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Practical Method for Modeling Conductor Surface Roughness Using The Cannonball Stack Principle

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Abstract: In this paper, a practical method for modeling conductor roughness is explored. By using available data published in material data sheets alone, an equivalent multi-sphere model, based on cubic close-packing of equal spheres, also known as Cannonball Stack, is developed. To test the accuracy, a case study was done on a lossy stripline geometry based on FR408HR dielectric materials with reverse-treated copper foils.

Author(s) Biography

Lambert (Bert) Simonovich graduated in 1976 from Mohawk College of Applied Arts and Technology, Hamilton, Ontario Canada, as an Electronic Engineering Technologist. Over a 32-year career, working at Bell Northern Research/Nortel, in Ottawa, Canada, he helped pioneer several advanced technology solutions into products. He has held a variety of engineering, research and development positions, eventually specializing in high-speed signal integrity and backplane architectures. After leaving Nortel in 2009, he founded Lamsim Enterprises Inc., where he continues to provide innovative signal integrity and backplane solutions as a consultant. He has also authored and coauthored several publications; posted on his web site at www.lamsimenterprises.com. His current research interests include: high-speed signal integrity, modeling and characterization of high-speed serial link architectures.

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PRACTICAL METHOD FOR MODELING CONDUCTOR SURFACE ROUGHNESS USING THE CANNONBALL STACK PRINCIPLE

Introduction

In the GB/s regime, accurate modeling of conductor losses is a precursor to successful high-speed serial link designs. Failure to model roughness effects can ruin you day. For example, Figure 1 shows the simulated total loss of a 40 inch printed circuit board (PCB) trace without roughness compared to measured data. Total loss is the sum of dielectric and conductor losses. As can be seen, with just -3dB delta in insertion loss between simulated and measured data at 12.5 GHz, there is half the eye height opening with rough copper at 25GB/s.

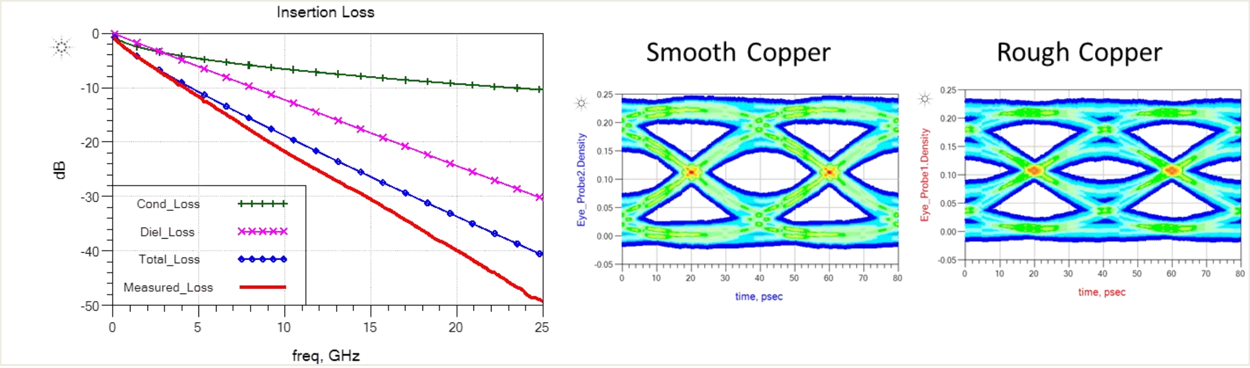


Figure 1 Comparisons of measured insertion loss of a 40 inch trace vs simulation. Eye diagrams show that with -3dB delta in insertion loss at 12.5GHz there is half the eye opening at 25GB/s. Modeled and simulated with Keysight EEsof EDA ADS software [13].

According to Wikipedia, close-packing of equal spheres is defined as "*a dense arrangement of congruent spheres in an infinite, regular arrangement (or lattice)*" [7]. The cubic close-packed and hexagonal close-packed are examples of two regular lattices. The cannonball stack is an example of a cubic close-packing of equal spheres, and is the basis of modeling the surface roughness of a conductor in this paper.

In my recent DesignCon2015 paper [1], I presented a practical method for modeling conductor surface roughness using the hexagonal close-packing of equal spheres (HCPES) model. A copy of the paper can be downloaded from my web site at Lamsimenterprises.com. Since writing that paper, further research has taken place in testing the original HCPES model with other material and copper foil types. The "Cannonball" model is simpler, and the results have proved to be equally valid (see Appendix).

Background

In printed circuit (PCB) construction there is no such thing as a perfectly smooth conductor surface. There is always some degree of roughness that promotes adhesion to the dielectric material. Unfortunately this roughness also contributes to additional conductor loss.

Electro-deposited (ED) copper is widely used in the PCB industry. The manufacturing process sees a large rotating drum, made of polished stainless steel or titanium, which is partially submerged in a bath of copper sulfate solution. The cathode terminal is attached to the drum, while the anode terminal is submerged in the solution. A DC voltage supplies the anode and cathode with the correct polarity.

As the drum slowly rotates, copper is deposited onto it. A finished sheet of ED copper foil has two sides. The matte side faces the copper sulfate bath, while the drum side faces the rotating drum. Consequently, the drum side is always smoother than the matte side.

The matte side is usually attached to the prepreg sheets, prior to final pressing and curing, to form the core laminate. To enhance adhesion, the matte side has additional treatment applied to roughen the surface. For high frequency boards, sometimes the drum side of the foil is laminated to the core. In this case it is referred to as reversed treated (RT) foil. Even after treatment, it is still smoother than standard treated foils.

Various foil manufacturers offer ED copper foils with varying degrees of roughness. Each supplier tends to market their product with their own brand name. Presently, there seems to be three distinct classes of copper foil:

- Standard
- Very-low profile (VLP)
- Ultra-low profile (ULP) or profile free (PF)

Some other common names referring to ULP class are HVLP or eVLP.

In lieu of scanning electron microscopy (SEM) analysis, profilometers are often used to quantify the roughness tooth profile of electro-deposited copper. Tooth profiles are typically reported in terms of 10-point mean roughness (R_z) for both sides, but sometimes the drum side reports average roughness (R_a) in manufacturers' data sheets. Some manufacturers also report RMS roughness (R_q).

Several modeling methods were developed over the years to determine a roughness correction factor (K_{sr}). When multiplicatively applied to the smooth conductor attenuation (α_{smooth}), the attenuation due to roughness (α_{rough}) can be determined by:

Equation 1

$$\alpha_{rough} = K_{SR}\alpha_{smooth}$$

The most popular method has been the Hammerstad and Jensen (H&J) model, based on work done in 1949 by S. P. Morgan. The H&J model assumes a triangular corrugated surface, representing the tooth structure of rough copper. It was thought that when the skin depth is small, compared to the tooth height, current begins to flow along the corrugated surface; thereby increasing its loss due to the longer path length. However, the theory breaks down from a physics perspective because there is no evidence of additional time delay (*TD*), compared to the fixed spatial length of the trace.

The H&J roughness correction factor (K_{HJ}), at a particular frequency, is solely based on a mathematical fit to S. P. Morgan's power loss data and is determined by [2]:

Equation 2

$$K_{HJ} = 1 + \frac{2}{\pi}\arctan\left(1.4\left(\frac{\Delta}{\delta}\right)^2\right)$$

Where:

K_{HJ} = H&J roughness correction factor;

Δ = RMS tooth height in meters;

δ = skin depth in meters.

Alternating current (AC) causes conductor loss to increase in proportion to the square root of frequency. This is due to the redistribution of current towards the outer edges caused by skin-effect. The resulting skin-depth (δ) is the effective thickness where the current flows around the perimeter and is a function of frequency.

