Thoughts on testing of devices with 10^{-15} confidence using test times historically used for 10^{-12}

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- The generic concept of speeding-up component test times through extrapolation and marginalization discussed in this paper are not the topic of IP/Patents held by SyntheSys Research, Inc.
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9 July 2004

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Abstract

The accuracy of extrapolation of test results down to very low BER levels is dependent upon the depth of the measurements being used as a basis, the model and the accuracy of the points taken. While the amplitude setting accuracy of instruments is relatively straightforward, calibrated time setting accuracy is both problematic, and also critical. Examples are given that show precision jitter, eye mask, eye contour and stressed eye measurements can be practical and fast. The absence of error floors should be verified periodically through direct measurement.

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1. Generic methods of component evaluation
2. Instrument fit
3. Factors affecting accuracy & test time
    1. Scope methods
    2. BERT methods
4. Transmitter Measurements
    1. Jitter Generation
    2. Eye Contour
    3. Mask
    4. Eye
    5. Error Floors
5. Receiver Measurements
6. Conclusions

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1. Generic Methods for Component Evaluation

- Transmitter Jitter Generation Tests
  - Grade/Measure/Analyze PDF of Signal
    - Jitter PDF (Scope Histogram, BER Bathtub)
    - Voltage PDF (Scope Histogram, BER Q-factor)
    - Two-Dimensional (Scope Mask, BER Contour)

- Channel Testing:
  - Direct BER
  - S-parameter predictions (e.g. StatEye)

- Receiver Test:
  - Operate error-free in face of stress
    - PG with stress insertion connected to DUT

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2. Instrument Fit

- Instrument capable of parametric testing at 10 Gb/s:
  - Sampling Oscilloscopes
  - BERTs
  - BERTScopes

Parameter	Sampling Scope	BERT	BERTScope
Eye Measurements	Y		Y
Mask Measurements	Y		Y
Jitter Evaluation	Y	Y	Y
Long Patterns (>2^15)		Y	Y
Deep Measurements		Y	Y
BER		Y	Y
Stressed Eye Generation		Y w/ rack	Y
Stressed Eye Calibration	Y		Y

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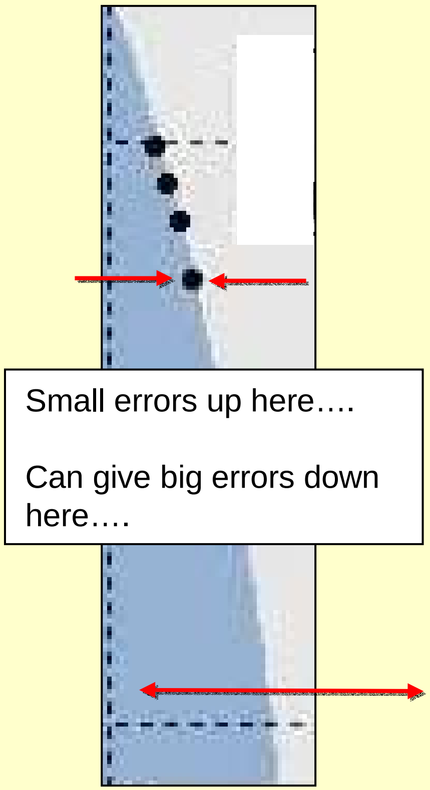
3. Factors Affecting Accuracy & Test Time

- Issues with 10^{-15} testing:
  - Test time >1 day for direct measurements
    - Impractical for multiple test runs, or manufacturing environments
  - Extrapolation:
    - Is it accurate enough?
    - Did I miss anything that was lurking, such as an error floor?
    - How do I ensure repeatability & correlation with direct measurements?
  - Addition of margin into stressed eye measurements:
    - Too much, yield hit
    - Too little, not confidently assuring operation

⇒ Critically depends upon accuracy of predictions made

3. Transmitter Jitter Generation Tests

- Larger extrapolations of distributions lead to greater chance of error at point of interest
- Inaccurate time or amplitude measurement (& lack of repeatability) also lead to large inaccuracies at the point of interest
- Deeper measurements:
  - Reduce effect of measurement inaccuracies
  - Reduce effect of model inaccuracies
  - Reduce the effect of infrequent bounded events



3.1 Today's Histogram Methods

- Directly measure PDF
- Samples accumulate into the jitter PDF as fast as
  *Transition Density * Sampling Rate*
  - (estimate 20K-100K samples/sec today)
- Analytical techniques can separate RJ from other jitter in the PDF; however fitting to tails in a Gaussian is noise-prone
- In 10 seconds, the PDF represents up to 10^6 samples. This is good enough to claim a BER of 1.0×10^{-5} or so.
- *Extrapolating this result to 10^{-15} means 10 orders of magnitude extrapolation*

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3.1 Efficiency Upgrades for Scopes

- Given fixed sampling rate, efficiency can be gained by making sure all samples taken are applicable to the region of interest for the histogram.
- *Still driven by the intrinsic sample rate of sampling scope.*

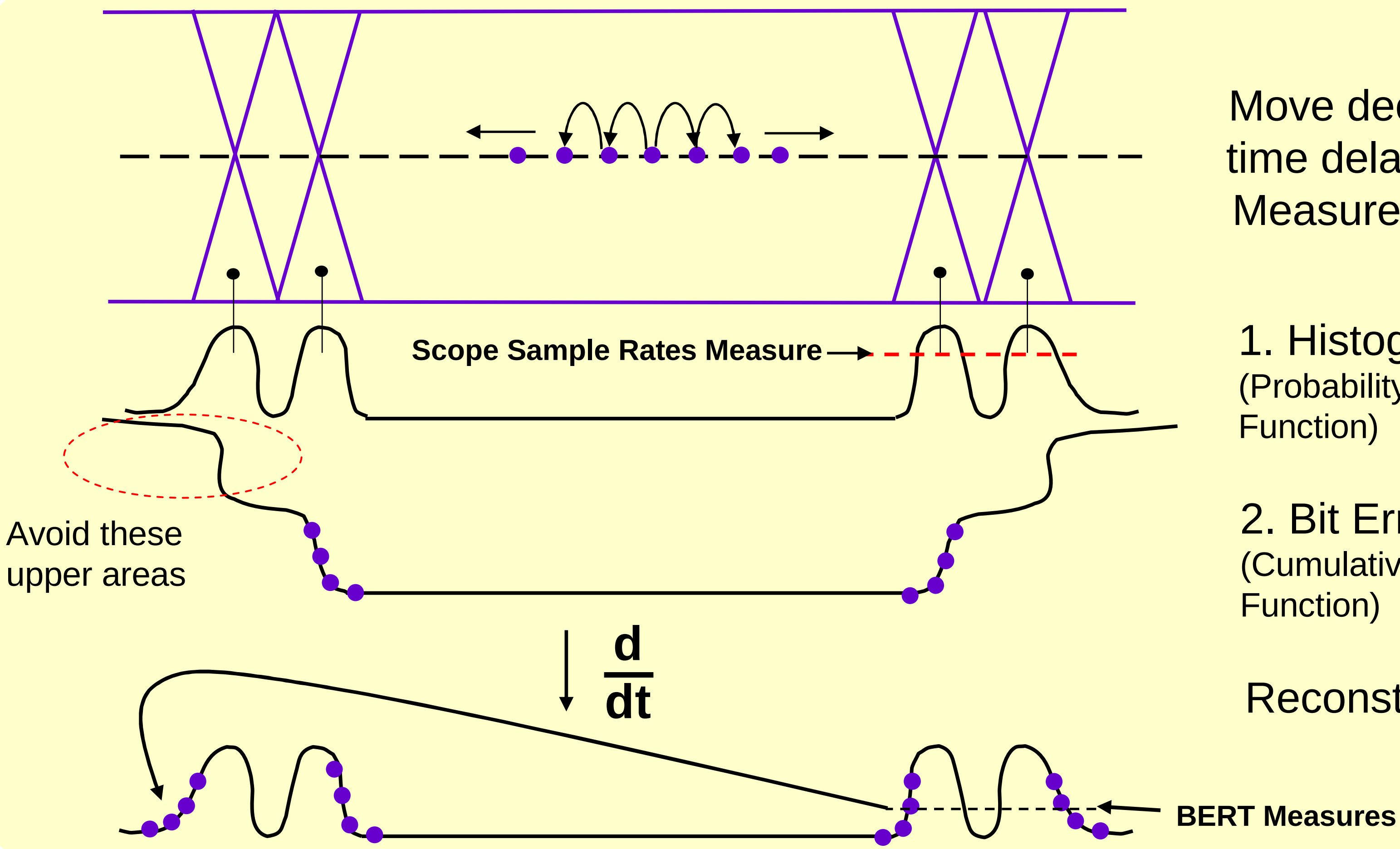
3.2 BER Bathtub Methods (as described in MJSQ)

- Tx Test
- BERTs

- Measures CDF (if needed, must calculate PDF)
- Samples CDF at
  - TransitionDensity * DataRate (e.g 5Gs/sec)
- CDF **<u>IS</u>** BER and can be used directly
- 6-10 Points on a CDF can accurately estimate CDF wave shape in area of interest
- In 10 seconds, CDF can assure BER to 10^{-11} and the CDF curve can have 10 points to virtually this same depth
- Measures lower probability events (reduces chance of error floor being undetected)

