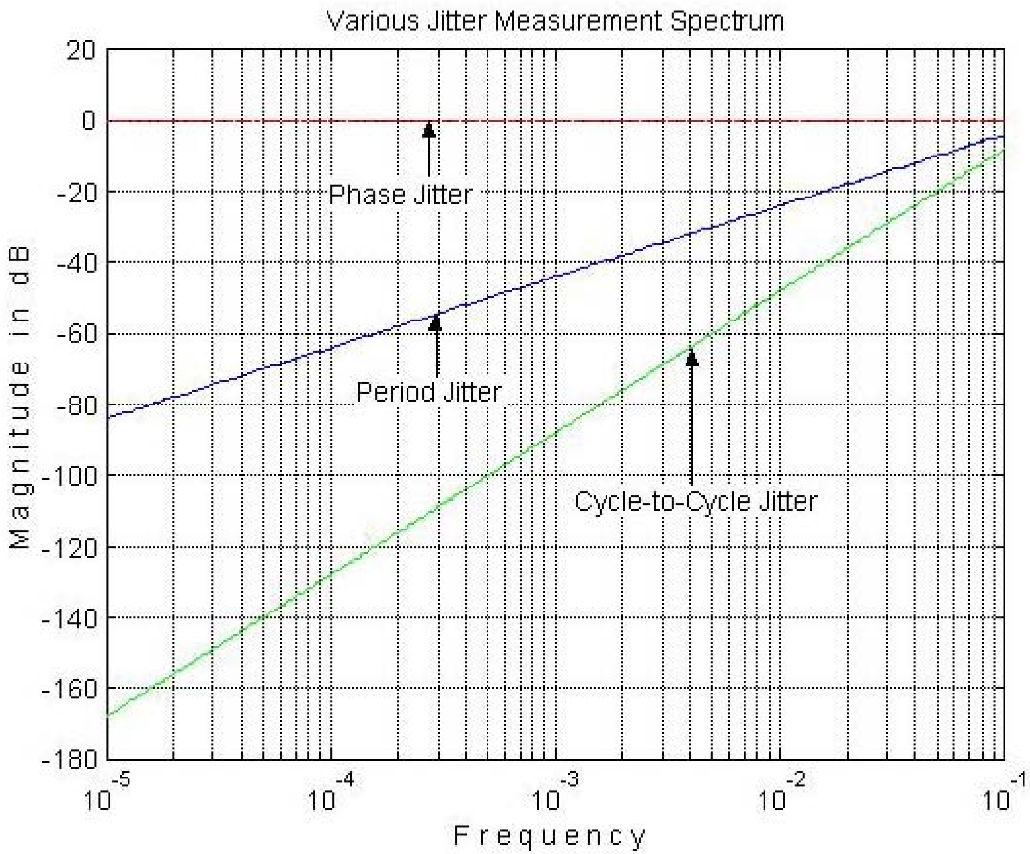


Phase (■) and Period Jitter (▲) and cycle-to-cycle jitter (♦)

The magnitude of the sinusoidal error decreases from phase to period to cycle-to-cycle jitter

Types of Jitter measurements

Each measurement type has a different frequency response



- Period jitter rolls off at ~20 dB/decade
- Cycle-to-cycle rolls off at ~40 dB/decade

Types of Jitter measurements

- The three preceding examples show different representations of the same data

- The measurement you make depends on your application

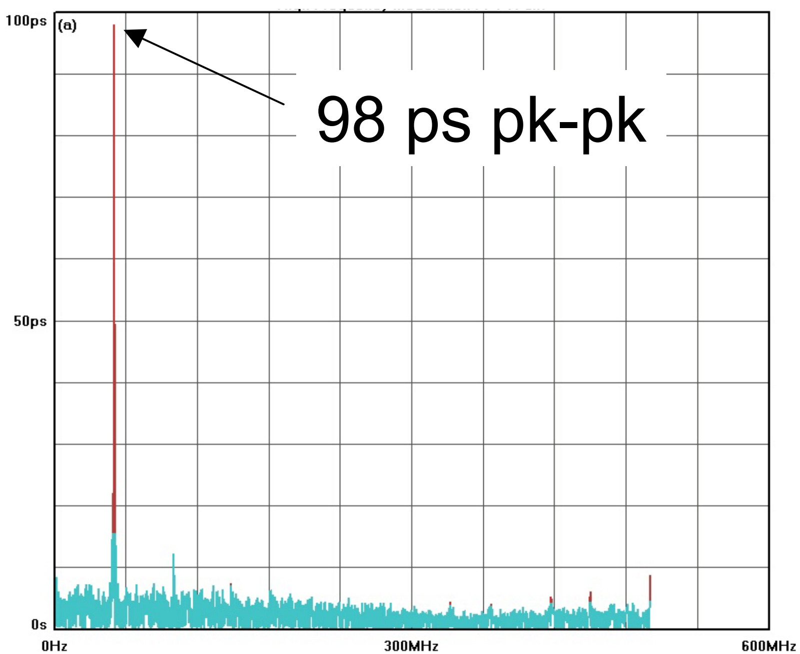
  - For clocks and PLL's phase jitter would be appropriate because the output is proportional to the phase error of the reference and output signal

  - For diagnosing modulation or crosstalk phase and/or period jitter is appropriate

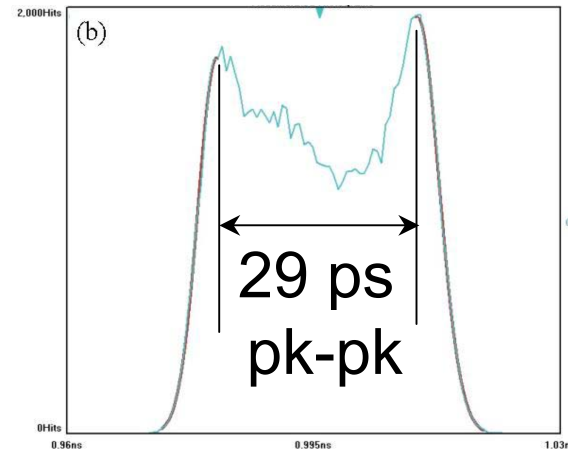
  - Applications for cycle-to-cycle jitter????

Types of Jitter measurements; Examples

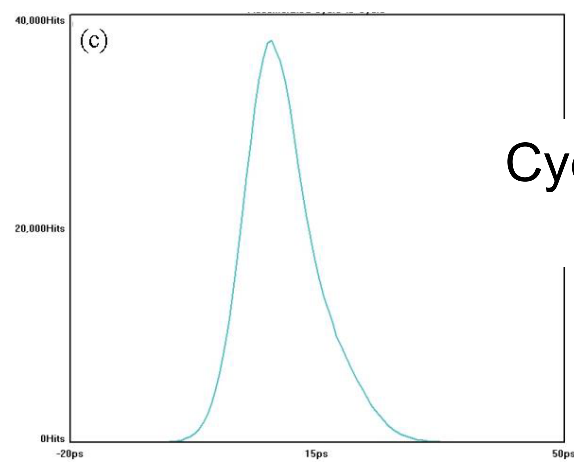
1 GHz clock with 50 MHz modulation



Accumulated Jitter



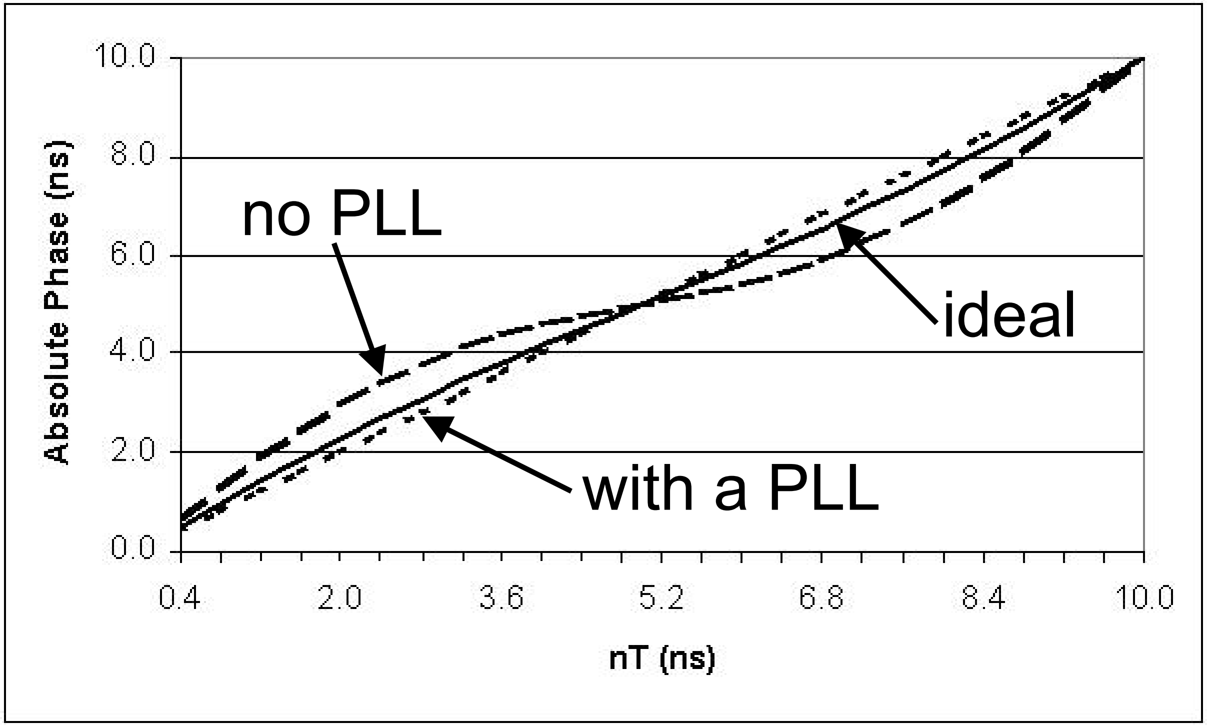
Period Jitter



Cycle-to-cycle Jitter

The effect of clock recovery in a system

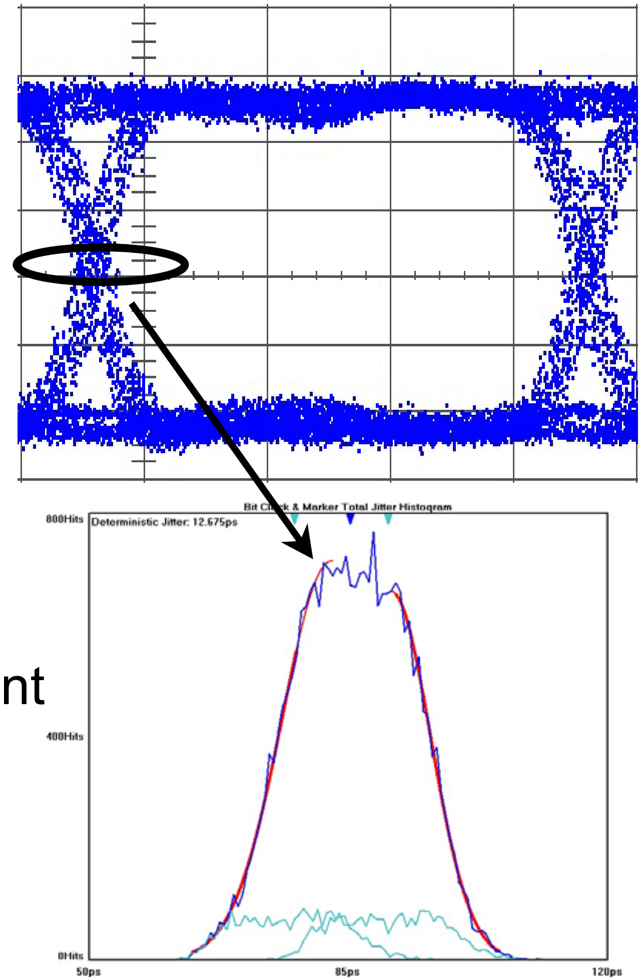
- Jitter seen by the receiver will have a high pass jitter transfer function
- The receiver will tolerate more low frequency jitter than high frequency jitter
- The frequency at which the PLL begins to track is the 3 dB or corner frequency, F_c
- For many serial data standards it is F_c = Data Rate/1667
- A system with clock recovery changes the Phase Jitter measurement



The magnitude of phase jitter is reduced or rejected by the clock recovery scheme-*this has implications for the measurements and instrumentation*

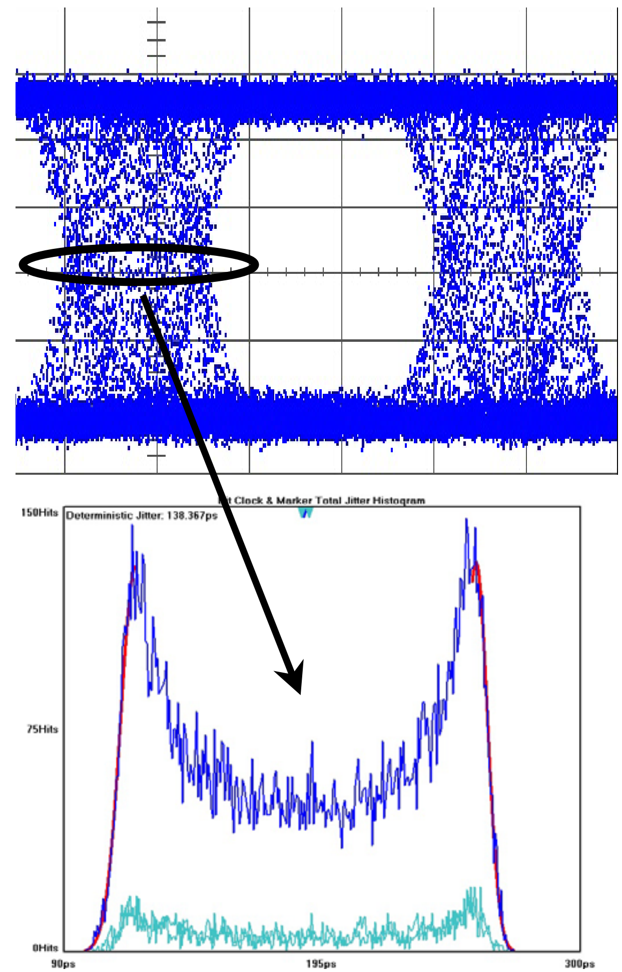
Effect of clock recovery on your measurements

