DesignCon® 2015

Electrodeposited Copper Foil Surface Characterization for Accurate Conductor Loss Modeling

OAK-MITSUI intel

UBM Tech

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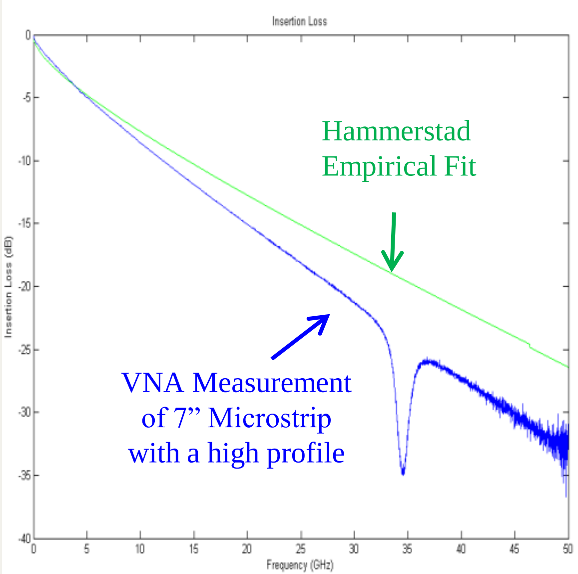
Agenda

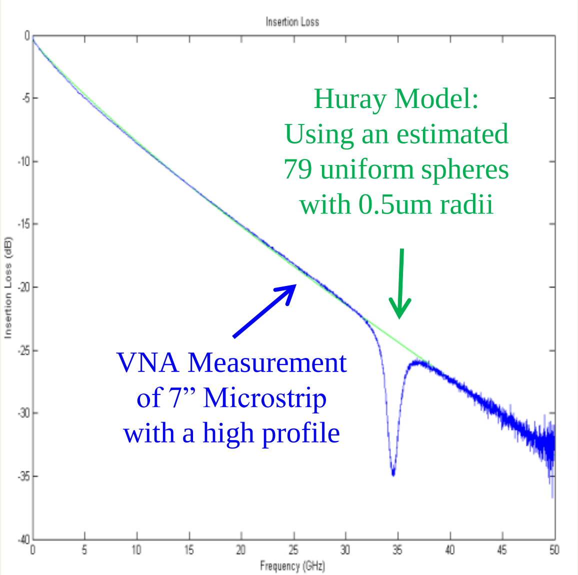
- Conductor loss by empirical fit compared to first principles model
- Identifying characterization parameters
- Characterizing the electrodeposited (ED) copper foil surface
- Applying parameters to simulation
- Conclusion

Conductor Loss by Empirical Fit v First Principles Model



The conventional Hammerstad equation is an empirical fit to Morgan's 2D calculations which fails above a few GHz. Modified versions provide minor improvements.

The Huray first principles 3D physical model has demonstrated accurate *dB/in* predictions up to 50 GHz by estimating ED copper foil surface parameters.

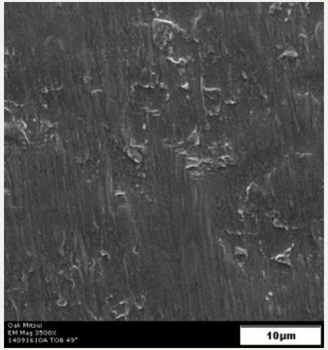


For designs above a few GHz, the conventional 2D conductor loss empirical fit fails.

The 3D Huray model is correct but needs improved parameters for characterizing ED copper.

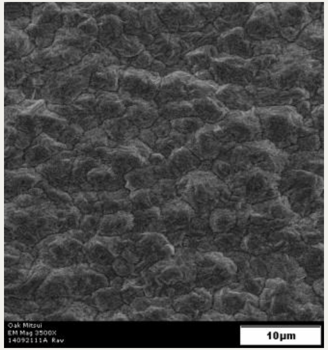
What parameters should be obtained?

Typical ED copper foil used for PCB fabrication begins with a raw untreated copper surface.

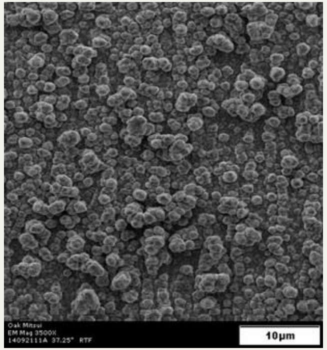


Untreated Drum Side

Untreated Matte Side

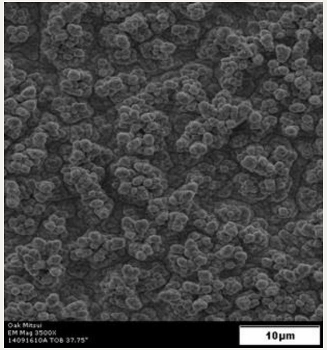


Copper "anchor nodules" are added to strengthen PCB adhesion on a treated copper surface.



Treated Drum Side

Treated Matte Side

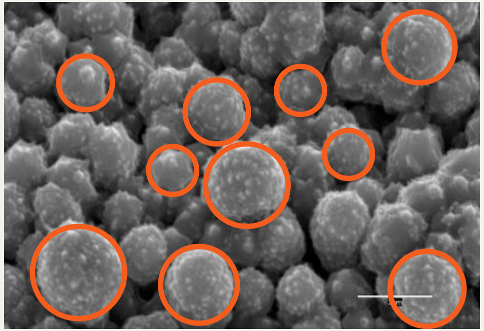


The Huray model describes the power loss associated with the untreated surface and anchor nodules.

$$\frac{P_{rough}}{P_{smooth}} \approx \frac{\frac{\mu_0 \omega \delta}{4}|H_0|^2 A_{matte} + \sum_{i=1}^{j} N_i \sigma_{total,i} \frac{\eta}{2}|H_0|^2}{\frac{\mu_0 \omega \delta}{4}|H_0|^2 A_{flat}}$$

$$\frac{P_{rough}}{P_{smooth}} \approx \frac{Untreated\ Area + Anchor\ Nodules}{Unit\ Area\ (Perfectly\ Flat)}$$

What parameters should be obtained?



Approximating the copper anchor nodules as spherical "snowballs" and substituting the dipole absorption cross section of a distribution of *j* different sized snowballs yields:

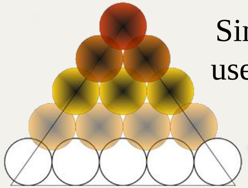
$$\frac{P_{rough}}{P_{smooth}} \approx \frac{A_{matte}}{A_{flat}} + 6\sum_{i=1}^{j}\left(\frac{N_i \pi a_i^2}{A_{flat}}\right) \Big/ \left(1 + \frac{\delta}{a_i} + \frac{\delta^2}{2a_i^2}\right)$$

The parameters for electrodeposited copper foil surface characterization are thus:

1. The radius of the i^{th} "snowball" (anchor nodule) — a_i
2. The number of snowballs with radius a_i per unit flat area — N_i/A_{flat}
3. The relative surface area without snowballs per unit flat area — A_{matte}/A_{flat}

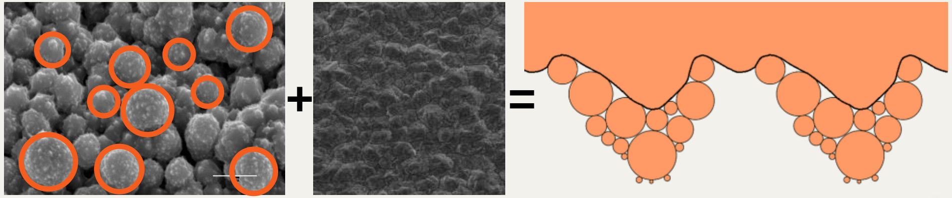
What parameters should be obtained?

Previous snowball model estimations assumed the untreated surface was perfectly flat and all the snowballs were of uniform average size.



