A Turnkey Method for Calculating Coaxial Cable Loss Effects on CDM Waveforms

Timothy J. Maloney

Center for Analytic Insights, Palo Alto, CA

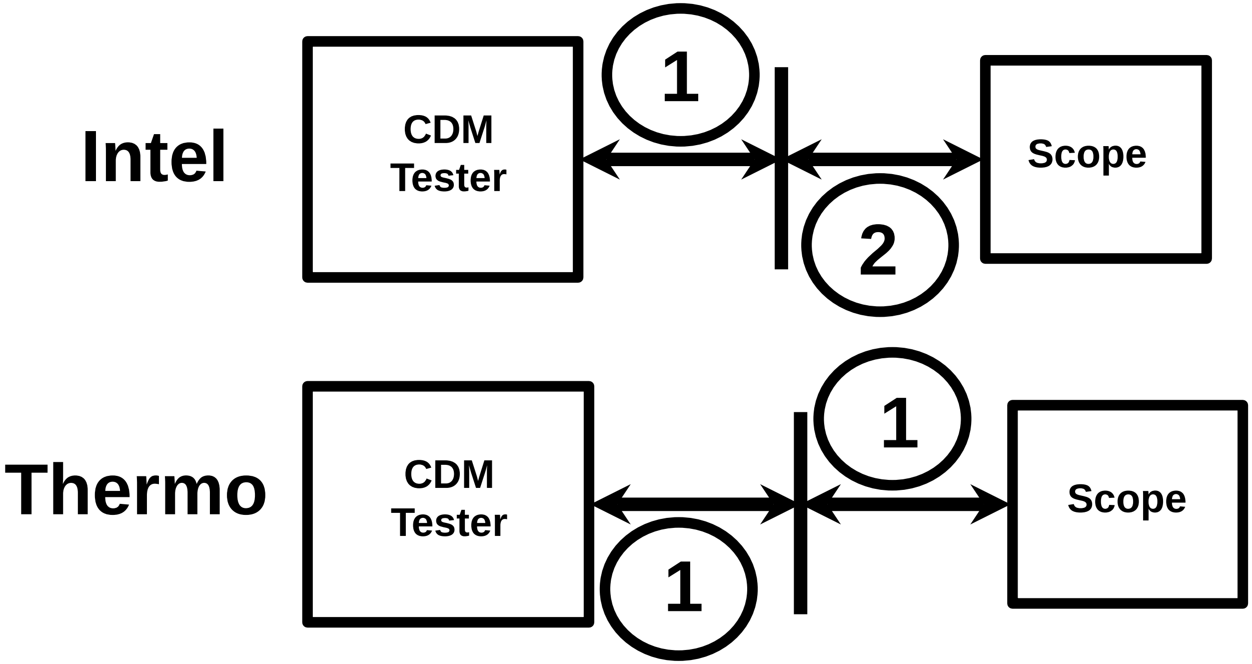
tjmaloney@sbcglobal.net

CAI

Objective and significance

- CDM waveforms are affected by losses in the coaxial cables (about two meters total) necessary to connect the test head to an oscilloscope. While losses in dB/meter vs. frequency for various cables are published and easily accessed, there has been no "turnkey" method for assessing the precise impact of cable loss on a specified CDM pulse in time domain. This work demonstrates <u>fast arrival at a time domain filter function</u> for a CDM tester cable setup, suitable for calculating waveforms on an Excel worksheet using numerical convolution.
- First the skin effect and dielectric loss components are deduced from dB/m data by curve fit, knowing that skin effect goes as $\sqrt{f}$ and dielectric loss goes as f. Then a complete filter function is synthesized and applied to the CDM waveform to assess cable attenuation, all through convolution. For a fast CDM pulse (using the small calibration target), a typical setup will reduce the peak current by a tolerable 4.7% for suitable fast cables, but by 10.9% for "ordinary" lab cable like RG58CU. The use of “available yet reasonably fast” cables is found to be indicated for CDM calibration, and the JS-002 CDM test standard was recently changed accordingly.

CDM Tester Measurement Setups



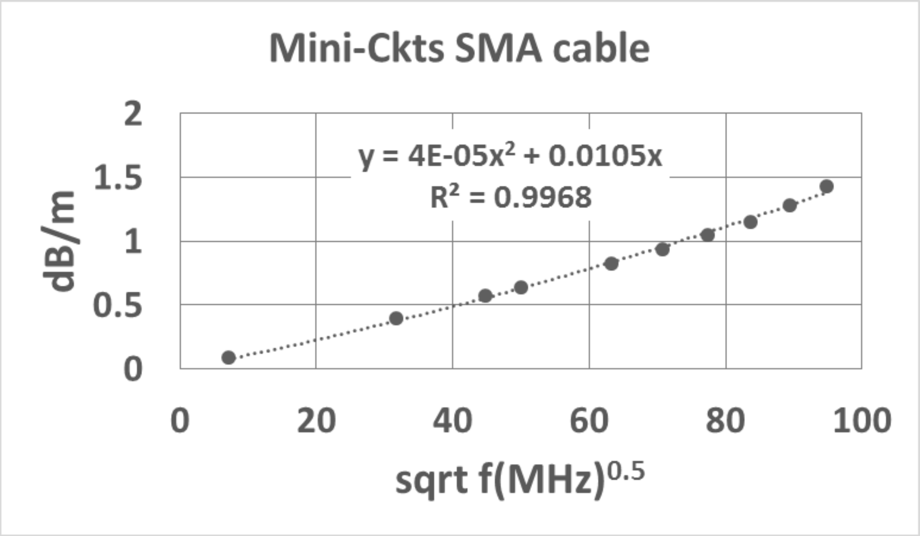
1. Mini-Ckts SMSM+, 3’, 18 GHz
2. Sucoflex 104, 1m, 26 GHz

