Controlling Common Mode Noise in High Speed Circuits

Dr. Bruce Archambeault
IEEE Fellow
Missouri University of Science/Technology Adjunct Professor

Archambeault EMI/EMC Enterprises
PO Box 1264
Four Oaks, NC 27524 USA
bruce@brucearch.com

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Differential vs... Common Mode

- If a signal is truly ‘differential’ the emissions from cables/traces is greatly reduced
- Small amounts of common mode currents can result in significant EMI emissions
- Any imbalance results in significance common mode signals
  - In-pair skew
  - rise/fall time mismatch
  - much more

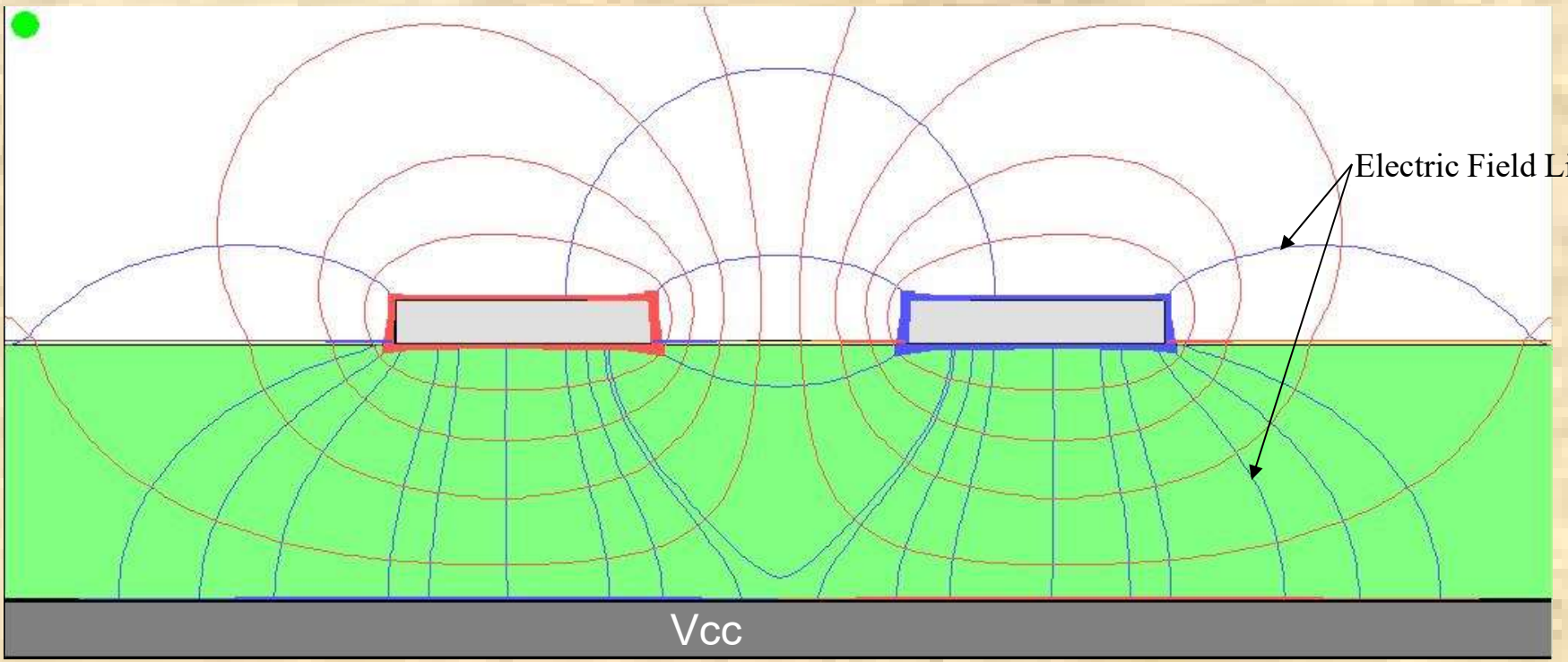
Pseudo-Differential Nets

- True differential requires no nearby reference plane
- Currents *will* exist on reference plane even when driven ‘differentially’!

Microstrip Electric/Magnetic Field Lines

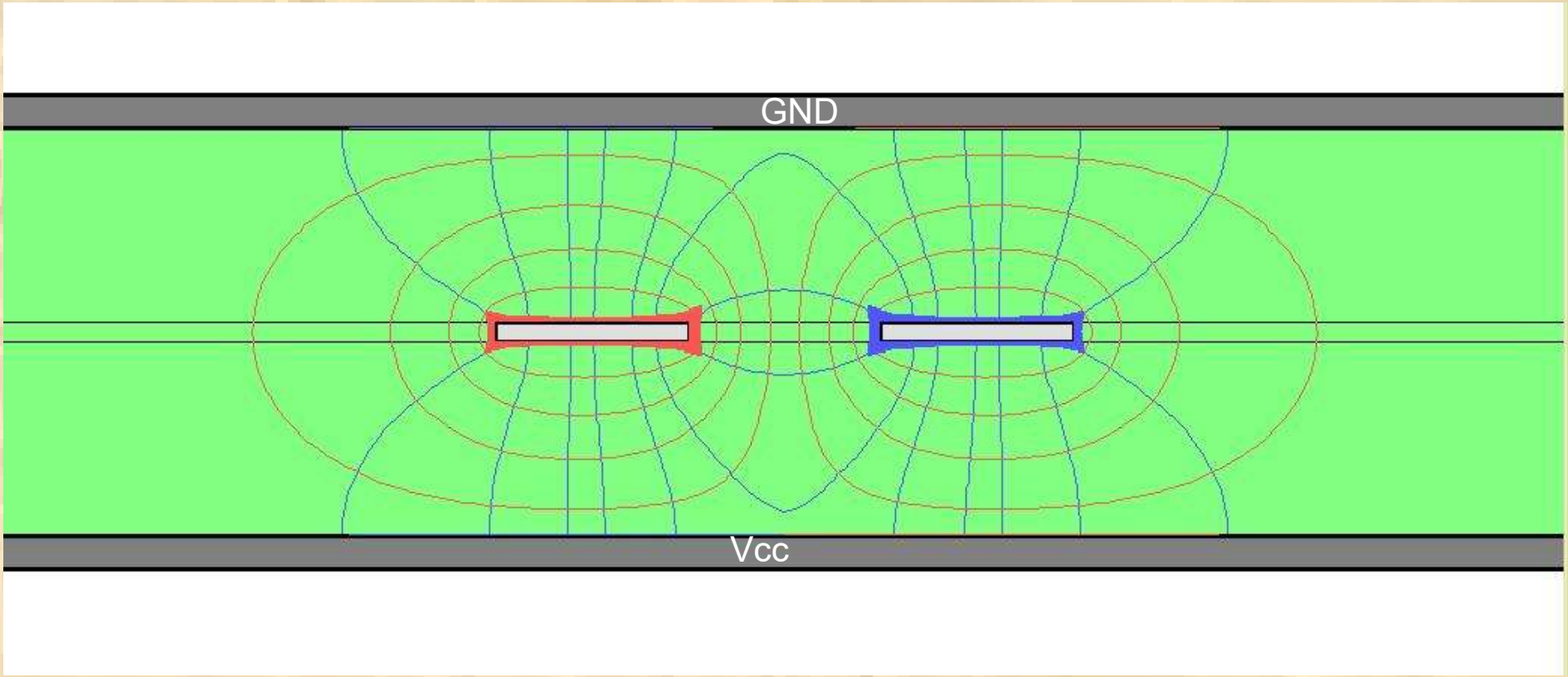
Differential Mode

8 mil wide trace, 8 mils above plane, 65/115 ohm)



Courtesy of Hyperlynx

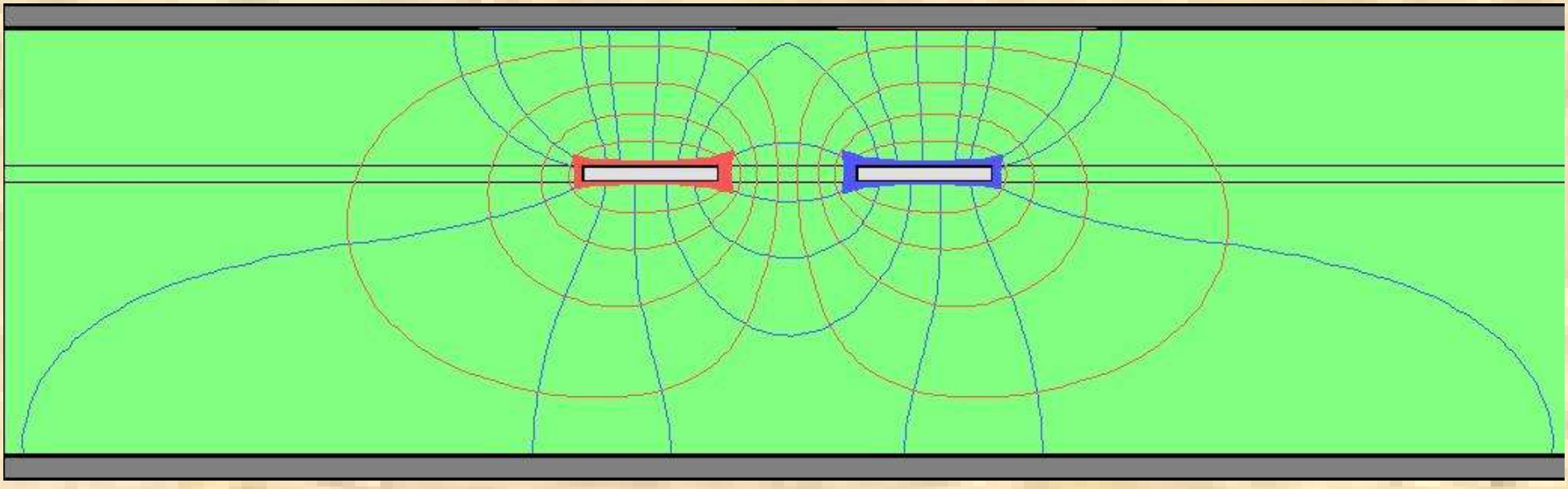
Electric/Magnetic Field Lines
Symmetrical Stripline (Differential)



Courtesy of Hyperlynx

Electric/Magnetic Field Lines

Asymmetrical Stripline (Differential)



Courtesy of Hyperlynx

Pseudo-Differential Nets
Reference Plane Currents

- Signal integrity is greatly helped by ‘differential’ nets
- Currents in reference plane
  - Balanced only if:
    - Traces are equal length (within few mils)
    - Drivers are EXACTLY balanced
  - Not likely!

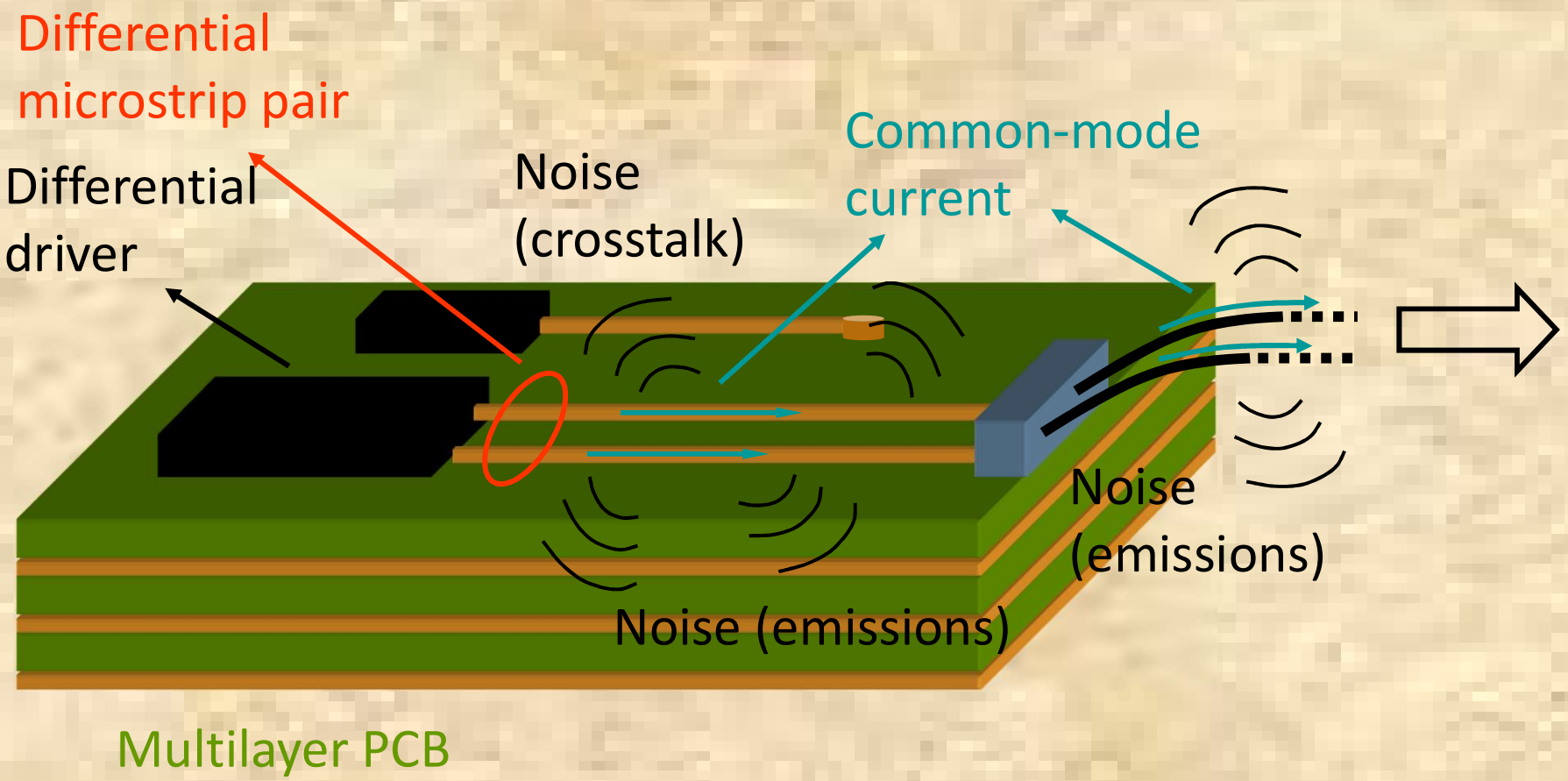
What About Pseudo-Differential Nets?

- So-called differential traces are NOT truly differential
  - Two complementary single-ended drivers
    - Relative to ‘ground’
  - Receiver is differential
    - Senses difference between two nets (independent of ‘ground’)
    - Provides good immunity to common mode noise
    - Good for signal quality/integrity

Pseudo-Differential Nets Current in Nearby Plane

- Balanced/Differential currents have matching current in nearby plane
  - No issue for discontinuities
- Any unbalanced (common mode) currents have return currents in nearby plane that must return to source!
  - All normal concerns for single-ended nets apply!

Common-Mode Noise on PCB

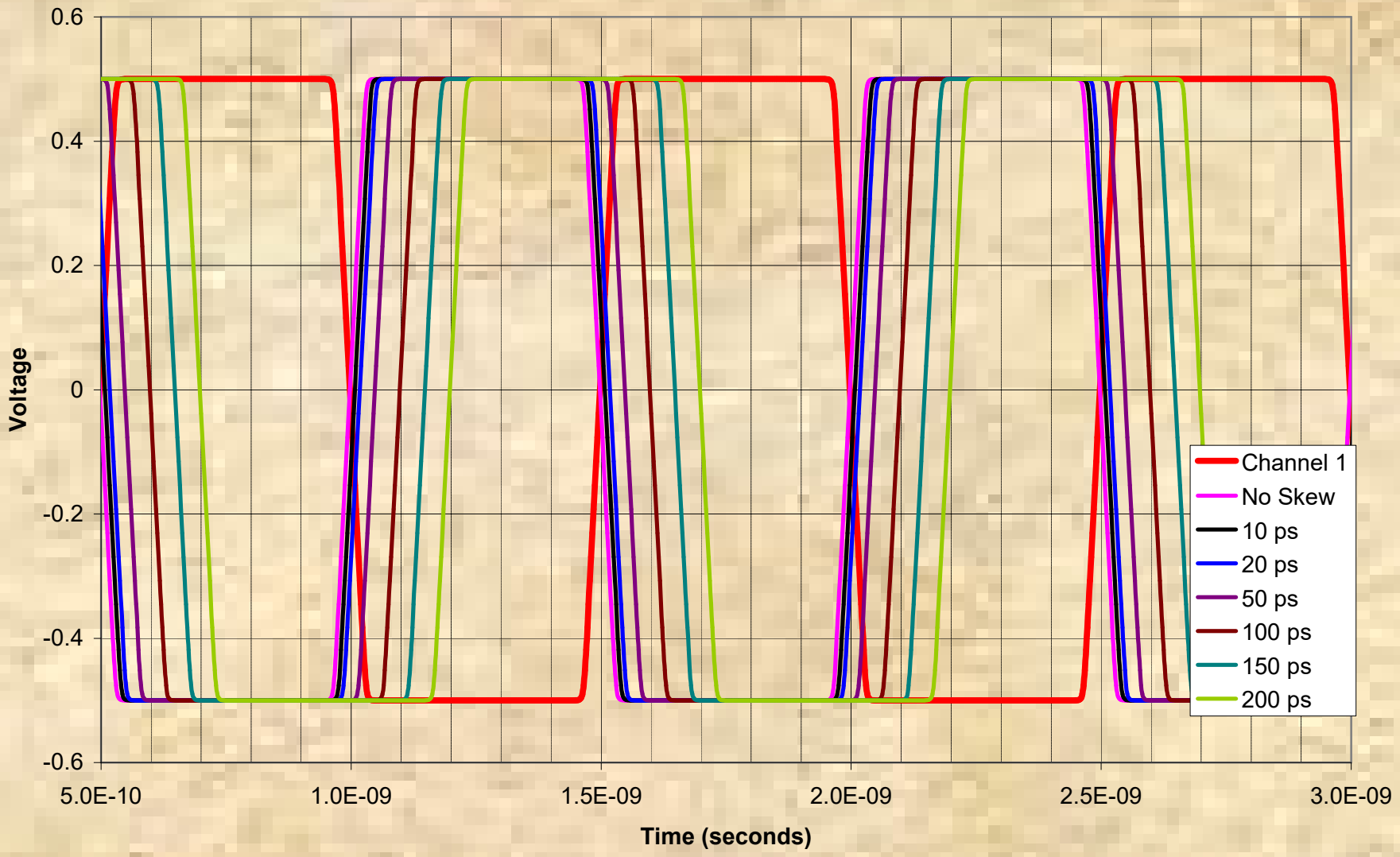


Why Control Common Mode Noise in Differential Pairs?

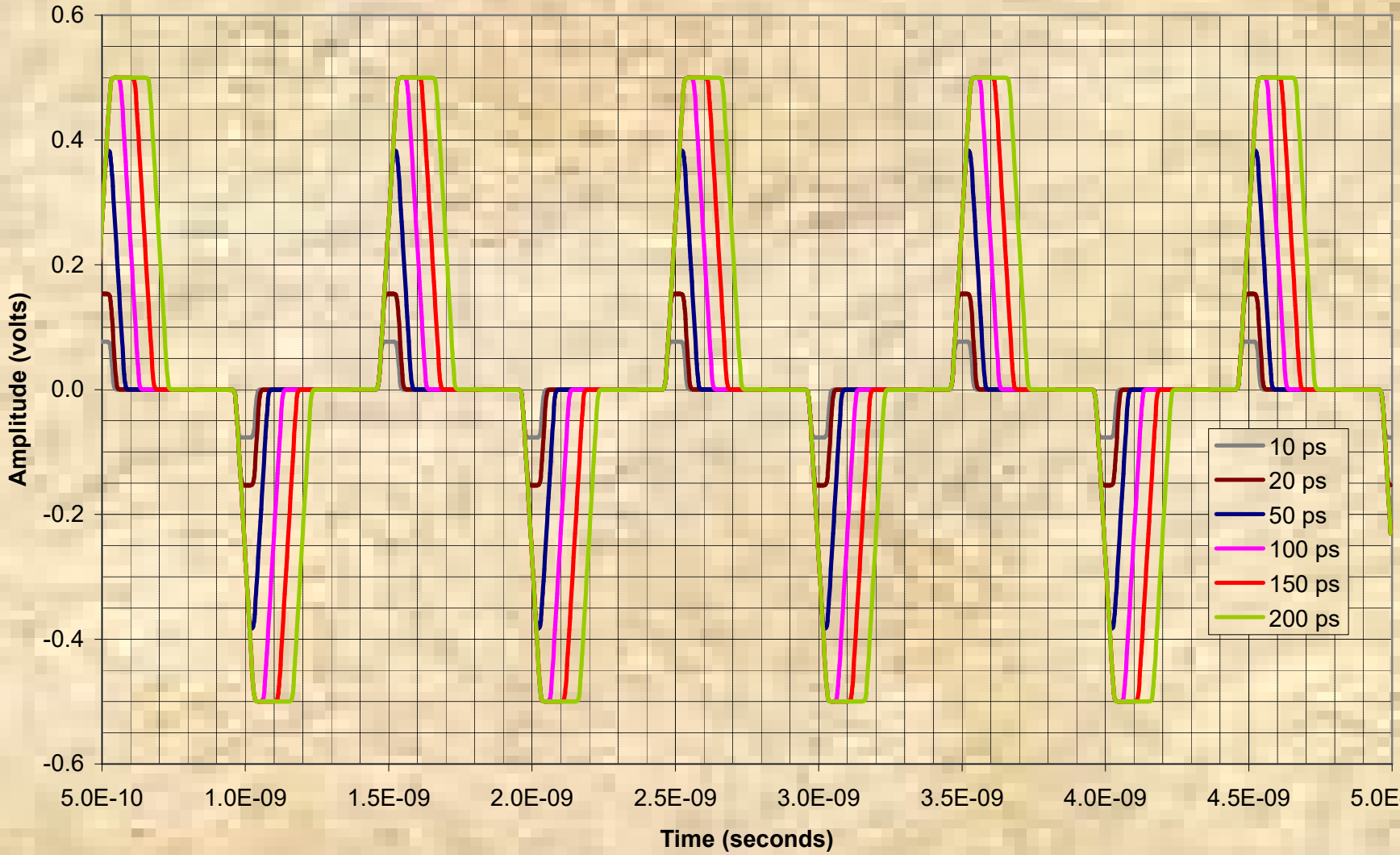
- Common Mode Noise is inevitable in differential pairs
  - Skew
  - Rise/fall time mismatch
  - Asymmetry in channel
- Common mode noise is a big problem in EMC!
- Common mode noise can increase differential crosstalk

Common Mode Noise Due to Skew

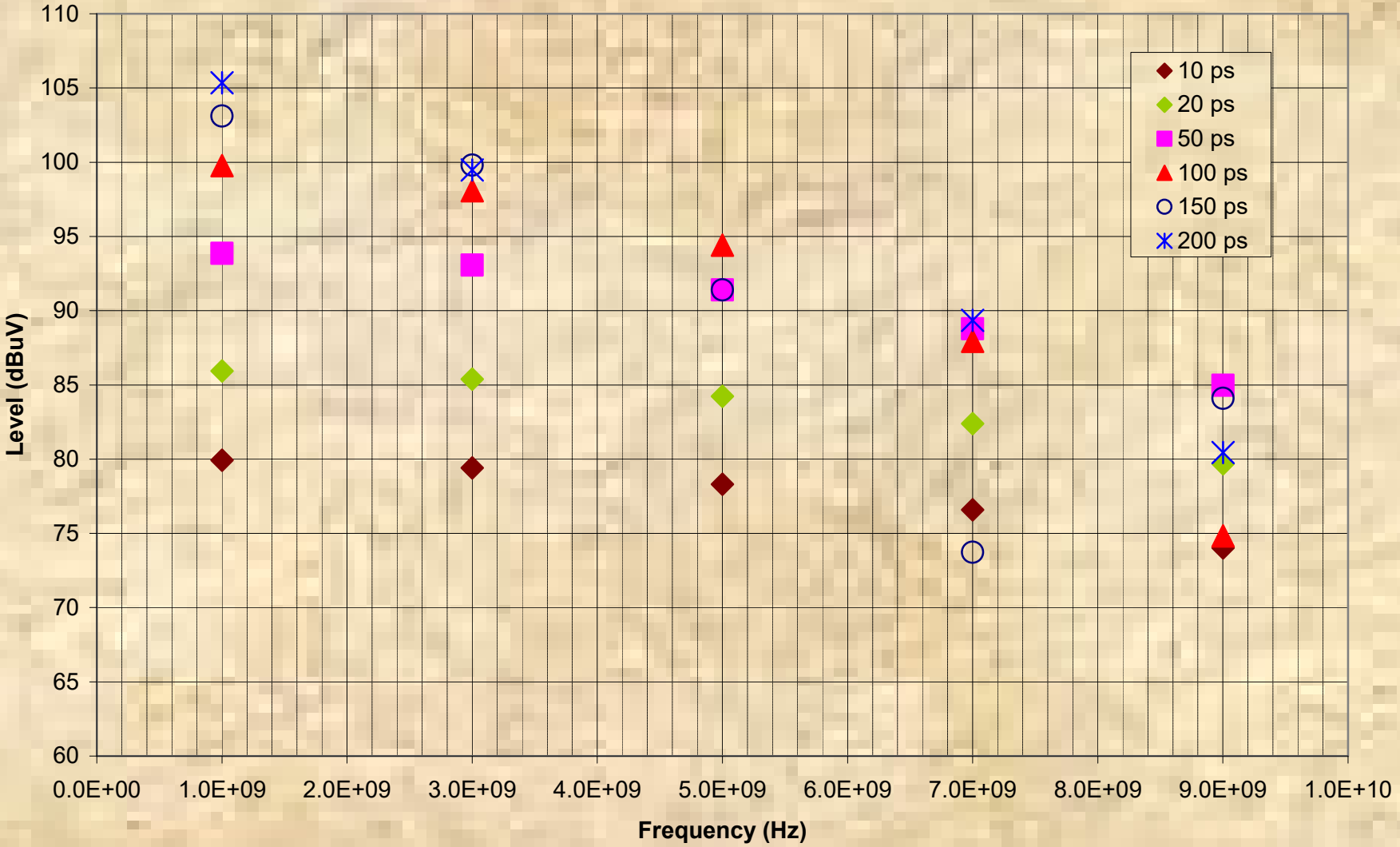
- Small amounts of skew create significant common mode nose
- As little as 1% of bit width for skew can have significant EMI effects
- As little as 10% of bit width skew creates CM signal of equivalent amplitude as initial signals


