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A First Principles, Multipole-Based Cable Braid Electromagnetic Penetration Model

Salvatore Campione[1], Larry K. Warne[1], William L. Langston[1], William A. Johnson[1,2], Rebecca S. Coats[1], and Lorena I. Basilio[1]

[1]Electromagnetic Theory Department, Sandia National Laboratories, Albuquerque NM USA
[2]Department of Mathematics, New Mexico Tech, Socorro NM USA

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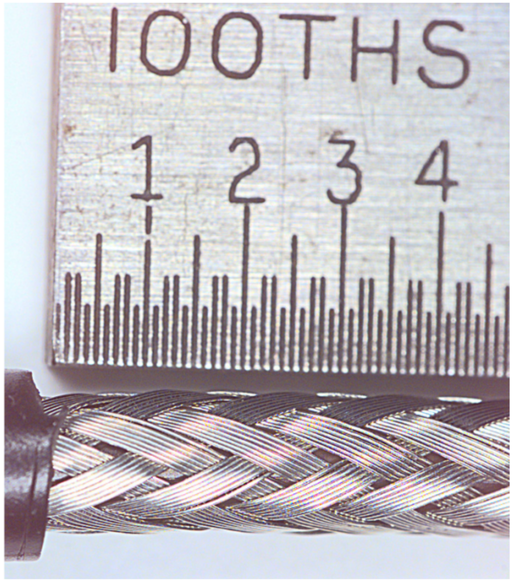
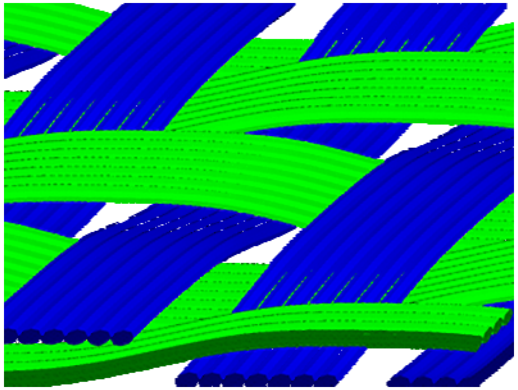
Motivation and background, 1

Belden 8240 cable



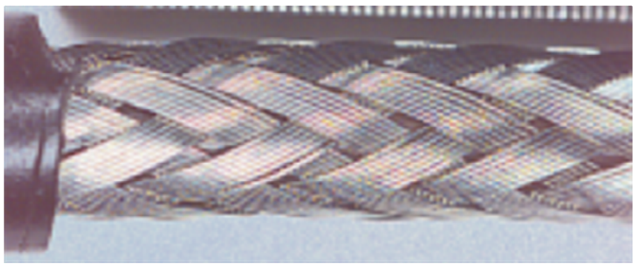
Belden 8240 model

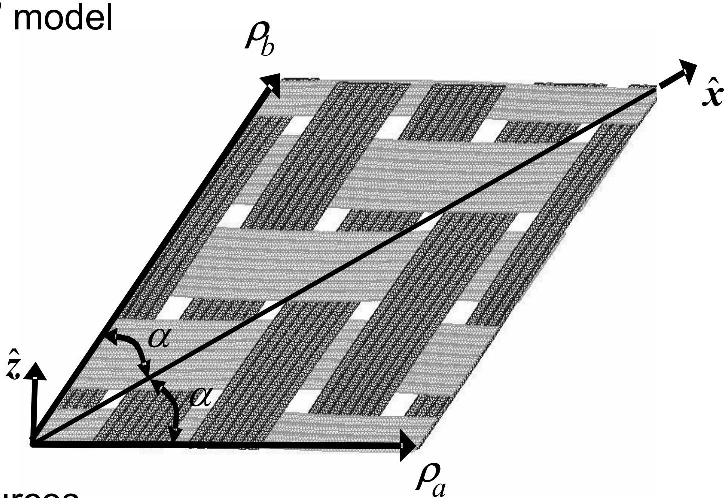


- ❑ Understanding electromagnetic pathways into critical components is essential in determining potential damage or upset due to electromagnetic coupling
- ❑ One important pathway into components is electromagnetic penetration through braided shields used in cables