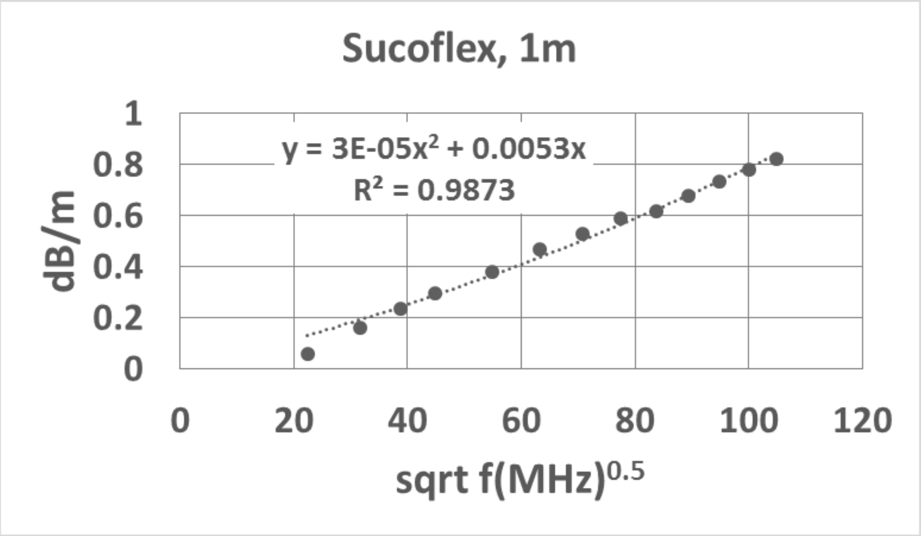
Ack. to Josh Morris (Intel), Tom Meuse (Thermo)

Cable Losses from Data Sheets

0.05-9 GHz

0.5-11 GHz





①

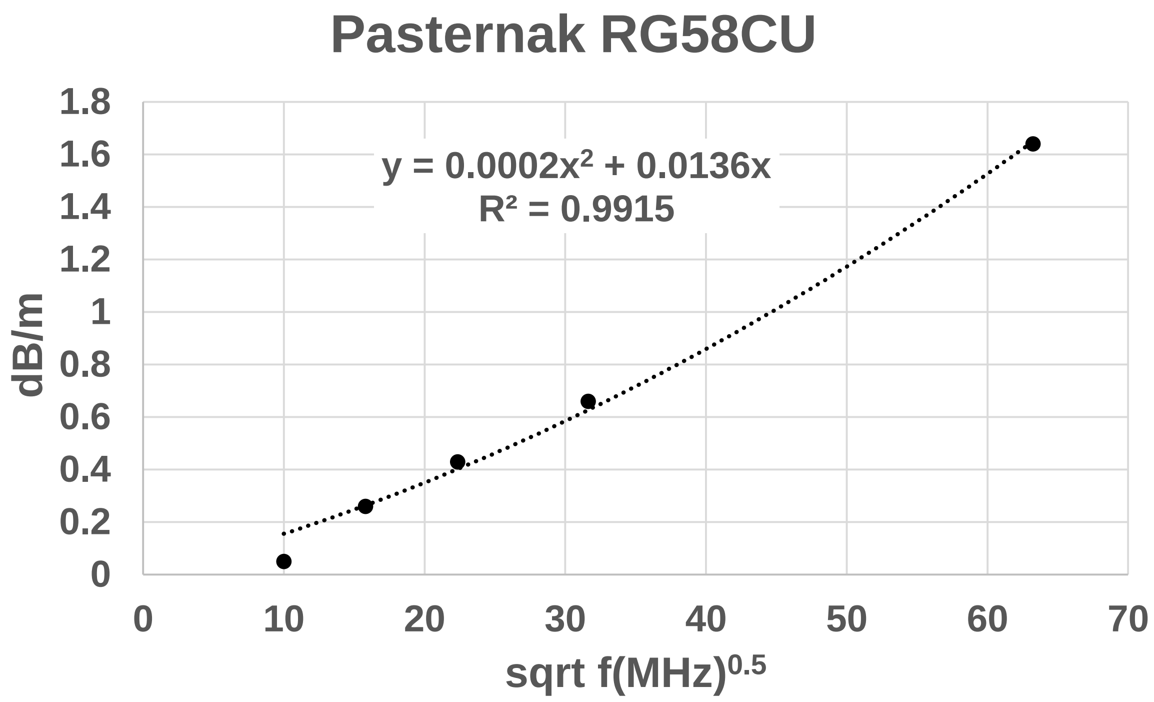
②

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

Plot and obtain quadratic fit to √f

Lossy Cable Example

0.1-4 GHz



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

Plot and obtain quadratic fit to √f

Impulse Functions for Cable Losses

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

Skin Effect [1]