3.2 BER Bathtub Process

- Tx Test
- BERTs



Move decision time delay and Measure BER

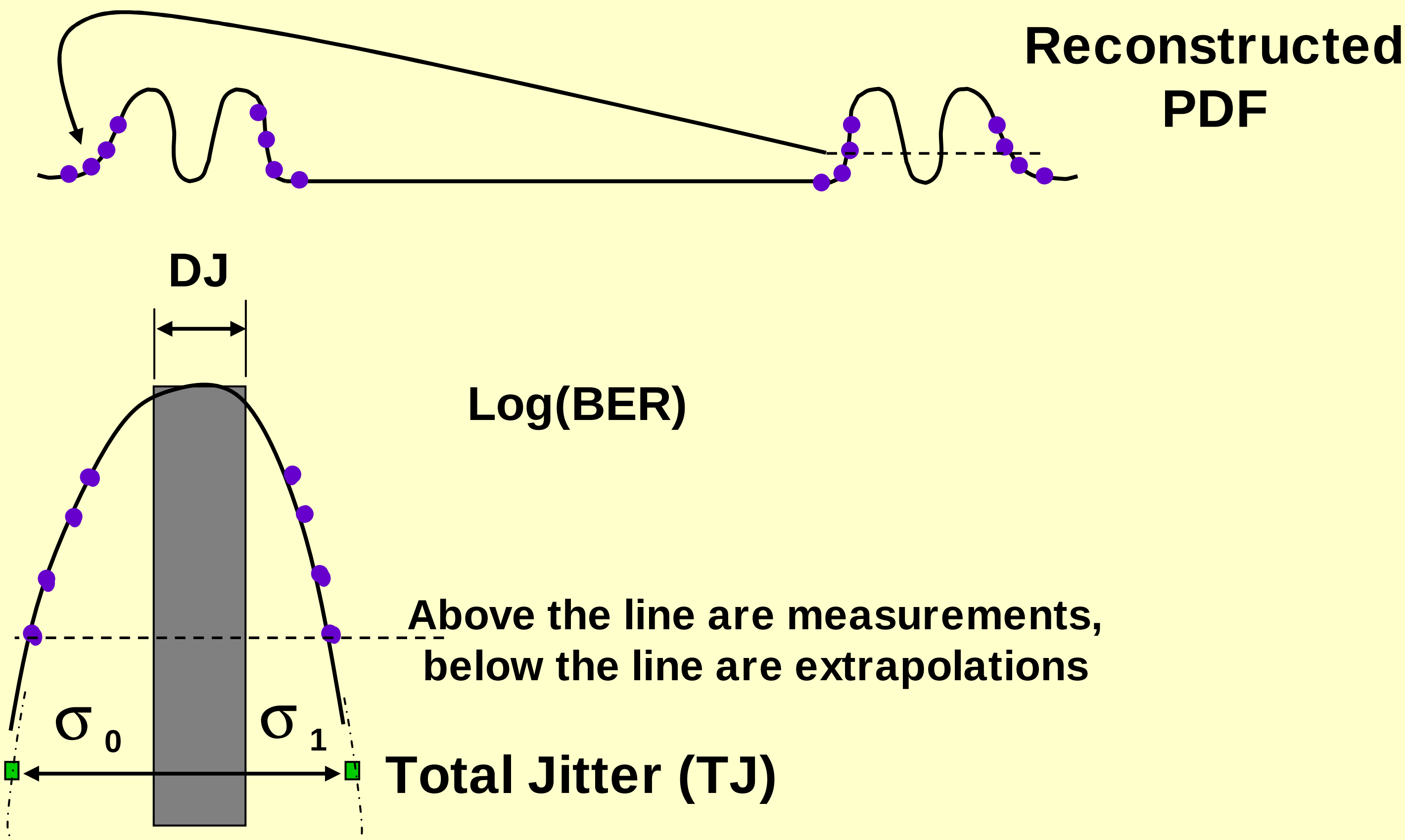
1. Histogram
(Probability Density Function)

2. Bit Error Rate
(Cumulative Density Function)

Reconstructed PDF

3.2 Depth of CDF Measurement

- Tx Test
- BERTs



$$RJ = \sigma_0 + \sigma_1$$

3.2 Efficiency Upgrades for Bathtubs

- Tx Test
- BERTs

- Fundamental Improvements to past Bathtubs:
  - Amplitude setting is usually accurate enough
  - Critical parameter is <u>delay</u>
    - Need precise variable delay functions (relative accuracy and fine resolution) (to measure RJs in the 300fs range when DJ is present, variable delays must have resolutions < 100fs)
    - Highly linear, calibrated & repeatable
    - Stable delays are required for long tests, immune from thermal effects etc.
    - Start measurement inside "crossing" and predict required step resolution for 10 points. Only make one LONG measurement
  - Ease-of-Use
    - Integrated "one-touch" operation required; not typically present in legacy BER testers, or were external GPIB programs
      ….aids test speed and repeatability

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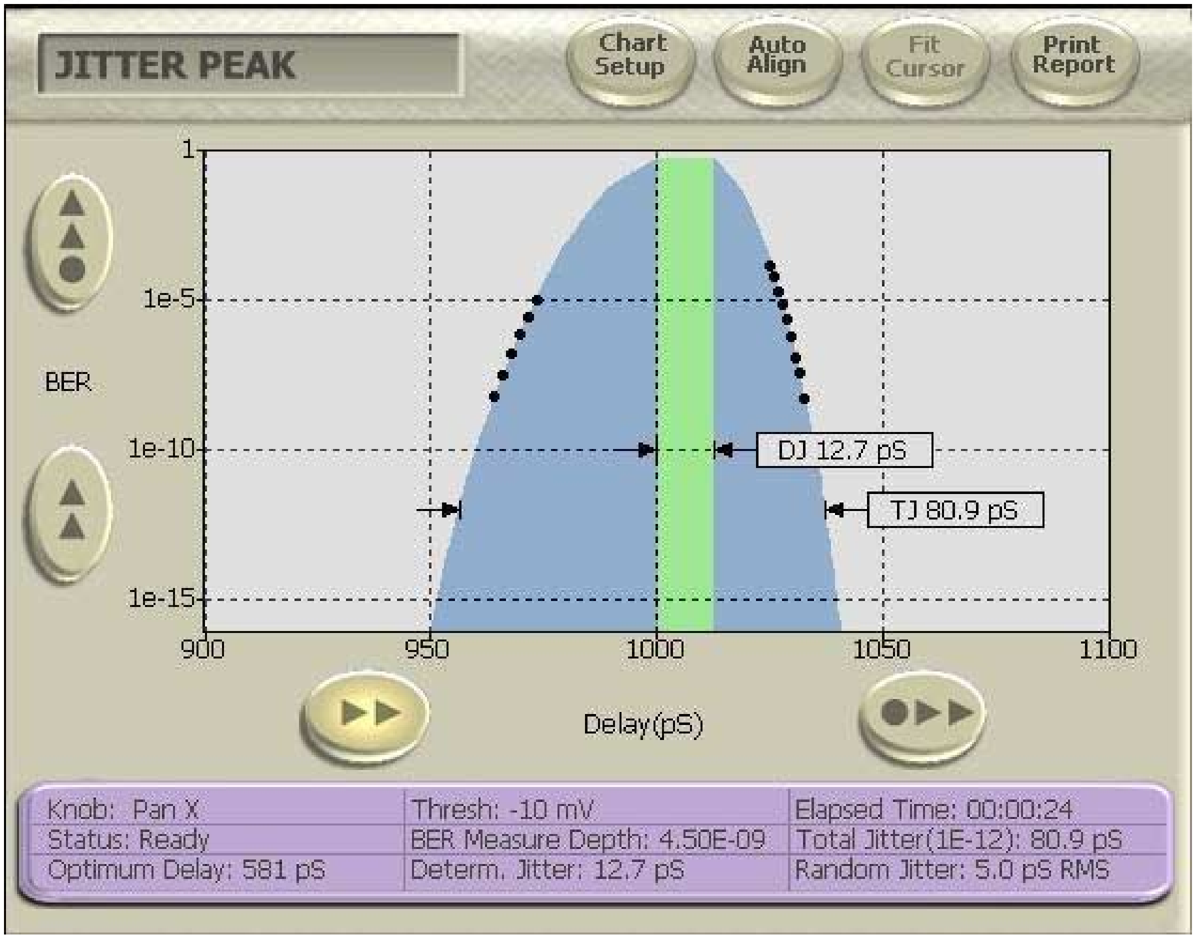
• Tx Test
• BERTs

4.1 Example BER-based Jitter Peak (Bathtub)

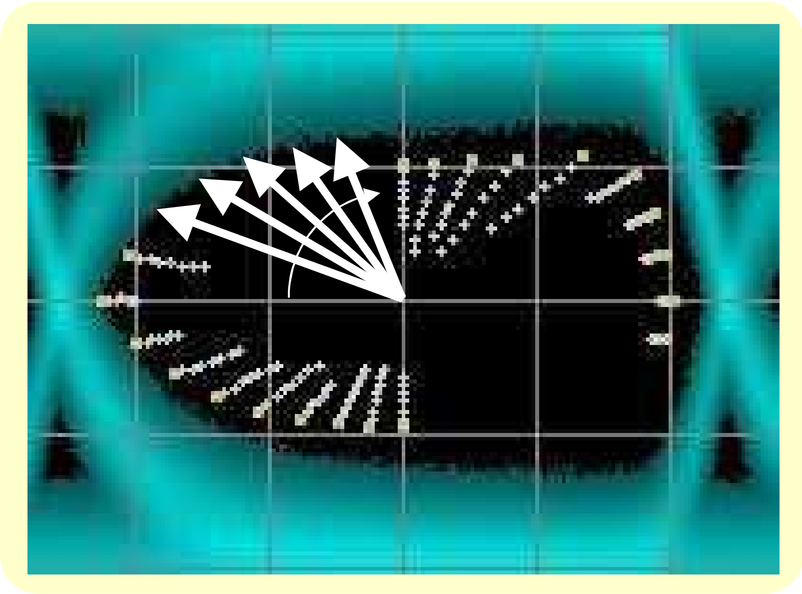


- Fast
- Stable & Repeatable
- Sample-rich means extrapolations start from lower points on the curve (adjustable)
- Easily copes with long patterns