Motivation and background, 2

- The purpose of this talk is to provide a 1st principles model based on solutions to electrostatic and magnetostatic 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)

Modeling of shielded cables

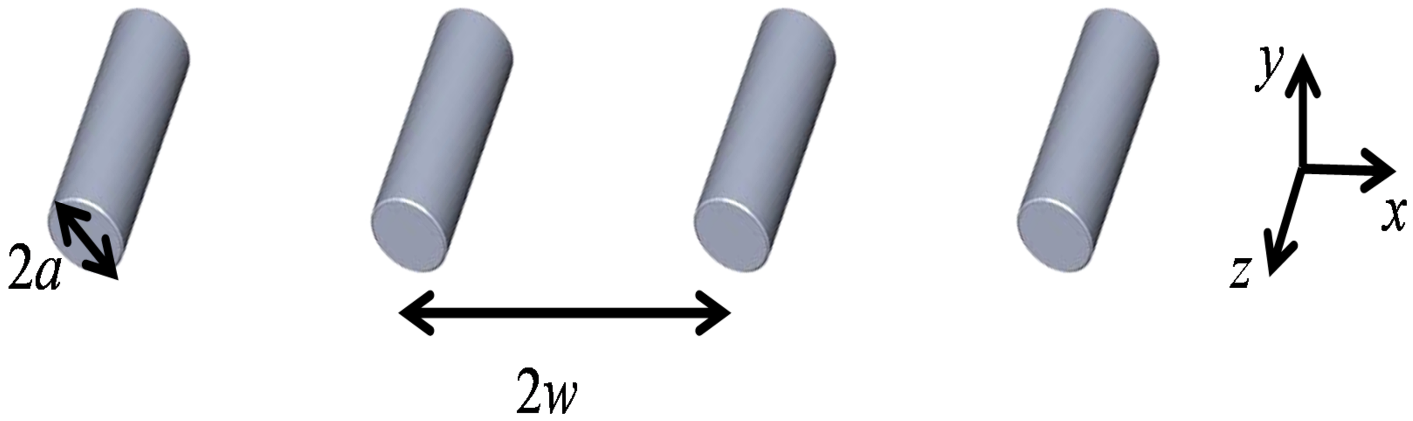
- A shielded cable is generally modeled via canonic parameters:
  - Transfer parameters to model the shield properties (related to the braid weave characteristics and material)
    - The per-unit length transfer impedance Z_T (proportional to the transfer inductance L_T and resistance R_T)
    - The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

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)

First-principles multipole based electric penetration model, 1

- The cable penetration model is based on finite-length electric line multipoles
- The unit cell contains a single wire (the number of conductors is infinite) in a similar manner to the unit cell of the cable braid. The unit cell identification, in addition to the planar approximation for the cylindrical braid, allows us to characterize the electric penetration by the single scalar constant quantities

