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First Principles Model of Electric and Magnetic Cable Braid Penetrations

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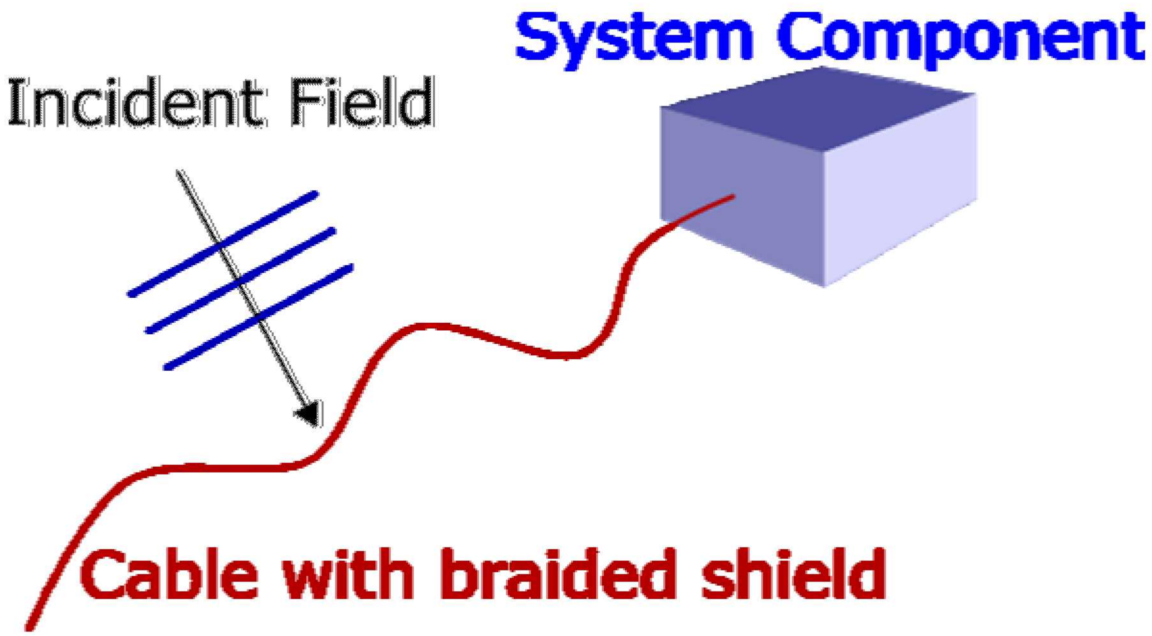
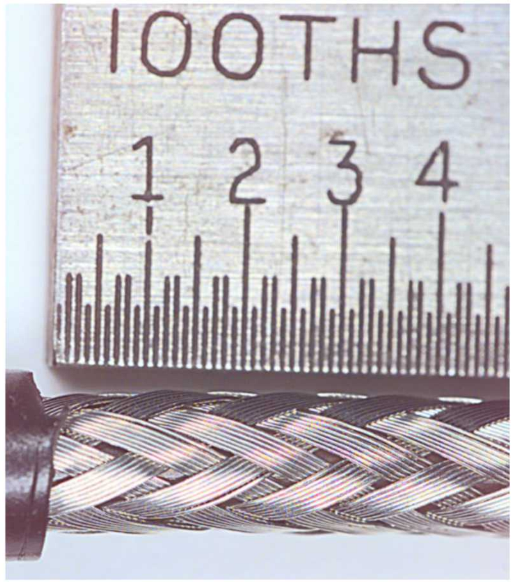
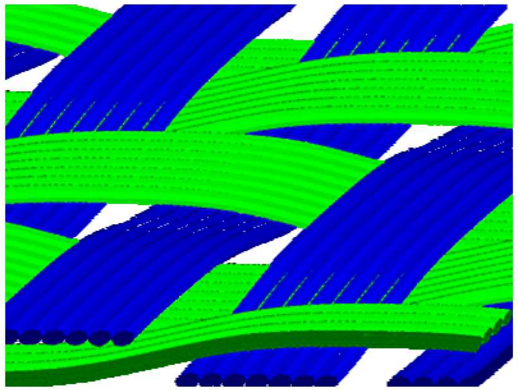
Motivation and background



Belden 8240 cable



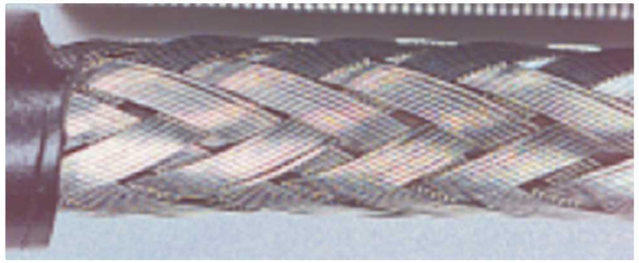
Belden 8240 Braid Mesh

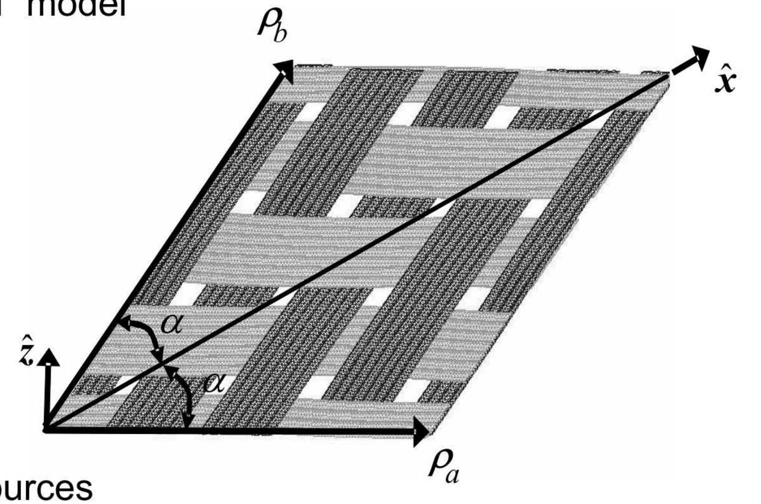


- ❑ Understanding electromagnetic pathways into critical components is essential in determining potential system damage or upset due to electromagnetic coupling
- ❑ One important pathway into components is electromagnetic penetration through braided shields used in cables