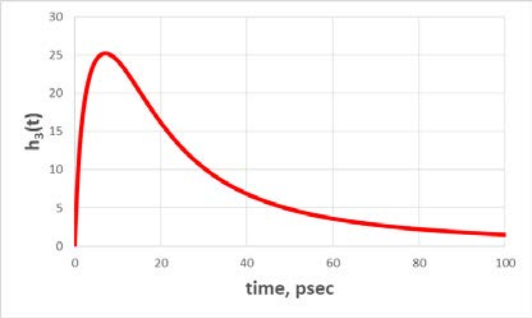
t > 0; integrates to 1

$$h_2(t) = \frac{2\tau_2}{\pi(\tau_2^2 + t^2)}$$

Dielectric Loss [2]

$$h_3(t) = h_1(t) \otimes h_2(t)$$

Result, through convolution



For

$$dB/m = a\sqrt{f} + bf$$

$$\tau_1 = \frac{\ln^2 10}{400\pi} a^2 \times 10^{-6} \sec$$

Skin Effect, 1m

$$\tau_2 = \frac{\ln 10}{20\pi} b \times 10^{-6} \sec$$

Dielectric Loss, 1m

Cable Losses, Skin Effect and Dielectric

			1 m		1 m	2 m	2 m
	Cable	**a,MHz$^{-0.5}$**	**τ_1,psec**	**b, µsec**	**τ_2,psec**	**τ_1,psec**	**τ_2,psec**
	RG58 lo-loss	0.01124	0.533	1.2×10^{-5}	0.4398	2.13	0.8795
	RG58CU (lossy)	0.0136	0.7804	2×10^{-4}	7.329	3.12	14.66
	Aircell7	0.0057	0.137	3×10^{-5}	1.099	0.5483	2.199
①	Mini-Ckts SMA	0.0105	0.465	4×10^{-5}	1.466	1.8606	2.932
②	Sucoflex 104	0.0053	0.1185	3×10^{-5}	1.099	0.474	2.199

For

$$dB/m = a\sqrt{f} + bf$$

$$\tau_1 = \frac{\ln^2 10}{400\pi} a^2 \times 10^{-6}\ \mathrm{sec}$$

Skin Effect, 1m

$$\tau_2 = \frac{\ln 10}{20\pi} b \times 10^{-6}\ \mathrm{sec}$$

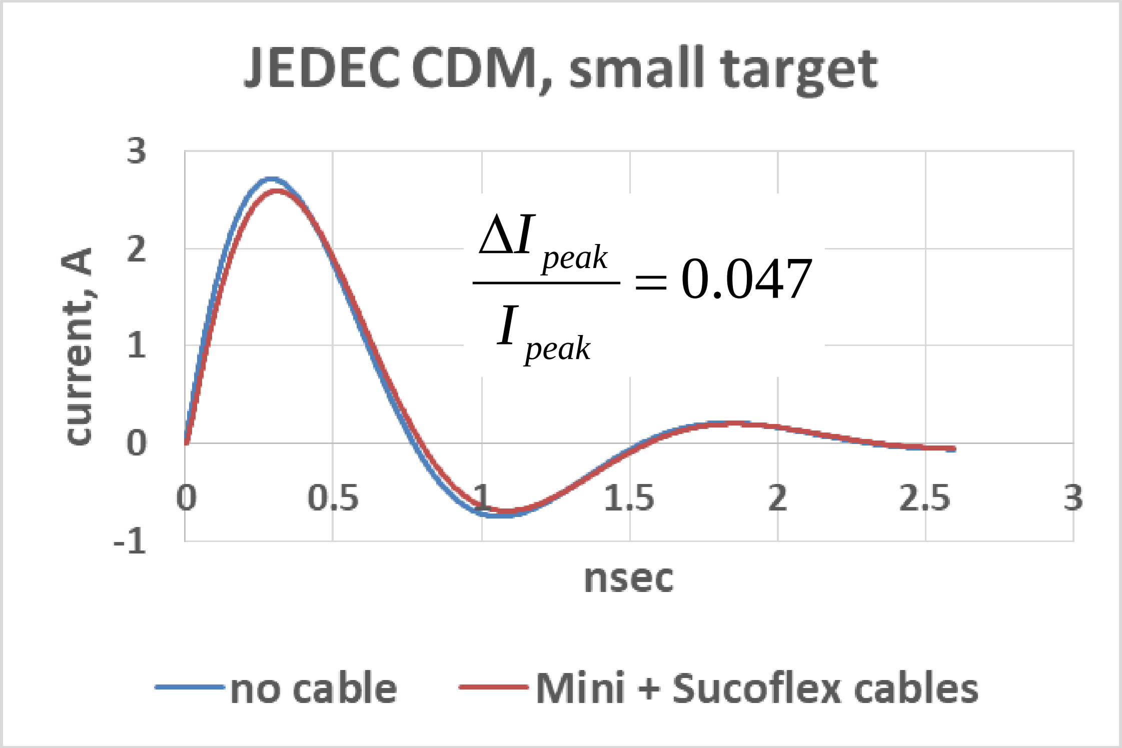
Dielectric Loss, 1m

Addition for multiple lines: $\sqrt{\tau_{1eff}} = \sqrt{\tau_{11}} + \sqrt{\tau_{12}}$; $\tau_{2eff} = \tau_{21} + \tau_{22}$