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

- 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

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

- With the total potential being

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

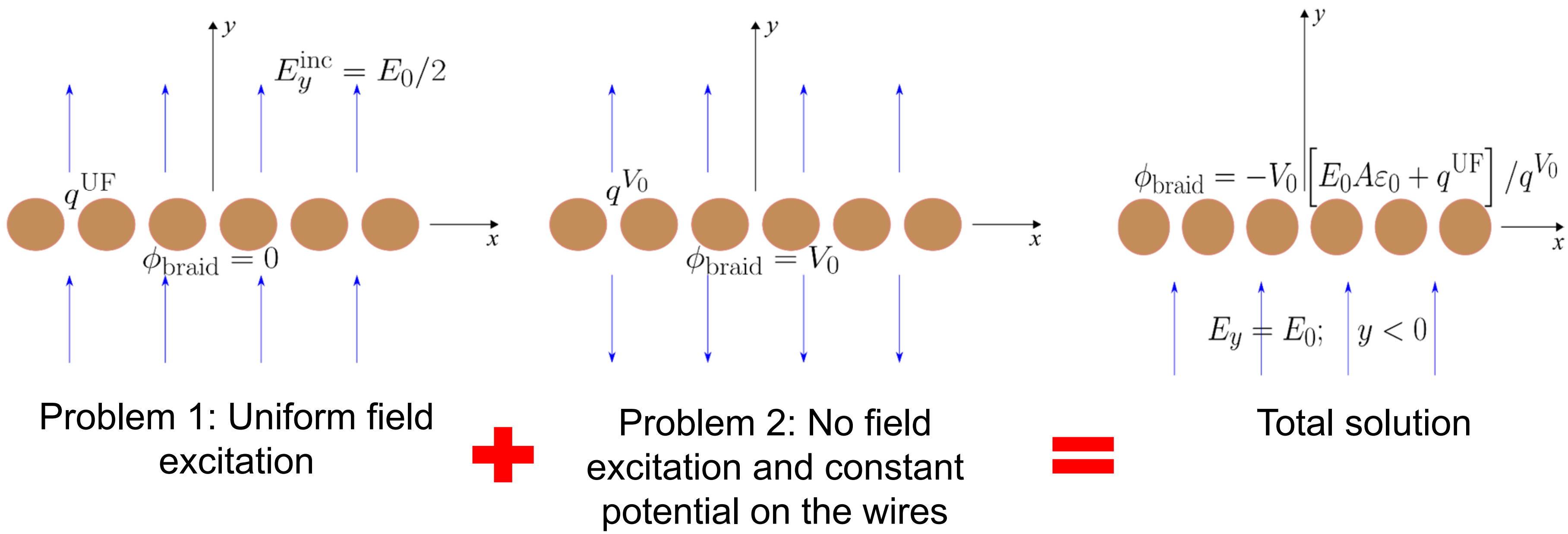
Warne et al., Sandia National Laboratories Report SAND2015-5019, Albuquerque, NM (2015)

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 problem of an electric field below the braid and zero electric 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 $\phi \rightarrow \phi_c$
- 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 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):

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

- And a quadrupolar solution:

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

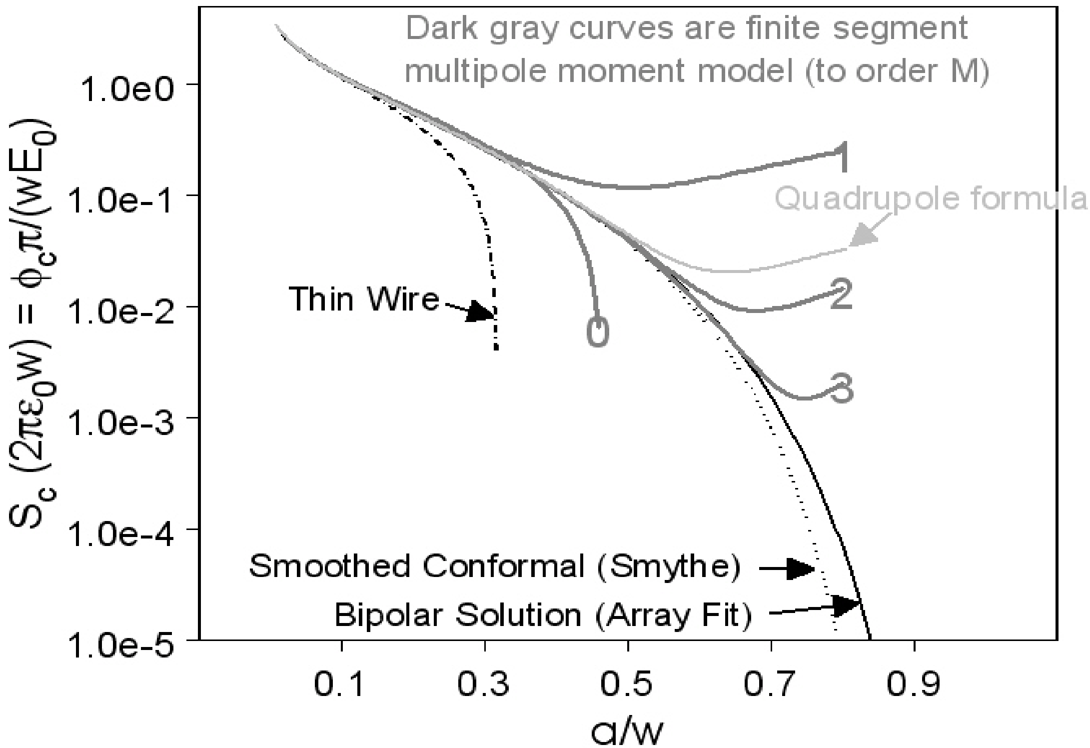
W. R. Smythe, Static and Dynamic Electricity. New York: Hemisphere Publishing Corp. (1989)

