# EMC problems from Common Mode Noise on High Speed Differential Signals

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# Differential Signals

- Commonly used for high speed communications
- Gb/s common

# Common Mode Effects are Important!

- Differential Signals ***will*** have some amount of common mode
  - Add individual signals rather than subtract
  - Small amount of skew, rise/fall time mismatch or pulse amplitude mismatch can cause significant CM
- Likely to cause negative EMC effects
- Likely to cause noise between GND planes between PCBs
  - Potential to not include these effects with eye pattern predictions
- Likely to cause problems on I/O cables

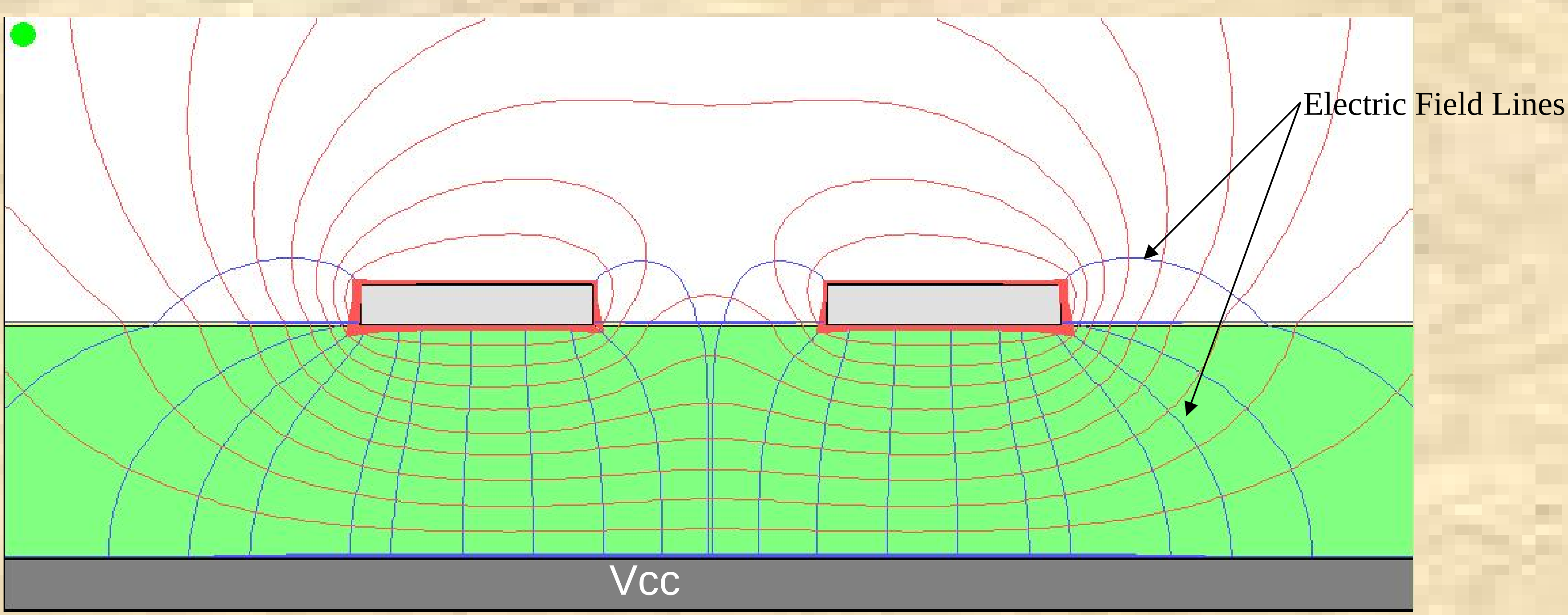
# Pseudo-Differential Nets

- Are the drivers really differential? Or complementary single ended nets?
- True differential requires no nearby reference plane
- Currents *will* exist on reference plane

# Microstrip Electric/Magnetic Field Lines

## Common Mode

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

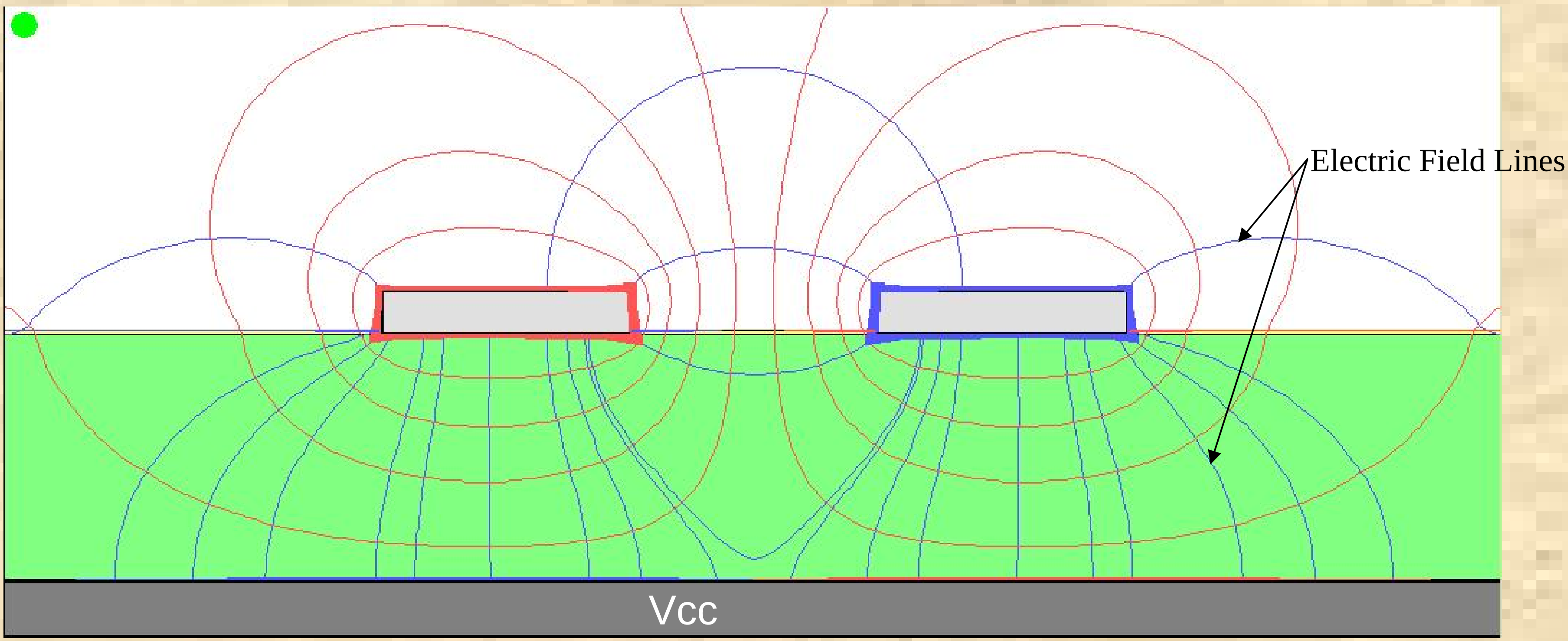



Courtesy of Hyperlynx

# Microstrip Electric/Magnetic Field Lines

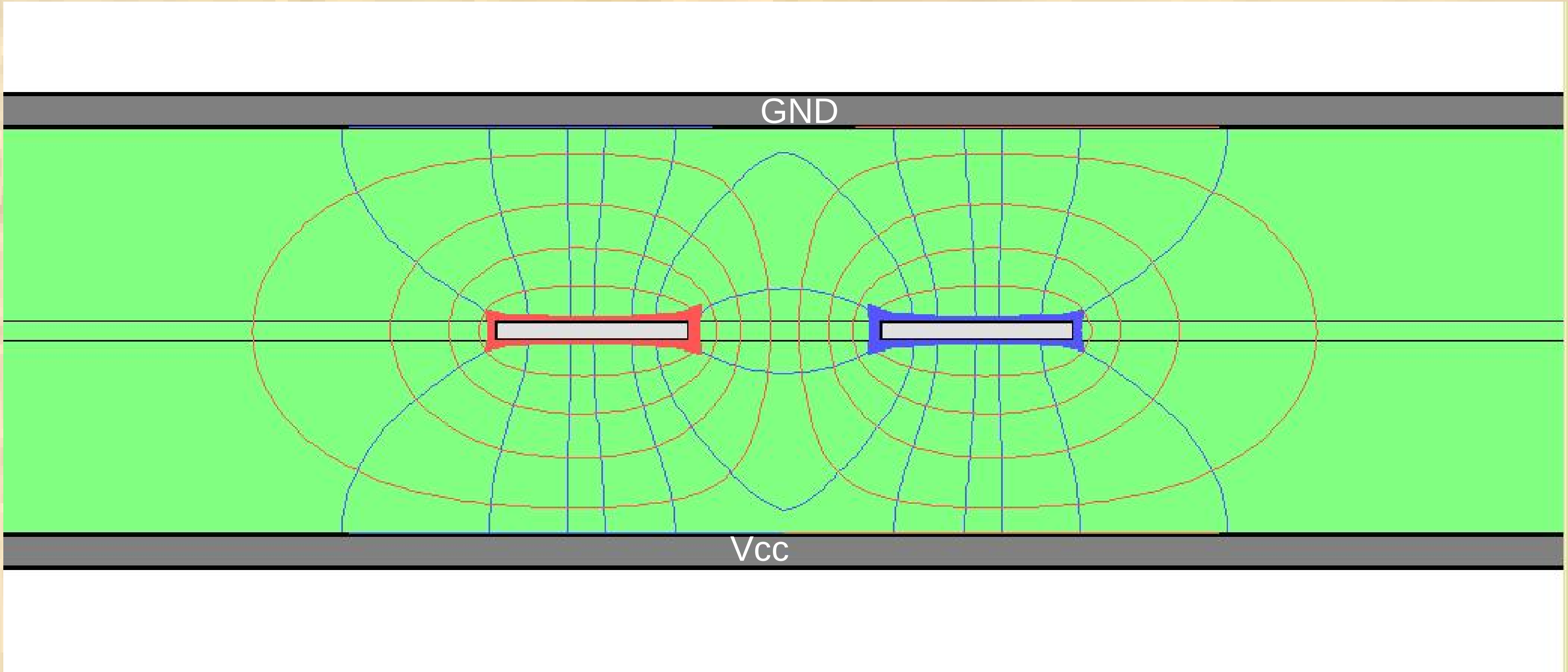
## Differential Mode

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




Courtesy of Hyperlynx

# Electric/Magnetic Field Lines
## Symmetrical Stripline (Differential)

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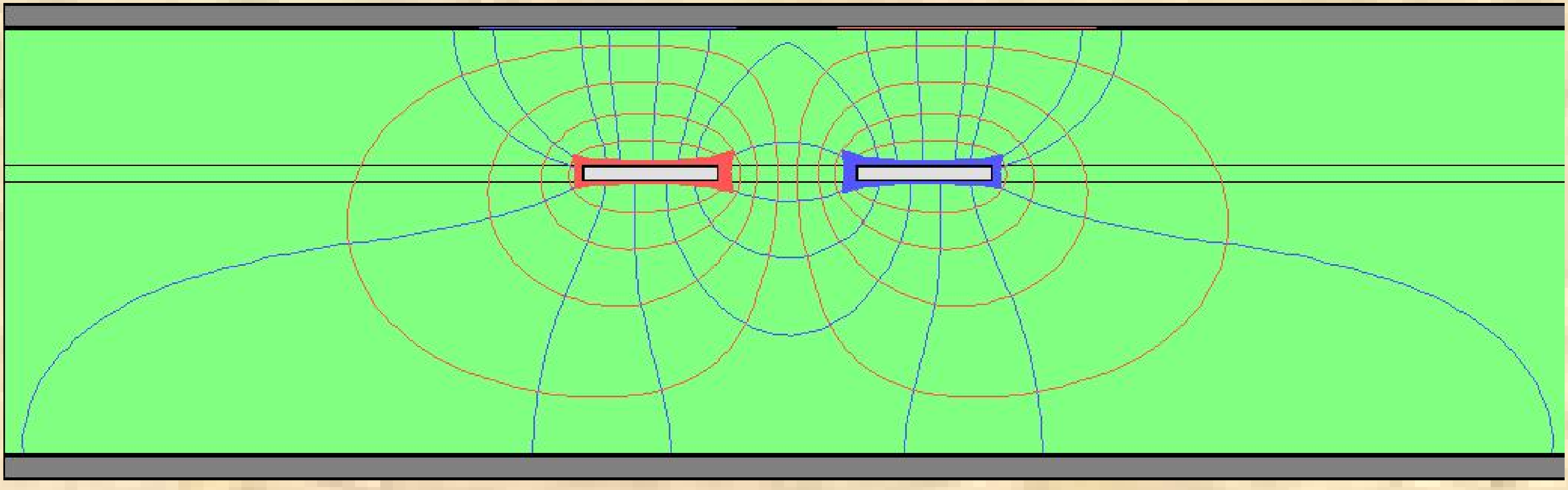
# Electric/Magnetic Field Lines

## Asymmetrical Stripline (Differential)



Courtesy of Hyperlynx

# Pseudo-Differential Nets
## Reference Plane Currents

- Signal integrity is greatly helped by the use of differential nets
  - Added redundancy allows more signal loss
    - Cheaper materials
  - Increased immunity from external disturbance
    - Disturbance is same on both traces, so ignored by differential receiver
- Currents in reference plane are balanced only if:
  - Traces are equal length (within 10-20 mils)
  - Drivers are EXACTLY balanced
  - Perfect wiring/material symmetry
  - Not likely!

# What About Pseudo-Differential Nets?

- So-called differential traces are typically NOT truly differential
  - Two complementary single-ended drivers relative to ‘ground’
  - Skew, rise/fall variation, and amplitude mismatch
  - Asymmetric spacing of pair to ‘ground’ plane
- Receiver is differential
  - Senses difference between two nets (independent of ‘ground’)
  - Provides good immunity to common mode noise
  - Good for signal quality/integrity

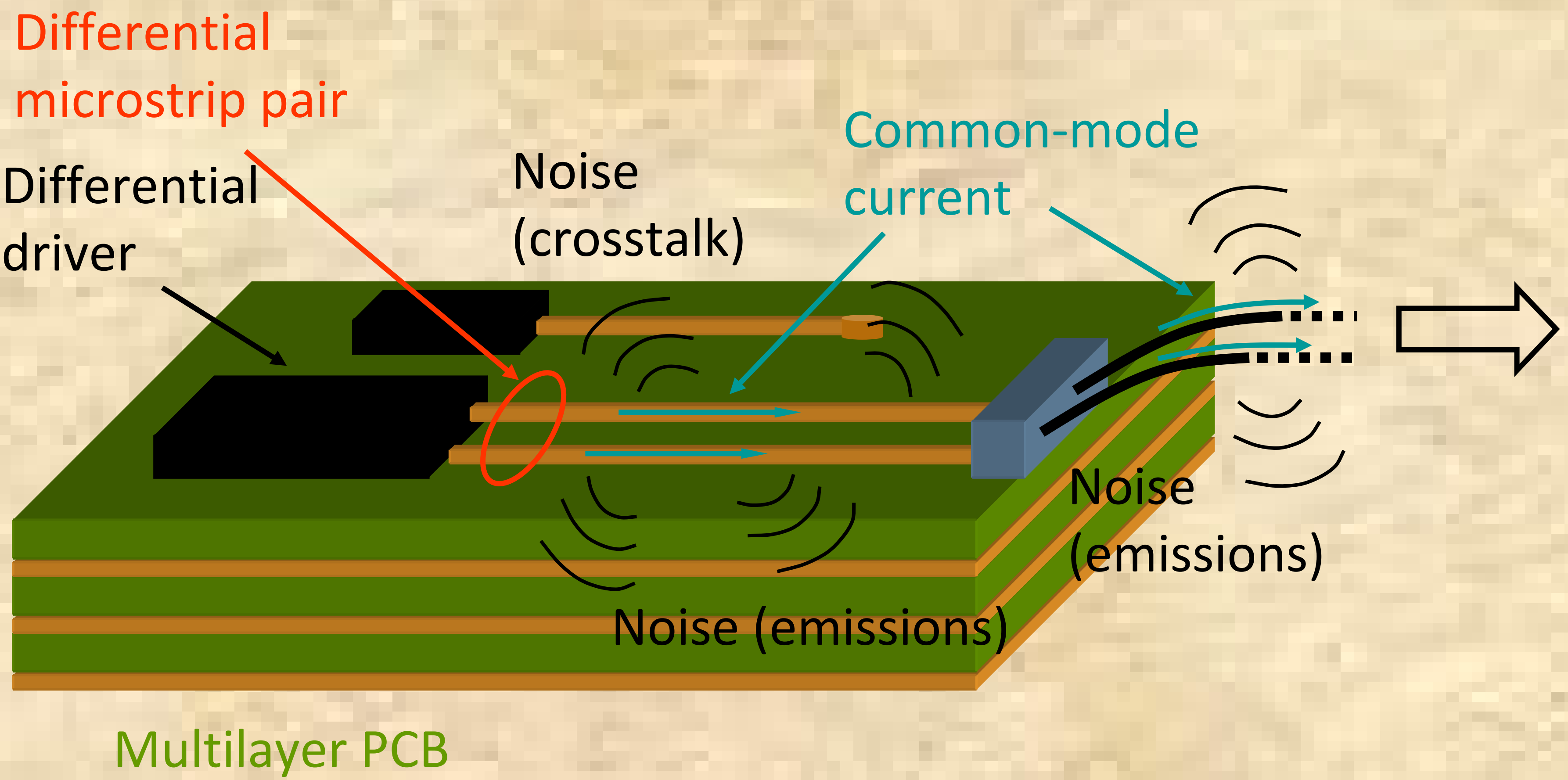
# Pseudo-Differential Nets Current in Nearby Plane

- 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!

