2017 International ESD Workshop

Skin-depth Losses in Measurement Cables and Their Effect on CDM Waveforms

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Biography

Timothy J. Maloney received an S.B. degree in physics from the Massachusetts Institute of Technology in 1971, an M.S. in physics from Cornell University in 1973, and a Ph.D. in electrical engineering from Cornell in 1976, where he was a National Science Foundation Fellow. He was a Postdoctoral Associate at Cornell until 1977, when he joined the Central Research Laboratory of Varian Associates, Palo Alto, CA. At Varian until 1984, he worked on III-V semiconductor photocathodes, solar cells and microwave devices, as well as silicon molecular beam epitaxy and MOS process technology. Since 1984 he was with Intel Corp., Santa Clara, CA, where he was concerned with integrated circuit ESD protection, CMOS latchup testing, fab process reliability, signal integrity, system ESD testing, and design and testing of standard IC layouts. He was a Senior Principal Engineer at Intel from 1999 until retirement in June of 2016. He received the Intel Achievement Award for his patented ESD protection devices, which have achieved breakthrough ESD performance enhancements for a wide variety of Intel products. He now holds thirty-nine patents.

Dr. Maloney received Best Paper/Outstanding Paper Awards for his contributions to the EOS/ESD Symposium in 1986, 1990, and 2015, was General Chairman for the 1992 EOS/ESD Symposium, and received the ESD Association's Outstanding Contributions Award in 1995. He has taught short courses at UCLA, University of Wisconsin, and UC Berkeley. He is co-author of a book, "Basic ESD and I/O Design" (Wiley, 1998), and is a Fellow of the IEEE.

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Abstract

The ESDA/JEDEC JS-002 Charged Device Model committee specifies CDM waveform measurement cable performance. The present spec (<2 dB @ 9 GHz) is not met by commonly-used assemblies. Some degradation of CDM signal strength is expected, but to date there has been no quantitative estimate of impact with computed CDM waveforms with and without cable losses.

Coaxial cable losses due to skin depth have long been studied [1], and those losses at RF have been found to dominate over dielectric losses in most transmission lines [2], at least up to 5 GHz. This covers the meaningful spectrum of even the fastest CDM calibration waveforms.

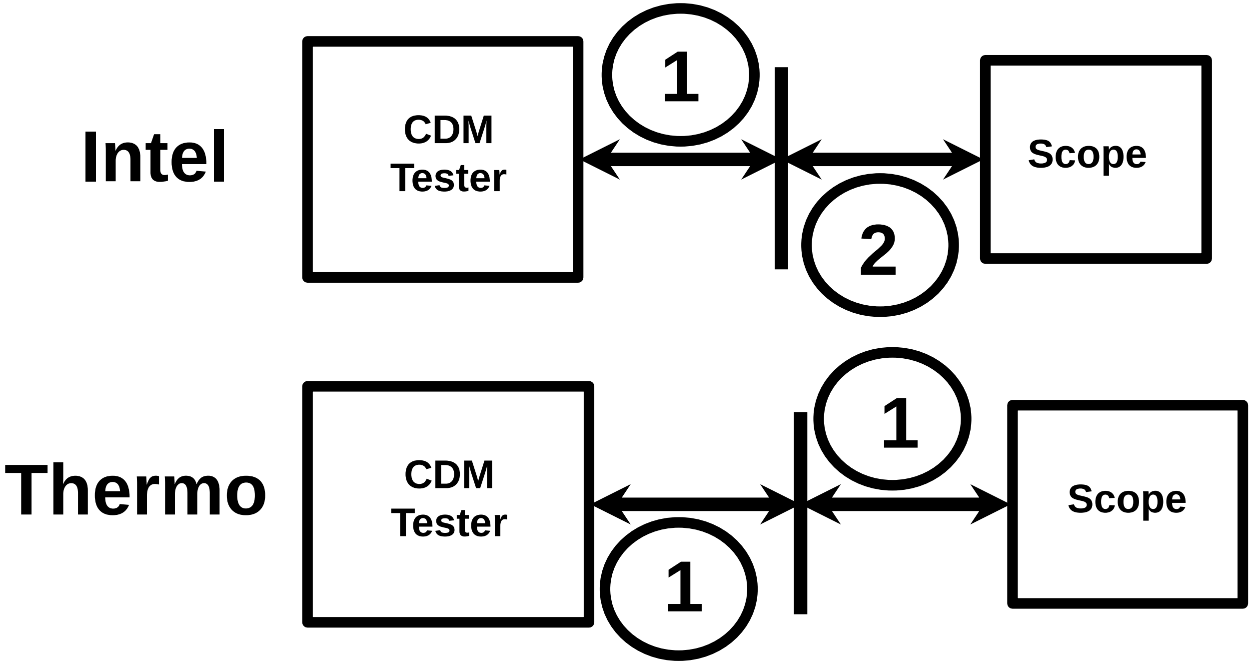
A single time parameter, proportional to the square of cable length, fully describes a normalized impulse response for a given length of cable [1,2]. These are on record for many transmission lines and can be calculated from published cable loss data [2].

