Effects of RF Pulses on Circuits and Systems
---- Pieces-----

J. L. Volakis, E. Siah, T. Yang and V. Liepa
Radiation Laboratory
Dept. of Electrical Engineering and Computer Science
University of Michigan
Ann Arbor, MI. 48109-2122

Phone: (734)647-1797, Fax: (734)647-2106
Email: volakis@umich.edu
http://www-personal.engin.umich.edu/~volakis/

Annual RF Effects MURI Review

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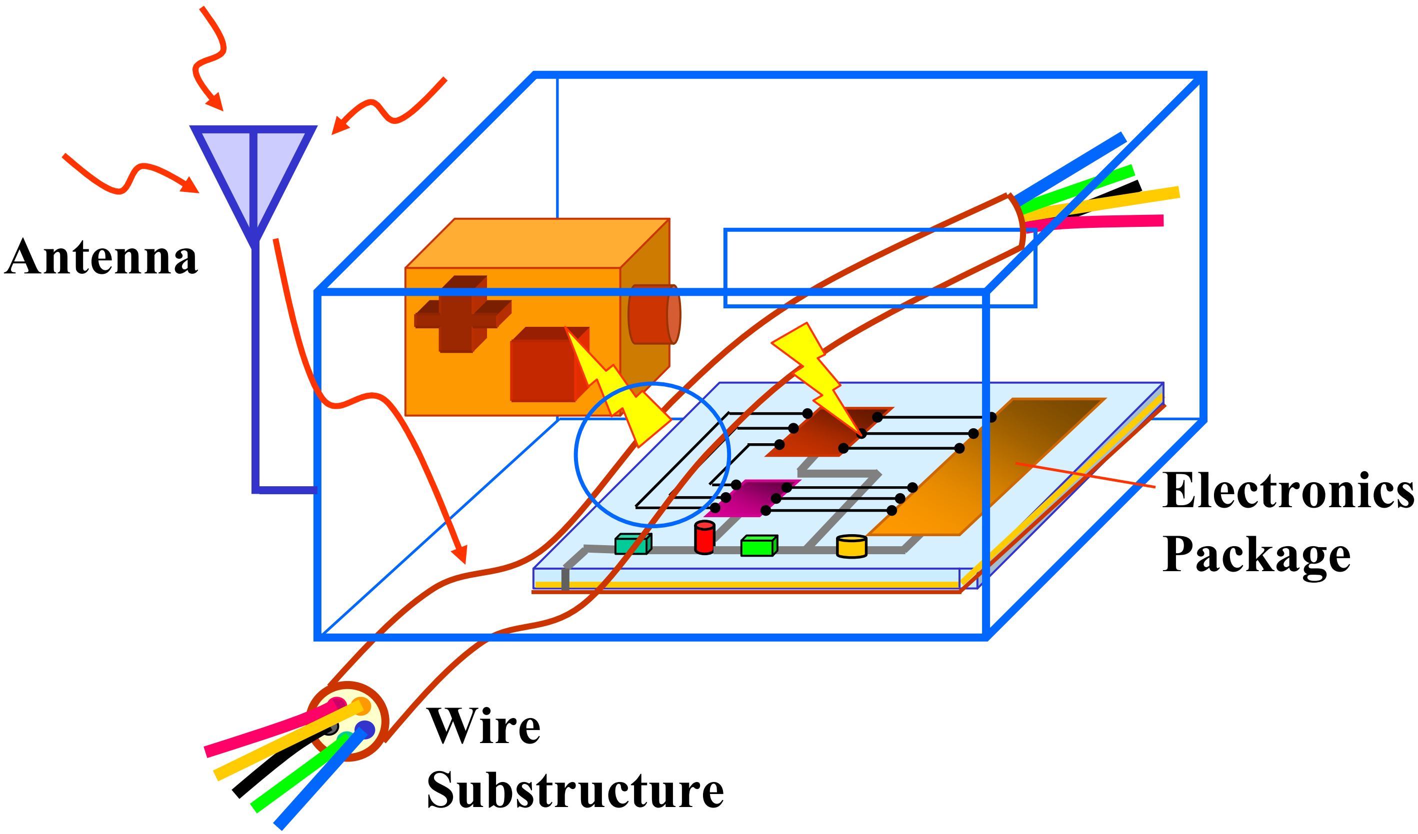
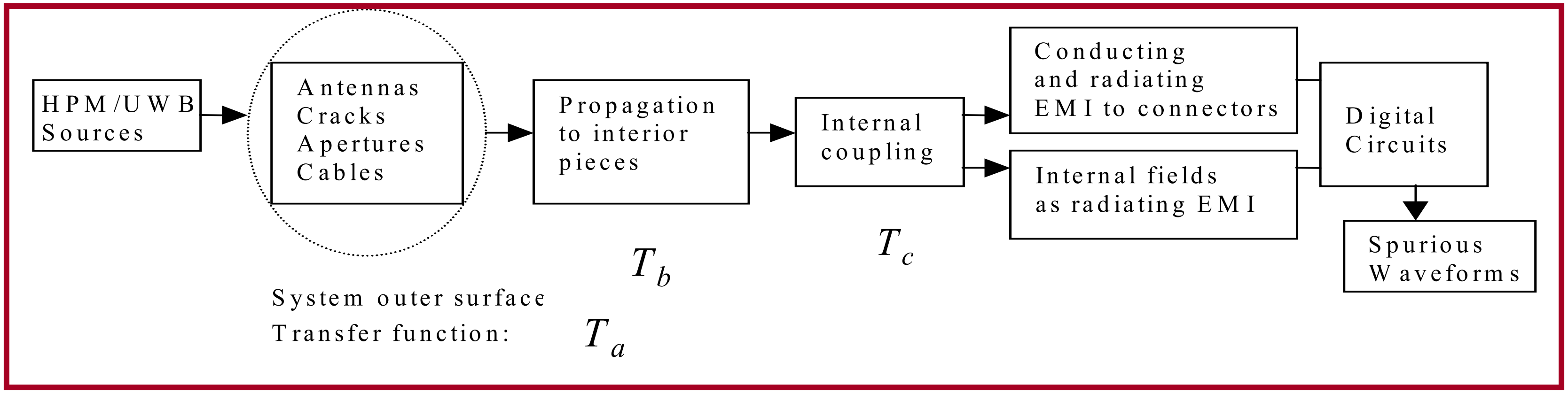
Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