# Why Control Common Mode Noise in Differential Pairs?

- Common Mode Noise is inevitable in practical differential pairs
  - Skew
  - Rise/fall time mismatch
  - Amplitude mismatch
  - Asymmetry in channel; e. g., vias, trace/dielectric variations, “glass weave” effect, etc.
- Common mode noise is a big problem in EMC!
- Common mode noise can increase differential crosstalk

# Common-Mode Noise on PCB

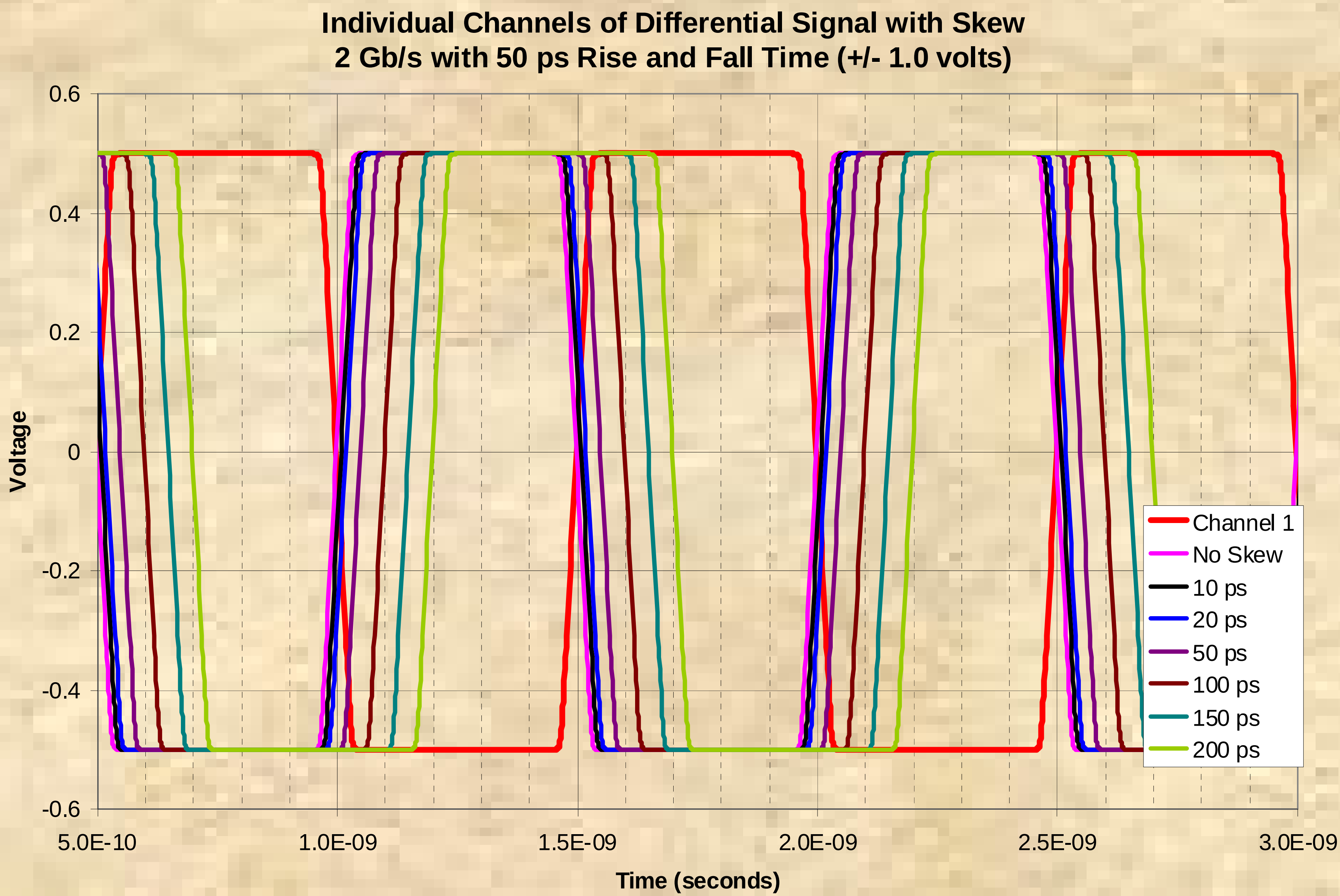


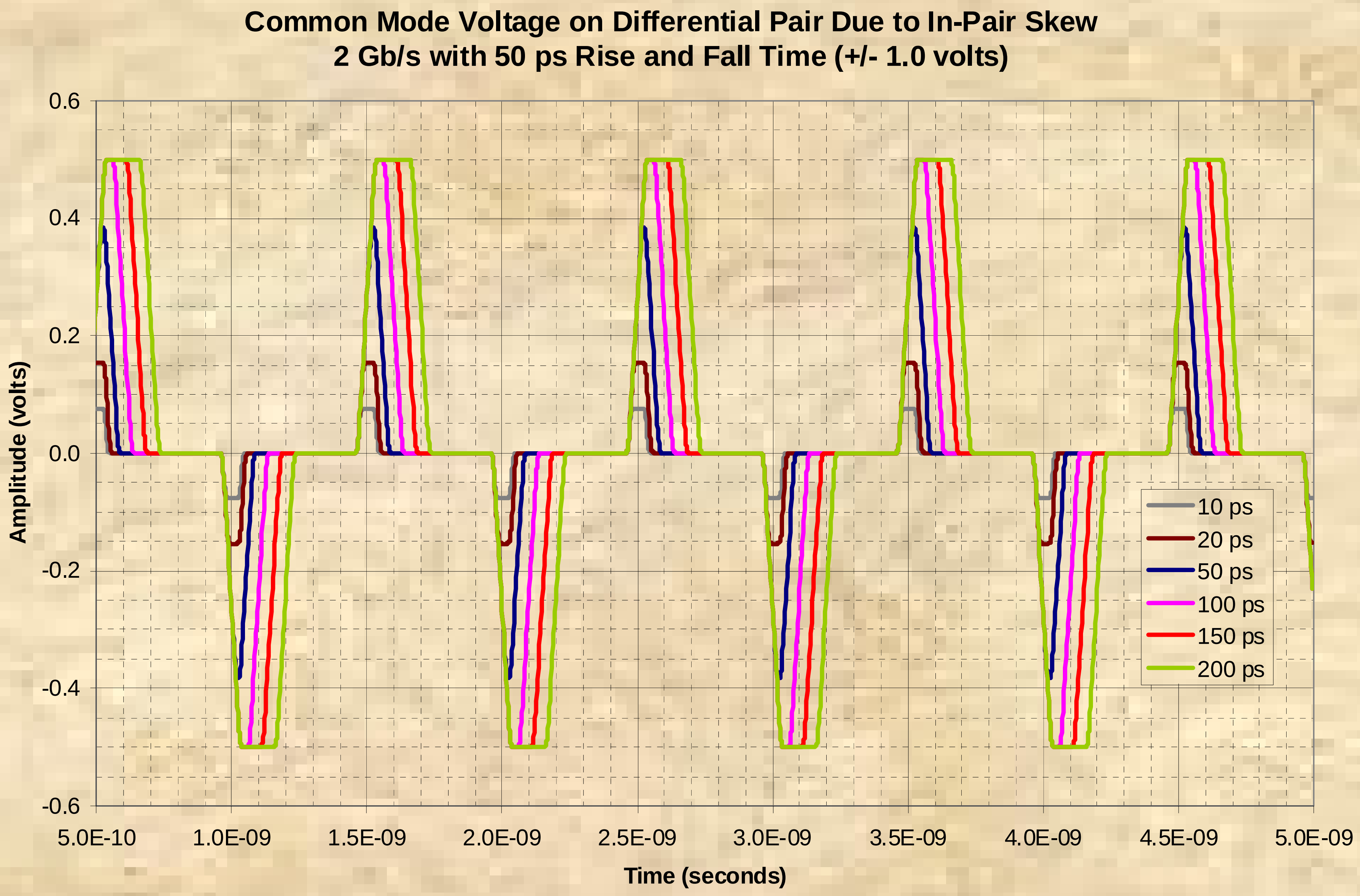
# Common Mode from skew on Differential Mode Signals

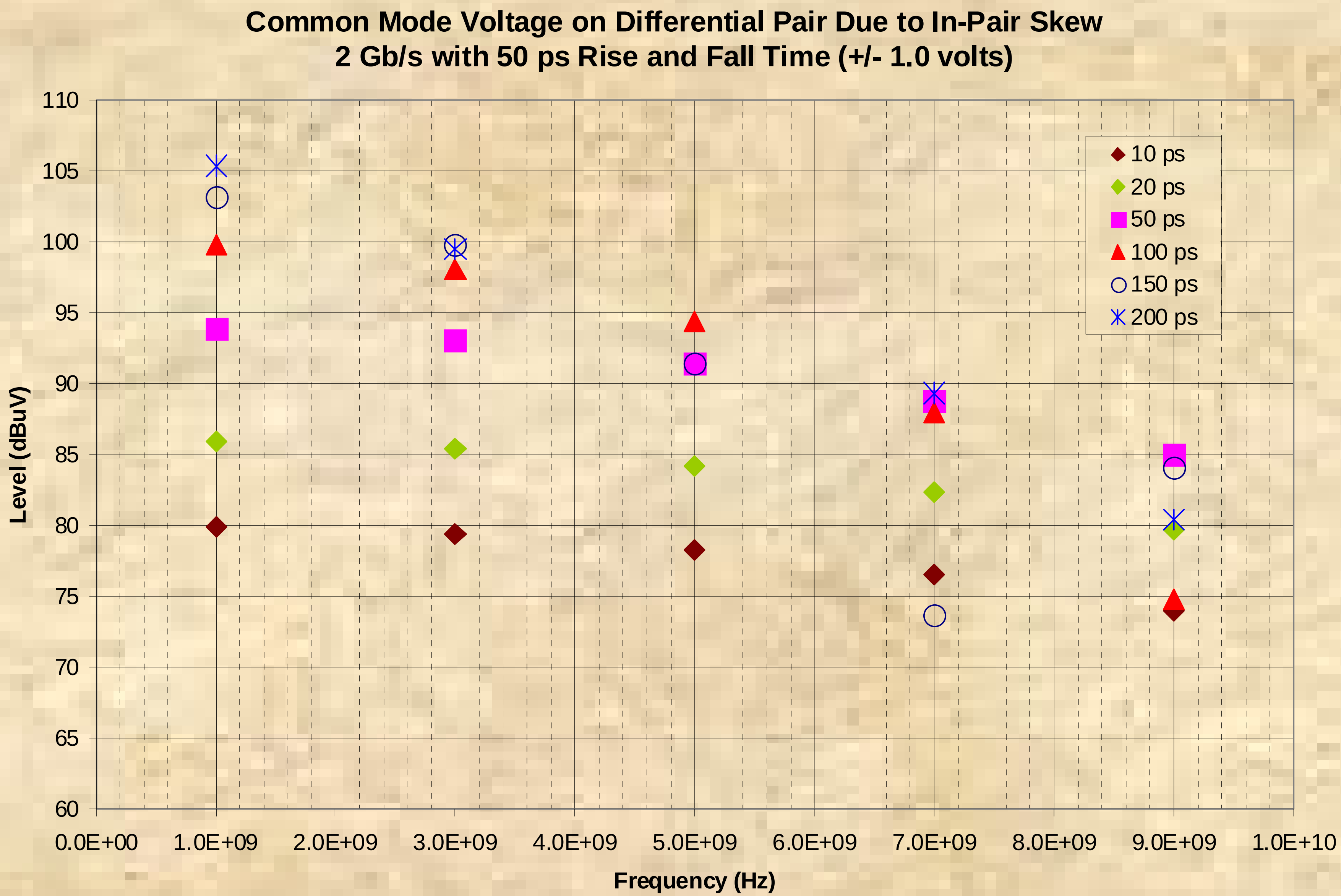
- Small amount of skew (from differential signal point of view) results in significant CM
- As little as 1% of bit width (UI) for skew can have significant EMI effects
- As little as 10% of bit width skew creates CM signal of equivalent amplitude as initial signals
- Simulation of CM from simple spreadsheet analysis

# What Causes In-Pair Skew?

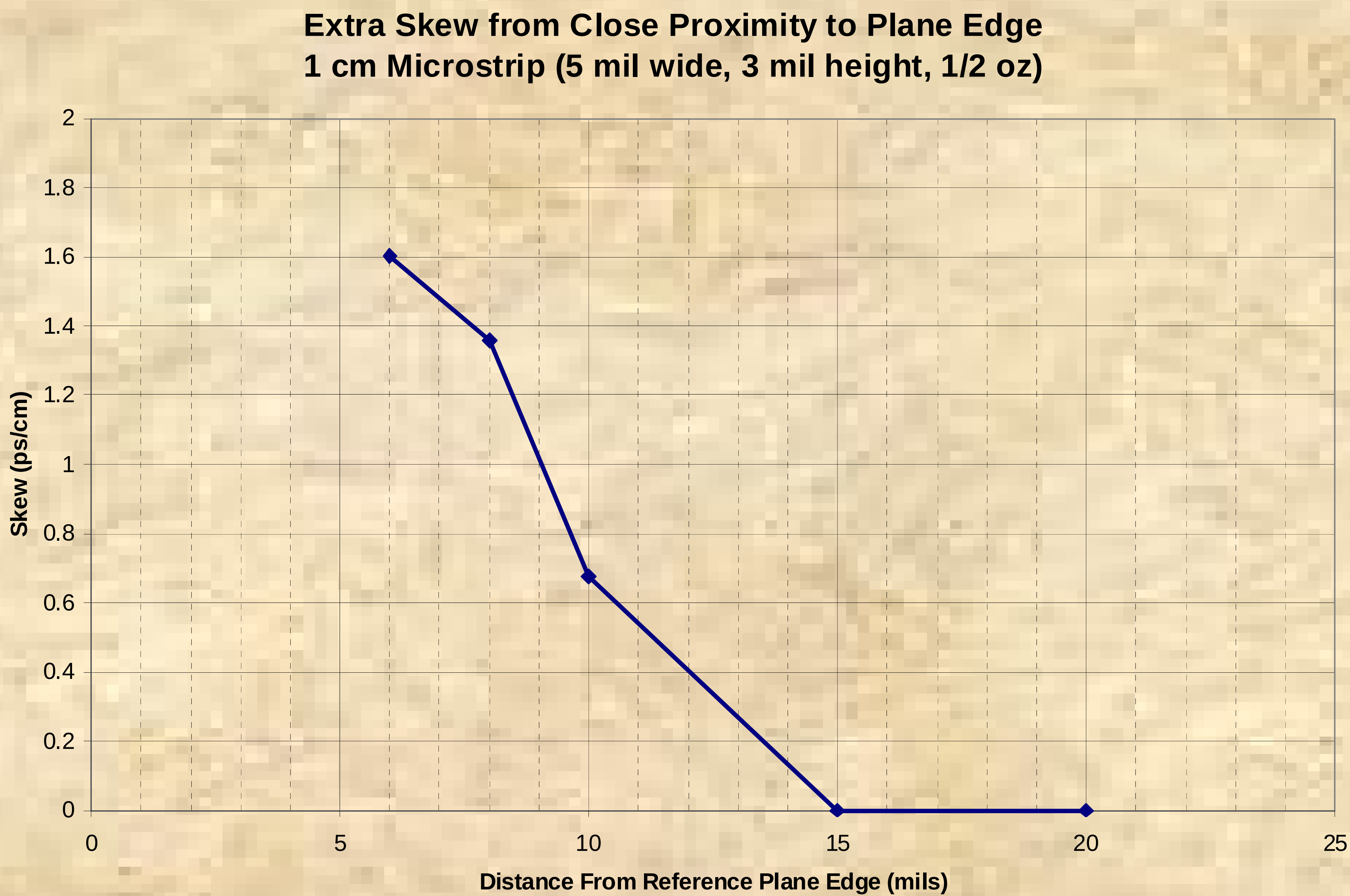
- Trace Length mis-match
- One trace close to edge of ground-reference plane
- Fiber weave effects
  - Different dielectric constant if trace over fiber or ‘goop’
- Asymmetrical ground-reference vias near differential vias