For the first time, this work presents familiar CDM waveforms convolved with impulse response for 2-meter cable assemblies for CDM by Thermo and Intel, thereby assessing the impact of skin depth. Around 6.4% lower Ipeak is seen for small objects for the Thermo setup, 5.3% for Intel. This is still difficult to see in the presence of air spark variations. The CDM committee should converge on an acceptable practice as it moves toward CCDM and more reproducible waveforms.

Purpose

- Need to know effect on CDM waveform of ~2 meters of cable in CDM tester for JS-002 specs
  - Filter function for skin depth captures nearly all of the effect for our waveforms
  - Examples given of CDM waveform with and without cable filter
    - Complete convolution integrals done for main cases
    - Simple formula for estimates also shown
- Evaluate present JS-002 cable spec
  - Asks for <2 dB at 9 GHz
    - We don‘t meet it but we would meet a scaled version at CDM waveform frequency (< 5 GHz); 1.5 dB @ 5 GHz is OK

CDM Tester Measurement Setups



1. Mini-Ckts SMSM+, 3’, 18 GHz
2. Sucoflex 104, 1m, 26 GHz

Ack. to Josh Morris (Intel), Tom Meuse (Thermo)

The Problem: JS-002, 5.2.1

5.2.1 Cable Assemblies

Cable assemblies with combined internal tester cable and external cable total loss of no more than 2 dB at frequencies up to 9 GHz and a nominal 50 ohm impedance.

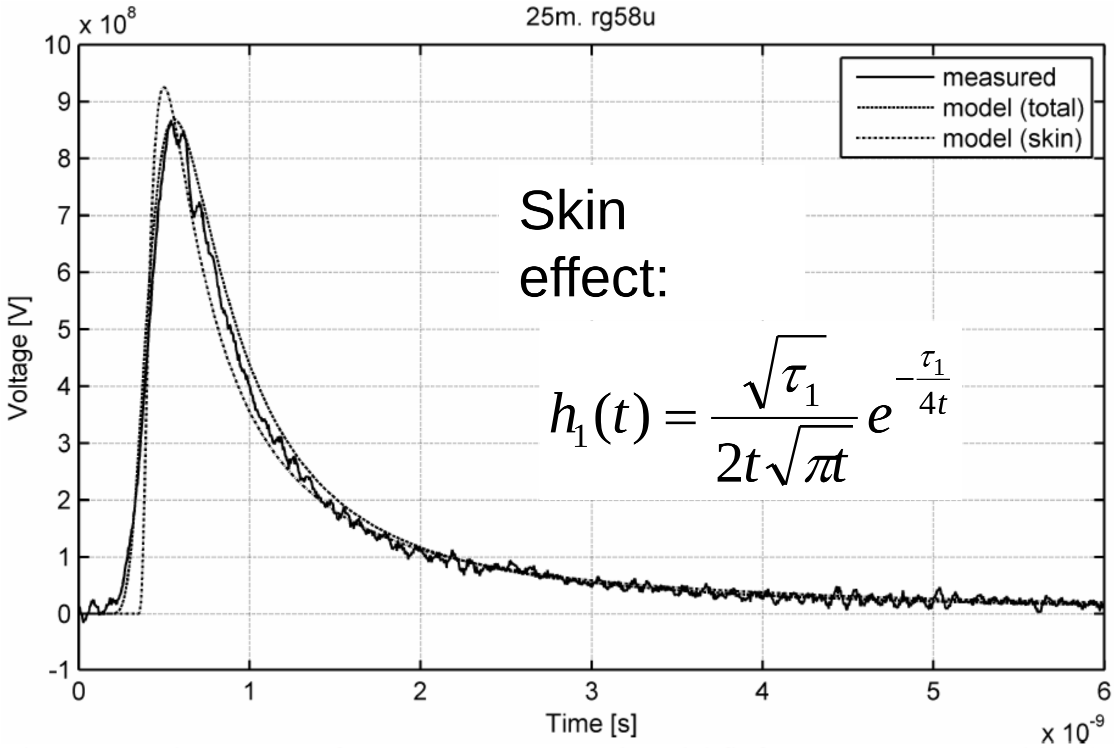
At 9 GHz, cables 1 + 1 losses are at 1.43 +1.43 dB = 2.86 dB ↓

At 9 GHz, cables 1 + 2 losses are at 1.43 + 0.74 dB = 2.17 dB ↓

Both arrangements do not pass the spec, what do we do?