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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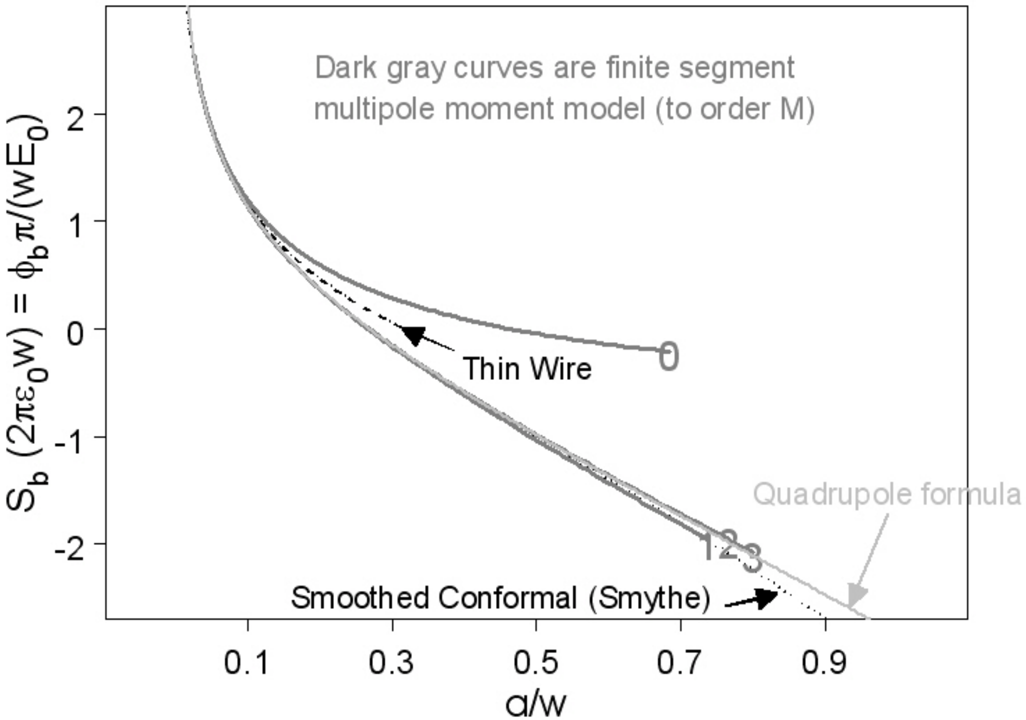
Self elastance results for a one dimensional array of wires

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



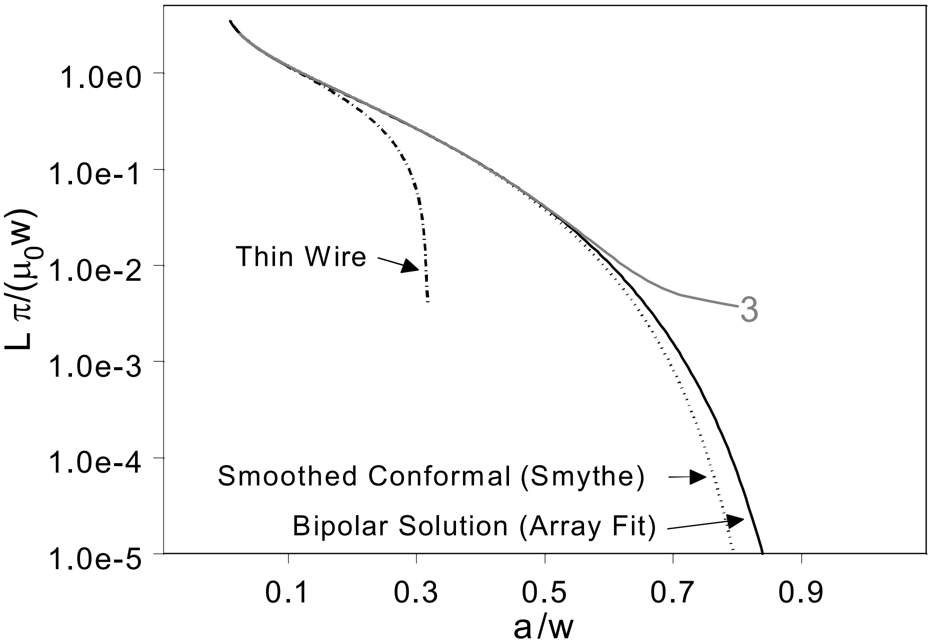
- One can notice that the agreement with the quadrupolar solution is best when using up to the octopole moment, covering a dynamic range of a/w = 0.6 and more.