With a compliant clock



DJ=12.6 ps

Without a compliant clock

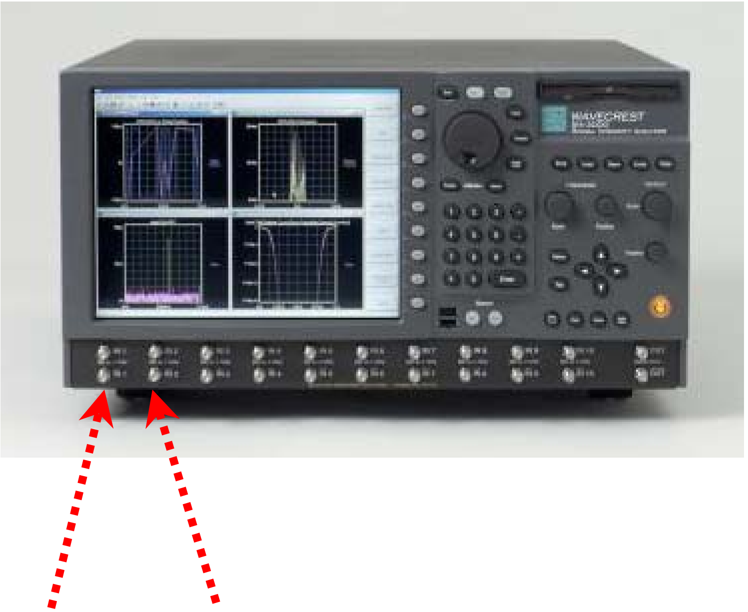


DJ=138 ps

Types of Jitter measurements: Data

- There are a variety of jitter measurement methods available today and they may not provide the same answer
- Test instruments may perform a jitter measurement with a software based clock, a noncompliant or compliant clock
- The measurement could be accomplished on two channels (clock and data) or the data alone
- For datacom applications, typically the clock is recovered from the data and used for timing the data, perform the analysis that emulates your device
- The methodology with the lowest jitter is not necessarily the best

Types of Datacom Measurements



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- Should I perform a phase (accumulated jitter), period or cycle-to-cycle jitter measurement? ***Depends on the application***
- Why do these measurements give different numbers for the same signal? ***Each measurement has a different frequency response***
- Does the measurement emulate the device? ***Choose a measurement that fits your application***

IV. Types of Jitter and Noise

Total Jitter Is Composed of Many Components

- Total Jitter
  - Deterministic Jitter
    - Periodic Jitter
    - Data Dependent Jitter
      - Duty Cycle Distortion
      - Intersymbol Interference
  - Random Jitter

Random Jitter

- Random jitter (RJ) is characterized by a Gaussian distribution and assumed to be unbounded
- The distribution is quantified by the standard deviation (σ) and mean (μ)
- Since RJ can be modeled as a Gaussian distribution it can be used to predict pk-pk jitter as a function of BER

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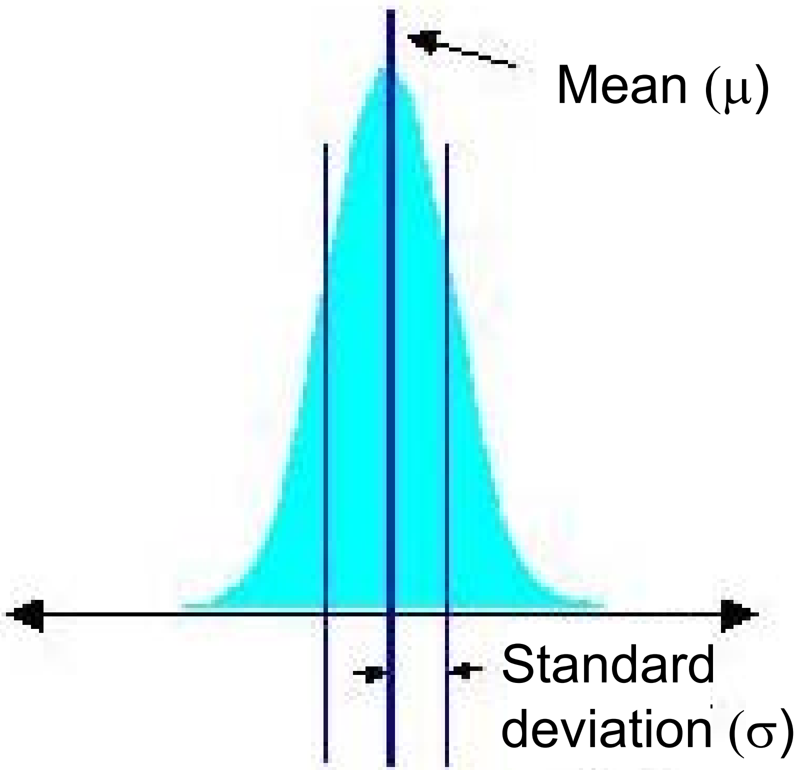
Random Jitter



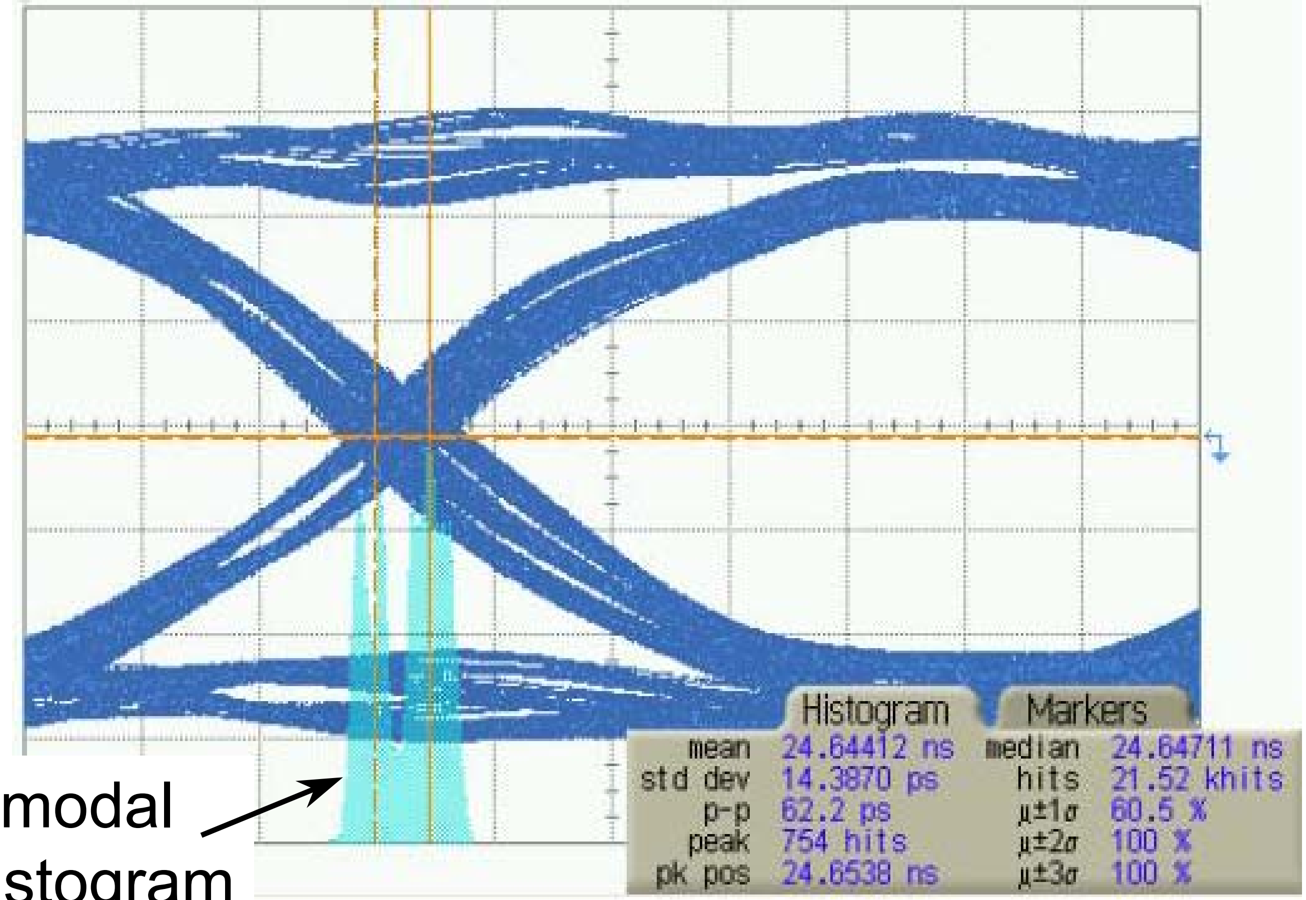
BER	TJ Value
1.3×10^{-3}	6σ
3.17×10^{-5}	8σ
2.87×10^{-7}	10σ
9.87×10^{-9}	12σ
1.28×10^{-12}	14σ
1.0×10^{-12}	14.069σ

- The Catch…

  This use of Standard Deviation (σ) is only valid in pure Gaussian distributions. If any deterministic components exist in the distribution, the use of σ for the estimation of probability of occurrence is invalid.

Random Jitter

What happens when the distribution isn't Gaussian?



Bimodal Histogram

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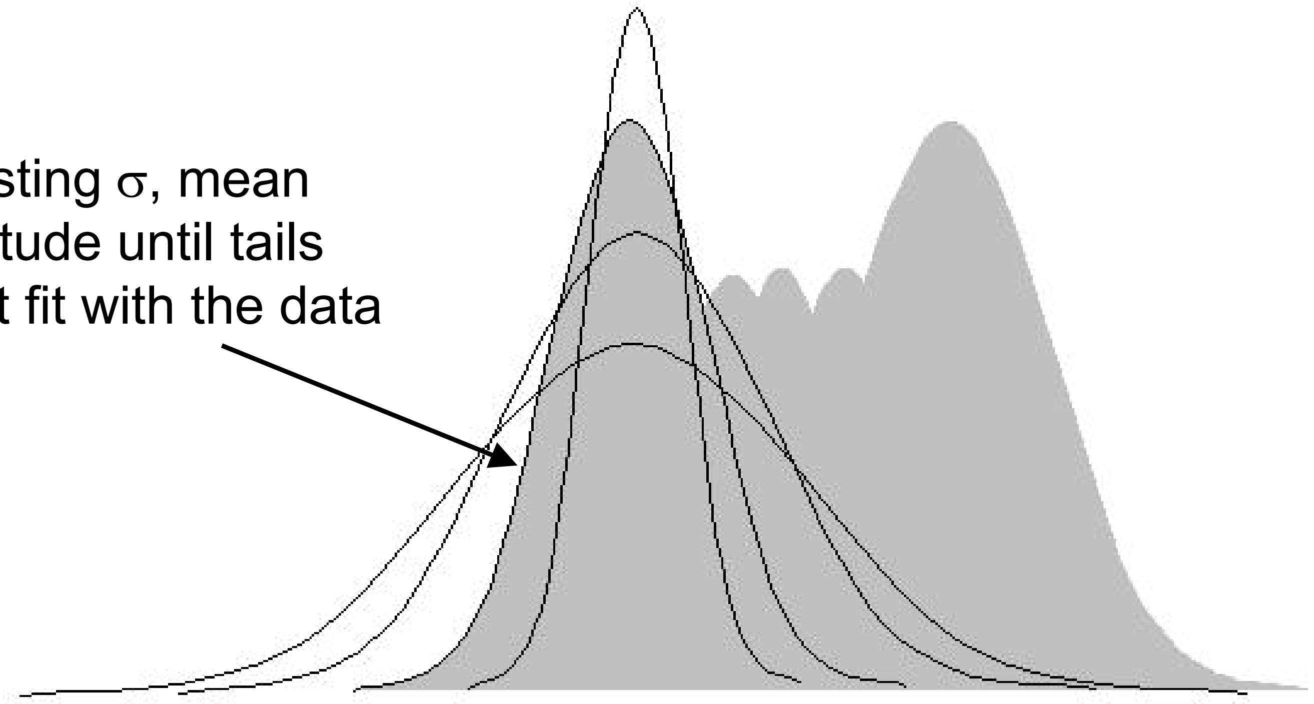
Measuring Random Jitter

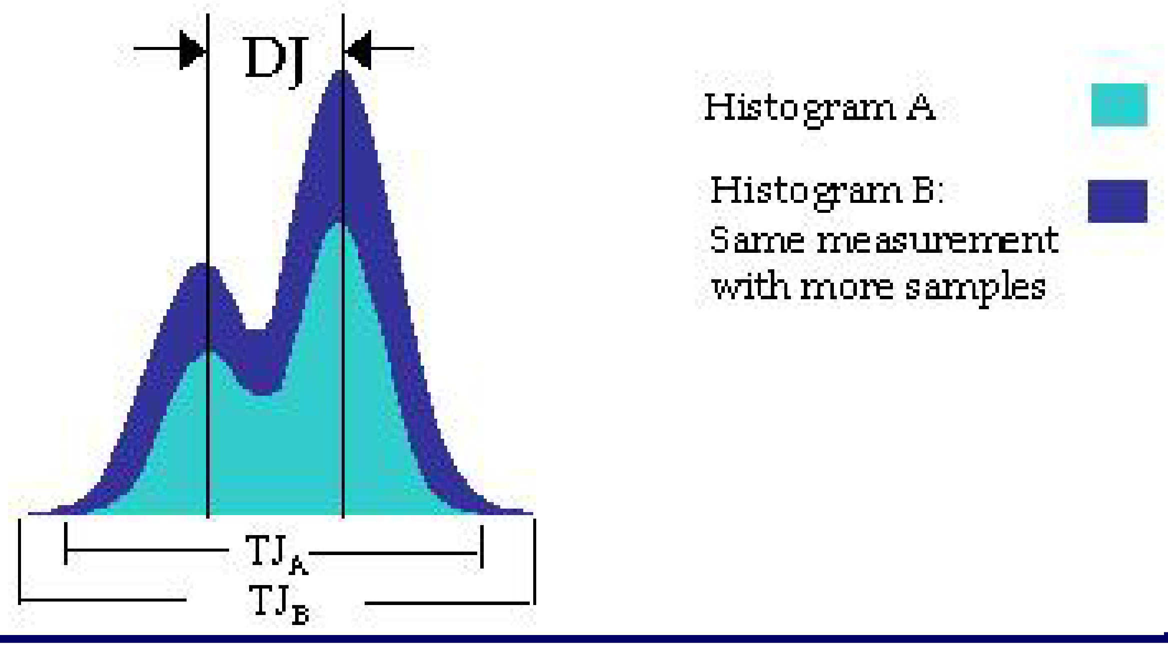
Fit Gaussian tails to left and right side of distribution, TailFit™