Introduction

- The purpose of this talk is to provide a 1st principles model based on solutions to electric and magnetic integral equations for braid penetration
  - Simplify geometry by using a doubly-infinite "planar braid" model





  - Simplify integral equations by using multipole-filament sources
  - Increase calculation efficiency of the Green's functions and their gradients by using Ewald techniques

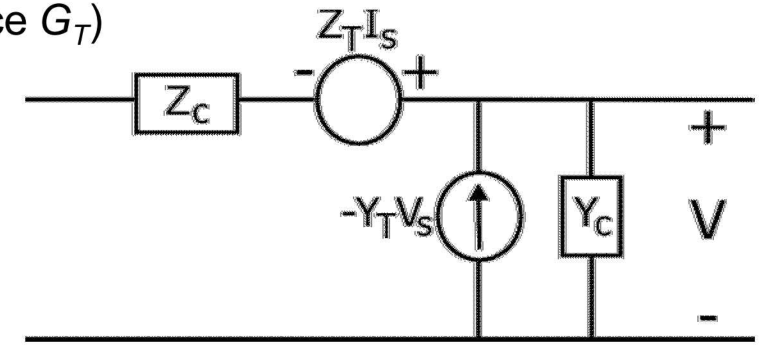
- The application is the capability to predict voltages and currents induced by external environments into shielded cables and, ultimately, into electronic devices.

The first principles models are used to compare to analytical and semi-empirical formulas when applicable, as well as to provide solutions for braids where these models are not available.

Warne et al., Sandia National Laboratories Report SAND2015-5019, Albuquerque, NM (2015)
Warne et al., *Progress in Electromagnetics Research B* **66**, 63-89 (2016)
Campione et al., *IEEE Transactions on Electromagnetic Compatibility,* DOI: 10.1109/TEMC.2017.2721101 (2017)

Circuit representation of shielded cables

- A shielded cable is generally modeled via canonical parameters:
  - Transfer parameters to model the shield properties (related to the braid weave characteristics and material)
    - The per-unit length transfer impedance Z_T (proportional to the transfer inductance L_T and resistance R_T)
    - The per-unit length transfer admittance Y_T (proportional to the transfer capacitance C_T and conductance G_T)



  - Self parameters formed by the inner conductor and the shield
    - The per-unit length (series) self-impedance Z_c
    - The per-unit length (parallel) self-admittance Y_c

The first principles models provide estimates for all these parameters

E. F. Vance, Coupling to shielded cables: R.E. Krieger (1987)

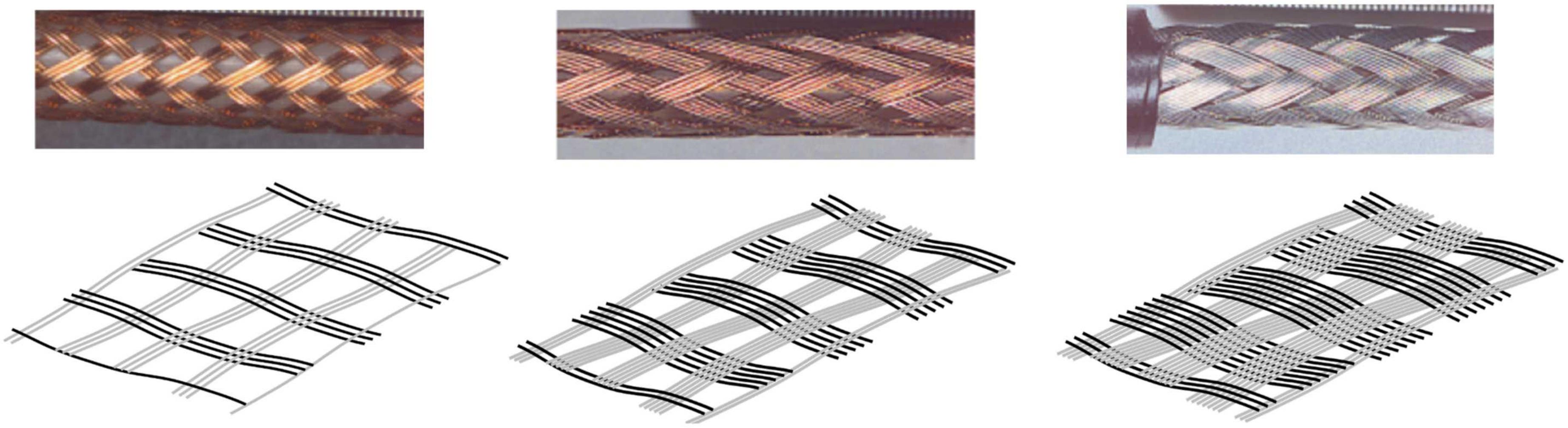
Celozzi et al., Electromagnetic shielding: John Wiley and Sons (2008)

Campione et al., *Progress in Electromagnetics Research C* **65**, 93-102 (2016)

Goal of modeling realistic cables

- We now apply the first principles model to realistic cables without dielectrics

(a) REMEE | (b) Belden 9201 | (c) Belden 8240



(a)	(b)	(c)
59% optical coverage	78% optical coverage	95% optical coverage
3 strands per carrier	5 strands per carrier	7 strands per carrier
34.2° braid angle	22.0° braid angle	24.4° braid angle

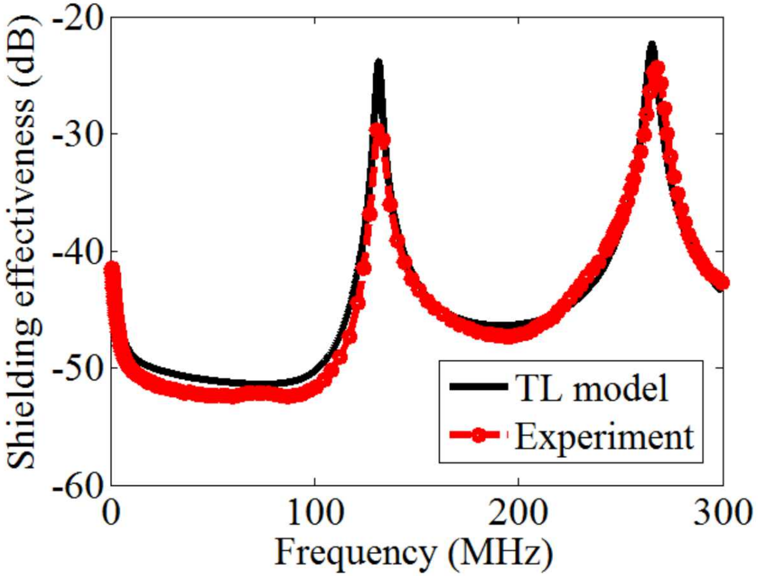
- In the model mesh of the cable braid, the wire strands follow a sinusoidal path that allows for the radial size of the individual strands and the specifications above.