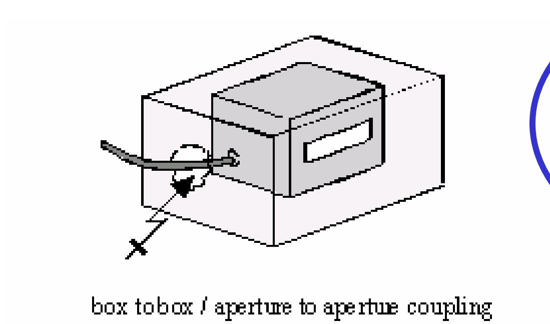
Project Statement

- Evaluate the response/induced voltages on electrical systems due to radiated EM field environments
  - Focus is on upset or damage of digital systems
  - For fast transient or pulsed CW excitations at GHz frequencies

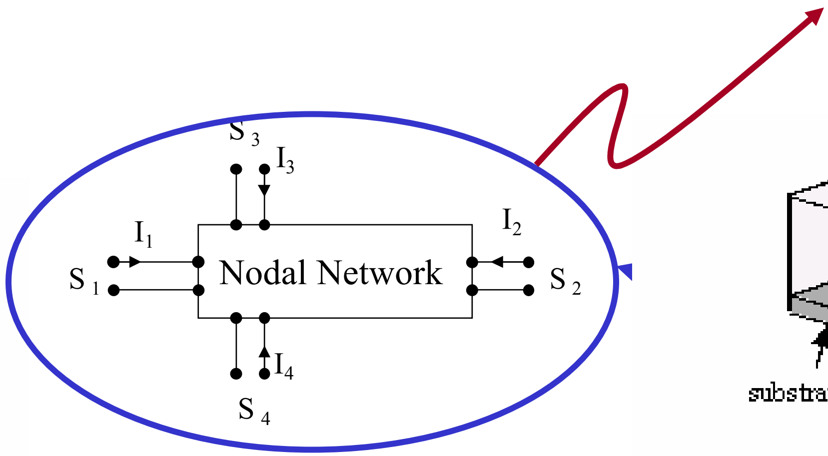


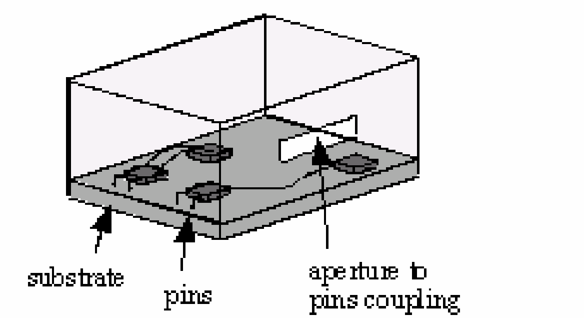
EMI/EMC Modeling Approach





(e) Nested Boxes





(f) aperture to circuit pins

Tasks 1 Focus

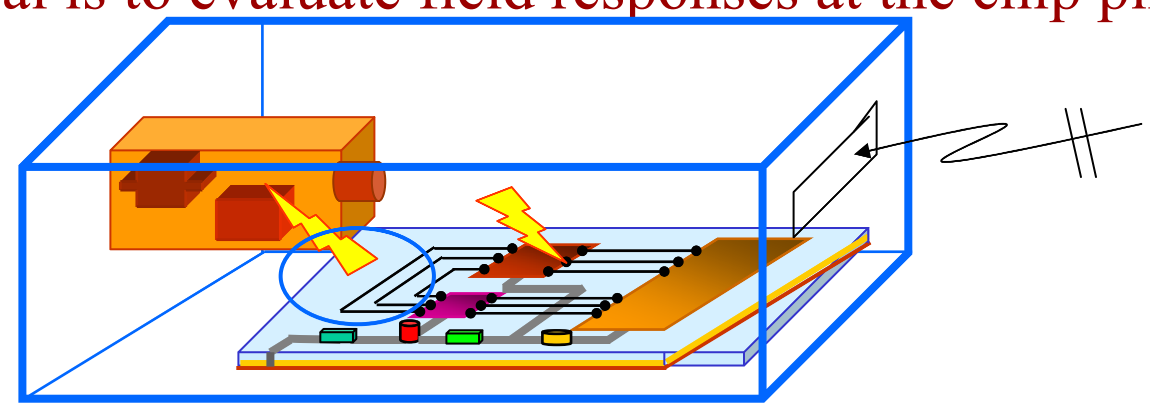
Numerically model penetration and coupling of HPM and UWB sources into large-scale, complex structures

- Employ frequency domain and time domain methods.
- Decompose structure into pieces
  - Black boxes with pins/connectors
  - Cable bundles;
  - Cavities with apertures
  - Cavities containing cable bundles
  - Antennas as direct (front door) and out-of-band (back door) entry ports
  - Aperture with cable bundle passing through;
  - Aperture in cavity with cable bundle passing through;
  - Seams in surfaces;