Keep adjusting σ, mean and magnitude until tails obtain best fit with the data



Deterministic Jitter

- Deterministic jitter (DJ) has a non-Gaussian PDF and is characterized by its bounded pk-pk value
- DJ includes PJ, DCD and ISI

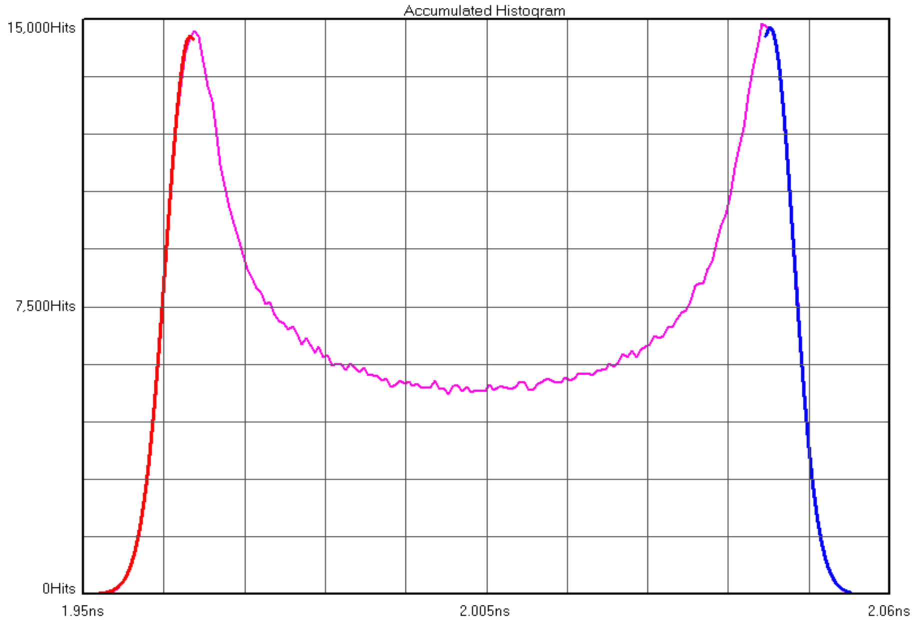


Deterministic Jitter-PJ

- PJ also known as sinusoidal jitter and it repeats at a fixed frequency. PJ is quantified as a pk-pk number with a frequency and magnitude.

- PJ could be the result of unwanted modulation such as EMI.

500 MHz clock signal with PJ added



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Deterministic Jitter-DDJ

- DCD is the result of any difference in the mean time allocated for the logic states in an alternating bit sequence (e.g. 0,1,0,1).
- Different rise and fall times and threshold variations of a device could cause DCD.
- DCD and ISI are functions of the data history that occur when the transition density changes.
- It is the DCD and ISI caused by the time difference that is required for the signal to arrive at the receiver threshold when starting from different places within the bit sequence (symbol).
- ISI occurs when the transmission medium propagates the frequency components of data (symbols) at different rates. For example when jitter changes as a function of edge density.

Measuring Deterministic Jitter

- TJ histograms represents the TJ PDF, therefore if the DJ and RJ process are independent the total PDF is the convolution of the DJ and RJ PDF.
- Removing DJ would produce a Gaussian distribution
- Adding DJ to the histogram broadens the distribution while maintaining Gaussian tails, effectively separating the mean of the left and right distributions.
- Difference between the two means is the DJ and the tail portions represent the RJ component.

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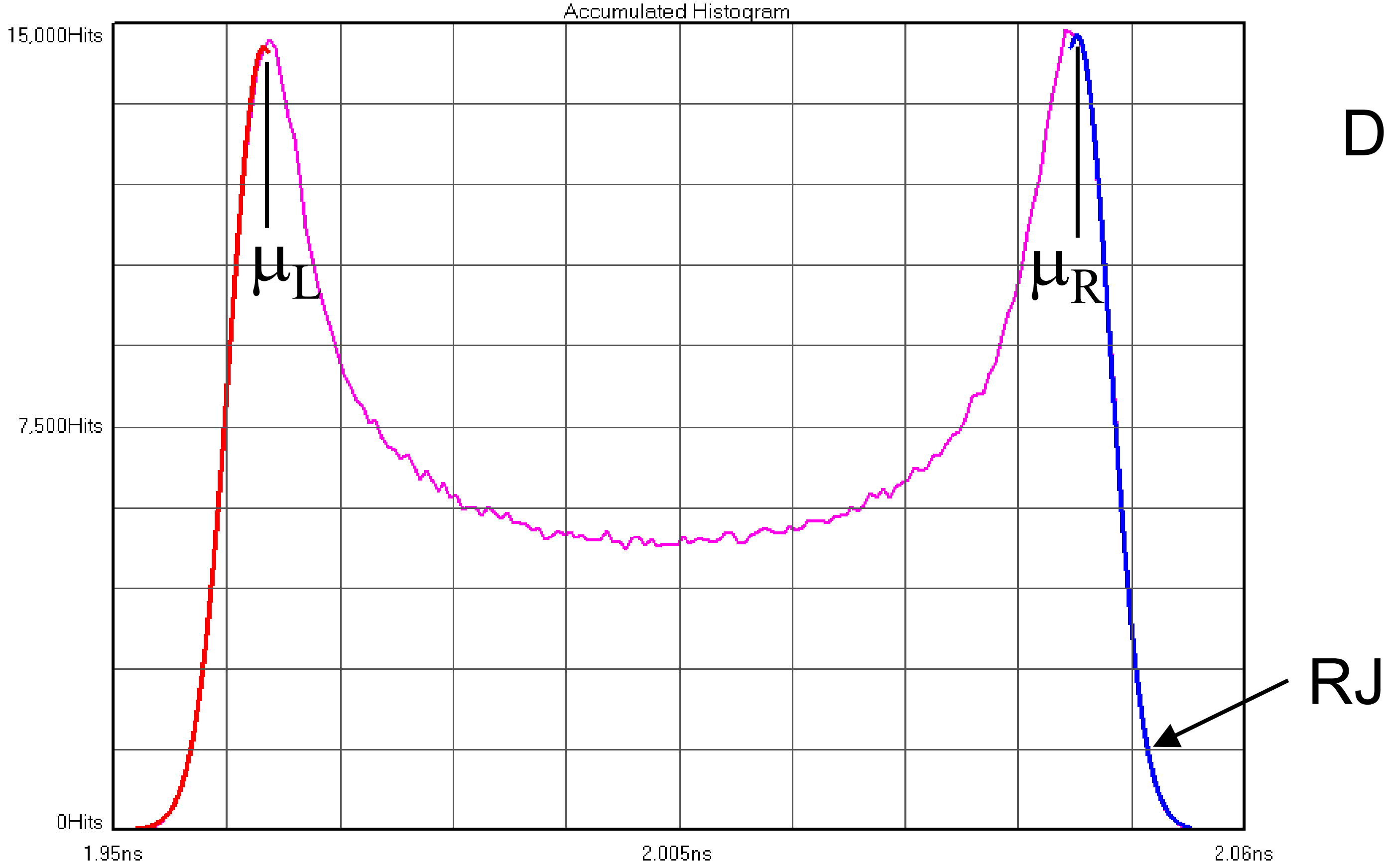
Measuring Deterministic Jitter



$DJ = \mu_L - \mu_R$

DJ is the difference between the two means μ_L and μ_R

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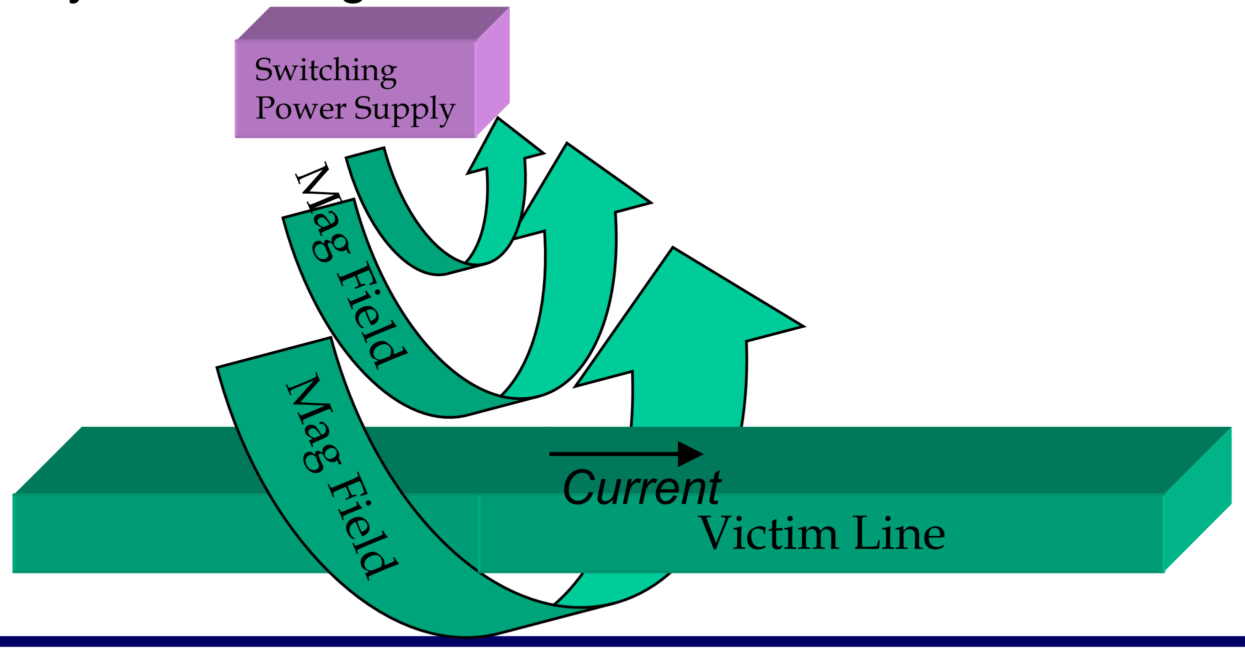
Sources of Jitter-EMI

- Common sources of DJ include EMI, crosstalk and reflections
- EMI is the result of unwanted radiated or conducted emissions from a local device or system. For example a switching type power supply.
- EMI may also corrupt a ground reference plane or supply voltage plane by introducing transient noise currents.



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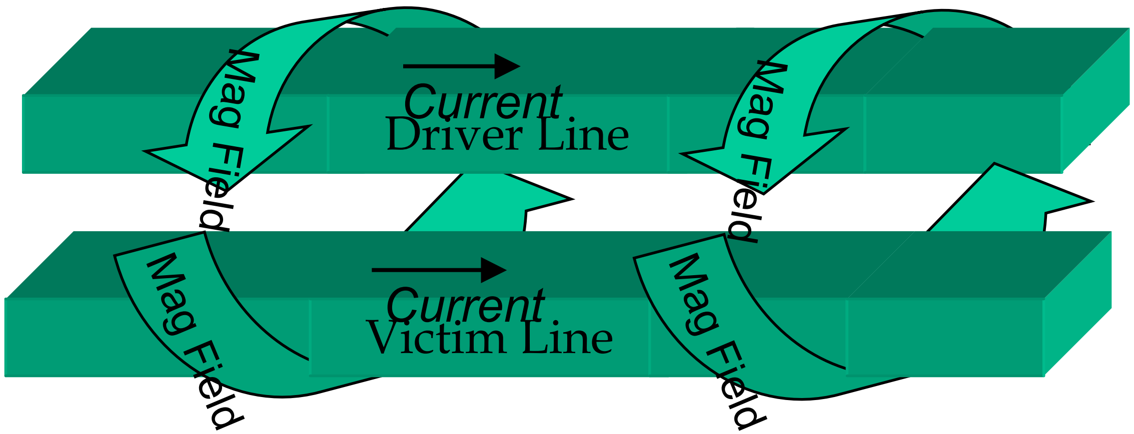
Sources of Jitter-Crosstalk and Reflections

- Crosstalk occurs when the magnetic or electric fields of a conductor are inadvertently coupled to an adjacent signal.



- Reflections in a data signal create DJ due to the signal interfering with itself. Reflections could be caused from impedance mismatches, uncontrolled stubbing and incorrect terminations.

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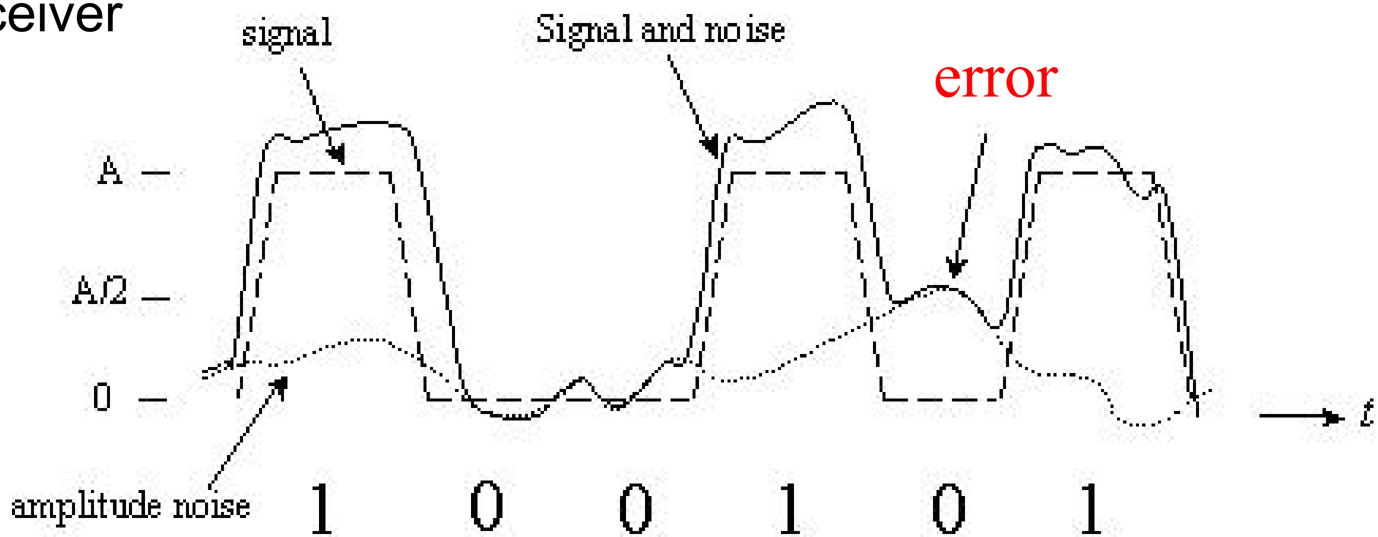
Sources of Jitter-RJ

- Common sources of RJ include shot noise, flicker noise and thermal noise
- Shot noise is broadband “white” noise generated when electrons and holes move in a semiconductor. Shot noise amplitude is a function of average current flow.
- Flicker noise has a spectral distribution that is proportional to 1/f. The origin of flicker noise is a surface effect due to fluctuations in the carrier density as electrons are randomly captured and emitted from oxide interface traps.
- Thermal noise can be represented by broadband “white” noise, and has flat spectral density. It is generated by the transfer of energy between “free” electrons and ions in a conductor.