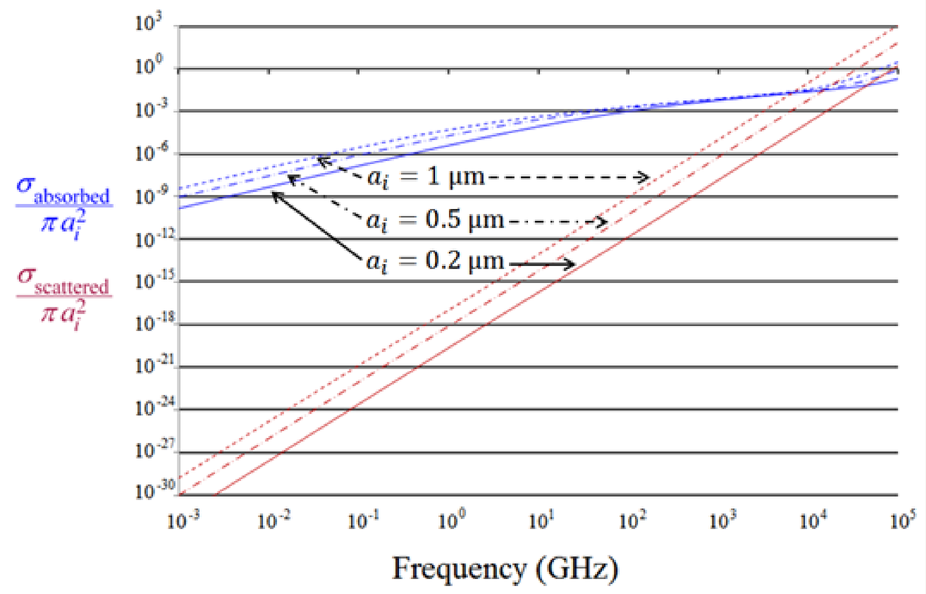
Simplified snowball stack-up used for previous estimations.

More realistic description.

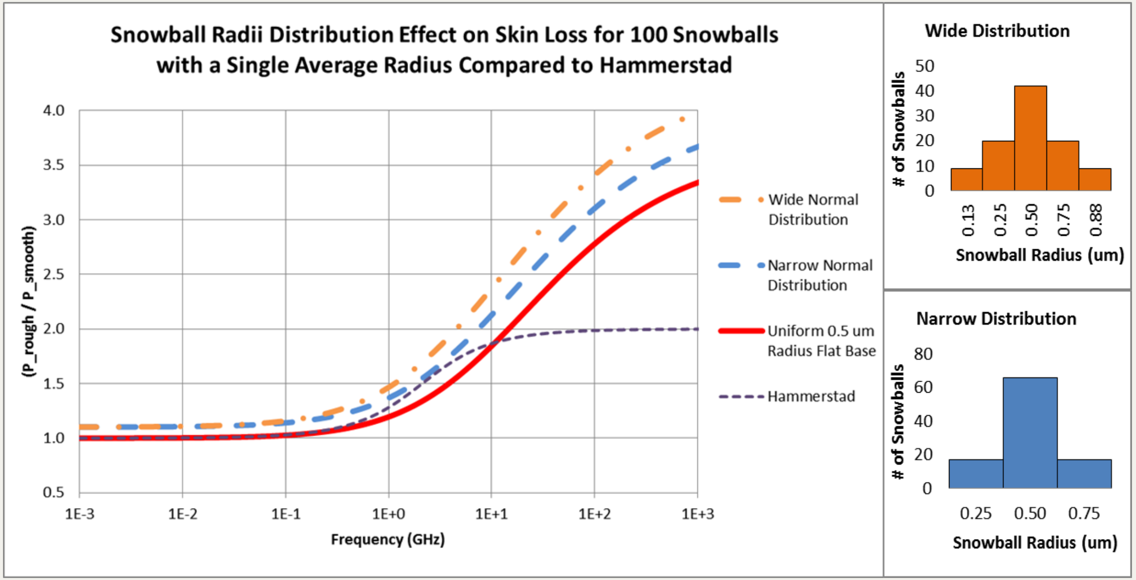


Does a distribution of different size snowballs on a non-flat surface have an impact on losses?

Absorption and scattering cross-sections of various size copper spheres as a function of frequency.



Does a snowball size distribution matter or can sizes be averaged for characterization?



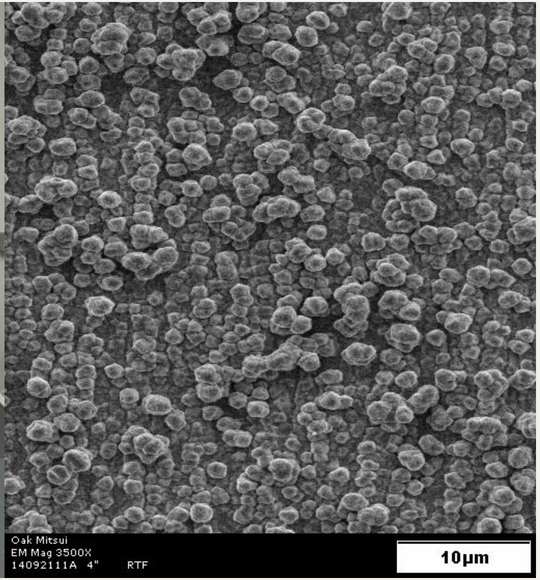
- A normal distribution with the same number of snowballs and same average radius of 0.5 μm can lead to higher loss
- A wider distribution with the same number of snowballs and same average radius of 0.5 μm can lead to higher loss
- The A_{matte}/A_{flat} parameter increases losses at all frequencies
- The Hammerstad empirical fit saturates at an arbitrary maximum of 2.0

Yes, a distribution of snowball sizes can impact losses and should not be averaged for characterization.

All model parameters a_i, N_i/A_{flat}, & A_{matte}/A_{flat} should be obtained for the most accurate results.

N_i/A_{flat} and a_i Distribution: SEM Analysis Method

SEII v 2.3 PCI
Scanning Electron Microscope

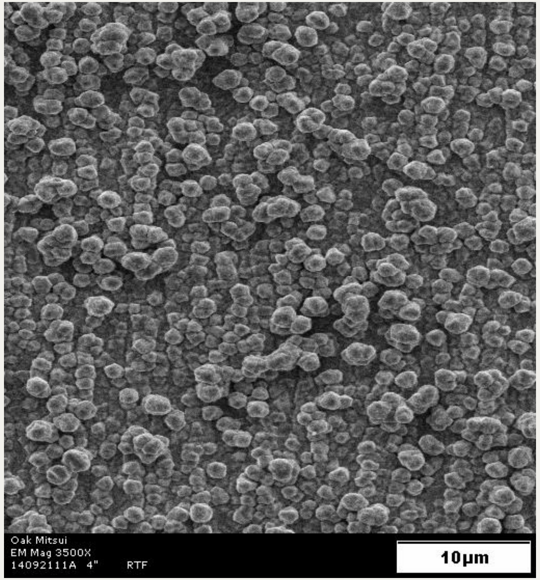


Images taken with
3500x Magnification

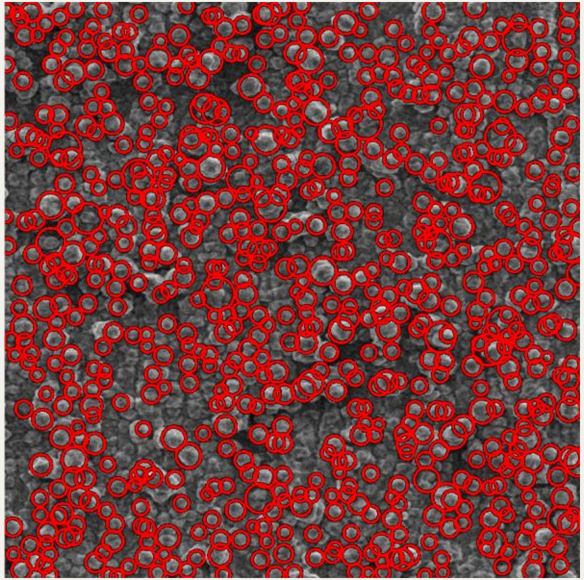
- 1^{st} challenge:
  Identify the snowballs
- 2^{nd} challenge:
  Count the snowballs
- 3^{rd} challenge:
  Measure the snowball radii

N_i/A_{flat} and a_i Distribution: SEM Analysis Method

- 1st challenge: Identify the snowballs



Use a ***Circular Hough Transform (CHT)*** to find and circle the snowballs.