Convolution Result for Small CDM Target

① + ②

$$I'(t) = h_3(t) \otimes I(t) = \int_0^t h_3(t-\tau) I(\tau) d\tau$$



$$\frac{\Delta I_{peak}}{I_{peak}} = 0.047$$

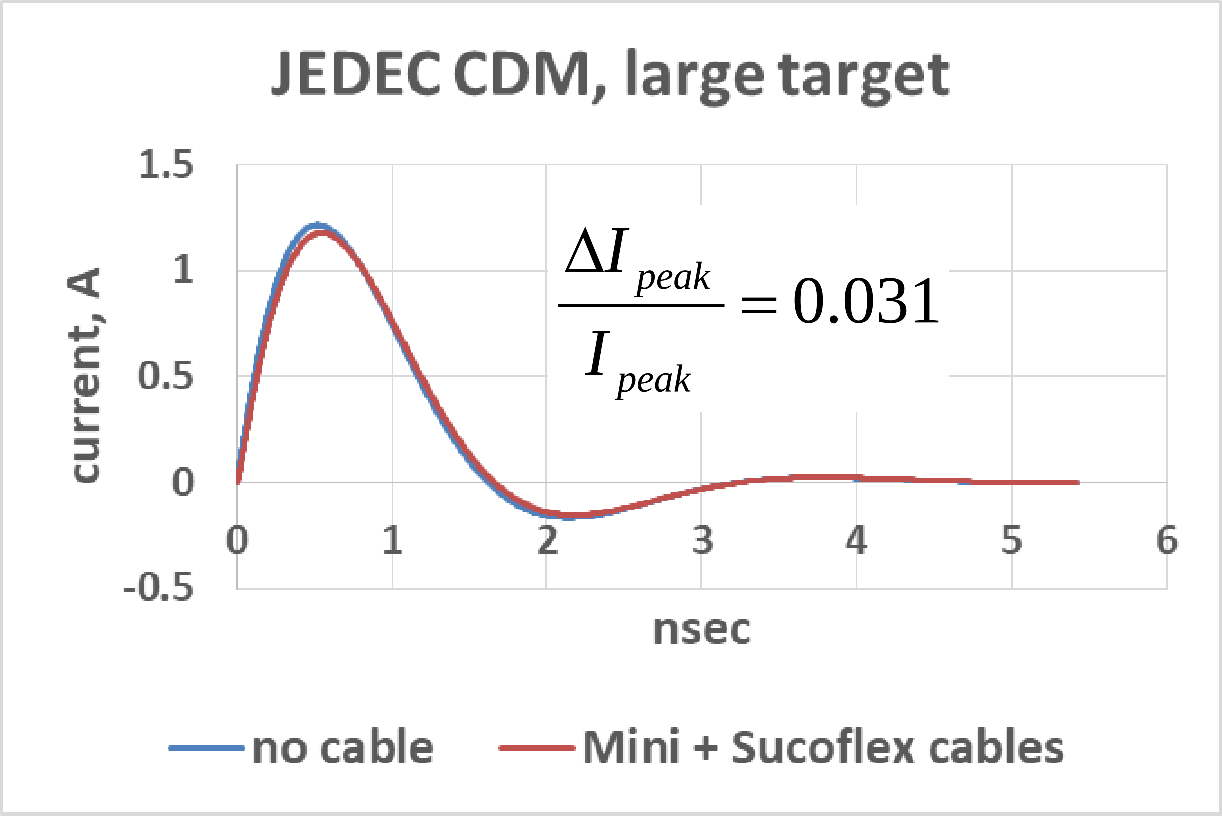
R = 34.3 ohms
C = 5 pF
L = 10.33 nH
Q= 1 nC (200V)

τ_1 = 1.053 psec
τ_2 = 2.565 psec

- 1 meter each of MiniCircuits and Sucoflex cables (Intel)
- Maloney and Jack, 2013 EOS/ESD pp. 374-82 describes CDM equivalent circuit and numerical convolution with Excel

Convolution Result for Large CDM Target

① + ②



$$\frac{\Delta I_{peak}}{I_{peak}} = 0.031$$

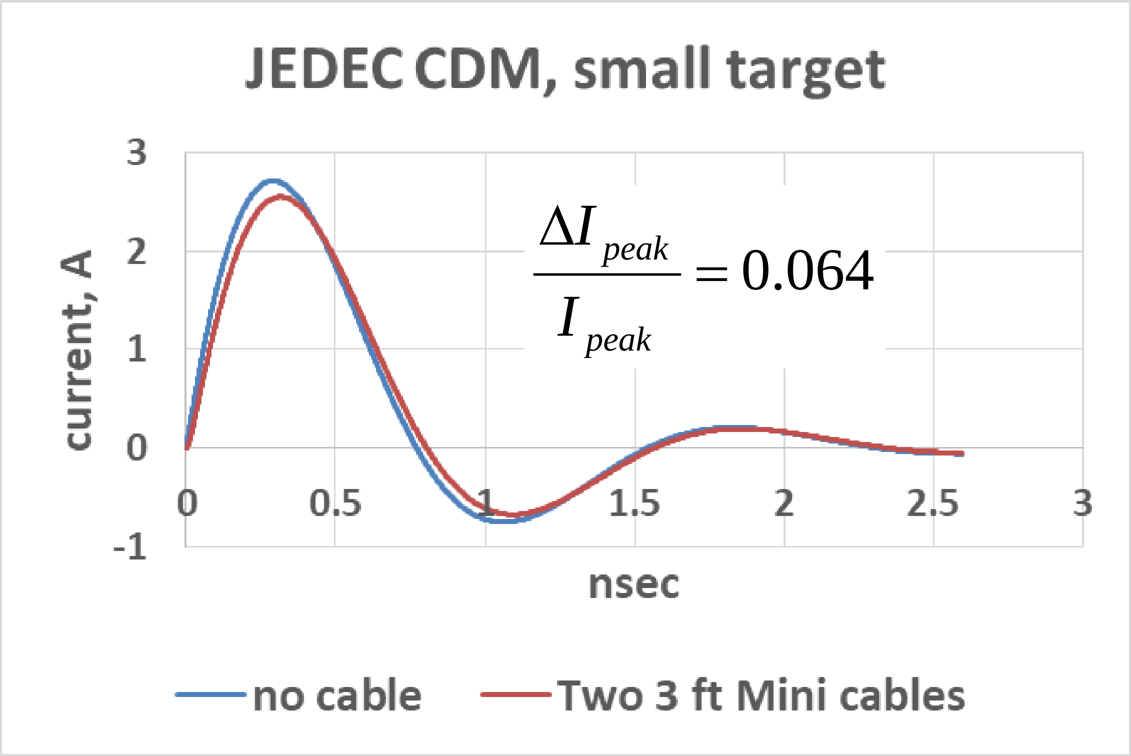
R = 28.6 ohms
C = 16.28 pF
L = 11.69 nH
Q= 1 nC
(normalized)