4.2 Bathtub vs. BER Contour

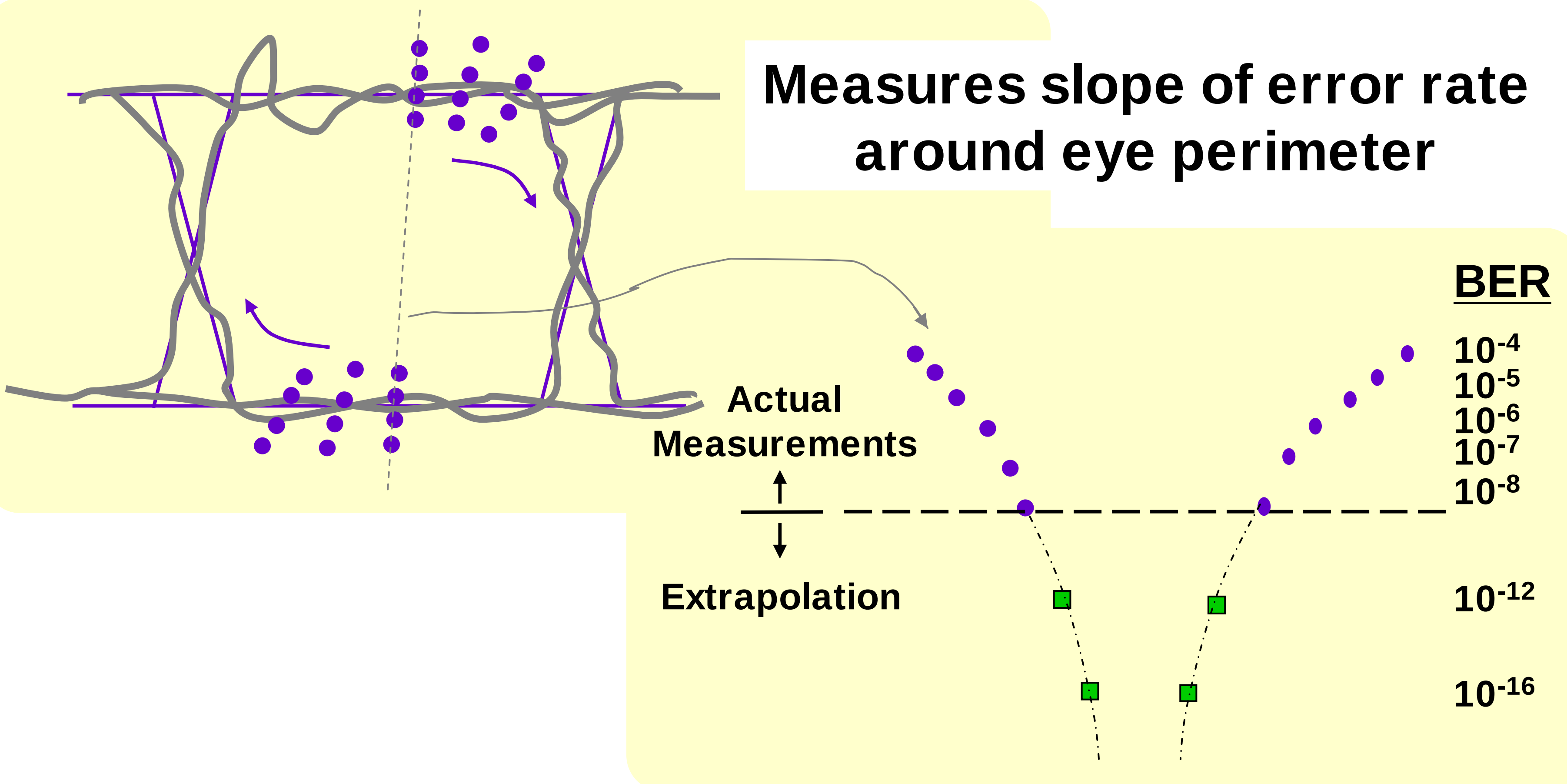
- Tx Test
- BERTs

- Bathtub gives good indication of horizontal slice through the eye
- BER contour simultaneously shows horizontal slice, vertical (Q) slice and points in between.
- Shows effects of ISI, noise, jitter
- Can be predictive –
  use same models to extrapolate
- Same principles apply – deep data
  & accurate delay needed
  for good extrapolation