Amplitude Noise

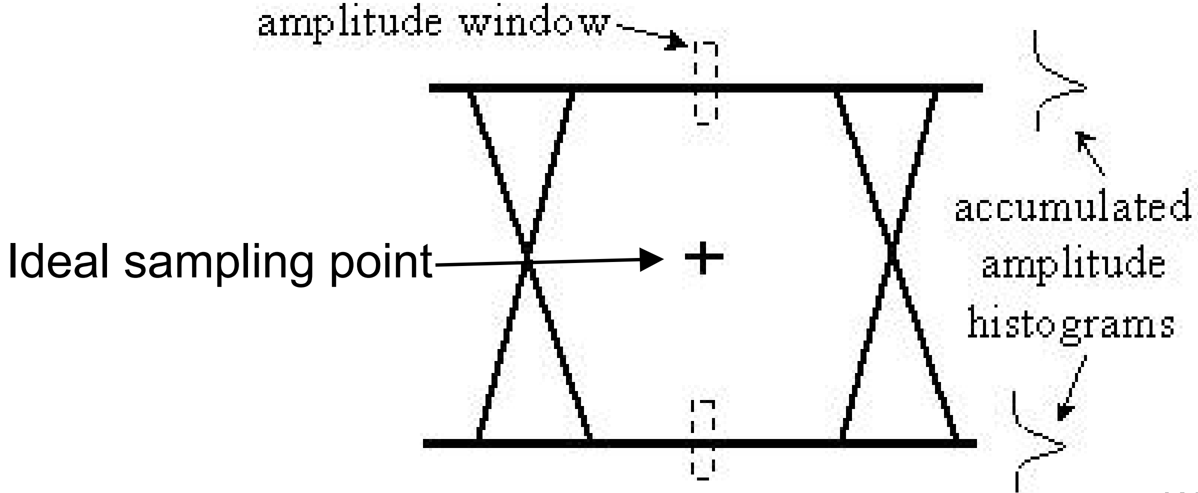
- Amplitude noise is present in all data signals and has random and deterministic sources. Common sources of random amplitude noise are thermal noise, shot noise, flicker noise and in optical systems noise due to lasers

- Random amplitude noise is assumed to have a Gaussian distribution and is unbounded. Random amplitude noise will become more dominant in low amplitude signals such as LVDS or signals at the receiver



Amplitude Noise

- Effect of only random amplitude noise. What is the probability that a 1 will be below the sampling point and a 0 above the sampling point?



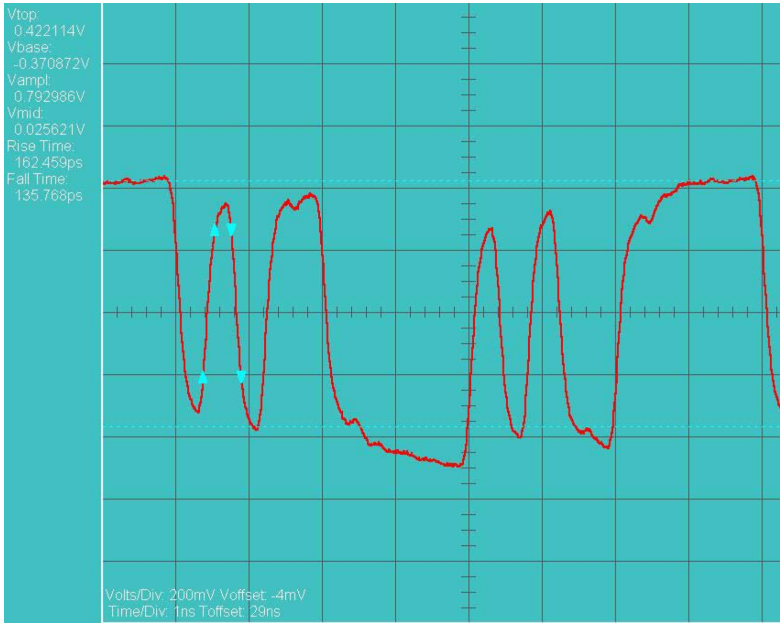
$$P_e = ½ \, erfc(A/\sqrt{2}*\sigma)$$

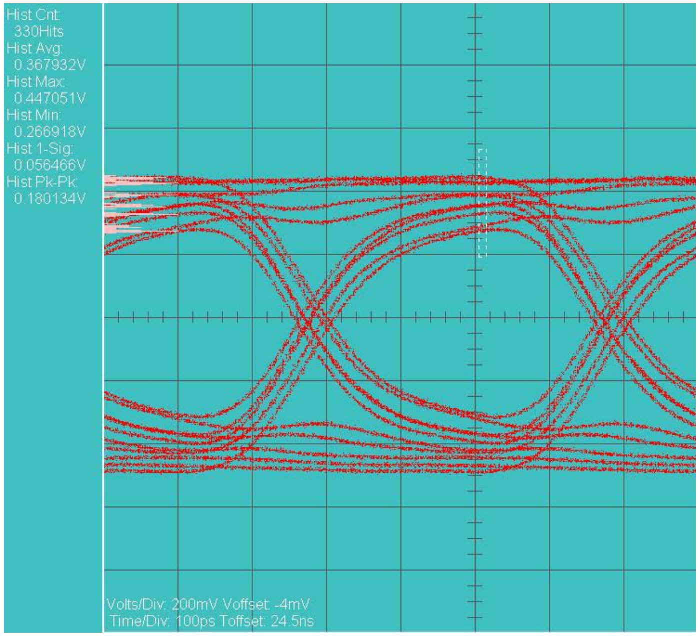
Where erfc is the complementary error function, A is the amplitude and σ is the standard deviation

P_e depends on the ratio of the amplitude to noise, i.e. the signal-to-rms noise ratio

Amplitude Noise

- Deterministic noise sources may also be present. Typical deterministic noise sources include crosstalk, reflections, EMI, periodics and bandwidth limitations (ISI)





Example of a 2.5 Gb/s signal through 16" of a backplane

V. Instrumentation for Measuring Signal Integrity

- Oscilloscopes
  - Sampling
  - Real time
- BERTs
- SIA's

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Instrumentation for Measuring Signal Integrity-Sampling Oscilloscopes

- Digital sampling oscilloscopes-generally have a very high bandwidth, 30-50 GHz.
- For repetitive sampling oscilloscopes the input signal is sampled at a time interval to obtain the voltage level. The waveform is “built up” after repetitive samples of the signal.
- This type of oscilloscope requires a trigger signal to control the timing of the sampling process. Digital sampling oscilloscopes measure voltage and timing accurately and can create “eye diagrams” for tolerance testing.

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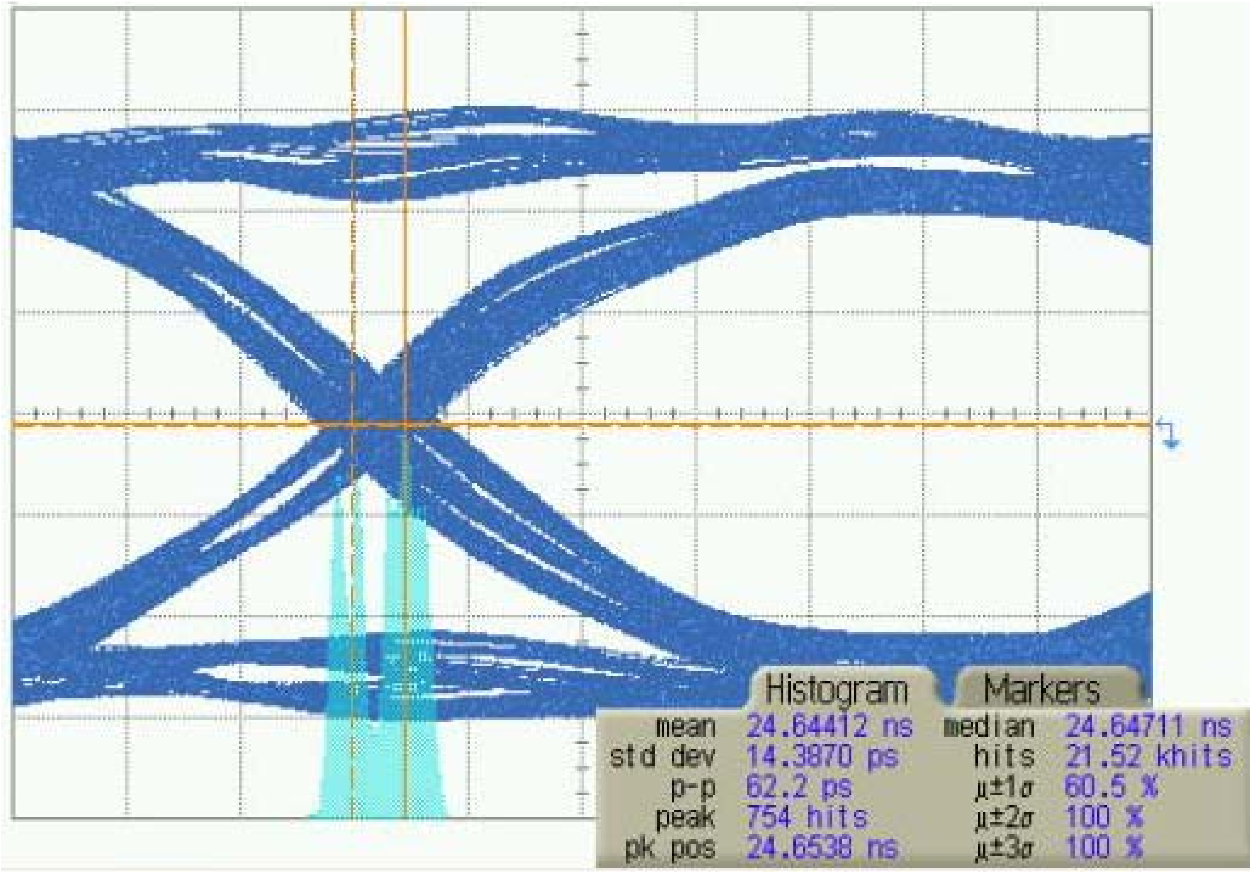
Instrumentation for Measuring Signal Integrity-Sampling Oscilloscopes



Determine:
TJ for small sample size, std. dev., pk-pk

Voltage levels, rise and fall times, eye diagrams and eye mask

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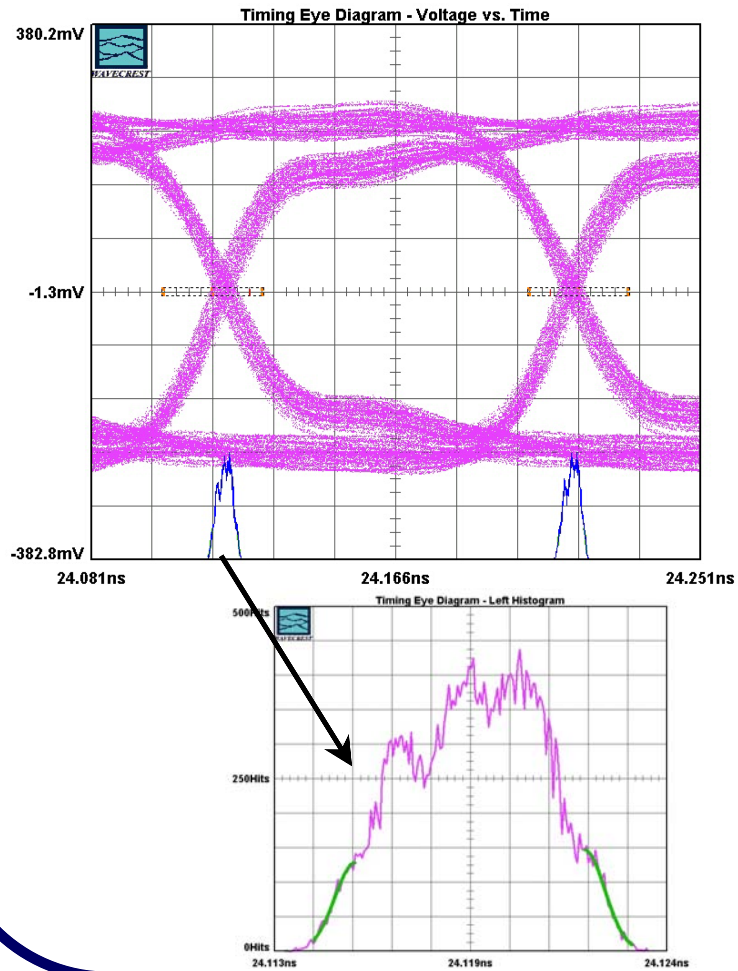
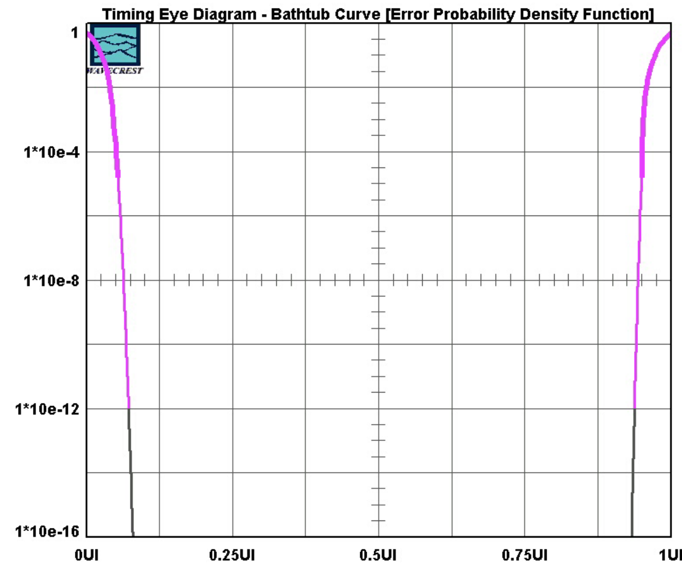
Instrumentation for Measuring Signal Integrity-Sampling Oscilloscopes