τ_1 = 1.053 psec
τ_2 = 2.565 psec

- 1 meter each of MiniCircuits and Sucoflex cables (Intel)
- Wider pulse, smaller effect

Convolution Result for Small CDM Target

① + ①



$$\frac{\Delta I_{peak}}{I_{peak}} = 0.064$$

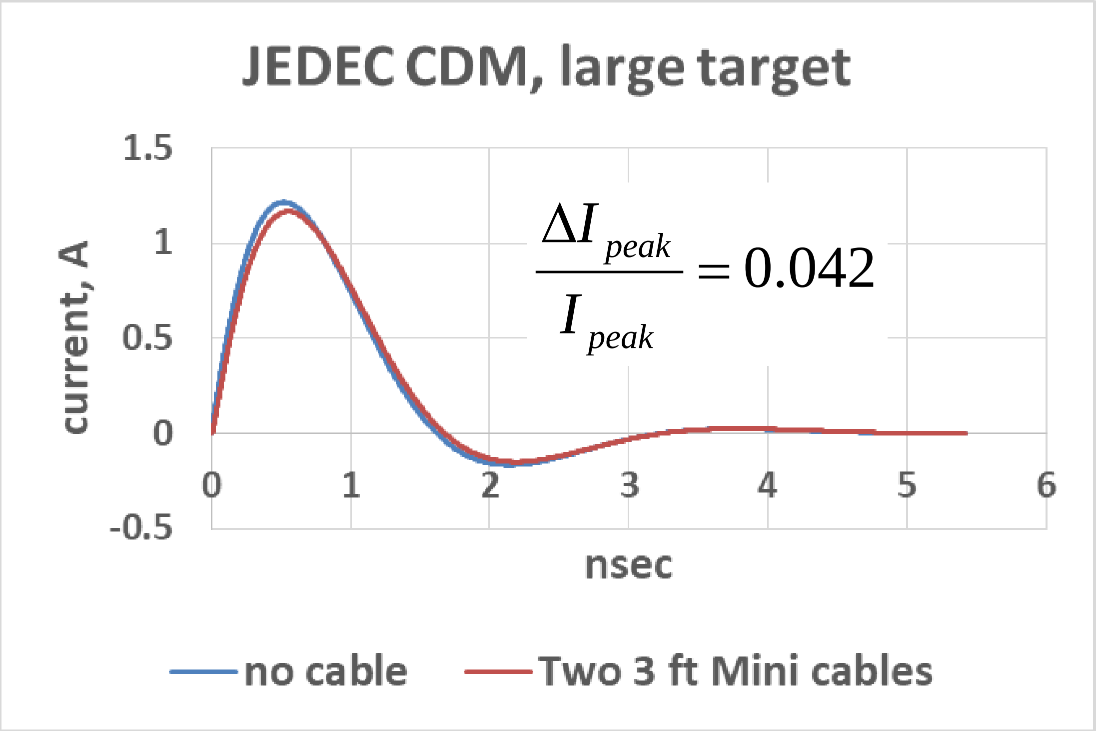
R = 34.3 ohms
C = 5 pF
L = 10.33 nH
Q= 1 nC (200V)

τ_1 = 1.8606 psec
τ_2 = 2.9317 psec

- Two 3 ft MiniCircuits SMA cables (Thermo)
- Maloney and Jack, 2013 EOS/ESD pp. 374-82 describes CDM equivalent circuit and numerical convolution with Excel