First Year Effort

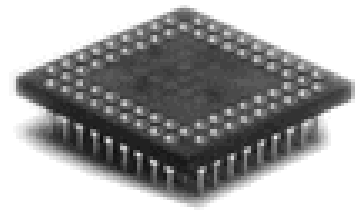
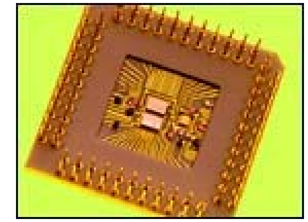
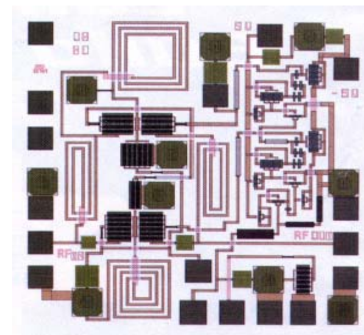
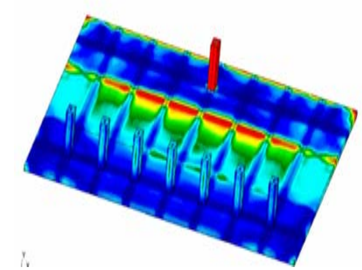
- Characterization of RF coupling into cavity structures using multilevel FMM (SIE) with
  - Apertures
  - With cables
- Phenomenology and shielding studies
- Simplified Circuit characterizations for integration into Topology/BLT model
- Initiated development of hybrid finite element-boundary method for general purpose analysis of enclosed RF circuits

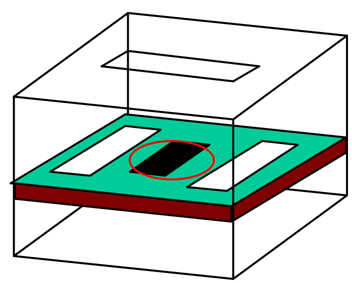
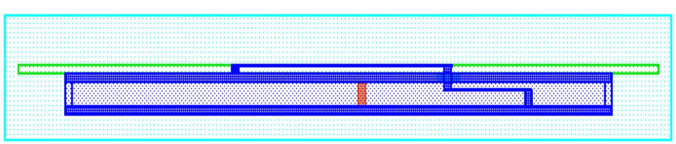
Goal is to evaluate field responses at the chip pins



EMC is an old Problem, with new concerns

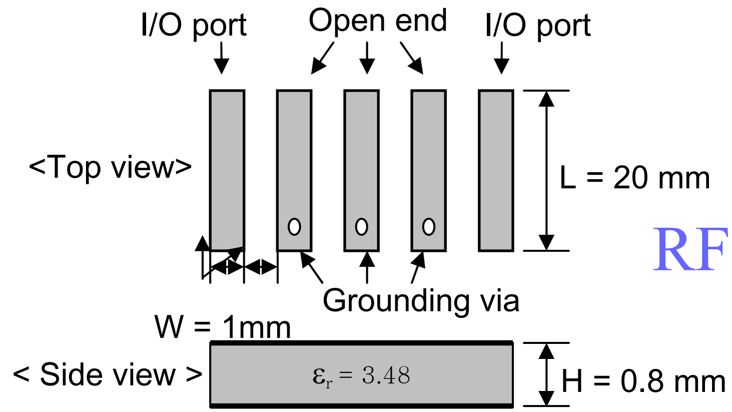
- High speed devices generate coupling and interference
  - Radiation from chip surfaces
  - Conduction noise from signal ports
  - Power-line conducting noise
- EMI from surrounding electronic environment.
- Cavity enclosures may cause reverberations that enhance interference, particularly at exposed wiring
- Intentional sources can cause significant high fields to disrupt logic functions