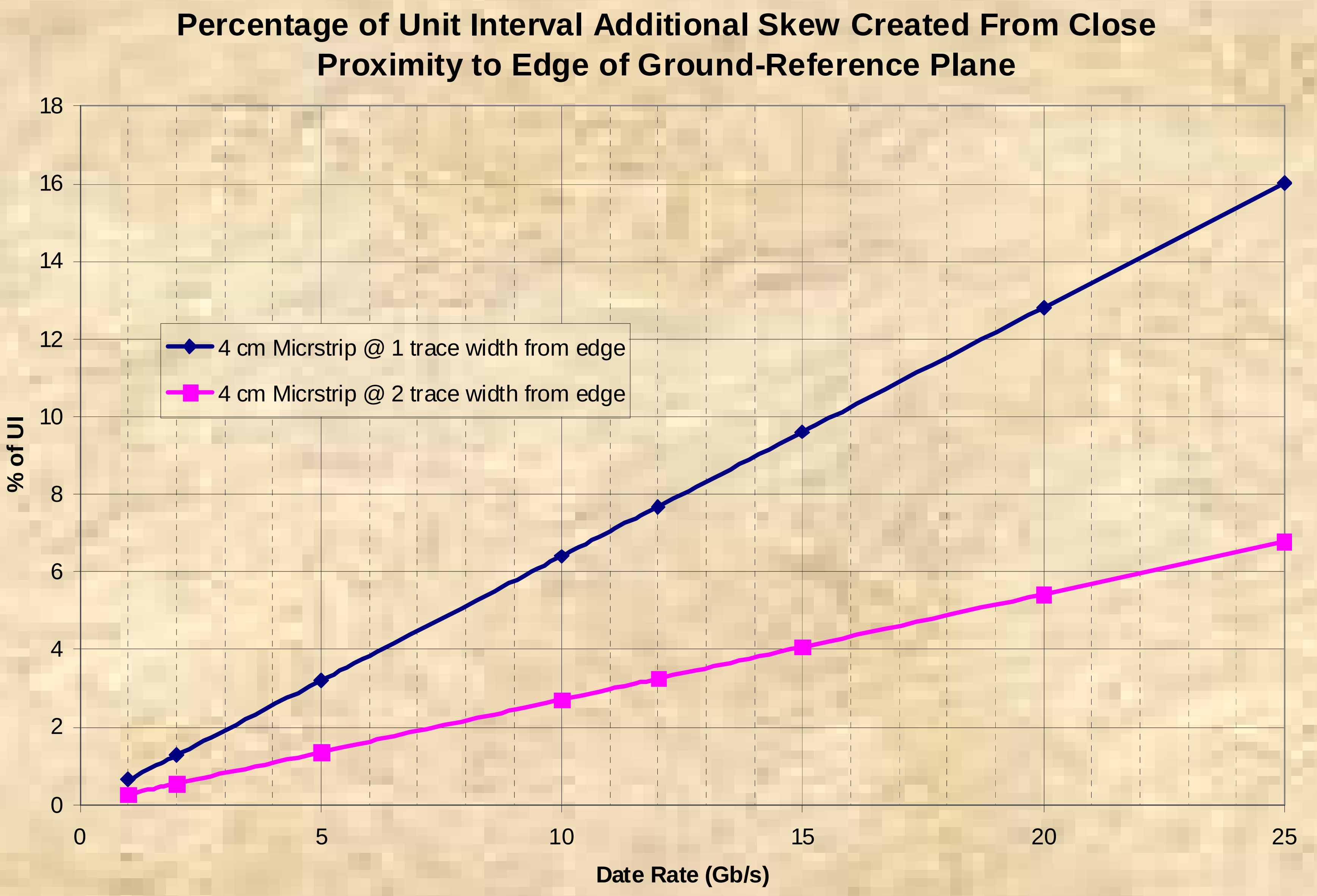

Individual Channels of Differential Signal with Skew
2 Gb/s with 50 ps Rise and Fall Time (+/- 1.0 volts)
Voltage
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
5.0E-10
1.0E-09
1.5E-09
2.0E-09
2.5E-09
3.0E-09
Time (seconds)
Channel 1
No Skew
10 ps
20 ps
50 ps
100 ps
150 ps
200 ps


Common Mode Voltage on Differential Pair Due to In-Pair Skew
2 Gb/s with 50 ps Rise and Fall Time (+/- 1.0 volts)
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
Amplitude (volts)
5.0E-10
1.0E-09
1.5E-09
2.0E-09
2.5E-09
3.0E-09
3.5E-09
4.0E-09
4.5E-09
5.0E-09
Time (seconds)
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)
Level (dBuV)
110
105
100
95
90
85
80
75
70
65
60
0.0E+00
1.0E+09
2.0E+09
3.0E+09
4.0E+09
5.0E+09
6.0E+09
7.0E+09
8.0E+09
9.0E+09
1.0E+10
Frequency (Hz)
10 ps
20 ps
50 ps
100 ps
150 ps
200 ps

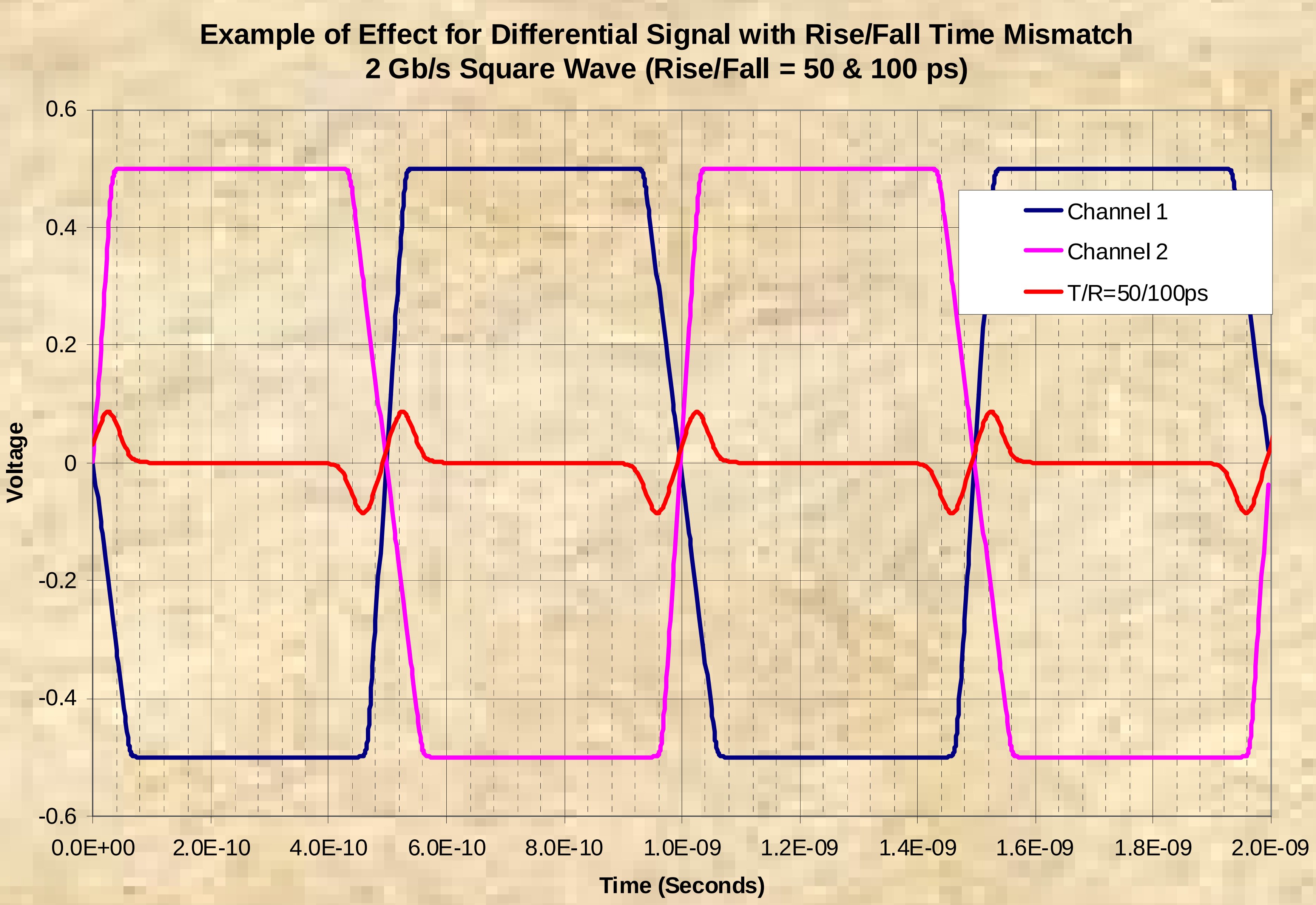

Extra Skew from Close Proximity to Plane Edge
1 cm Microstrip (5 mil wide, 3 mil height, 1/2 oz)
Skew (ps/cm)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
Distance From Reference Plane Edge (mils)



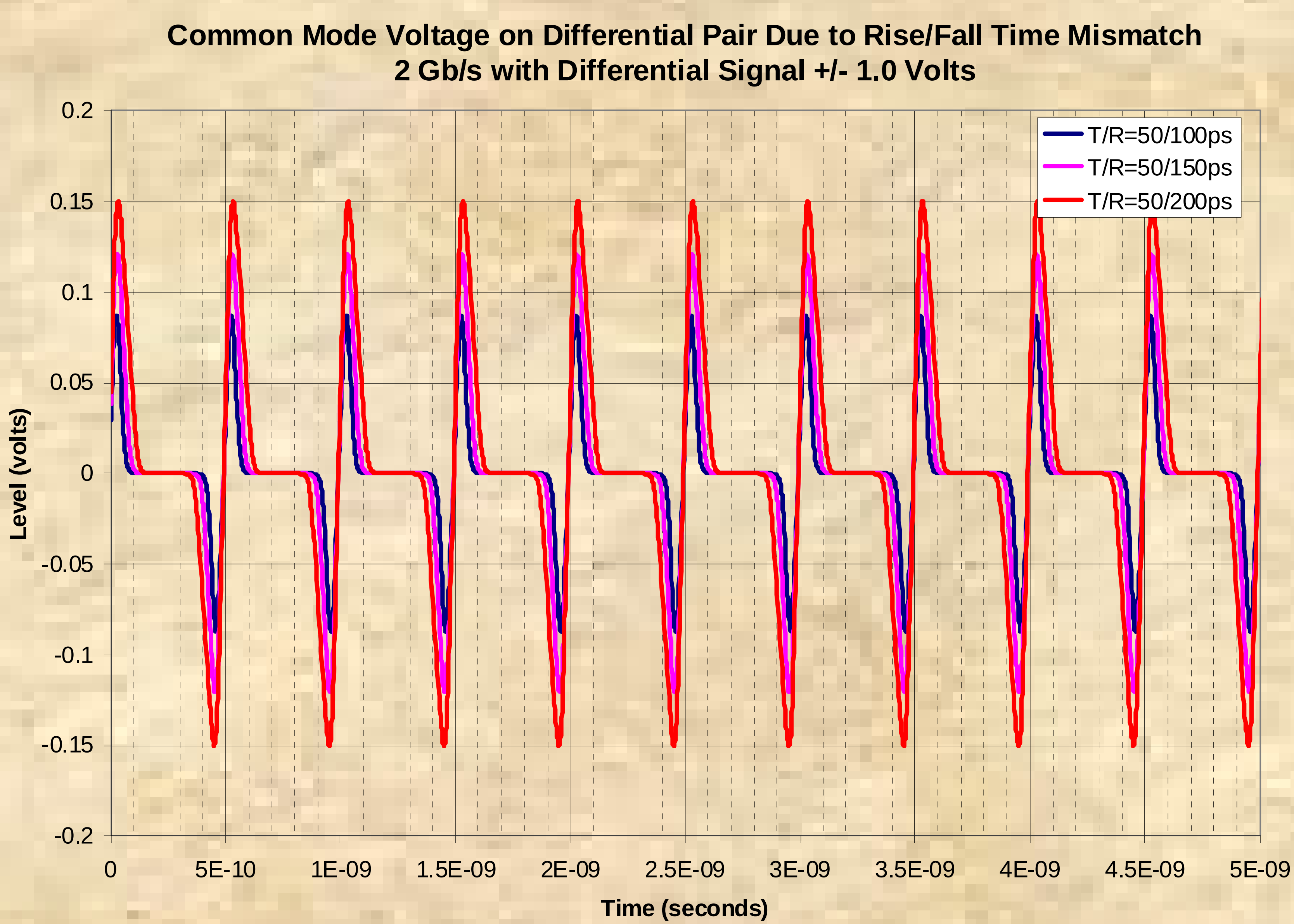
Percentage of Unit Interval Additional Skew Created From Close Proximity to Edge of Ground-Reference Plane
18
16
14
12
10
8
6
4
2
0
% of UI
0
5
10
15
20
25
Date Rate (Gb/s)
4 cm Micrstrip @ 1 trace width from edge
4 cm Micrstrip @ 2 trace width from edge

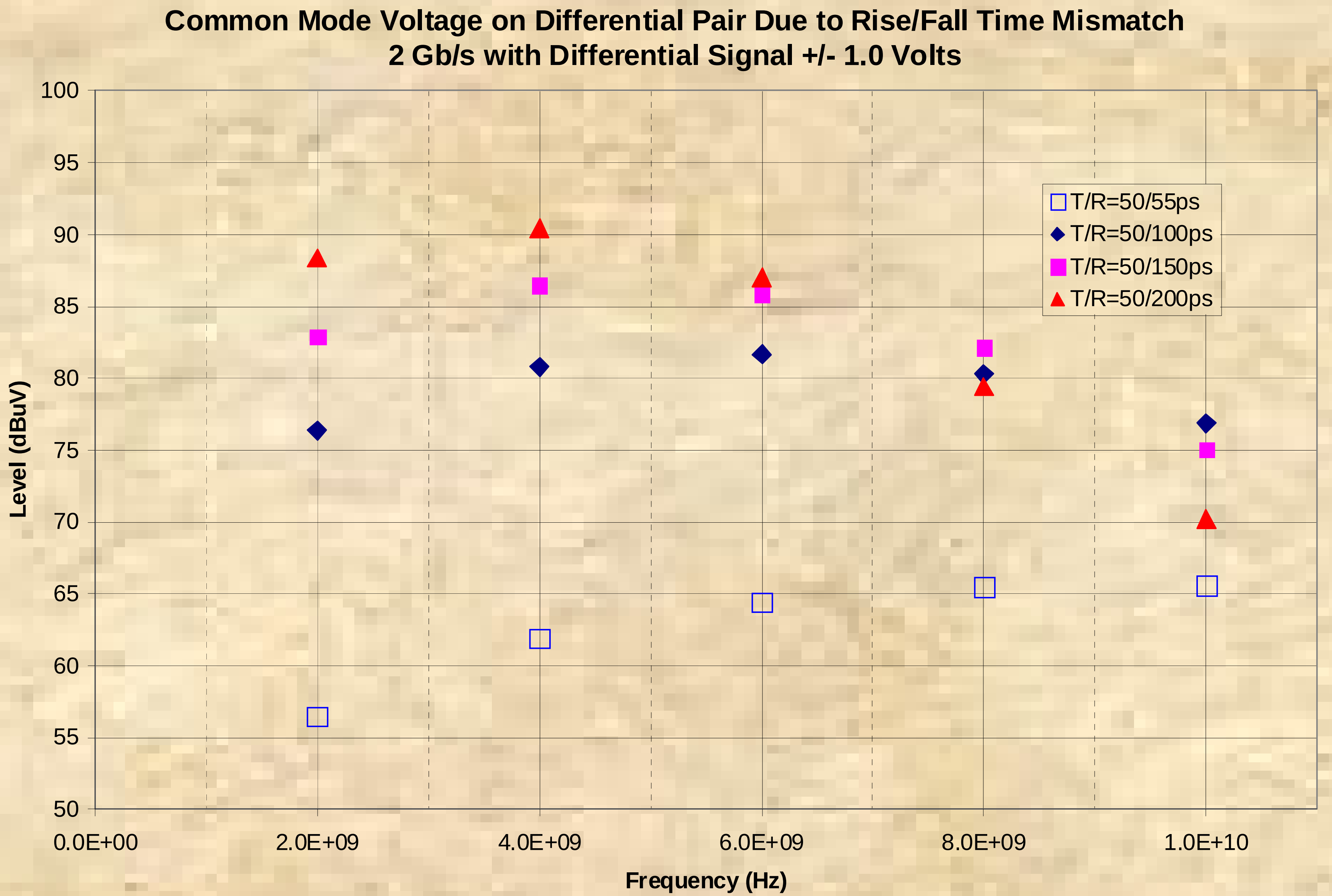
# Rise/Fall Time Mismatch

- Small amounts of mismatch create significant CM noise
- Not as significant as skew, but harder to control!
- Causes
  - Charge/discharge time within IC/ASIC