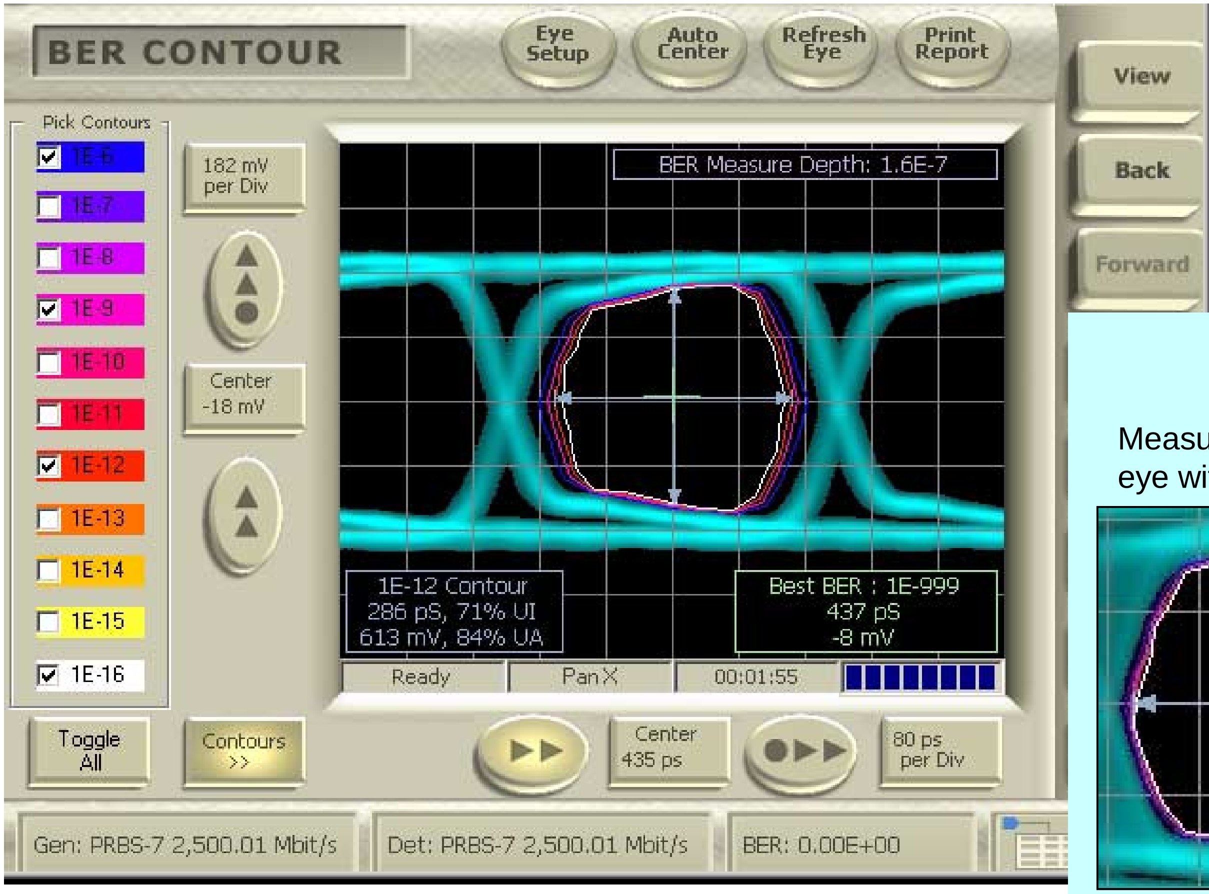


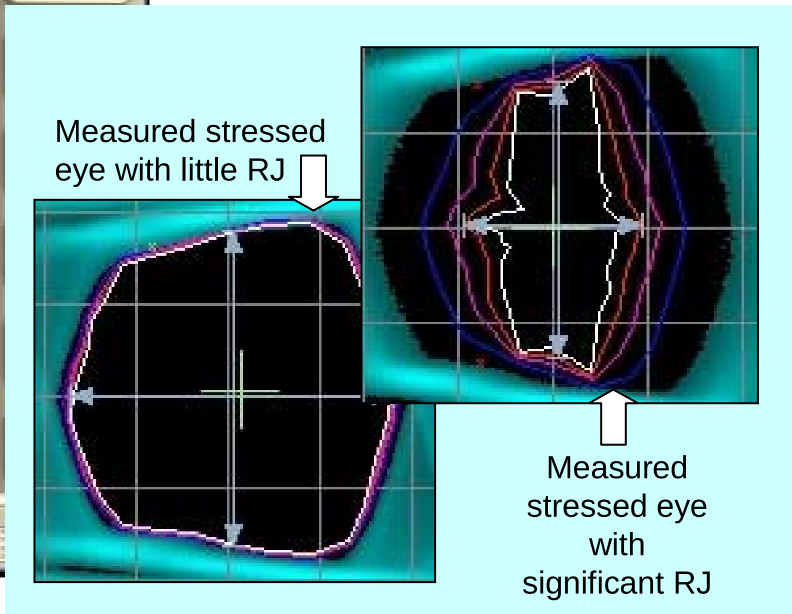
4.2 BER Contour

Measures slope of error rate around eye perimeter



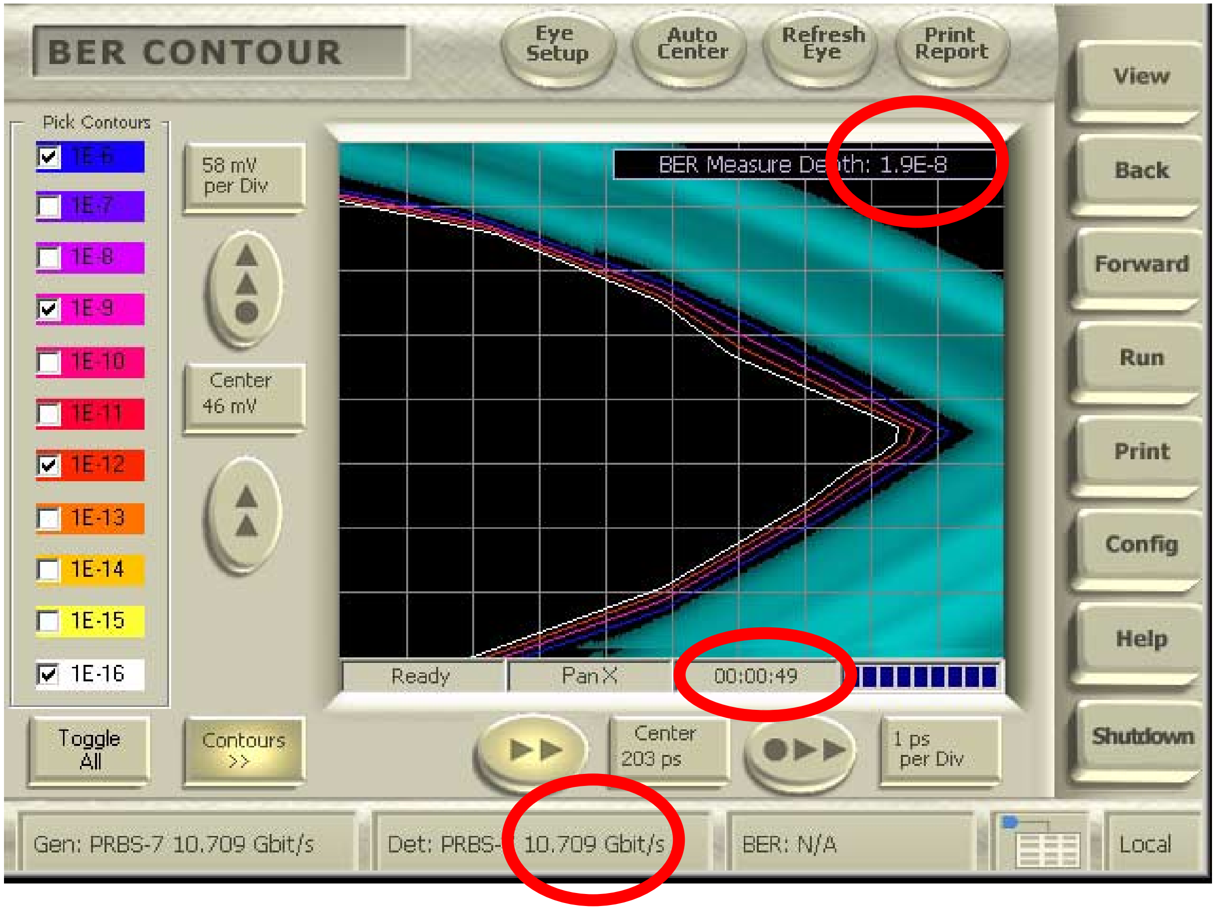
4.2 BER Contour Example





4.2 BER Contour Detail

- Tx Test
- BERTs



- Fast implementation
- Accurate, auto-calibrated delay leads to accurate underlying data for extrapolation
- Underlying raw measurement data available for export

4.3 Eyes & Masks – Deeper Measurements

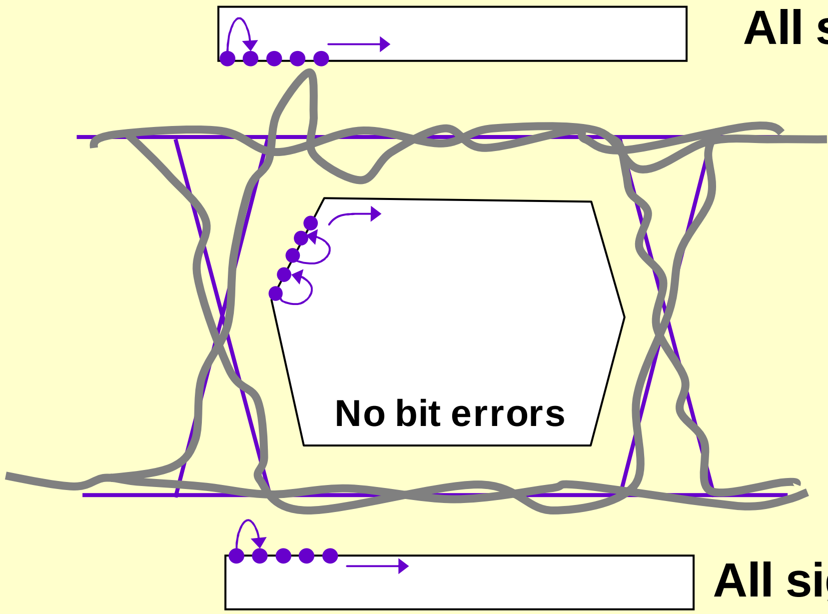
- BERTs can provide fast eye & mask testing

- Scope Mask tests are proportional to scope sampling speeds (~40-200Ks/sec)
  - E.g. a standard mask test may accumulate at 100-500 waveforms per second

- Mask tests done with BERTs are proportional to data rate
  - ⇨ sample-rich in short time
  - E.g. a 400 point mask test at 10G can accumulate 2,000,000 waveforms per second
  - Tightly integrated with BER Contour to “learn” stressed mask

4.3 What is BER-based MASK Testing?

- Tx Test
- BERTs



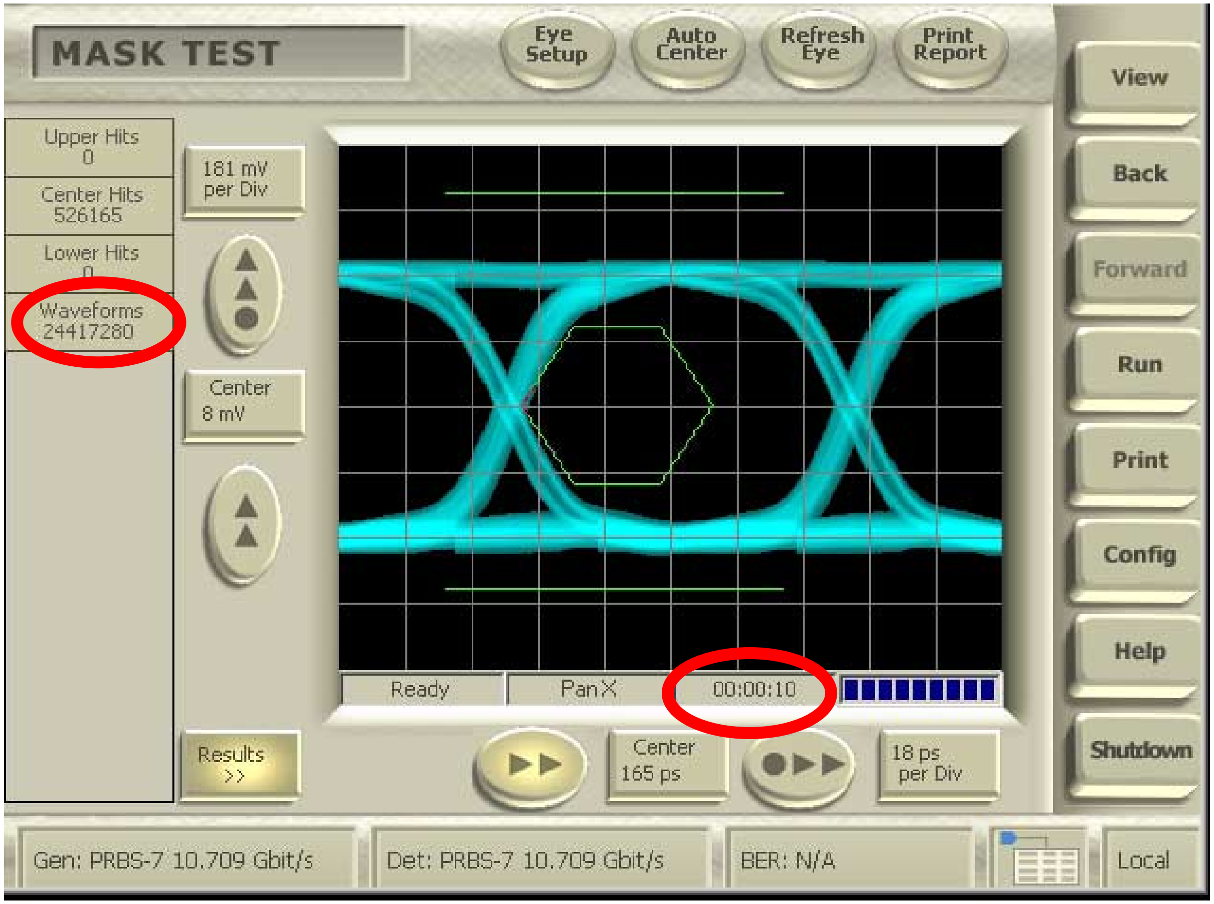
10,000,000,000 bits/sec

400 samples/Mask waveform

25,000,000 Mask Waveforms/sec
(theoretical limit)