For a comprehensive analysis of horizontal ***and*** vertical eye opening for a to 10^{-16} BER use other software packages

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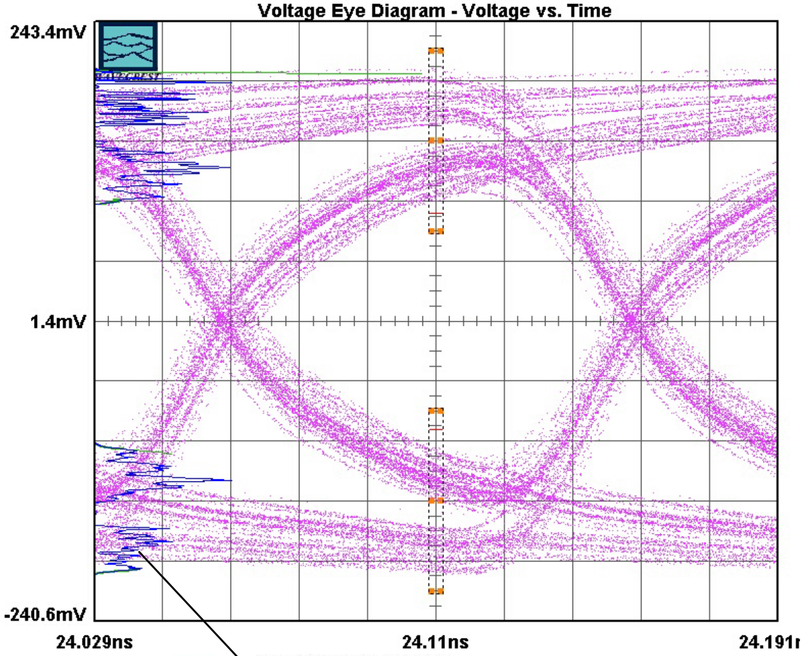
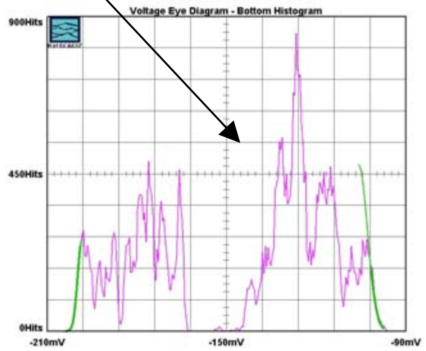
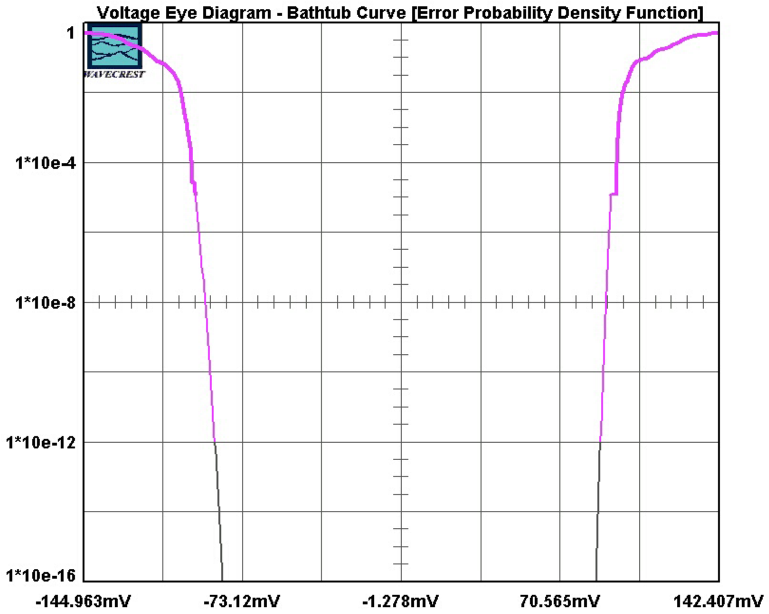
Instrumentation for Measuring Signal Integrity- Sampling Oscilloscopes







Vertical Eye opening to 10^{-16} BER

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Instrumentation for Measuring Signal Integrity-Real time oscilloscopes

- Real time oscilloscopes have bandwidths upto 6 GHz and acquire data upto 20 GSa/Sec (50 ps intervals). Bandwidth and sample rate sufficient for data upto 2.5 - 3 Gb/s.
- Maximum memory length of 96M or ~5 ms.
- Many companies claim capability of determining RJ, DJ, DCD, ISI, TJ. No correlation data or white papers on methodology yet.

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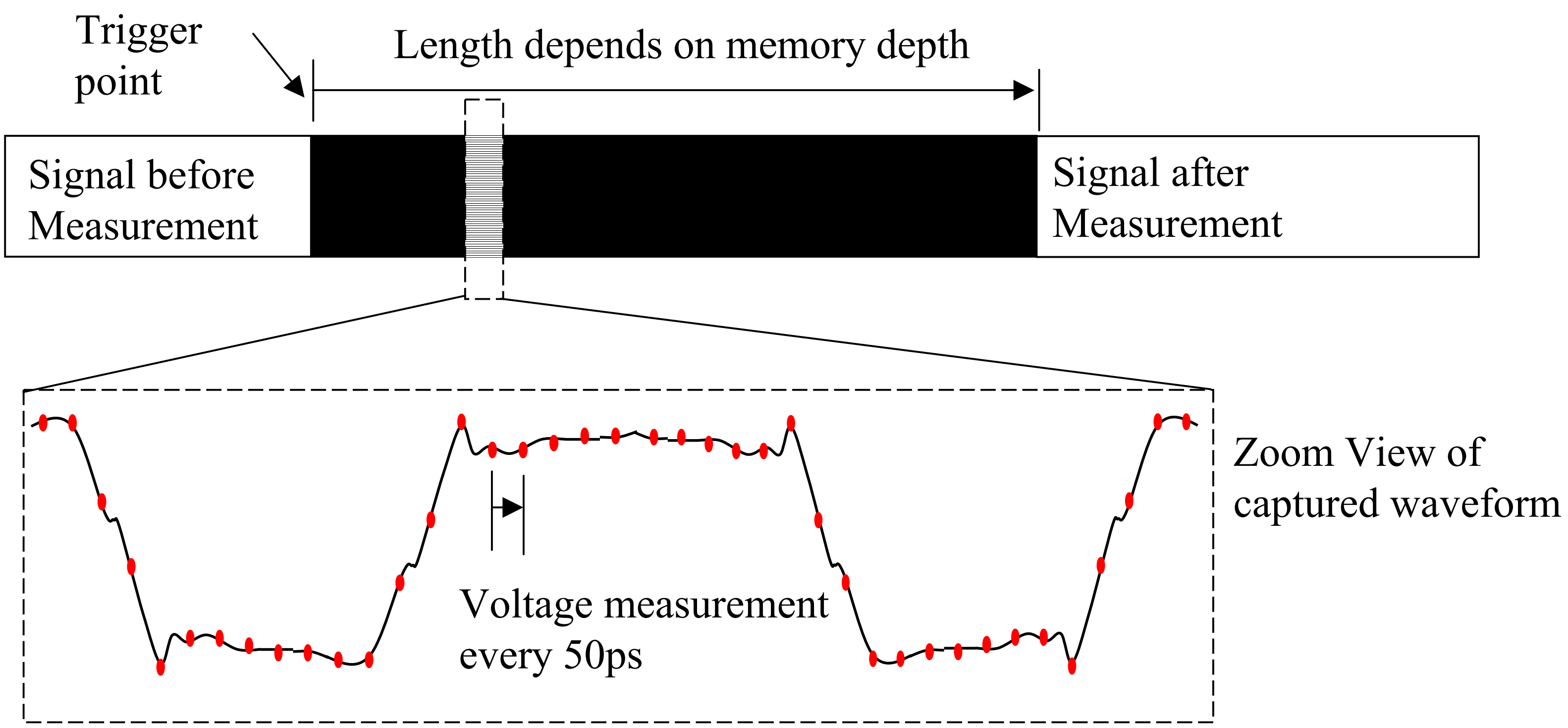
Instrumentation for Measuring Signal Integrity-Real time oscilloscopes

Example of Real-time Data Acquisition Methodology



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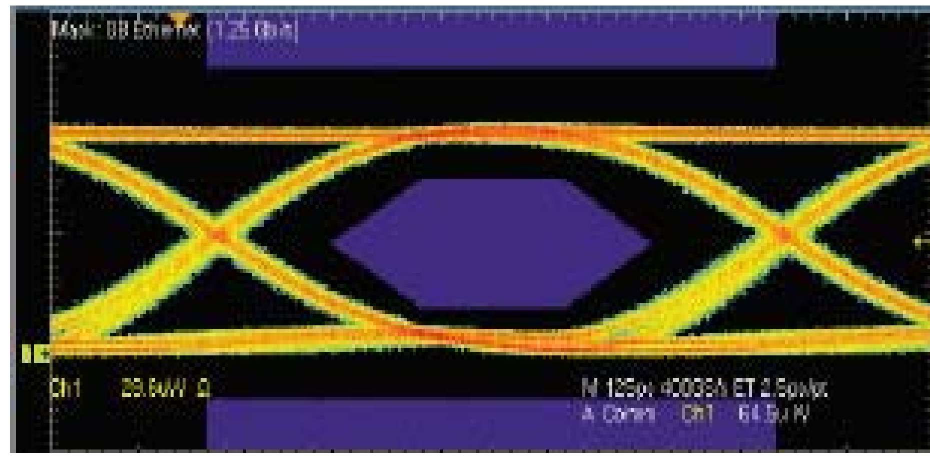
Instrumentation for Measuring Signal Integrity-Real time oscilloscopes

Eye diagram analysis



Feature analysis

Determine:
TJ, RJ, DJ, DCD, ISI, PJ and bathtub curve*

*No instrument correlation study yet

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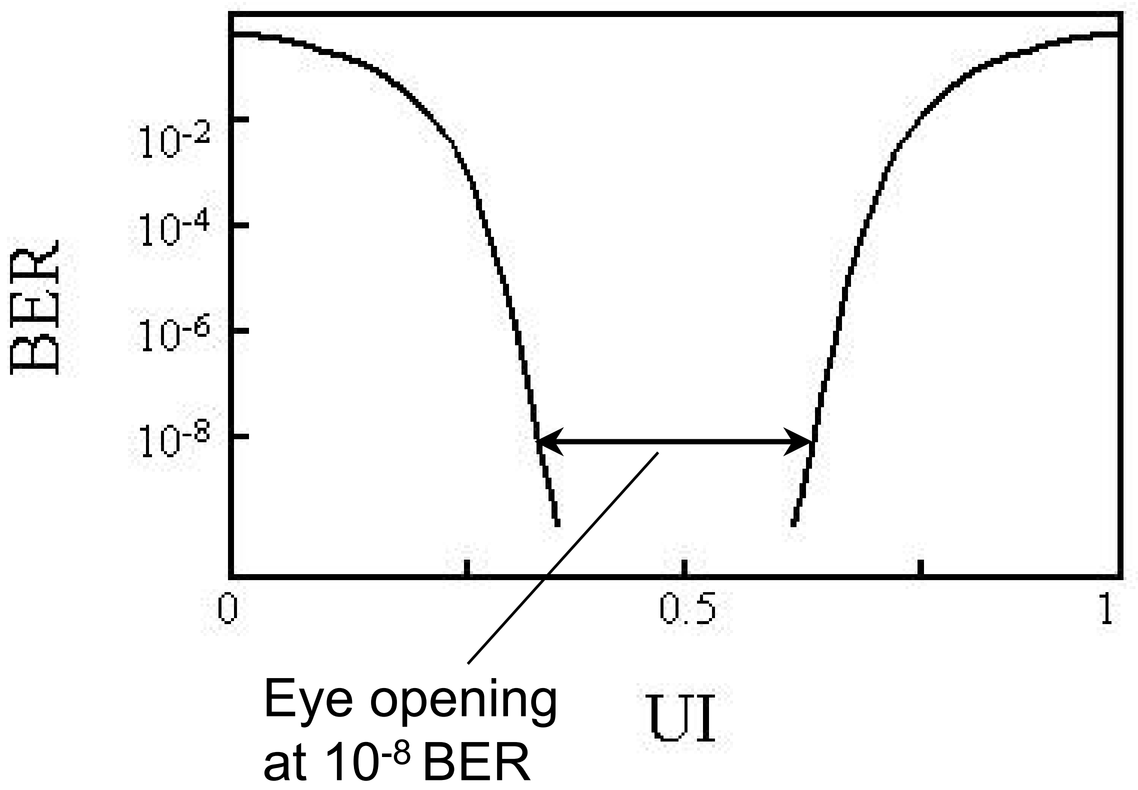
Instrumentation for Measuring Signal Integrity-Bit Error Ratio Testers (BERTs)

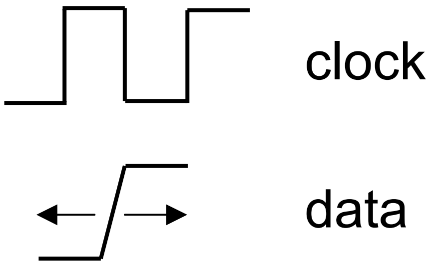
- BERTs are comprised of two components, a pattern generator and an analyzer or error detector.

- BERT operates by transmitting a pattern to the device under test and the error detector analyzes and records the differences between the transmitted and received pattern.

- In order to obtain the amount of eye closure as a function of BER, the BERT must vary the data edge placement with respect to the clock edge in order to obtain a BER, this is commonly called the BERT scan technique.