Example of Effect for Differential Signal with Rise/Fall Time Mismatch
2 Gb/s Square Wave (Rise/Fall = 50 & 100 ps)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Voltage
0.0E+00
2.0E-10
4.0E-10
6.0E-10
8.0E-10
1.0E-09
1.2E-09
1.4E-09
1.6E-09
1.8E-09
2.0E-09
Time (Seconds)
Channel 1
Channel 2
T/R=50/100ps

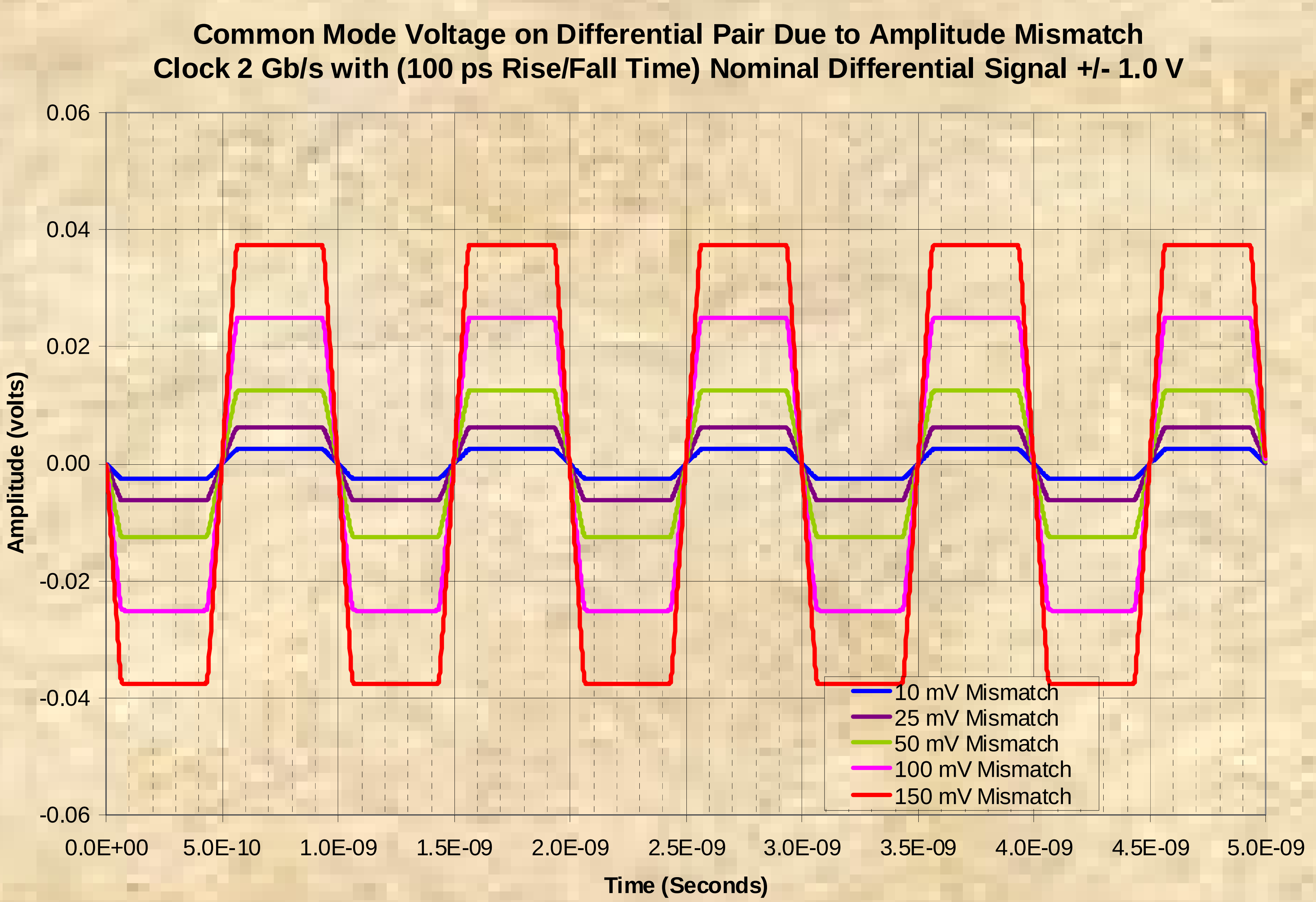

Common Mode Voltage on Differential Pair Due to Rise/Fall Time Mismatch
2 Gb/s with Differential Signal +/- 1.0 Volts
T/R=50/100ps
T/R=50/150ps
T/R=50/200ps
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Level (volts)
0
5E-10
1E-09
1.5E-09
2E-09
2.5E-09
3E-09
3.5E-09
4E-09
4.5E-09
5E-09
Time (seconds)



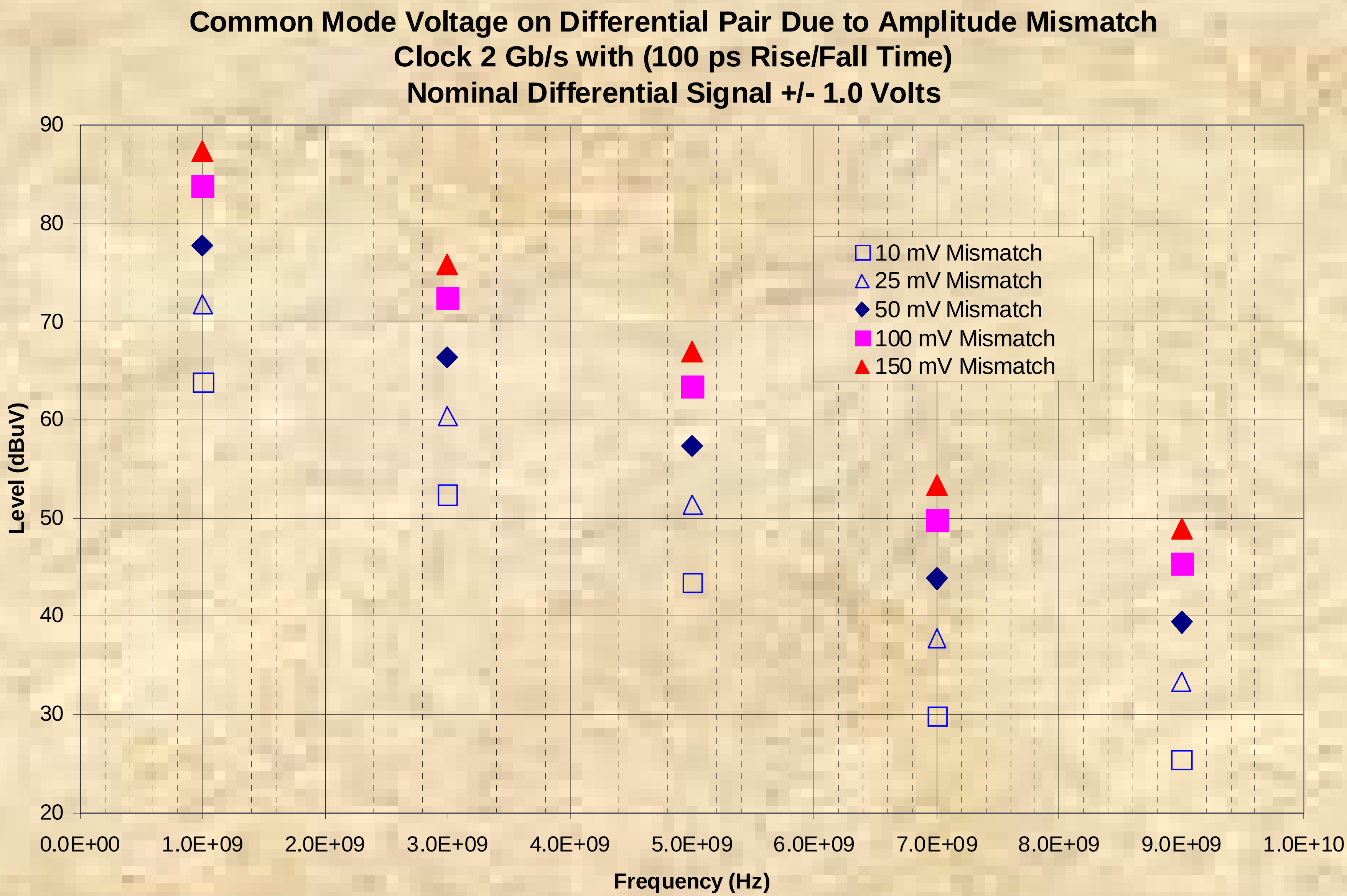
Common Mode Voltage on Differential Pair Due to Rise/Fall Time Mismatch
2 Gb/s with Differential Signal +/- 1.0 Volts
Level (dBuV)
100
95
90
85
80
75
70
65
60
55
50
0.0E+00
2.0E+09
4.0E+09
6.0E+09
8.0E+09
1.0E+10
Frequency (Hz)
T/R=50/55ps
T/R=50/100ps
T/R=50/150ps
T/R=50/200ps

# Amplitude Mismatch

- Small amounts of mismatch create significant CM noise
- Harmonics are additive with other sources of CM noise
- Causes
  - Typically imbalance within ASIC/IC

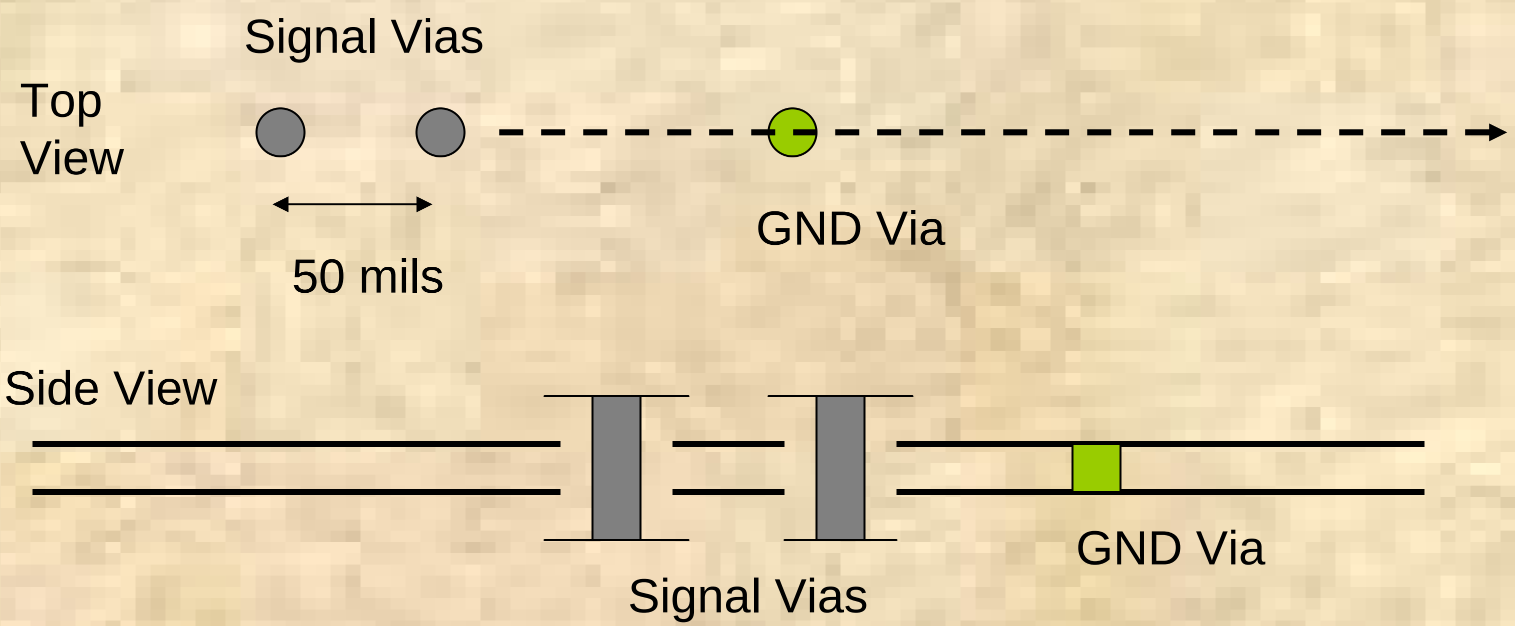


Common Mode Voltage on Differential Pair Due to Amplitude Mismatch
Clock 2 Gb/s with (100 ps Rise/Fall Time) Nominal Differential Signal +/- 1.0 V
Amplitude (volts)
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
0.0E+00
5.0E-10
1.0E-09
1.5E-09
2.0E-09
2.5E-09
3.0E-09
3.5E-09
4.0E-09
4.5E-09
5.0E-09
Time (Seconds)
10 mV Mismatch
25 mV Mismatch
50 mV Mismatch
100 mV Mismatch
150 mV Mismatch

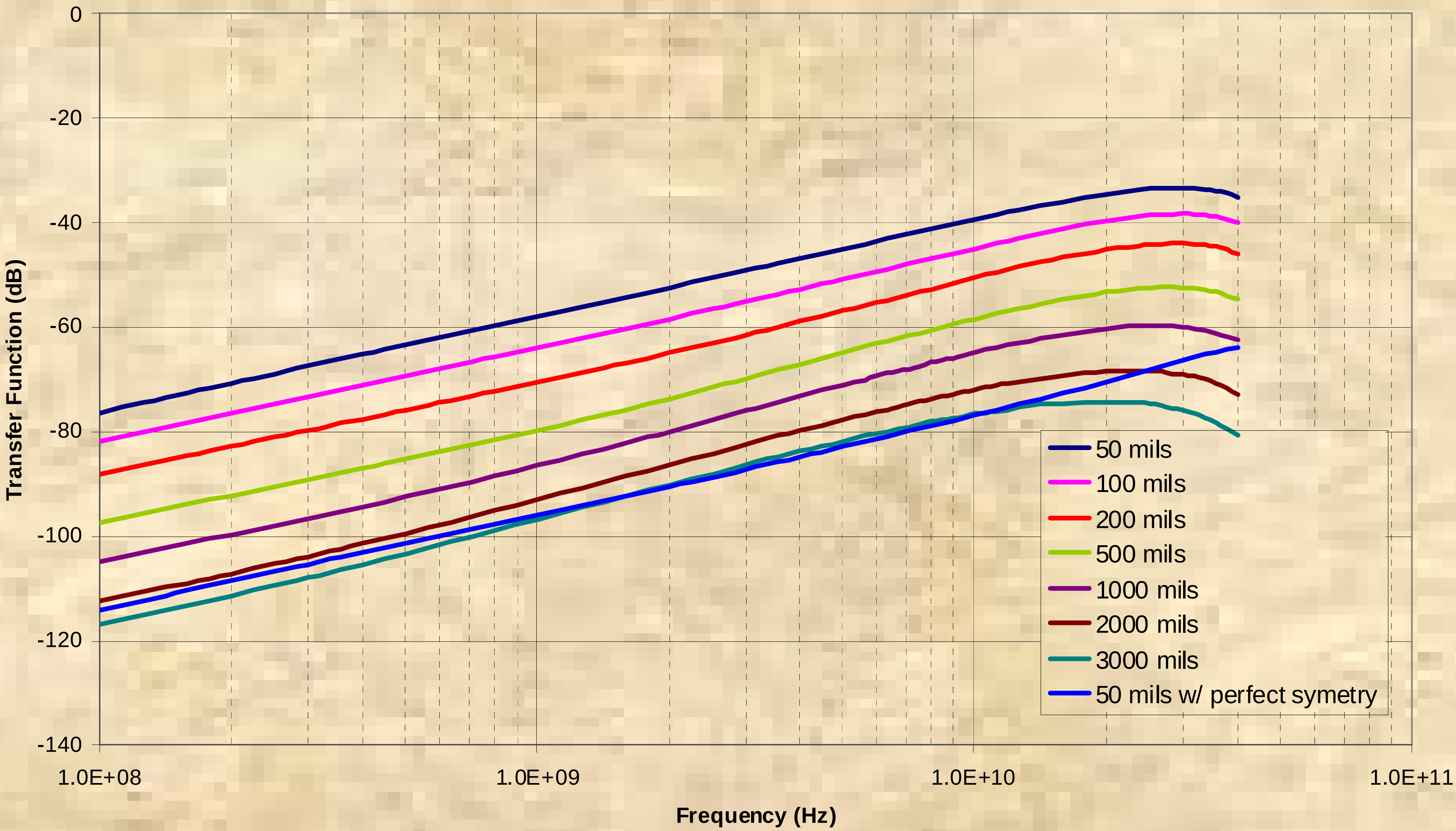

Common Mode Voltage on Differential Pair Due to Amplitude Mismatch
Clock 2 Gb/s with (100 ps Rise/Fall Time)
Nominal Differential Signal +/- 1.0 Volts
Level (dBuV)
90
80
70
60
50
40
30
20
0.0E+00
1.0E+09
2.0E+09
3.0E+09
4.0E+09
5.0E+09
6.0E+09
7.0E+09
8.0E+09
9.0E+09
1.0E+10
Frequency (Hz)
10 mV Mismatch
25 mV Mismatch
50 mV Mismatch
100 mV Mismatch
150 mV Mismatch