Filter Function for Skin Effect in Cables

Skin effect dominates [2]



Skin effect:

$$h_1(t) = \frac{\sqrt{\tau_1}}{2t\sqrt{\pi t}} e^{-\frac{\tau_1}{4t}}$$

Fig. 17. Impulse response from measurements and model fit for 25m RG-58CU cable (a).

$$\tau_1 = \frac{l^2 \lambda^2}{2Z_c^2},$$

l = line length

$$f(s) = \exp(-\sqrt{as})$$

$$s = \sigma + j\omega$$

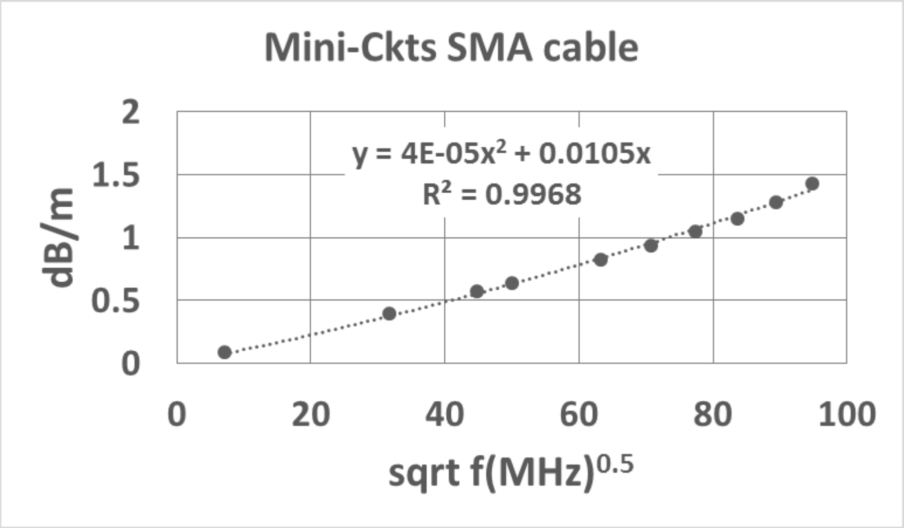
For 25m, τ_1 = 1 nsec

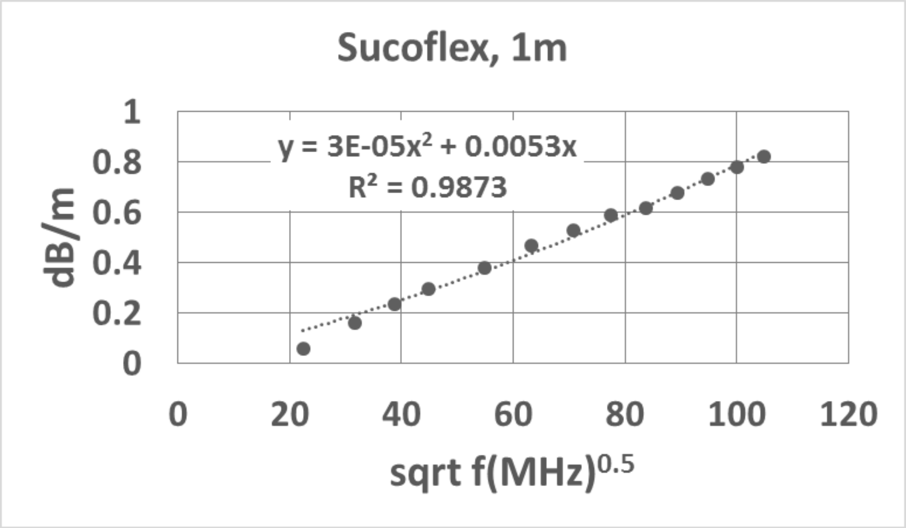
A single τ_1 describes a cable or cable assembly

Cable Losses from Data Sheets

0.05-9 GHz

0.5-11 GHz





①

skin effect dominates (x term), but dielectric loss (x^2 term) gets more important with freq

②

Filter Function from Cable Loss

From [1], for $K = \frac{1}{2\pi r}\sqrt{\frac{\mu}{\sigma}}$, $C(f) = \frac{K\sqrt{\pi f}}{2Z_0}$

r = (effective) inner conductor radius of cable
μ = permeability
σ = conductivity
C = attenuation in nepers/meter
Z_0 = cable impedance (e.g., 50 Ω) = Z_c

Do not have to know
r, μ, σ, or even Z_0

Take dB/m at a frequency, convert to C(f) and find K/Z_0.