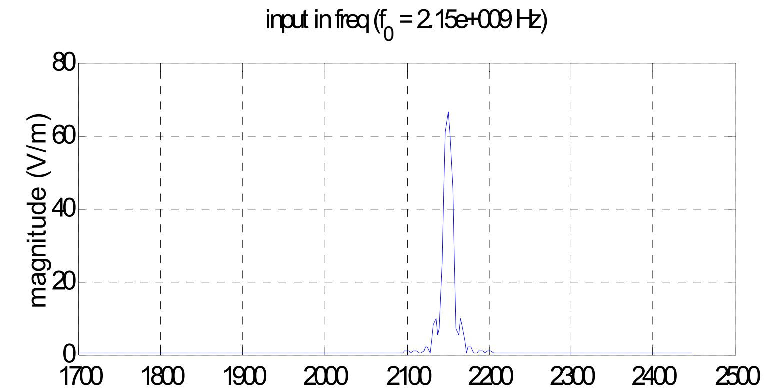



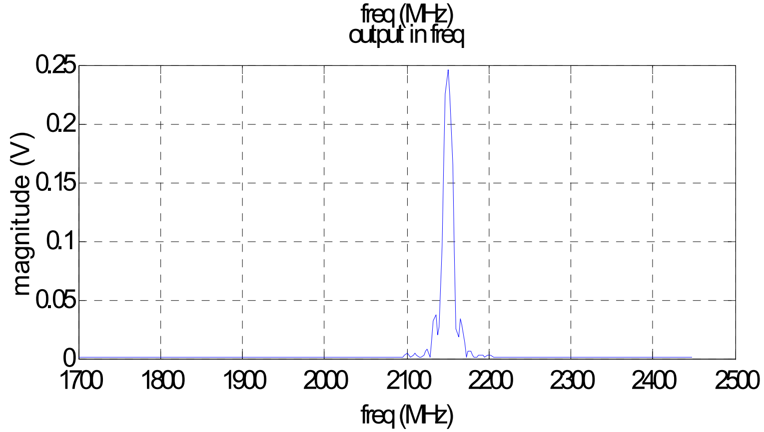
Example Excitation with Pulse Train

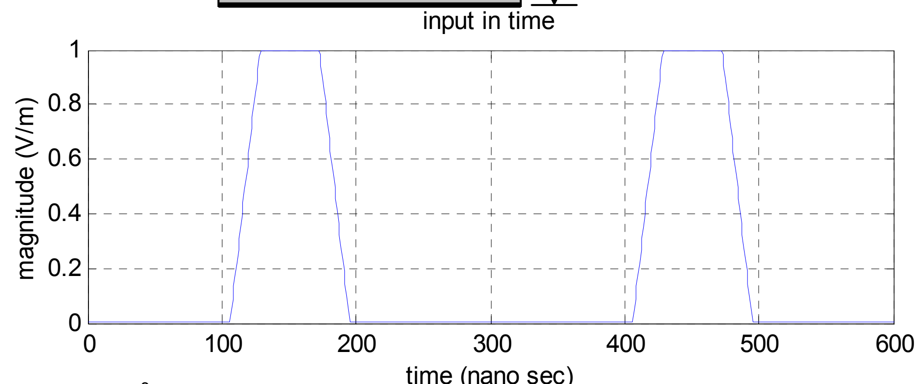
Input in time domain : 100 V/m
Output in time domain : 0.4 V