Skin-depth at a particular frequency is determined by:

Equation 3

$$\delta = \sqrt{\frac{1}{\pi f \mu_0 \sigma}}$$

Where:

δ = skin-depth in meters;

f = sine-wave frequency in Hz;

μ_0= permeability of free space =1.256E-6 Wb/A-m;

σ = conductivity in S/m. For annealed copper σ = 5.80E7 S/m.

The model has correlated well for microstrip geometries up to about 15 GHz, for surface roughness of less than 2 μm RMS. However, it proved less accurate for frequencies above about 5GHz for very rough copper [3] .

In recent years, the Huray model [4] has gained popularity due to the continually increasing data rate's need for better modeling accuracy. It takes a real world physics approach to explain losses due to surface roughness. The model is based on a non-uniform distribution of spherical shapes resembling "snowballs" and stacked together forming a pyramidal geometry, as shown by the SEM photo in Figure 2.

Figure 2 SEM photograph of electrodeposited copper nodules on a matte surface resembling "snowballs" on top of heat treated base foil. Photo credit Oak-Mitsui.

By applying electromagnetic wave analysis, the superposition of the sphere losses can be used to calculate the total loss of the structure. Since the losses are proportional to the surface area of the roughness profile, an accurate estimation of a roughness correction factor (K_{SRH}) can be analytically solved by [1]:

Equation 4

$$K_{SRH}(f) = \frac{A_{matte}}{A_{flat}} + \frac{3}{2}\sum_{i=1}^{j} \frac{\left(\frac{N_i \times 4\pi a_i^2}{A_{flat}}\right)}{\left(1 + \frac{\delta(f)}{a_i} + \frac{\delta^2(f)}{2a_i^2}\right)}$$

Where:

$K_{SRH}(f)$ = roughness correction factor, as a function of frequency, due to surface roughness based on the Huray model;

$\frac{A_{matte}}{A_{flat}}$ = relative area of the matte base compared to a flat surface;

a_i = radius of the copper sphere (snowball) of the i^{th} size, in meters;

$\frac{N_i}{A_{flat}}$ = number of copper spheres of the i^{th} size per unit flat area in sq. meters;

$\delta(f)$ = skin-depth, as a function of frequency, in meters.

It is theoretically possible to build an accurate snowball model of the surface roughness by extracting parameters through detailed analysis of SEM photographs. But practically, it is beyond the capabilities of most companies who do not have access to such equipment. Even if such equipment was available, the size, number of spheres and general tooth shape must be approximated anyways.

This leads us into the Cannonball model. Using the concept of cubic close-packing of equal spheres, the radius of the spheres (*ai*) and tile area (A_{flat}) parameters for the Huray model can now be determined solely by the roughness parameters published in manufacturers' data sheets.

Recalling that losses are proportional to the surface area of the roughness profile, the Cannonball model can be used to optimally represent the surface roughness. As illustrated in Figure 3, there are three rows of spheres stacked on a square tile base. Nine spheres are on the first row, four spheres in the middle row, and one sphere on top.

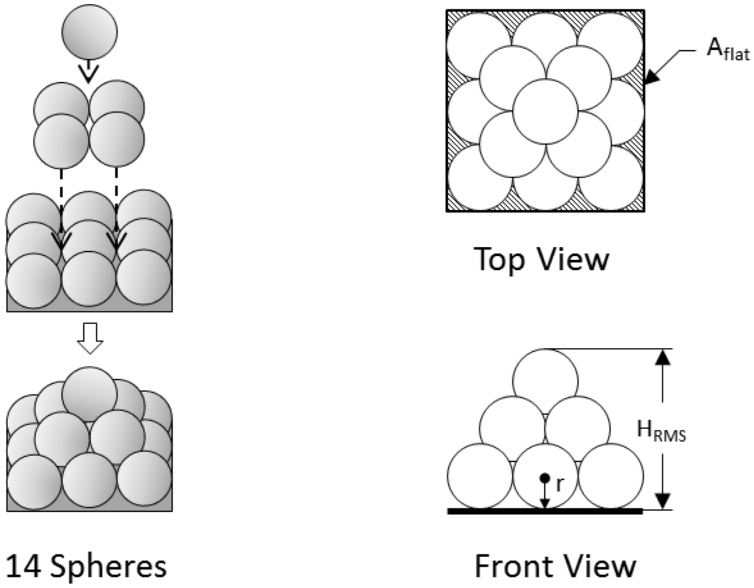


Figure 3 Cannonball model showing a stack of 14 uniform size spheres (left). Top and front views (right) shows the area (A_{flat}) of base, height (H_{RMS}) and radius of sphere (r).

Because the Cannonball model assumes the ratio of A_{matte}/A_{flat} = 1, and there are 14 spheres, Equation 4 can be simplified to:

Equation 5

$$K_{SR}(f) = 1 + 84\left(\frac{\left(\frac{\left(\pi r^2\right)}{A_{flat}}\right)}{\left(1 + \frac{\delta(f)}{r} + \frac{\delta^2(f)}{2r^2}\right)}\right)$$

Where:

$K_{SR}(f)$ = roughness correction factor, as a function of frequency, due to surface roughness based on the Cannonball model;

r = sphere radius in meters; $\delta(f)$ = skin-depth, as a function of frequency in meters;

A_{flat} = area of square tile base surrounding the 9 base spheres in sq. meters.

As shown in Figure 4, there are 5 square-based pyramids connecting the centers of all 14 spheres forming a stacked lattice structure. A single pyramid, labeled ABCDE, is shown for reference.

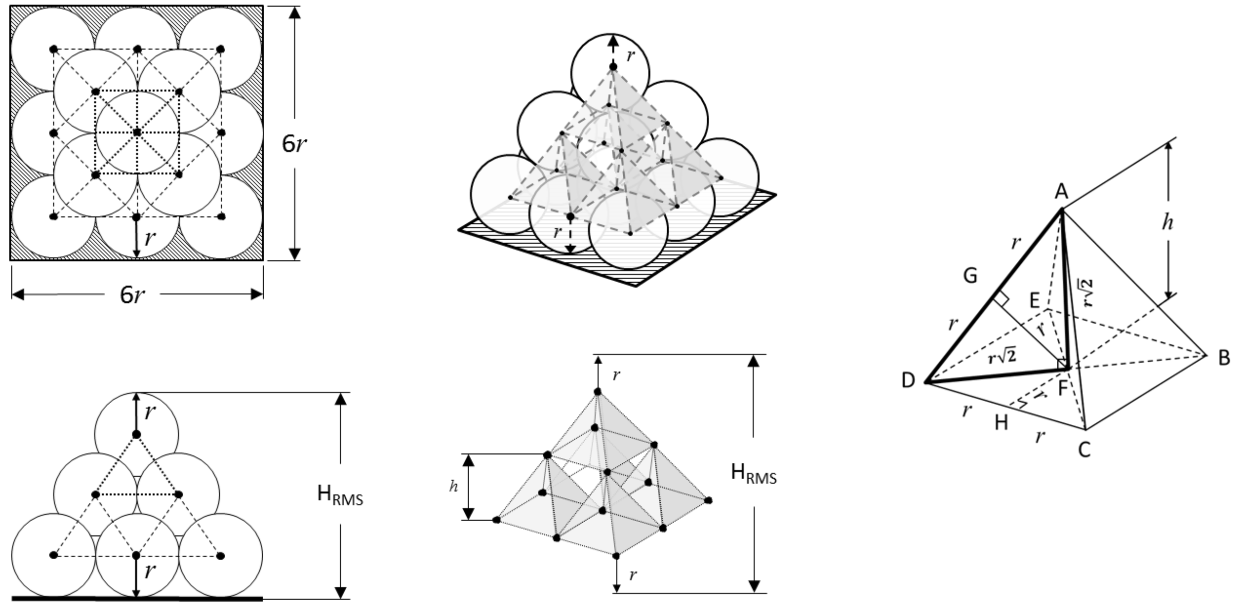


Figure 4 Cannonball model with pyramid lattice structure. Five pyramids form a stacked lattice structure connecting the centers of all 14 spheres. Total height (H_{RMS}) equals the stacked height of 2 pyramids plus the diameter (2*r*) of a single sphere.