Individual Channels of Differential Signal with Skew
2 Gb/s with 50 ps Rise and Fall Time (+/- 1.0 volts)
Voltage
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
5.0E-10
1.0E-09
1.5E-09
2.0E-09
2.5E-09
3.0E-09
Time (seconds)
Channel 1
No Skew
10 ps
20 ps
50 ps
100 ps
150 ps
200 ps

Common Mode Voltage on Differential Pair Due to In-Pair Skew
2 Gb/s with 50 ps Rise and Fall Time (+/- 1.0 volts)



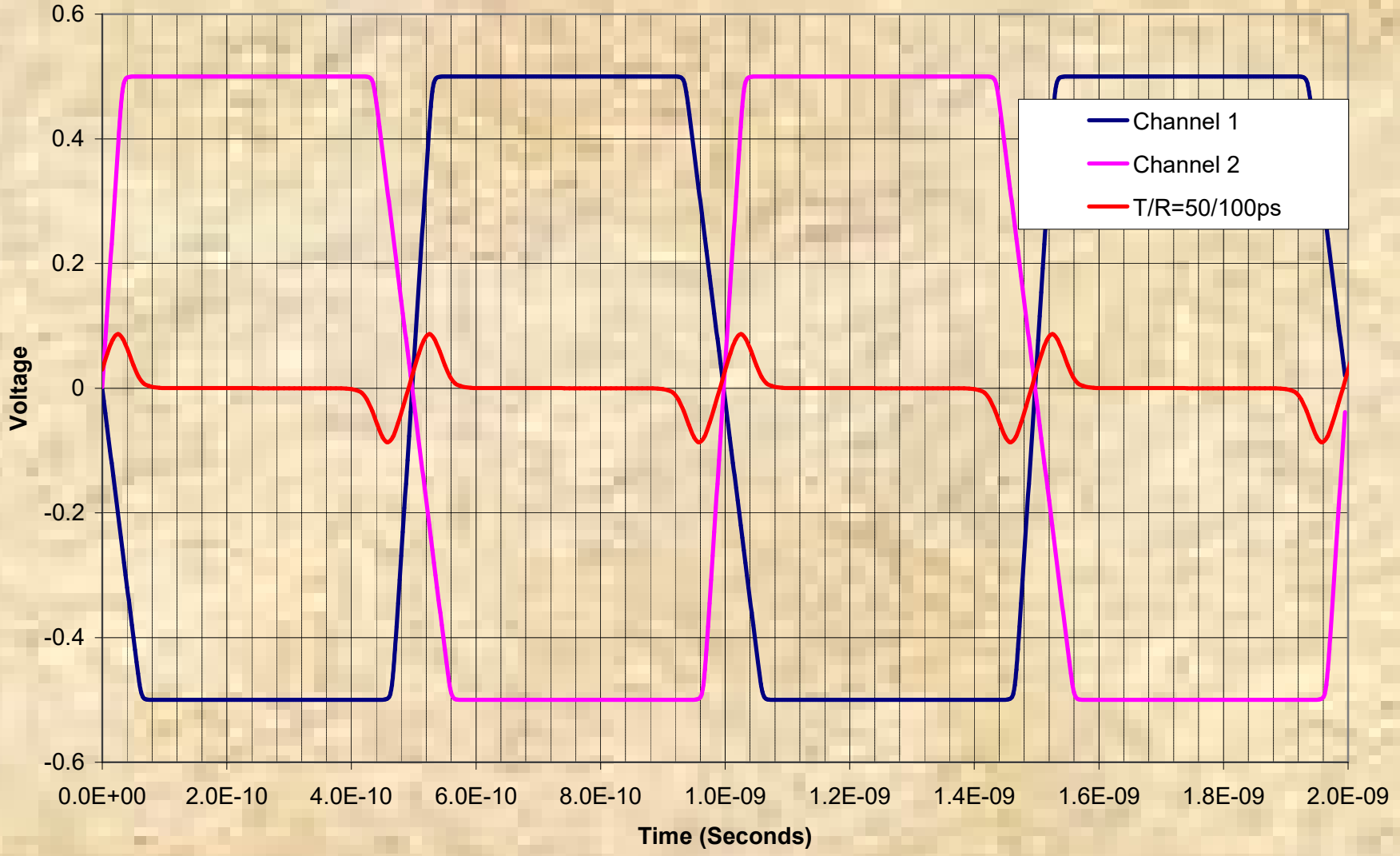
Common Mode Voltage on Differential Pair Due to In-Pair Skew
2 Gb/s with 50 ps Rise and Fall Time (+/- 1.0 volts)



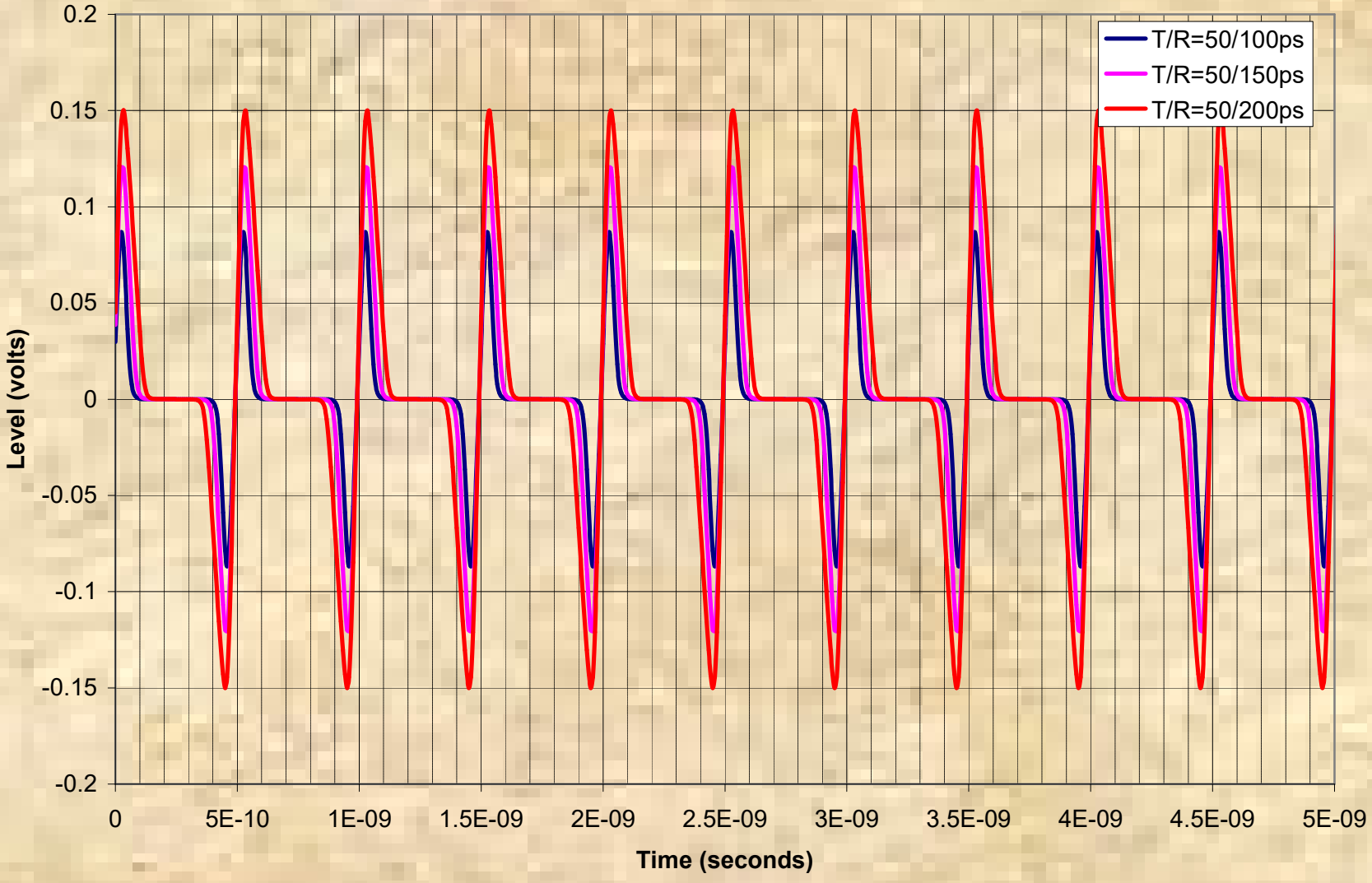
Common Mode from Rise/Fall Time Mismatch

- Small amounts of mismatch create significant CM noise
- Not as significant as skew, but harder to control!

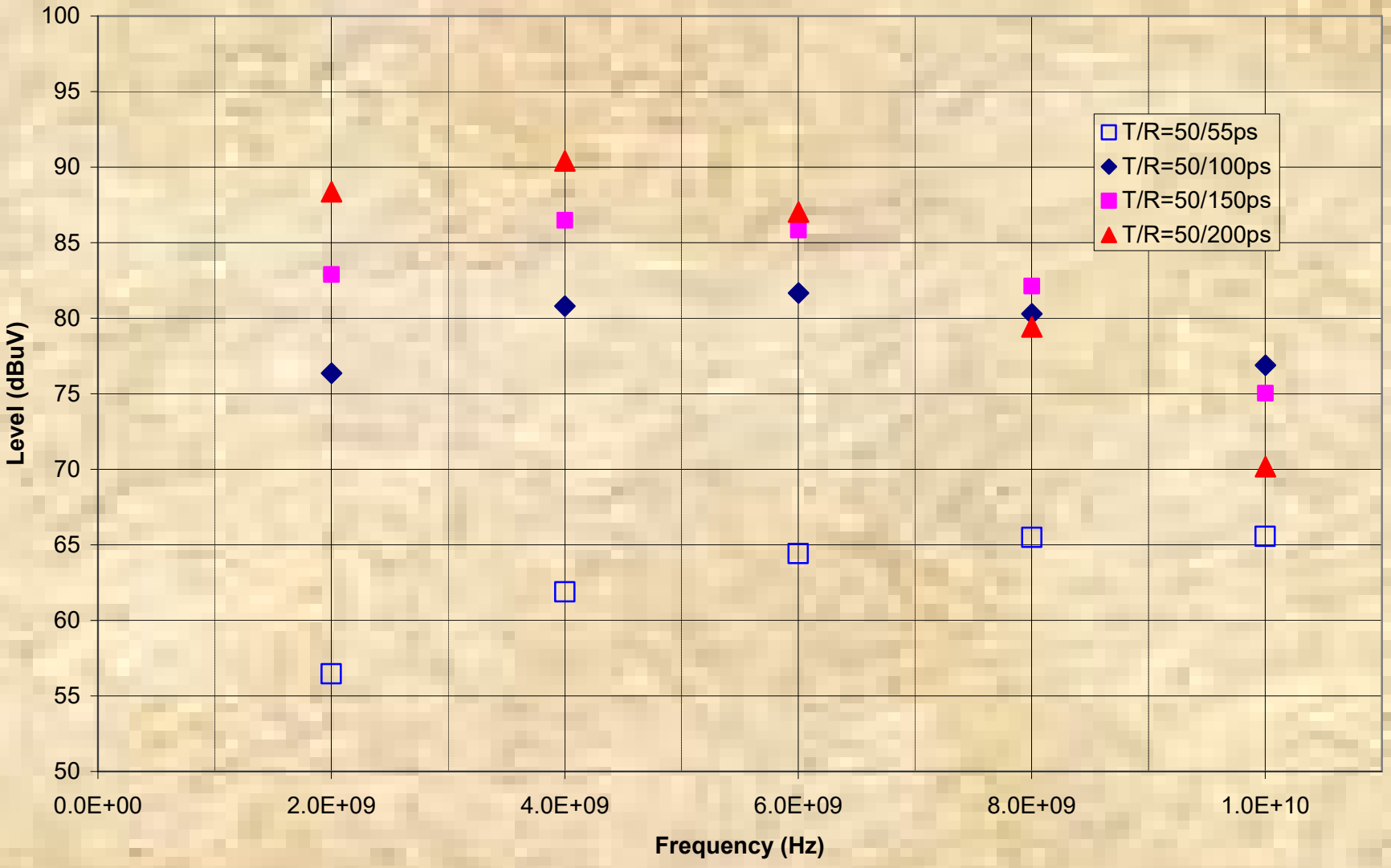
Example of Effect for Differential Signal with Rise/Fall Time Mismatch
2 Gb/s Square Wave (Rise/Fall = 50 & 100 ps)



Common Mode Voltage on Differential Pair Due to Rise/Fall Time Mismatch
2 Gb/s with Differential Signal +/- 1.0 Volts



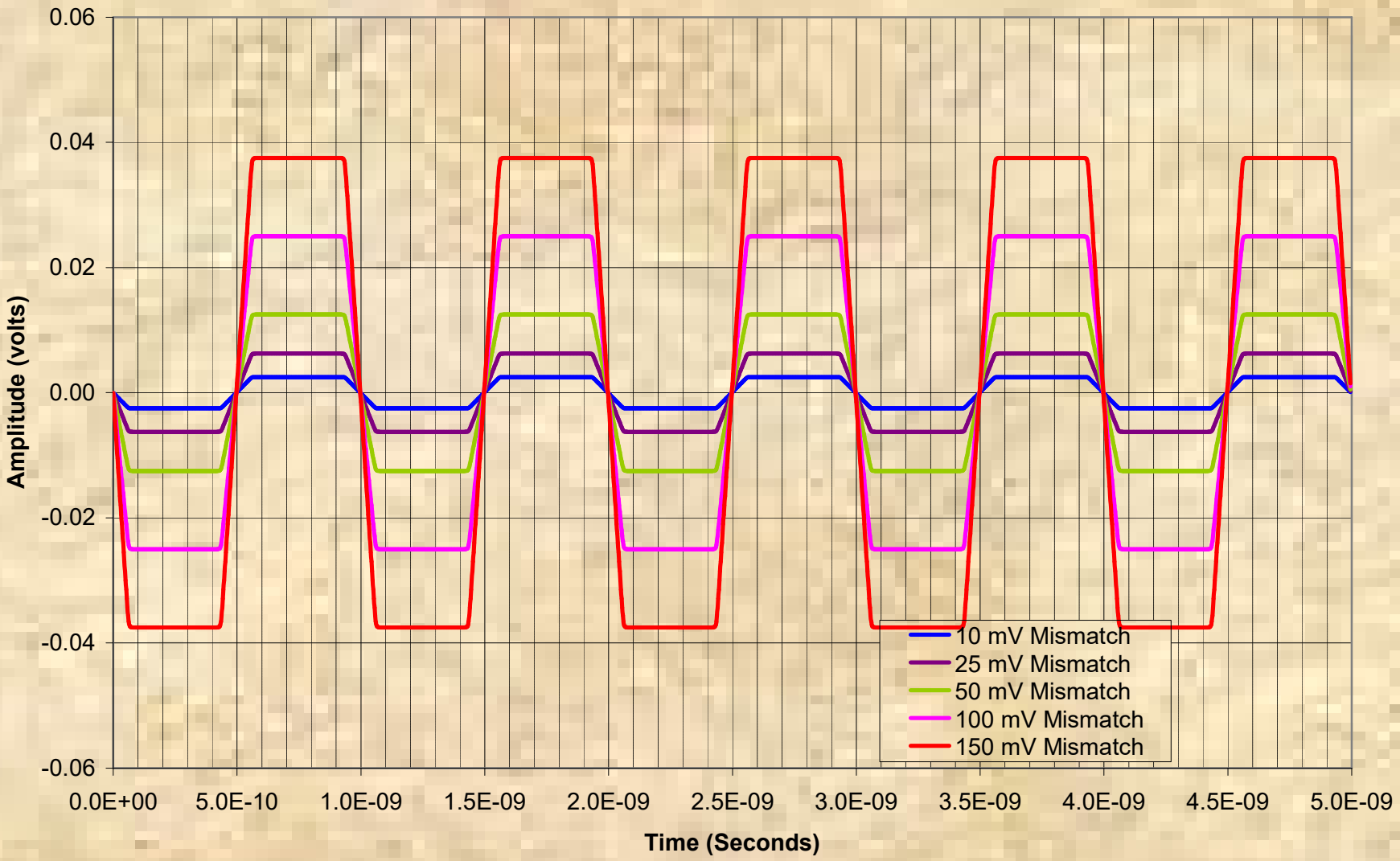
Common Mode Voltage on Differential Pair Due to Rise/Fall Time Mismatch
2 Gb/s with Differential Signal +/- 1.0 Volts



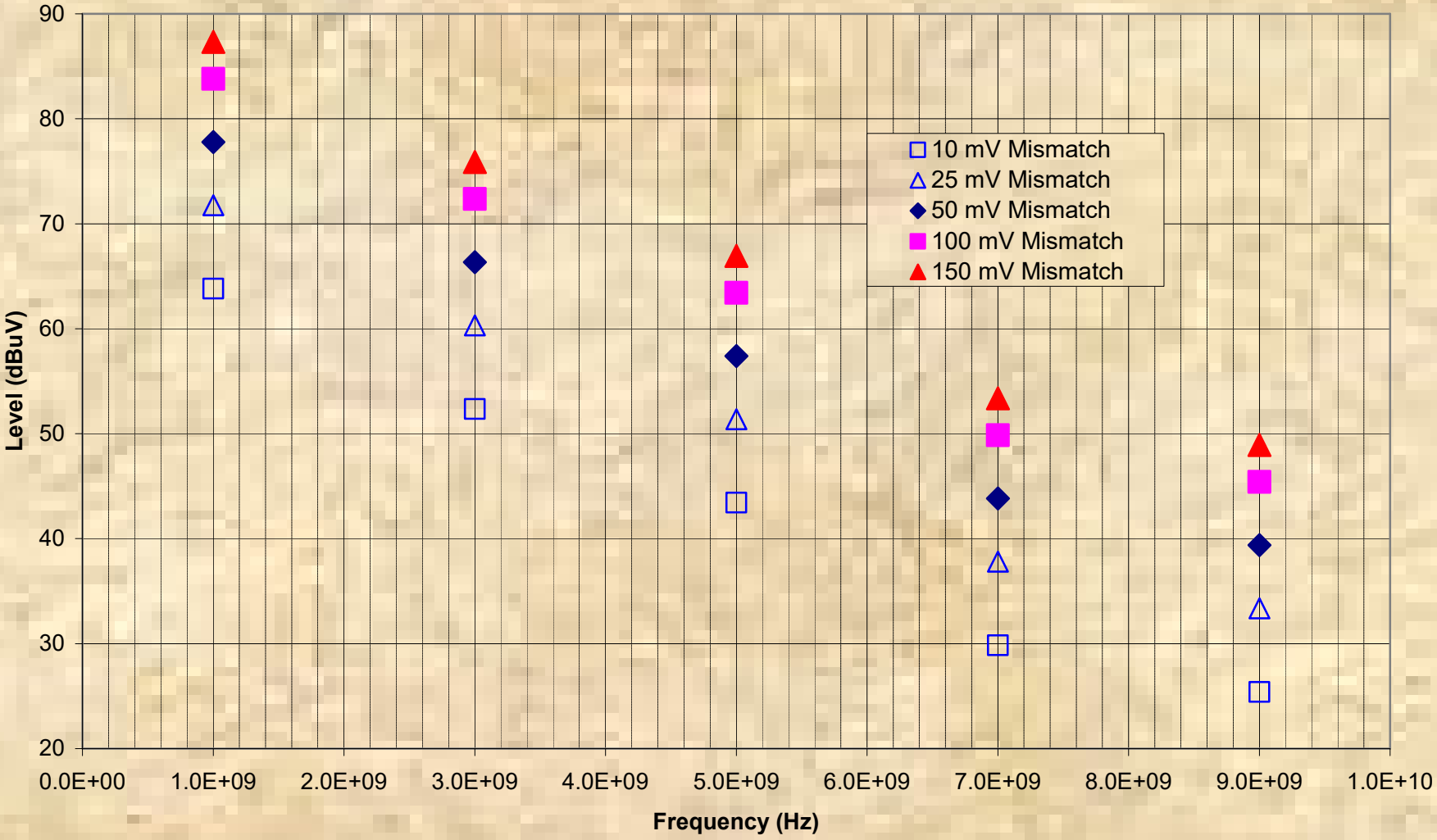
Common Mode from Amplitude Mismatch

- Small amounts of mismatch create significant CM noise
- Harmonics are additive with other sources of CM noise

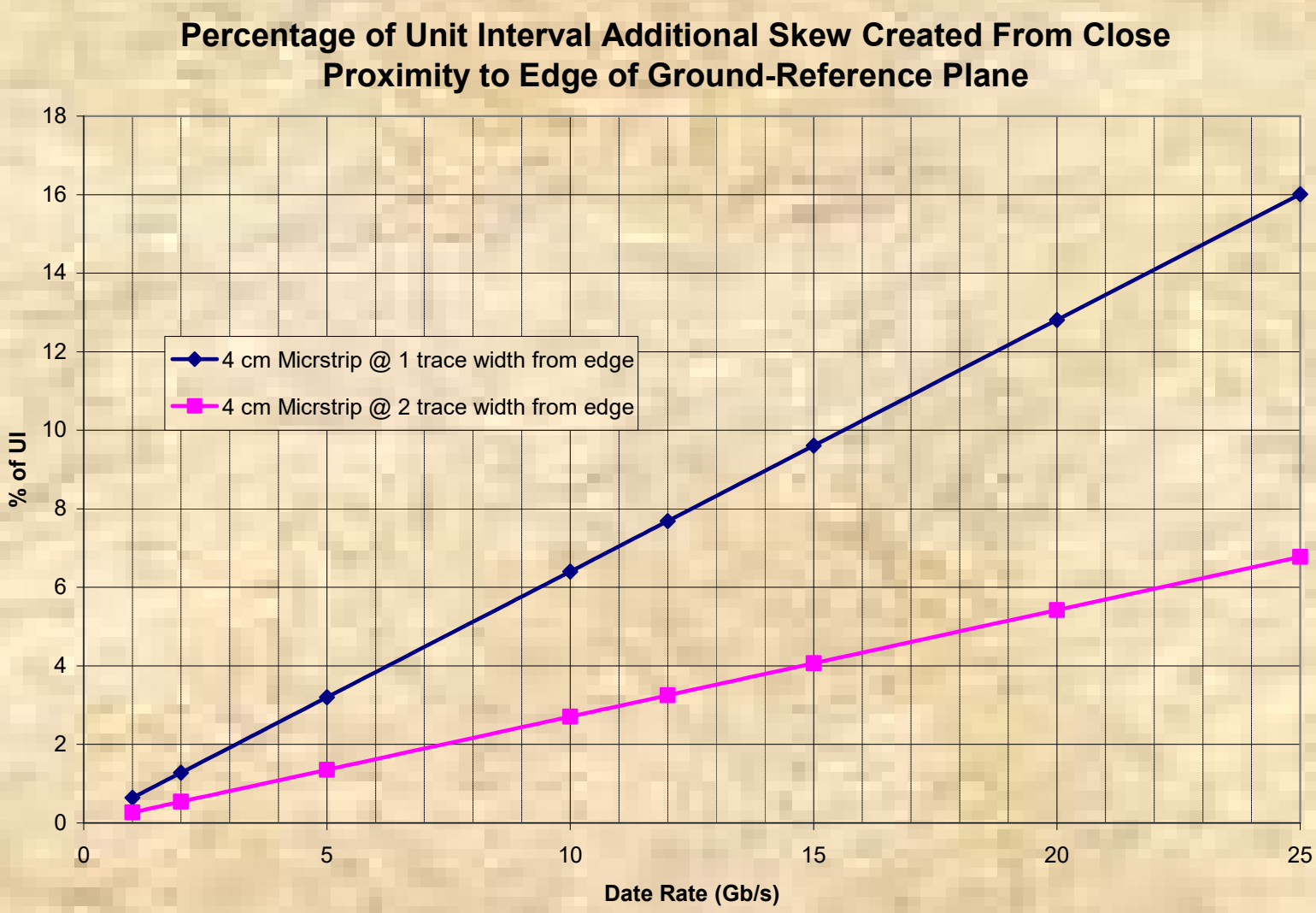
Common Mode Voltage on Differential Pair Due to Amplitude Mismatch
Clock 2 Gb/s with (100 ps Rise/Fall Time) Nominal Differential Signal +/- 1.0 V