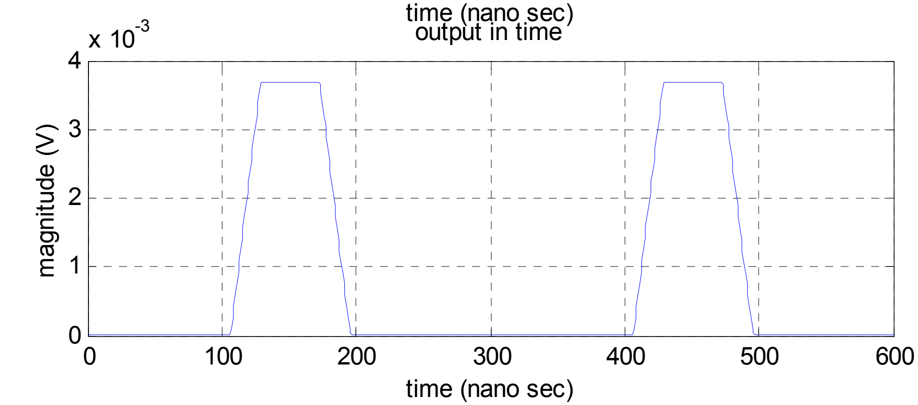


RF filter

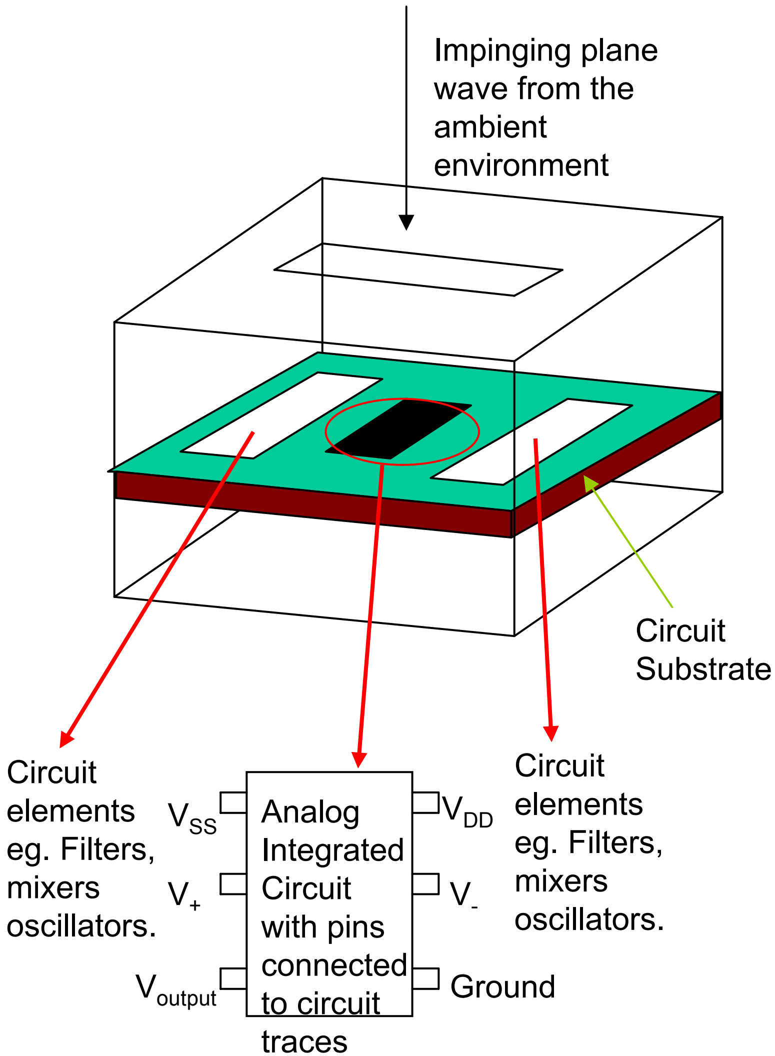








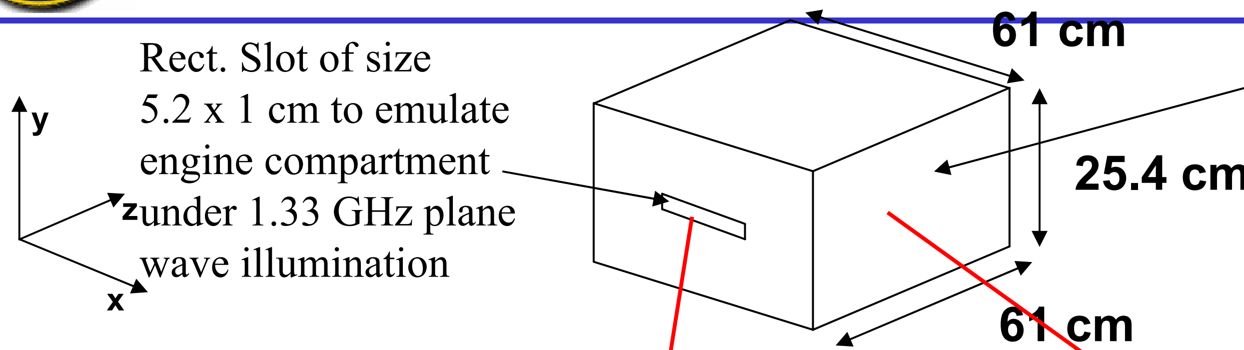
Cavities Can Cause Amplification



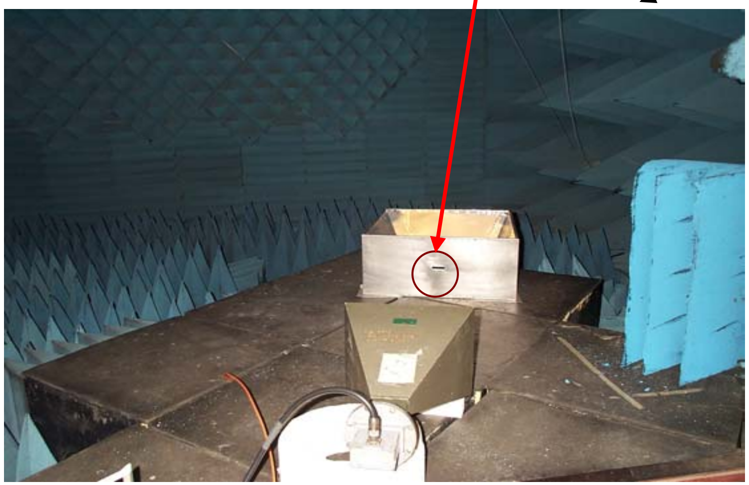
- Cavities can exhibit a resonance amplification of 10 to 20 dB amplification of the ambient radiation.
- Amplification of signals can have a significant impact on circuits with Analog ICs and high frequency amplifiers.
- Induced voltage fluctuations on ground, power supply and signal lines can change circuit devices performance.

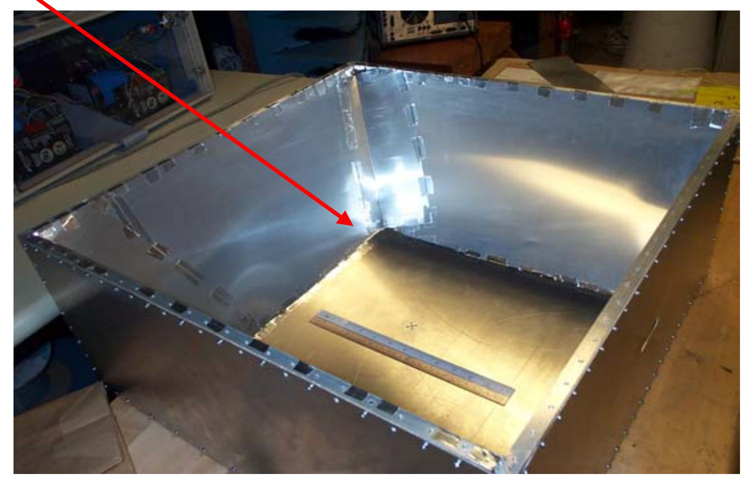
Measured Over-Moded Cavity

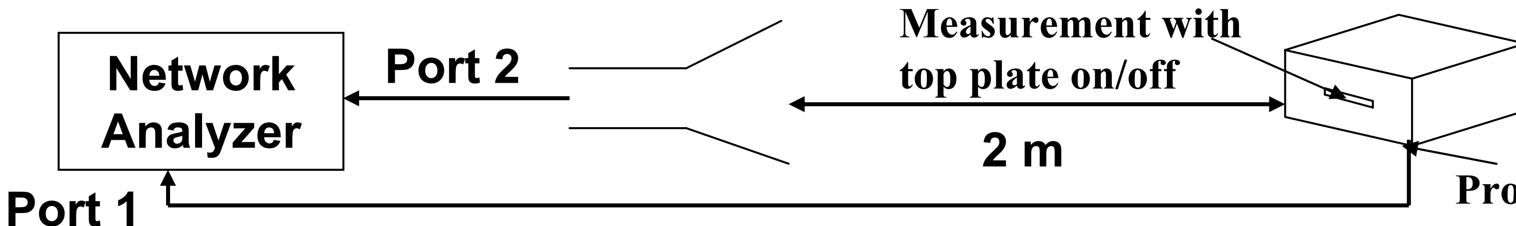
Rect. Slot of size 5.2 x 1 cm to emulate engine compartment under 1.33 GHz plane wave illumination



Box has trapezoidal sides to avoid some of the higher order modal effects.