4.3 Example BER-based Mask Test

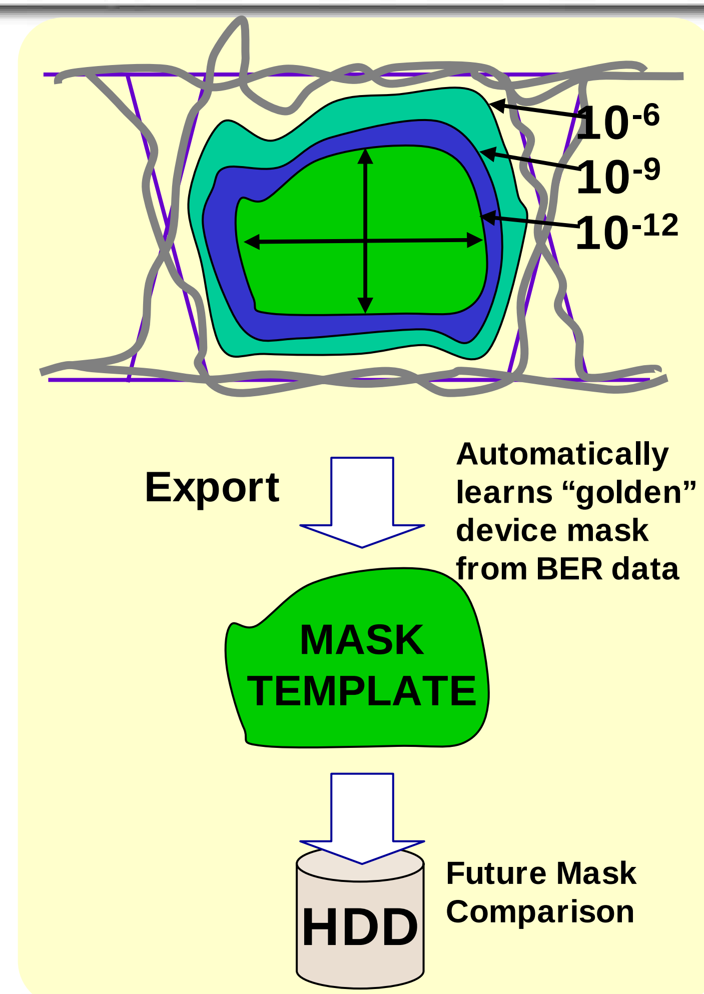
- Tx Test
- BERTs



4.3 Margined Masks are "Learned"

- Tx Test
- BERTs

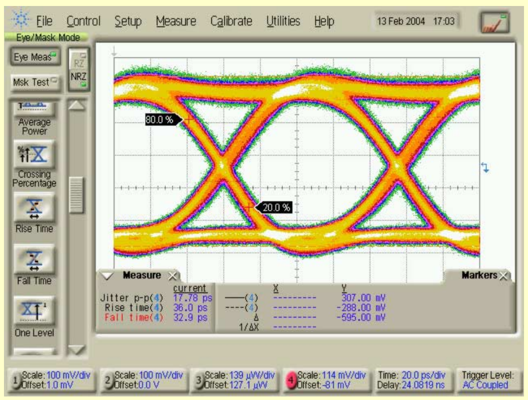
- Perform a BER Contour
  - Radially outward from the center of the eye
- Curve-fit inside walls for BER -> 10^{-15}
- "Join-the-Dots" to create an eye opening mask at the desired BER
- Potentially solve for even better BER to add margin to the mask.

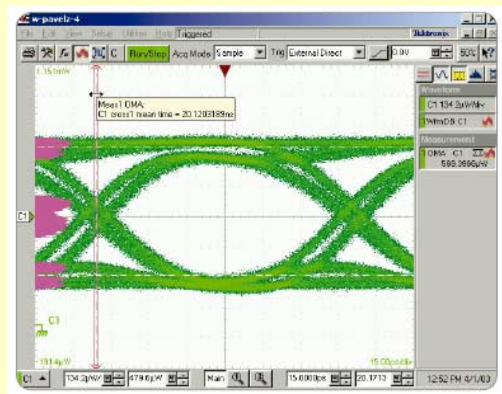


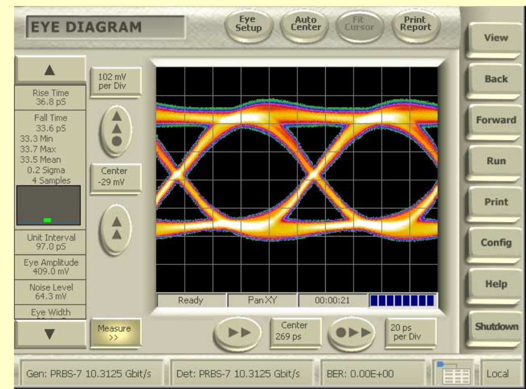
4.4 Qualitative Eye Measurements

- Tx Test
- BERTs

- Many standards require eye diagram parametric measurements as well as bit-error related measurements.





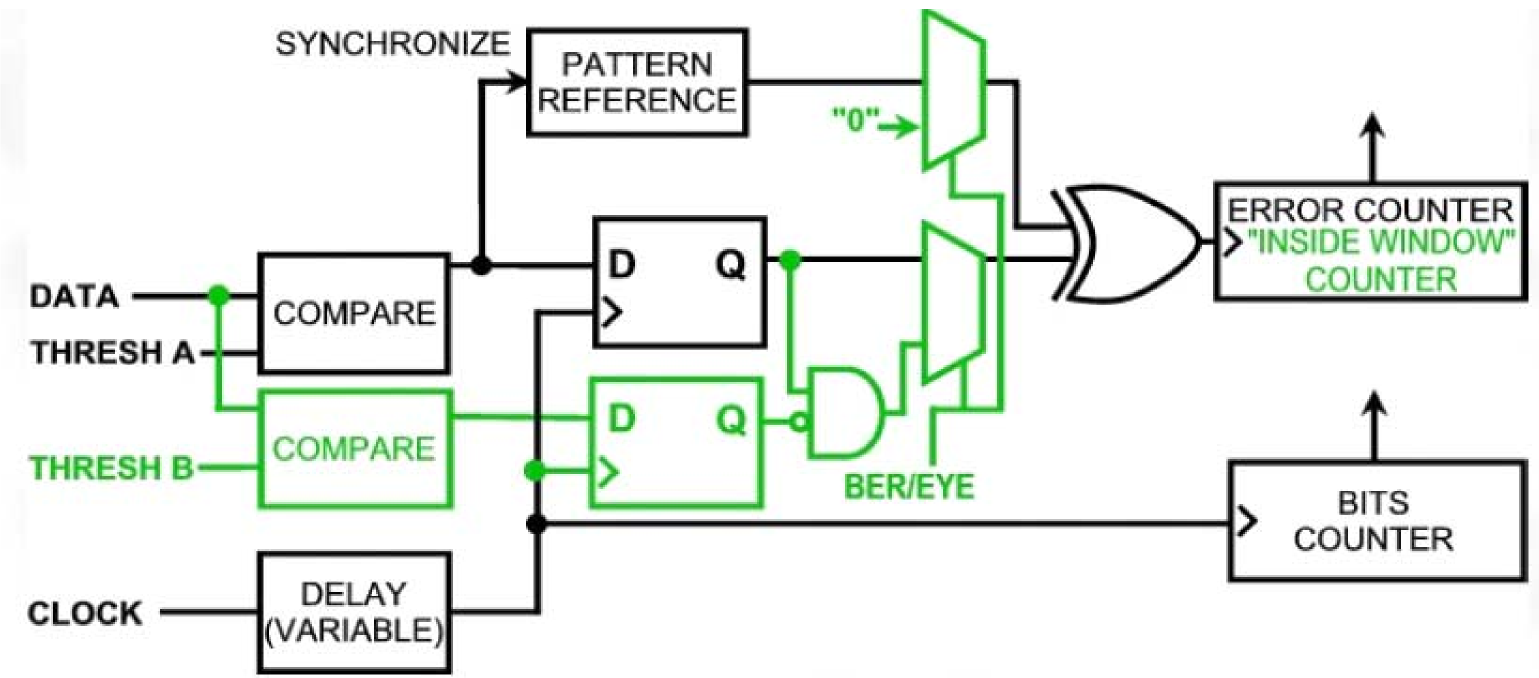


- Production performance requirements for these eyes do not require the very-high bandwidth supported by sampling oscilloscopes
  - E.g. a 0.75 * Baud low-pass filter is used

- Qualitative eye measurements can also be made with a Bit Error Rate testing device using an improved sampler.