Campione et al., *IEEE Transactions on Electromagnetic Compatibility,* DOI: 10.1109/TEMC.2017.2721101 (2017)

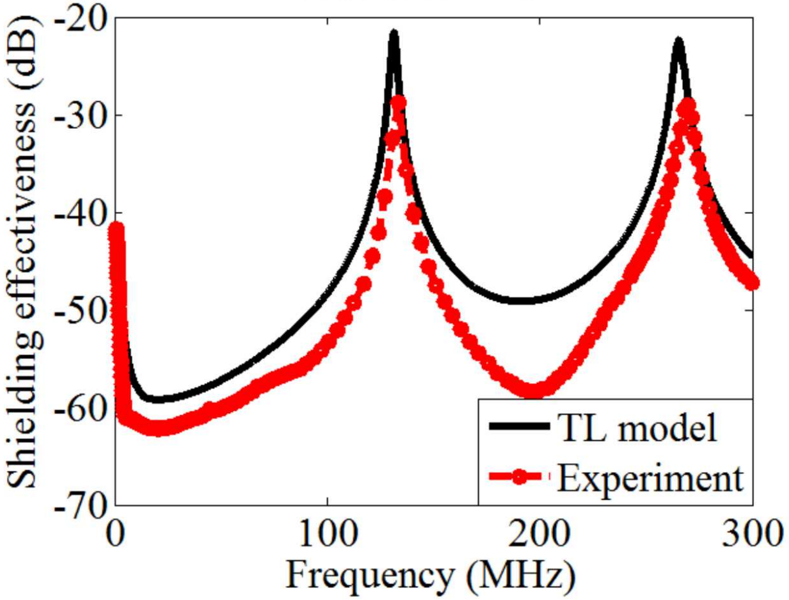
Goal to determine pin-level voltages due to cable coupling

- Previous comparisons used commercial cables and Kley's semi-empirical formulas for the transfer parameters
- These are standard commercial cables where Kley's forumulas work well.

Belden 8240



Belden 9201



- In the future, we plan to have shielding effectiveness validation between the first-principles braided shield model and real commercial and non-commercial cables
- **Goal: First-principles model tied to the geometry of the braided shield.**

Campione et al., *Progress in Electromagnetics Research C* **65**, 93-102 (2016)

Discussion Of Multipole Approach & Parallel Wire Array Test Cases

- ❑ First principles model of braid using general line multipole wire model

- ❑ Parallel wire array test cases
  - Electric line multipoles & elastance per unit length
  - Dielectric interfaces and images
  - Magnetic line multipoles & inductance per unit length

First-principles multipole based electric penetration model, 1

- The unit cell contains a small part of the braid (in the test cases this is a single wire) with the remainder replicated by the periodic structure
- The electric penetration (transfer elastance or capacitance per unit length) as well as the braid propagation (self elastance or capacitance per unit length) are described by the two asymptotic scalar constant potentials on either side of the braid
- Although a cylindrical structure could be treated we simplify the problem (the potential constants then become only functions of the local braid structure) by rolling it out as a planar approximation (which for small unit cell size should be accurate)

ϕ_c / E_0	ϕ_b / E_0
To compute transfer admittance	To compute self admittance

- The cable penetration model is based on finite-length electric line multipoles

- The potential of an axially varying line charge discretized as pulses of strength q_n is given as the superposition of the potentials from the N wire segments as

$$\phi_{scatt} = -\sum_{n=1}^{N} \frac{q_n}{4\pi\varepsilon} \ln\left[\frac{(s - s_n/2) + \sqrt{\rho^2 + (s - s_n/2)^2}}{(s + s_n/2) + \sqrt{\rho^2 + (s + s_n/2)^2}}\right],$$

Warne et al., Sandia National Laboratories Report SAND2015-5019, Albuquerque, NM (2015)

Warne et al., *Progress in Electromagnetics Research B* **66**, 63-89 (2016)

Campione et al., *IEEE Transactions on Electromagnetic Compatibility,* DOI: 10.1109/TEMC.2017.2721101 (2017)

First-principles multipole based electric penetration model, 2

- The total potential in the periodic problem is given by

$$\phi_{scatt}^{tot} = \sum_{n=1}^{N} \frac{-q_n}{4\pi\varepsilon} \sum_{j=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} \ln\left[\frac{\left(s - s_n/2 - ju_{sn} - kv_{sn}\right) + \left|\underline{r} - \underline{r}_n^{+} - j\underline{u} - k\underline{v}\right|}{\left(s + s_n/2 - ju_{sn} - kv_{sn}\right) + \left|\underline{r} - \underline{r}_n^{-} - j\underline{u} - k\underline{v}\right|}\right]$$

- The monopole moments are not sufficient to match the potential condition

$$\phi_{scatt}^{tot} + \phi_{inc} = V_{n'}$$

- We thus include a series of line multipole moments in the potential, which for a given position *n*, is written as

$$\phi_{scatt}^{n} = \frac{-1}{4\pi\varepsilon} \sum_{m=0}^{M} \underline{p}^{(0)} \underline{p}^{(1)} \Lambda\ \underline{p}^{(m)} \cdot \nabla_t^m \ln\left[\frac{\left(s - s_n/2\right) + \sqrt{\rho^2 + \left(s - s_n/2\right)^2}}{\left(s + s_n/2\right) + \sqrt{\rho^2 + \left(s + s_n/2\right)^2}}\right]$$