Convolution Result for Large CDM Target

① + ①



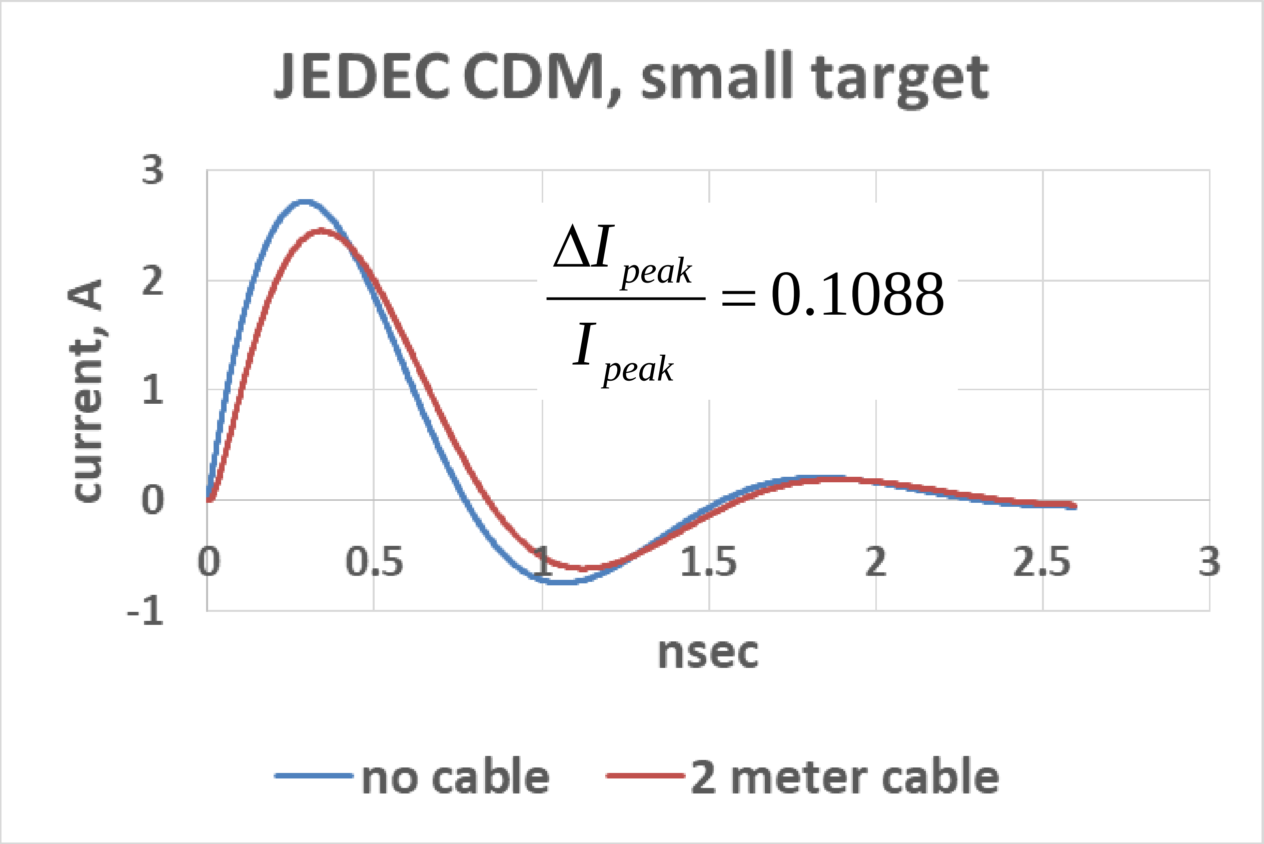
$$\frac{\Delta I_{peak}}{I_{peak}} = 0.042$$