4.4 BER Sampler Improvement

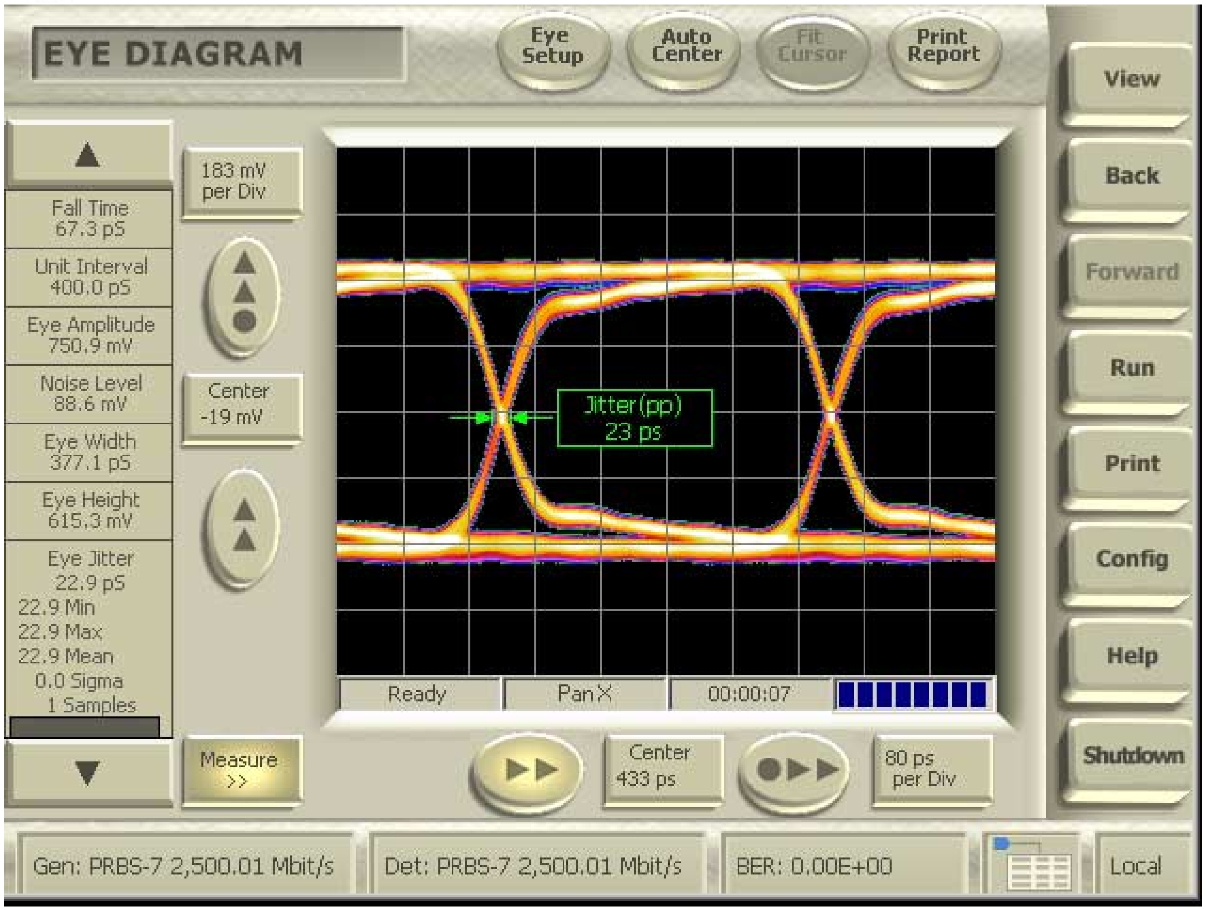
- Tx Test
- BERTs



(Patent applied for)

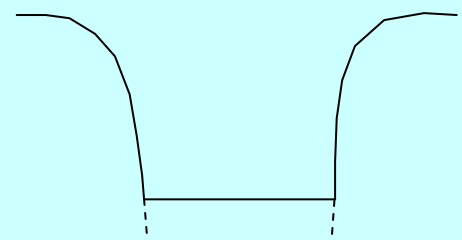
4.4 Improved BER Sampler Eye Diagram

- Tx Test
- BERTs



- Comparable to sampling scope eye diagram results (rise/fall etc.)
- More sample-rich – see less frequently occurring features (e.g. to 10^{-8} probability)
- Greater confidence that there is nothing lurking.

4.5 Error Floors



- Error floors can arise from SNR issues
- Infrequent occurrences of worst-case patterns (long polynomial scrambling etc.)
- In-phase addition of infrequent pattern effects with interference, triple transit

Test Philosophy

- Gaussian noise-related effects should be uncovered by deep eye contour measurements
- Need to make direct measurement down to 10-15 occasionally to verify extrapolations are correctly predicting behavior.

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5. Marginalization through Stressed Eyes

- Rx Test
- BERTs

- To the degree possible, stress can be added to a test signal presented to a DUT to decrease the DUT margin.

- Stressed should be added in ways that emulate real-world situations

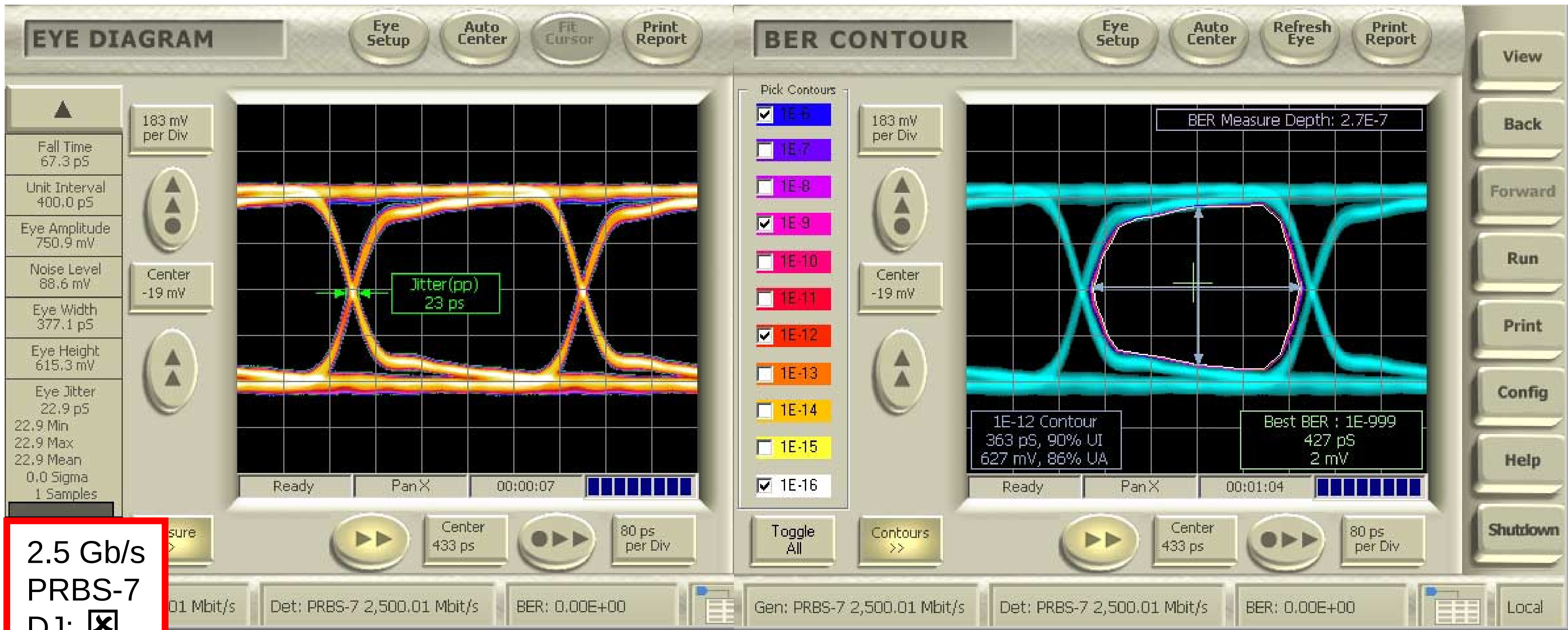
- Examples of stresses are:
  - Sinewave Interference
  - Sinewave Jitter
  - Random Jitter
  - Pattern-dependent Jitter
  - PRBS (BUJ) Jitter

- **BER Contours can be used to visualize these impacts to eye margin**

- Once again, delay accuracy underpins the accurate measurement of BER contour and therefore the construction of a stressed eye that optimizes highest yield with greatest confidence.