- With the total potential being

$$\phi_{scatt}^{tot} = \sum_{n=1}^{N} \sum_{j=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} \phi_{scatt}^{n}$$

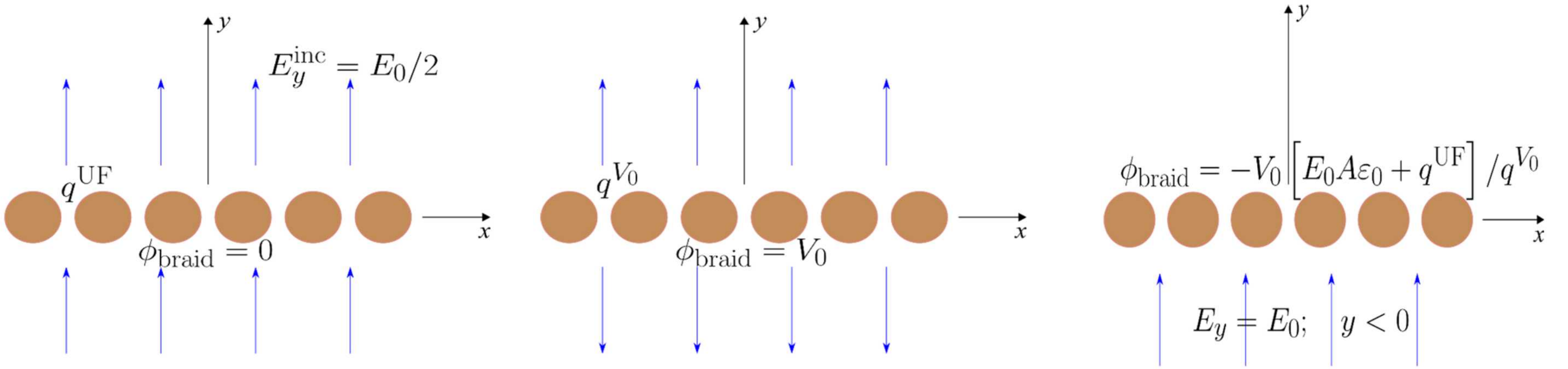
Warne et al., Sandia National Laboratories Report SAND2015-5019, Albuquerque, NM (2015)

Warne et al., *Progress in Electromagnetics Research B* **66**, 63-89 (2016)

Campione et al., *IEEE Transactions on Electromagnetic Compatibility,* DOI: 10.1109/TEMC.2017.2721101 (2017)

First-principles multipole based electric penetration model, 3

- The actual solution technique decomposes the approximate planar problem of an electric field below the braid and zero electric field above the braid into the superposition of two problems as shown below



Problem 1: Uniform field excitation + Problem 2: No field excitation and constant potential on the wires = Total solution

- For the shadow side of the structure, we evaluate a total potential far from the braid to find $\phi \rightarrow \phi_c$

- For the illuminated side of the structure, we evaluate the potential to find $\phi \rightarrow -E_0 y + \phi_b$

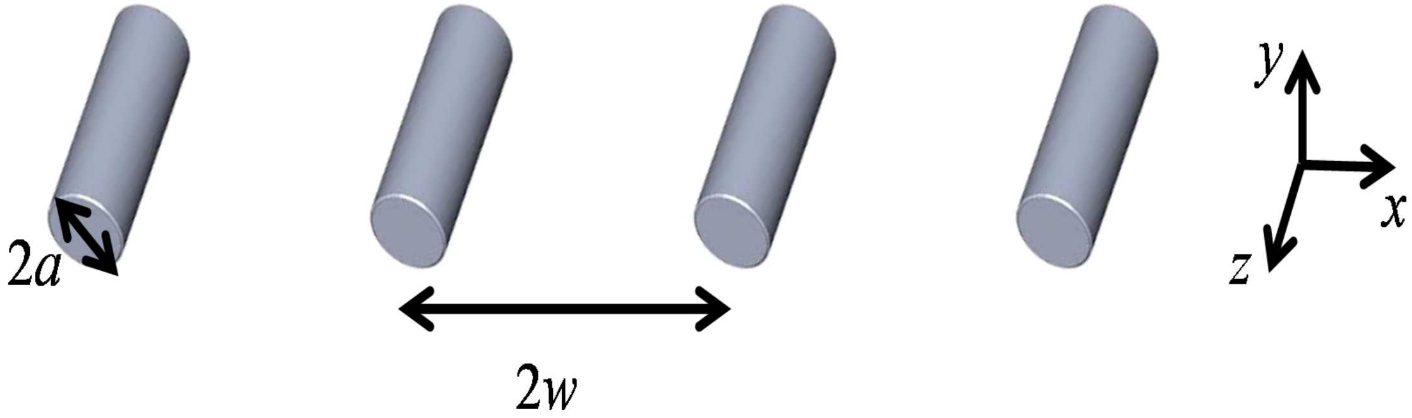
Warne et al., Sandia National Laboratories Report SAND2015-5019, Albuquerque, NM (2015)

Warne et al., *Progress in Electromagnetics Research B* **66**, 63-89 (2016)

Campione et al., *IEEE Transactions on Electromagnetic Compatibility,* DOI: 10.1109/TEMC.2017.2721101 (2017)

Analytic test case: one dimensional array of wires (electric penetration)

- The problem of field leakage through an array of cylinders is the basic canonical periodic shield



- The transfer elastance (i.e. the inverse of the capacitance) is defined as

$$S_c = \phi_c / (wq) = \phi_c / (2w\varepsilon_0 E_0 w),$$

ϕ_c difference of the electric potential at the point $y \to \infty$ and a point on the wire

E_0 vertical uniform field below the wires

Warne et al., Sandia National Laboratories Report SAND2016-6180, Albuquerque, NM (2016)
Campione et al., *IEEE Transactions on Electromagnetic Compatibility,* DOI: 10.1109/TEMC.2017.2721101 (2017)