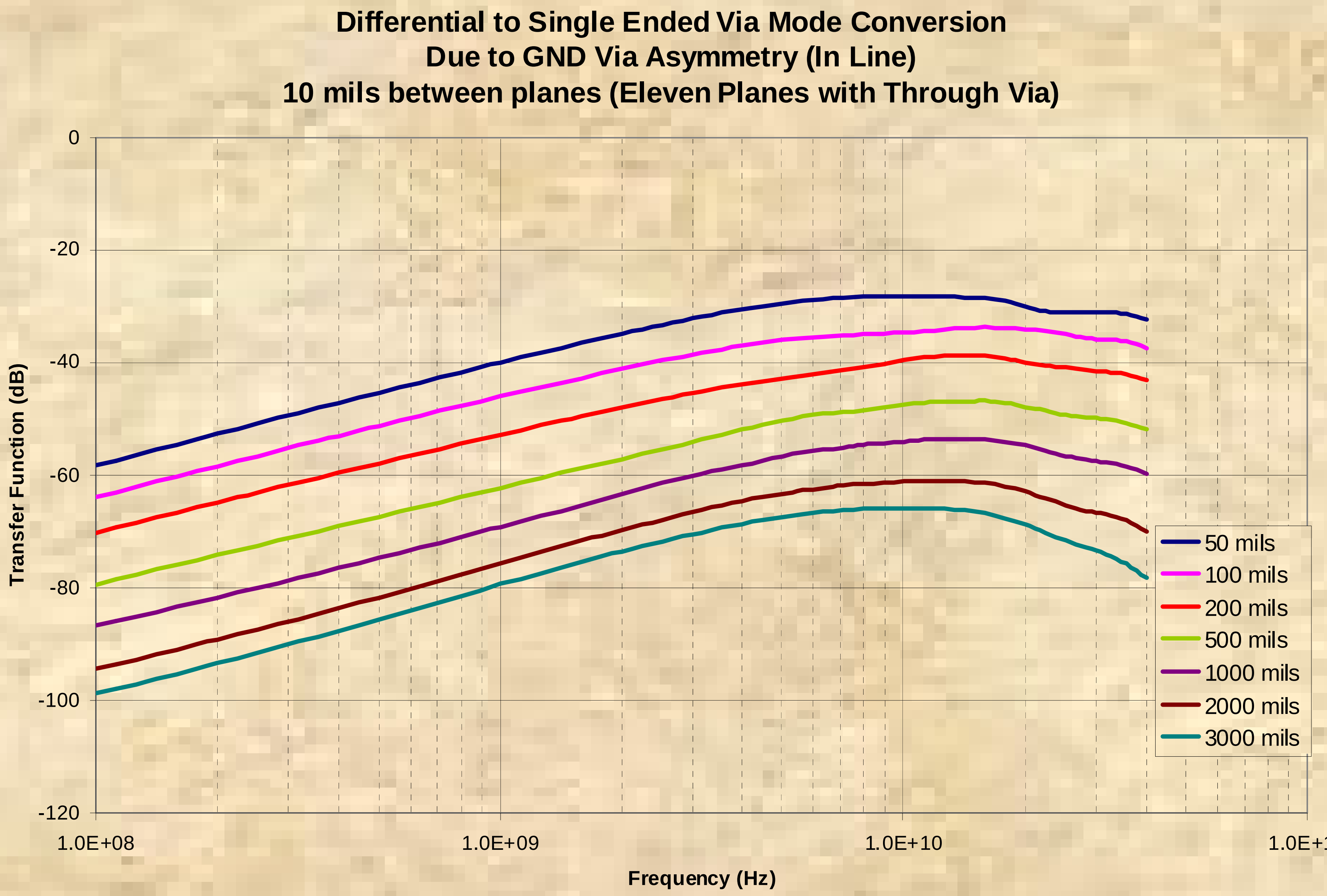
# Common Mode from Via Asymmetry

- Significant CM created!



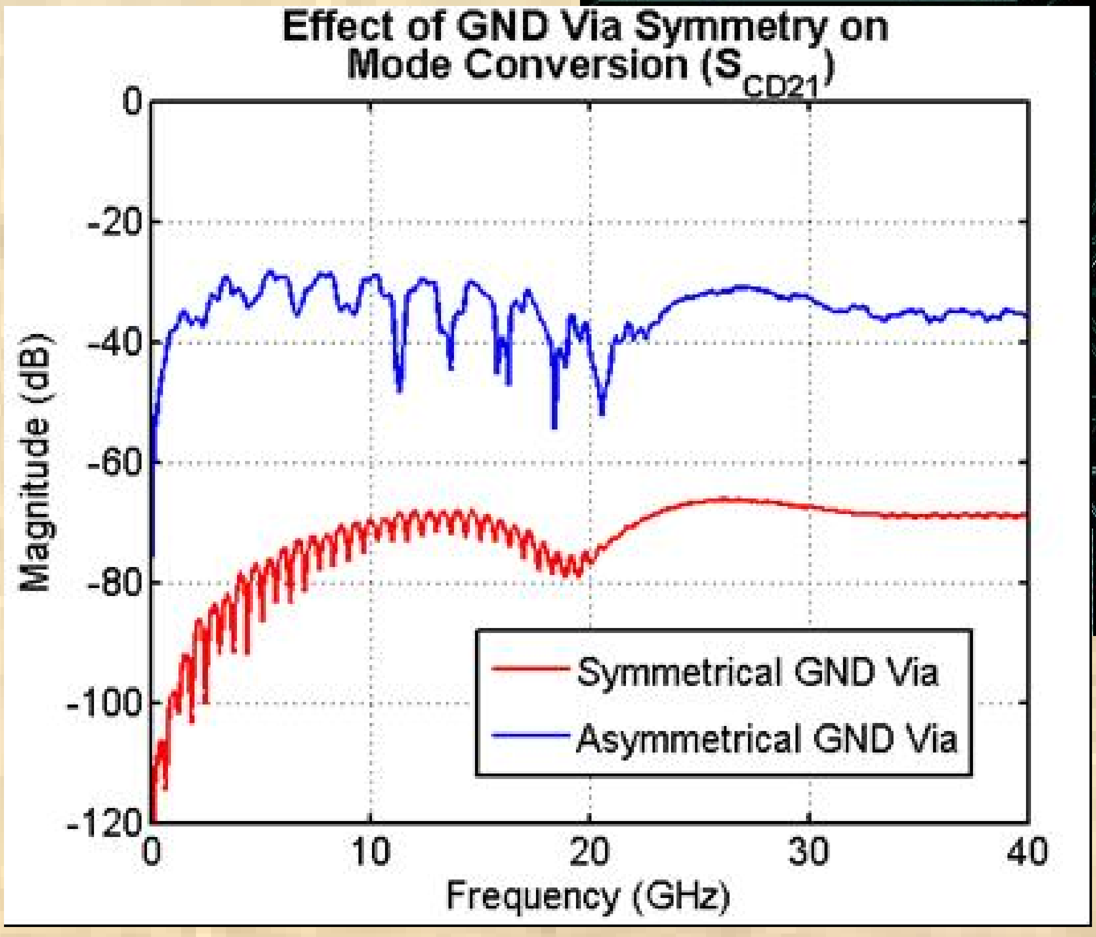
## Differential to Single Ended Via Mode Conversion
## Due to GND Via Asymmetry (In Line)
## 10 mils between planes

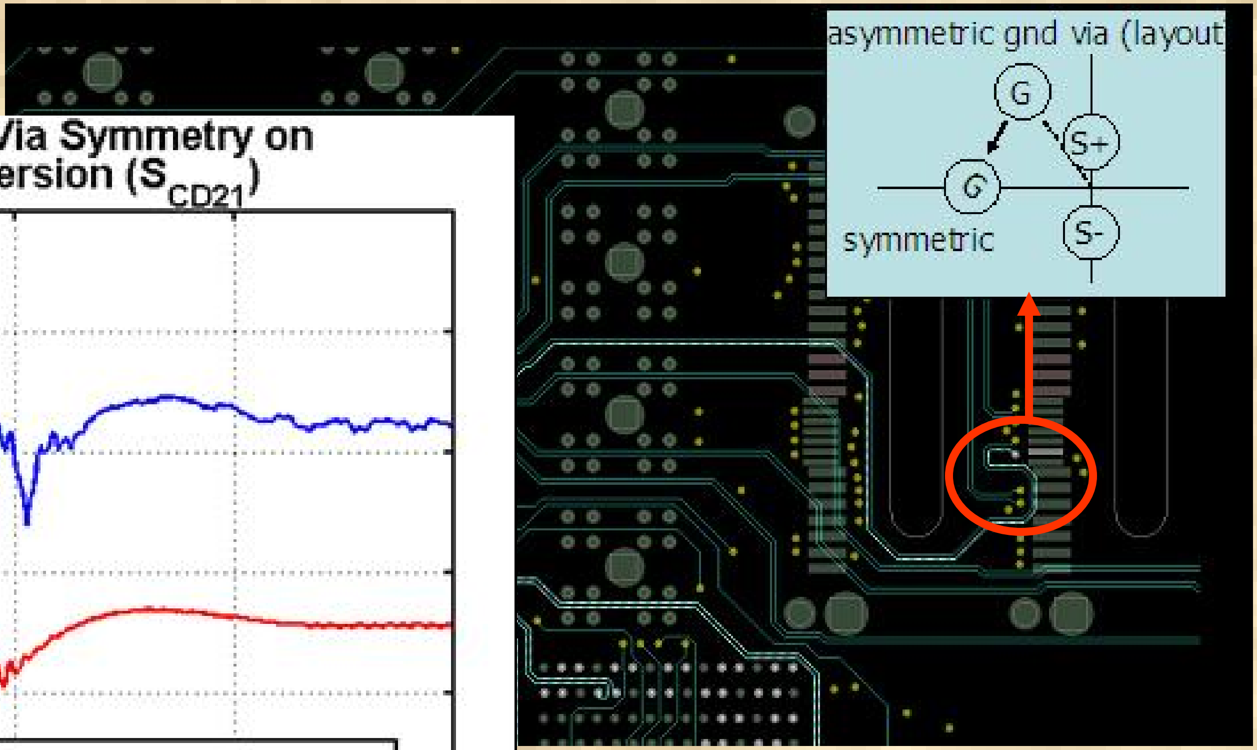




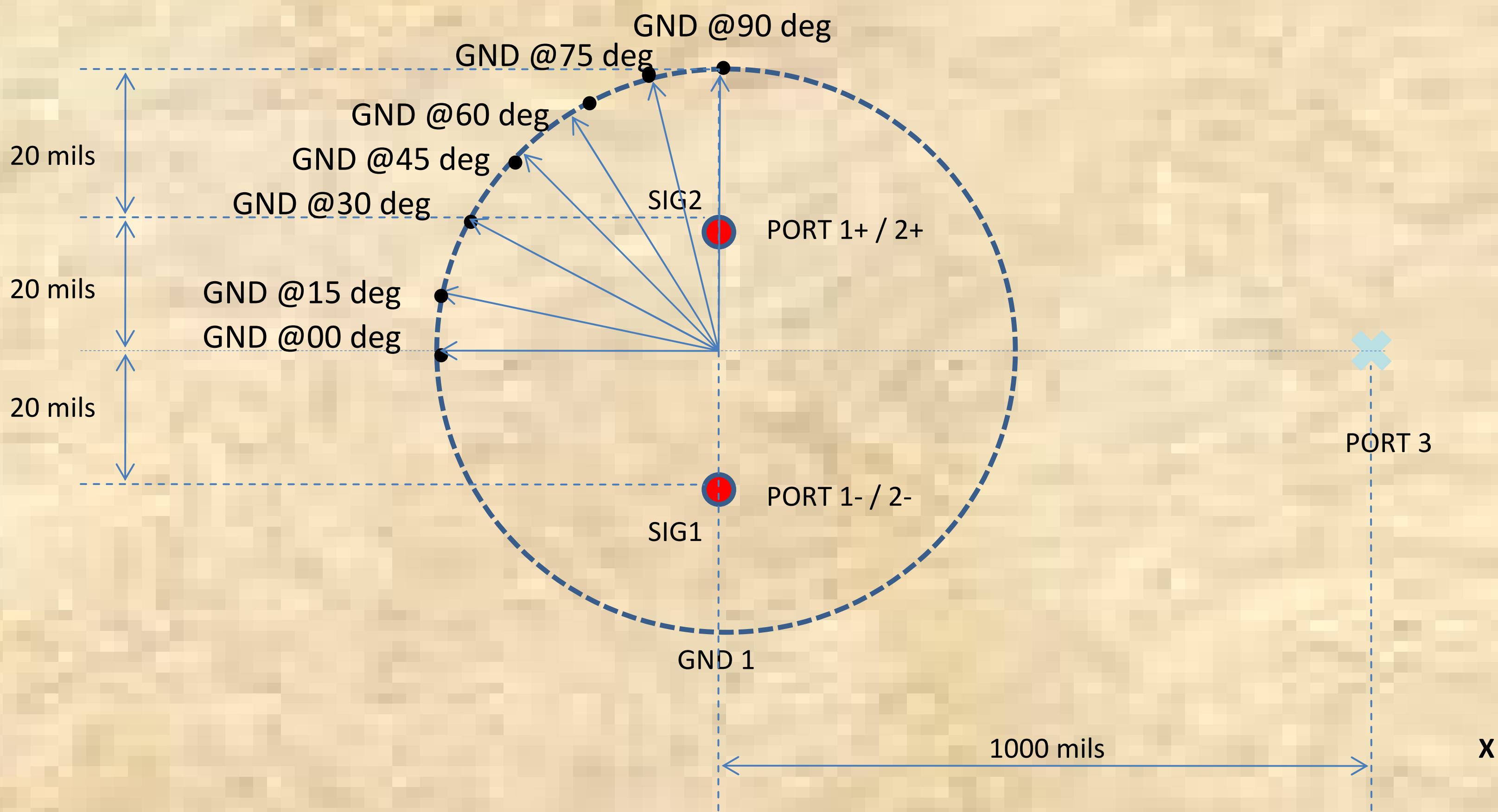
Differential to Single Ended Via Mode Conversion
Due to GND Via Asymmetry (In Line)
10 mils between planes (Eleven Planes with Through Via)
0
-20
-40
-60
-80
-100
-120
Transfer Function (dB)
1.0E+08
1.0E+09
1.0E+10
1.0E+11
Frequency (Hz)
50 mils
100 mils
200 mils
500 mils
1000 mils
2000 mils
3000 mils