Impulse response is $h_1(t) = \alpha t^{-\frac{3}{2}} e^{-\frac{\beta}{t}}$ (normalized),

where $\alpha = \frac{lK}{4Z_0\sqrt{\pi}} = \frac{1}{2}\sqrt{\frac{\tau_1}{\pi}}$ $\beta = \left(\frac{lK}{4Z_0}\right)^2 = \frac{\tau_1}{4}$

$$\tau_1 = \frac{l^2\lambda^2}{2Z_c^2},$$

l = line length. Note that for 2 lengths, $\sqrt{\tau_{eff}} = \sqrt{\tau_1}+\sqrt{\tau_2}$

Convolution Operation

For unfiltered waveform F(t) and cable filter impulse response $h_1(t)$, response f(t) is

$$f(t) = \int_0^t F(t-\tau) h_1(\tau) d\tau$$

$$\tau_1 = \frac{l^2 \lambda^2}{2Z_c^2},$$

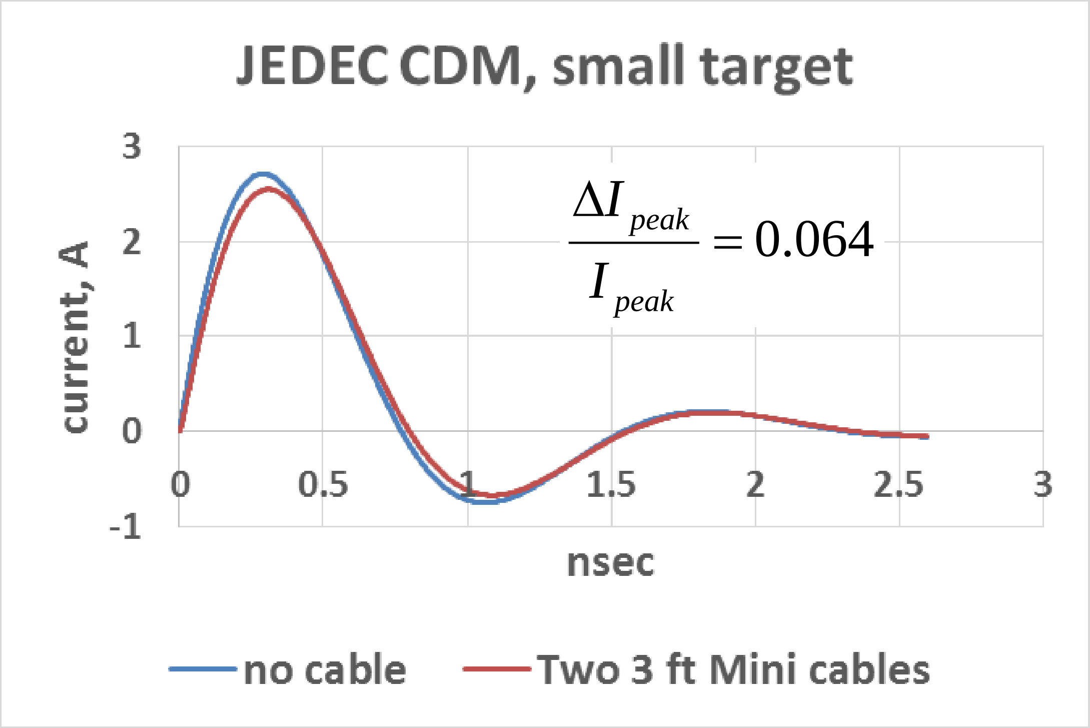
$$h_1(t) = \frac{\sqrt{\tau_1}}{2t\sqrt{\pi t}} e^{-\frac{\tau_1}{4t}}$$

l = line length

Tail of $h_1(t)$ goes as $t^{-3/2}$, integrates to $t^{-1/2}$, thus $\Delta I_p/I_p$ should have a sqrt dependence on t_0, where $I(t_0)=I_p$, as compared with τ_1. This is the unfinished convolution integral at I_p. See later slide.

Convolution Result for Small CDM Target (1)

① + ①



R = 34.3 ohms
C = 5 pF
L = 10.33 nH
Q= 1 nC (200V)