Analytic models for transfer elastance for one dimensional array of wires

- The transfer elastance can be analytically derived using a thin wire approximation:

$$S_{c,tw}(2\pi\varepsilon_0 w) \approx \ln\left(\frac{w}{\pi a}\right).$$

- A smoothed conformal transformation:

$$\csc\left[\frac{\pi a}{2w}(1+\lambda)\right] = \coth\left[\frac{\pi a}{2w\lambda}(1+\lambda)\right] \qquad S_{c,sc}(2\pi\varepsilon_0 w) = \ln\left[\csc\left\{\frac{\pi a}{2w}(1+\lambda)\right\}\right],$$

- A bipolar solution (which uses the exponential decay from the bipolar system of coordinates (representing two cylinders) times the conformal mapping filament array result):

$$S_{c,bs}(2\pi\varepsilon_0 w) \approx -\ln\left(1-e^{-\pi a/w}\right)\cdot \exp\left[-2\pi\frac{\arctan\left(c/\sqrt{w^2/a^2-1}\right)}{\ln\left(w/a+\sqrt{w^2/a^2-1}\right)}\right], \qquad c = \frac{1}{2}\sqrt{1+\frac{\pi a}{2w}}$$

- And a quadrupolar solution:

$$S_{c,q}(2\pi\varepsilon_0 w) = -\ln\left[2\sinh\left(\frac{\pi a}{2w}\right)\right] + \left(\frac{\pi a}{2w}\right)\tanh\left(\frac{\pi a}{2w}\right) + \frac{\ln\left\{\sinh\left(\frac{\pi a}{2w}\right)/\sin\left(\frac{\pi a}{2w}\right)\right\}}{1+\sinh^2\left(\frac{\pi a}{2w}\right)/\sin^2\left(\frac{\pi a}{2w}\right)}$$

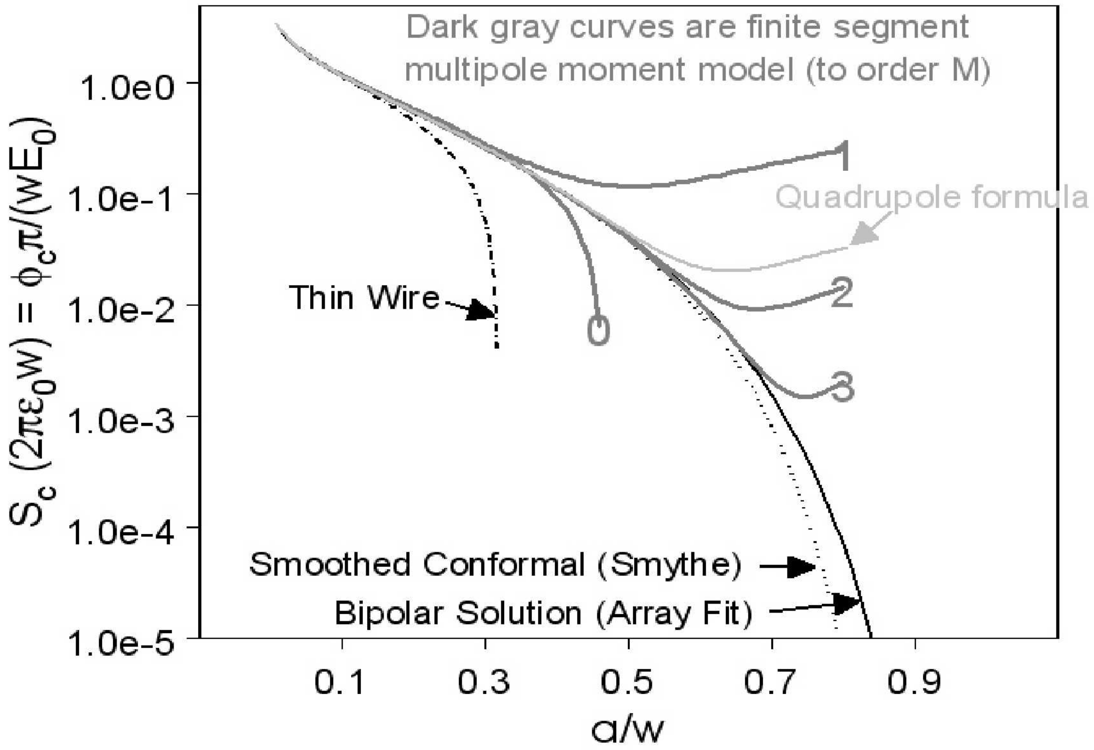
W. R. Smythe, Static and Dynamic Electricity. New York: Hemisphere Publishing Corp. (1989)

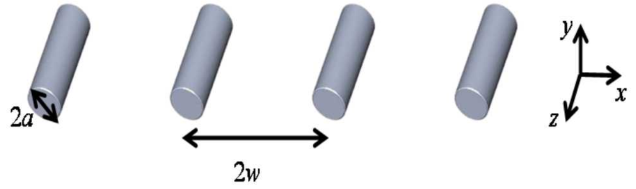
Warne et al., Sandia National Laboratories Report SAND2016-6180, Albuquerque, NM (2016)

Campione et al., *IEEE Transactions on Electromagnetic Compatibility,* DOI: 10.1109/TEMC.2017.2721101 (2017)

Transfer elastance results for a one dimensional array of wires

- The transfer elastance with the various methods are shown below:





- One can notice that the agreement with the bipolar solution is best when using up to the octopole moment, covering a dynamic range of up to a/w = 0.6.

- These results give us the confidence that our first principles model works within the geometric characteristics of many commercial cables.