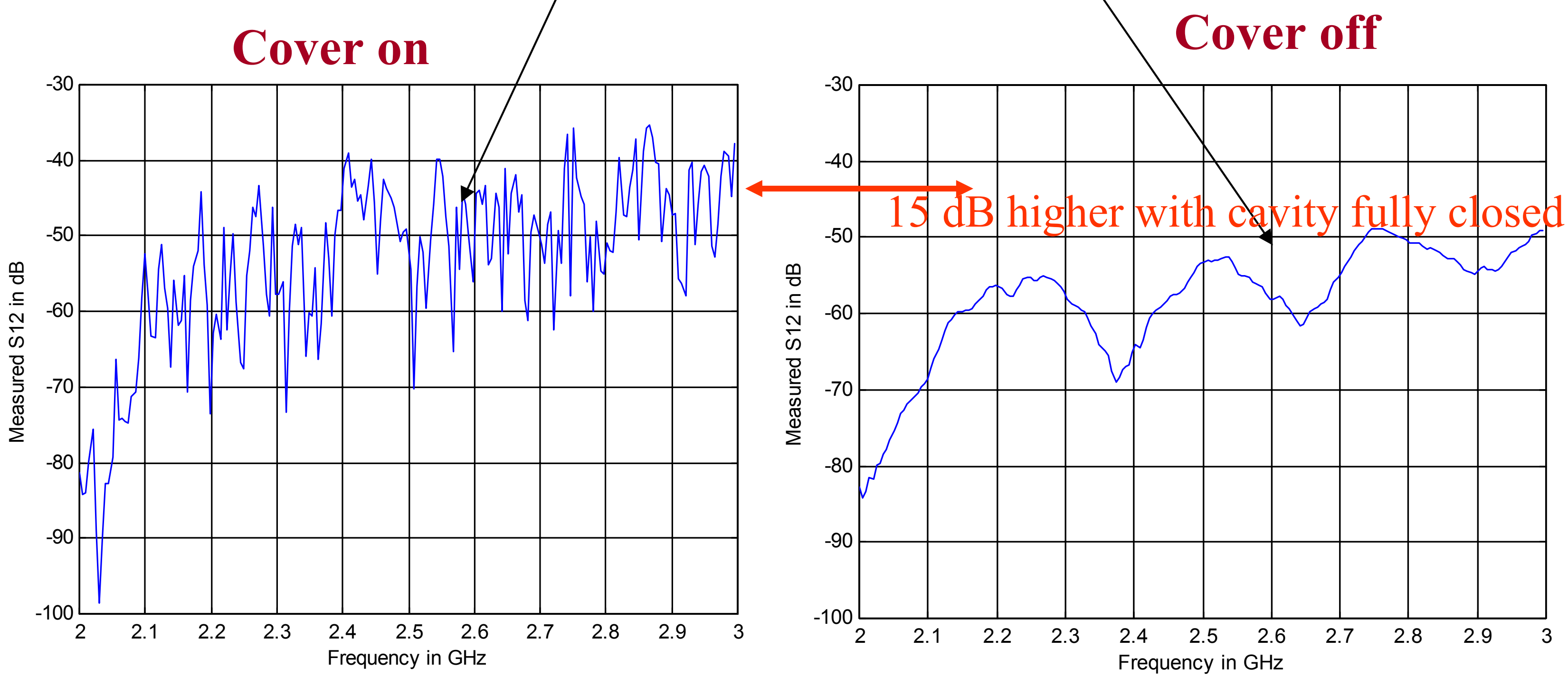


Probe inserted at bottom of box

Cavity is placed at the far field of reference horn antenna

Measured Cavity

- Measured data is Transmission S12 with the Horn Antenna connected to Port 2 and the field Probe connected to Port 1 in dB.
- Measured with the top cover on and without the top cover.
- Absence of top cover avoids most of the higher order resonances.



Definition of Coupling Parameters

- **Electric Field Shielding**

$$EFS = -20\log\left|\frac{E^{total}}{E^{inc}}\right| \quad (dB)$$

- **Magnetic Field Shielding**

$$MFS = -20\log\left|\frac{H^{total}}{H^{inc}}\right| \quad (dB)$$

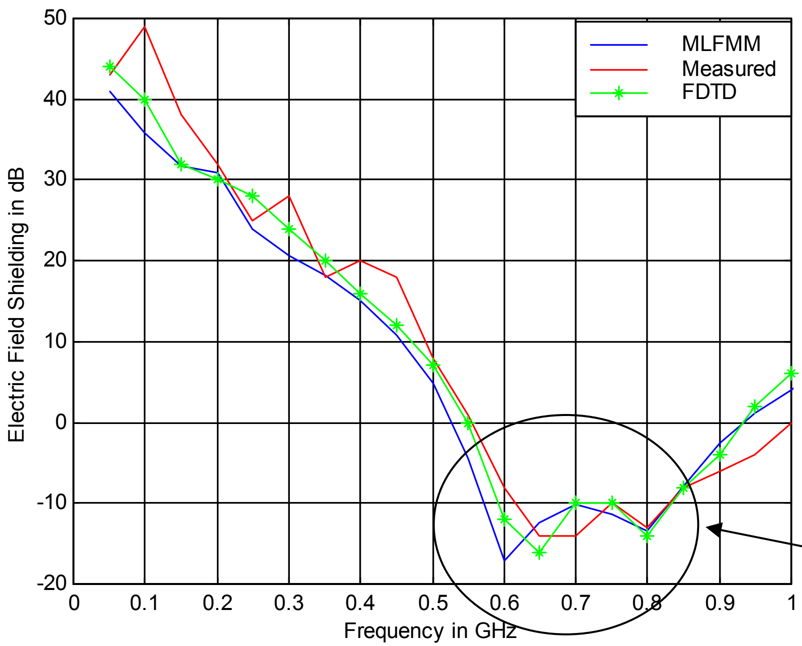
where E/H^{total} is the total E/H field in the presence of the scattering object and E/H^{inc} is the incident E/H field in the absence of the scattering object.

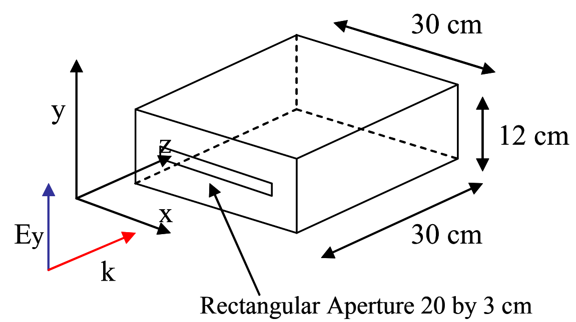
- EFS and MFS are parameters to indicate the degree of coupling from external illumination to points within a cavity. Higher values indicate better shielding and thus weaker total field values.