τ_1 = 2.984 psec

$$\tau_1 = \frac{l^2 \lambda^2}{2Z_c^2},$$

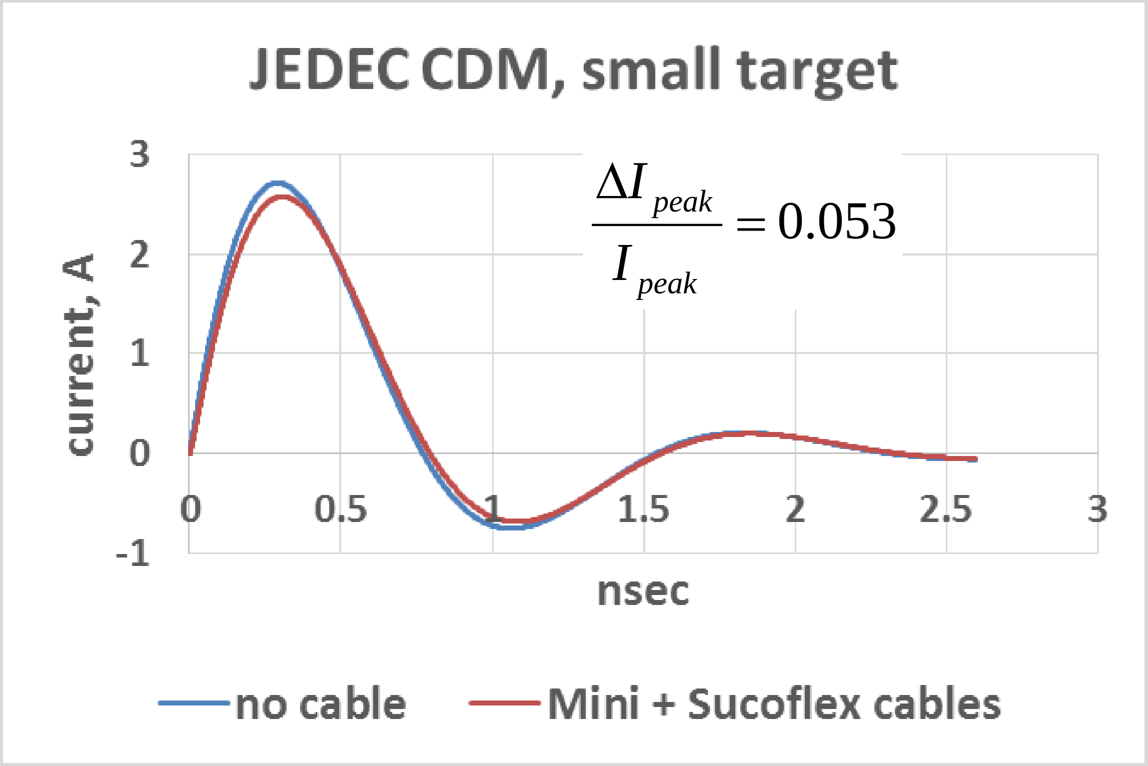
Numerical convolution [3]

Equivalent circuit from [4]

Thermo cables

Convolution Result for Small CDM Target (2)

① + ②



$$\frac{\Delta I_{peak}}{I_{peak}} = 0.053$$

R = 34.3 ohms
C = 5 pF
L = 10.33 nH
Q= 1 nC (200V)

τ_1 = 1.824 psec

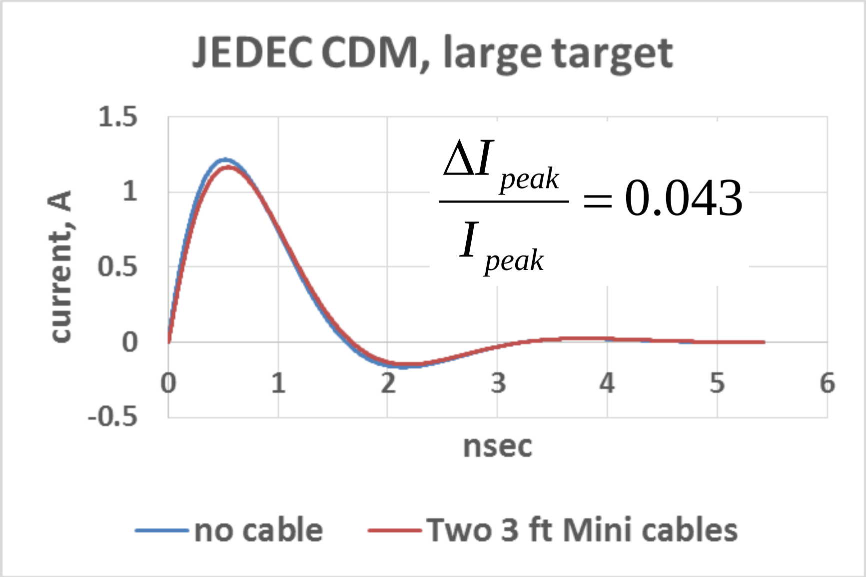
$$\tau_1 = \frac{l^2 \lambda^2}{2Z_c^2},$$