Common Mode Voltage on Differential Pair Due to Amplitude Mismatch
Clock 2 Gb/s with (100 ps Rise/Fall Time)
Nominal Differential Signal +/- 1.0 Volts

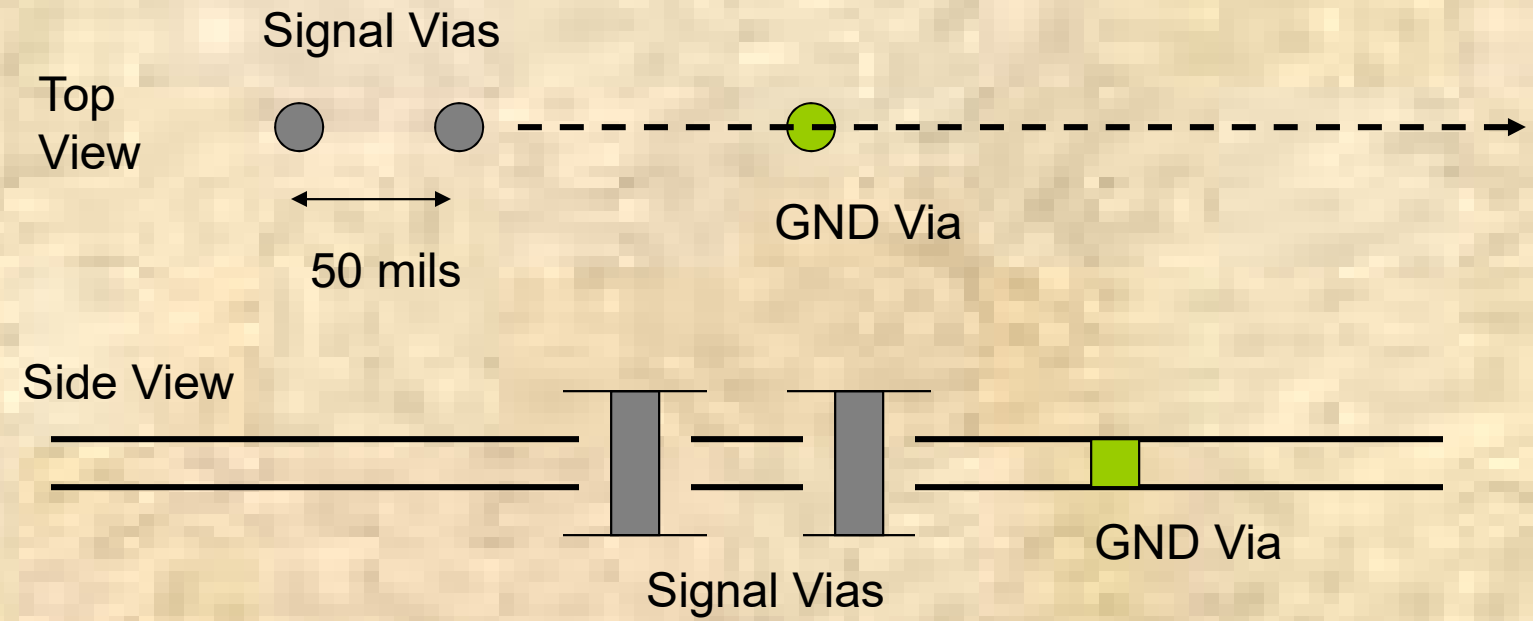


Trace Near Edge of Ground-Reference Plane

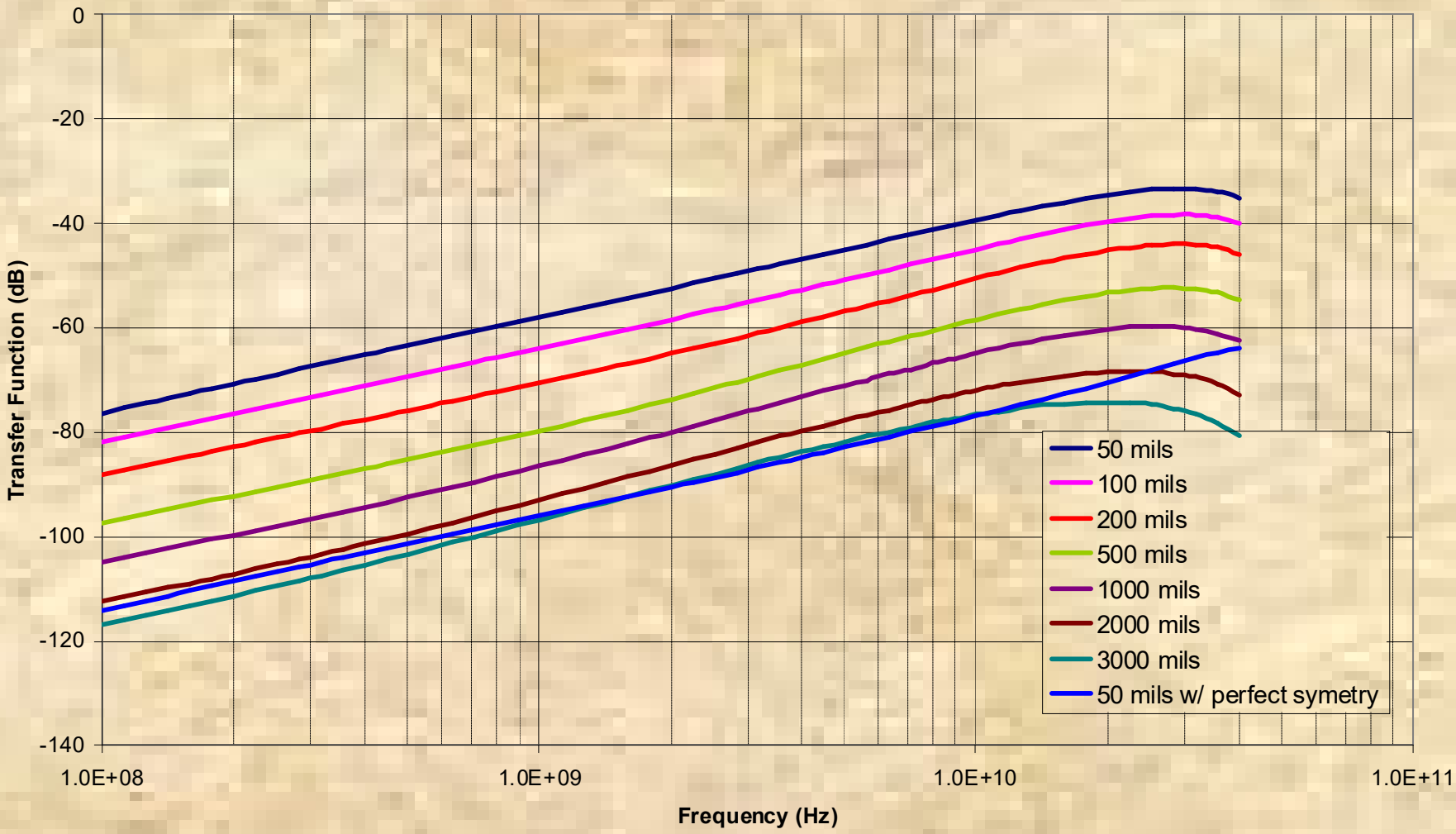


Common Mode from Via Asymmetry

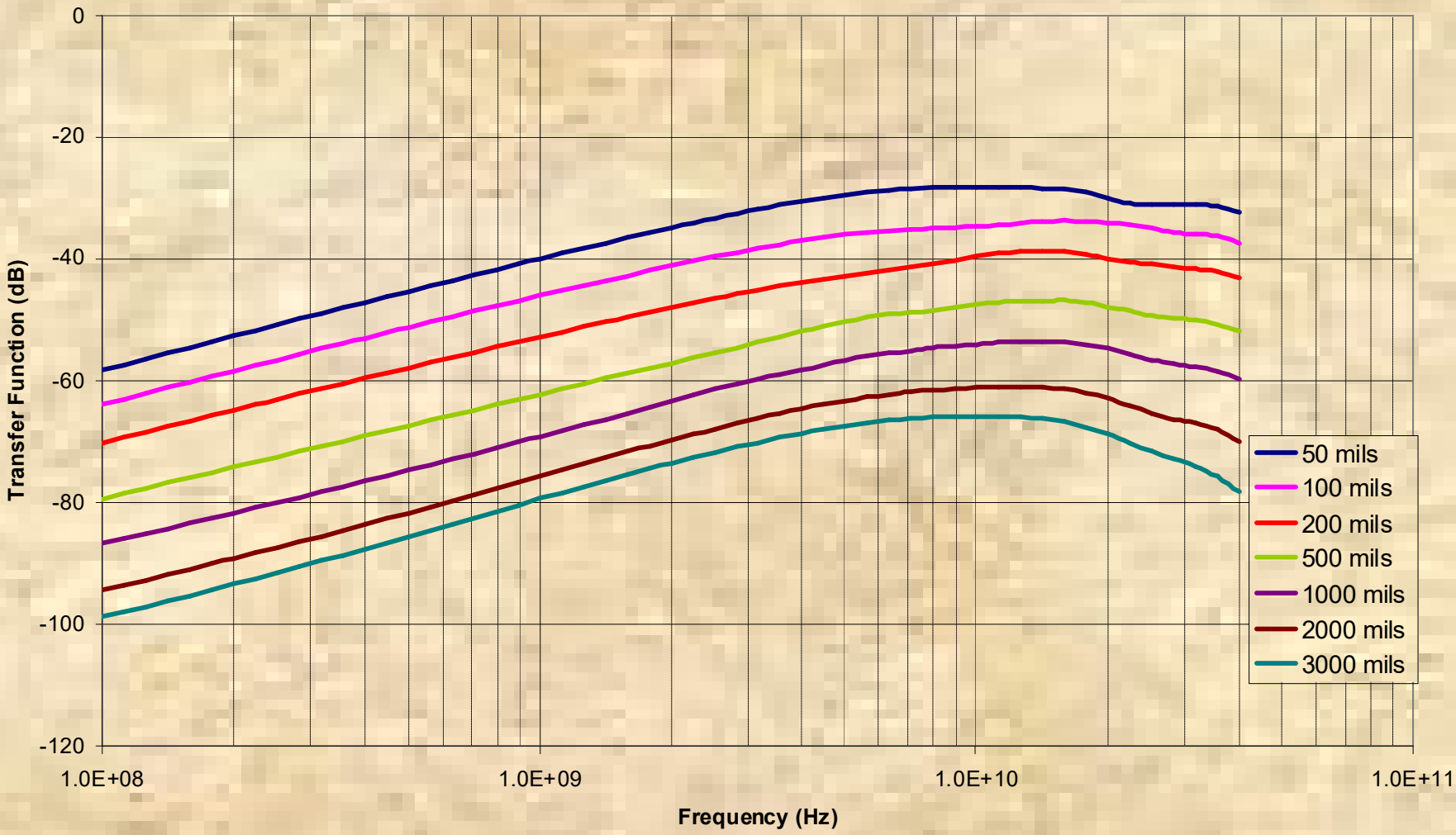
- Significant CM created!



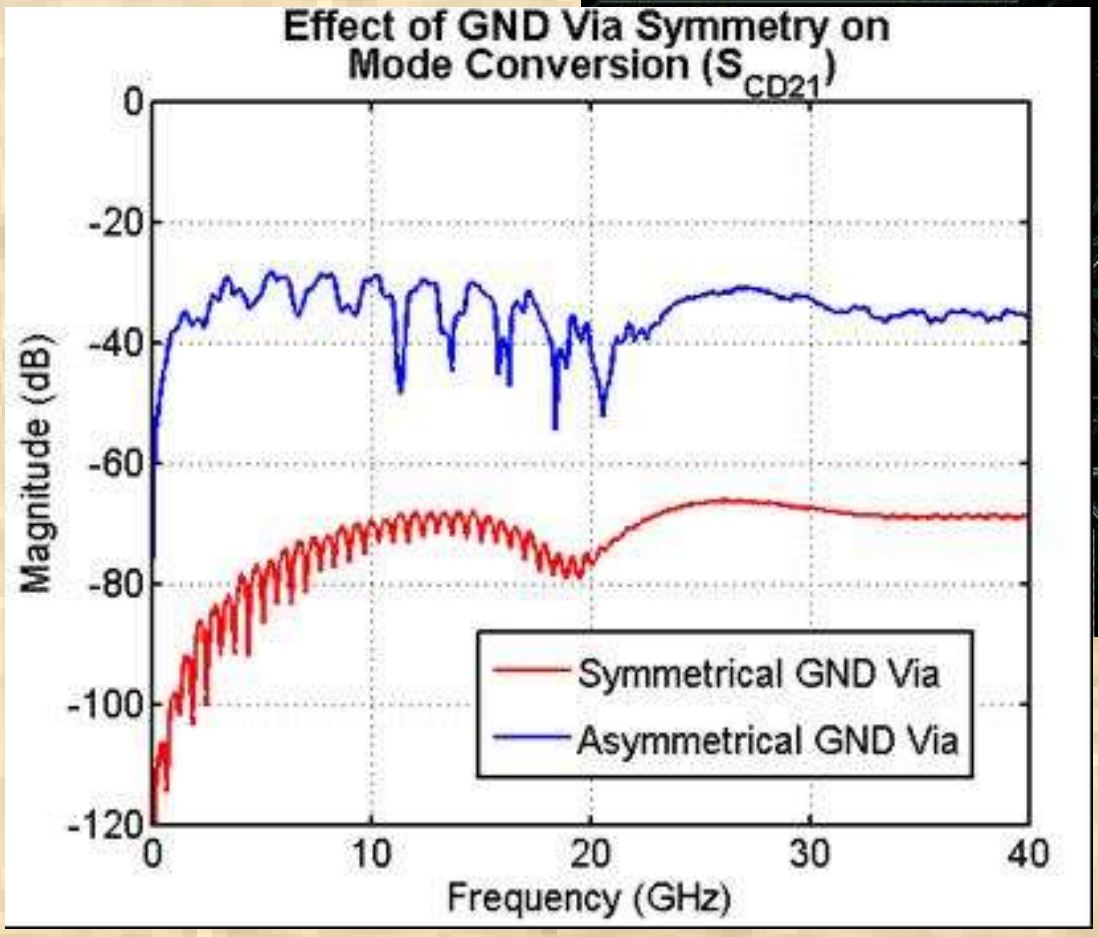
Differential to Single Ended Via Mode Conversion
Due to GND Via Asymmetry (In Line)
10 mils between planes

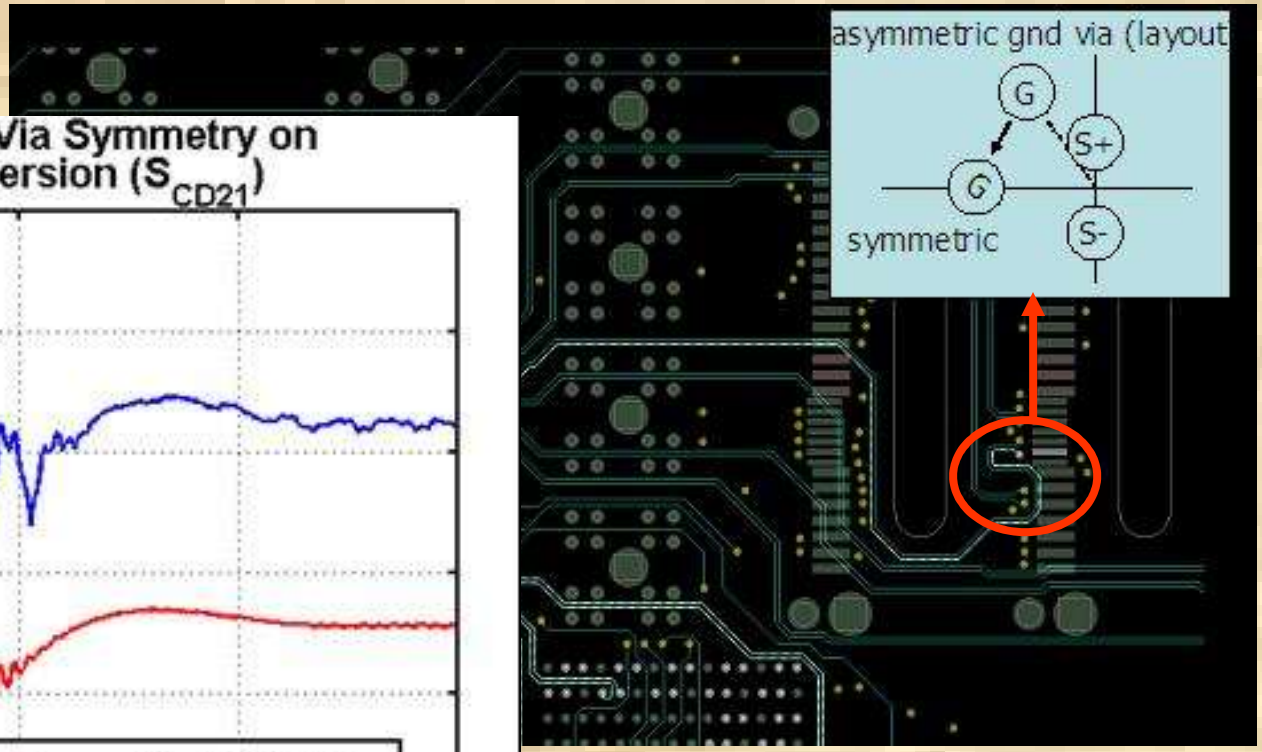


Differential to Single Ended Via Mode Conversion
Due to GND Via Asymmetry (In Line)
10 mils between planes (Eleven Planes with Through Via)