Given that each side of the pyramid ABCDE = 2*r*, it can be shown that:

$$h = r\sqrt{2}$$

Since:

$$\begin{aligned} H_{RMS} &= 2r + 2h \\ &= 2r\left(1+\sqrt{2}\right) \end{aligned}$$

Then the radius of a single sphere is:

$$r = \frac{H_{RMS}}{2\left(1+\sqrt{2}\right)}$$

And the area of the square flat base is:

$$A_{flat} = (6r)^2$$

For the purpose of determining the RMS height of the matte and drum sides of a rough conductor, a dual triangular sawtooth profile (DTSP) model is used, as illustrated in Figure 5 (not to scale). The matte side is modeled by a matte triangular sawtooth profile (MTSP) with a peak-peak height $R_{MTSP} = R_{z\_matte}$. The drum side is modeled by a drum triangular sawtooth profile (DTSP) with a peak-peak height $R_{DTSP} = R_{z\_drum}$ or R_{a_drum}; depending on data sheet.

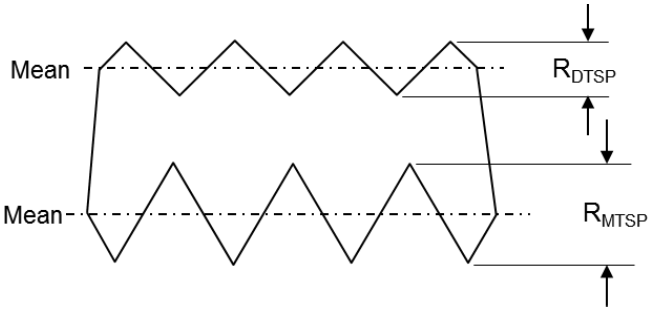


Figure 5 Dual triangular sawtooth profile (DTSP) model (not to scale) of the conductor profile used to determine H_{RMS} of the matte and drum side.

The RMS height H_{RMS_drum}, in meters, of the DTSP is approximated by Equation 6 and the RMS height H_{RMS_matte}, in meters, of the MTSP is approximated by Equation 7 below:

Equation 6

$$H_{RMS\_drum} \approx \frac{R_{DTSP}}{2\sqrt{3}} \approx \frac{R_{z\_drum}}{2\sqrt{3}}$$

Where: R_{z_drum} is the 10-point mean roughness in meters. If the data sheet reports average roughness, then R_{a_drum} is used instead.

Equation 7

$$H_{RMS\_matte} \approx \frac{R_{MTSP}}{2\sqrt{3}} \approx \frac{R_{z\_matte}}{2\sqrt{3}}$$

Where: R_{z_matte} is the 10-point mean roughness in meters.

Practical Example

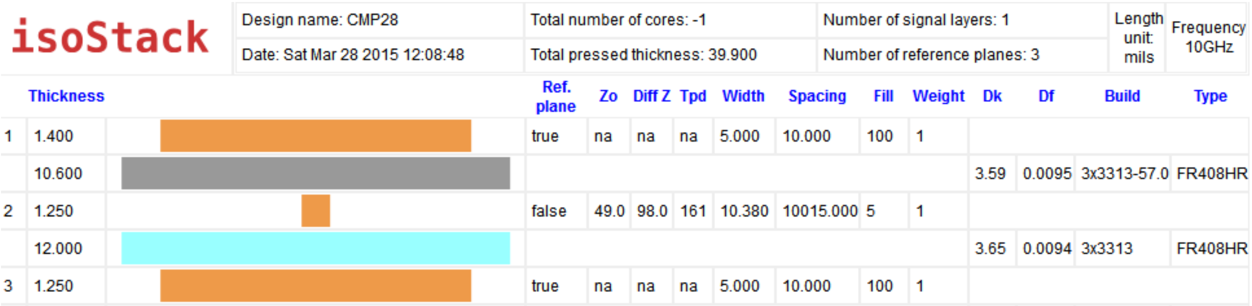
To test the accuracy of the model, board parameters from a PCBDesign007 February 2014 article, by Yuriy Shlepnev [5] was used. Measured data was obtained from Simbeor software design examples courtesy of Simberian Inc. [8]. The extracted de-embedded generalized modal S-parameter (GMS) data was computed from 2 inch and 8 inch single-ended stripline traces. They were originally measured from the CMP-28 40 GHz High-Speed Channel Modeling Platform from Wild River Technology [14].

The CMP-28 Channel Modeling Platform, shown in Figure 6, is a powerful tool for development of high-speed systems up to 40 GHz, and is an excellent platform for model development and analysis. It contains a total of 27 microstrip and stripline interconnect structures. All are equipped with 2.92mm connectors to facilitate accurate measurements with a vector network analyzer (VNA).

Figure 6 CMP-28 Modeling Platform from Wild River Technology. Photo credit Wild River Technology

The PCB was fabricated with Isola FR408HR material and reverse treated (RT) 1oz. foil. The dielectric constant (*Dk*) and dissipation factor (*Df*), at 10GHz for FR408HR 3313 material, was obtained from Isola's isoStack® web-based online design tool [9]. This is a free online stack-up design tool and you need to register to use it. An example is shown in Figure 7.

Typical traces usually have a trapezoidal cross-section after etching due to etch factor. Since the tool does not handle trapezoidal cross-sections in the impedance calculation, an equivalent rectangular trace width was determined based on a 2:1 etch-factor (60^0 taper). The as designed nominal trace width of 11 mils, and a 1oz trace thickness of 1.25 mils per isoStack® was used in the analysis.


isoStack

Design name: CMP28
Date: Sat Mar 28 2015 12:08:48
Total number of cores: -1
Total pressed thickness: 39.900
Number of signal layers: 1
Number of reference planes: 3
Length unit: mils
Frequency 10GHz

	Thickness	Ref. plane	Zo	Diff Z	Tpd	Width	Spacing	Fill	Weight	Dk	Df	Build	Type
1	1.400	true	na	na	na	5.000	10.000	100	1				
	10.600									3.59	0.0095	3x3313-57.0	FR408HR
2	1.250	false	49.0	98.0	161	10.380	10015.000	5	1				
	12.000									3.65	0.0094	3x3313	FR408HR
3	1.250	true	na	na	na	5.000	10.000	100	1				

Figure 7 Example of Isola's isoStack® online software used to determine dielectric thicknesses, *Dk*, *Df* and characteristic impedance for the CMP-28 board.

The default foil used on FR408HR core laminates is MLS, Grade 3, controlled elongation RT foil. The roughness parameters were easily obtained from Oak-mitsui [10] (see Figure 14 in Appendix). Reviewing the data sheet, it can be seen that 1 oz. copper roughness parameters R_z for drum and matte sides are 120μin (3.175 μm) and 225μin (5.715μm) respectively. Because this is RT foil, the drum side is the treated side and bonded to the core laminate.

An oxide or micro-etch treatment is usually applied to the copper surfaces prior to final lamination. This provides enhanced adhesion to the prepreg material. CO-BRA BOND® [11] or MultiBond MP [12] are two examples of oxide alternative micro-etch treatments commonly used in the industry. Typically 50 μin (1.27μm) of copper is removed when the treatment is completed. But depending on the board shop's process control, this can be 70-100 μin (1.78-2.54μm) The etch treatment creates a surface full of micro-voids which follows the underlying rough profile and allows the resin to squish in and fill the voids providing a good anchor. Because some of the copper is removed during the micro-etch treatment, we need to reduce the published roughness parameter of the matte side by nominal 50 μin for a new thickness of 175μin (4.443μm).