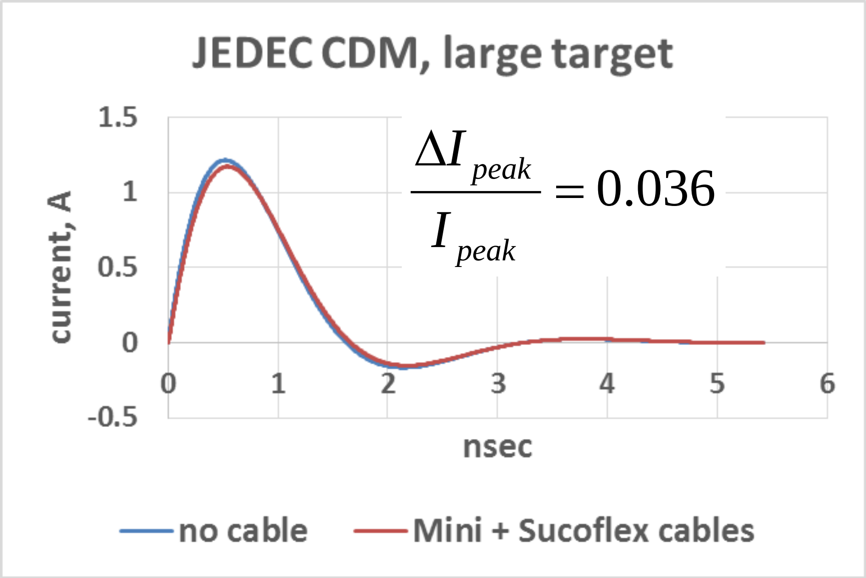
Numerical convolution [3]

Equivalent circuit from [4]

Intel cables

Convolution Result for Large CDM Targets





Thermo

τ_1 = 2.984 psec

R = 28.6 ohms
C = 16.28 pF
L = 11.69 nH
Q= 1 nC
(normalized)

Numerical convolution as in [3]

Intel

τ_1 = 1.824 psec

Equivalent circuit from [4]

$$\tau_1 = \frac{l^2 \lambda^2}{2Z_c^2},$$

Wider pulse, smaller effect

Estimating ΔI_{peak} for Short Cable Length

Convolution integral estimate (see earlier convolution slide) agrees with numerical results when effect is small (<10%):

$$\frac{\Delta I_{peak}}{I_{peak}} \approx \sqrt{\frac{5\tau_1}{4\pi t_0}}$$

$$\tau_1 = \frac{l^2 \lambda^2}{2Z_c^2},$$

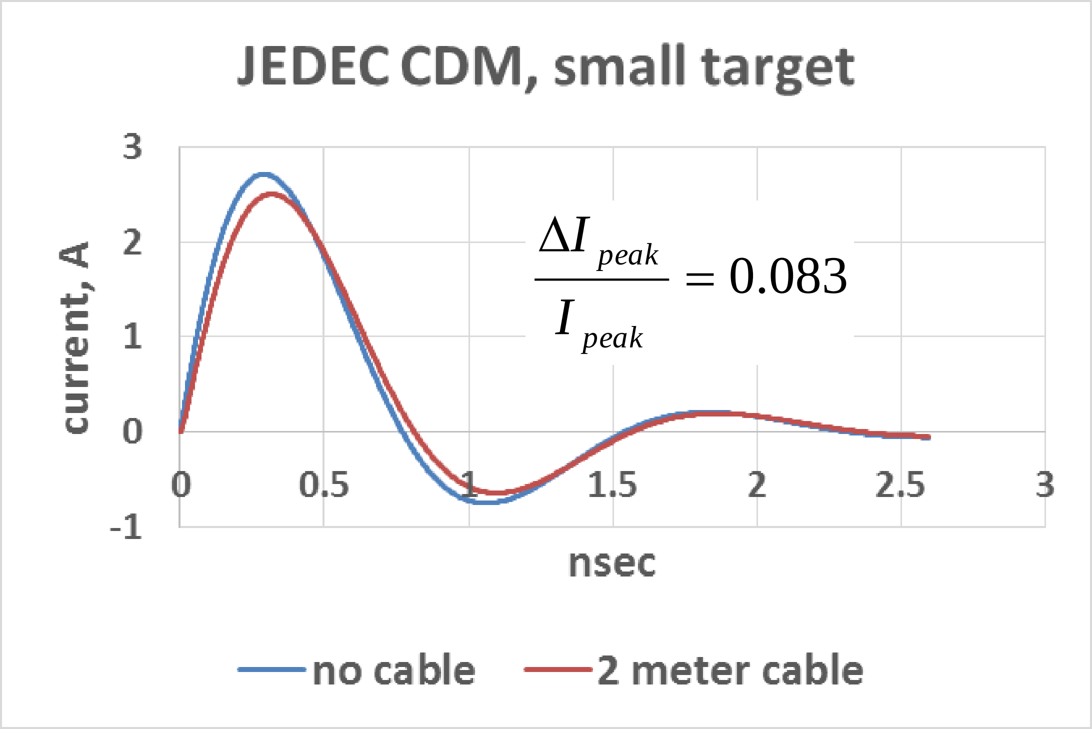
l = line length

where t_0 is such that $I_{peak} = I(t_0)$. t_0 can scale with FWHM*

Predicts JEDEC target examples within a few %; impact proportional to line length

* JS-002 min of 250 psec FWHM, small target, gives $\Delta I_p/I_p$ of ~0.069 for Thermo cables if first cycle is symmetric and t_0 = FWHM