# Via Symmetry Effect on Common Mode Conversion

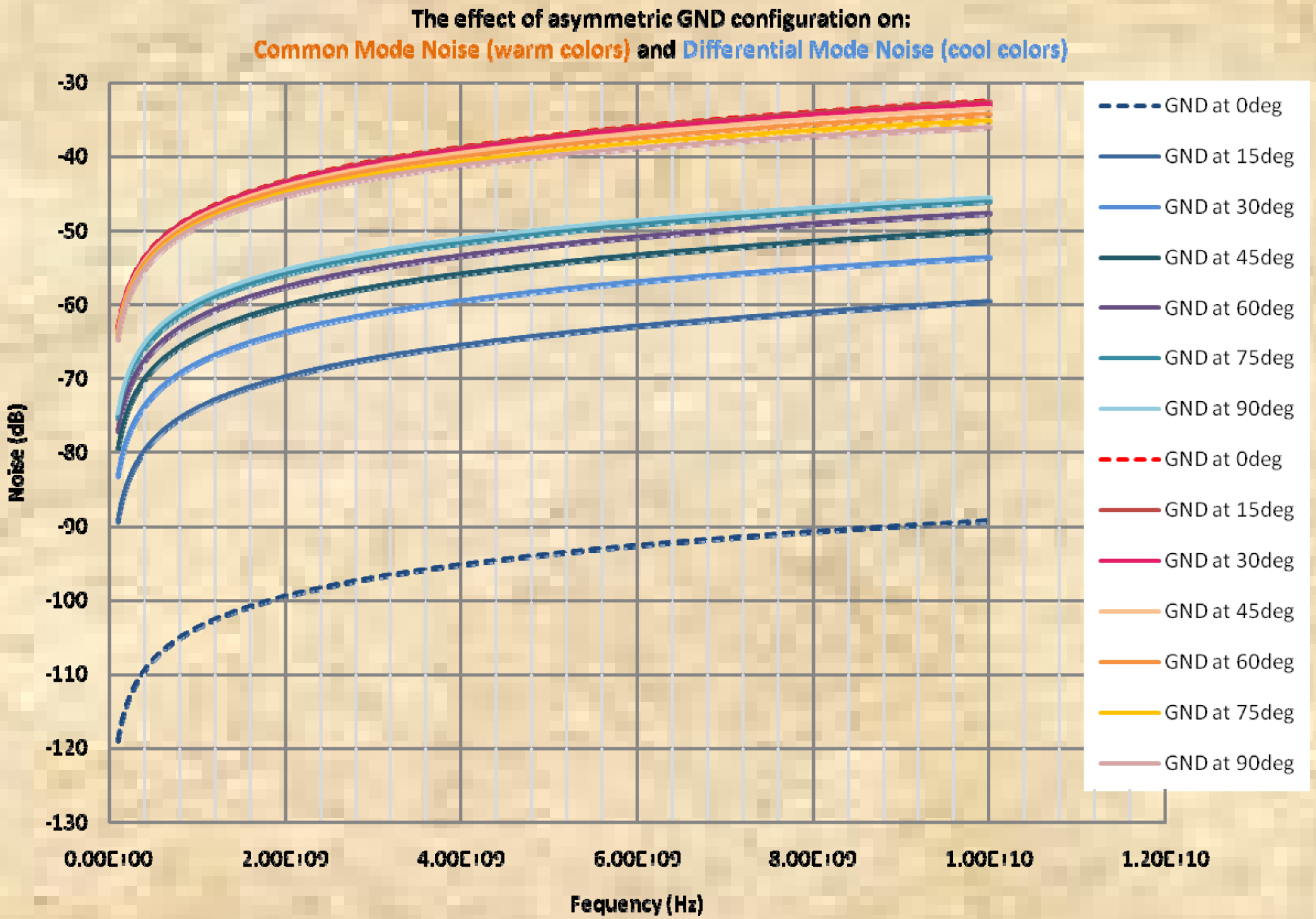


# Top View of the Board: Different GND configurations



# Asymmetric Ground Via Effects





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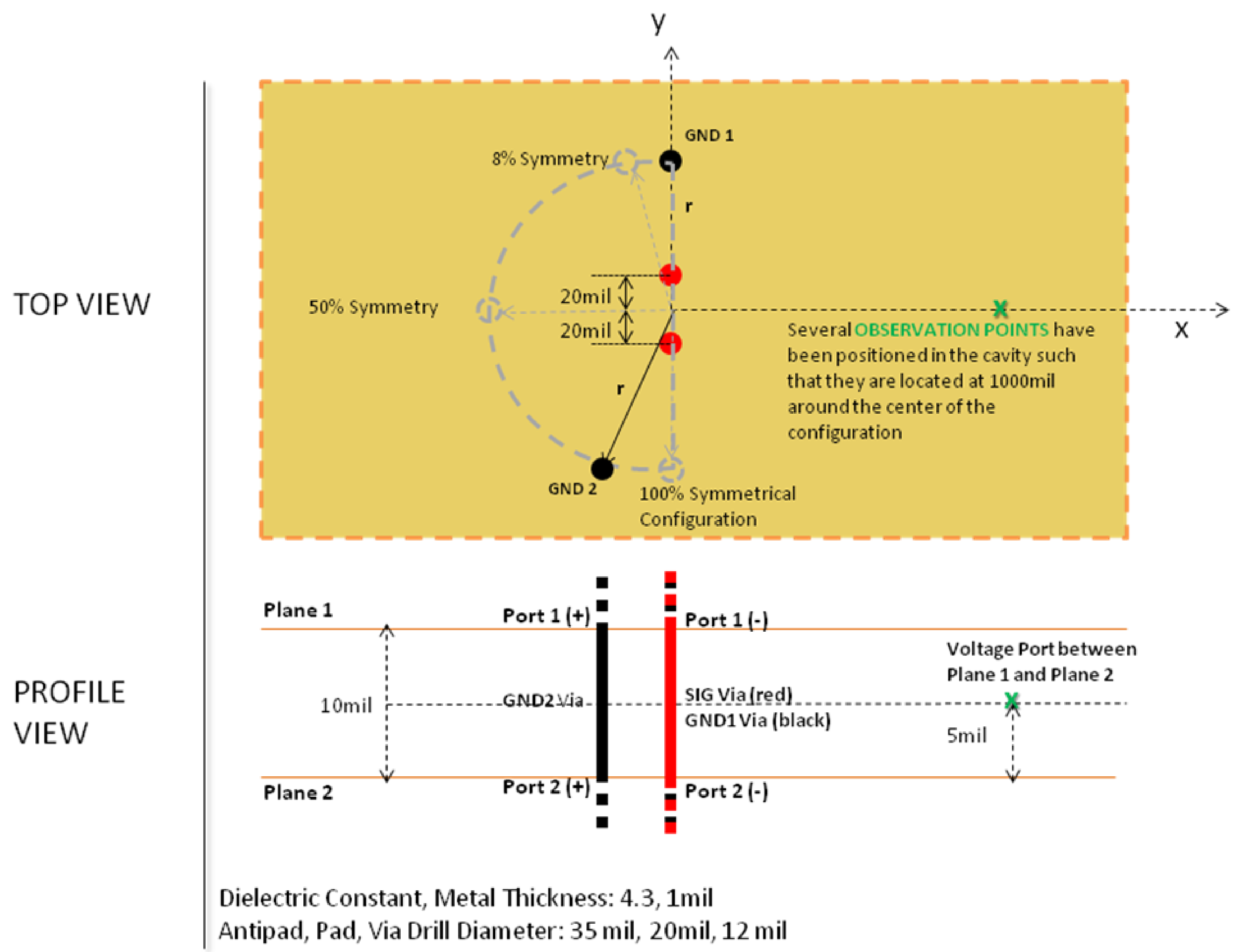
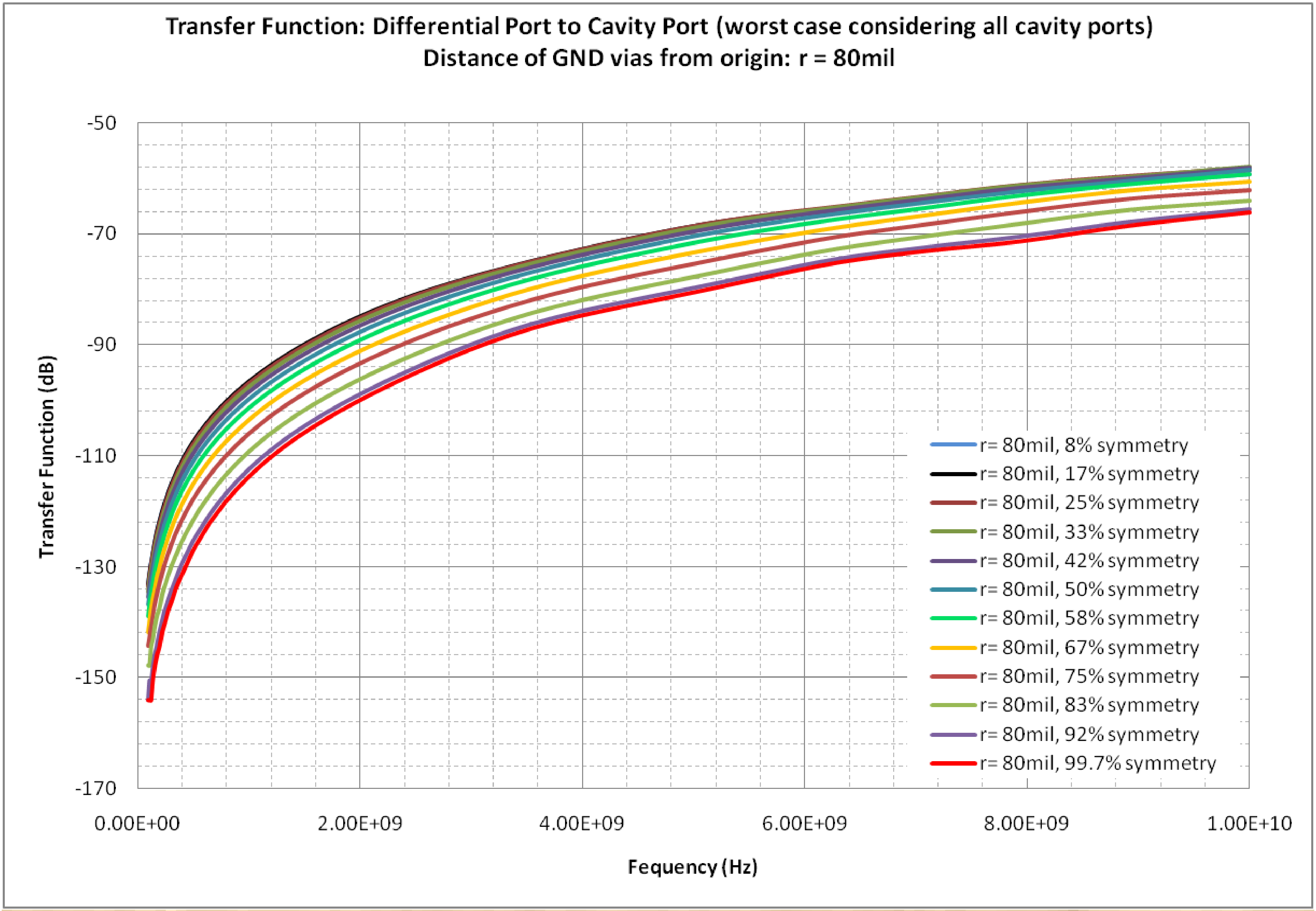
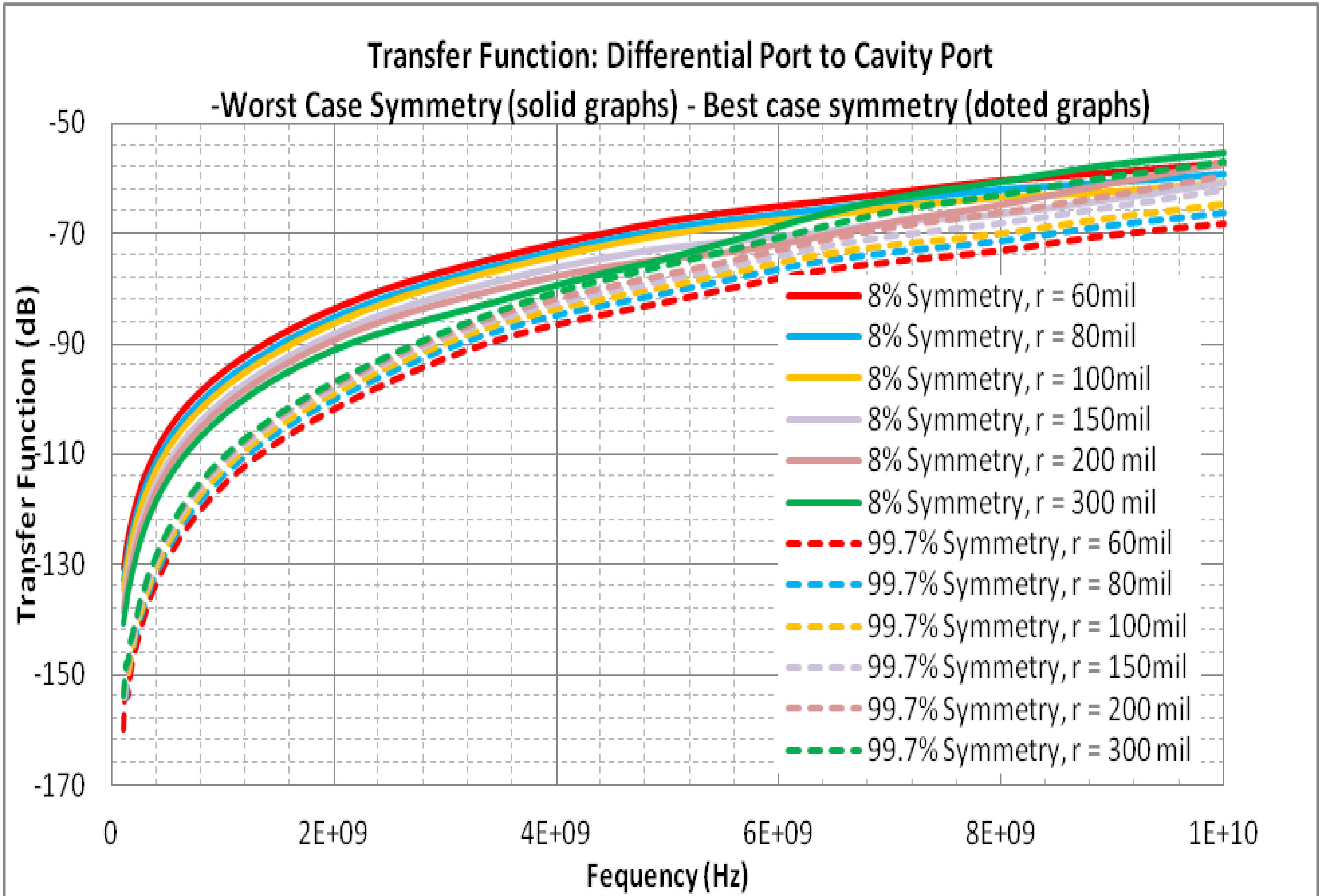
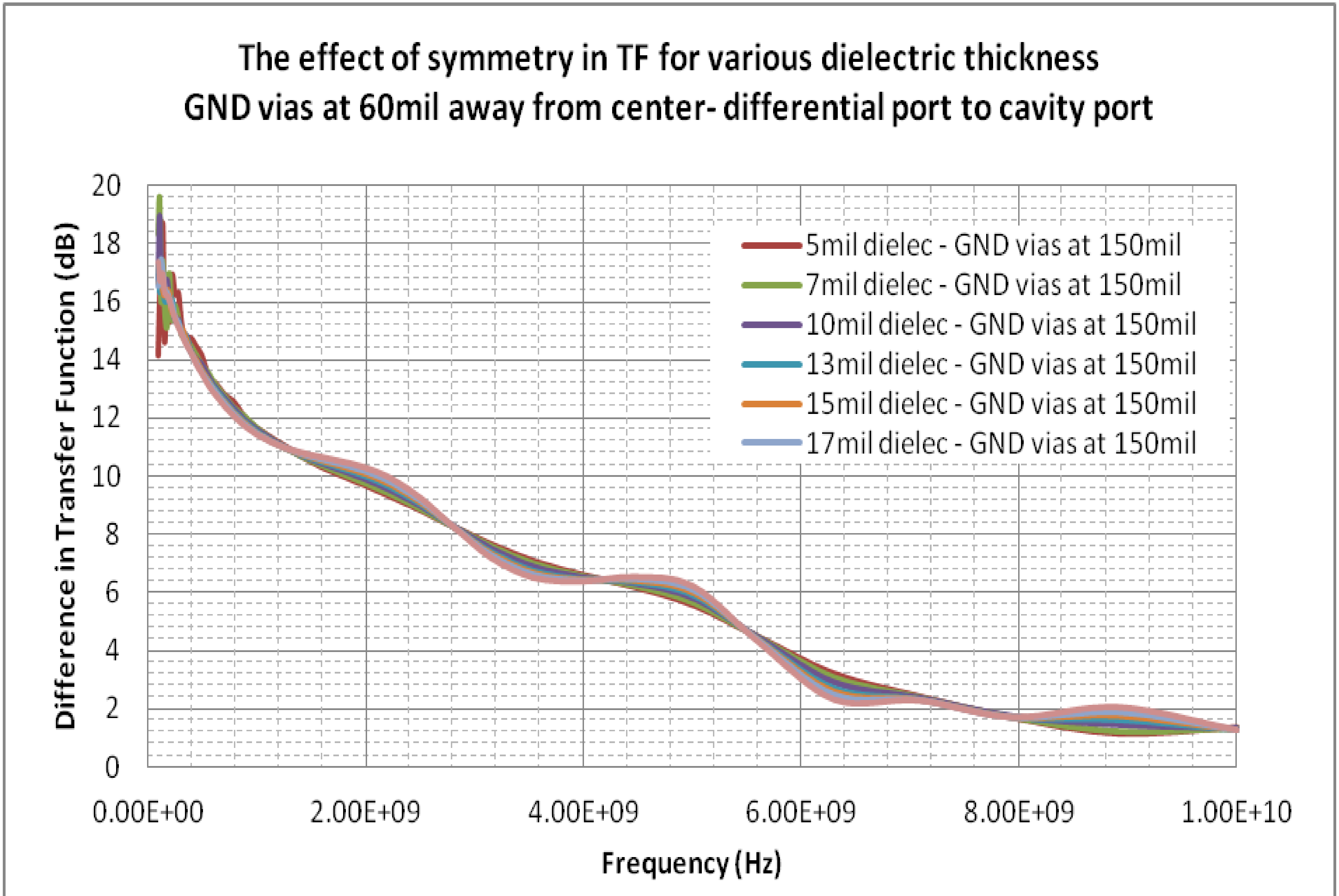
# Asymmetry with Two GND Vias