Typical data set from a BERT





Determine:
TJ vs. BER, post processing software can determine RJ & DJ assuming double delta model

A bathtub curve showing BER as a function of eye closure

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Instrumentation for Measuring Signal Integrity-Signal Integrity Analyzers (SIA's)

- SIA's integrate capabilities from a variety of test instruments to provide application solutions. SIA's have the capabilities of an oscilloscope, time interval analyzer, can count bit errors and estimate BER. Can analyze up to 10 channels.

- The statistics of these measurements along with algorithms provide information on total jitter, deterministic jitter, random jitter, BER, propagation delay, skew, amplitude, rise/fall times…for clock and data applications

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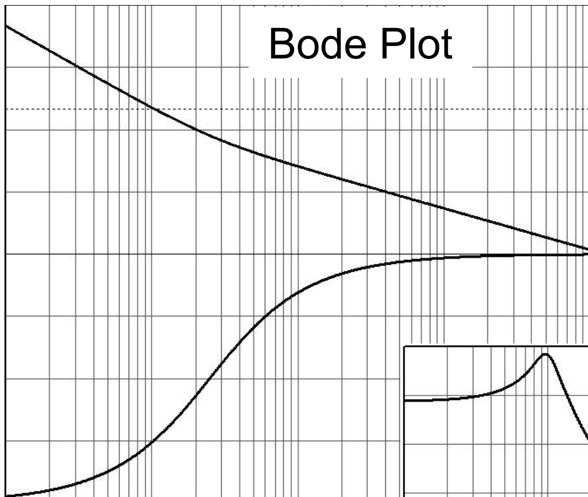
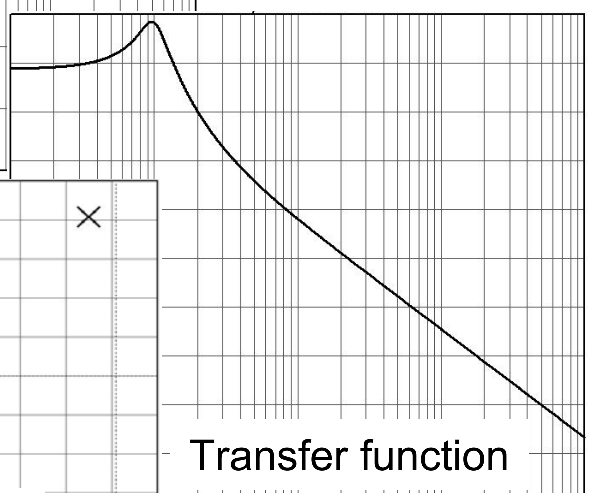
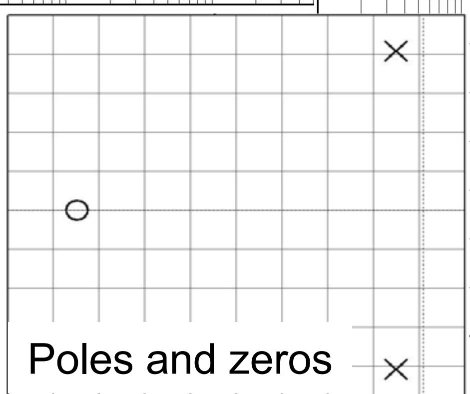
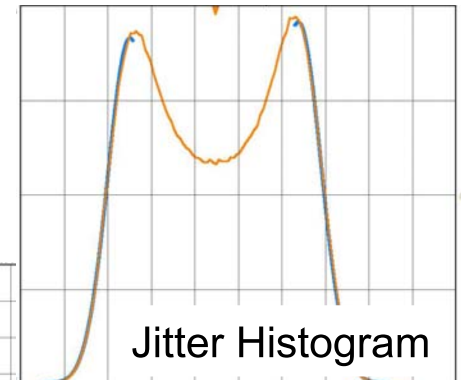
Instrumentation for Measuring Signal Integrity-Signal Integrity Analyzers (SIA's)-Clocks/PLLs jitter

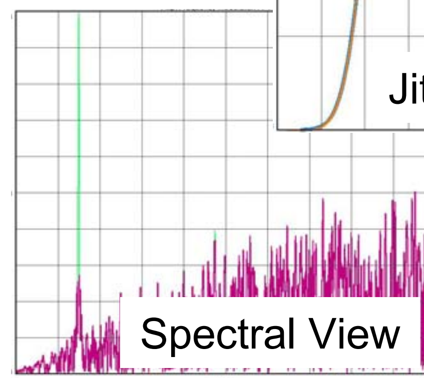


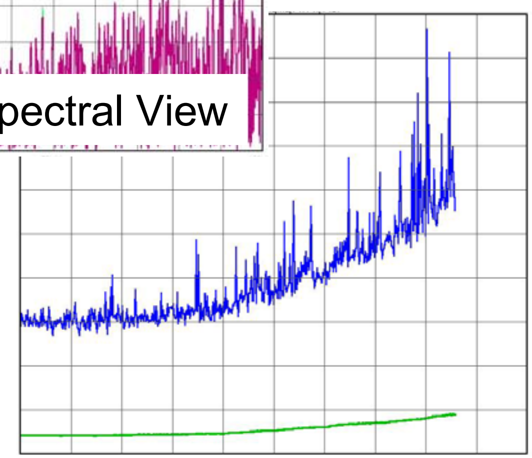




Jitter, spectral analysis, jitter vs. time, PLL characterization…







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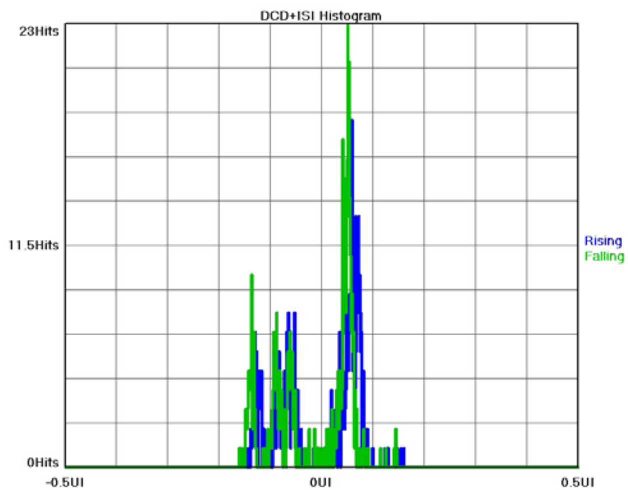
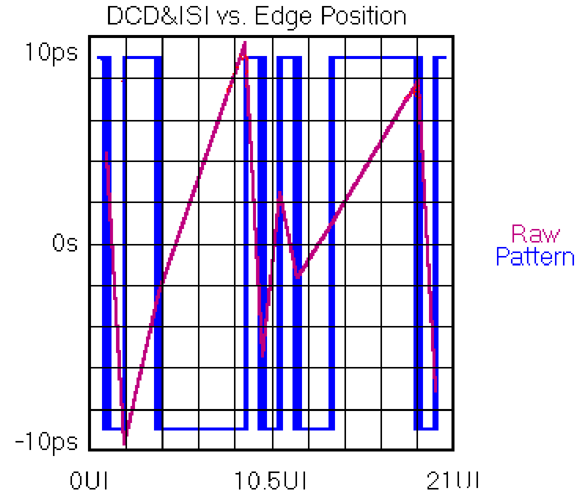
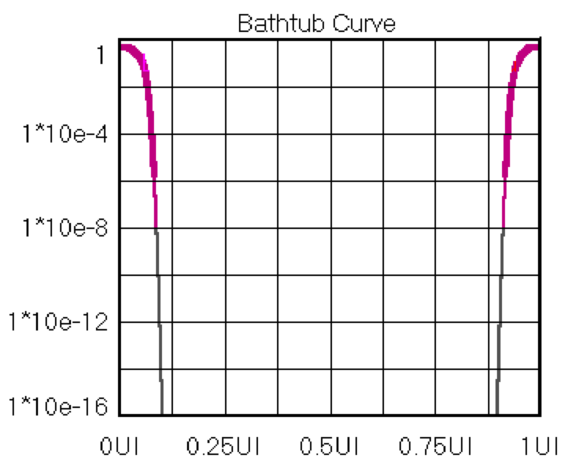
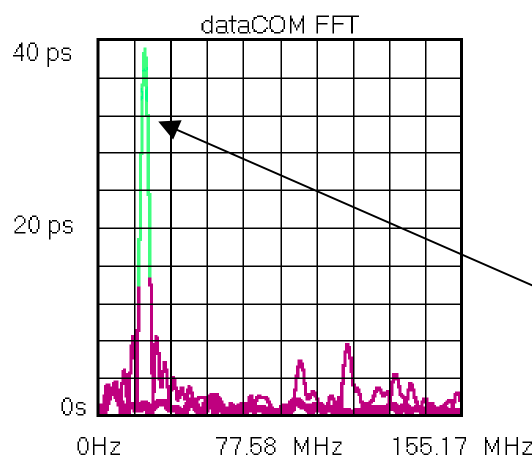
Instrumentation for Measuring Signal Integrity-Signal Integrity Analyzers (SIA's)-DataCom Jitter





Repeating pattern and marker





Determine: TJ, RJ, DJ, DCD&ISI, PJ and bathtub curve

Due to EMI or crosstalk?

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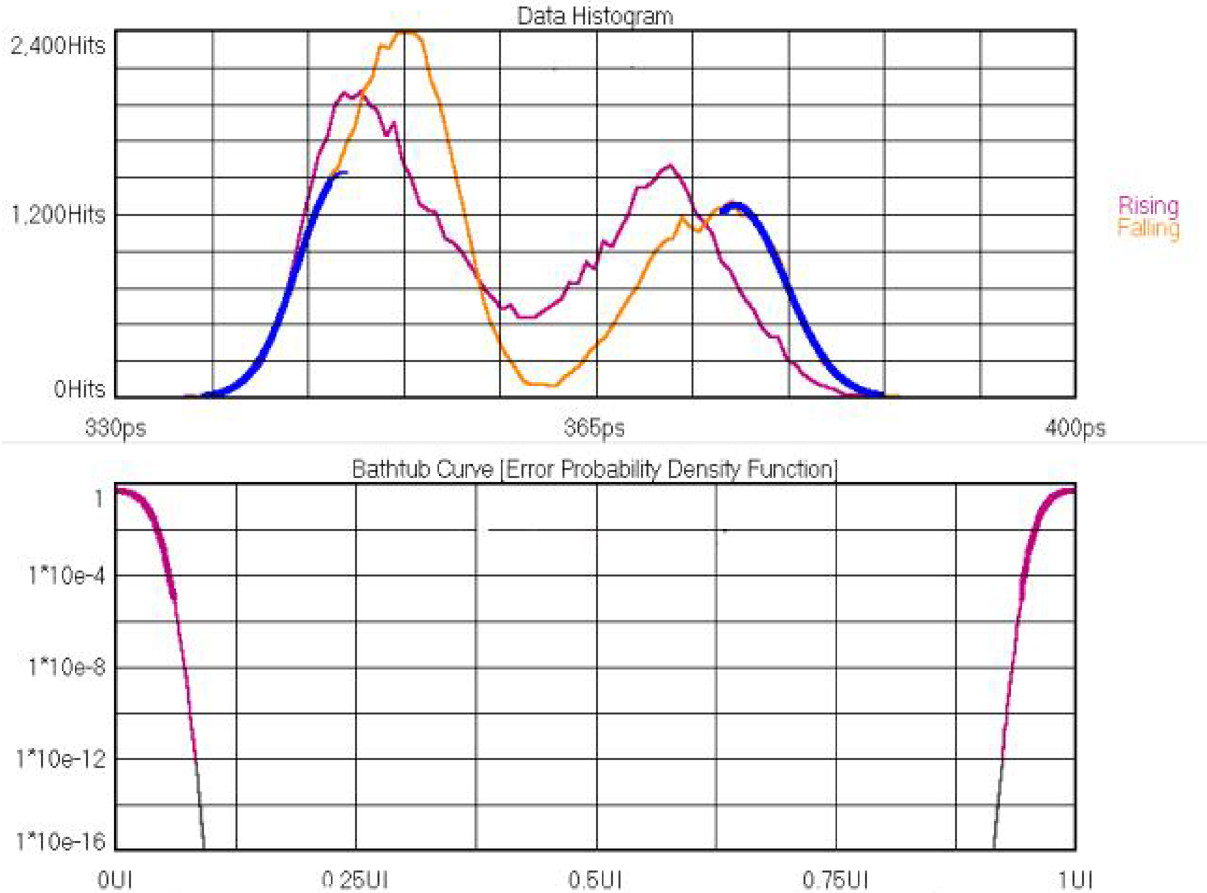
Instrumentation for Measuring Signal Integrity-Signal Integrity Analyzers (SIA's)-DataCom jitter



SIA-Clock to data

Determine: TJ, RJ, DJ, bathtub curve and histograms for rising and falling edges, skew between clock and data

Instrumentation for Measuring Signal Integrity- Signal Integrity Analyzers (SIA's)- Voltage

Timing and Voltage compliance measurements

OSCILLOSCOPE MEASUREMENTS

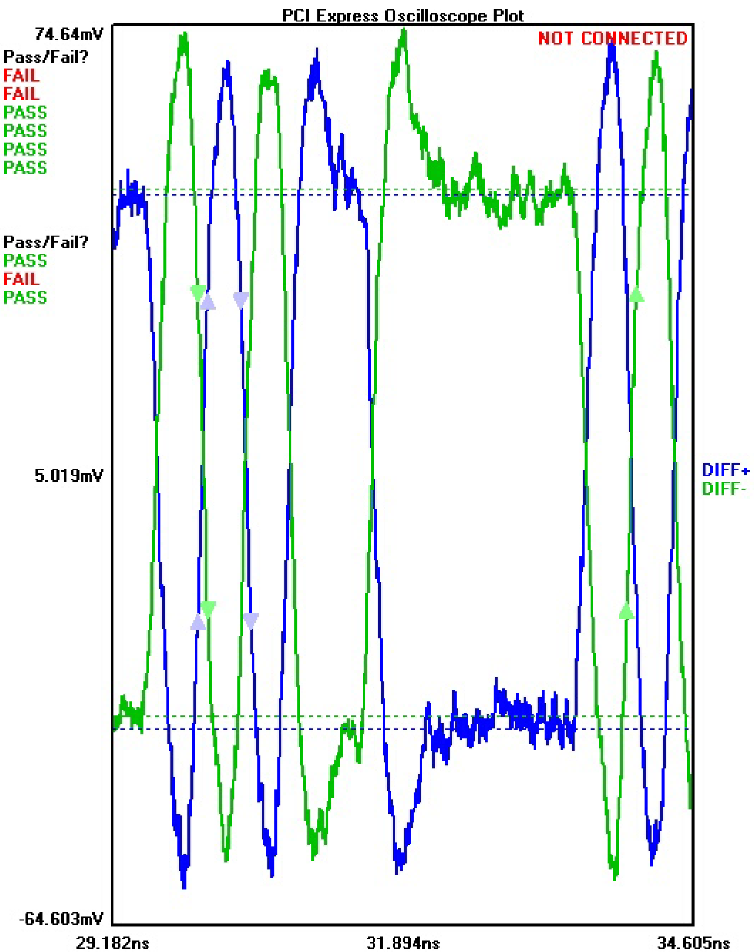
Quantity	Specification	Measured	Pass/Fail?
VTX-DIFFp-p	800mV-1.2V	267mV	FAIL
VTX-DE-Ratio	-4dB--3dB	-4.6dB	FAIL
D+ TTX-Rise	>50ps	89.456ps	PASS
D- TTX-Rise	>50ps	86.964ps	PASS
D+ TTX-Fall	>50ps	91.141ps	PASS
D- TTX-Fall	>50ps	92.906ps	PASS