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

τ_1 = 1.8606 psec
τ_2 = 2.9317 psec

- Two 3 ft MiniCircuits SMA cables (Thermo)
- Wider pulse, smaller effect

Lossy RG58CU Cable, Small JEDEC Target



$$\frac{\Delta I_{peak}}{I_{peak}} = 0.1088$$

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

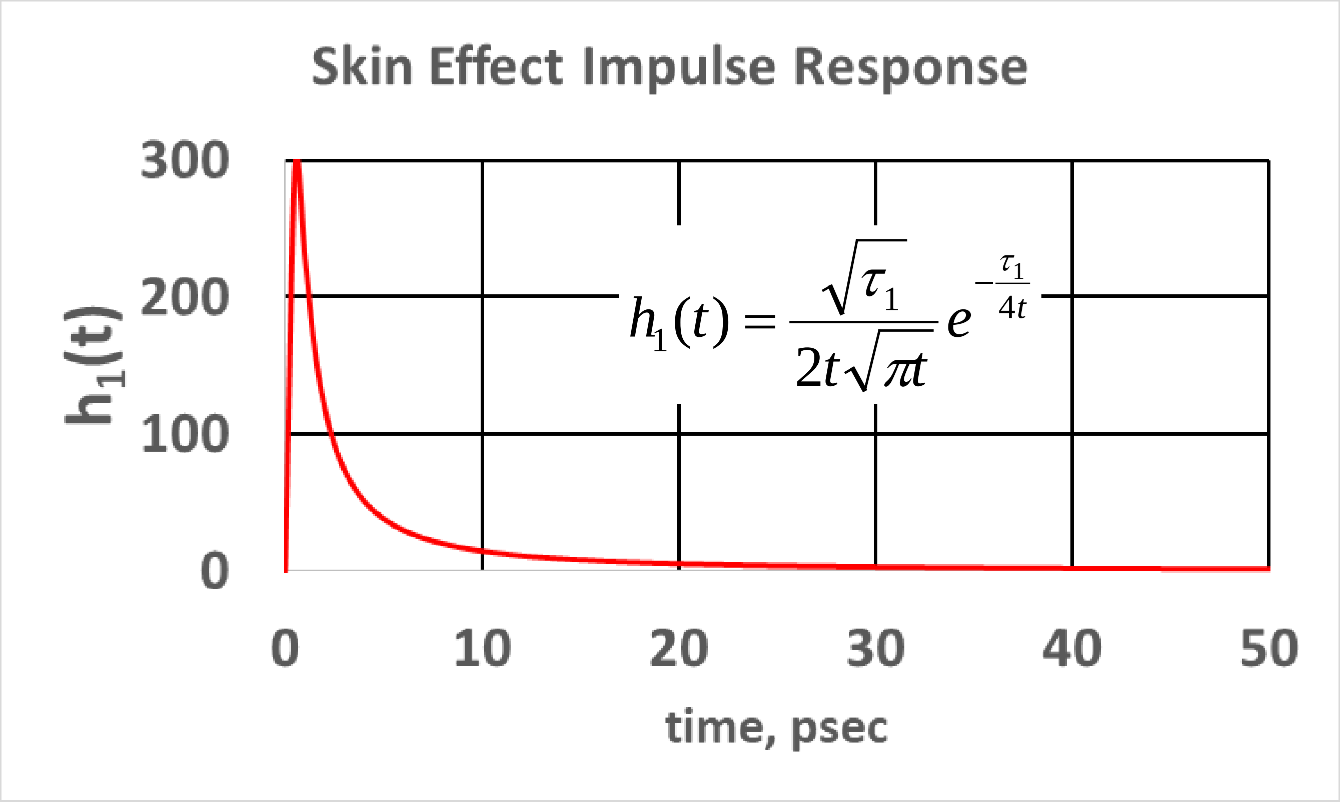
τ_1 = 3.121 psec
τ_2 = 14.565 psec

10.9% effect (vs. 4.7 %) due to lower frequency cable

Bonus: Quick Assessment Method

- What if we could roughly approximate the deconvolved, unattenuated waveform with a single factor α that would amplify measured I(t) and compress it in time?
  - ☐ Transformed waveform would be $I'(t)=\alpha I(\alpha t)$; no DC change
- To do this, first find FWHM of the main CDM peak
  - ☐ Calculate $f_0=1/[\pi * \mathrm{FWHM}]$
- Find $\mathrm{dB}(f_0)$ of the cable assembly
  - ☐ Then $\alpha=10^{\mathrm{dB}(f_0)/20}$
- For RG58CU, this gives 11.32% $\Delta I_{peak}/I_{peak}$ (10.88% exact)
- For Thermo (MiniCkts SMA), 6.9% $\Delta I_{peak}/I_{peak}$ (6.4% exact)
- No convolution required! Close, but no guarantees on accuracy.
  - ☐ $I'(t)$ is a good trial function for iterative deconvolution

Impulse Response, Skin Effect



Skin Effect Impulse Response

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

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

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

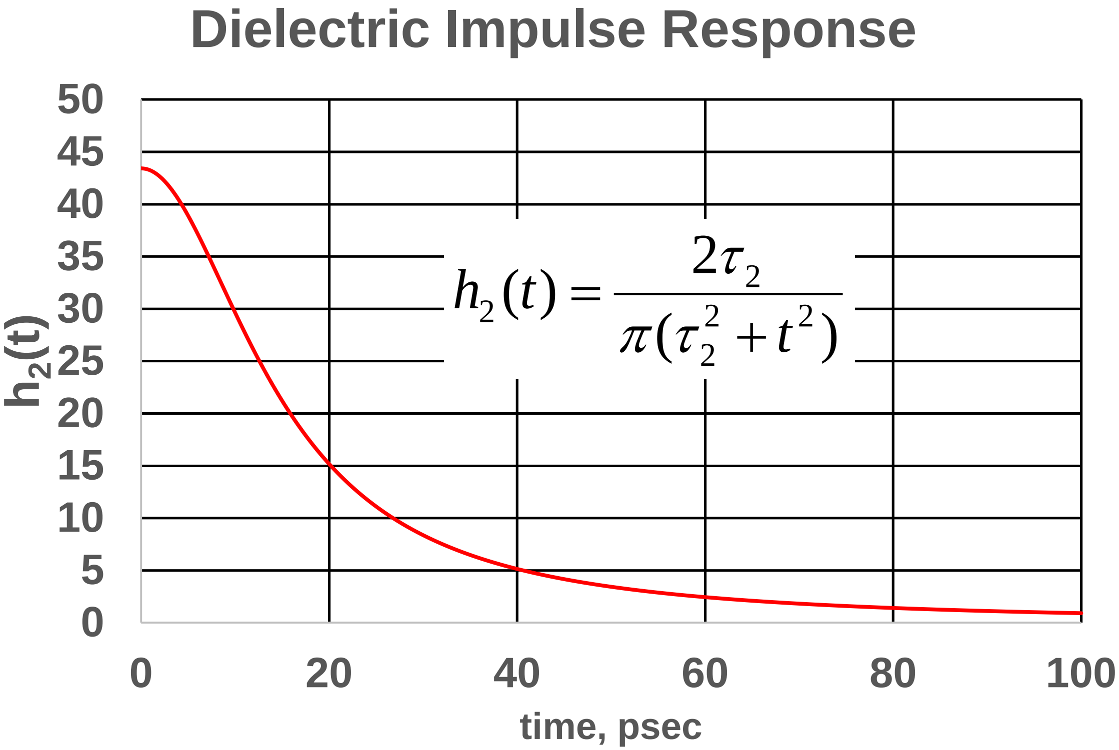
Exact inverse Laplace transform $h_1(t)$ exists [1]

$h_1(t)$ integrates to unity

A single τ_1 describes skin effect for a cable or cable assembly. $\tau_1 \propto l^2$ (l=line length)