Figure 8 are SEM photos of typical surfaces for MLS RT foil courtesy of Oak-mitsui. The left and center photos are the treated drum side and untreated matte side respectively. The right photo is a 5000x SEM photo matte side showing micro-voids after etch treatment .

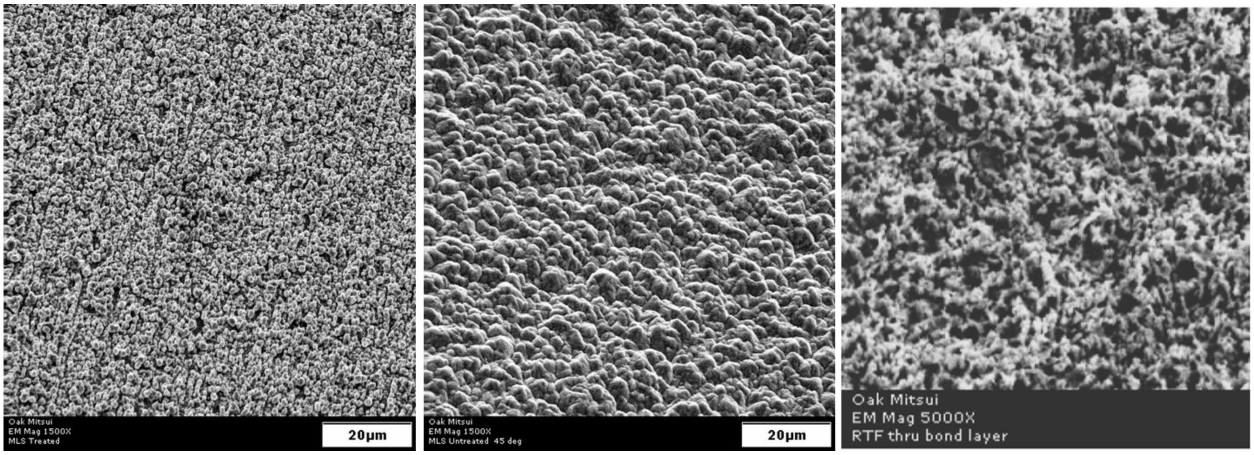


Figure 8 Example SEM photos of MLS RT foil courtesy of Oak-mitsui. Left is the treated drum side and center is untreated matte side. SEM photo on the right is the matte side after etch treatment.

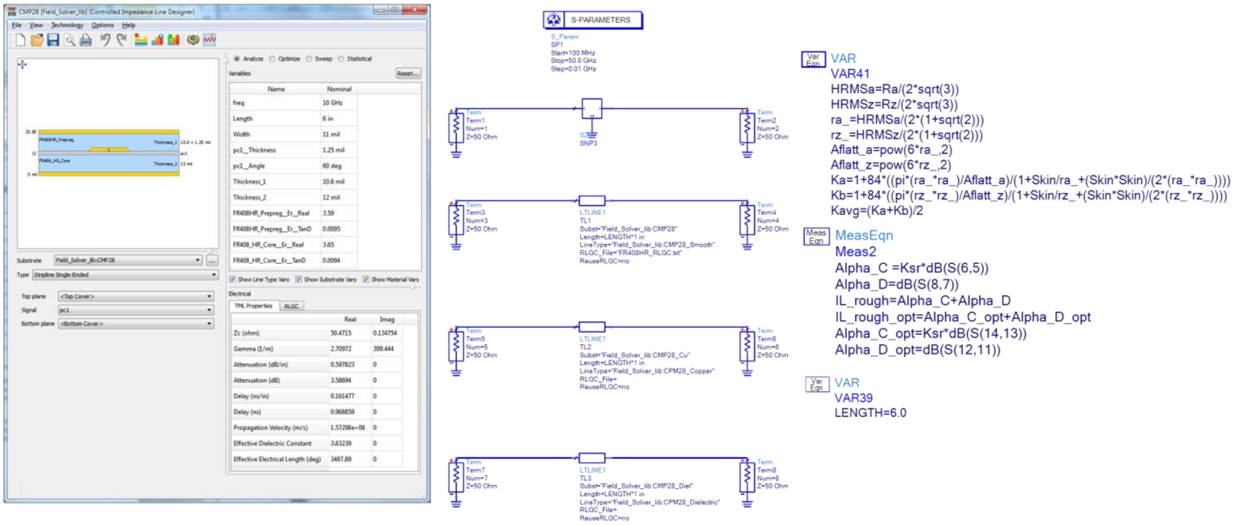
The data sheet and design parameters are summarized in Table 1. Respective *Dk, Df,* core, prepreg and trace thickness were obtained from the isoStack® software in Figure 7. Roughness parameters were obtained from Oak-mitsui data sheet. R_z of the matte side after micro-etch treatment (R_z = 4.443μm) was used to determine K_{sr_matte}.

Table 1 CMP-28 test board parameters obtained from manufacturers' data sheets and design objective.

Parameter	FR408HR
Dk Core/Prepreg	**3.65/3.59 @10GHz**
Df Core/Prepreg	**0.0094/0.0095 @ 10GHz**
R_z Drum side	**3.175 μm**
R_z Matte side before Micro-etch	**5.715 μm**
R_z Matte side after Micro-etch	**4.443 μm**
Trace Thickness, *t*	**31.730 μm**
Etch Factor	**2:1 (60 deg taper)**
Trace Width, w	**11 mils (279.20 μm)**
Core thickness, H1	**12 mils (304.60 μm)**
Prepreg thickness, H2	**10.6 mils (269.00 μm)**
GMS trace length	**6 in (15.23 cm)**

Keysight EEsof EDA ADS software [13] was used for modeling and simulation analysis. A new controlled impedance line (CIL) designer enhancement, in version 2015.01, makes modeling the transmission line substrate easy. Unlike earlier substrate models, the CIL model allows you to model trapezoidal traces.

Figure 9 is the general schematic used for analysis. There are three transmission line substrates; one for dielectric loss; one for conductor loss and the other for total loss without roughness.



Substrate: Field_Solver_lib:CMP28
Type: Stripline Single-Ended
Top plane: <Top Cover>
Signal: pc1
Bottom plane: <Bottom Cover>

● Analyze ○ Optimize ○ Sweep ○ Statistical

Variables

Name	Nominal
freq	10 GHz
Length	6 in
Width	11 mil
pc1__Thickness	1.25 mil
pc1__Angle	60 deg
Thickness_1	10.6 mil
Thickness_2	12 mil
FR408HR_Prepreg__Er__Real	3.59
FR408HR_Prepreg__Er__TanD	0.0095
FR408_HR_Core__Er__Real	3.65
FR408_HR_Core__Er__TanD	0.0094