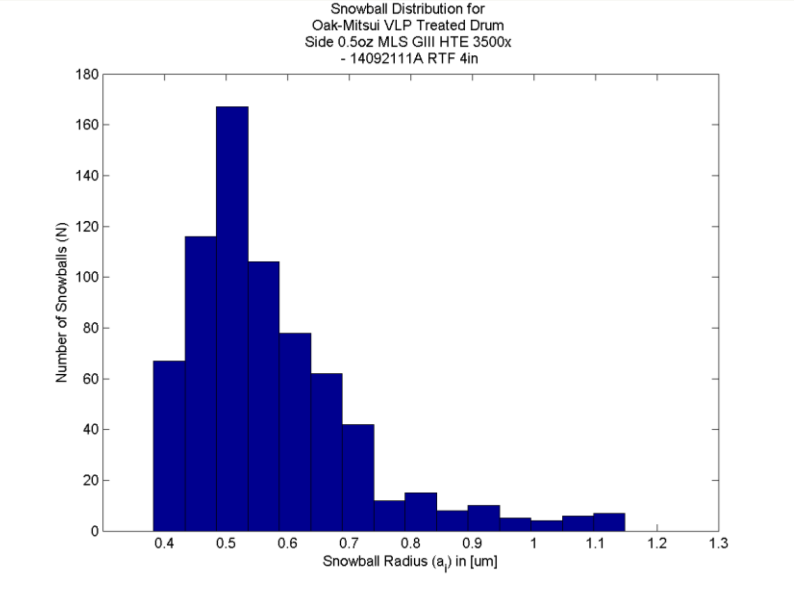


A CHT uses image intensity to search for 'dark' or 'bright' circles after edge detection. This is not binarization.

**Once the first CHT parameters are set, they can be used for subsequent analyses.

N_i/A_{flat} and a_i Distribution: SEM Analysis Method

- 2nd and 3rd challenge: Count the number of snowballs and measure their radii

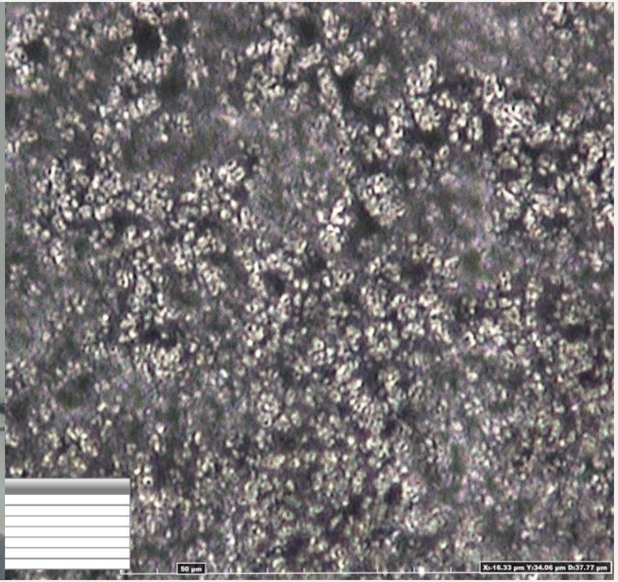


Once the snowballs (or circles) are found using a *Circular Hough Transform* **(**CHT), they can be counted and measured.

**This is easy to extract as they are defined by the CHT.

N_i/A_{flat} and a_i Distribution: 3D Microscope Method

Hirox KH-8700E
3D Digital Microscope

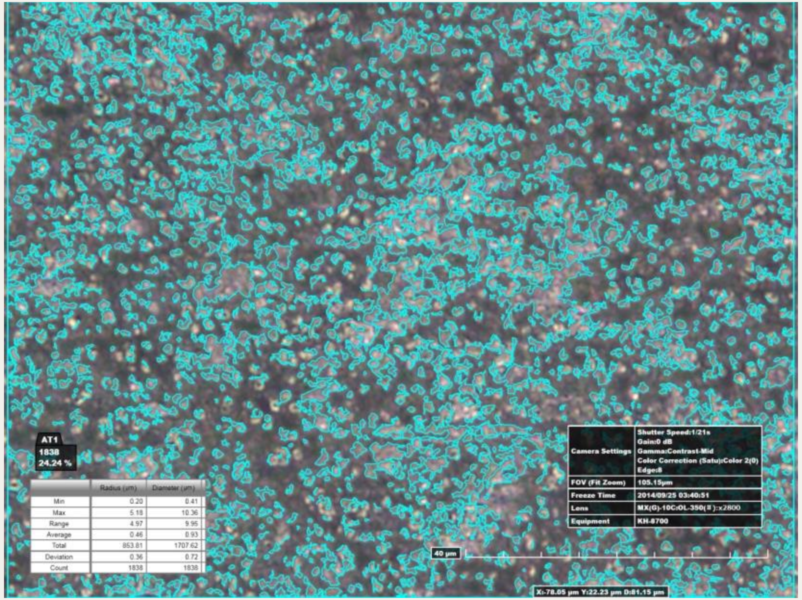


Images taken with
2800x Magnification

- Images were taken at 2800x
  - Excessive vibration made it difficult to increase
- Image processing software built-in
  - Supports external image processing
- Built-in particle counting software
  - Choose between binarization or Red-Green-Blue (RGB) algorithm
- Same 3 Challenges as before:
  - 1st: Identify the snowballs
  - 2nd: Count the snowballs
  - 3rd: Measure the snowball radii

N_i/A_{flat} and a_i Distribution: 3D Microscope Method

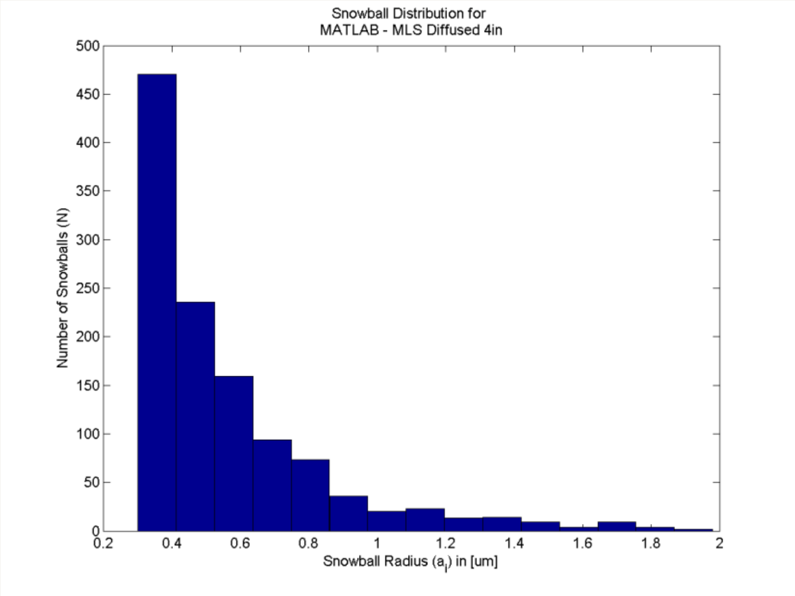
- 1st challenge: Identify the snowballs



- Built-in binarization particle counter used to identify snowballs
- Requires manual threshold adjustments for every image (very subjective)
- Some statistics are provided immediately that can help standardize thresholding, such as a ratio of the selected area to the total area
- Note missed or clumped snowballs

N_i/A_{flat} and a_i Distribution: 3D Microscope Method

- 2nd and 3rd challenge: Count the number of snowballs and measure their radii



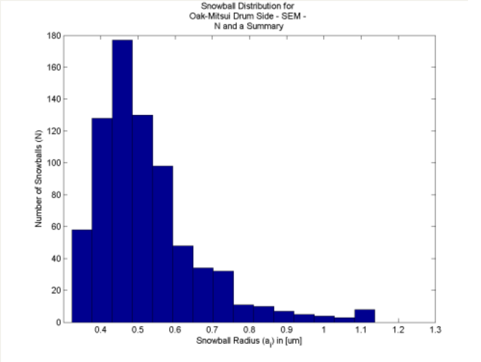
- Distribution binning cannot be performed with the microscope's software
- Data can be exported as a comma separated values (csv) file for external analysis and binning
- A csv provides an opportunity to filter unrealistic snowball sizes
- But, there's no inherent justification to choose which sizes are unrealistic
  - SEM images used to justify filtering 0.3 μm < a_i < 2.0 μm

N_i/A_{flat} and a_i Distribution: Results

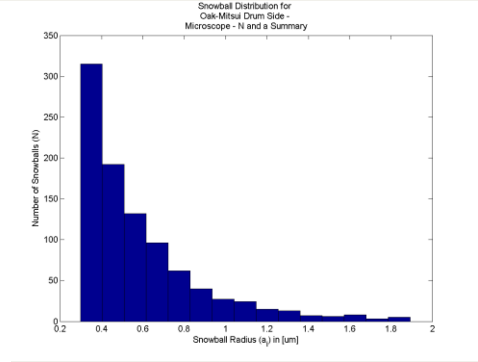
(5 Samples from 1 Drum)