- 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)

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:



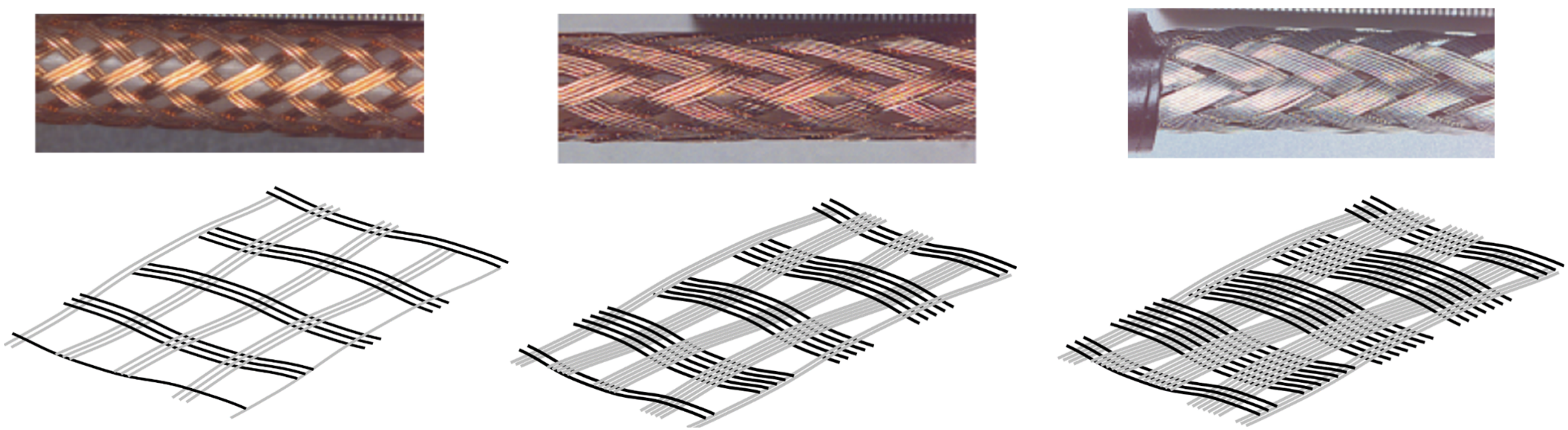
- One can notice that the agreement with the bipolar solution is best when using up to the octopole moment, covering a dynamic range of up to a/w = 0.6.

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

Realistic cables (electric penetration), 1

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

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



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

Realistic cables (electric penetration), 2

- We calculate the potentials ϕ_c and ϕ_b that will be used to determine, for a uniform cylindrical braid, the transfer capacitance C_T and the self-capacitance C_1 as

$$C_T = \frac{\phi_c}{E_0} \frac{C_1 C_{sh}}{2\pi b \varepsilon}$$

for a cylindrical shield h above a ground plane

$$C_{sh} = \frac{2\pi\varepsilon}{\operatorname{arccosh}(h/b)}$$

$$C_1 = C_0 + \Delta C = \frac{2\pi\varepsilon}{\ln\left[\left(b + \phi_b / E_0\right)/a\right]}$$

ΔC correction to the self - capacitance per unit length

$$C_0 = \frac{2\pi\varepsilon}{\ln\left[b/a\right]}$$

a and *b* are the inner and outer radii of a cylindrical coax

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

REMEE (electric penetration)

- The transfer and self capacitance and elastances are reported below:

Highest Multiple	$\phi_b/(aE_0)$		C_1 (pF)	
	30	60	30	60
Filament	-1.543	-1.551	45.10	45.11
Dipole	-1.910	-1.919	45.71	45.72
Quadrupole	-1.948	-1.957	45.77	45.79
Octopole	-1.951	-1.961	45.78	45.79

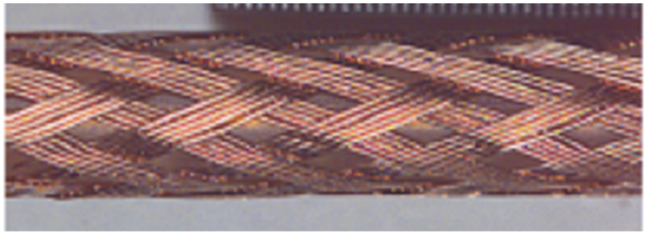
segments per wire

Highest Multiple	C_T (fF/m)					$\phi_c/(a\,E_0)$ $[\times 10^{-1}]$				
	30	60	120	240	480	30	60	120	240	480
Filament	171.94	172.73	173.40	173.80	173.94	1.15	1.16	1.16	1.17	1.17
Dipole	230.76	231.21	231.76	231.97	232.04	1.55	1.55	1.55	1.56	1.56
Quadrupole	213.62	214.14	214.71	214.95	215.02	1.43	1.44	1.44	1.44	1.44
Octopole	215.16	215.64	216.22	216.45	216.53	1.44	1.45	1.45	1.45	1.45
Kley	411.36					2.76				

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

Belden 9201 (electric penetration)

- The transfer and self capacitance and elastances are reported below:



Highest Multiple	$\phi_b/(aE_0)$		C_1 (pF)	
	30	60	30	60
Filament	-1.973	-1.984	45.82	45.83
Dipole	-2.402	-2.409	46.56	46.58
Quadrupole	-2.463	-2.474	46.67	46.69
Octopole	-2.469	-2.479	46.68	46.70

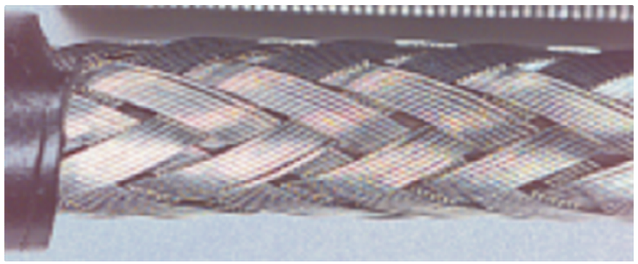
\# segments per wire

Highest Multiple	C_T (fF/m)					$\phi_c/(a\,E_0)$ $[\times 10^{-2}]$				
	30	60	120	240	480	30	60	120	240	480
Filament	8.87	13.17	14.32	15.20	-2447	0.603	0.894	0.973	1.03	-166
Dipole	77.90	79.11	80.34	81.05	81.13	5.29	5.37	5.46	5.51	5.51
Quadrupole	57.28	58.94	60.19	60.91	60.98	3.89	4.00	4.09	4.14	4.14
Octopole	58.77	60.41	61.65	62.36	62.44	3.99	4.10	4.19	4.24	4.24
Kley	71.97					4.89				

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

Belden 8240 (electric penetration)

- The transfer and self capacitance and elastances are reported below:



Highest Multiple	$\phi_b/(aE_0)$		C_1 (pF)	
	30	60	30	60
Filament	-2.464	-2.471	46.67	46.69
Dipole	-2.928	-2.932	47.53	47.54
Quadrupole	-3.011	-3.022	47.69	47.72
Octopole	-3.019	-3.029	47.71	47.73