RG58CU Cable, Small JEDEC Target



$$\frac{\Delta I_{peak}}{I_{peak}} = 0.083$$

R = 34.3 ohms
C = 5 pF
L = 10.33 nH
Q= 1 nC (200V)

τ_1 = 6.4 psec

Numerical convolution [3]

Equivalent circuit from [4]

RG58CU cable

8.3% effect (vs. 5-6 %) due to lower frequency cable

Scaling back to 5 GHz

- 2 dB, 9 GHz corresponds to skin depth impulse with 1.88 psec scaling parameter

- 2 dB, 9 GHz scales back by sqrt law to 1.49 dB at 5 GHz (bulk of waveform is at 5 GHz and below) by pretending all losses are skin effect

  - At 5 GHz, 1 + 1 (Thermo cable) losses are at 0.94 + 0.94 dB = 1.88 dB; 2.98 psec. ↓
  - At 5 GHz, 1 + 2 (Intel cable) losses are at 0.94 + 0.53 dB = 1.47 dB; 1.824 psec. ↑
    - This is improved because at 9 GHz there's disproportionate dielectric loss, which goes as freq, while the skin effect goes as sqrt(freq)

- What do we do with spec at 5 GHz?
  - Allow 1.49 dB losses (Intel scheme OK; 1.88 psec skin depth scaling constant)
  - Allow 1.9 dB losses (both Intel and Thermo schemes ok; 3.05 psec skin depth scaling constant)

Estimated $\Delta I_p/I_p$ for minimum FWHM (250 psec)

$$\frac{\Delta I_{peak}}{I_{peak}} \approx \sqrt{\frac{5\tau_1}{4\pi t_0}}$$

Suppose we have a

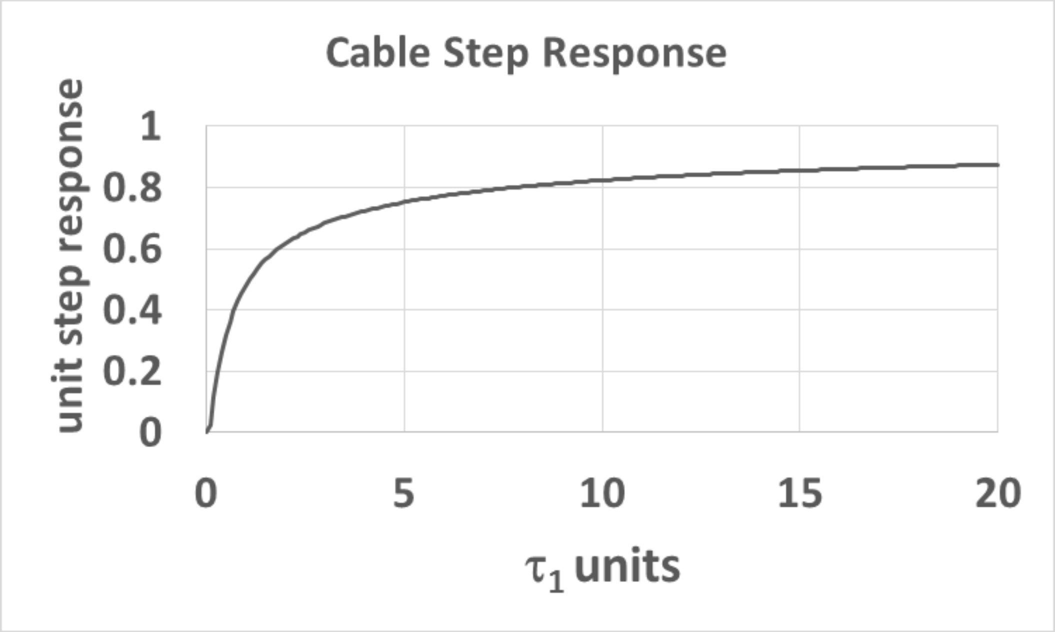
1.9 dB, 5 GHz cable spec: $\Delta I_p/I_p \approx 0.069$

1.49 dB, 5 GHz cable spec: $\Delta I_p/I_p \approx 0.055$

Suggest 1.5 dB, 5 GHz as a round number

Bonus: Cable as a Rise Time Filter for CCDM

Cable affects only measurement of regular JS-002 CDM but cable affects the pulse and the measurement in CCDM. If a rise time filter is needed for agreement with legacy CDM, consider cable choice and length for filter synthesis.