Drum Side

SEM Method

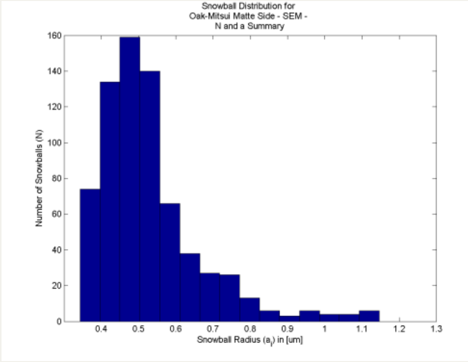


Microscope Method

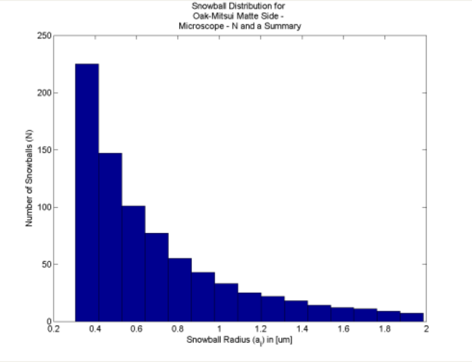


Matte Side

SEM Method



Microscope Method



N_i/A_{flat} and a_i Distribution: Results

(5 Samples from 1 Drum)

Drum Side

SEM Method (Oak-Mitsui ED Foil)

Average Snowball Radius [a]	0.54 µm
Averaged Number Snowballs [$N/88.36\ \mu m^2$]	40

Microscope Method (Oak-Mitsui ED Foil)

Average Snowball Radius [a]	0.59 µm
Averaged Number Snowballs [$N/88.36\ \mu m^2$]	10

Previous Estimates (Gould ED Foil)

Effective Snowball Radius [a]	0.5 µm
Effective Number Snowballs [$N/88.36\ \mu m^2$]	50

Matte Side

SEM Method (Oak-Mitsui ED Foil)

Average Snowball Radius [a]	0.56 µm
Averaged Number Snowballs [$N/88.36\ \mu m^2$]	38

Microscope Method (Oak-Mitsui ED Foil)

Average Snowball Radius [a]	0.7 µm
Averaged Number Snowballs [$N/88.36\ \mu m^2$]	9

Previous Estimates (Gould ED Foil)

Effective Snowball Radius [a]	1.0 µm
Effective Number Snowballs [$N/88.36\ \mu m^2$]	79

N_i/A_{flat} and a_i Distribution: Results

Drum Side

SEM Method (Oak-Mitsui ED Foil)

Area difference compared to Gould estimate	-6.7 %

Microscope Method (Oak-Mitsui ED Foil)

Area difference compared to Gould estimate	-72.2 %

Matte Side

SEM Method (Oak-Mitsui ED Foil)

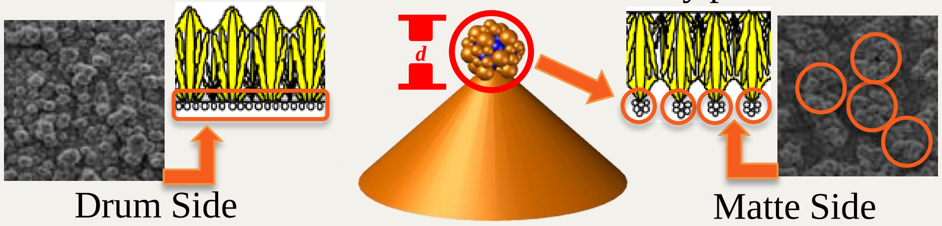
Area difference compared to Gould estimate	-83.8 %

Microscope Method (Oak-Mitsui ED Foil)

Area difference compared to Gould estimate	-94.4 %

Microscope method was convenient but struggled to isolate snowballs. May improve with anti-vibe table and CHT algorithm.

A possible correction to the matte side SEM method could be to account for the different snowball density per unit area:



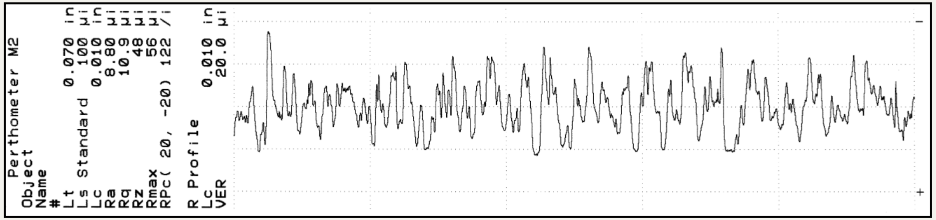
Matte Side

SEM Method with correction (Oak-Mitsui ED Foil)

Average Snowball Radius [a]	0.56 μm
Averaged Number Snowballs [$N/88.36\ \mu m^2$]	234
Area difference compared to Gould estimate	-7.1 %

A_{matte}/A_{flat}: Perthometer Method

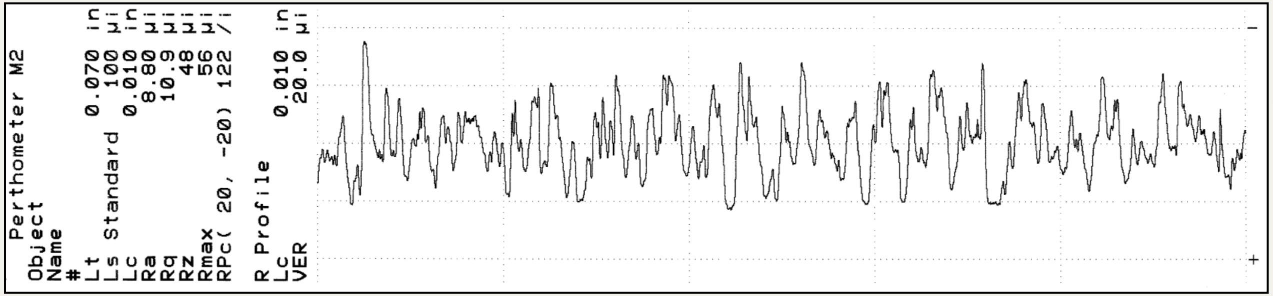
- 2 Measurements must be made per untreated sample
  - 1 in X direction (width) & 1 in Y direction (length)
- Data points are only provided for R_a, R_q, R_z, R_{max}, etc.
  - But, analog profile can be printed



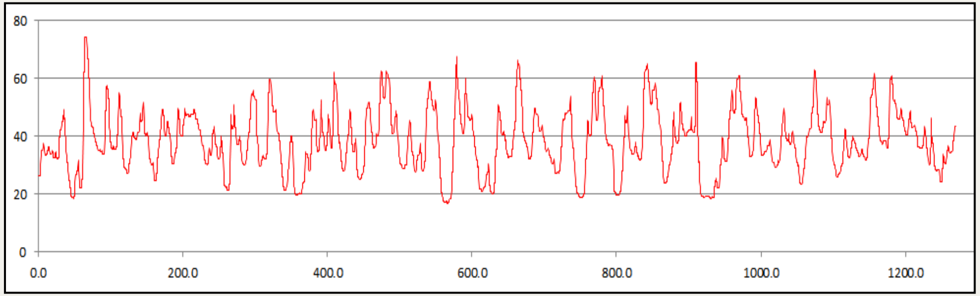
- 1st challenge: Convert printed graph to digital data
- 2nd challenge: Properly interpolate curve between points
- 3rd challenge: Measure total length and calculate area

A_{matte}/A_{flat}: Perthometer Method

- 1st challenge: Image was scanned then Python was used to convert the pixels to linear units