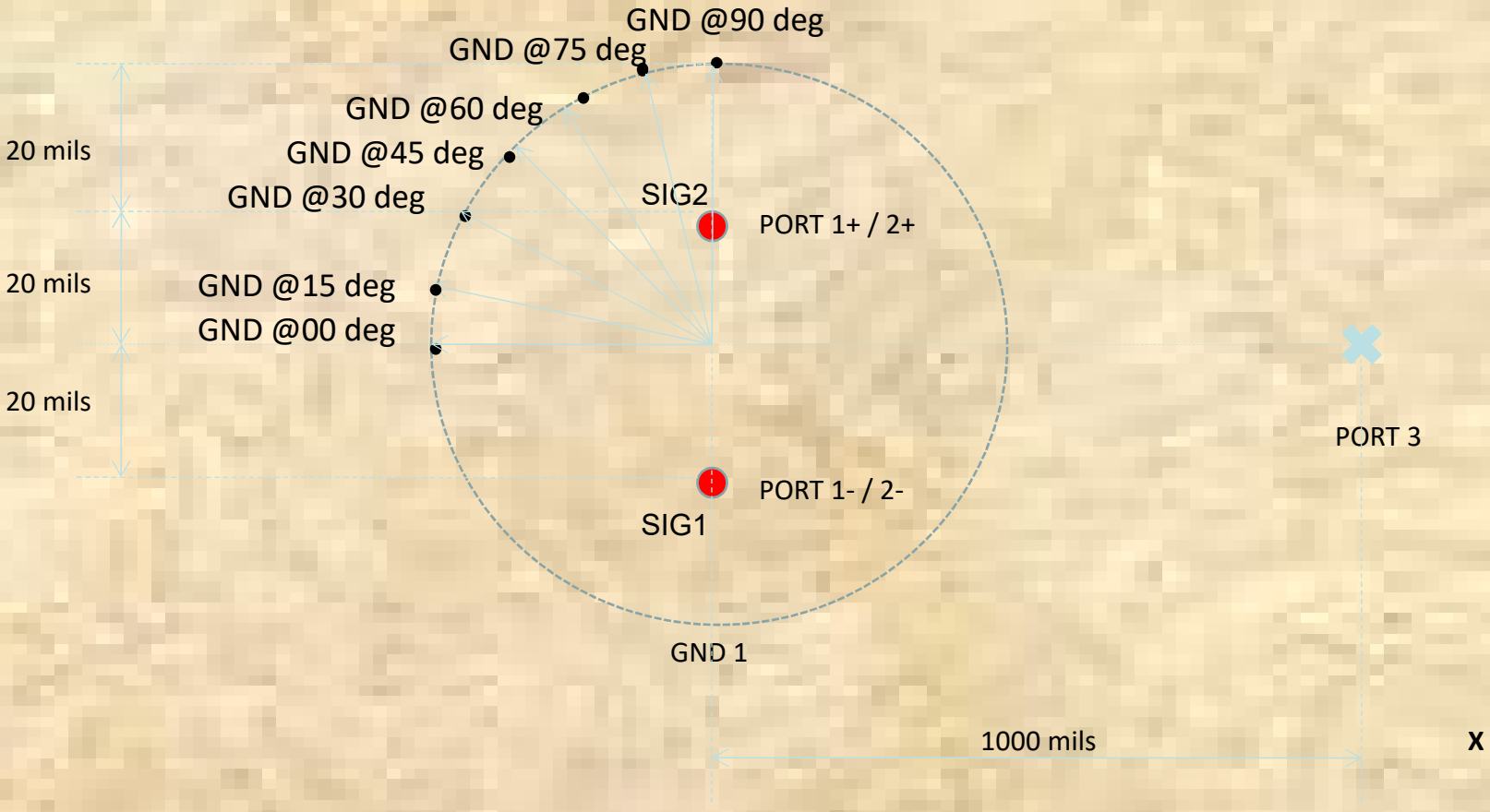


Via Symmetry Effect on Common Mode Conversion



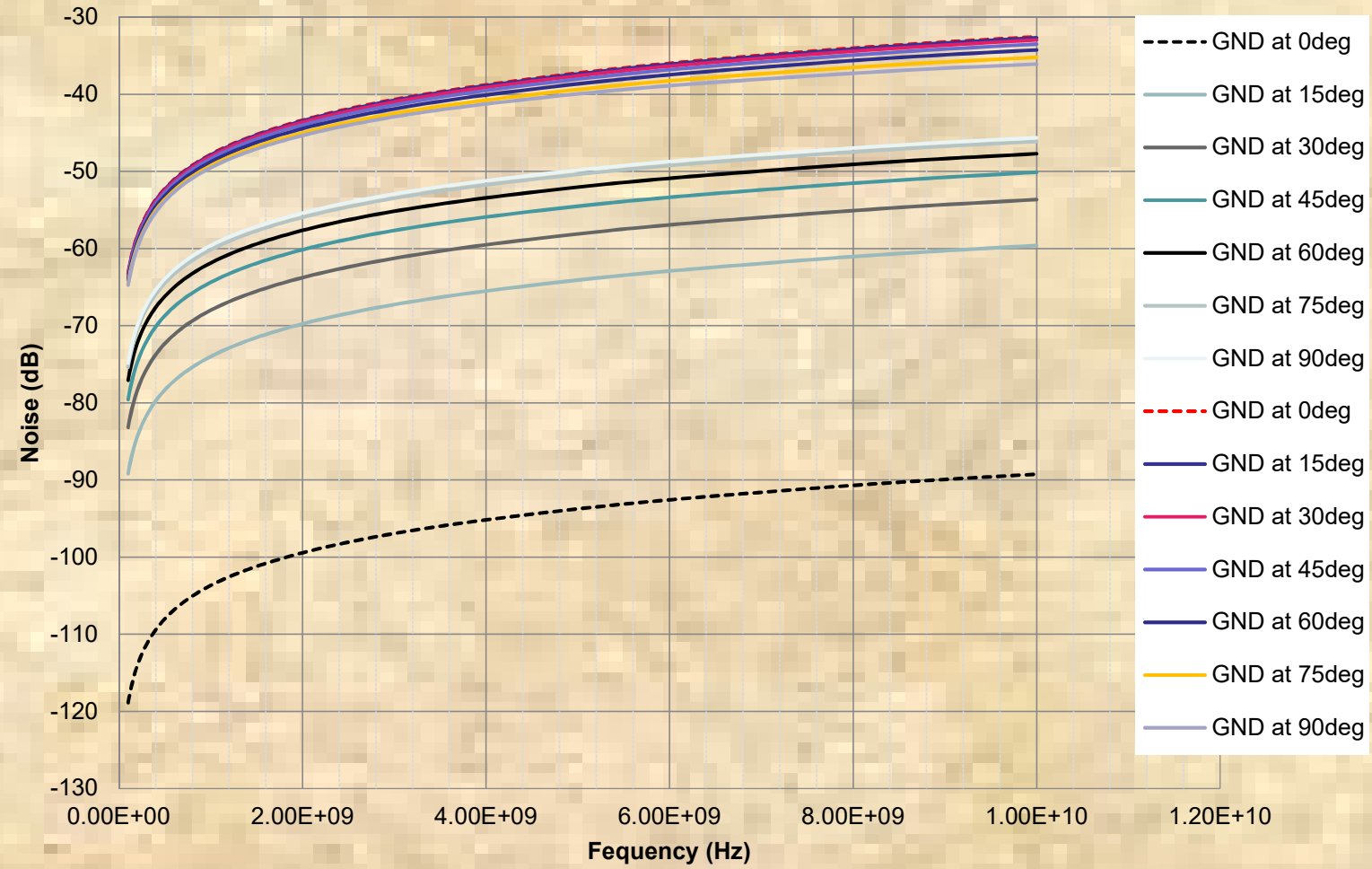


Top View of the Board: Different GND configurations

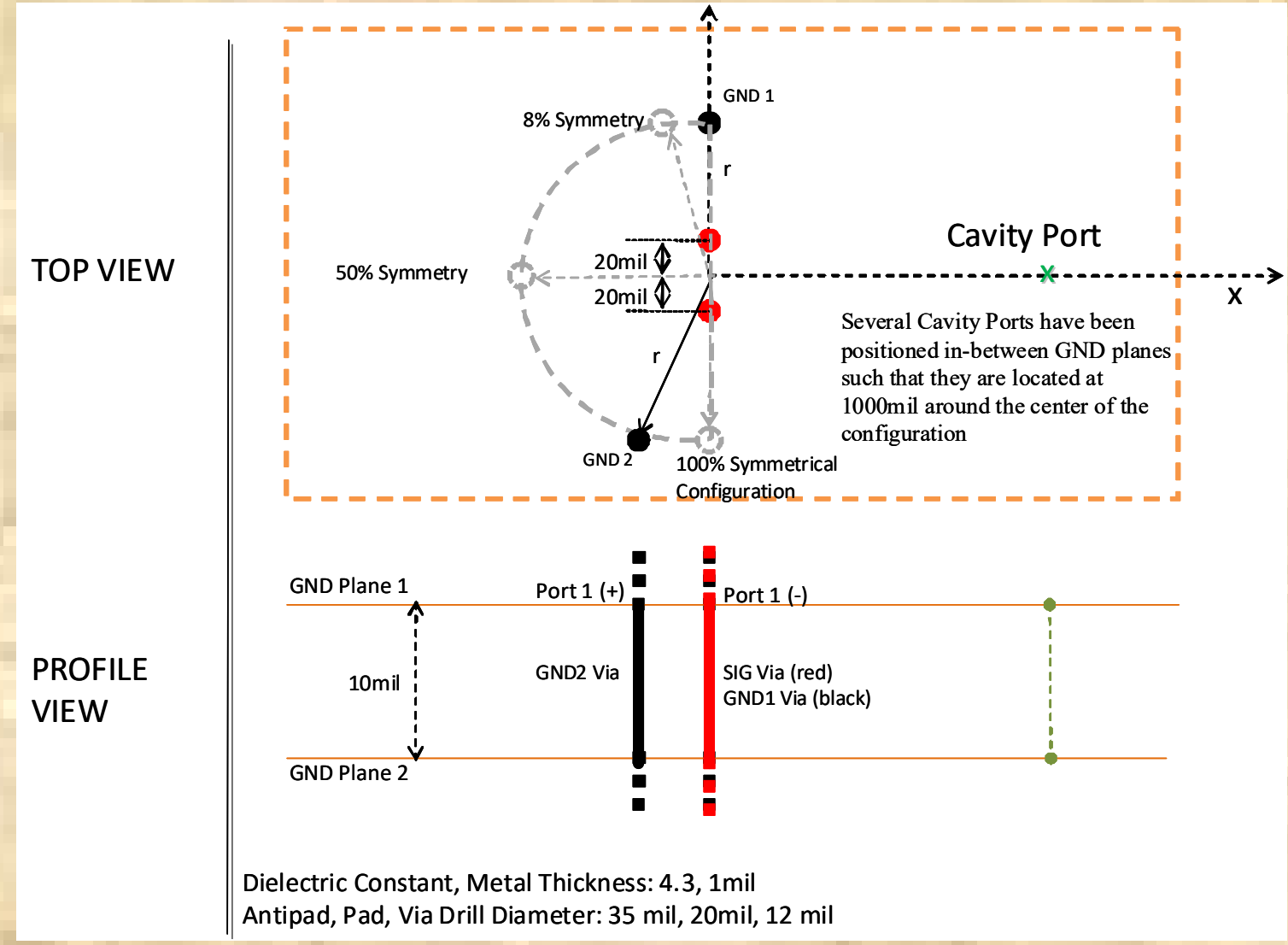


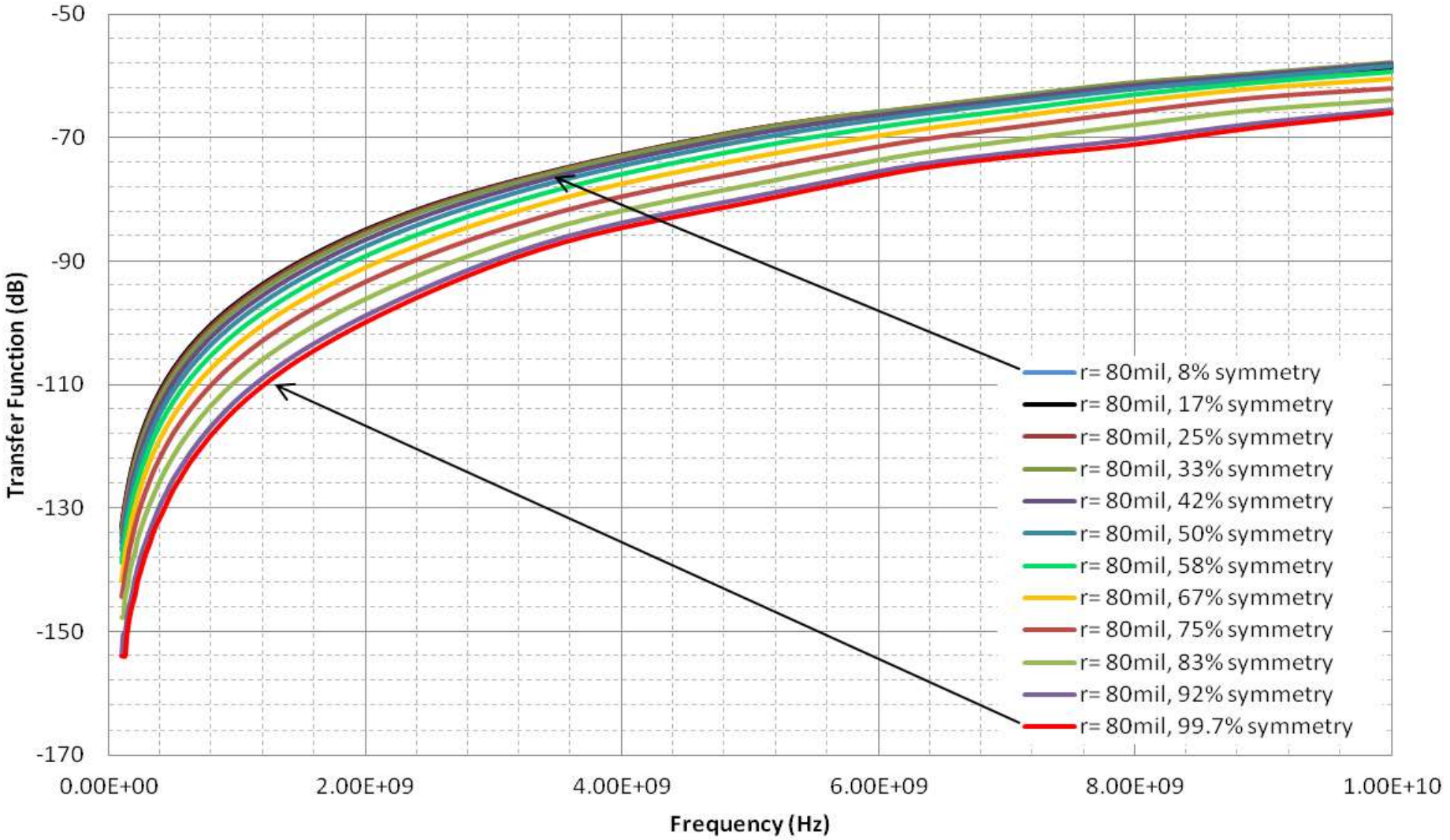
Asymmetric Ground Via Effects
Via to Noise Between Planes

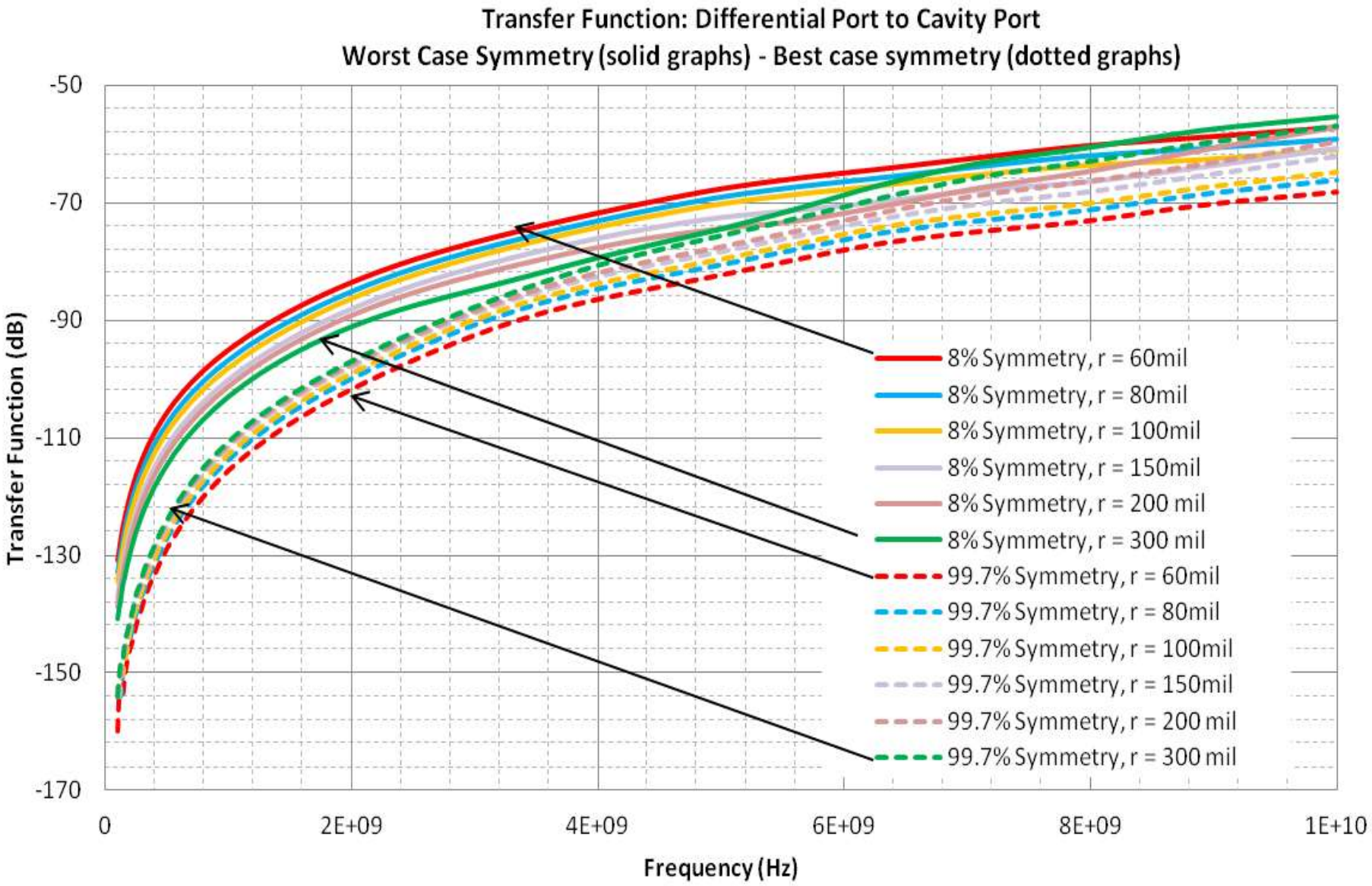
The effect of asymmetric GND configuration on:
Common Mode Noise (warm colors) and Differential Mode Noise (cool colors)

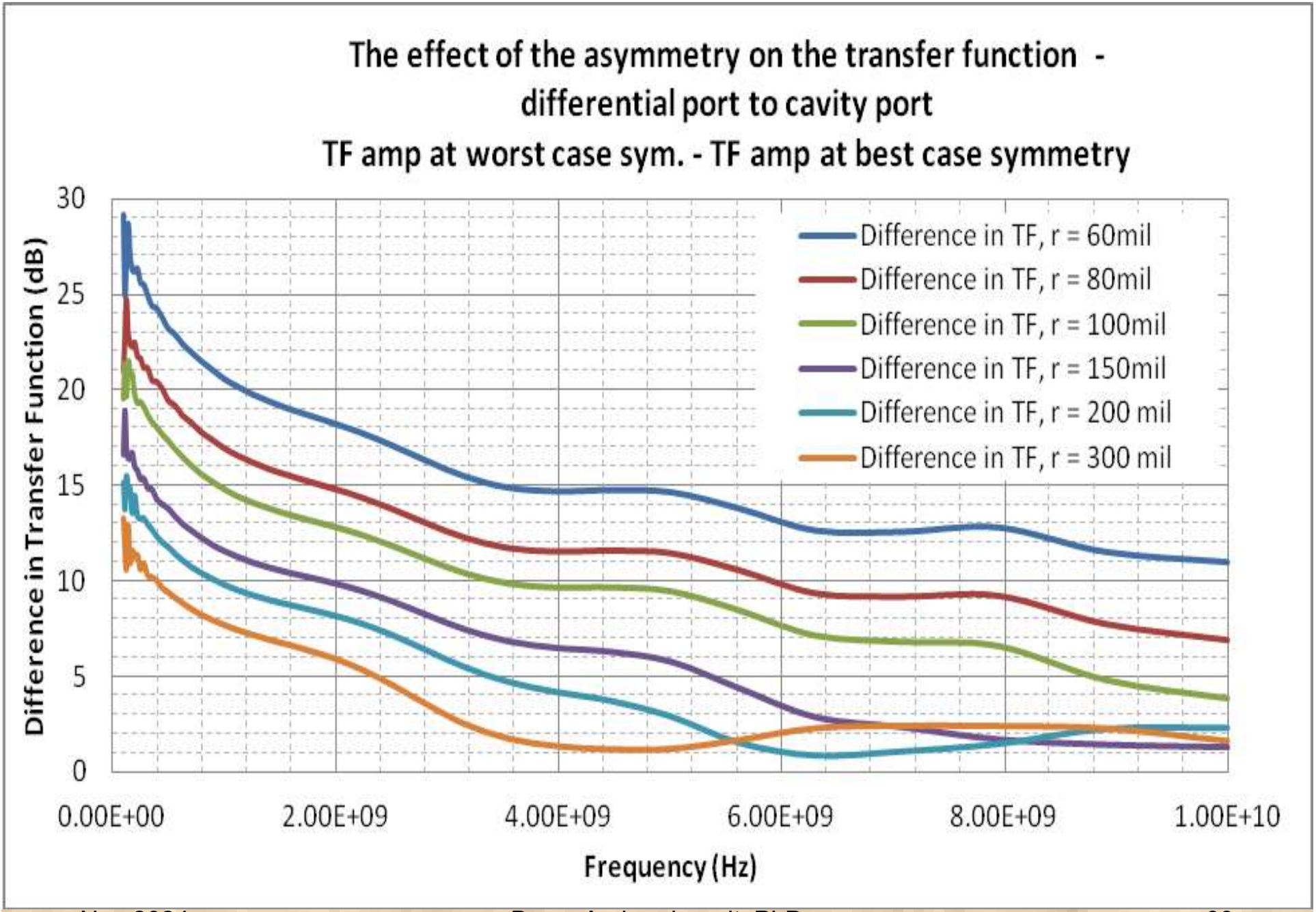


Asymmetry with Two GND Vias




Transfer Function: Differential Port to Cavity Port (worst case considering all cavity ports)
Distance of GND vias from origin: r = 80mil
Transfer Function (dB)
-50
-70
-90
-110
-130
-150
-170
0.00E+00
2.00E+09
4.00E+09
6.00E+09
8.00E+09
1.00E+10
Frequency (Hz)
r= 80mil, 8% symmetry
r= 80mil, 17% symmetry
r= 80mil, 25% symmetry
r= 80mil, 33% symmetry
r= 80mil, 42% symmetry
r= 80mil, 50% symmetry
r= 80mil, 58% symmetry
r= 80mil, 67% symmetry
r= 80mil, 75% symmetry
r= 80mil, 83% symmetry
r= 80mil, 92% symmetry
r= 80mil, 99.7% symmetry

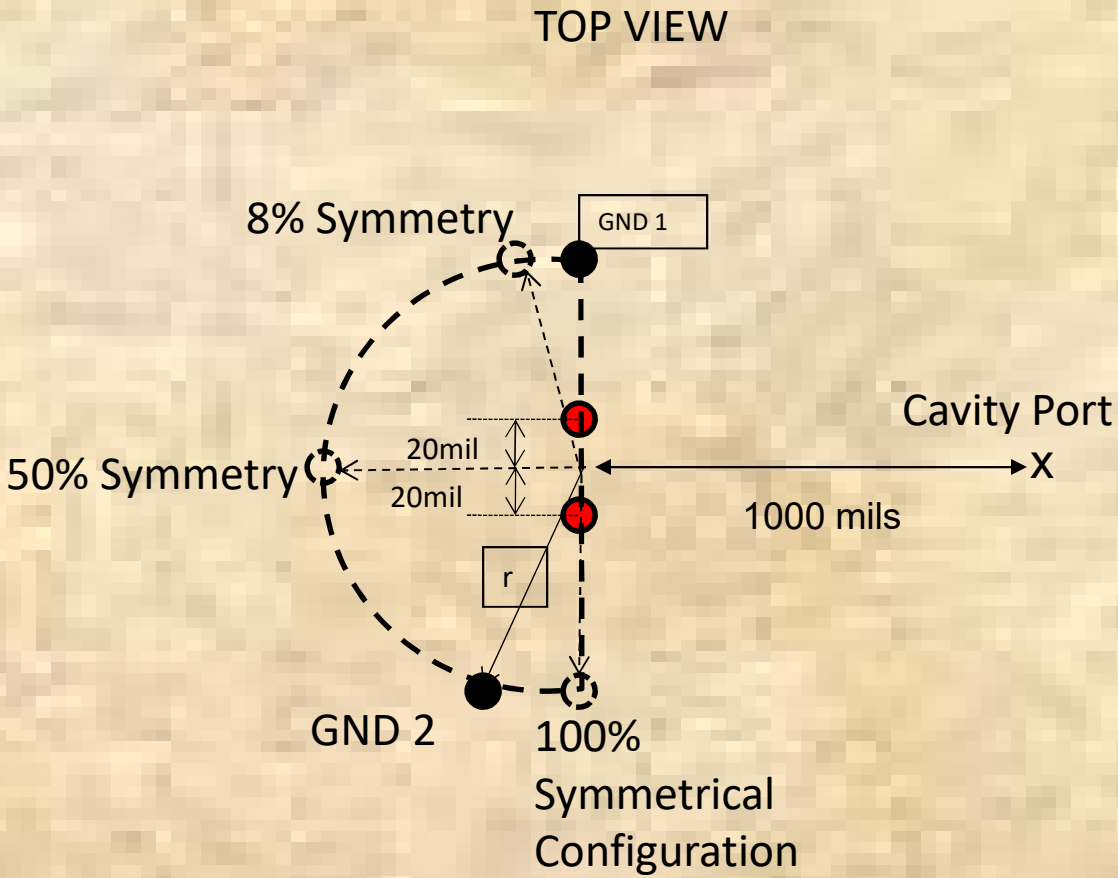

Transfer Function: Differential Port to Cavity Port
Worst Case Symmetry (solid graphs) - Best case symmetry (dotted graphs)
Transfer Function (dB)
-50
-70
-90
-110
-130
-150
-170
0
2E+09
4E+09
6E+09
8E+09
1E+10
Frequency (Hz)
8% Symmetry, r = 60mil
8% Symmetry, r = 80mil
8% Symmetry, r = 100mil
8% Symmetry, r = 150mil
8% Symmetry, r = 200 mil
8% Symmetry, r = 300 mil
99.7% Symmetry, r = 60mil
99.7% Symmetry, r = 80mil
99.7% Symmetry, r = 100mil
99.7% Symmetry, r = 150mil
99.7% Symmetry, r = 200 mil
99.7% Symmetry, r = 300 mil


The effect of the asymmetry on the transfer function -
differential port to cavity port
TF amp at worst case sym. - TF amp at best case symmetry
Difference in Transfer Function (dB)
30
25
20
15
10
5
0
0.00E+00
2.00E+09
4.00E+09
6.00E+09
8.00E+09
1.00E+10
Frequency (Hz)
Difference in TF, r = 60mil
Difference in TF, r = 80mil
Difference in TF, r = 100mil
Difference in TF, r = 150mil
Difference in TF, r = 200 mil
Difference in TF, r = 300 mil