Long impulse tail means slow finish after 8-10 τ_1 units

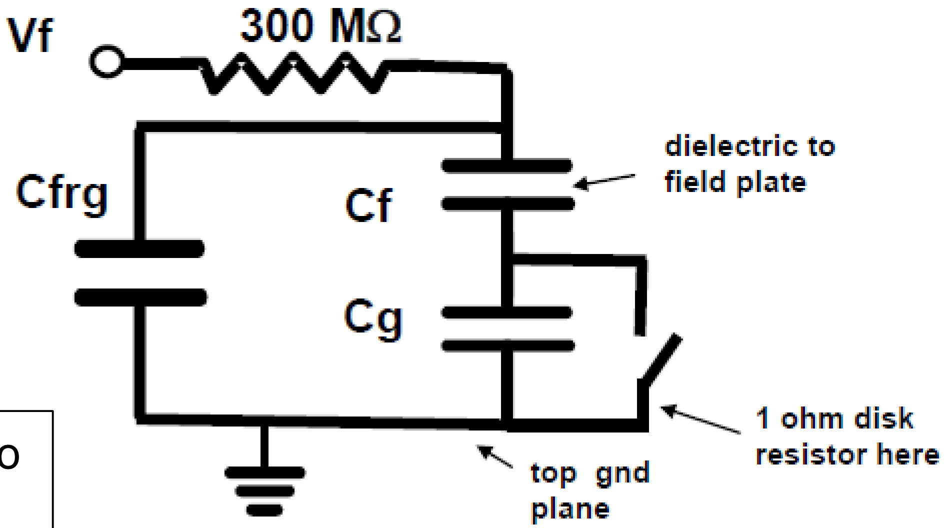
$$\tau_1 = \frac{l^2 \lambda^2}{2Z_c^2},$$

l = line length

Step response $$h_2(t) = \int_0^t h_1(\tau)d\tau = erfc\sqrt{\frac{\tau_1}{4t}}$$

See more accurate step response with complete 2016 cable model in [5]

Bonus #2: CDM Field Capacitance Variation



Applies to dielectric and disk variations

$$C_{eq} = C_g + \frac{C_f C_{frg}}{C_f + C_{frg}} \qquad \frac{\Delta C_{eq}}{C_{eq}} = \frac{1 - \dfrac{C_g}{C_{eq}}}{1 + \dfrac{C_f}{C_{frg}}} \frac{\Delta C_f}{C_f}$$

$I_{pk} \sim \sqrt{C_{eq}}$ or weaker:

$$\frac{\Delta I_{pk}}{I_{pk}} \le \frac{1}{2} \left[\frac{1 - \dfrac{C_g}{C_{eq}}}{1 + \dfrac{C_f}{C_{frg}}} \right] \frac{\Delta C_f}{C_f}$$

For small cal disk,

$C_f \approx 7$ pF
$C_g \approx 0.3$ pF
$C_{frg} \approx 10$ pF

$C_{eq} \approx 4.4$ pF, so

$$\frac{\Delta I_{pk}}{I_{pk}} \le 0.27 \frac{\Delta C_f}{C_f}$$

For large cal disk, it is about

$$\frac{\Delta I_{pk}}{I_{pk}} \le 0.05 \frac{\Delta C_f}{C_f}$$

Conclusion

- Computed the effect on CDM waveform of ~2 meters of coaxial cable in CDM tester for JS-002 specs
  - ☐ Skin effect filter function used to find I_{peak} of small CDM target is lower by 6.4% for Thermo CDM setup, 5.3% for Intel setup
  - ☐ Simple formula for ΔI_{peak} estimates follows square root law, derivable from convolution integral
  - ☐ Rise time filter using cable is possible for CCDM
- Present JS-002 cable spec should be revised
  - ☐ No setup meets <2 dB at 9 GHz
  - ☐ But cal waveform spectrum is almost all < 5 GHz
    - $\leq$1.5 dB @ 5 GHz would work for a practical CDM setup

References

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2. J.H.R. Schrader, "Wireline Equalization using Pulse-Width Modulation", Ph.D. thesis, Universiteit Twente, The Netherlands (2007). Available at http://www.nikhef.nl/pub/services/biblio/theses_pdf/thesis_J_R_Schrader.pdf.

3. Web resource, “Excellaneous” VB macros; see MacroBundle12 at http://www.bowdoin.edu/~rdelevie/excellaneous/#downloads.

4. T.J. Maloney and N. Jack, "CDM Tester Properties as Deduced from Waveforms", 2013 EOS/ESD Symposium, Sept. 2013, pp. 374-382. Expanded version in IEEE Trans. Dev. and Materials Rel., Vol. 14, No. 3, Sept. 2014, pp. 792-800. Available at https://www.sites.google.com/site/esdpubs/documents/tdmr14.pdf.

5. P. Belforte, “Digital Wave Simulation of Lossy Lines for Multi-Gigabit Applications, IEEE Electromagnetic Compatibility Magazine, Vol. 5, no. 2, pp. 48-55, 2nd Quarter 2016. Has complete “fancy, 21st century” circuit model for cables with all effects. More than we need; not very accessible, but impressive.

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