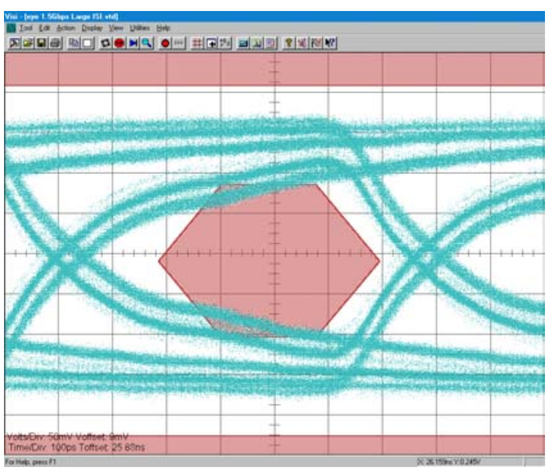
TIMING MEASUREMENTS

Quantity	Specification	Measured	Pass/Fail?
UI	399.88ps-400.12ps	400.012ps	PASS
T TX-EYE	>0.7UI	0.651827UI	FAIL
T TX-Median to Max	<0.15UI	0.117425UI	PASS

ADDITIONAL VALUES

DJ (pk-pk)	58.087ps
RJ (1-sigma)	6.073ps
Histogram Hits	16,000Hits

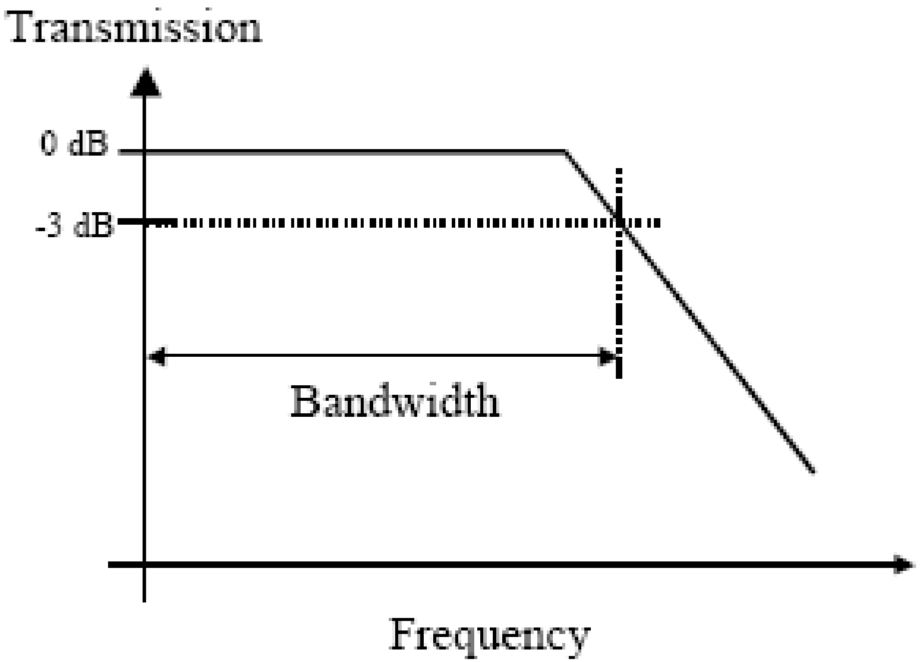




Eye diagram analysis

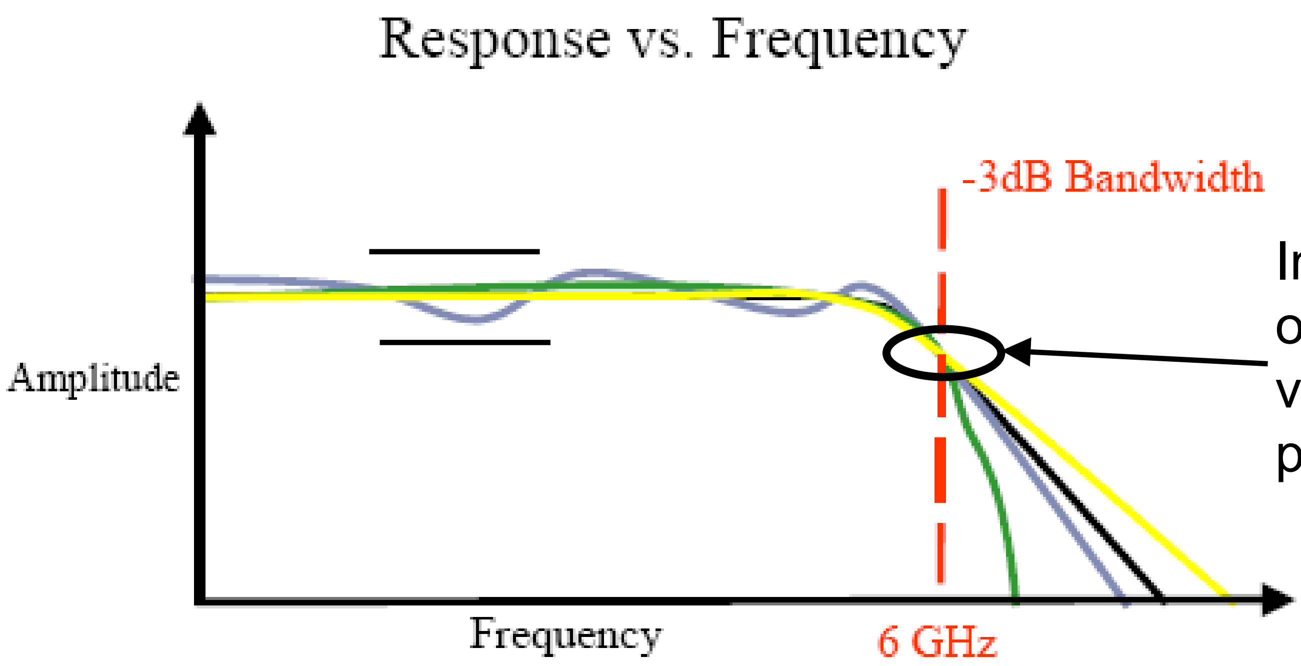
Test Instrumentation Bandwidth

Is bandwidth a good metric for determining instrument performance?



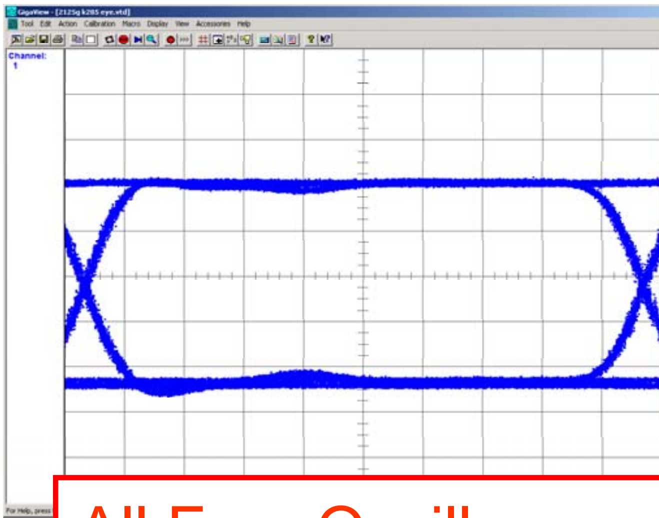
Should a time domain instrument be specified in the frequency domain?

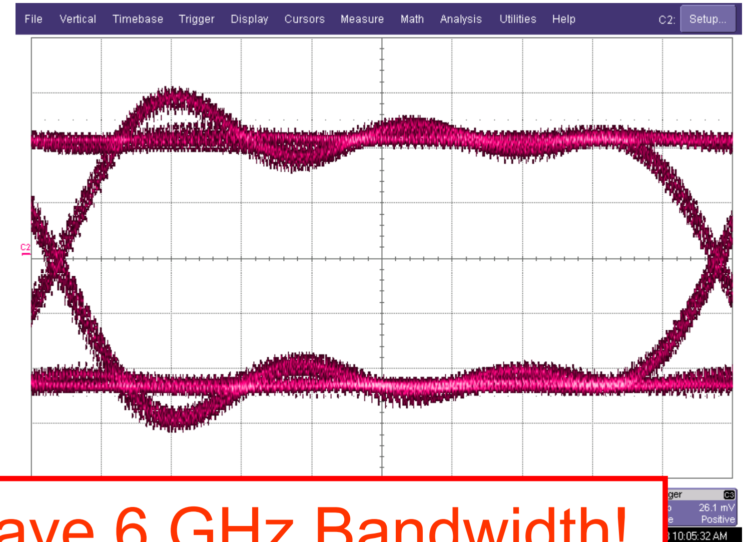
For a given bandwidth specification the performance can be very different



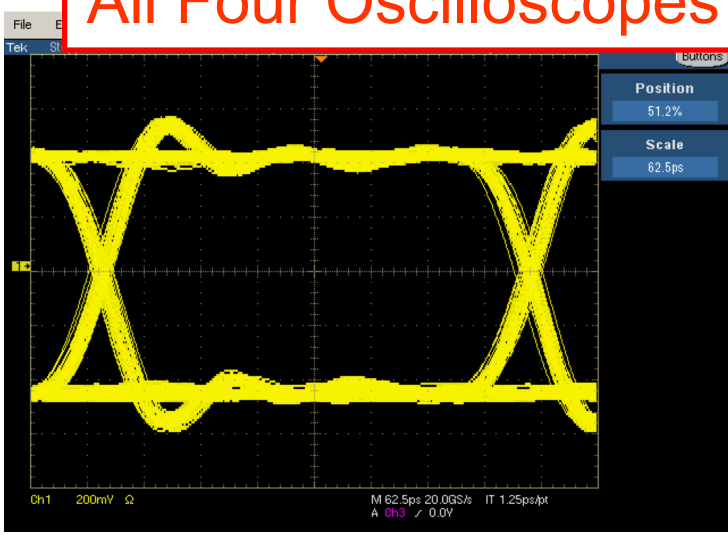
In general you only know this value, not the plot

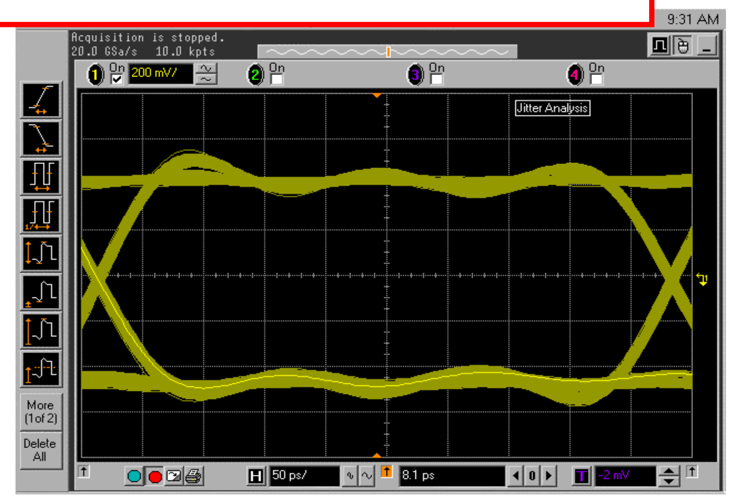
4 Different Oscilloscopes Analyze the Same 2.125 Gb/s Signal



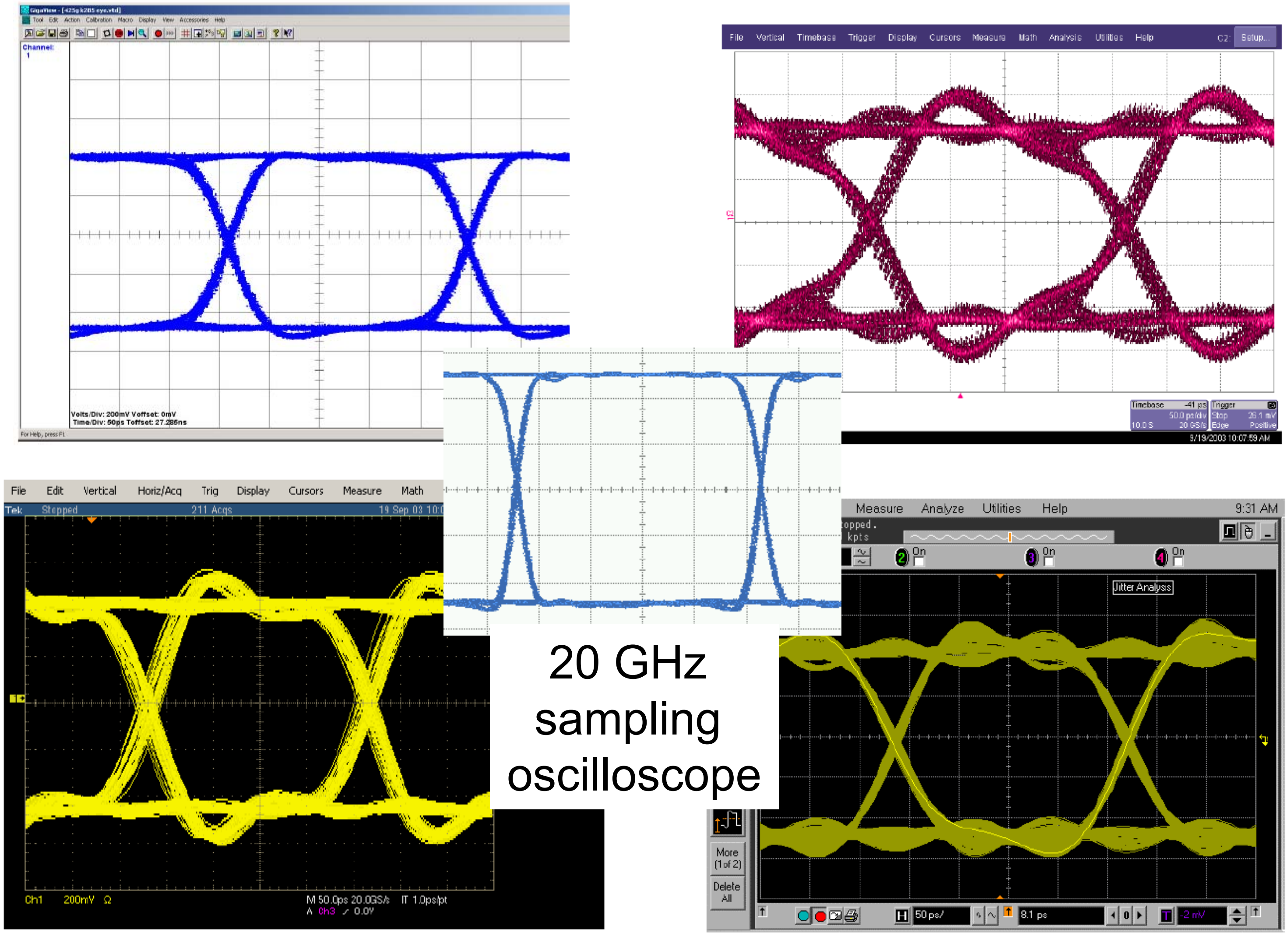


All Four Oscilloscopes have 6 GHz Bandwidth!