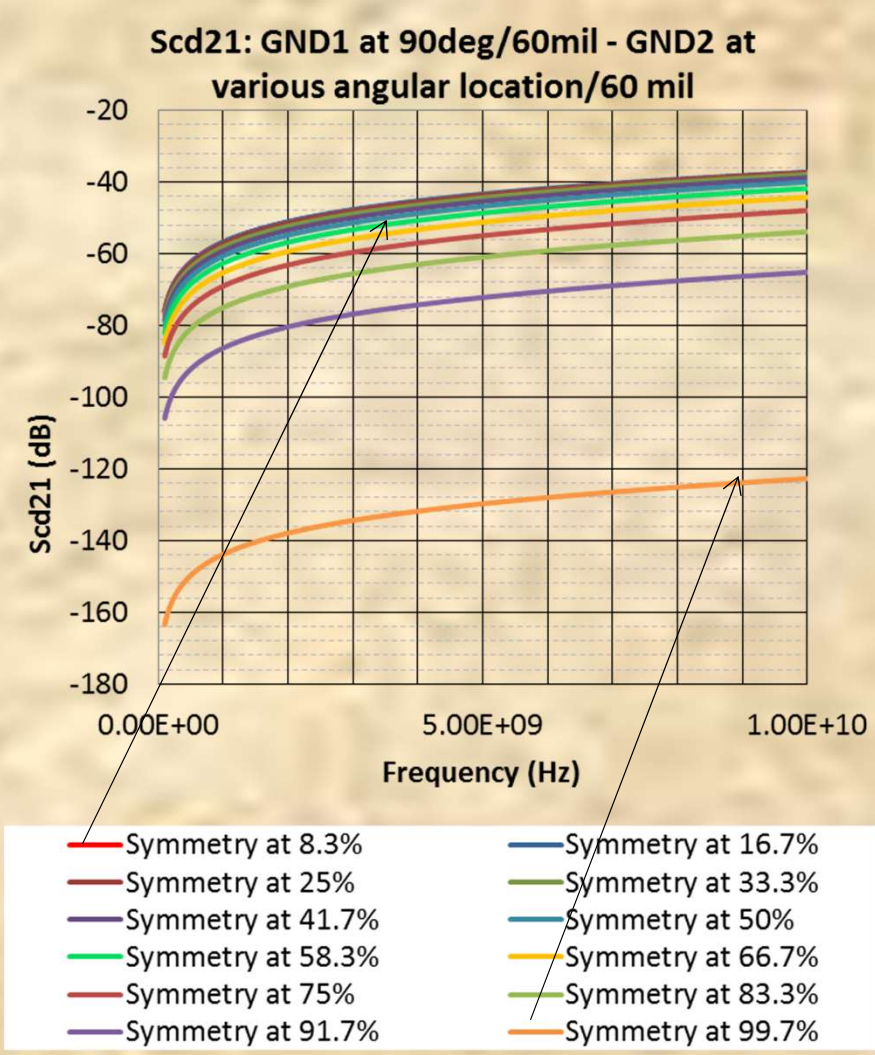
Differential Via Configuration

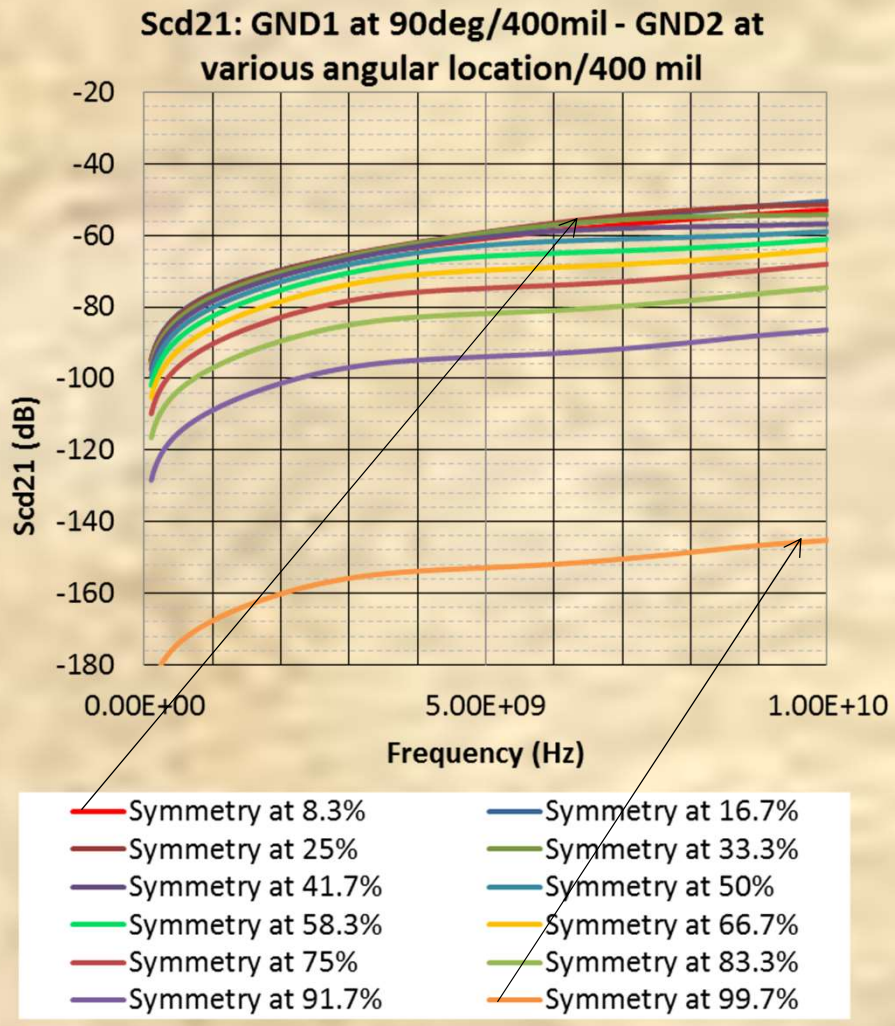
Two 'Ground' Vias

Differential to Common Mode Conversion S_{cd21}

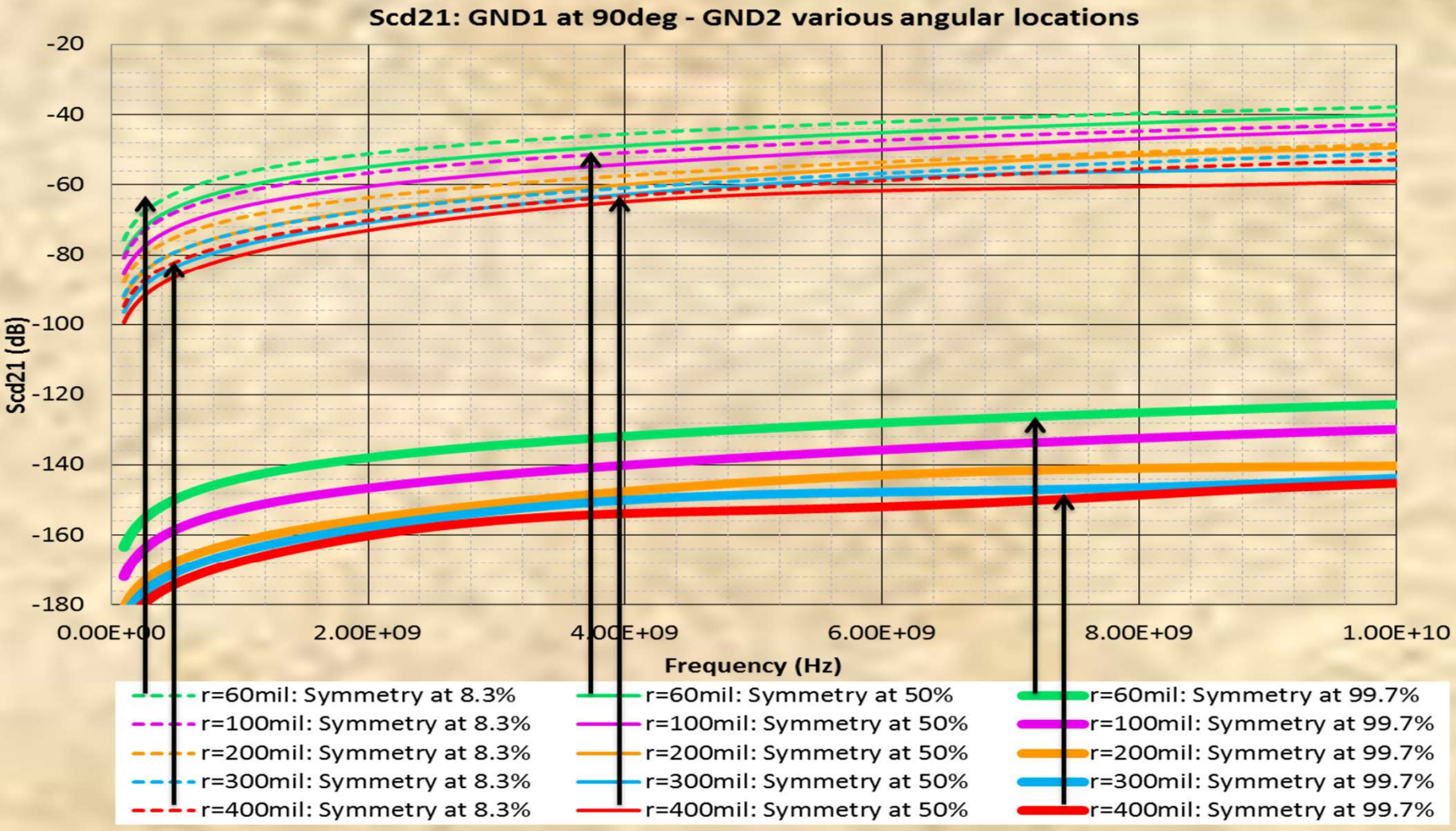


Effect of Asymmetry on S_{cd21} at 60 mil & 400 mil Distance to GND Vias

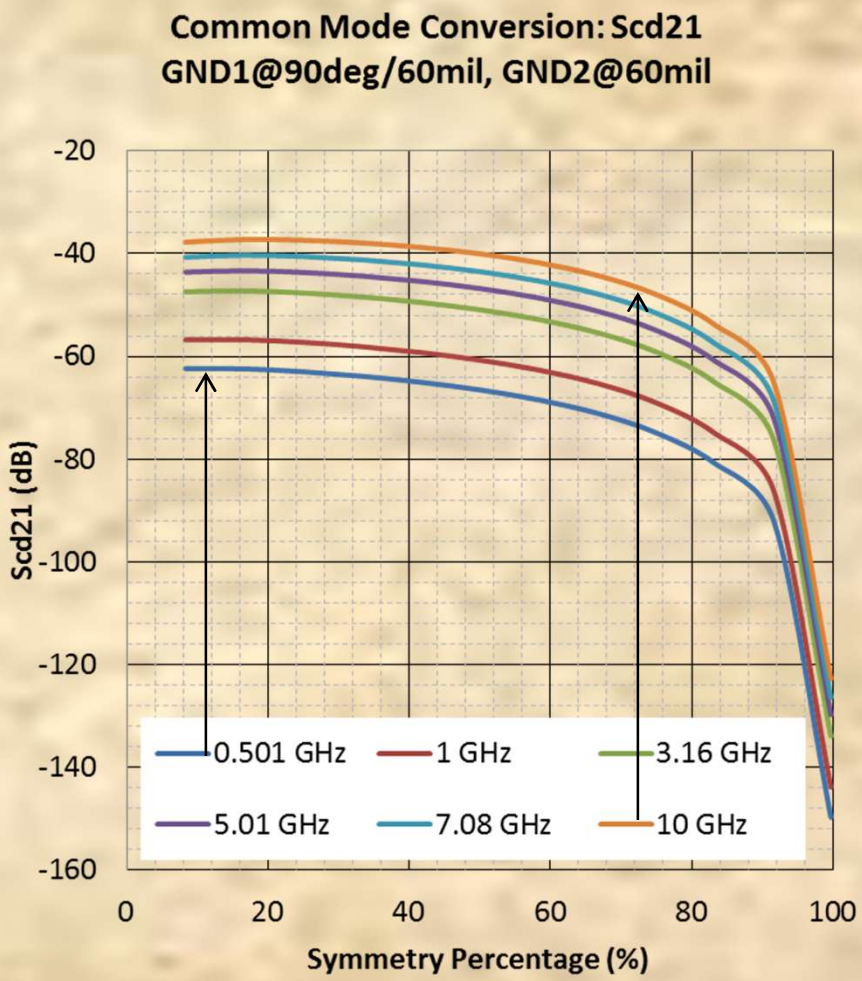


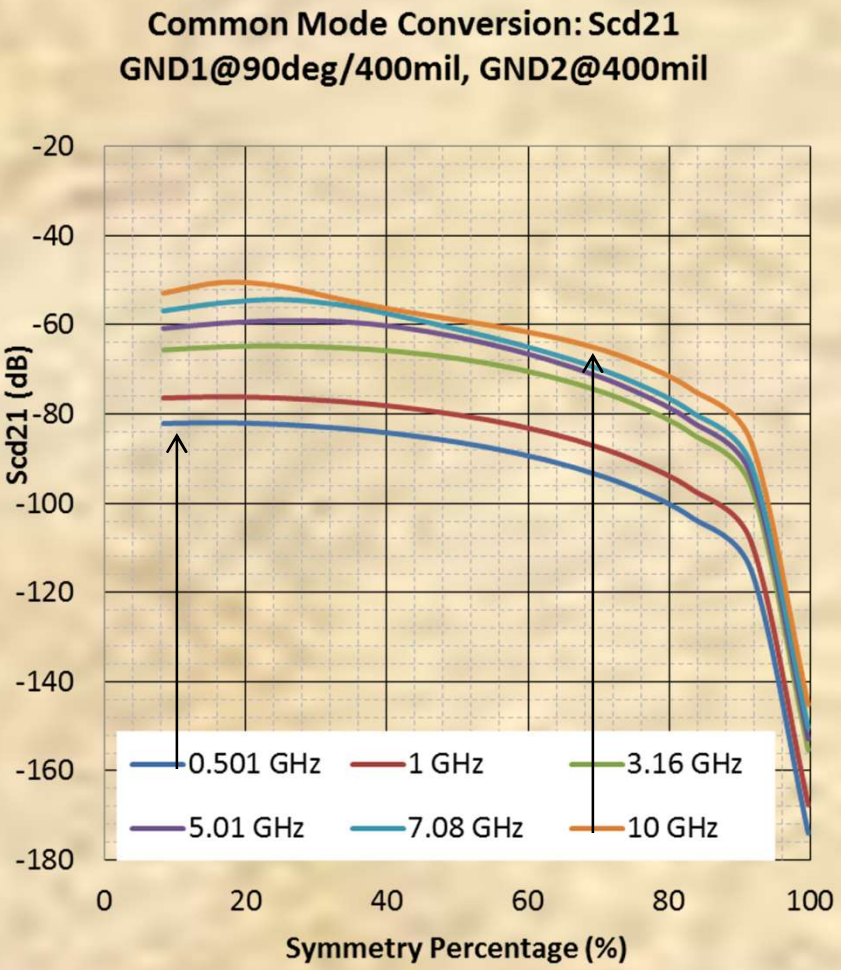


Effect of Asymmetry on S_{cd21} at Various Distance to GND Vias



Effect of Asymmetry on S_{cd21} at Various Frequencies



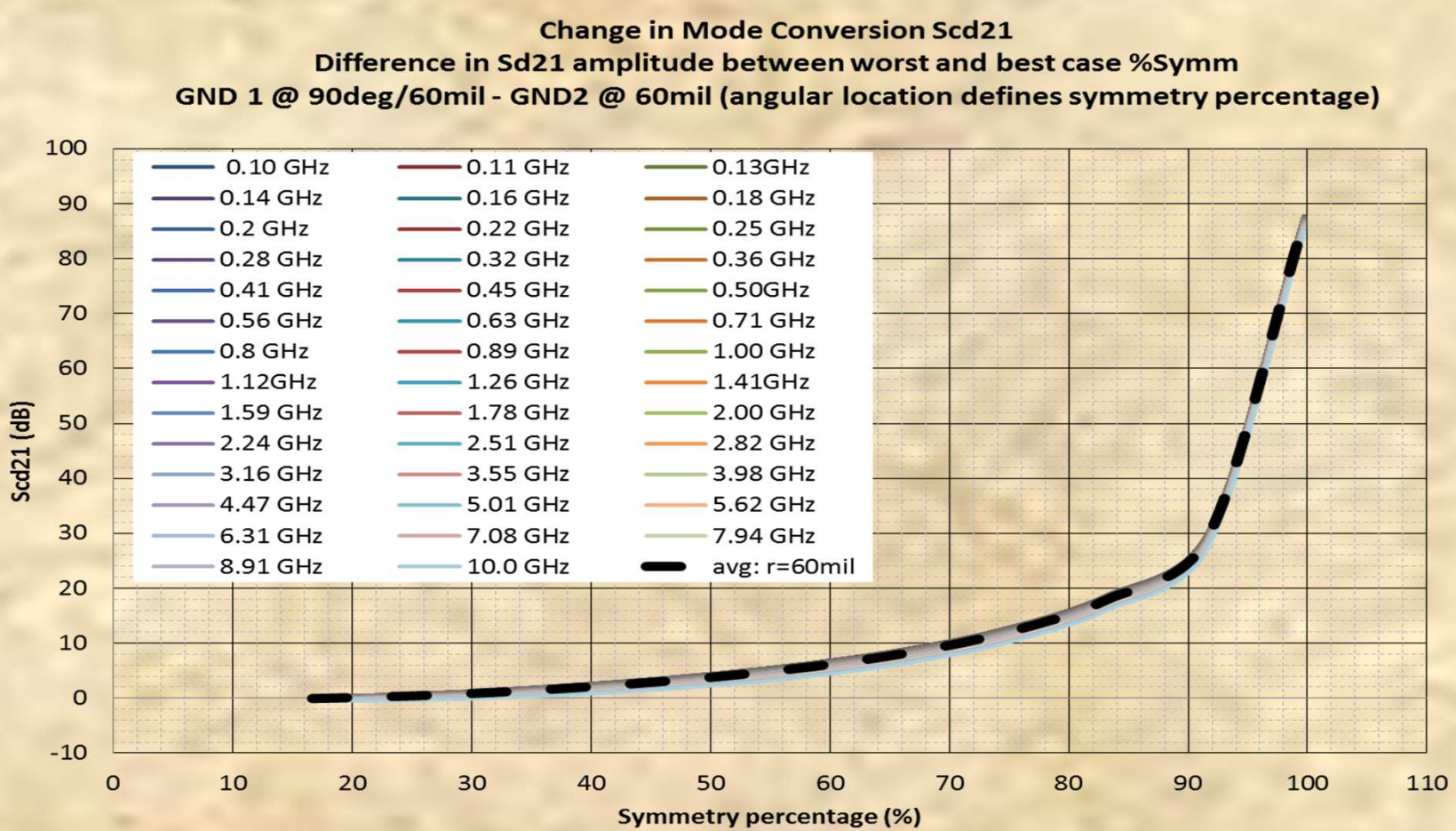


Maximum Impact of Asymmetry

- For a given distance, all frequencies have same impact vs symmetry
  - Biggest maximum impact possible with good symmetry
  - Maximum impact is frequency independent

Maximum Impact of Asymmetry

Change in S_{cd21}

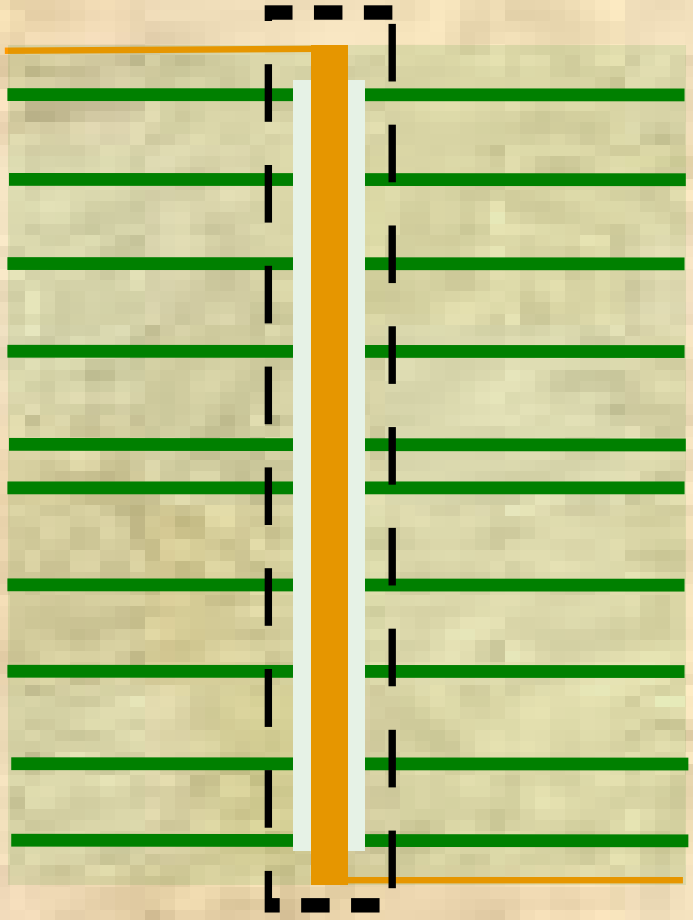


Differential Via Configuration

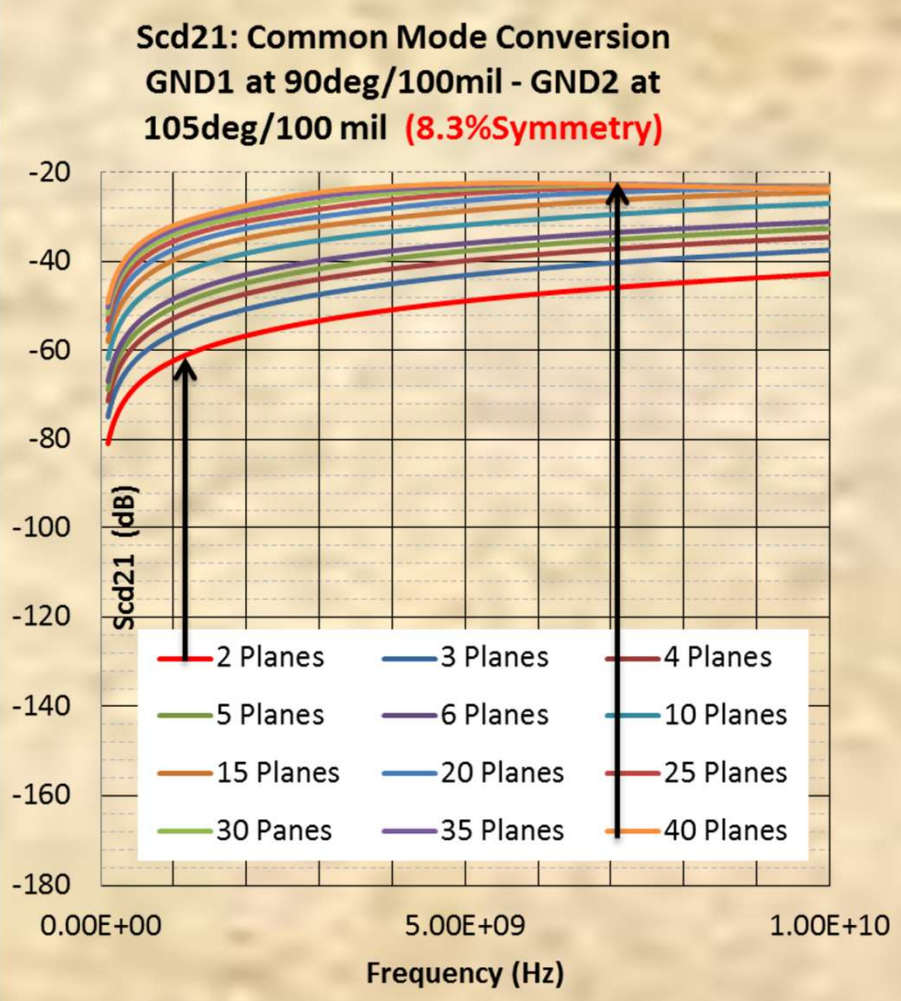
Two ‘Ground’ Vias

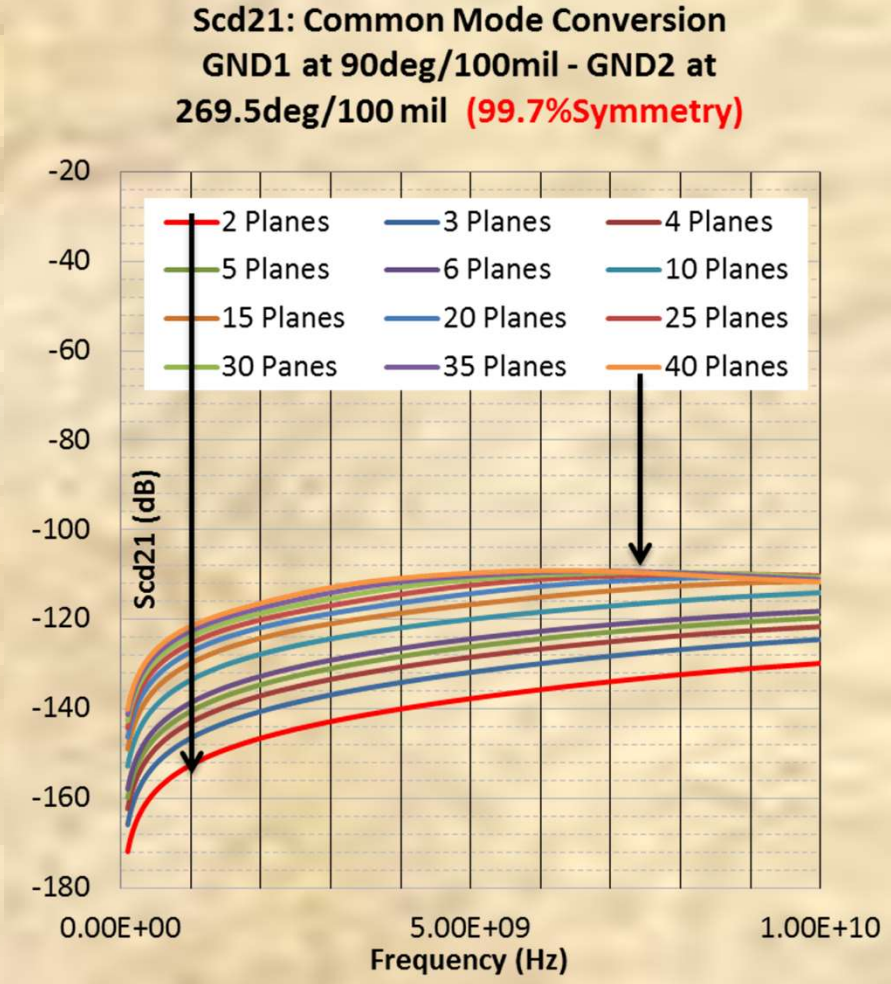
Differential to Common Mode Conversion Scd21