Original Printout with Continuous Graph

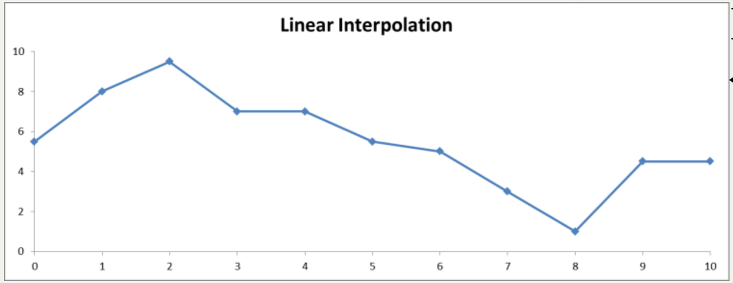


Recreated with Discrete Data Points

*Data Points at Original Minima

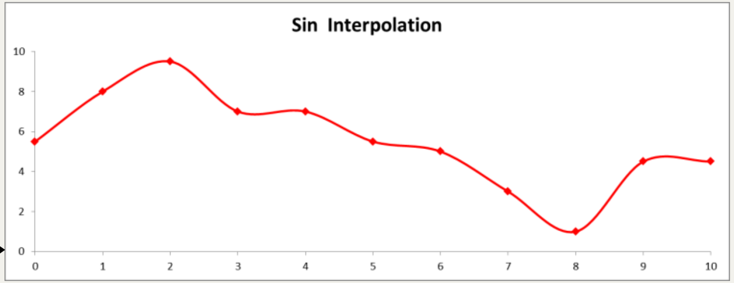
A_{matte}/A_{flat}: Perthometer Method

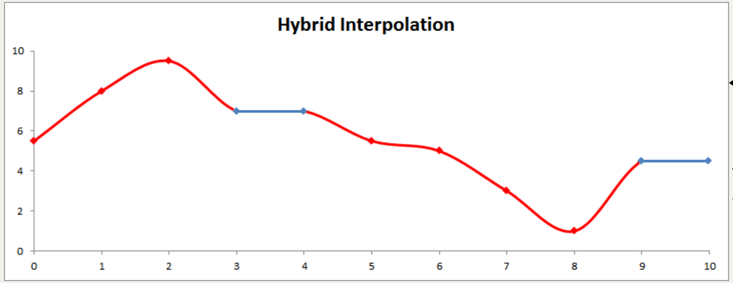
- 2nd challenge: Establish a minimum and maximum interpolation, then consider alternatives



Linear Interpolation (Minimum)

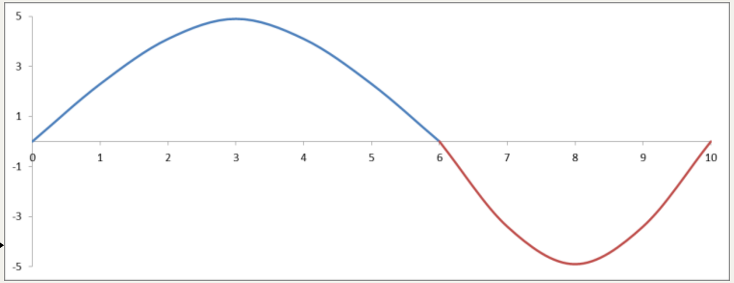
Sin Interpolation (Maximum)





Hybrid Interpolation (Sin | Linear)

Periodic Interpolation (Nonlinear Average)



A_{matte}/A_{flat}: Perthometer Method

- 3rd challenge: Sum interpolated arc lengths and calculate area from XY lengths

Linear (Absolute Minimum): Pythagorean Theorem

Length = $\sqrt{(Flat\ Length)^2 + (Height)^2}$

Sin (Effective Maximum): Arc Length by Composite Simpson's Rule

Length = $\int_0^{\pi/2} \sqrt{1 + \left(\frac{dy}{dx}\right)^2}\, dx \approx \frac{\Delta x}{3}\left[f(x_0) + 2\sum_{j=1}^{n/2-1} f(x_{2j}) + 4\sum_{j=1}^{n/2} f(x_{2j-1}) + f(x_n)\right]$

Where $\frac{dy}{dx}(\sin(x)) = \cos(x)$ ➔ $f(x_n) = \sqrt{1 + \cos^2(x_n)}$

Hybrid (Intermediate): If $\Delta x = 0$ ➔ Linear Interpolation Else ➔ Sin Interpolation

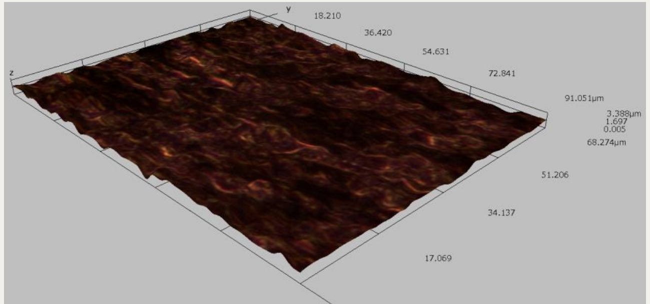
Periodic: Binarize & average peaks & valleys from R_a ➔ Arc Length by Simpson's Rule

Where $\frac{dy}{dx}(ax^2) = 2ax$ ➔ $f(x_n) = \sqrt{1 + 4a^2x^2}$ And $a = \left[\frac{4R_a}{l_{flat}^2}\right]$

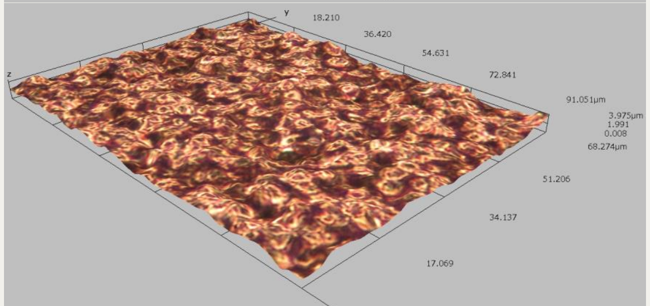
A_{matte}/A_{flat}: 3D Microscope Method

Hirox KH-8700E
3D Digital Microscope

- Series of images taken at different focal points
  - Focal range and number of steps set by user
  - Again, vibrations reduced resolution
- Image processing software built-in
  - Supports external image processing
- 3D image provides A_{matte} and A_{flat} measurements
  - Accuracy and interpolation is undetermined
- Measurement is simple
  1. Record image 2. Select area 3. Click surface



Drum Side



Matte Side

A_{matte}/A_{flat}: Results

Drum Side

Perthometer Method
(10 Samples from 2 Drums)

	Linear	Sin	Hybrid	Periodic
Average	1.0224	1.0758	1.0549	1.0222
σ_s	0.003	0.003	0.003	0.006

Microscope Method
(5 Samples from 1 Drum)

Average	1.13
σ_s	0.028

Matte Side

Perthometer Method
(10 Samples from 2 Drums)

	Linear	Sin	Hybrid	Periodic
Average	1.1095	1.1674	1.1455	1.1165
σ_s	0.006	0.007	0.007	0.028

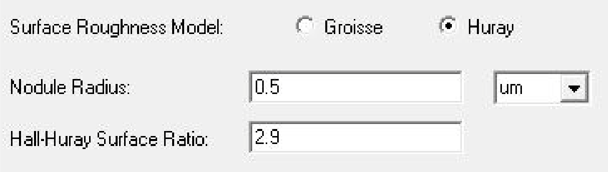
Microscope Method
(5 Samples from 1 Drum)

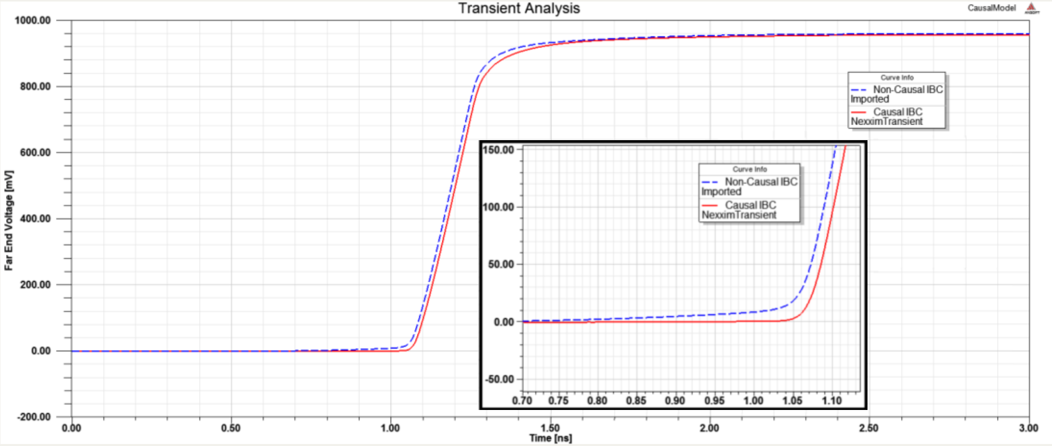
Average	1.17
σ_s	0.022

Using the snowball model in Ansys® HFSS™

- HFSS can define a finite conductivity boundary for selected conductors.
- Causal boundary function using a "single snowball form":

$$\frac{P_{rough}}{P_{smooth}} \approx 1 + \left(\frac{3}{2}\right)(SR)\left(\frac{1}{1+\frac{\delta(f)}{a}+\frac{1}{2}\left(\frac{\delta(f)}{a}\right)^2}\right) \quad \text{where} \quad SR = \frac{N_i 4\pi a_i^2}{A_{flat}}$$