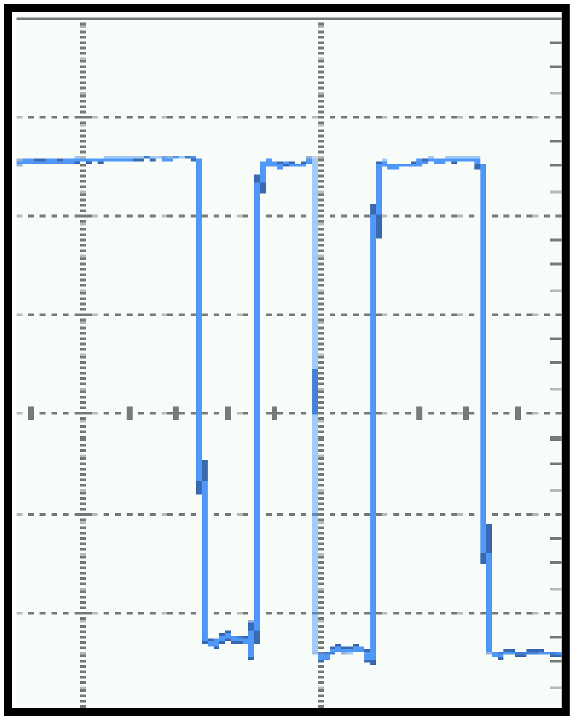




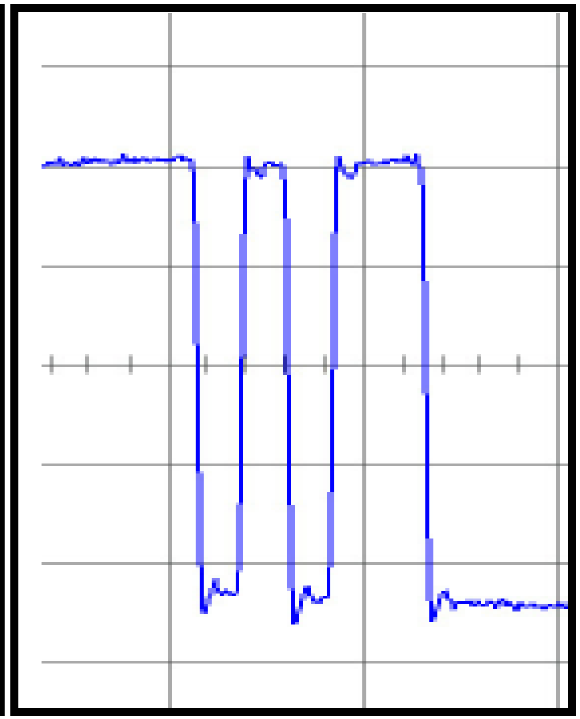
4 Different 6 GHz Oscilloscopes Analyze the Same 4.25 Gb/s Signal



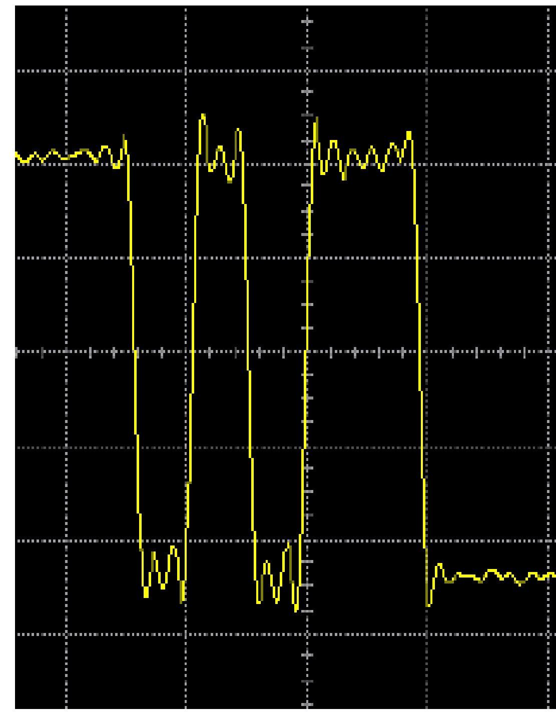
Feature Analysis



20 GHz sampling oscilloscope

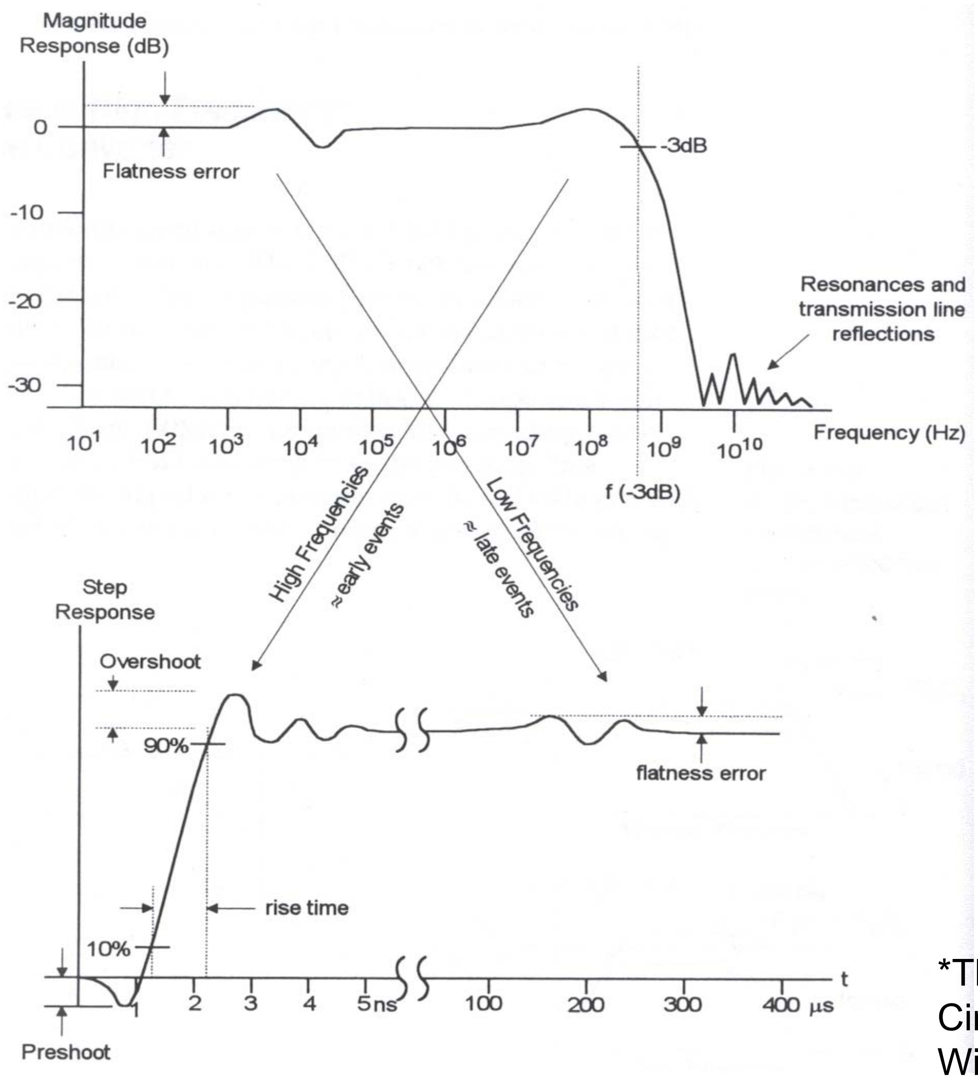


6 GHz sampling oscilloscope



6 GHz realtime oscilloscope

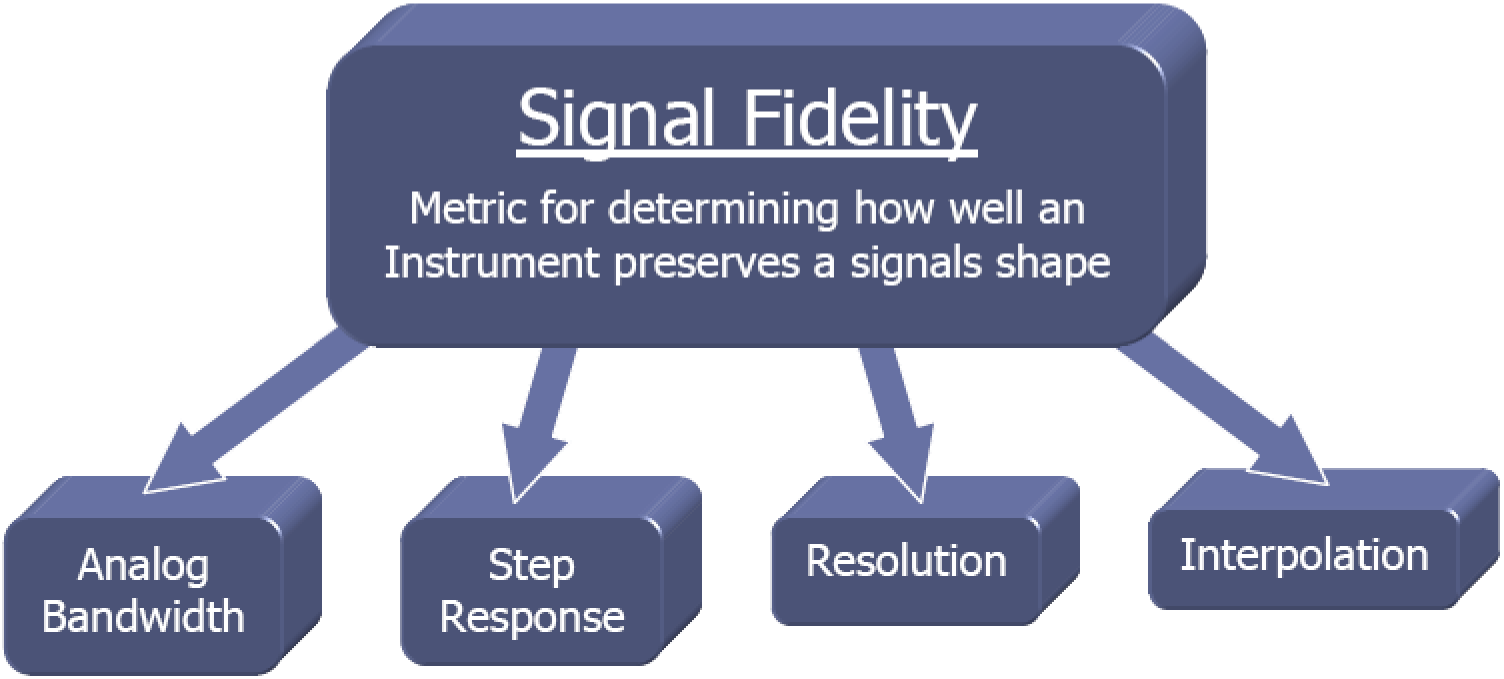
Relationship between Frequency Magnitude and Step Response*



Consider how the test instrument responds to a step or fast edge in order to evaluate its performance

*The Art and Science of Analog Circuit Design, edited by Jim Williams, 1998, pg. 65

Bandwidth is **not** the only metric for determining instrument performance



Evaluate the test instrument in your application and compare it to a known standard

Summary

I. Measurement Statistics-*Quantify and Characterize the Histogram*

II. Types of Jitter Measurements
   a. Phase, period, cycle-to-cycle-*Determine the Application*
   b. Role of clock recovery-*CR affects your measurement*
   c. Data-*Different Jitter Analysis methods*

III. Types of Jitter and Noise
   a. Timing Jitter-*Types and Sources*
   b. Amplitude Noise

IV. Instrumentation for Measuring Signal Integrity
   a. Oscilloscopes } *They all perform different functions*
   b. BERT's
   c. SIA's
   d. Bandwidth-*It's not the only metric for performance*

More Signal Integrity Presentations

Statistical and System Transfer Function Based Method for Jitter and Noise in Communication Design and Test- Track 4, 2:00 pm Tuesday, Mike Li and Jan Wilstrup, Wavecrest

One final thought

"The old concept of histogram based peak-to-peak jitter has been replaced by the concept of total jitter that is associated with a certain bit error rate for the serial link (typically 10^{-12})"

ITRS Roadmap for Semiconductors: 2003