- Mode conversion is additive for each plane-pair transition

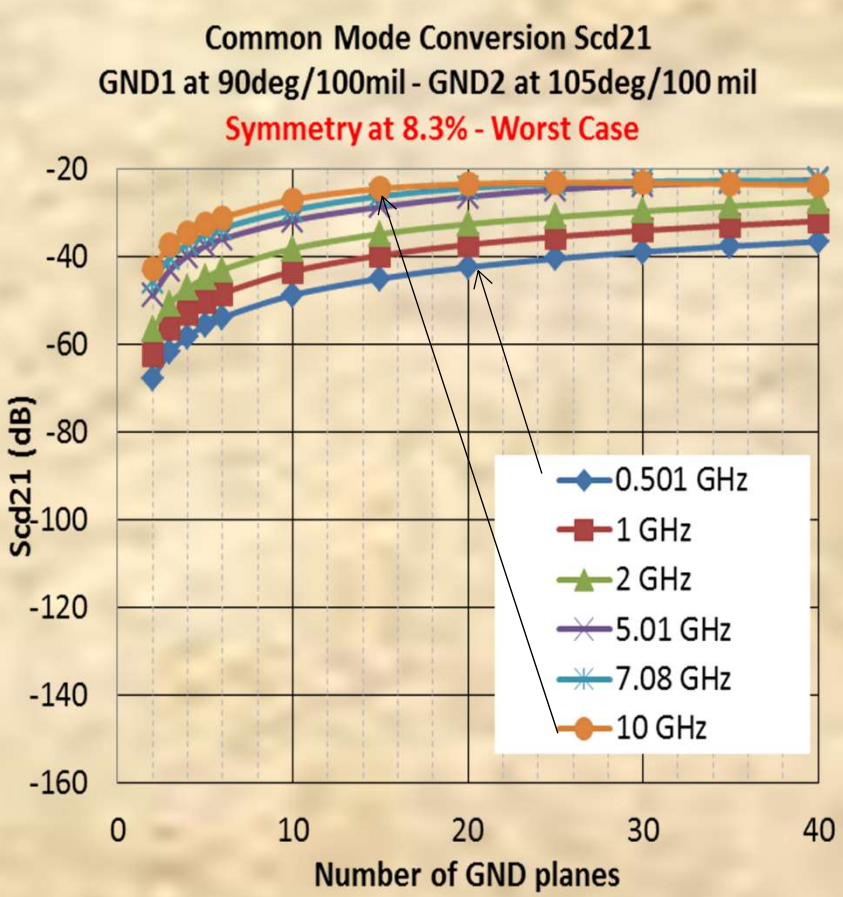


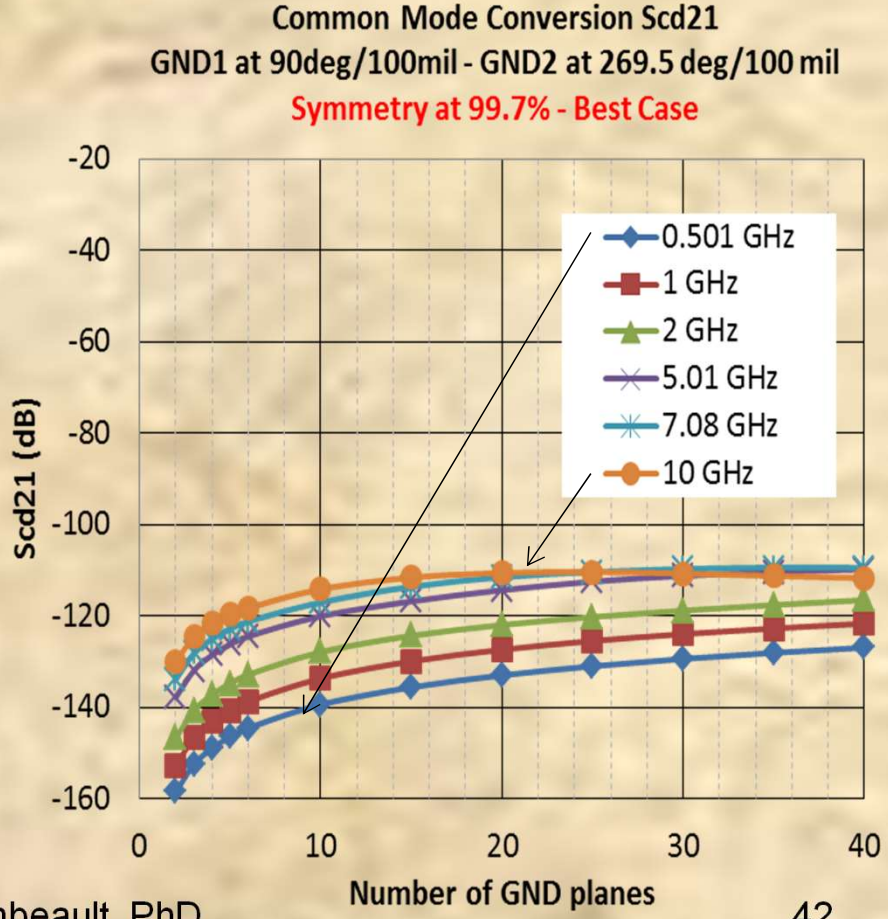
Mode Conversion for Poor and Good Symmetry for Multiple Plane-Pairs





Mode Conversion for Poor and Good Symmetry for Multiple Plane-Pairs for Various Frequencies





Differential Via Summary

- Differential Via
  - Effect of symmetry shown to be very important
    - Noise between planes
    - Mode conversion
    - Multiple vias
  - Important for BOTH emissions and Immunity

Common Mode is Impossible to Avoid

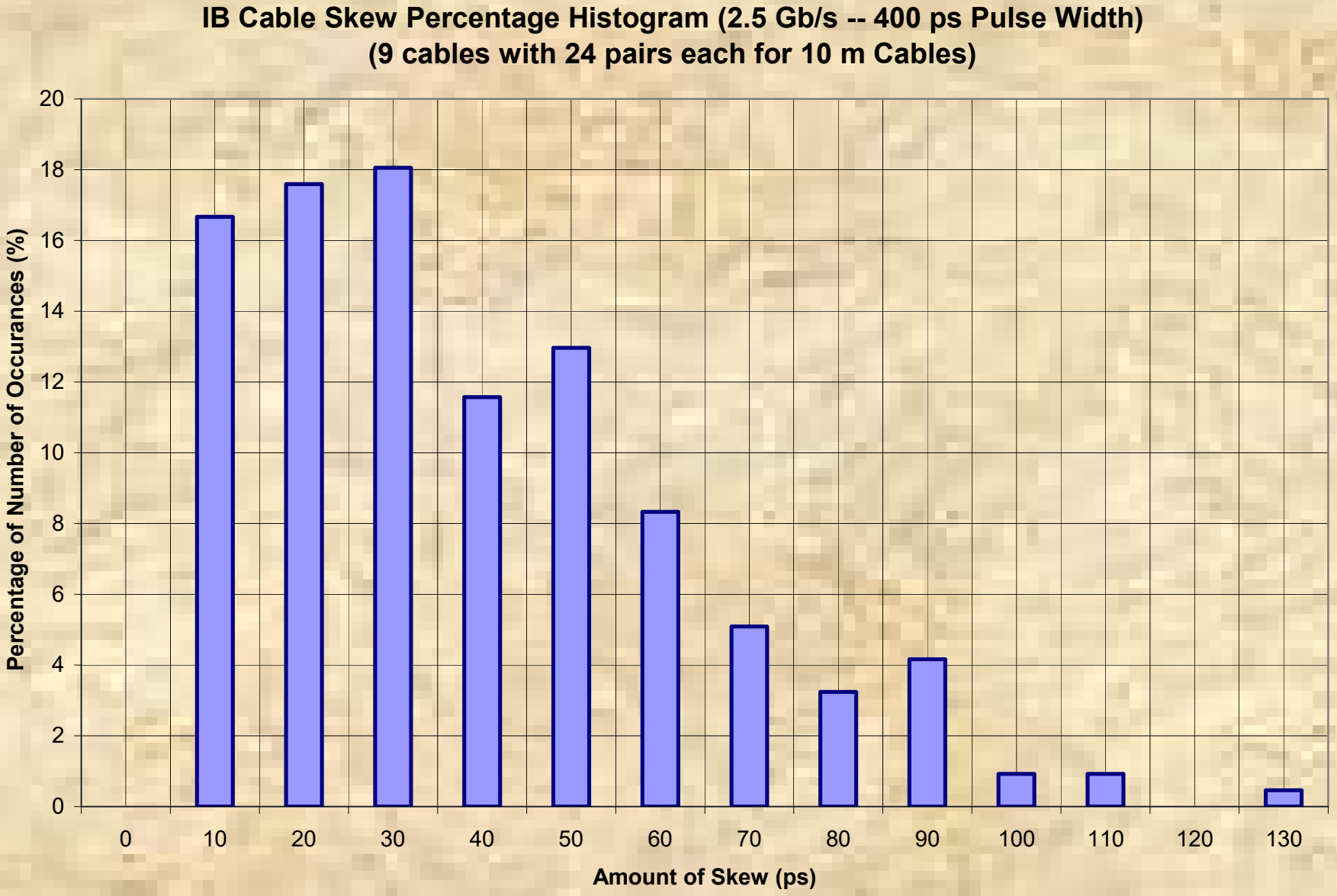
- Many other asymmetries can add to common mode noise creation
  - Dielectric weave effects
- For EMI, small amounts of CM noise is significant!
  - Above 1 GHz, 1 mV of CM noise is risky!
  - CM filters are required if cables not heavily shielded

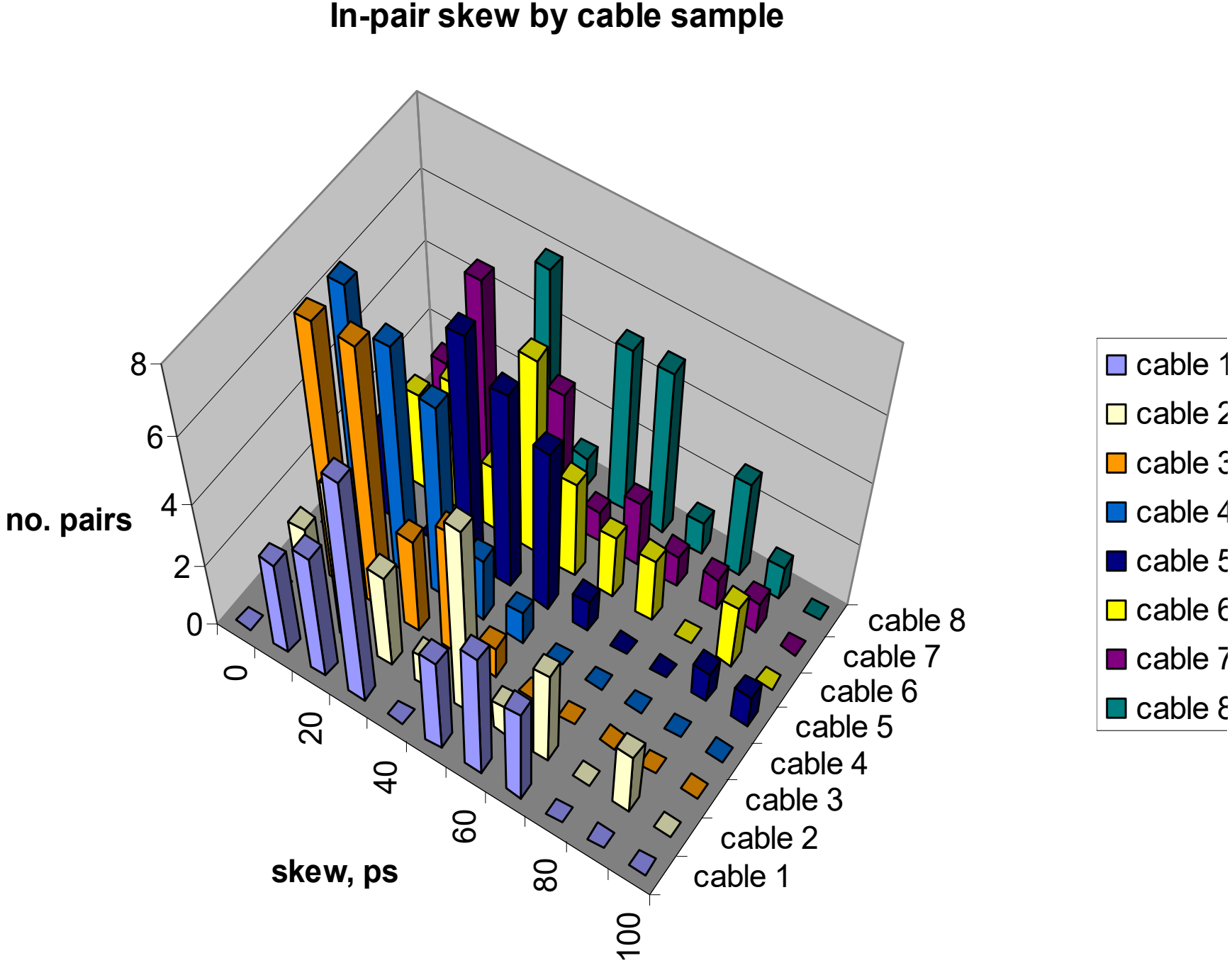
Differential Cable Measurements

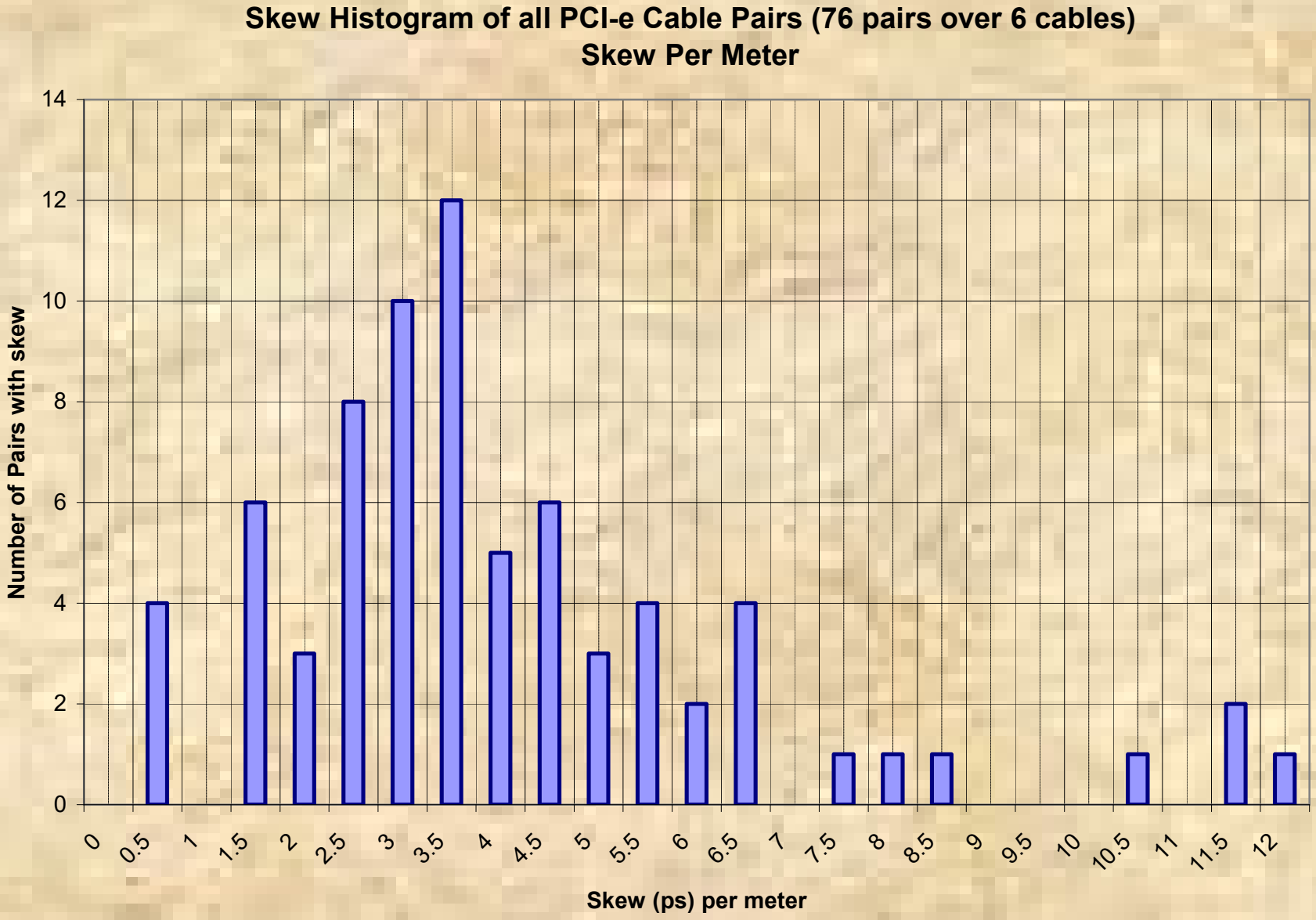
- Measured skew data from cables
  - Infiniband, SAS, PCIe, Cat 7 Ethernet
- Time domain measurements with pulse generator source
- S-parameter frequency domain measurements

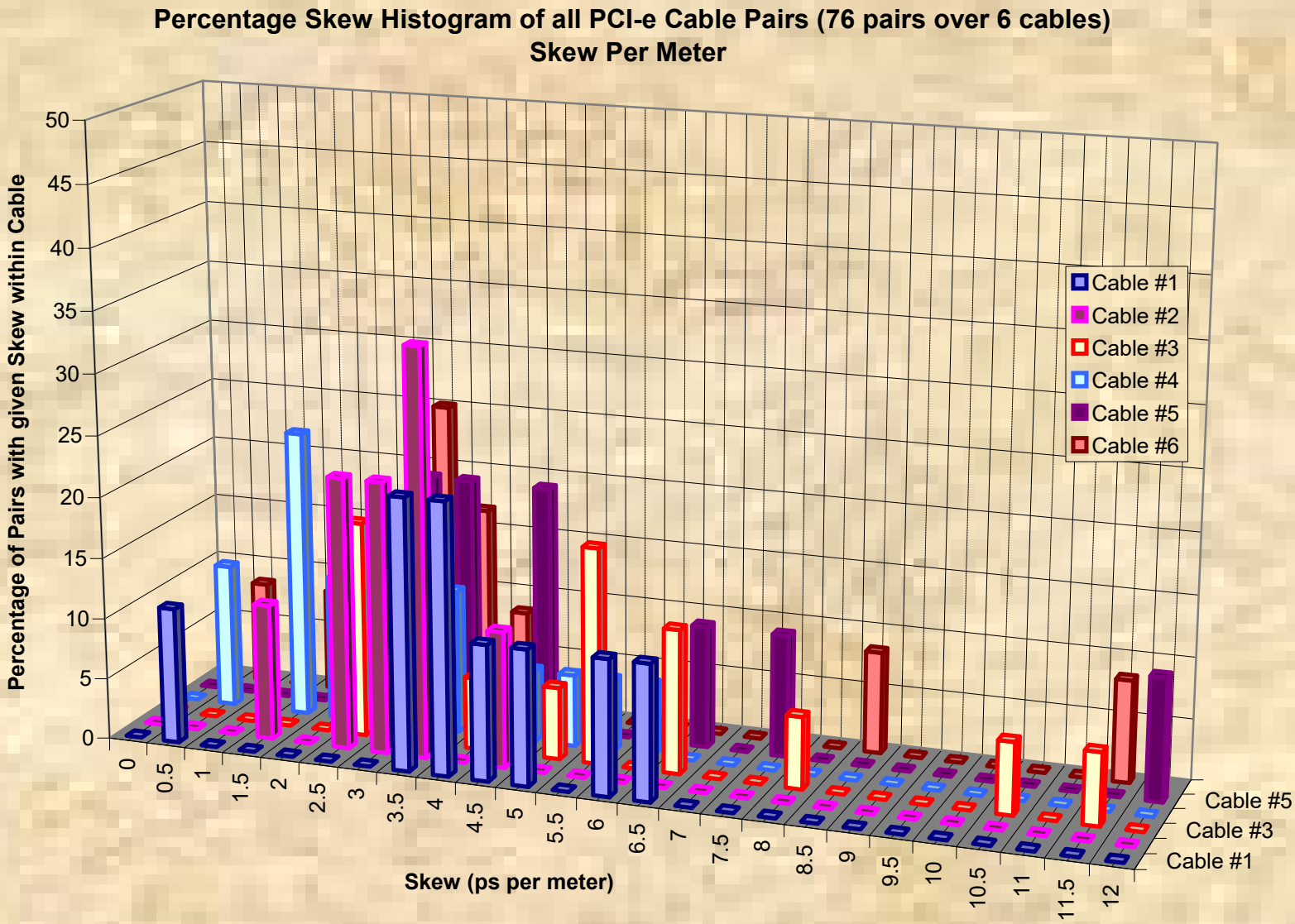
Cable Skew Measurements

- Infiniband, SAS, PCIe, Cat 7 cables
- Multiple pairs within multiple cables
- Look for amount of skew and consistency

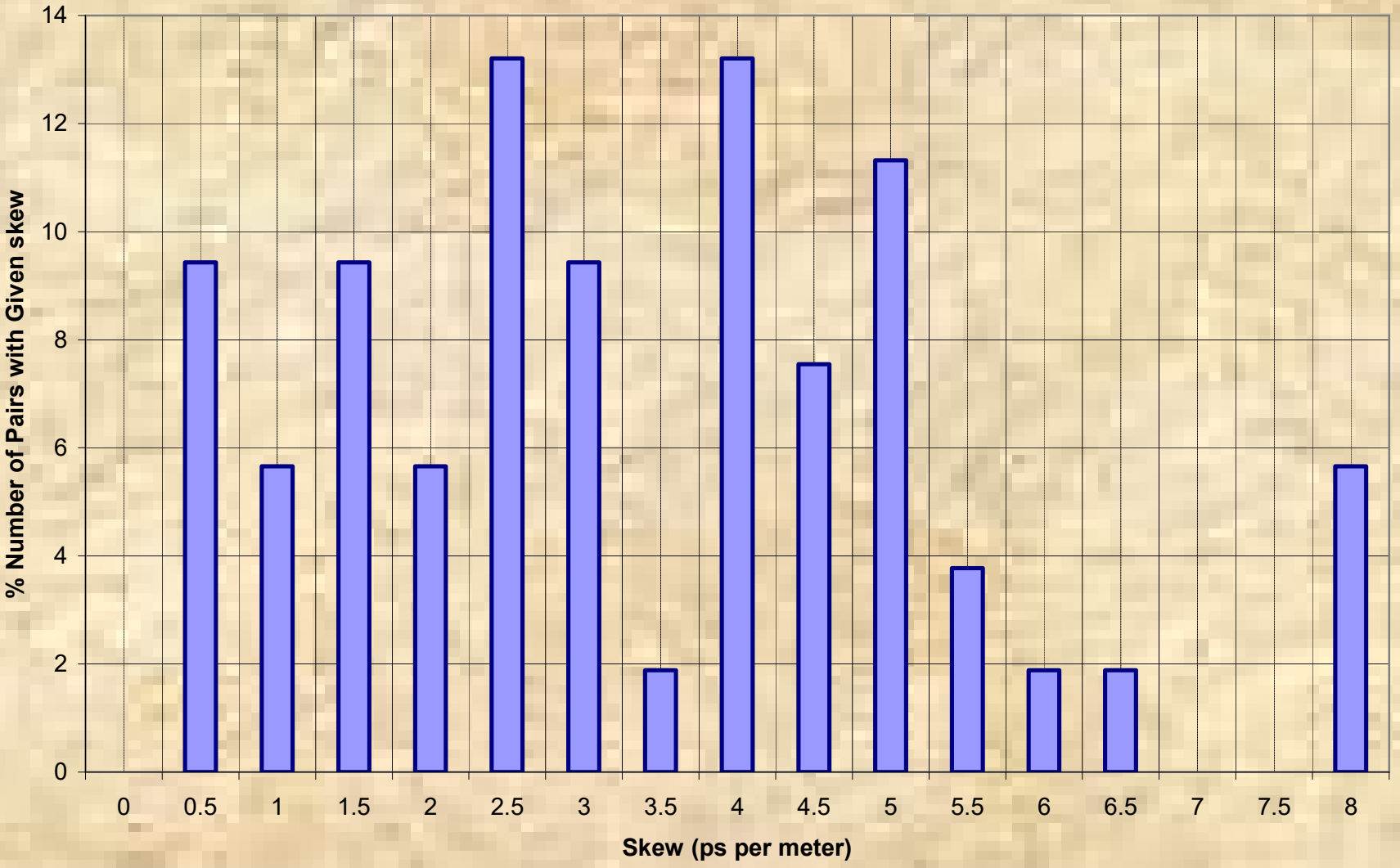

IB Cable Skew Percentage Histogram (2.5 Gb/s -- 400 ps Pulse Width)
(9 cables with 24 pairs each for 10 m Cables)
Percentage of Number of Occurances (%)
0
2
4
6
8
10
12
14
16
18
20
0
10
20
30
40
50
60
70
80
90
100
110
120
130
Amount of Skew (ps)