5. Stressed Eye Example

- Rx Test
- BERTs

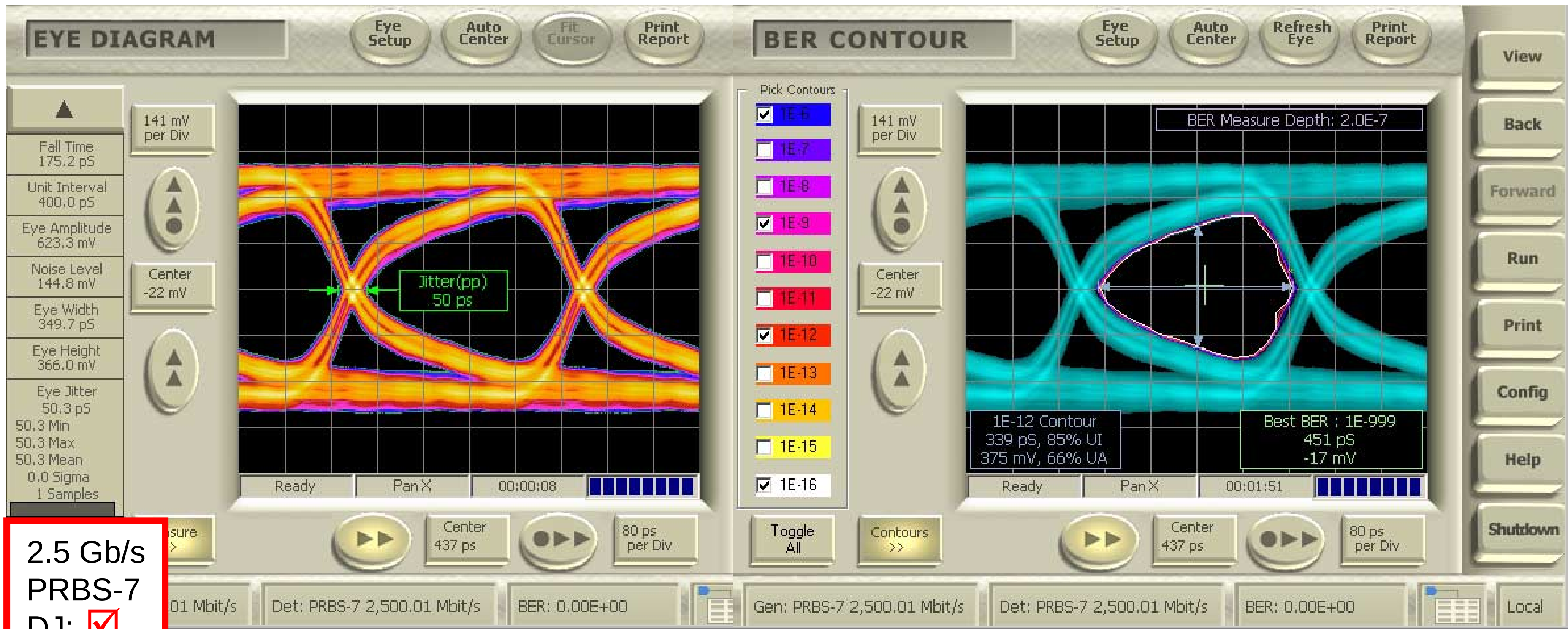


2.5 Gb/s
PRBS-7
DJ: ☒
SJ: ☒
RJ: ☒
SI: ☒

(Example is at 2.5 Gbit/s)

5. Add Pattern Dependent DJ (filter)

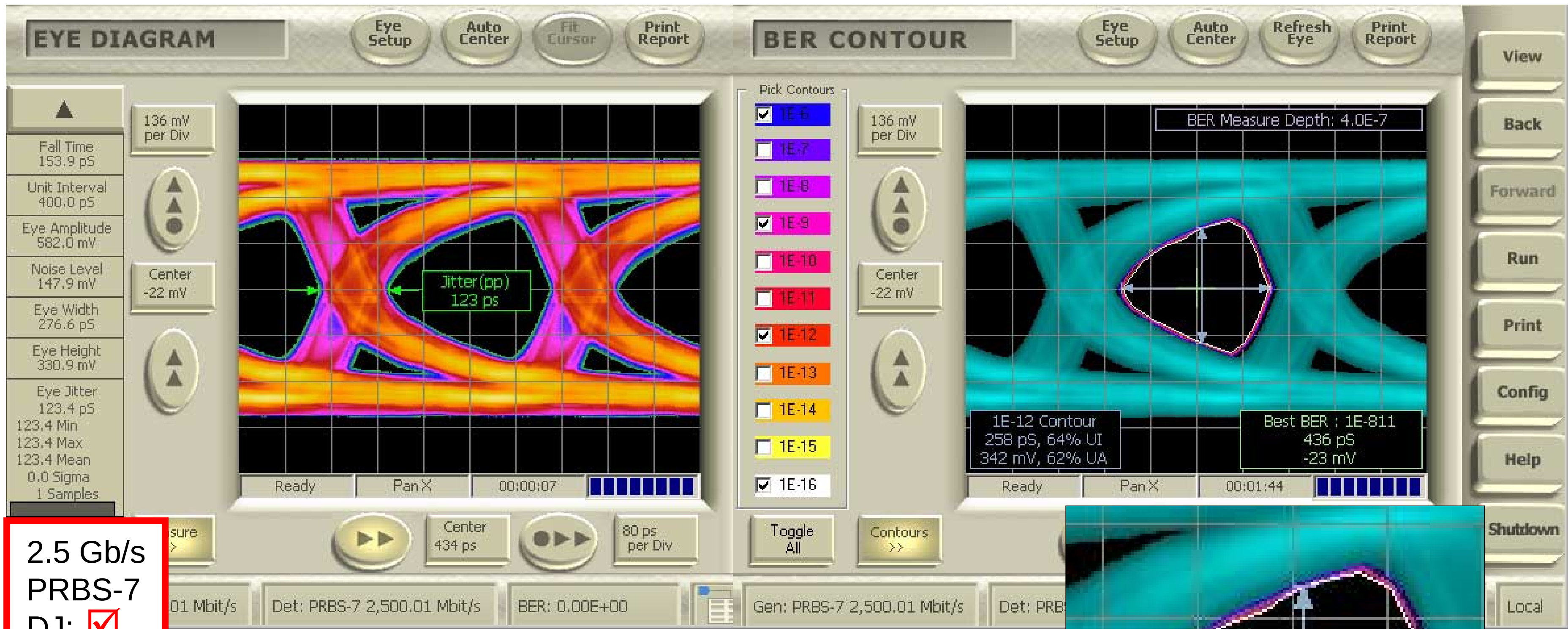
- Rx Test
- BERTs

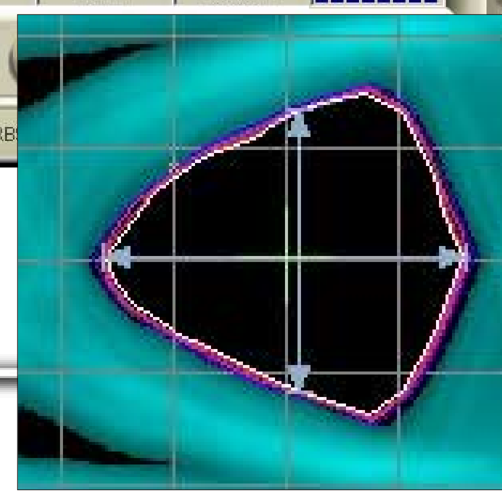


2.5 Gb/s
PRBS-7
DJ: ☑
SJ: ☒
RJ: ☒
SI: ☒

5. Add Sine Jitter

- Rx Test
- BERTs





2.5 Gb/s
PRBS-7
DJ: ☑
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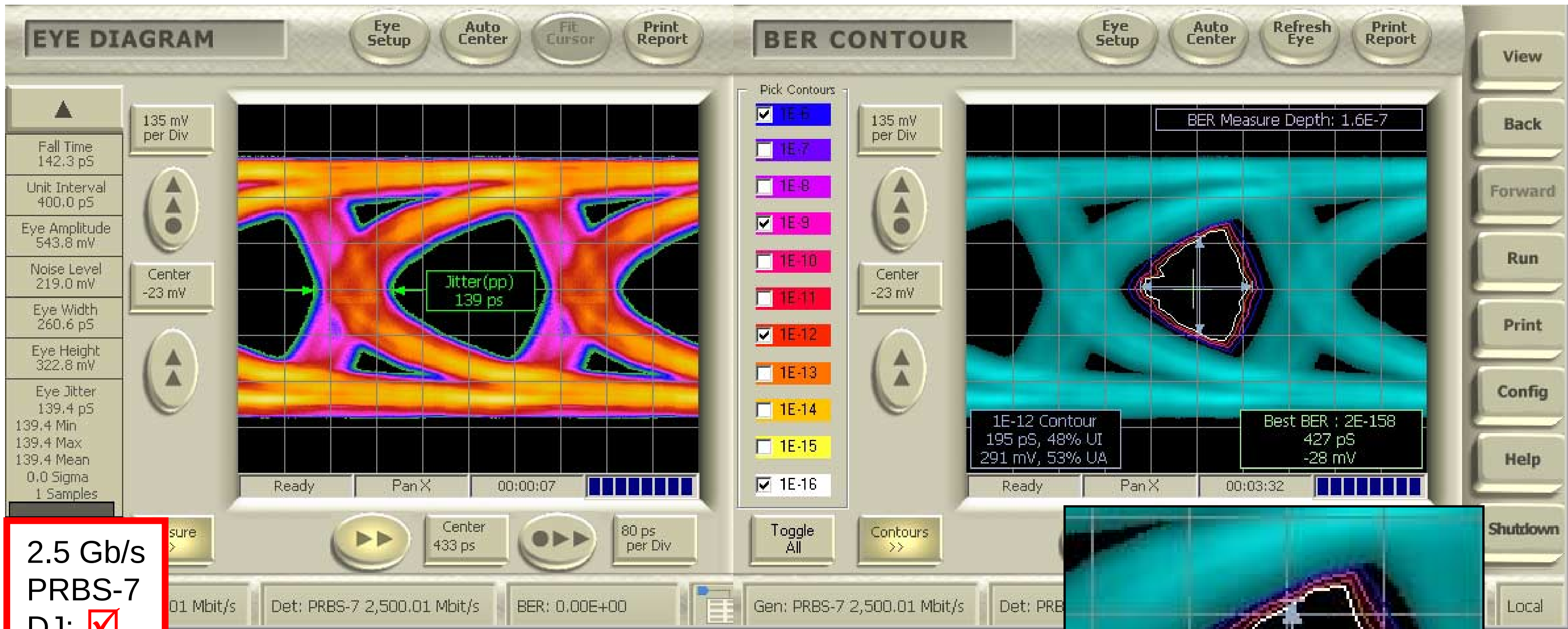
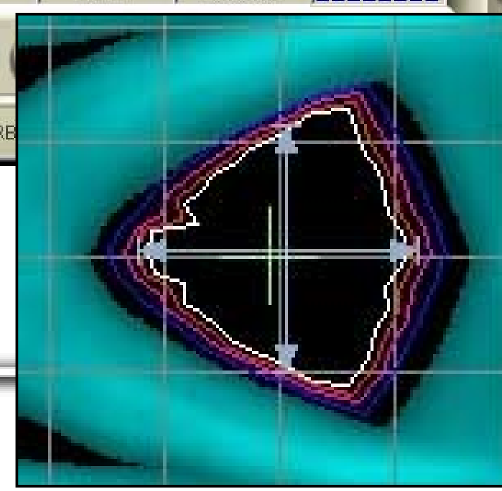
RJ: ☒
SI: ☒