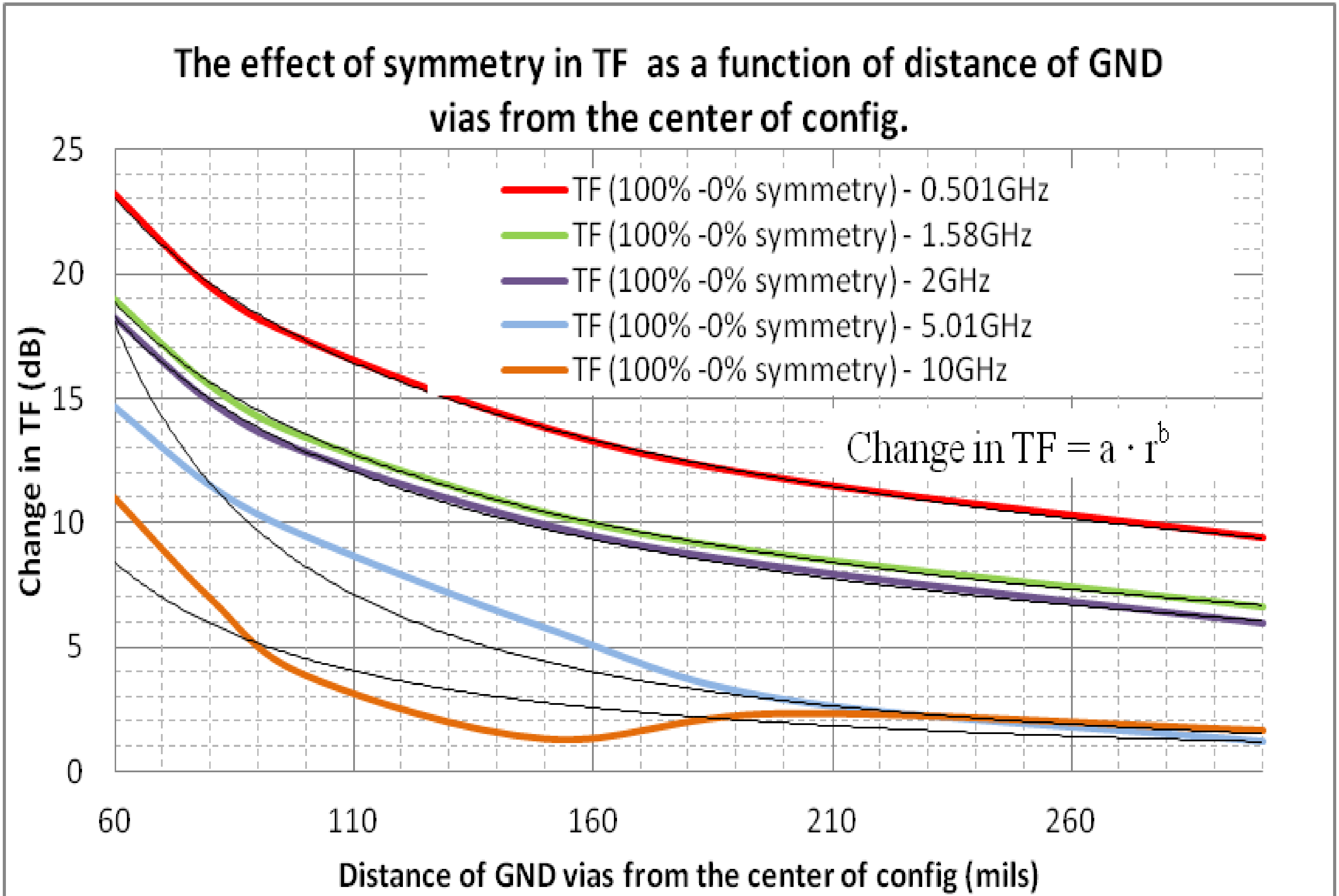


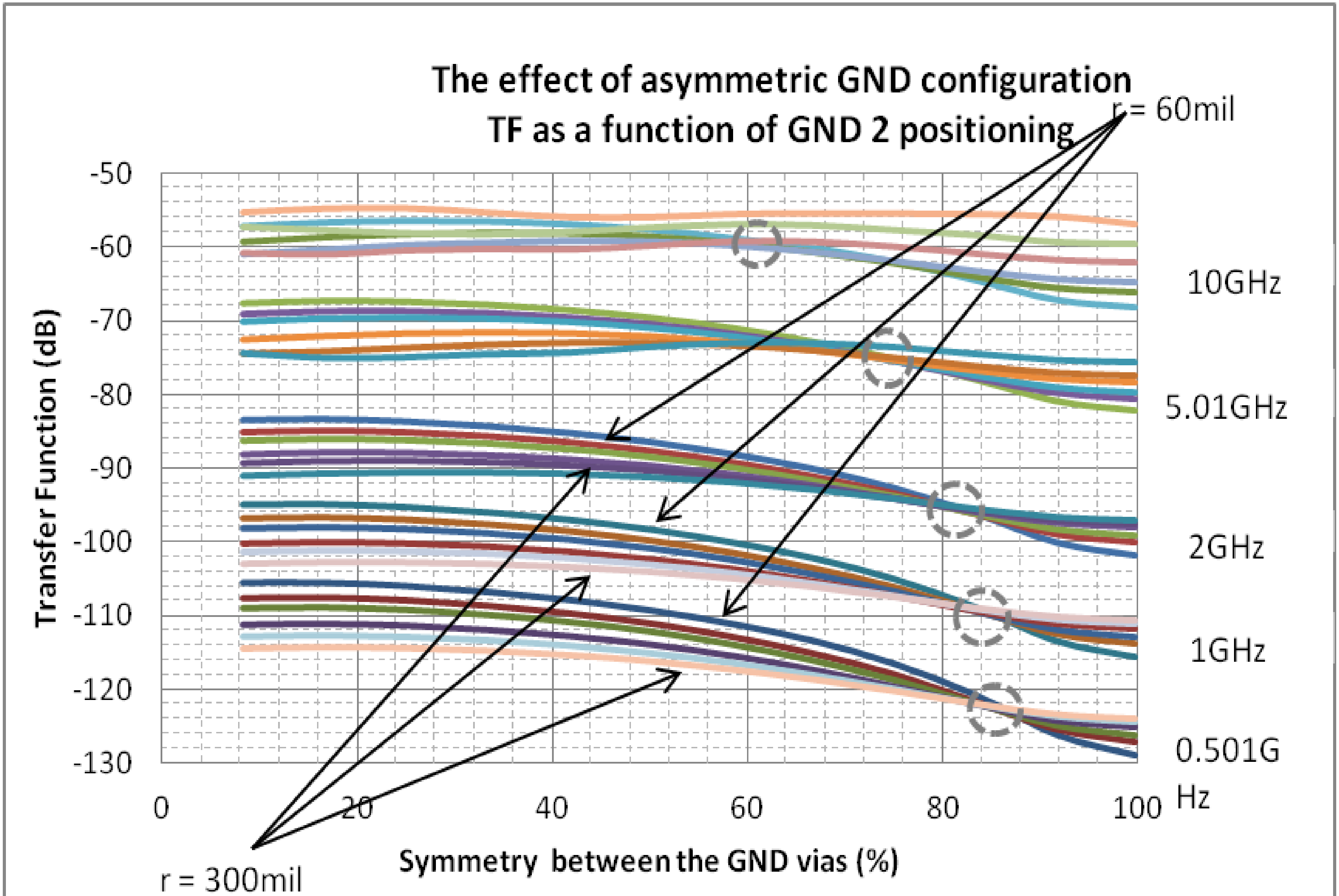

Transfer Function: Differential Port to Cavity Port (worst case considering all cavity ports)
Distance of GND vias from origin: r = 80mil
-50
-70
-90
-110
-130
-150
-170
Transfer Function (dB)
0.00E+00
2.00E+09
4.00E+09
6.00E+09
8.00E+09
1.00E+10
Fequency (Hz)
r= 80mil, 8% symmetry
r= 80mil, 17% symmetry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

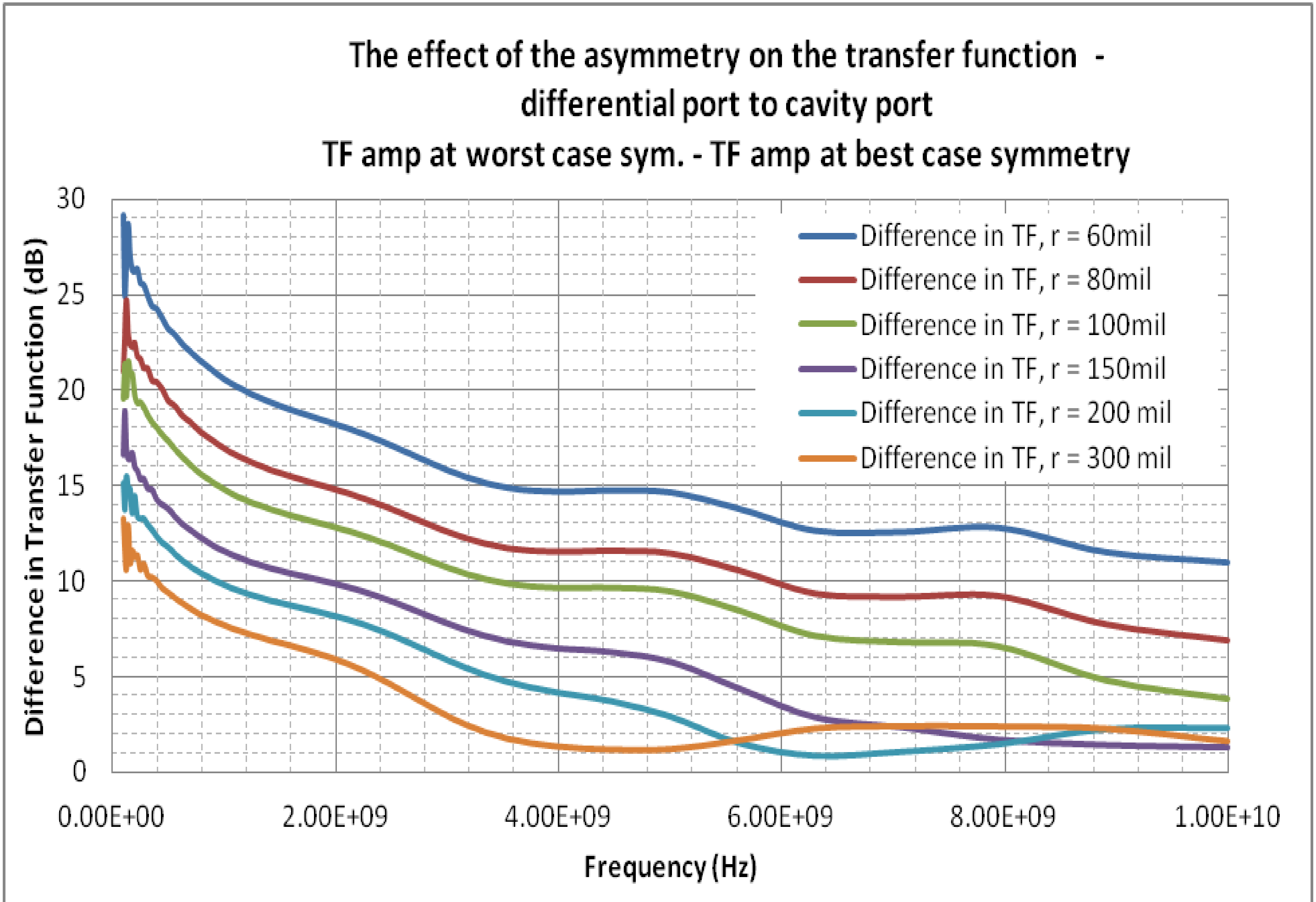


Transfer Function: Differential Port to Cavity Port
-Worst Case Symmetry (solid graphs) - Best case symmetry (doted graphs)
Transfer Function (dB)
-50
-70
-90
-110
-130
-150
-170
0
2E+09
4E+09
6E+09
8E+09
1E+10
Fequency (Hz)
8% Symmetry, r = 60mil
8% Symmetry, r = 80mil
8% Symmetry, r = 100mil
8% Symmetry, 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 symmetry in TF for various dielectric thickness
GND vias at 60mil away from center- differential port to cavity port
Difference in Transfer Function (dB)
20
18
16
14
12
10
8
6
4
2
0
0.00E+00
2.00E+09
4.00E+09
6.00E+09
8.00E+09
1.00E+10
Frequency (Hz)
5mil dielec - GND vias at 150mil
7mil dielec - GND vias at 150mil
10mil dielec - GND vias at 150mil
13mil dielec - GND vias at 150mil
15mil dielec - GND vias at 150mil
17mil dielec - GND vias at 150mil


The effect of symmetry in TF as a function of distance of GND vias from the center of config.
TF (100% -0% symmetry) - 0.501GHz
TF (100% -0% symmetry) - 1.58GHz
TF (100% -0% symmetry) - 2GHz
TF (100% -0% symmetry) - 5.01GHz
TF (100% -0% symmetry) - 10GHz
Change in TF = a · r^b
Change in TF (dB)
25
20
15
10
5
0
60
110
160
210
260
Distance of GND vias from the center of config (mils)

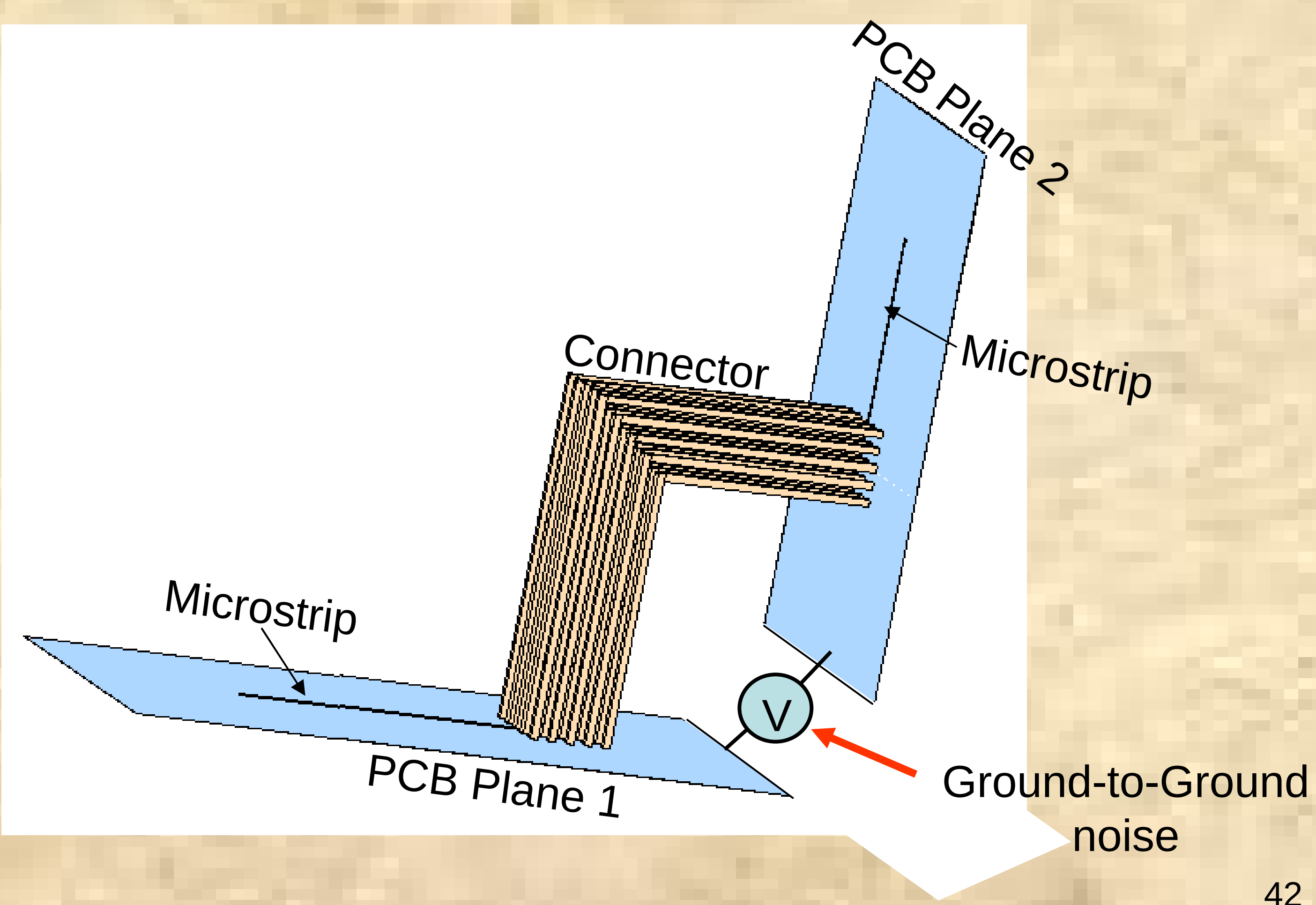

The effect of asymmetric GND configuration
TF as a function of GND 2 positioning
r = 60mil
r = 300mil
Transfer Function (dB)
Symmetry between the GND vias (%)
10GHz
5.01GHz
2GHz
1GHz
0.501G
Hz
-50
-60
-70
-80
-90
-100
-110
-120
-130
0
20
40
60
80
100