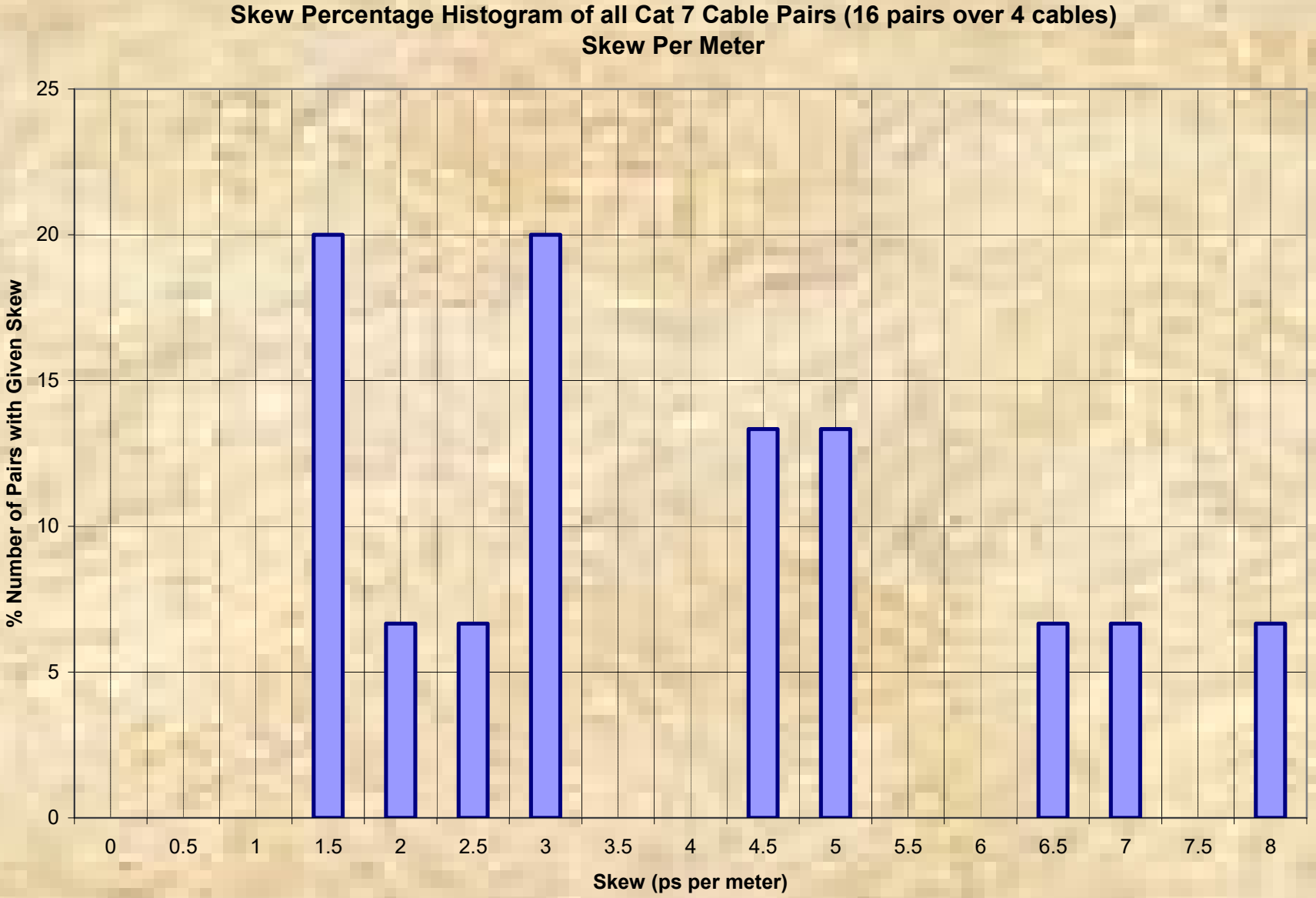

In-pair skew by cable sample
no. pairs
0
2
4
6
8
skew, ps
0
20
40
60
80
100
cable 1
cable 2
cable 3
cable 4
cable 5
cable 6
cable 7
cable 8
cable 1
cable 2
cable 3
cable 4
cable 5
cable 6
cable 7
cable 8


Skew Histogram of all PCI-e Cable Pairs (76 pairs over 6 cables)
Skew Per Meter
Number of Pairs with skew
0
2
4
6
8
10
12
14
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10
10.5
11
11.5
12
Skew (ps) per meter


Percentage Skew Histogram of all PCI-e Cable Pairs (76 pairs over 6 cables)
Skew Per Meter
Percentage of Pairs with given Skew within Cable
50
45
40
35
30
25
20
15
10
5
0
Cable #1
Cable #2
Cable #3
Cable #4
Cable #5
Cable #6
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10
10.5
11
11.5
12
Skew (ps per meter)
Cable #5
Cable #3
Cable #1

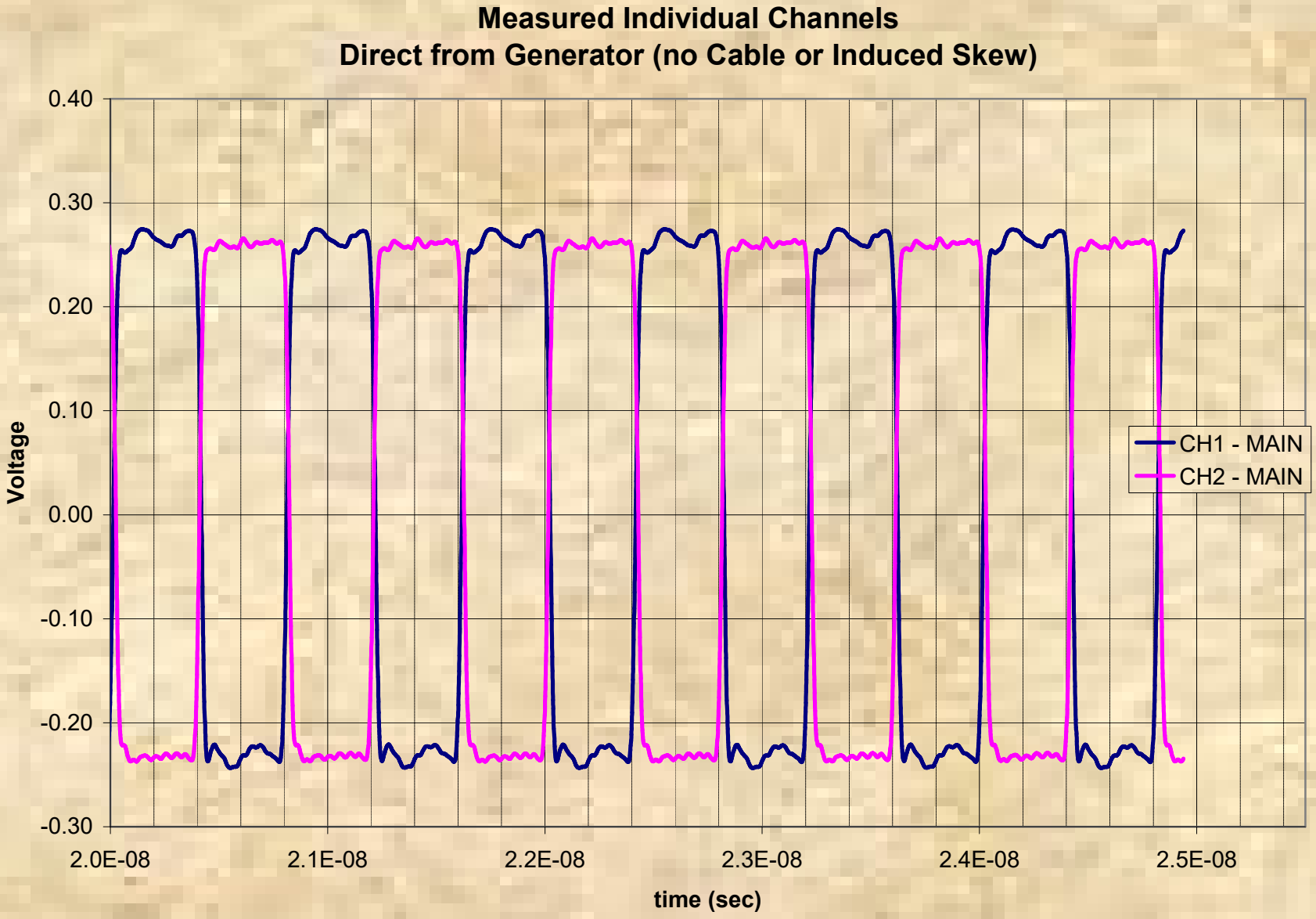
Skew Percentage Histogram of all SAS Cable Pairs (56 pairs over 7 cables)
Skew Per Meter



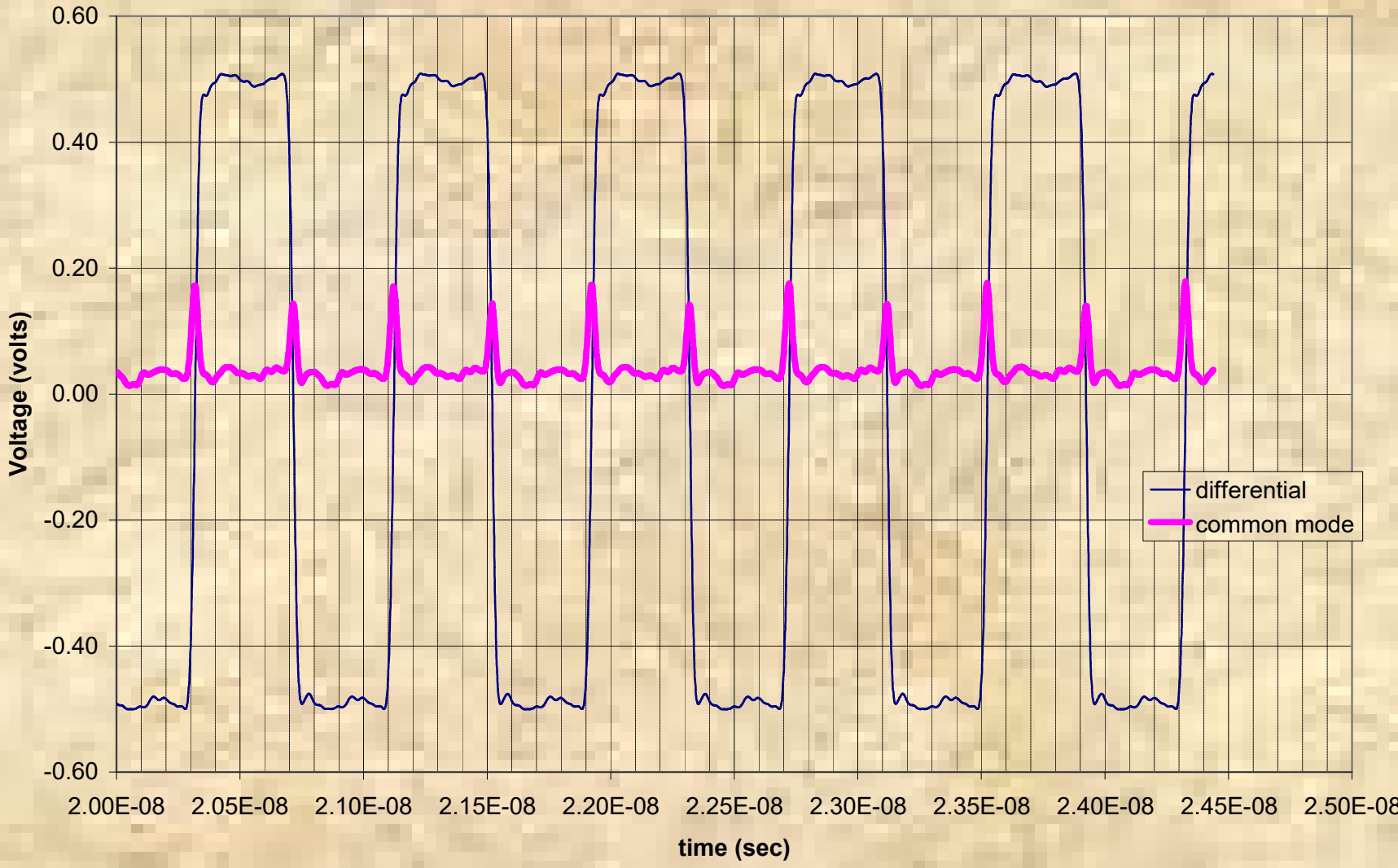

Skew Percentage Histogram of all Cat 7 Cable Pairs (16 pairs over 4 cables)
Skew Per Meter
% Number of Pairs with Given Skew
25
20
15
10
5
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
Skew (ps per meter)

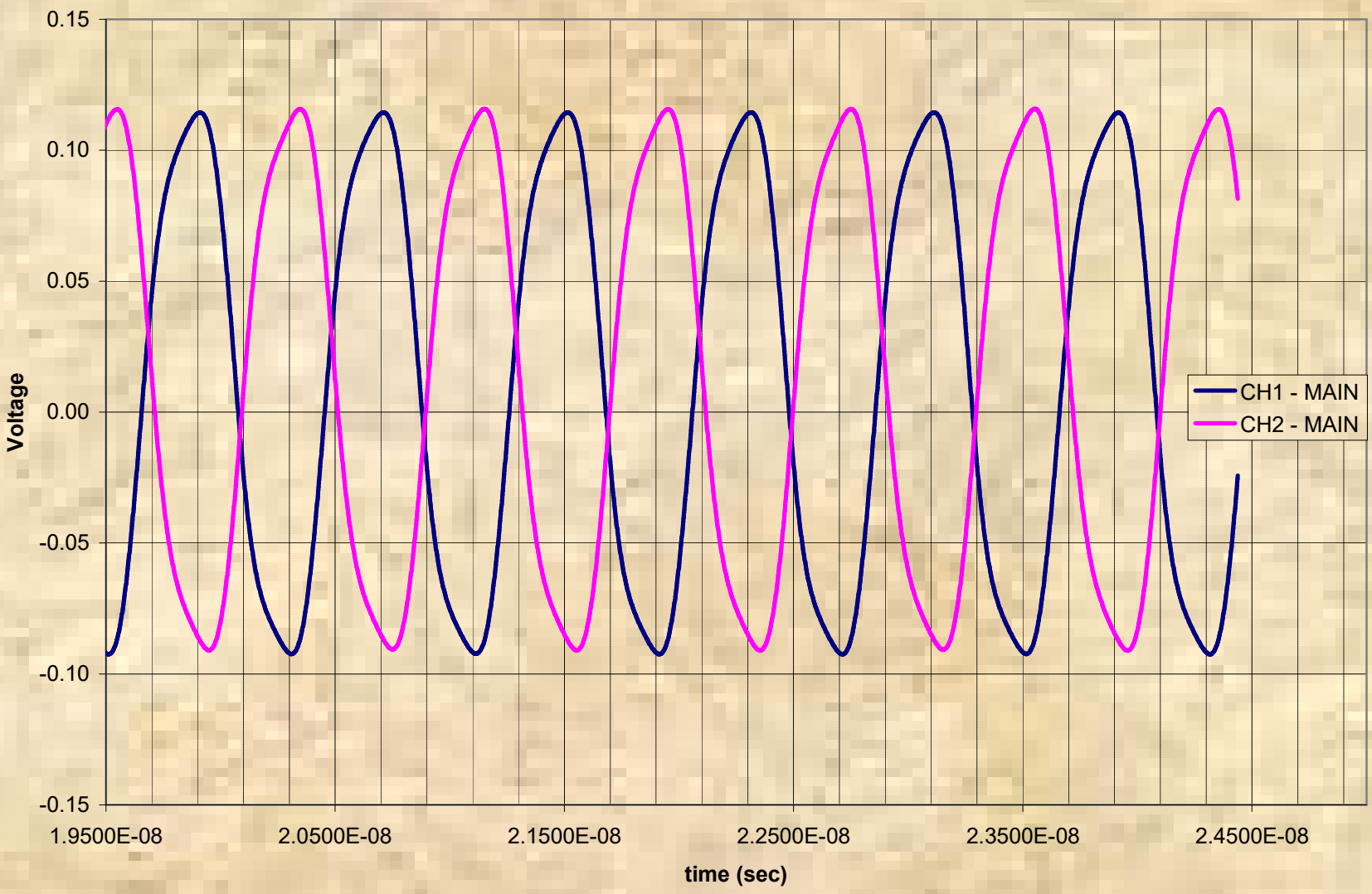
Time Domain Measurements

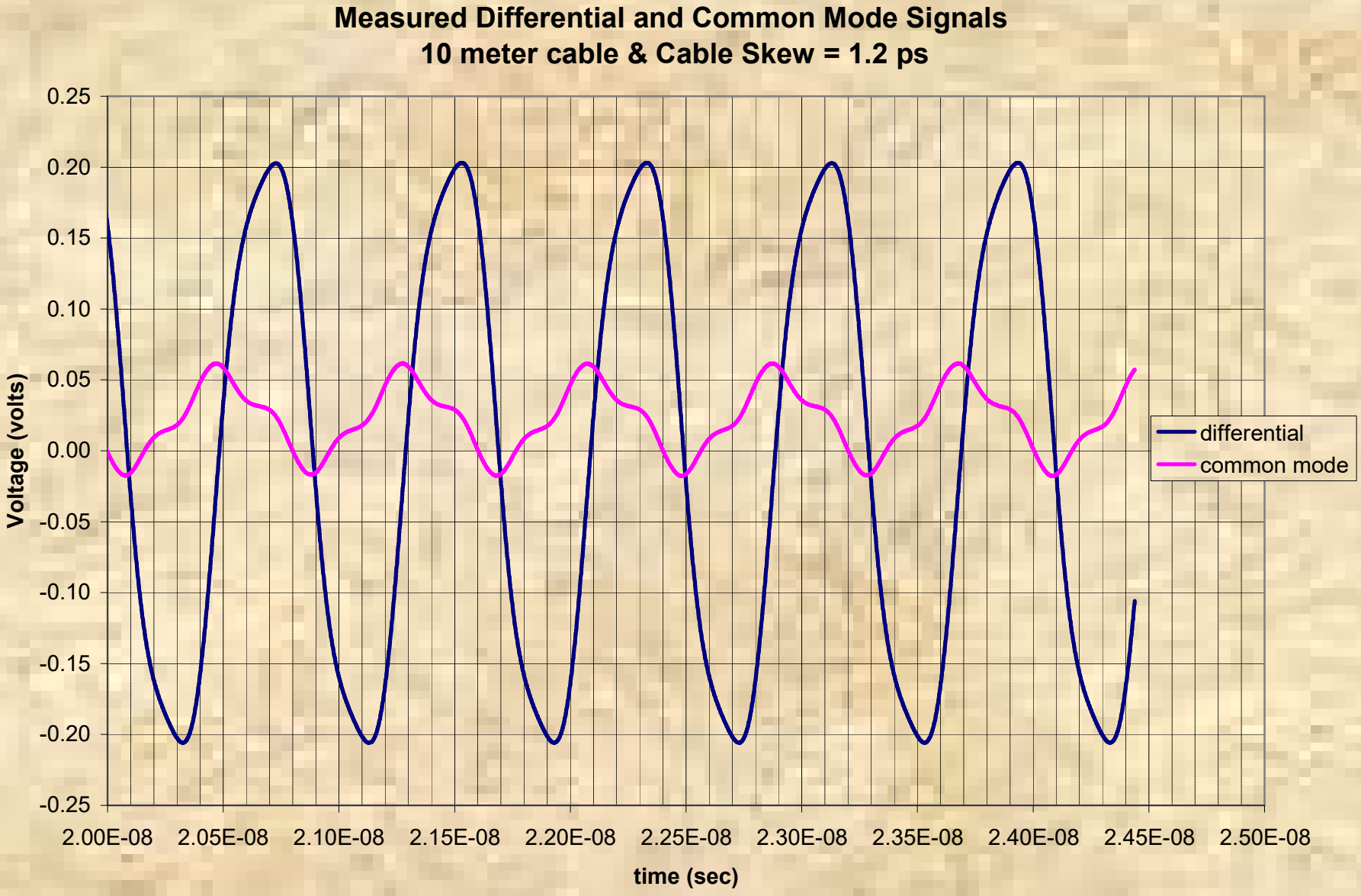
- High speed BERT generator
- Measure differential and common mode signal at far end

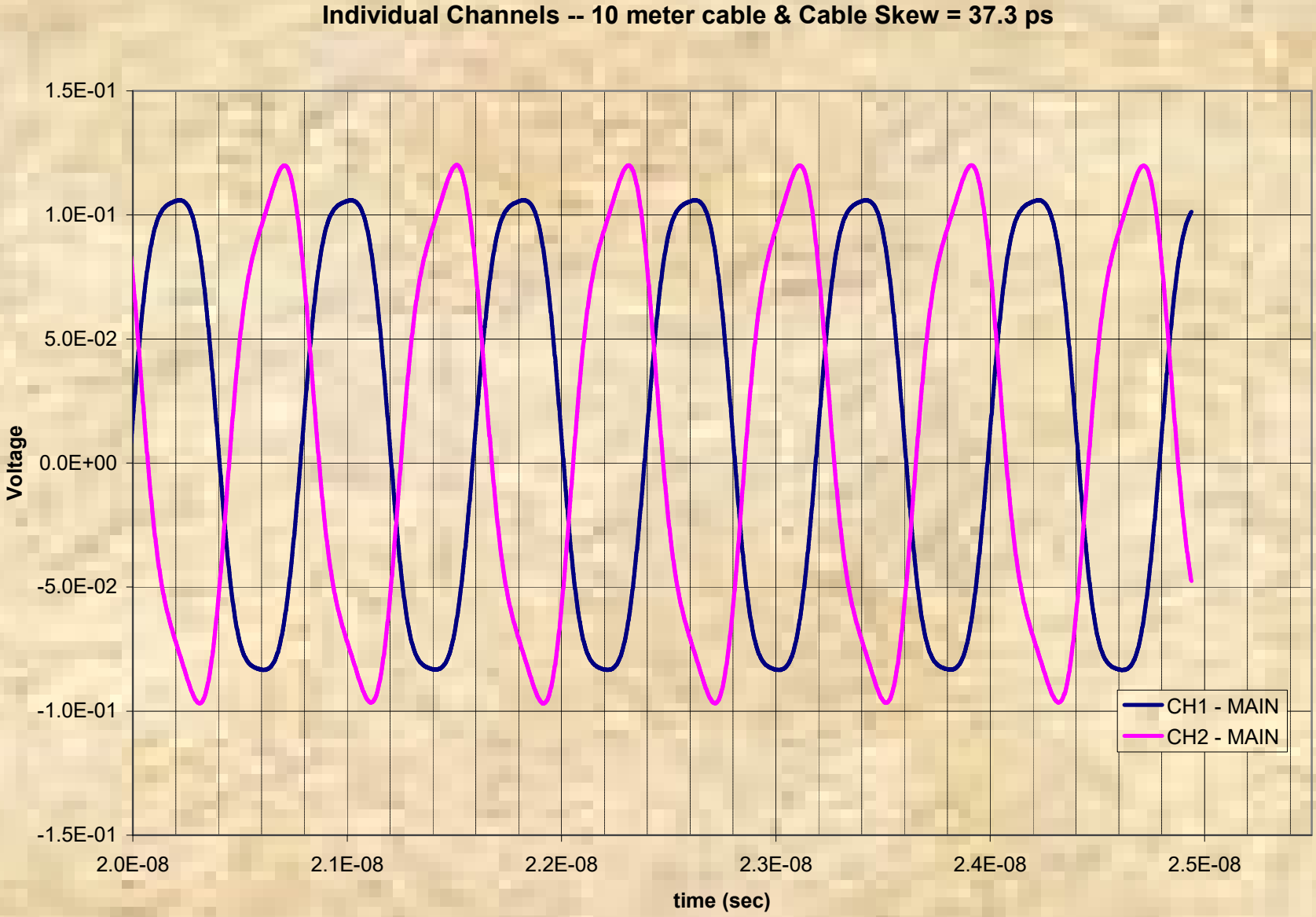

Measured Individual Channels
Direct from Generator (no Cable or Induced Skew)
0.40
0.30
0.20
0.10
0.00
-0.10
-0.20
-0.30
Voltage
2.0E-08
2.1E-08
2.2E-08
2.3E-08
2.4E-08
2.5E-08
time (sec)
CH1 - MAIN
CH2 - MAIN