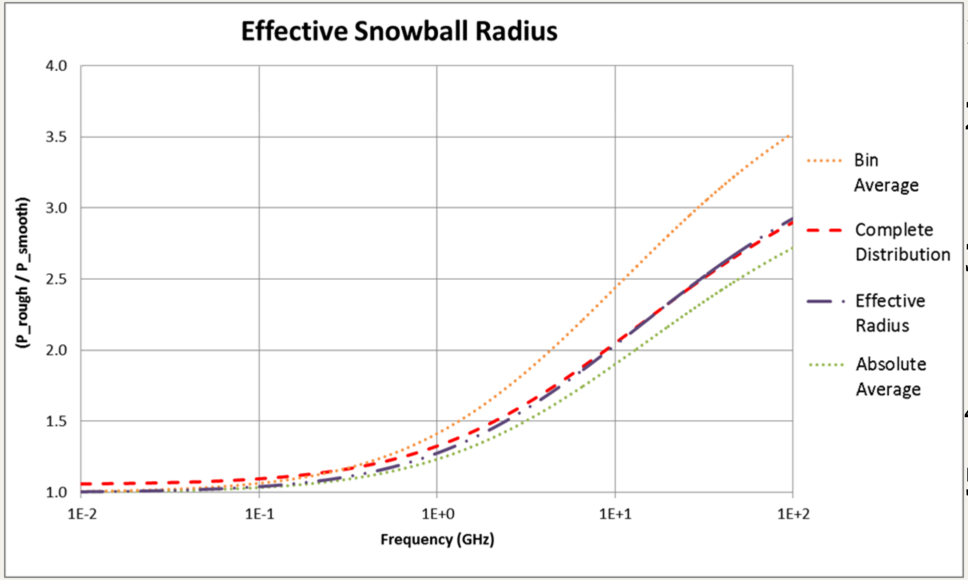


But...

It was concluded a uniform snowball radius could lead to errors.

Using the snowball model in Ansys® HFSS™

The error from using a single uniform radius can be reduced by determining an **Effective Radius**.



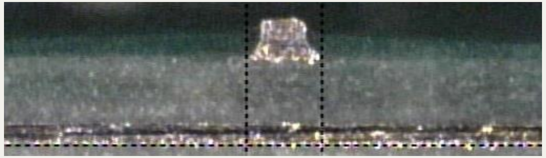
"Absolute Average" = Average a_i of **ALL** N_i snowballs
"Bin Average" = Average of the distribution bins

1. Characterize a_i, N_i/A_{flat} , and A_{matte}/A_{flat}
2. Calculate and plot $\frac{P_{rough}}{P_{smooth}}$ properly with a complete snowball distribution
3. Calculate and plot again using the same snowball packing density $\frac{N_{total}}{A_{flat}}$ but $\frac{A_{matte}}{A_{flat}} = 1$
4. Tune $a_{effective}$ to best fit the complete distribution
5. Calculate SR based on $a_{effective}$

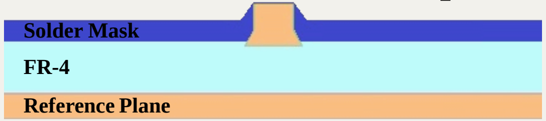
This is not the same as an *average* radius.

Using the snowball model in Ansys® HFSS™

Actual 5" Microstrip

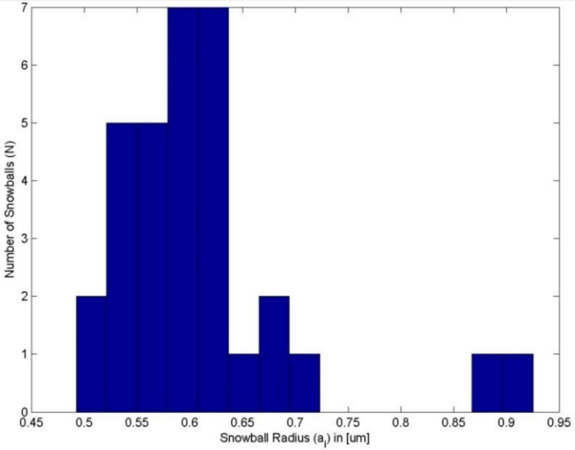


Modeled 5" Microstrip



Trace Width (top)	2.4579 mils
Trace Width (bottom)	3.6256 mils
Trace Thickness	2.5746 mils
Substrate Thickness	2.8957 mils
Ground Thickness	1.3907 mils

Gould Foil Distribution



Substrate

ε_r (2 GHz)	3.78
$\tan\delta$ (2 GHz)	0.0086

- Gould ED Foil was used in test board
- Gould not available for full characterization
- 1 image analyzed by SEM method at 10,000x
- A_{matte}/A_{flat} assumed same as Oak-Mitsui
- $a_{effective} = 0.63\ \mu\text{m}$ & $SR = 1.77$

- Model dimensions obtained from previous measurements
- Substrate parameters obtained from manufacturer specifications

Conclusion

- The Huray surface roughness model has demonstrated accurate *dB/in* conductor loss predictions up to 50 GHz using the snowball approximation and parameter estimations but needed a more accurate method of characterizing the surface of electrodeposited (ED) foil to obtain model parameters.
  - RMS deviation has no influence in a first principles theory.
- It was observed that a distribution of snowball sizes can impact conductor losses and should not be averaged for characterization; therefore each parameter of the snowball approximation a_i, N_i/A_{flat}, and A_{matte}/A_{flat} should be characterized completely for the most accurate results.
- A few methods of more accurately characterizing an ED foil surface to obtain a_i, N_i/A_{flat}, and A_{matte}/A_{flat} were demonstrated using a profilometer, an SEM, and/or a 3D digital microscope.
- A method of determining $a_{effective}$ for simulation was demonstrated and implemented in an Ansys® HFSS™ model of a SE 5” microstrip with treated drum side ED copper foil that correlated well with VNA measurements up to 50 GHz using the Huray model with characterized parameters.

References

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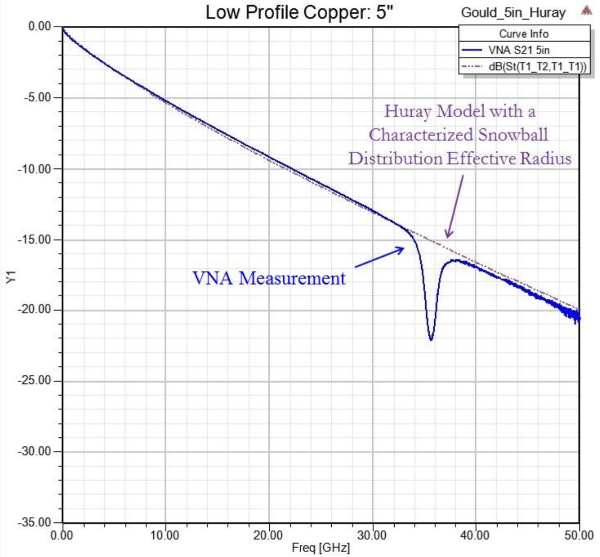
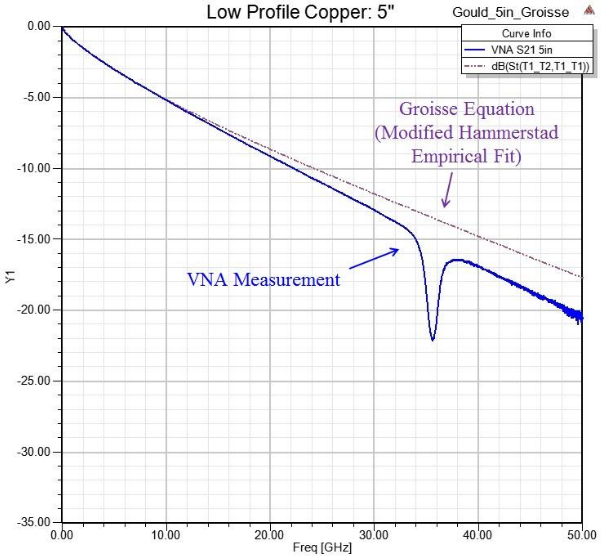
Backup

- Simulation results for 5” microstrip (drum side treated) ED copper foil
- Can the snowball approximation ignore scattered power?
- Periodic interpolation binarize process

Using the snowball model in Ansys® HFSS™: Results

- Using the Gould characterized distribution with parameters from last slide
- Using a flat substrate model





- Using built-in Groisse Equation
- Using measured $R_{RMS} = 1.2$ µm
- Using a flat substrate model

Groisse equation (a modified Hammerstad equation) accurately predicted up to about 12 GHz.
The Huray model demonstrated a strong correlation up to 50 GHz.