☑ Show Line Type Vars ☑ Show Substrate Vars ☑ Show Material Vars

Electrical

TML Properties | RLGC

	Real	Imag
Zc (ohm)	50.4715	0.134754
Gamma (1/m)	2.70972	399.444
Attenuation (dB/in)	0.597823	0
Attenuation (dB)	3.58694	0
Delay (ns/in)	0.161477	0
Delay (ns)	0.968859	0
Propagation Velocity (m/s)	1.57298e+08	0
Effective Dielectric Constant	3.63239	0
Effective Electrical Length (deg)	3487.89	0

```
S_Param
SP1
Start=100 MHz
Stop=50.0 GHz
Step=0.01 GHz
```

```
Term
Term1
Num=1
Z=50 Ohm

S2P
SNP3

Term
Term2
Num=2
Z=50 Ohm
```

```
Term
Term3
Num=3
Z=50 Ohm

LTLINE1
TL1
Subst="Field_Solver_lib:CMP28"
Length=LENGTH*1 in
LineType="Field_Solver_lib:CMP28_Smooth"
RLGC_File="FR408HR_RLGC.txt"
ReuseRLGC=no

Term
Term4
Num=4
Z=50 Ohm
```

```
Term
Term5
Num=5
Z=50 Ohm

LTLINE1
TL2
Subst="Field_Solver_lib:CMP28_Cu"
Length=LENGTH*1 in
LineType="Field_Solver_lib:CPM28_Copper"
RLGC_File=
ReuseRLGC=no

Term
Term6
Num=6
Z=50 Ohm
```

```
Term
Term7
Num=7
Z=50 Ohm

LTLINE1
TL3
Subst="Field_Solver_lib:CMP28_Diel"
Length=LENGTH*1 in
LineType="Field_Solver_lib:CPM28_Dielectric"
RLGC_File=
ReuseRLGC=no

Term
Term8
Num=8
Z=50 Ohm
```

```
VAR
VAR41
HRMSa=Ra/(2*sqrt(3))
HRMSz=Rz/(2*sqrt(3))
ra_=HRMSa/(2*(1+sqrt(2)))
rz_=HRMSz/(2*(1+sqrt(2)))
Aflatt_a=pow(6*ra_,2)
Aflatt_z=pow(6*rz_,2)
Ka=1+84*((pi*(ra_*ra_)/Aflatt_a)/(1+Skin/ra_+(Skin*Skin)/(2*(ra_*ra_))))
Kb=1+84*((pi*(rz_*rz_)/Aflatt_z)/(1+Skin/rz_+(Skin*Skin)/(2*(rz_*rz_))))
Kavg=(Ka+Kb)/2
```

```
MeasEqn
Meas2
Alpha_C =Ksr*dB(S(6,5))
Alpha_D=dB(S(8,7))
IL_rough=Alpha_C+Alpha_D
IL_rough_opt=Alpha_C_opt+Alpha_D_opt
Alpha_C_opt=Ksr*dB(S(14,13))
Alpha_D_opt=dB(S(12,11))
```

```
VAR
VAR39
LENGTH=6.0
```

Figure 9 Keysight EEsof EDA ADS generic schematic of controlled impedance line designer used in the modeling and simulation analysis.

Dielectric loss was modeled using the Svensson/Djordjevic wideband Debye model to ensure causality. By setting the conductivity parameter to a value much-much greater than the normal conductivity of copper ensures the conductor is lossless for the simulation. Similarly the conductor loss model sets the *Df* to zero to ensure lossless dielectric.

Total insertion loss (IL) of the PCB trace, as a function of frequency, is the sum of dielectric and rough conductor insertion losses.

Equation 8

$$IL_{rough}\left(f\right)=K_{SR\_avg}\left(f\right)\left(IL_{smooth}\left(f\right)\right)+IL_{diel}\left(f\right)$$

To accurately model the effect of roughness, the respective roughness correction factor (K_{sr}) must be multiplicatively applied to the AC resistance of the drum and matte sides of the traces separately. Unfortunately ADS, and many other commercial simulators, do not allow access to these surfaces to apply the correction properly. They have the appropriate roughness model buried within the tools, and you must input the appropriate parameters accordingly. The best you can do with commercial tools is to use their roughness model or apply the average of (K_{SR_drum}) and (K_{SR_matte}) side to the smooth conductor loss (IL_{smooth}).

The following are the steps to determine K_{SR_avg} (*f*) and total IL with roughness:

1. Determine H_{RMS_drum} and H_{RMS_matte} from Equation 6 and Equation 7.

$$H_{RMS\_drum}\approx\frac{R_{z\_drum}}{2\sqrt{3}};\quad H_{RMS\_matte}\approx\frac{R_{z\_matte}}{2\sqrt{3}}$$

2. Determine the radius of spheres for drum and matte sides:

$$r_{drum} = \frac{H_{RMS\_drum}}{2\left(1+\sqrt{2}\right)}; \quad r_{matte} = \frac{H_{RMS\_matte}}{2\left(1+\sqrt{2}\right)}$$

3. Determine the area of the square flat base for drum and matte sides:

$$A_{flat\_drum} = \left(6r_{drum}\right)^2; \quad A_{flat\_matte} = \left(6r_{matte}\right)^2$$

4. Determine $K_{SR\_drum}(f)$ and $K_{SR\_matte}(f)$:

$$K_{SR\_drum}\left(f\right) = 1+84\left(\frac{\left(\frac{\left(\pi r_{drum}^2\right)}{A_{flat\_drum}}\right)}{\left(1+\frac{\delta\left(f\right)}{r_{drum}}+\frac{\delta^2\left(f\right)}{2r_{drum}^2}\right)}\right)$$

$$K_{SR\_matte}\left(f\right) = 1+84\left(\frac{\left(\frac{\left(\pi r_{matte}^2\right)}{A_{flat\_matte}}\right)}{\left(1+\frac{\delta\left(f\right)}{r_{matte}}+\frac{\delta^2\left(f\right)}{2r_{matte}^2}\right)}\right)$$

5. Determine the average $K_{SR\_drum}(f)$ and $K_{SR\_matte}(f)$:

$$K_{SR\_avg}\left(f\right) = \frac{K_{SR\_drum}\left(f\right)+K_{SR\_matte}\left(f\right)}{2}$$

6. Apply Equation 8 to determine total insertion loss of the PCB trace.

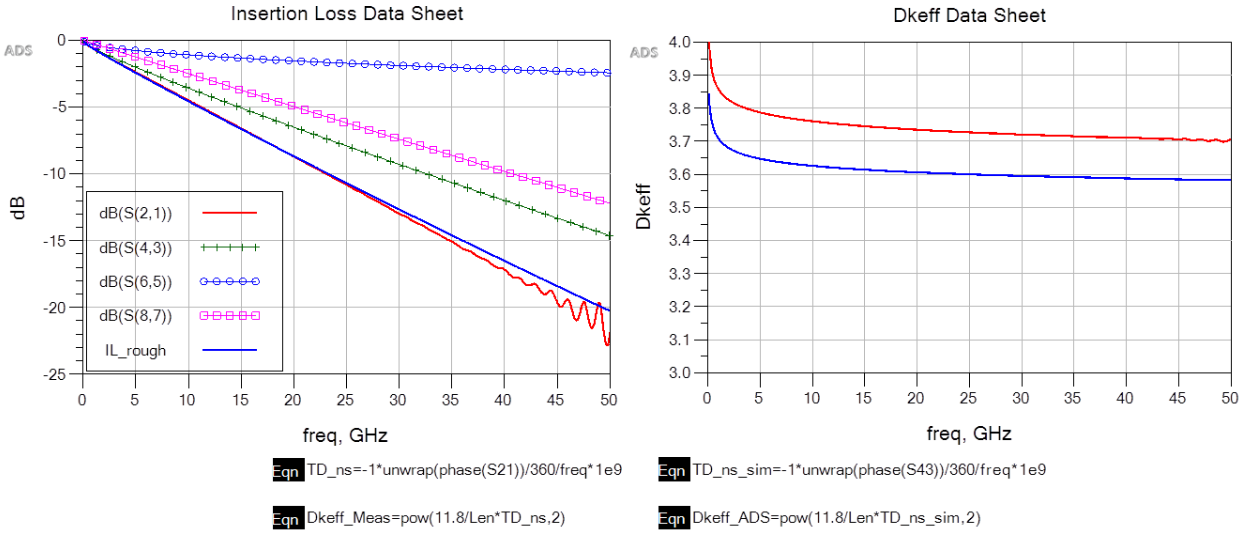
$$IL_{rough}\left(f\right) = K_{SR\_avg}\left(f\right)\left(IL_{smooth}\left(f\right)\right)+IL_{diel}\left(f\right)$$

Summary and Results:

The results are plotted in Figure 10. The left plot compares the simulated vs measured insertion loss for data sheet values and design parameters. Also plotted is the total smooth insertion loss (crosses) which is the sum of conductor loss (circles) and dielectric loss (squares). Remarkably there is excellent agreement up to about 30GHz by just using algebraic equations and published data sheet values for *Dk*, *Df* and roughness.