Campione et al., *IEEE Transactions on Electromagnetic Compatibility,* DOI: 10.1109/TEMC.2017.2721101 (2017)

Analytic models for self elastance for one dimensional array of wires

- The self elastance can be analytically derived using a thin wire approximation:

$$S_{b,tw}\left(2\pi\varepsilon_0 w\right) \approx \ln\left(\frac{w}{\pi a}\right).$$

- A smoothed conformal transformation:

$$S_{b,sc}\left(2\pi\varepsilon_0 w\right) = \ln\left|\csc\left\{\frac{\pi a}{2w}(1+\lambda)\right\}\right| + \left(\frac{2\lambda}{1+\lambda}\right)\ln\left|\cos\left\{\frac{\pi a}{2w}(1+\lambda)\right\}\right|,$$

- And a quadrupolar solution:

$$S_{b,q}\left(2\pi\varepsilon_0 w\right) = -\ln\left[2\sinh\left(\frac{\pi a}{2w}\right)\right] - \left(\frac{\pi a}{2w}\right)\tanh\left(\frac{\pi a}{2w}\right) + \frac{\ln\left\{\sinh\left(\frac{\pi a}{2w}\right)/\sin\left(\frac{\pi a}{2w}\right)\right\}}{1+\sinh^2\left(\frac{\pi a}{2w}\right)/\sin^2\left(\frac{\pi a}{2w}\right)}.$$

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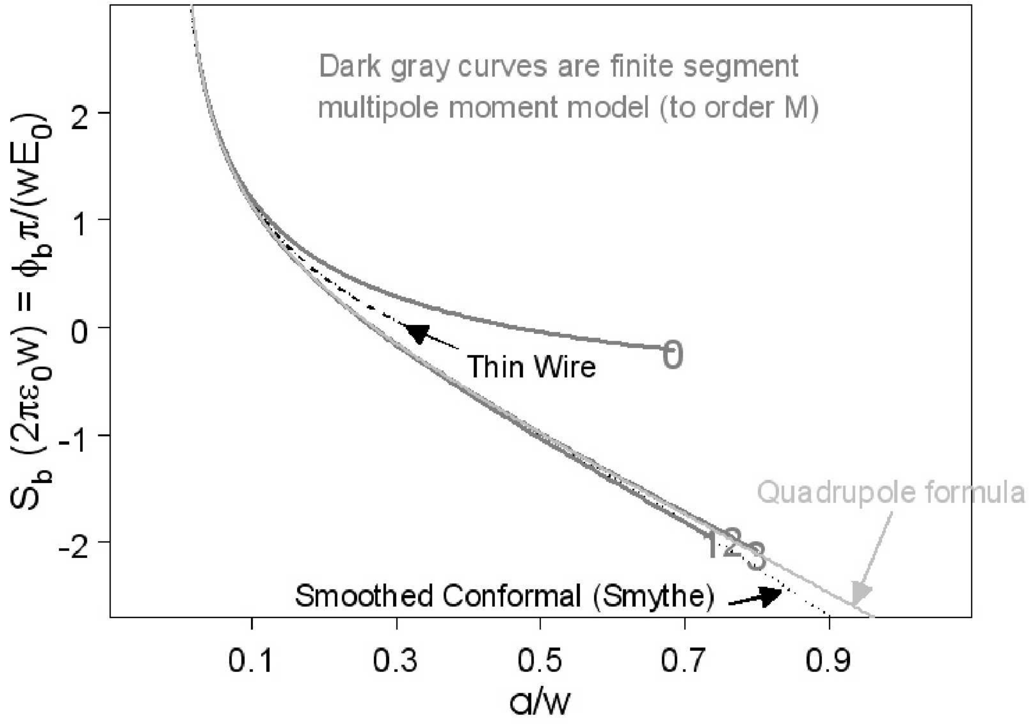
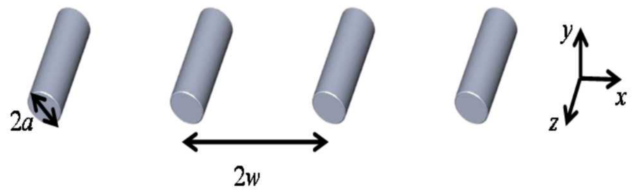
Self elastance results for a one dimensional array of wires

- The self elastance with the various methods are shown below:





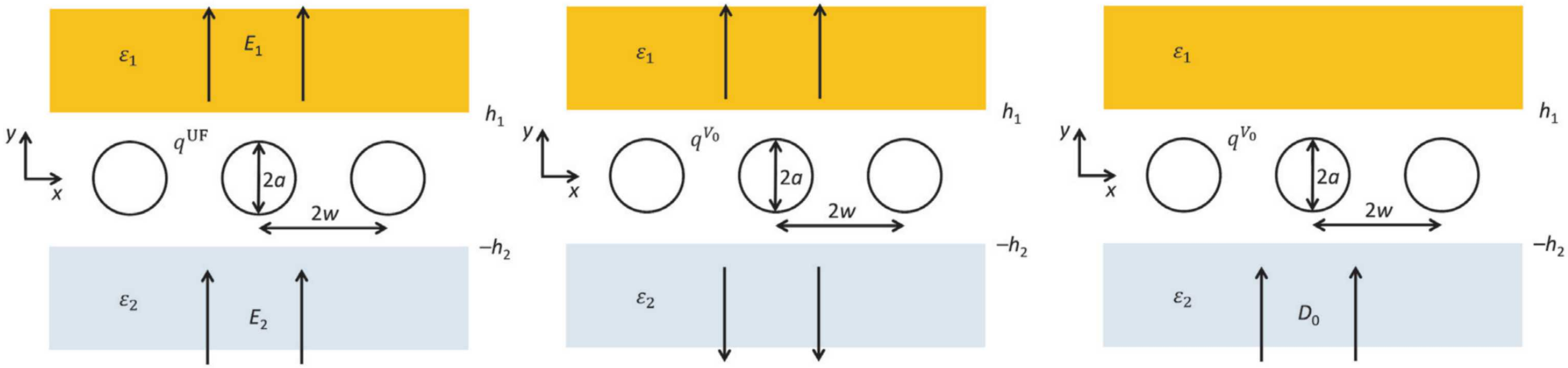
- One can notice that the agreement with the quadrupolar solution is best when using up to the octopole moment, covering a dynamic range of a/w = 0.6 and more.

- These results give us the confidence that our first principles model works within the geometric characteristics of many commercial cables.