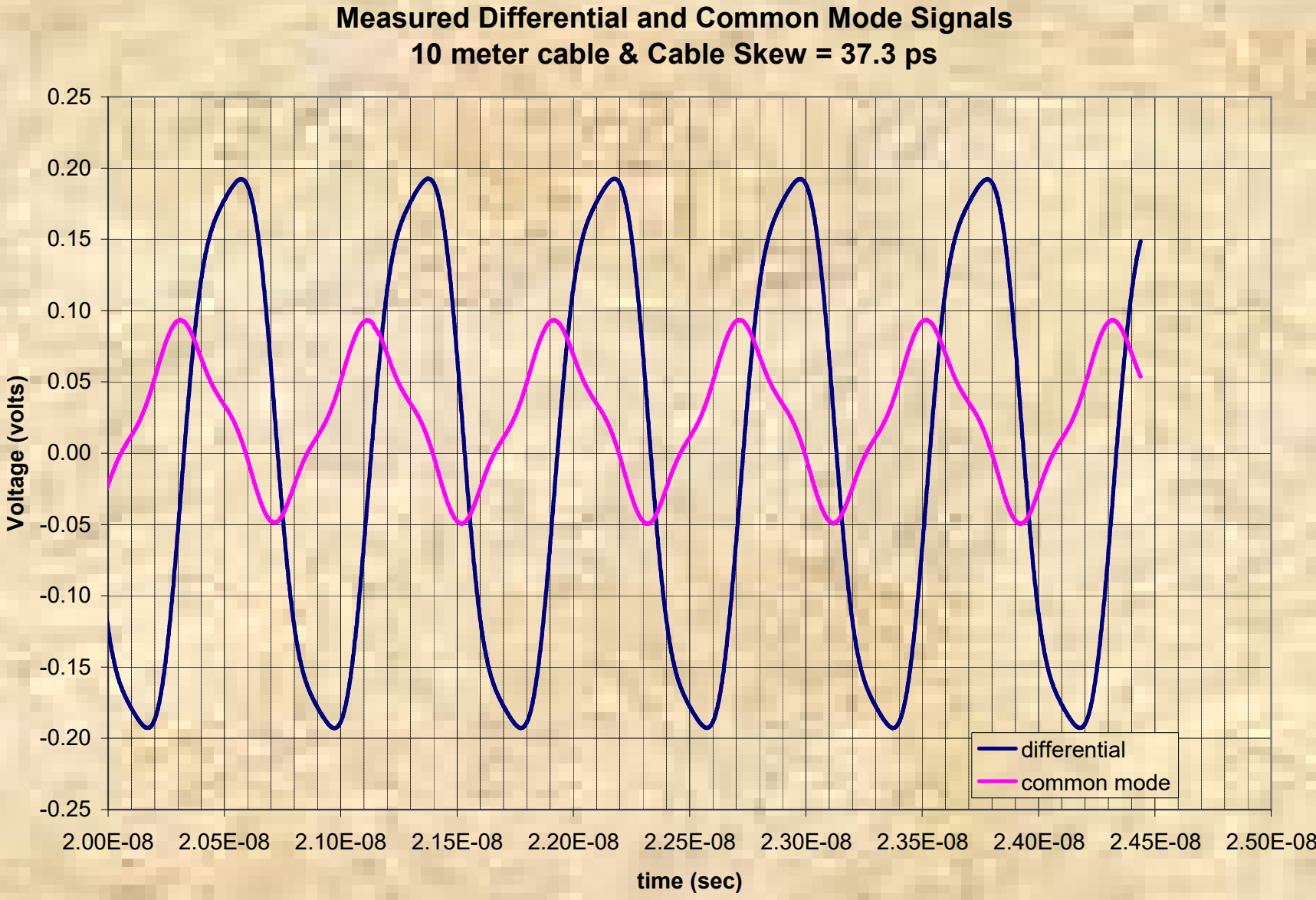
Measured Differential and Common Mode Signals -- Direct from Generator

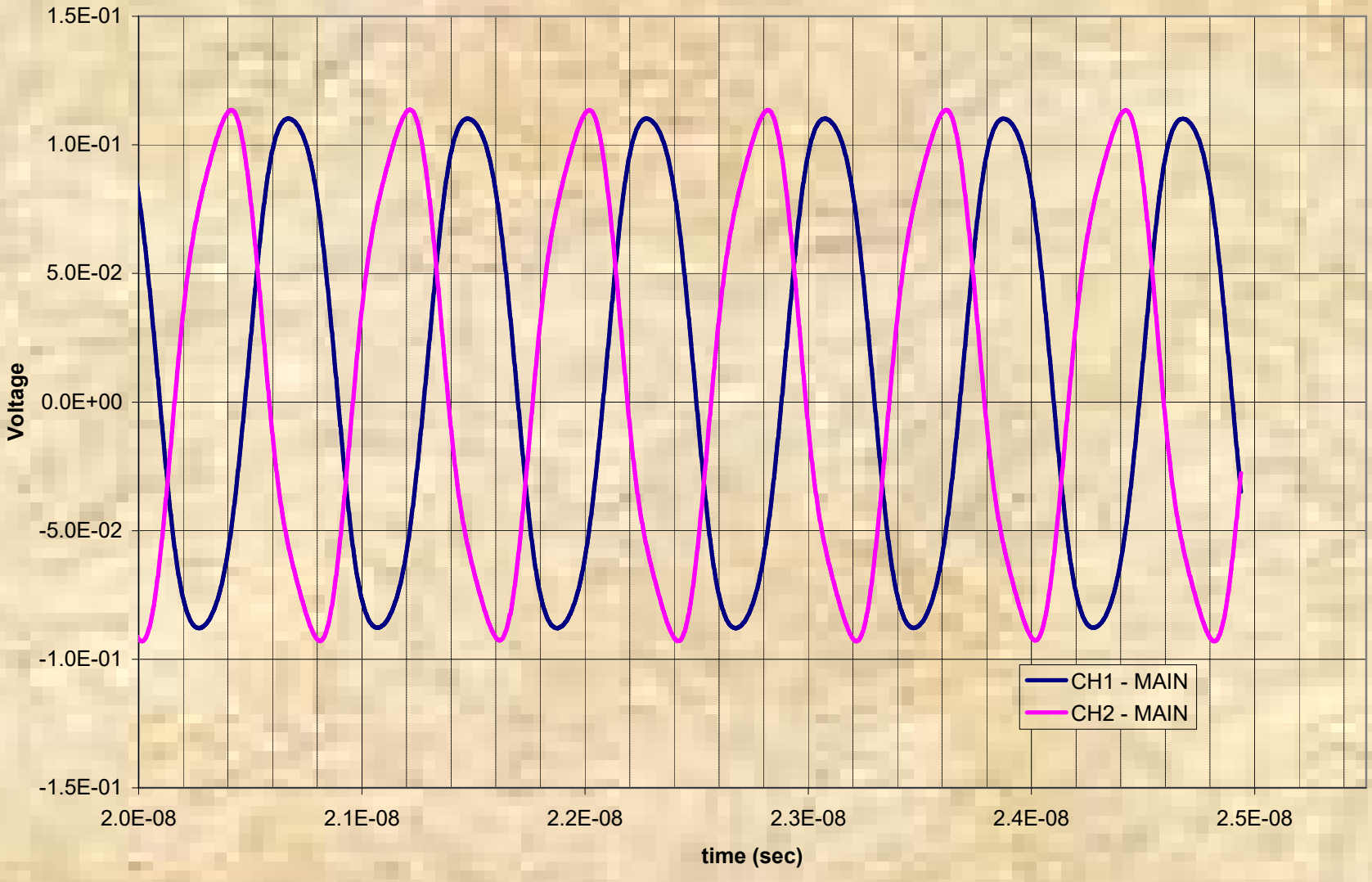


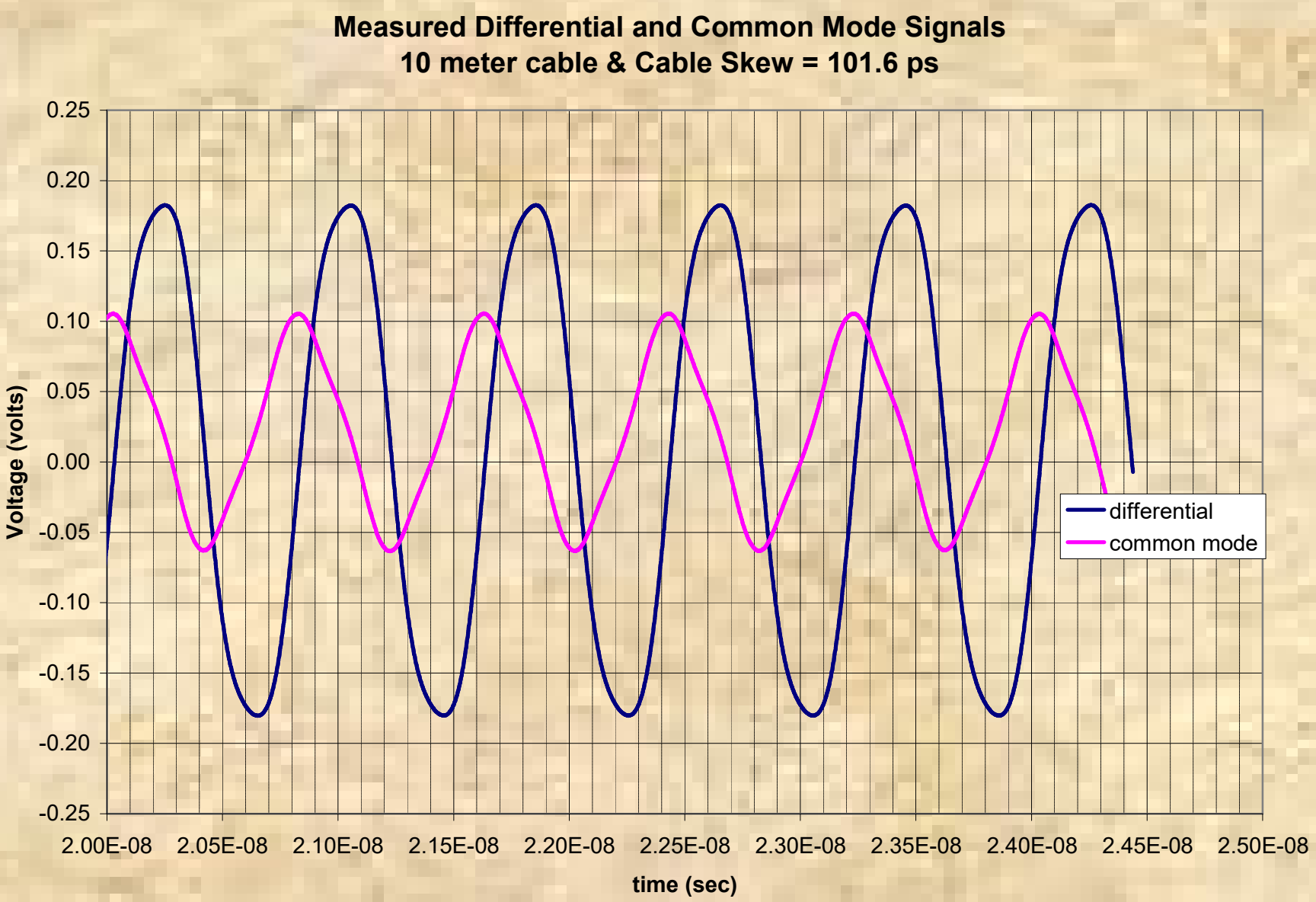

Individual Channels -- 10 meter cable & Cable Skew = 1.2 ps
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
Voltage
1.9500E-08
2.0500E-08
2.1500E-08
2.2500E-08
2.3500E-08
2.4500E-08
time (sec)
CH1 - MAIN
CH2 - MAIN


Measured Differential and Common Mode Signals
10 meter cable & Cable Skew = 1.2 ps
Voltage (volts)
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
-0.25
2.00E-08
2.05E-08
2.10E-08
2.15E-08
2.20E-08
2.25E-08
2.30E-08
2.35E-08
2.40E-08
2.45E-08
2.50E-08
time (sec)
differential
common mode

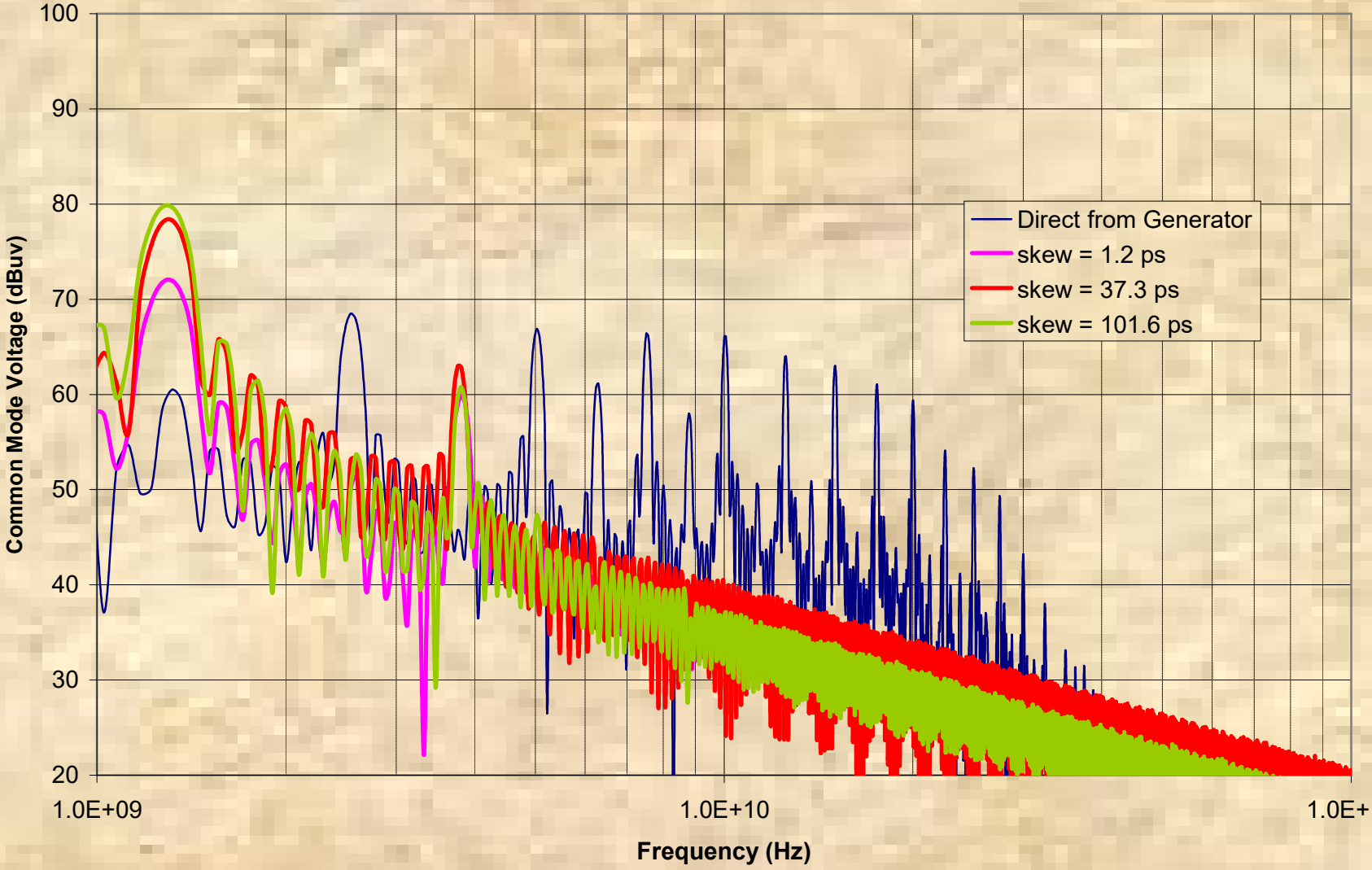

Individual Channels -- 10 meter cable & Cable Skew = 37.3 ps
1.5E-01
1.0E-01
5.0E-02
0.0E+00
-5.0E-02
-1.0E-01
-1.5E-01
Voltage
2.0E-08
2.1E-08
2.2E-08
2.3E-08
2.4E-08
2.5E-08
time (sec)
CH1 - MAIN
CH2 - MAIN


Measured Differential and Common Mode Signals
10 meter cable & Cable Skew = 37.3 ps
Voltage (volts)
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
-0.25
2.00E-08
2.05E-08
2.10E-08
2.15E-08
2.20E-08
2.25E-08
2.30E-08
2.35E-08
2.40E-08
2.45E-08
2.50E-08
time (sec)
differential
common mode


Individual Channels -- 10 meter cable & Cable Skew = 101.6 ps
1.5E-01
1.0E-01
5.0E-02
0.0E+00
-5.0E-02
-1.0E-01
-1.5E-01
Voltage
2.0E-08
2.1E-08
2.2E-08
2.3E-08
2.4E-08
2.5E-08
time (sec)
CH1 - MAIN
CH2 - MAIN

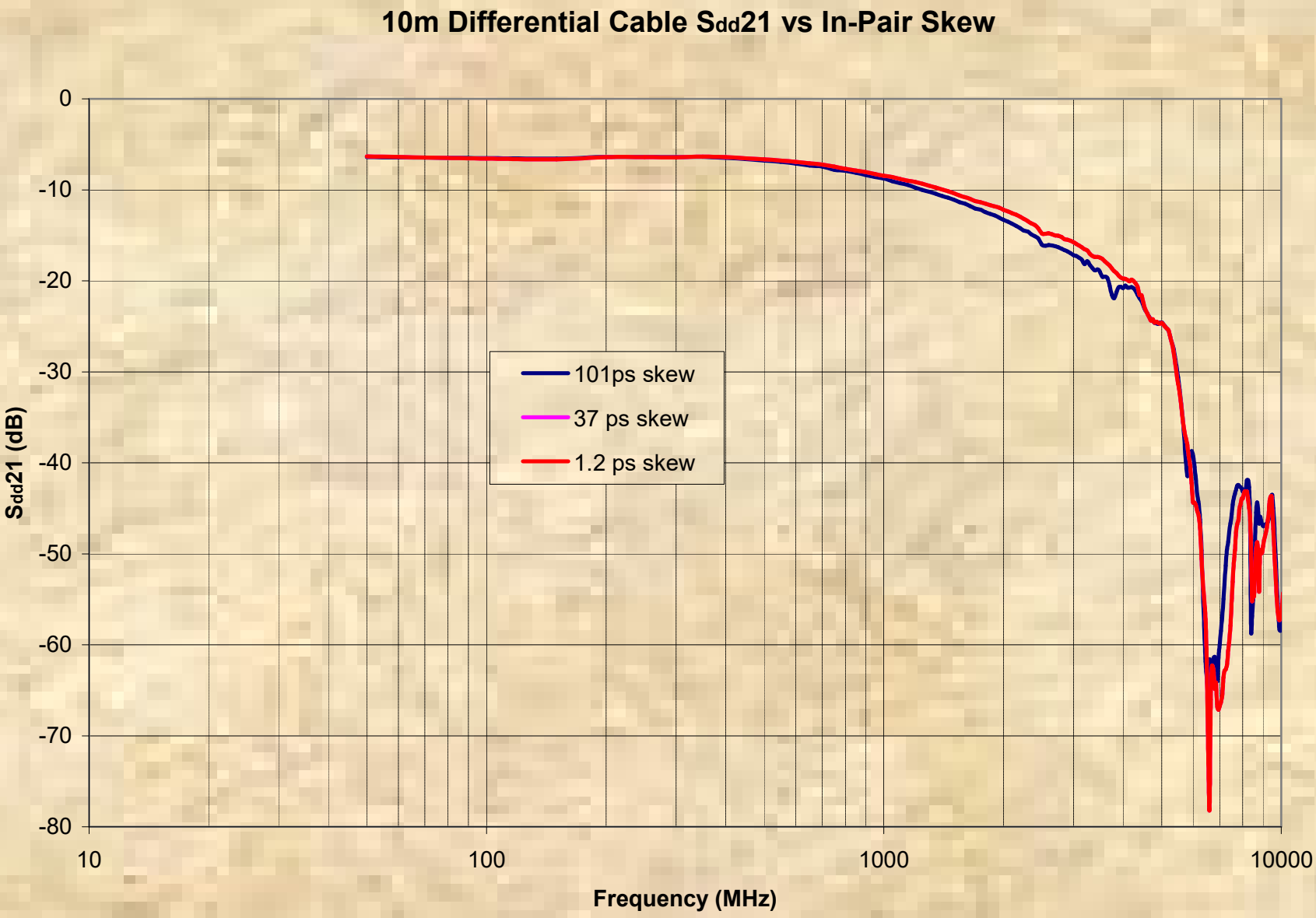

Measured Differential and Common Mode Signals
10 meter cable & Cable Skew = 101.6 ps
Voltage (volts)
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
-0.25
2.00E-08
2.05E-08
2.10E-08
2.15E-08
2.20E-08
2.25E-08
2.30E-08
2.35E-08
2.40E-08
2.45E-08
2.50E-08
time (sec)
differential
common mode

Common Mode Voltage from Measured in-pair Cable Skew
2.5 Gb/s Data Rate

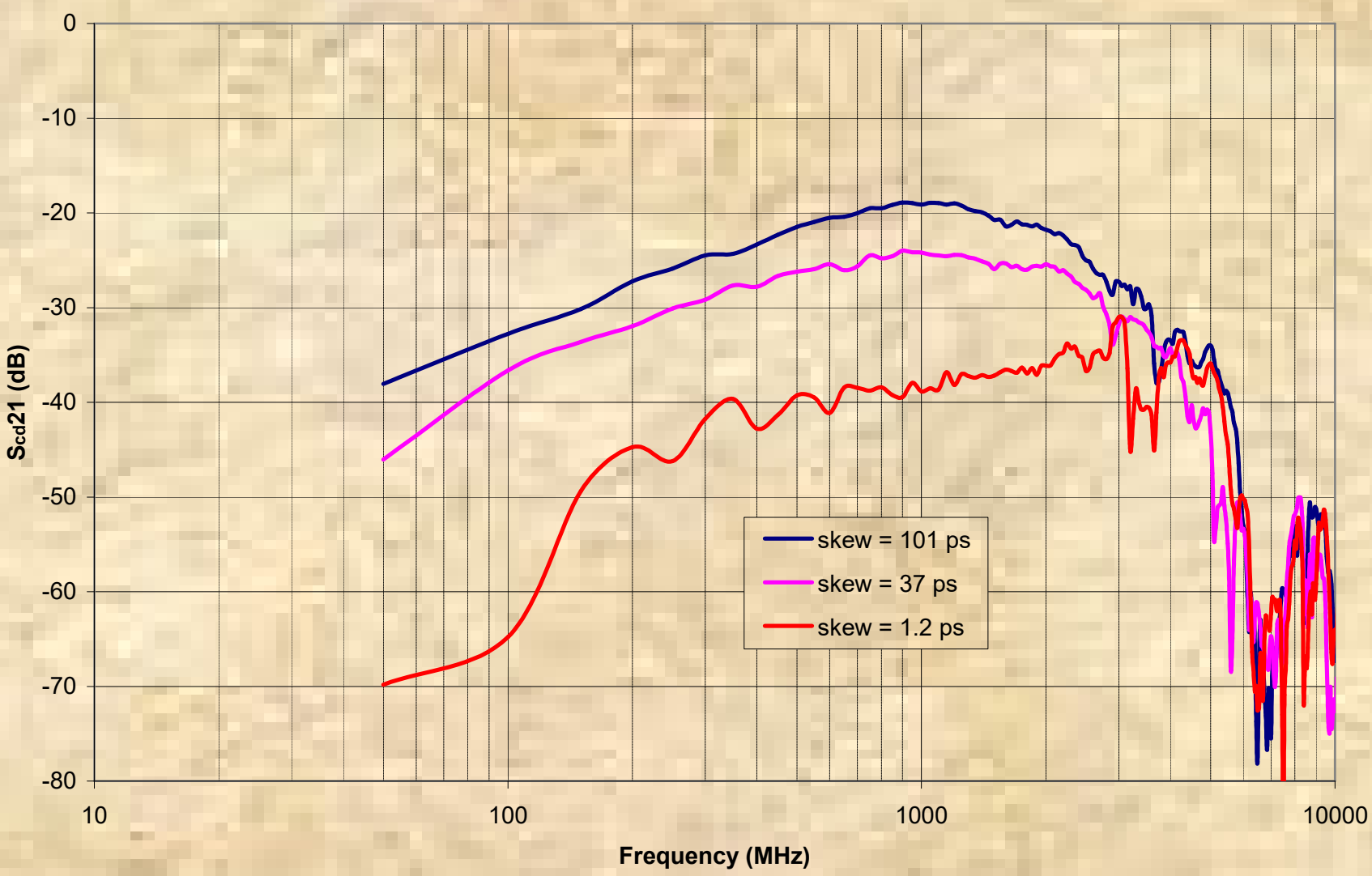


S-parameter Measurements

- $S_{dd}21$ measures loss vs.. frequency for the differential pair
- $S_{cd}21$ measures the amount of differential to common mode conversion (and the loss of the 10 meter cable)
- S-parameter measurement removes the data rate dependence of the previous skew measurements


10m Differential Cable Sdd21 vs In-Pair Skew
0
-10
-20
-30
-40
-50
-60
-70
-80
Sdd21 (dB)
101ps skew
37 ps skew
1.2 ps skew
10
100
1000
10000
Frequency (MHz)

10 m Differential Cable $S_{cd}21$ vs In-Pair Skew



Differential Cable Summary

- ***Expect*** significant cable skew in differential pair cables
  - Specifications for cable skew weak or non-existent
  - Significant variation pair-to-pair within cable and cable-to-cable
- Cable skew creates significant common mode signals
  - EMI emissions increase requirement for more expensive cable shielding
- Higher speed data signals will be more sensitive to cable skew since pulse width is smaller for a given cable skew

Pseudo-Differential Net Summary

- Small amounts of skew can cause significant common mode current
- Small amount of rise/fall time deviation can cause significant amount of common mode current
- Discontinuties (vias, crossing split planes, etc) and convert significant amount of differential current into common mode current
- Cables create CM noise