Can the snowball approximation ignore scattered power?

When a propagating signal encounters a good conducting *sphere*, like copper, the *dipole* signal can either be

scattered (outgoing power): $\sigma_{scattered}(\omega) \approx \frac{10\pi}{3} k_2^4 a_1^6 \left[1 + \frac{2}{5}\left(\frac{\delta}{a_i}\right)\right]$

or

absorbed (incoming power): $\sigma_{absorbed}(\omega) \approx 3\pi k_2 a_1^2 \delta / \left[1 + \frac{\delta}{a_i} + \frac{\delta^2}{2a_i^2}\right]$

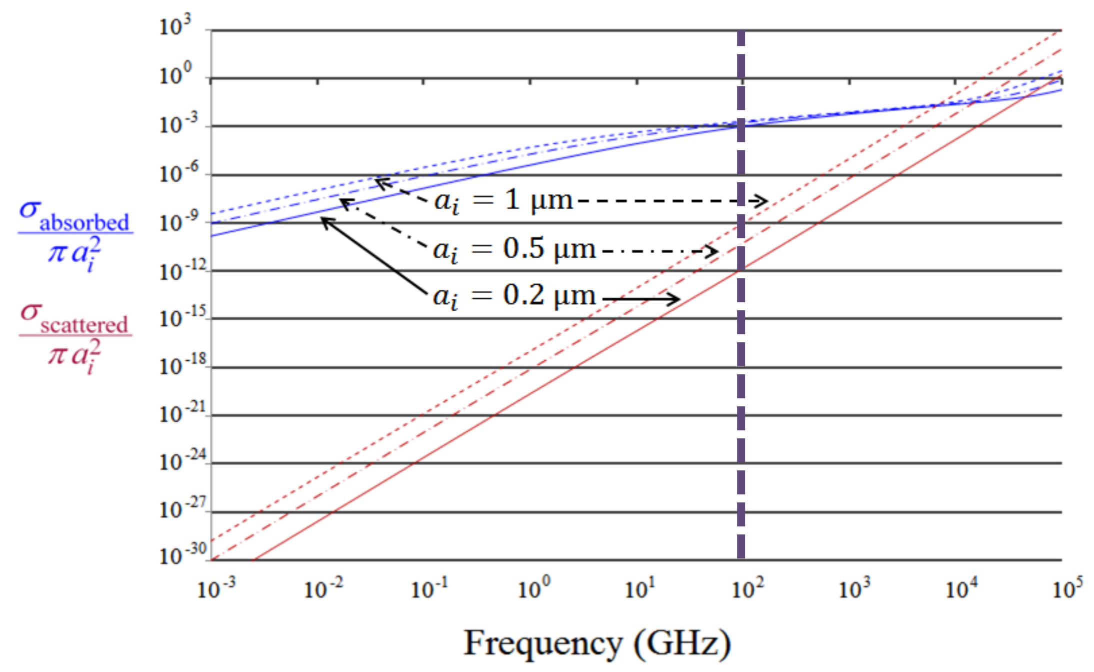
The snowball approximation estimates the $\sigma_{total,i}$ of the Huray model using only the *dipole* $\sigma_{absorbed}$ for a good conducting *sphere*:

$$\frac{P_{rough}}{P_{smooth}} \approx \frac{\frac{\mu_0\omega\delta}{4}|H_0|^2 A_{matte} + \sum_{i=1}^{j} N_i \sigma_{total,i} \frac{\eta}{2}|H_0|^2}{\frac{\mu_0\omega\delta}{4}|H_0|^2 A_{flat}} \rightarrow \frac{P_{rough}}{P_{smooth}} \approx \frac{A_{matte}}{A_{flat}} + 6\sum_{i=1}^{j}\left(\frac{N_i \pi a_i^2}{A_{flat}}\right) \Big/ \left(1 + \frac{\delta}{a_i} + \frac{\delta^2}{2a_i^2}\right)$$

The 3 following slides conclude: Yes, scattered power can be ignored for frequencies under 100 GHz.

Can the snowball approximation ignore scattered power?

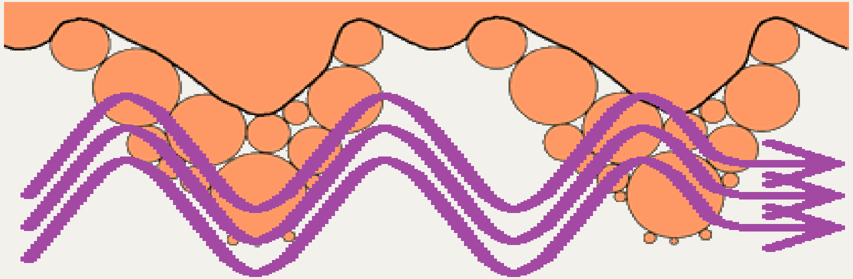
Absorption and scattering cross-sections of various size copper spheres as a function of frequency.



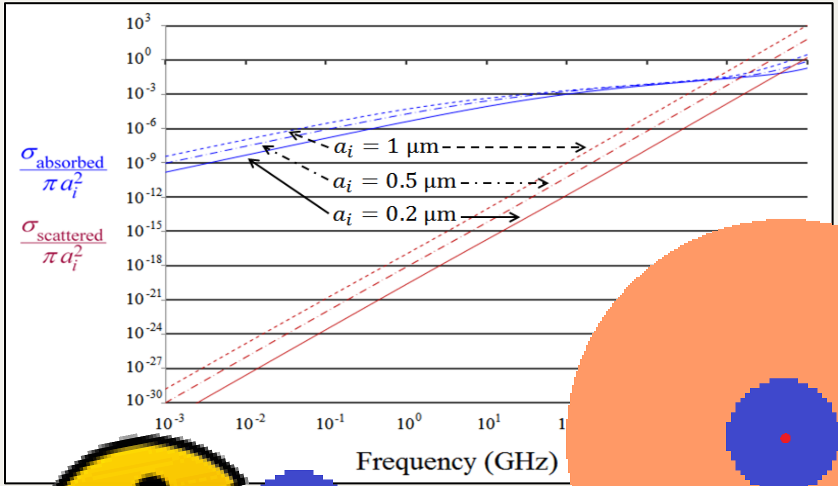
Comparing the effective absorption and scattering cross section to the geometric area, power is primarily absorbed for frequencies < **100 GHz**.

So… Yes, scattering effects are insignificant below 100 GHz

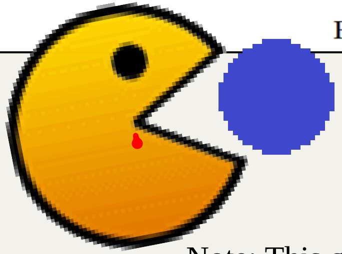
Can the snowball approximation ignore scattered power?

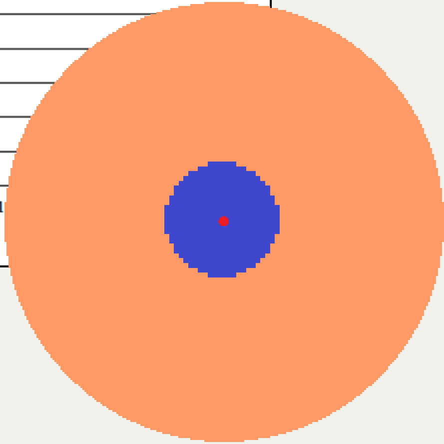


As a signal propagates across many snowballs, the effective area increases and power continues to be absorbed with almost no power being scattered.