Impulse Response, Dielectric Loss

$$f(\omega) = C\exp(-K|\omega|)$$



$$h_2(t) = \frac{2\tau_2}{\pi(\tau_2^2 + t^2)}$$

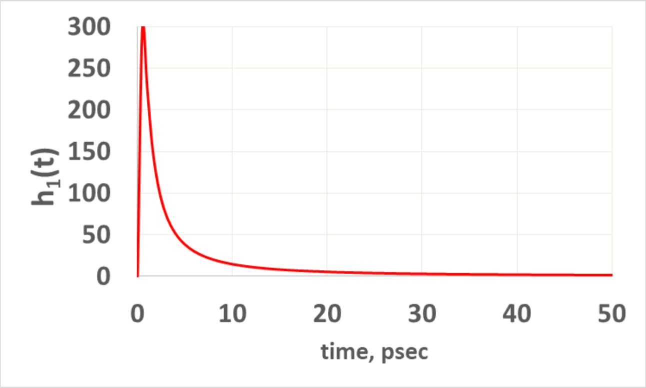
Abrupt step is needed to convert inverse Fourier transform to a causal filter [2]

$h_2(t)$ integrates to unity

A single τ_2 describes dielectric loss for a cable or cable assembly. $\tau_2 \propto l$ (line length)

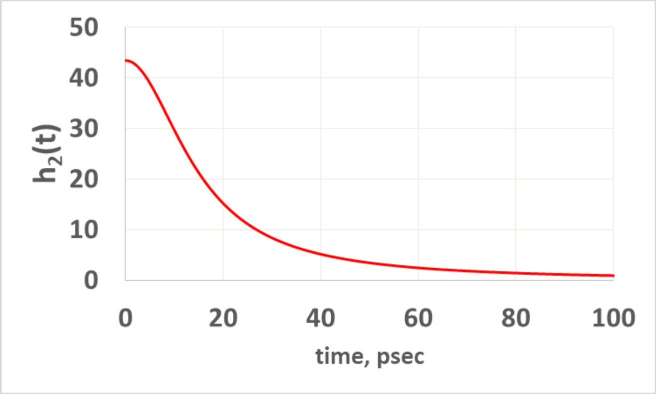
Final Impulse Response Function $h_3(t)$

Skin Effect

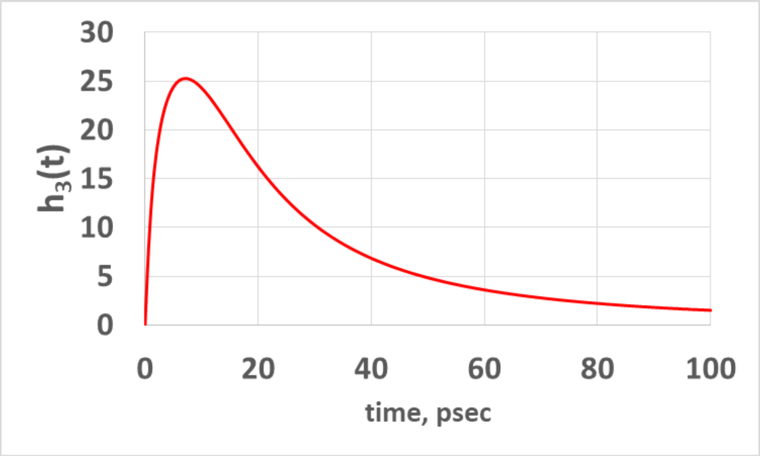


$$\otimes$$

Dielectric



$$=$$



$$I(s) = \frac{CV_0}{1 + RCs + LCs^2}$$

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

$$I(t) = \mathscr{L}^{-1} I(s)$$

$$I'(t) = h_3(t) \otimes I(t) = \int_0^t h_3(t-\tau) I(\tau)\, d\tau$$

$$h_3(t) = h_1(t) \otimes h_2(t) = \int_0^t h_1(t-\tau) h_2(\tau)\, d\tau$$

Conclusions

- Published dB/m vs. f data for cables are polynomial-fit to find skin effect and dielectric loss elements
  - ☐ Use Excel convolution to find resultant impulse filter function
  - ☐ Then convolve filter with input pulse waveform to find measured waveform (more Excel)
- Quick estimate from dB/m data and pulse width can assess the problem and provide a good trial function for iterative exact solution of input I′(t) given measured I(t).
- Results for typical (Intel, Thermo) CDM setups presented
  - ☐ Using two high-f cables about 1 meter each
    - Small CDM target worst; find 4.7-6.4% I_{peak} loss
    - Large CDM target only 3.1-4.2% I_{peak} loss
  - ☐ Typical lossy lab cable (RG58CU) gives 10.88% I_{peak} loss
    - Good reason to examine cable setup

References

1. R.L. Wigington and N.S. Nahman, "Transient Analysis of Coaxial Cables Considering Skin Effect", Proc. IRE, vol. 45, pp. 166-174, Feb. 1957. Skin effect impulse function.

2. R.B. Wu, Fast Eye-Diagram Analysis, http://cc.ee.ntu.edu.tw/~rbwu/rapid_content/course/highspeed/SI11_Fast_Eye.pdf. Simple causal form for dielectric loss impulse function.

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.

Author's email: tjmaloney@sbcglobal.net

Publication web site: https://www.sites.google.com/site/esdpubs/documents