The plot shown on the right is the simulated (blue) vs measured (red) effective dielectric constant (*Dkeff*), and is determined by the equations shown. As can be seen, the measured curve has a slightly higher *Dkeff* (3.76 vs 3.63 @ 10GHz) than published. According to [6], the small increase in the *Dk* is due to the anisotropy of the material.

When the measured *Dkeff* (3.76) was used in the model, for core and prepreg, the IL results shown in Figure 11 (left) are even more remarkable up to 50 GHz!



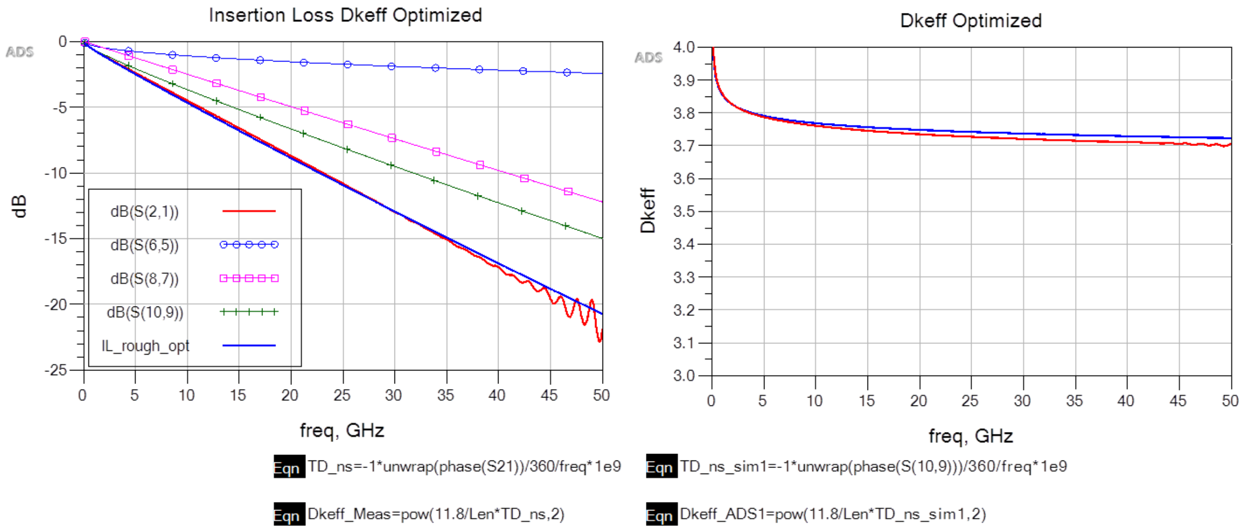
TD_ns=-1*unwrap(phase(S21))/360/freq*1e9

Dkeff_Meas=pow(11.8/Len*TD_ns,2)

TD_ns_sim=-1*unwrap(phase(S43))/360/freq*1e9

Dkeff_ADS=pow(11.8/Len*TD_ns_sim,2)

Figure 10 IL (left) for a 6 inch trace in FR408HR RTF using supplier data sheet values for *Dk*, *Df* and *Rz*. Effective *Dk* is shown right.



TD_ns=-1*unwrap(phase(S21))/360/freq*1e9

Dkeff_Meas=pow(11.8/Len*TD_ns,2)

TD_ns_sim1=-1*unwrap(phase(S(10,9)))/360/freq*1e9

Dkeff_ADS1=pow(11.8/Len*TD_ns_sim1,2)

Figure 11 IL (left) for a 6 inch trace in FR408HR RTF and effective *Dk* (right).

Figure 12 compares the Cannonball model against the H&J model. The results show that the H&J is only accurate up to approximately 15 GHz compared to the Cannonball model's accuracy to 50GHz.

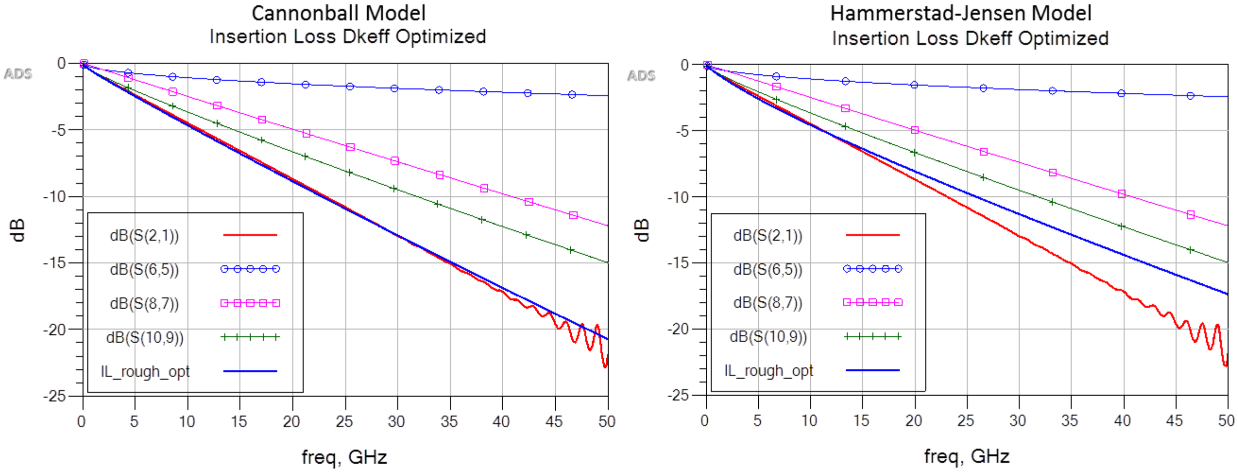


Figure 12 Cannonball Model (left) vs Hammerstad-Jensen model (right).

Figure 13 shows simulated vs measured results for N4000-13EP VLP foil as described in DesignCon 2015 paper [1] using the Cannonball model instead of HCPES model. *Dkeff* is optimized from the data sheet value of 3.65 to 3.867 at 10GHz. The rest of the data sheet and board parameters remained unchanged. *Df* =0.0085; R_{a_drum} = 1.5 µm; R_{z_matte} =2.5 µm.

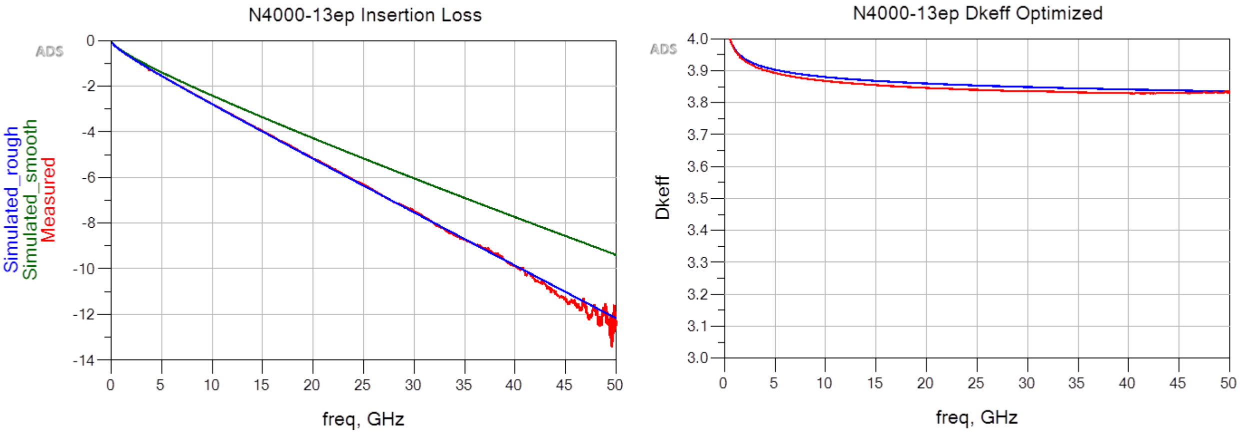


Figure 13 Simulated vs measured results for N4000-13EP VLP foil as described in DesignCon 2015 paper [1] using the Cannonball model.