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

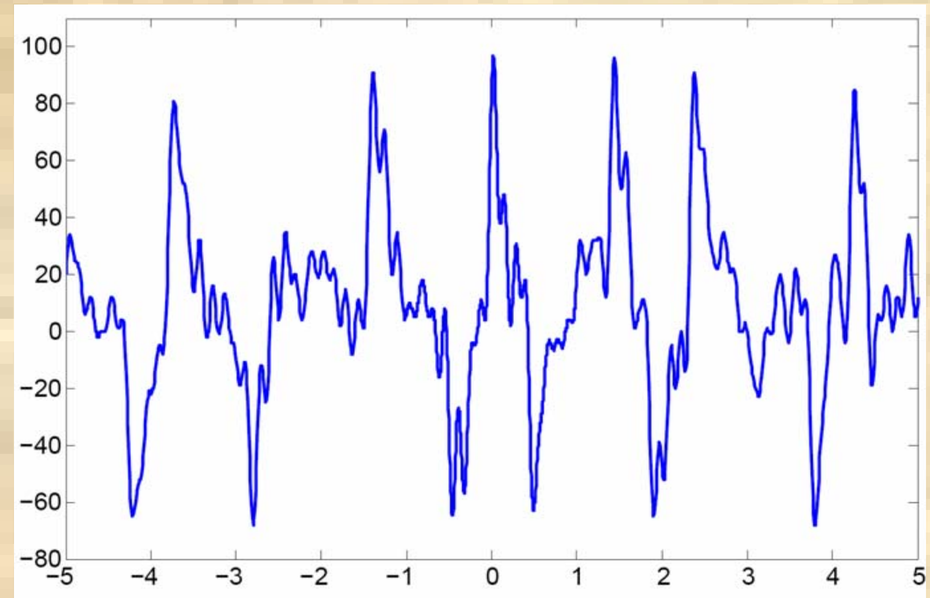
# Common Mode is Impossible to Avoid

- Many other asymmetries can add to common mode noise creation
  - Differential pair routed near edge of plane
  - Dielectric effects
- For EMI, small amounts of CM noise is significant!
  - Above 1 GHz, 1 mV of CM noise is risky!
    - 1mV = 60 dBuV
  - CM filters are required if cables not heavily shielded

# Board-to-Board Differential Pair Issues



# Example Measured Differential Individual Signal-to-GND

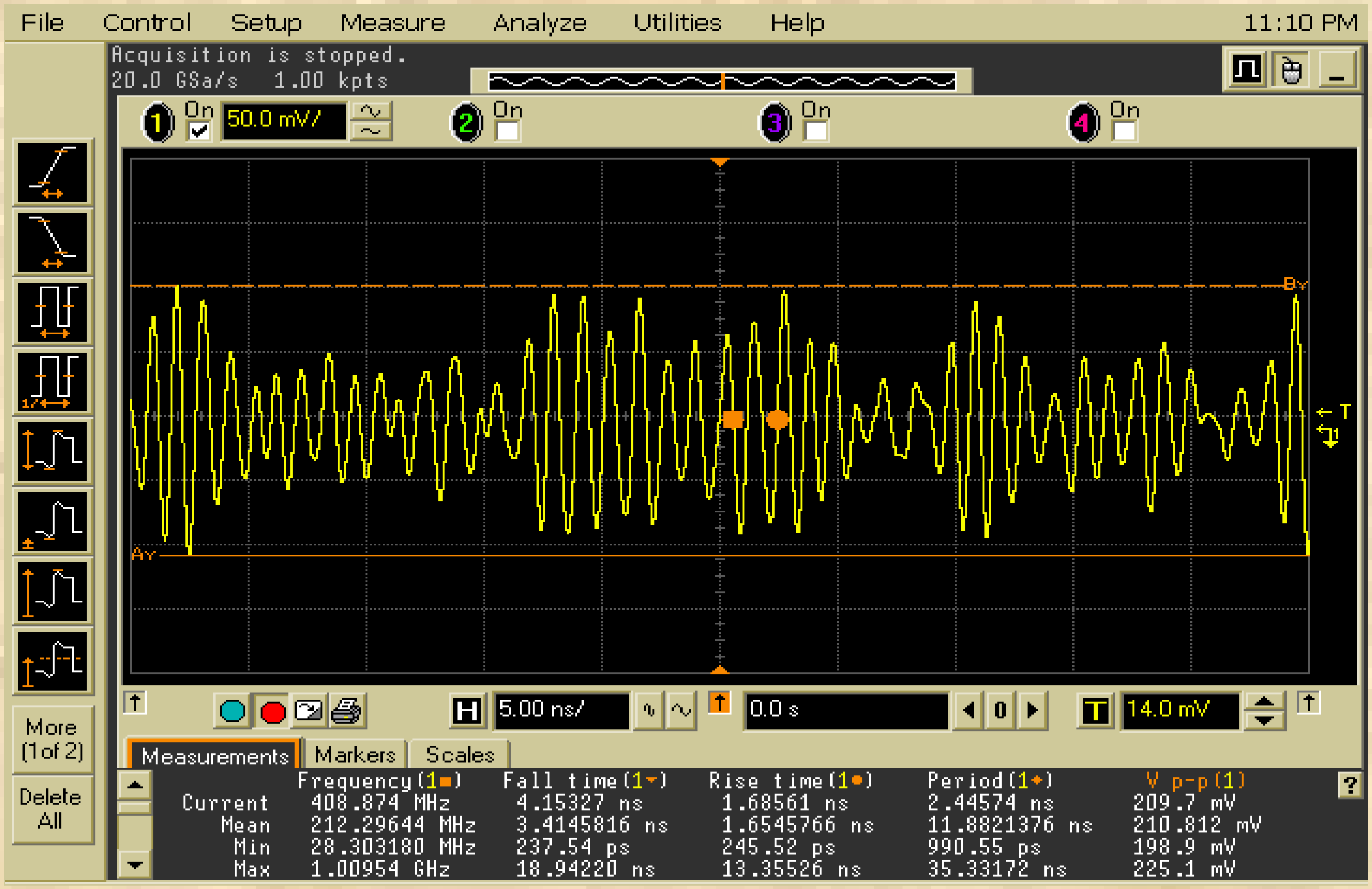




500 mV P-P (each)

Individual Differential Signals ADDED

Common Mode Noise 170 mV P-P

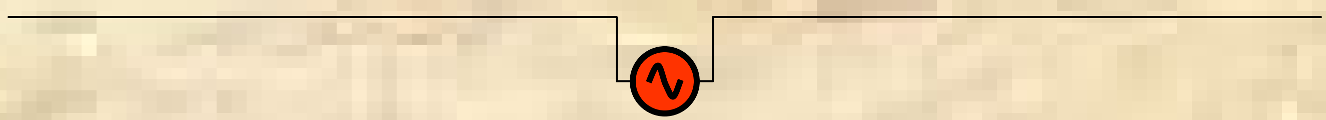
# Measured GND-to-GND Voltage



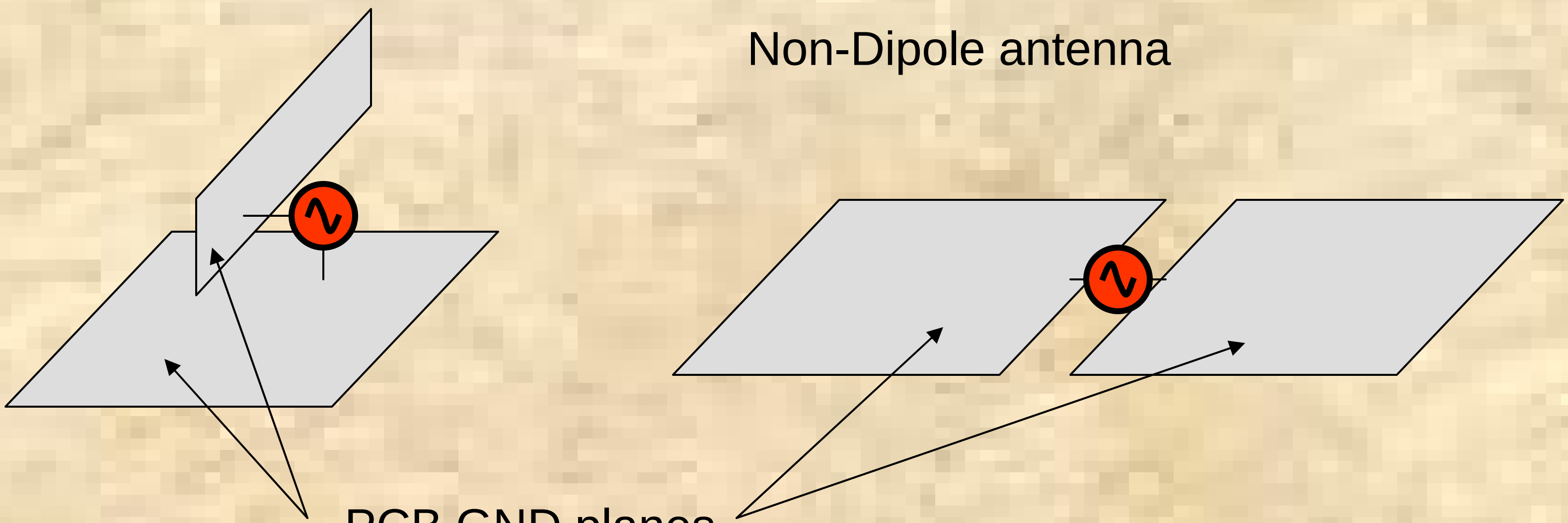

205 mV P-P

# Antenna Structures

Dipole antenna

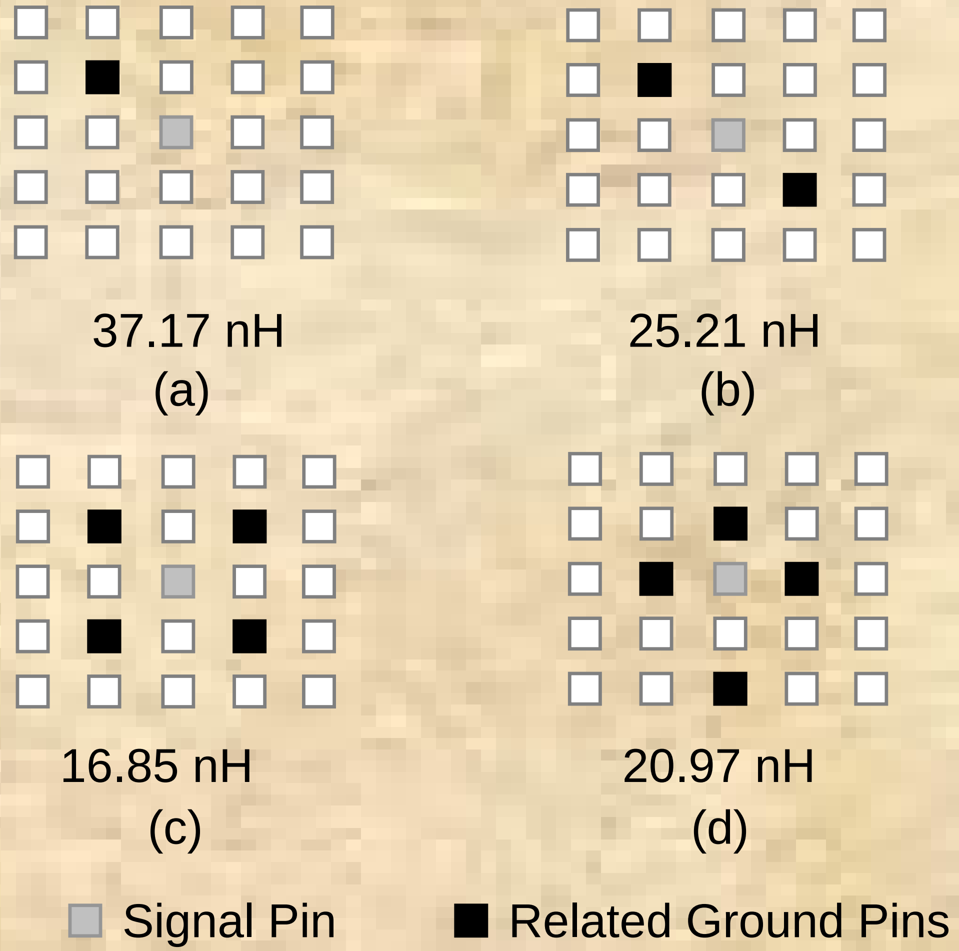


Non-Dipole antenna



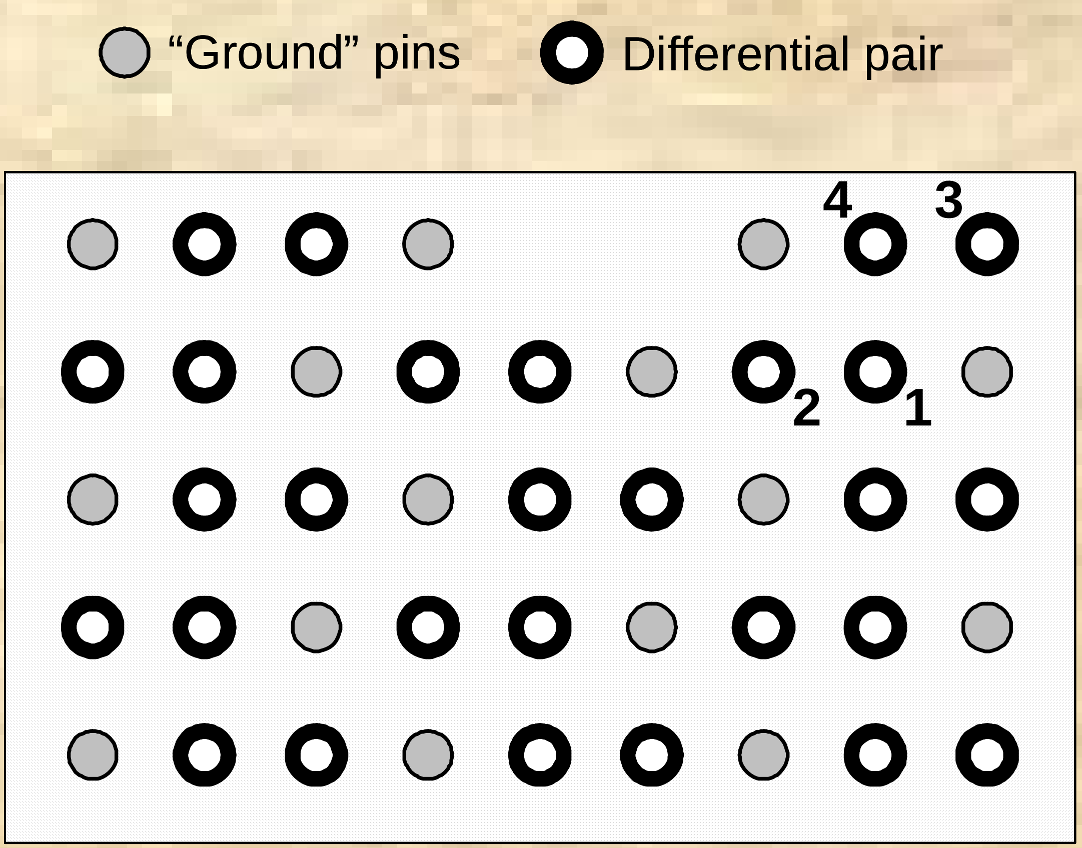
PCB GND planes

# Pin Assignment Controls Inductance for CM signals



# Connector Pin Assignment

- Different pins within same pair may have different loop Inductance for CM




pin 1 -- 26.6nH

pin 2 -- 23.6nH

pin 3 -- 31.8nH

pin 4 -- 28.8nH

# Summary

- Real-world “differential” signals still have currents in ground-reference planes
- Differential signals ***WILL*** have common mode noise
  - Care is needed to minimize common mode noise
- Common mode noise causes EMC issues on external cables and between boards
- In-pair skew, rise/fall time mismatch, amplitude mismatch, and physical channel asymmetry cause common mode noise
  - GND via asymmetry
  - Trace close to edge of ground-reference plane
  - Dielectric weave effects