Campione et al., *IEEE Transactions on Electromagnetic Compatibility,* DOI: 10.1109/TEMC.2017.2721101 (2017)

First-principles multipole based electric penetration model with dielectrics

- The actual solution technique decomposes the problem of an electric field below the braid and zero electric field above the braid into the superposition of two problems as shown below



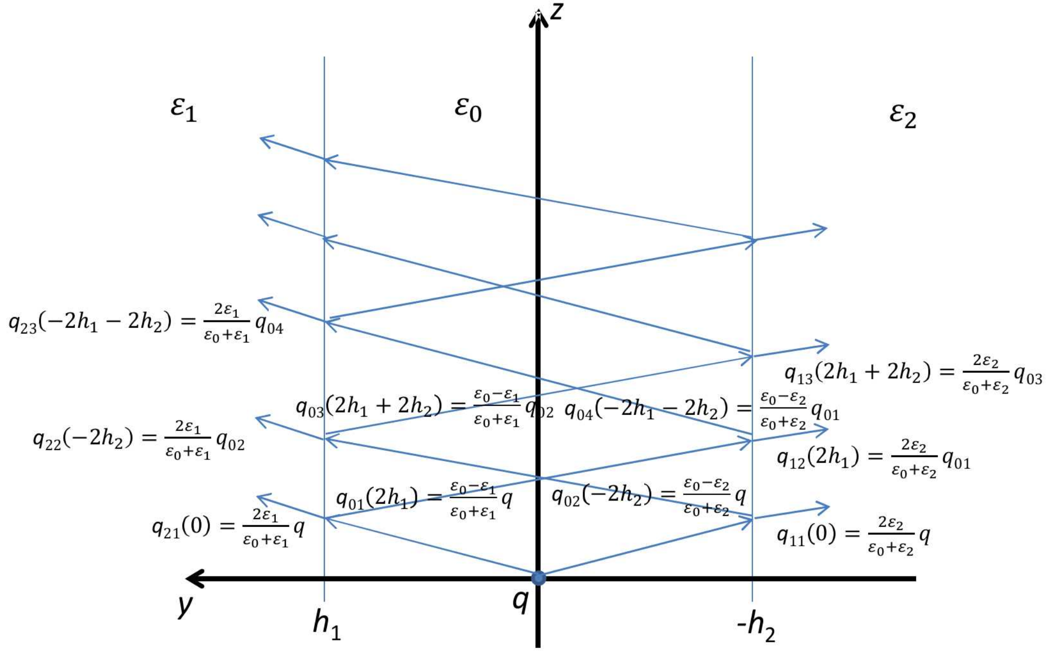
Problem 1: Uniform field excitation + Problem 2: No field excitation and constant potential on the wires = Total solution

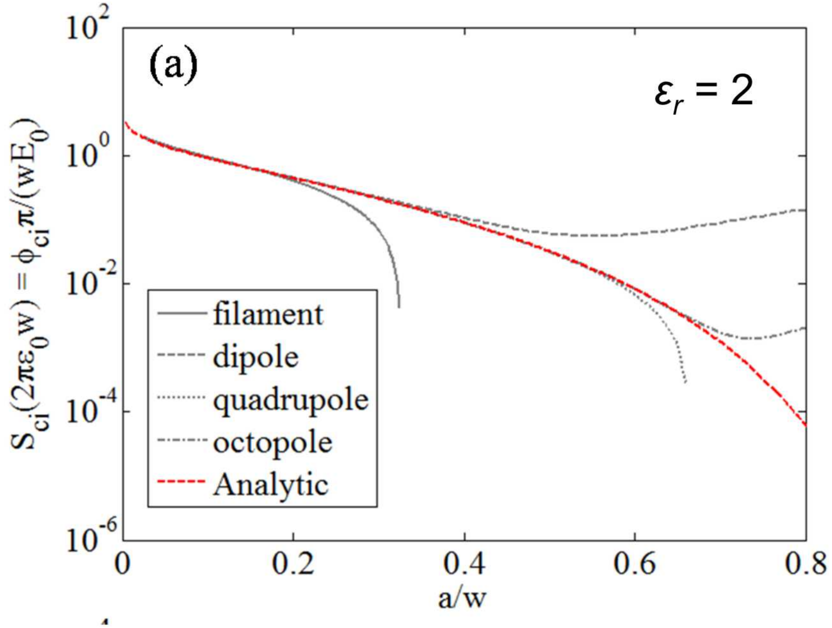
- For the shadow side of the structure, we evaluate a total potential far from the braid to find $\phi \to \phi_c$
- For the illuminated side of the structure, we evaluate the potential to find ϕ_b

Campione et al., Progress in Electromagnetics Research C **82**, 1-11 (2018)

Account for the effects of dielectrics in the electric penetration

- The effect of dielectrics can be included via image charges





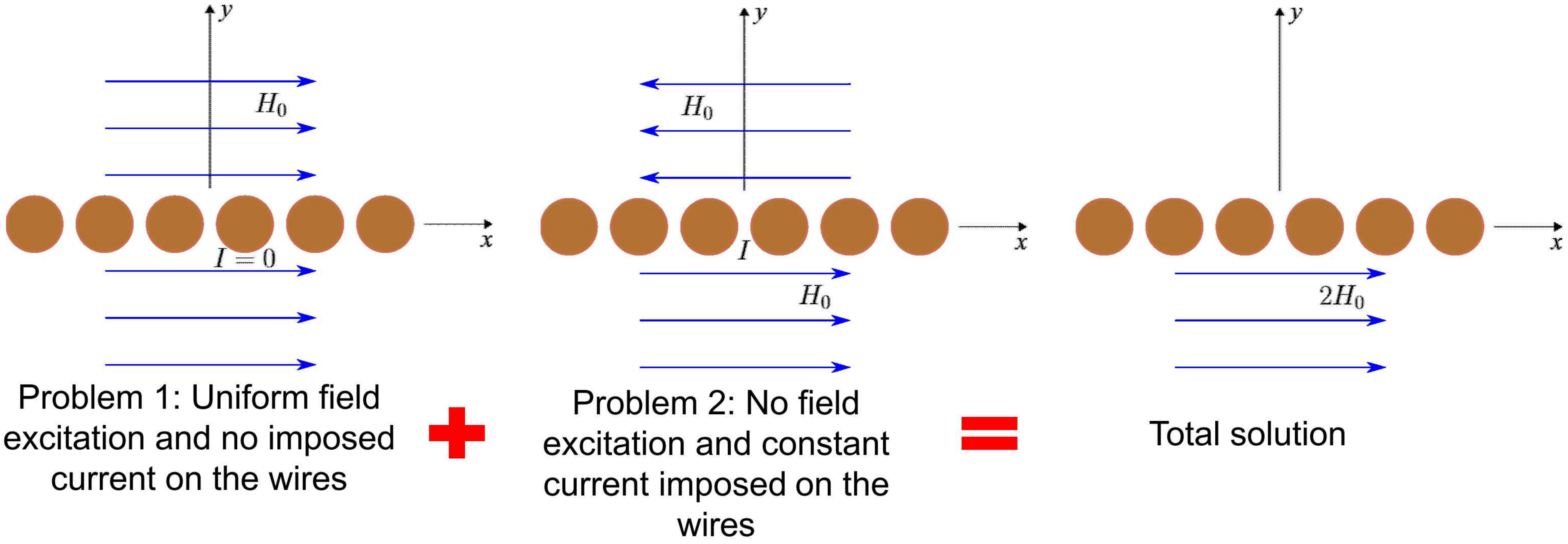
- Note the good agreement between the first principles method and the analytic solution when using the octopole.