Conclusions:

Using the concept of cubic close-packing of equal spheres to model copper roughness, a practical method to accurately calculate sphere size and tile area was devised for use in the Huray model. By using published roughness parameters and dielectric properties from manufacturers' data sheets, it has been demonstrated that the need for further SEM analysis or experimental curve fitting, may no longer be required for preliminary design and analysis.

When measurements from CMP-28 modeling platform, fabricated with FR408HR and RT foil, was compared to this method, there was excellent correlation up to 50GHz compared to the H&J model accuracy to 15GHz.

Like the HCPES model described in my DesignCon 2015 paper [1], the Cannonball model looks as promising for a practical alternative to building a test board and extracting fitting parameters from measured results to predict insertion loss due to surface roughness.

References:

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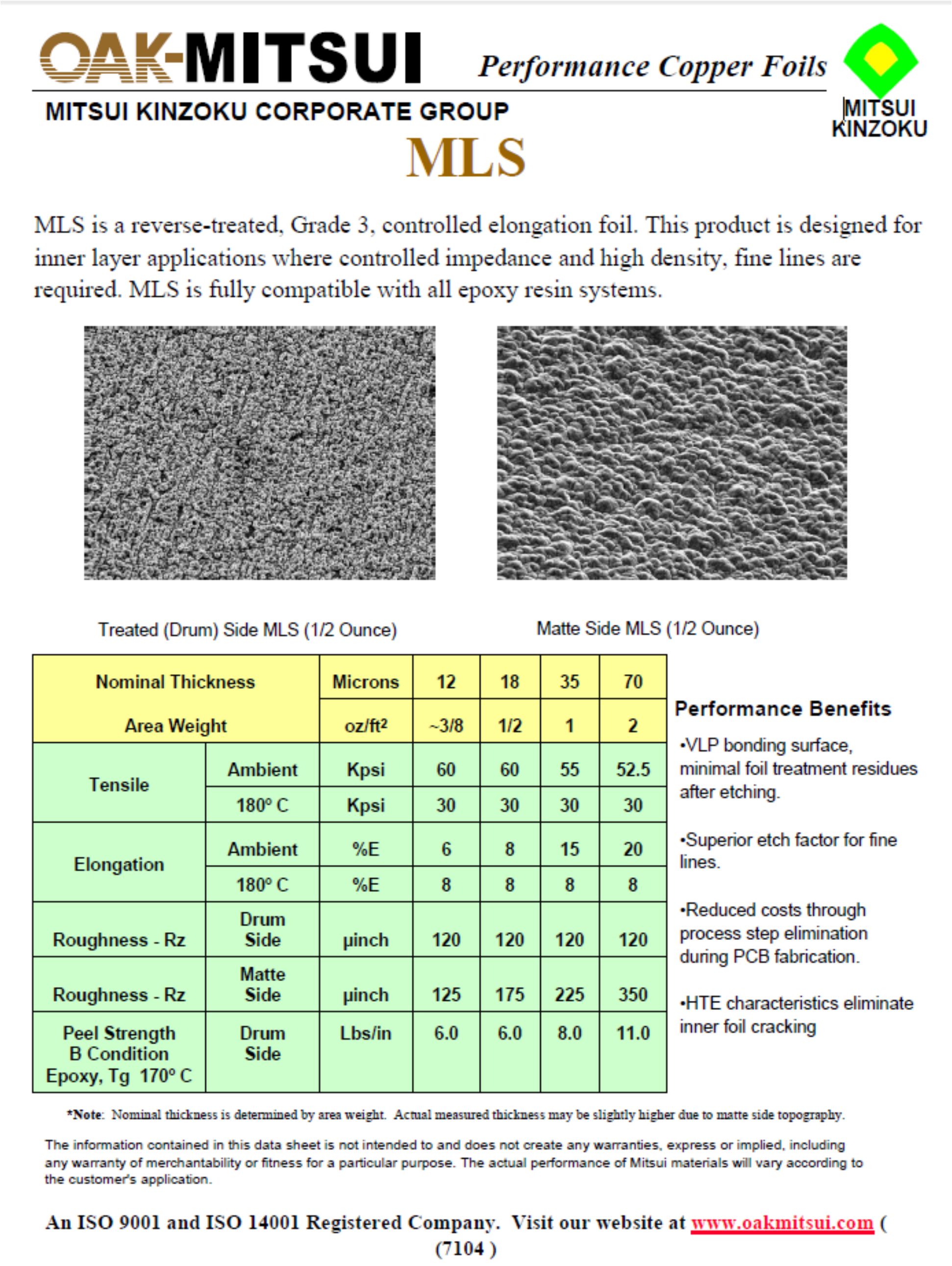
[14]Wild River Technology LLC 8311 SW Charlotte Drive Beaverton, OR 97007. URL: http://wildrivertech.com/home/

Appendix:



OAK-MITSUI *Performance Copper Foils*

MITSUI KINZOKU CORPORATE GROUP

MITSUI
KINZOKU

MLS

MLS is a reverse-treated, Grade 3, controlled elongation foil. This product is designed for inner layer applications where controlled impedance and high density, fine lines are required. MLS is fully compatible with all epoxy resin systems.

Treated (Drum) Side MLS (1/2 Ounce)

Matte Side MLS (1/2 Ounce)

Nominal Thickness		Microns	12	18	35	70
Area Weight		oz/ft²	~3/8	1/2	1	2
Tensile	Ambient	Kpsi	60	60	55	52.5
	180° C	Kpsi	30	30	30	30
Elongation	Ambient	%E	6	8	15	20
	180° C	%E	8	8	8	8
Roughness - Rz	Drum Side	µinch	120	120	120	120
Roughness - Rz	Matte Side	µinch	125	175	225	350
Peel Strength B Condition Epoxy, Tg 170° C	Drum Side	Lbs/in	6.0	6.0	8.0	11.0

Performance Benefits

- VLP bonding surface, minimal foil treatment residues after etching.
- Superior etch factor for fine lines.
- Reduced costs through process step elimination during PCB fabrication.
- HTE characteristics eliminate inner foil cracking

***Note:** Nominal thickness is determined by area weight. Actual measured thickness may be slightly higher due to matte side topography.

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(7104)

Figure 14 MLS reverse-treated foil data sheet credit Oak-mitsui.

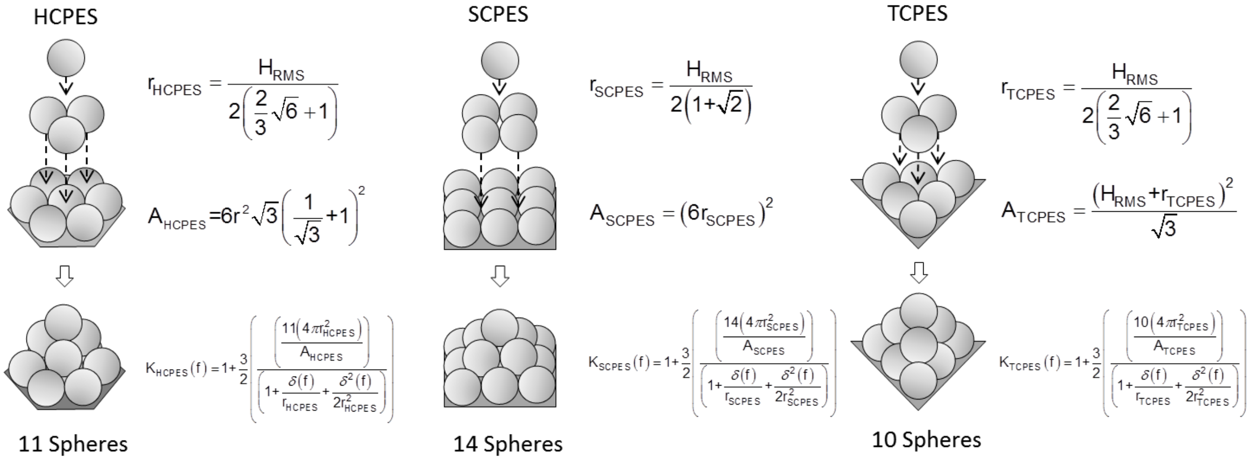


Figure 15 Close-packing of equal sphere model variations. Hexagonal close-packing of equal spheres, HCPES (left) as described in DesignCon 2015 paper [1]; Square close-packing of equal spheres, SCPES (center); and Triangular close-packing of equal spheres, TCPES (right).