segments per wire

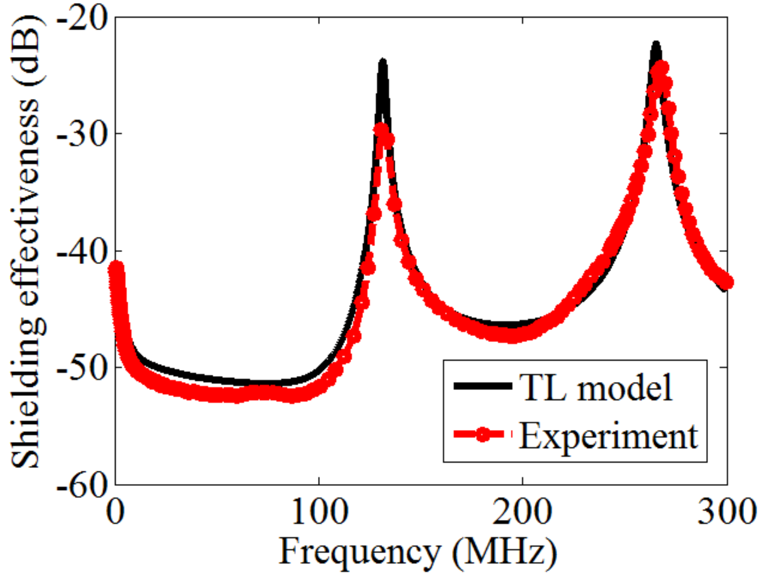
Highest Multiple	C_T (fF/m)					$\phi_c/(a\,E_0)\ [\times 10^{-3}]$				
	30	60	120	240	480	30	60	120	240	480
Filament	-8.28	-5.34	-3.95	-3.21	-406.2	-5.60	-3.61	-2.67	-2.17	-275
Dipole	7.75	8.84	10.21	10.73	10.76	5.25	5.98	6.91	7.26	7.28
Quadrupole	-1.79	-0.129	1.27	1.79	1.81	-1.21	-0.087	0.861	1.21	1.22
Octopole	-1.33	0.280	1.68	2.19	2.21	-0.901	0.190	1.14	1.48	1.50
Kley	3.16					2.14				

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

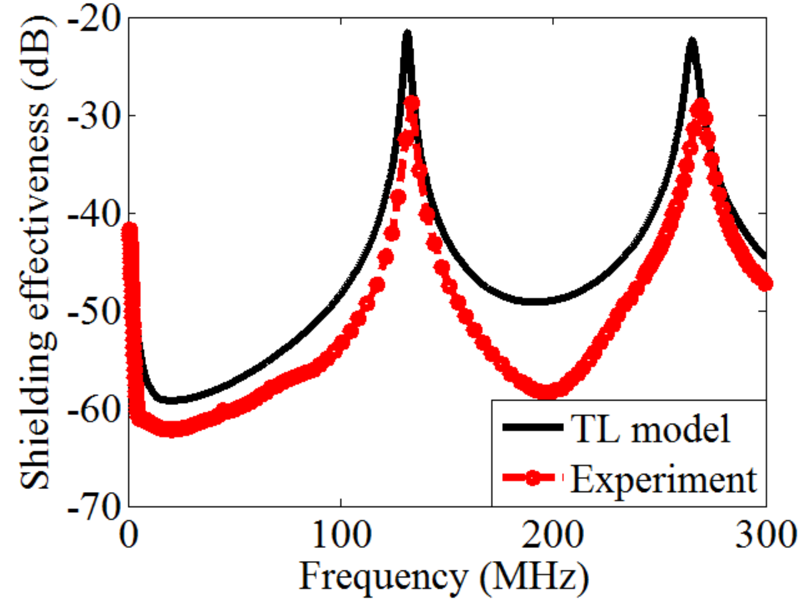
Determine pin-level voltages due to cable coupling

- Previous comparisons used commercial cables and Kley's semi-empirical formulas for the transfer parameters

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

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

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 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.

- Two possible perturbations are: 1) interweave changes (an example is a situation where the two layers of the braid interchange at every carrier crossing rather than the typical interchange at every second carrier crossing), and 2) a case where the geometry is slightly distorted by twisting.

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

Acknowledgments

- **Larry K. Warne**

- **Lorena I. Basilio**

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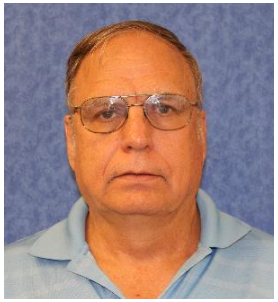

- **William L. Langston**

- **Rebecca S. Coats**