- Note that the transfer results with dielectrics go to the free space results when the interface is 2*a* away. This is the average distance for the meander of the braid of realistic cables.

Campione et al., Progress in Electromagnetics Research C **82**, 1-11 (2018)

First-principles multipole based magnetic penetration model

- Like the electric penetration model, the solution technique decomposes the problem of a magnetic field below the braid and zero magnetic field above the braid into the superposition of two problems as shown below

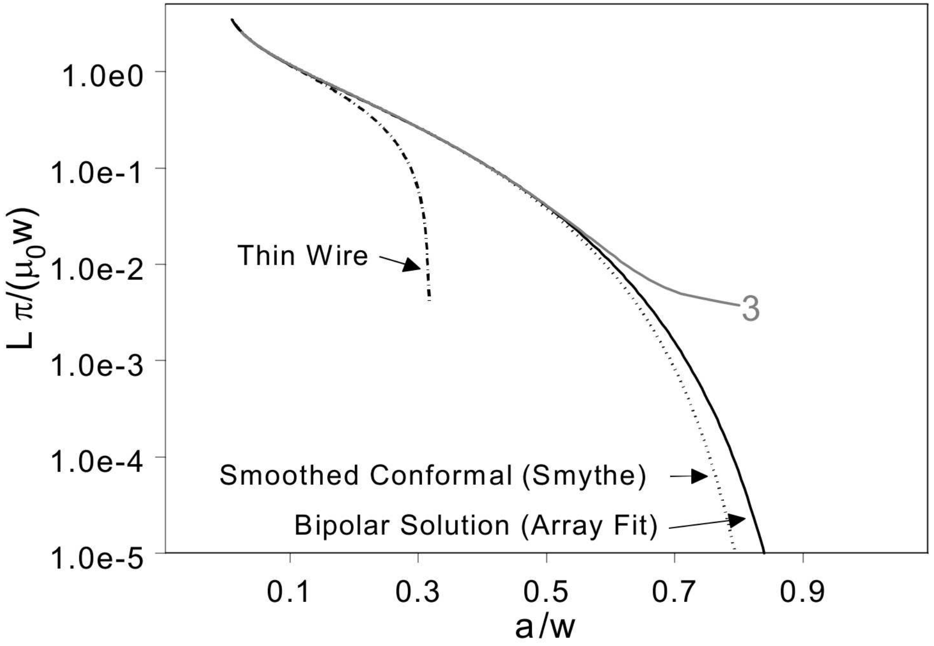


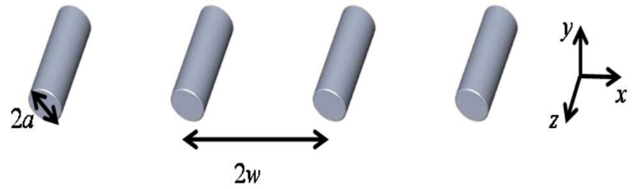
- For the shadow side of the structure, we evaluate a total potential far from the braid to find ϕ_c^m
- For the illuminated side of the structure, we evaluate the potential to find ϕ_b^m

Warne et al., Sandia National Laboratories Report SAND2015-5019, Albuquerque, NM (2015)
Warne et al., *Progress in Electromagnetics Research B* **66**, 63-89 (2016)

Transfer inductance results for a one dimensional array of wires

- The transfer inductance can be obtained in a similar manner to the transfer elastance with the various methods:





- One can notice that the agreement with the bipolar solution is best when using up to the octopole moment, covering a dynamic range of up to $a/w = 0.6$.

- These results give us the confidence that our first principles model works within the geometric characteristics of many commercial cables.

- A scalar and vector potential magnetic formulation is being implemented to allow for transverse currents in the braided shield geometry.

Conclusions

- We have reported the electric and magnetic penetrations of our first principles, multipole-based cable braid electromagnetic penetration model
- We have studied the case of a one dimensional array of wires and compared the elastance and inductance results from our first principles penetration model to the ones obtained via analytical solutions. These results were found in good agreement up to a radius to half spacing ratio of 0.6, within the characteristics of many commercial cables.
- We also considered three realistic cables without dielectrics, namely REMEE, Belden 9201, and Belden 8240, and compared the results from our first principles model to the results reported by Kley based on measurements of typical commercial cables.
- In contrast to Kley's methodology, the dependence on the actual cable geometry is accounted for only in our proposed first principles multipole model, which is also particularly useful if perturbations exist in the geometry versus nominal commercial braid parameters.
- A scalar and vector potential magnetic formulation is being implemented to allow for transverse currents in the braided shield geometry. This will complete the lossless first principles braided shield model. Extension to include magnetic diffusion into the model will follow.

Campione et al., *IEEE Transactions on Electromagnetic Compatibility,* DOI: 10.1109/TEMC.2017.2721101 (2017)
Campione et al., Progress in Electromagnetics Research C **82**, 1-11 (2018)