- Ratio of the Stored Electric/Magnetic Energy within the volume of the cavity of the total fields to the incident fields.

- EFS and MFS are computed using the multi-level FMM code EMCAR.

- Rectangular slot in a 30cmx30cmx12cm cavity (slot size 20x3cm)

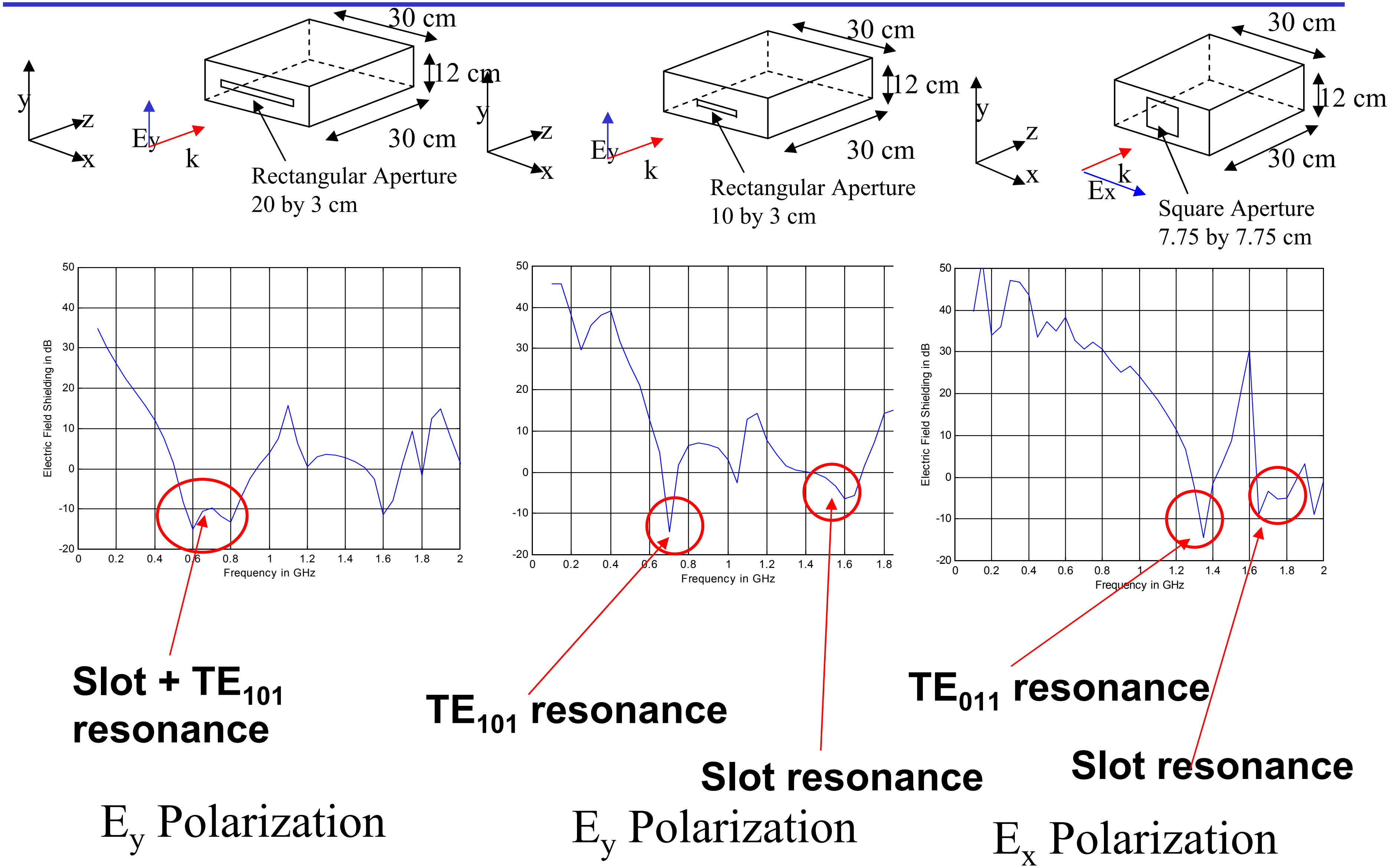




Slot resonance (0.75 GHz)

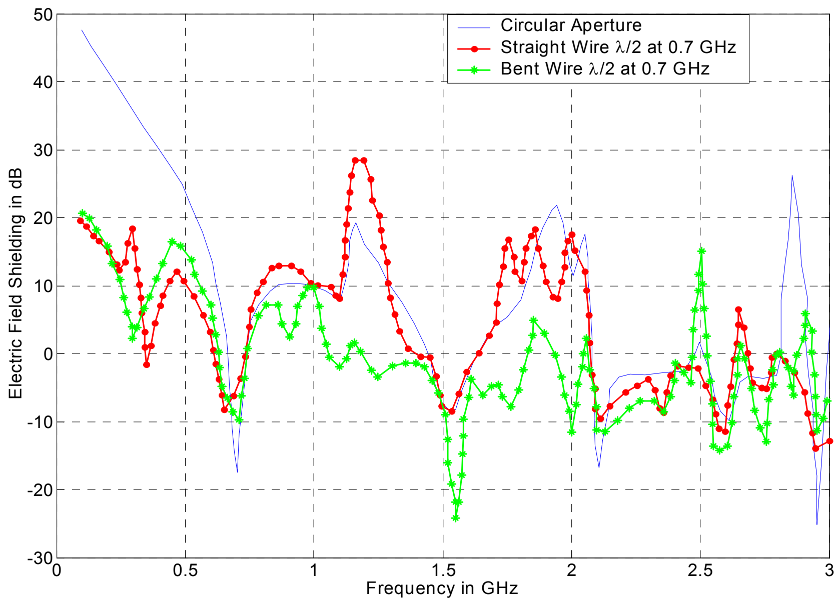
The first resonance (0.7GHz) of the lowest order mode in the cavity