5. Add Random Jitter

- Rx Test
- BERTs

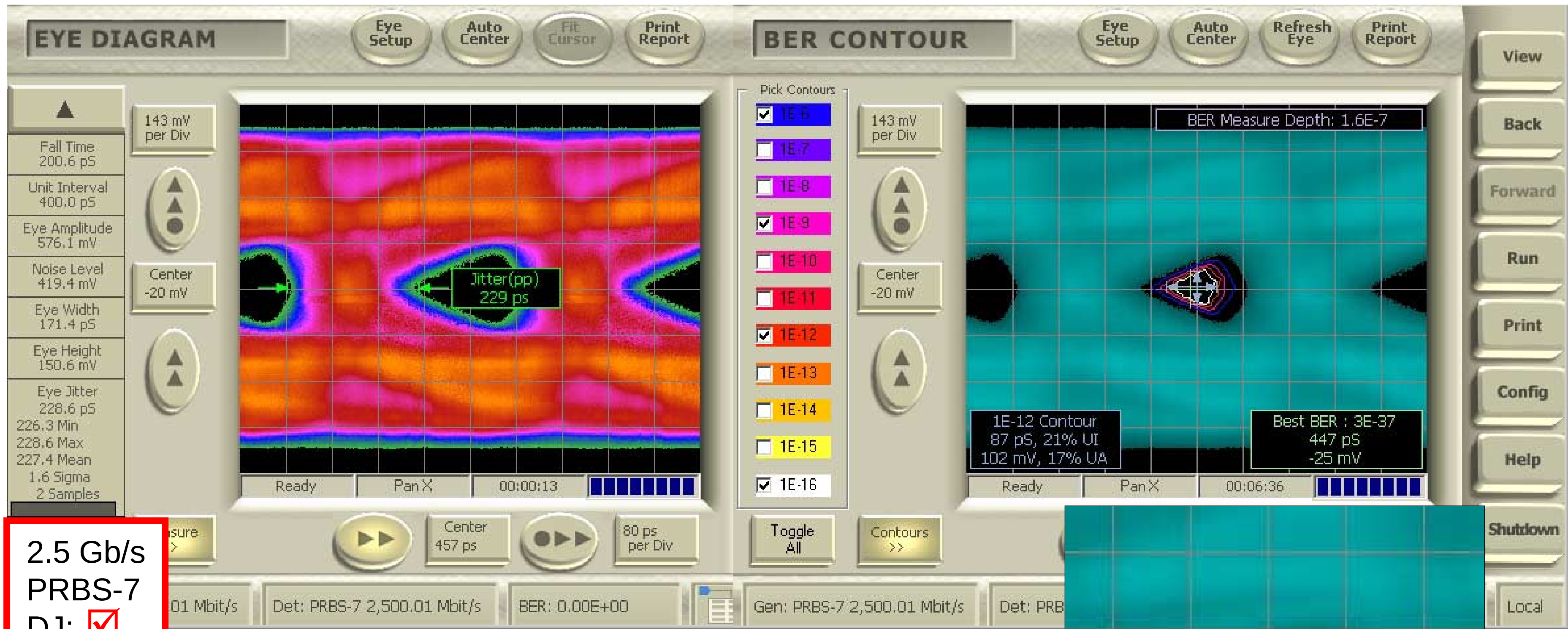


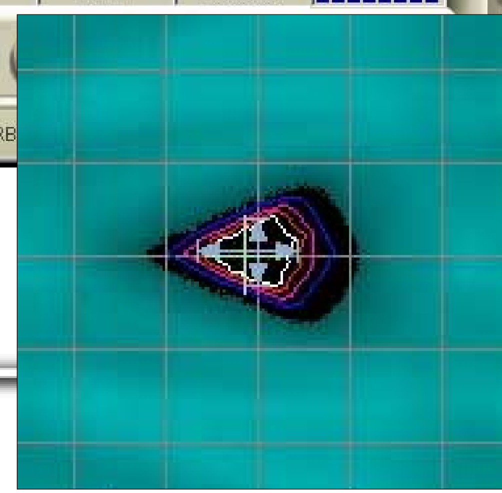


2.5 Gb/s
PRBS-7
DJ: ☑
SJ: ☑
RJ: ☑
SI: ☒

5. Add Sine Interference

- Rx Test
- BERTs





2.5 Gb/s
PRBS-7
DJ: ☑
SJ: ☑
RJ: ☑
SI: ☑

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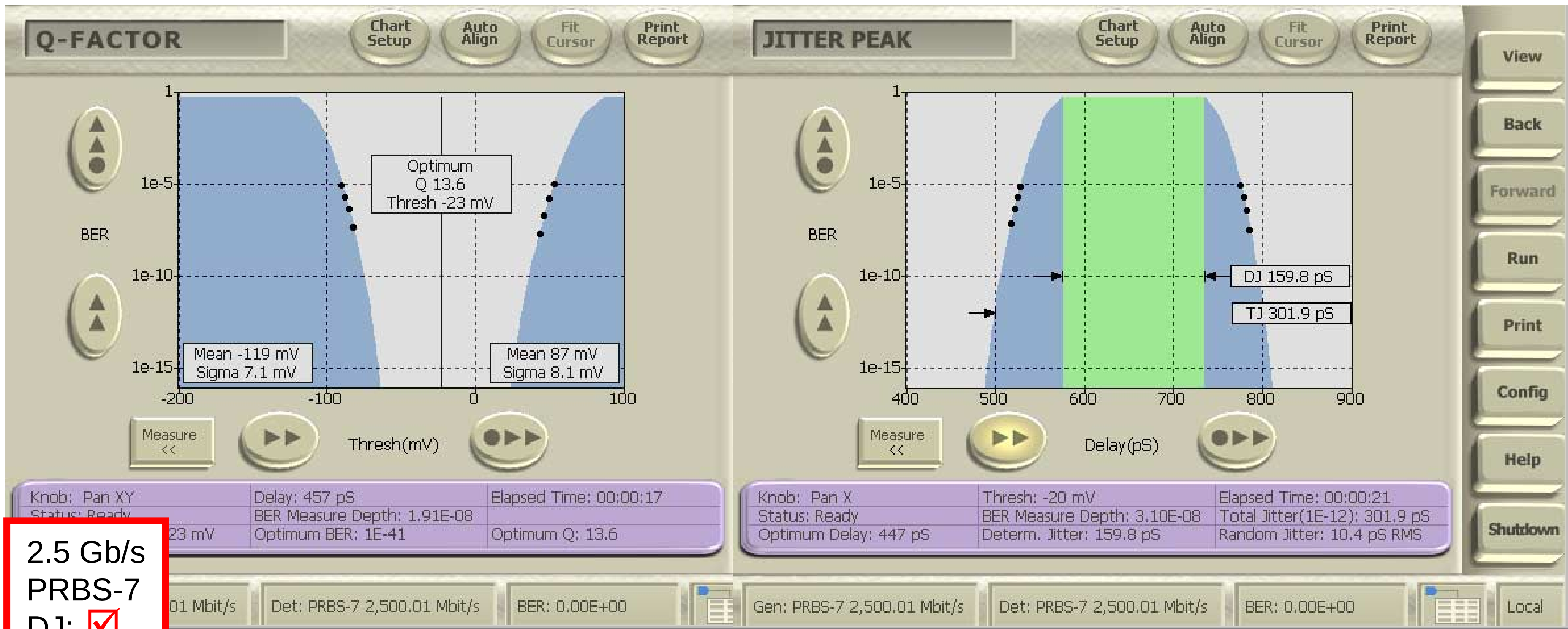
5. Q-factor & Jitter Analysis of Stressed Eye

- Rx Test
- BERTs



2.5 Gb/s
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1. Accuracy of extrapolations depend upon accuracy of points taken, depth of points taken
2. These apply to transmitter & receiver measurements
3. BERTs can be made that provide an array of measurements with enough depth & accuracy to give confidence extrapolating from 10^{-12} to 10^{-15}.
4. Direct measurements to 10^{-15} at judicious points in development are recommended to ensure extrapolations are correct, and ensure the absence of error floors.