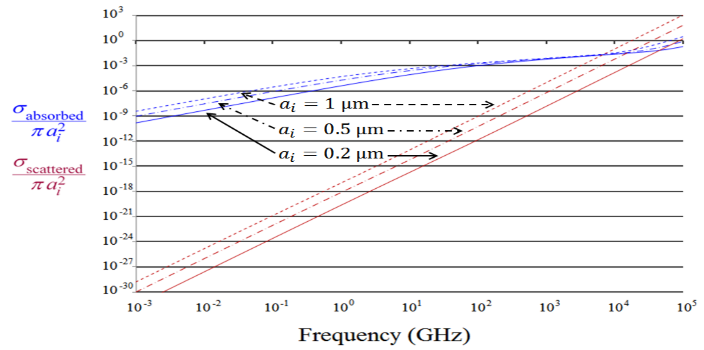
At frequencies <100 GHz, snowballs are more like small Pac-Mans eating (absorbing) power rather than big boulders scattering it.

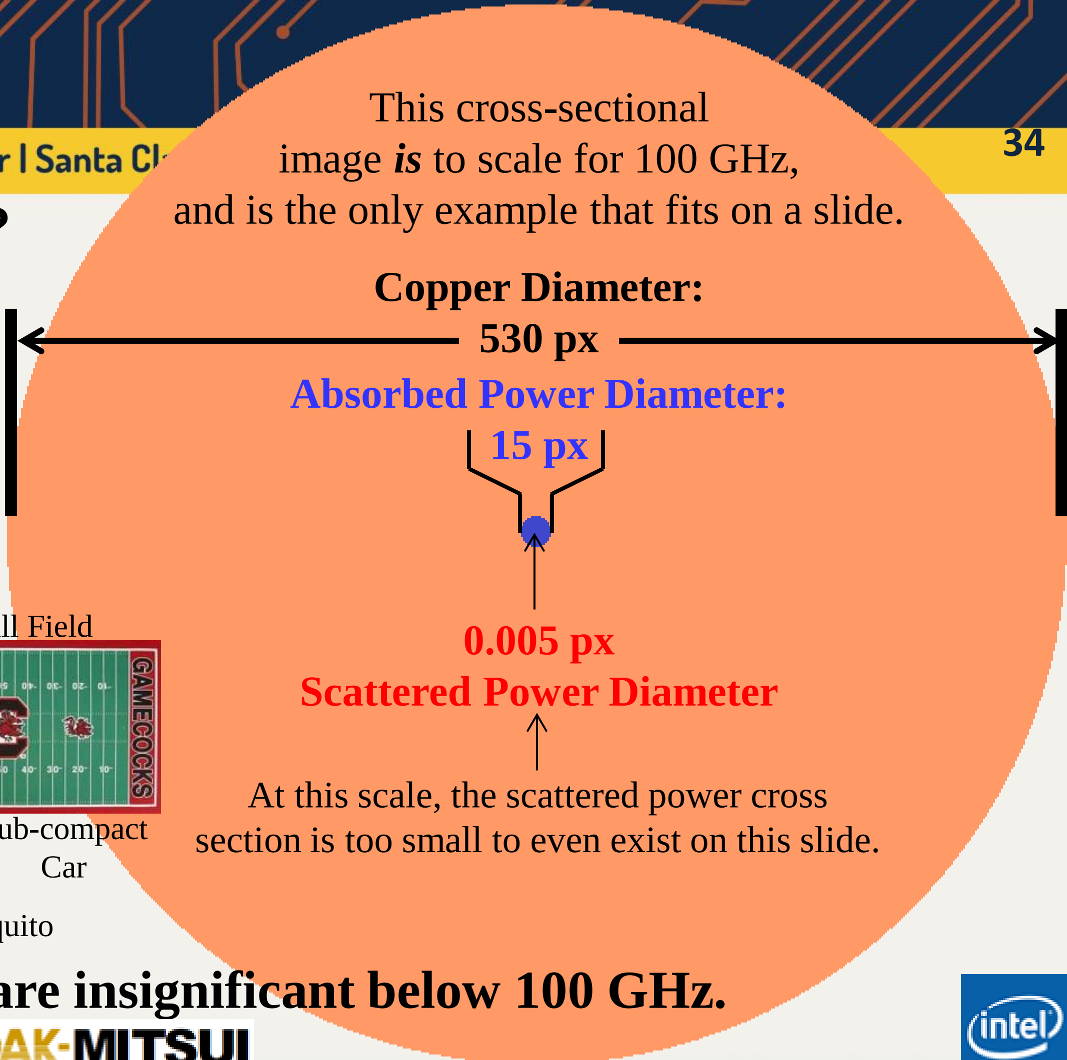




Note: This growing snowball illustration is only a qualitative visual aid. It does not represent the actual physics nor are their relative sizes accurate.

Can scattered power be ignored?





Some perspective (@ 100 GHz):

X-Sectional Area	Diameter	Diameter
Copper Snowball	1 µm	100 m
Absorbed Power	0.029 µm	2.9 m
Scattered Power	5 pm	0.001 m

Football Field

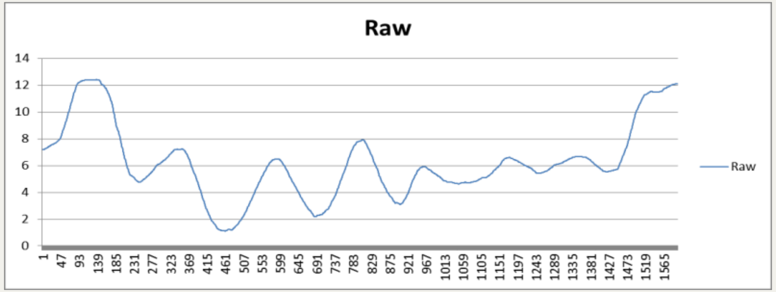
Sub-compact Car

Mosquito

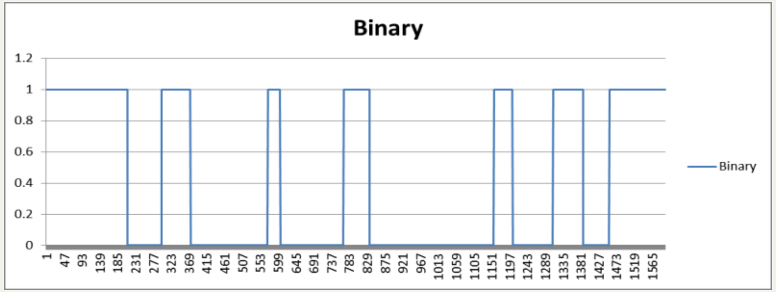
Yes, scattering effects are insignificant below 100 GHz.

Periodic Interpolation Binarization Process

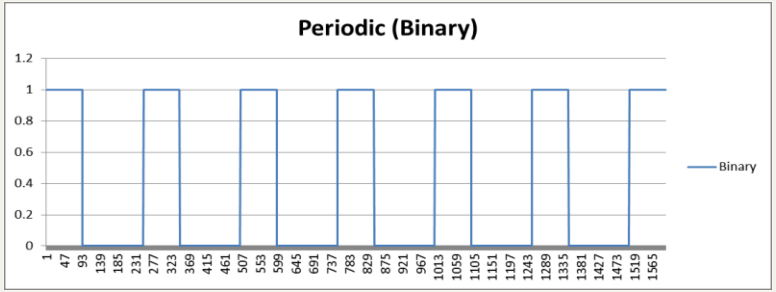
1.



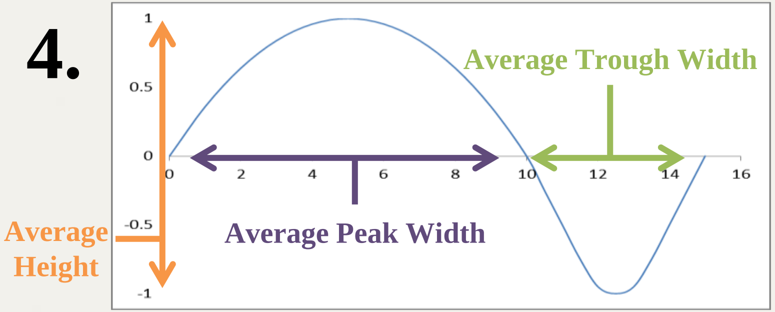
2.



3.



4.



Calculate the arc length of 1 average peak and 1 average trough: $L_{total} = N_{peaks}L_{peak} + N_{troughs}L_{trough}$