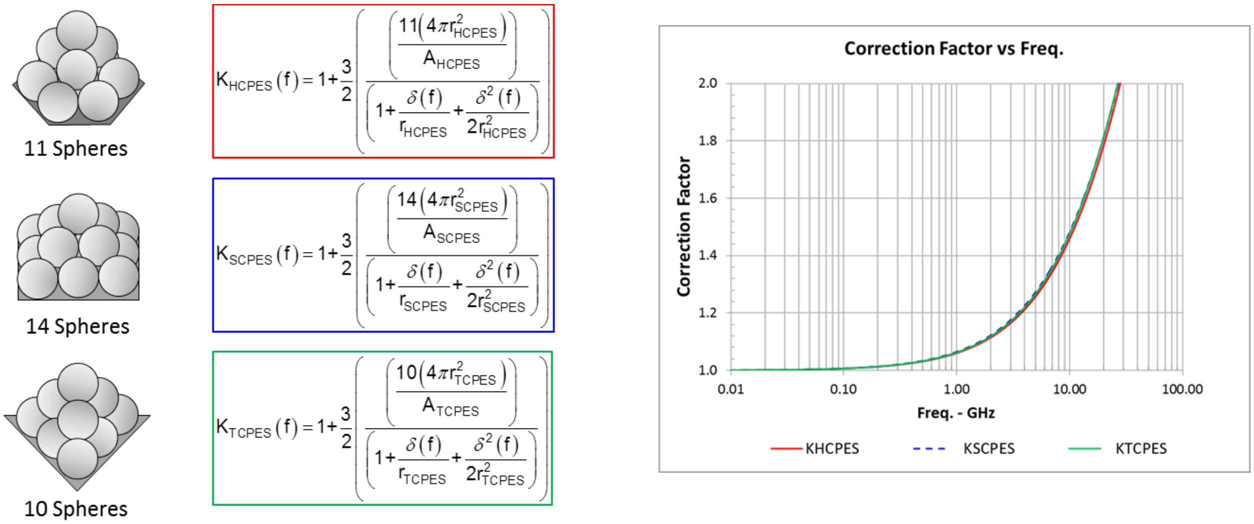
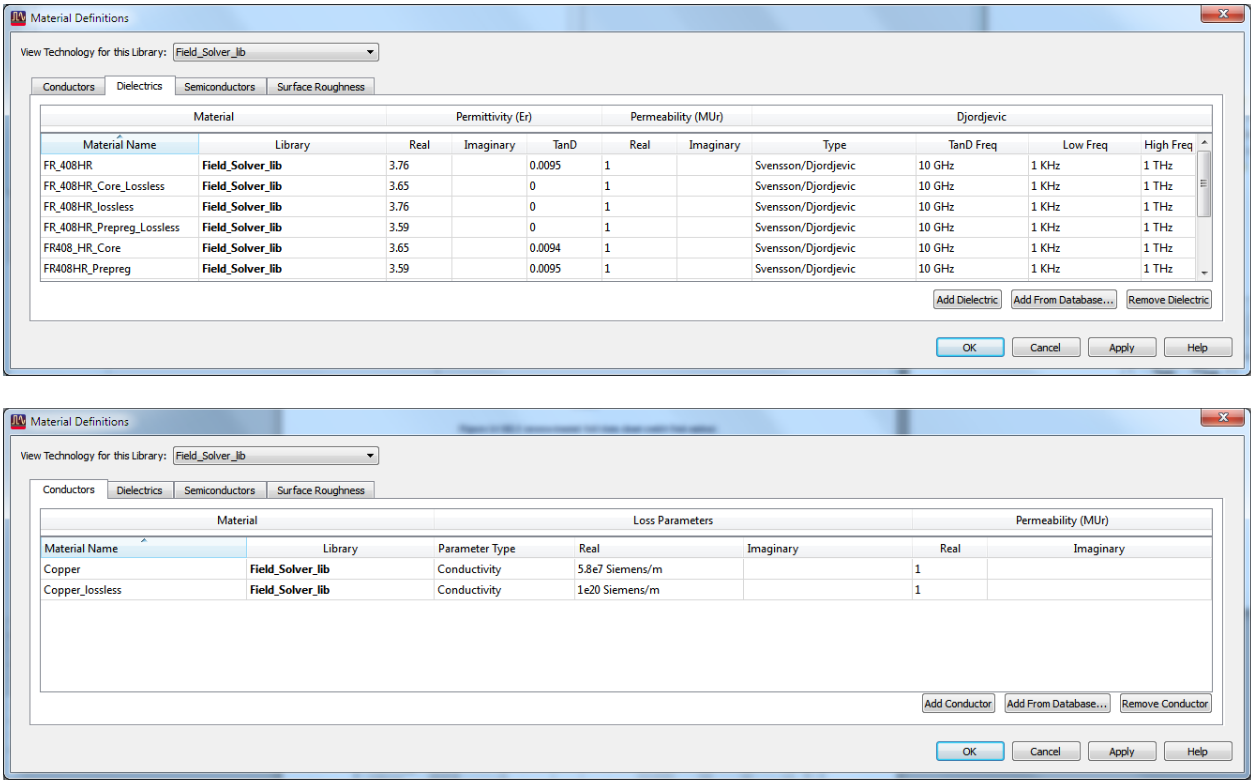


Figure 16 Comparing correction factors for each model. As can be seen all three models provides equivalent correction factors.



View Technology for this Library: Field_Solver_lib

Material		Permittivity (Er)			Permeability (MUr)		Djordjevic			
Material Name	Library	Real	Imaginary	TanD	Real	Imaginary	Type	TanD Freq	Low Freq	High Freq
FR_408HR	**Field_Solver_lib**	3.76		0.0095	1		Svensson/Djordjevic	10 GHz	1 KHz	1 THz
FR_408HR_Core_Lossless	**Field_Solver_lib**	3.65		0	1		Svensson/Djordjevic	10 GHz	1 KHz	1 THz
FR_408HR_lossless	**Field_Solver_lib**	3.76		0	1		Svensson/Djordjevic	10 GHz	1 KHz	1 THz
FR_408HR_Prepreg_Lossless	**Field_Solver_lib**	3.59		0	1		Svensson/Djordjevic	10 GHz	1 KHz	1 THz
FR408_HR_Core	**Field_Solver_lib**	3.65		0.0094	1		Svensson/Djordjevic	10 GHz	1 KHz	1 THz
FR408HR_Prepreg	**Field_Solver_lib**	3.59		0.0095	1		Svensson/Djordjevic	10 GHz	1 KHz	1 THz

View Technology for this Library: Field_Solver_lib

Material		Loss Parameters			Permeability (MUr)	
Material Name	Library	Parameter Type	Real	Imaginary	Real	Imaginary
Copper	**Field_Solver_lib**	Conductivity	5.8e7 Siemens/m		1	
Copper_lossless	**Field_Solver_lib**	Conductivity	1e20 Siemens/m		1	

Figure 17 FR408HR dielectric material parameters (top); Copper conductivity (bottom) used for various Keysight ADS CIL models in general schematic of Figure 9.