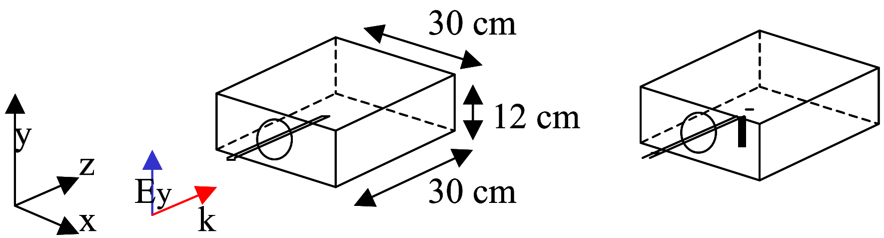
EFS for Different Slot Apertures



Presence of wire through apertures increases EFS

Electric Field Shielding for the 2 wire configurations



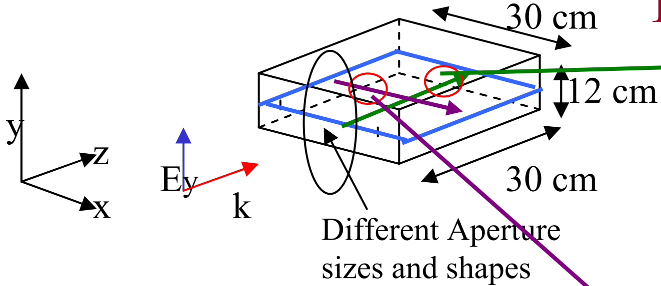


➢Presence of wires changes significantly the shielding characteristic of a resonant metallic cavity.

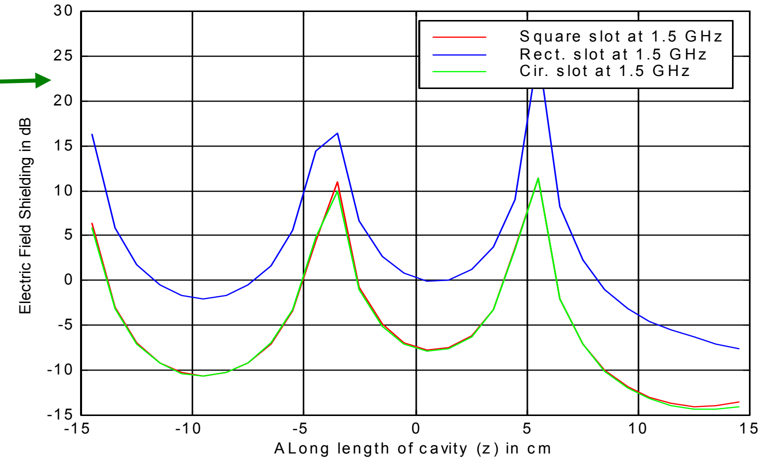
➢Bent and longer wire configurations couple more energy from external illumination into the metallic enclosure.

➢ Increase in coupled energy due to wire penetrations poses a challenge to proper circuit device performance.

Variation of EFS for different locations-1.5GHz



1.5 GHz

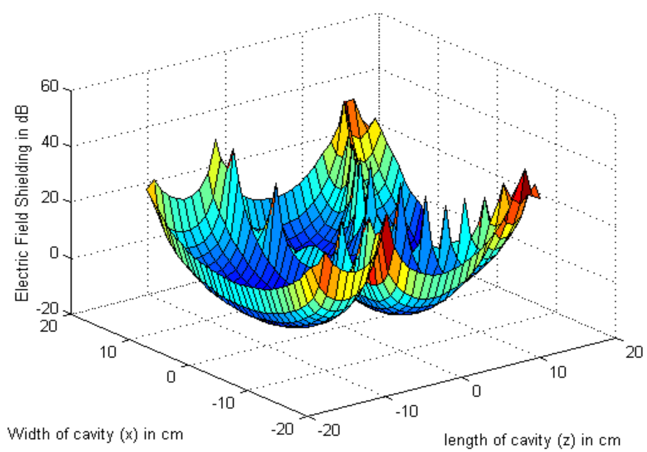


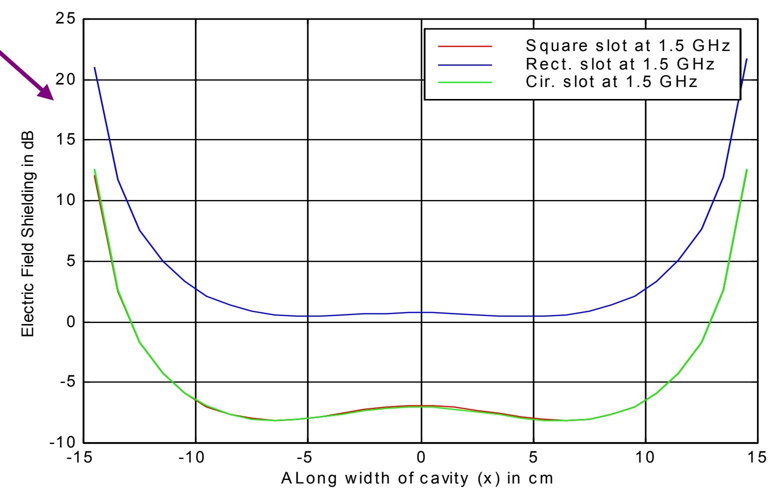
Combination of slot and cavity resonance at 1.5 GHz

Back of cavity **Radiating Aperture**

EFS distribution for square slot at 1.5 GHz

1.5 GHz

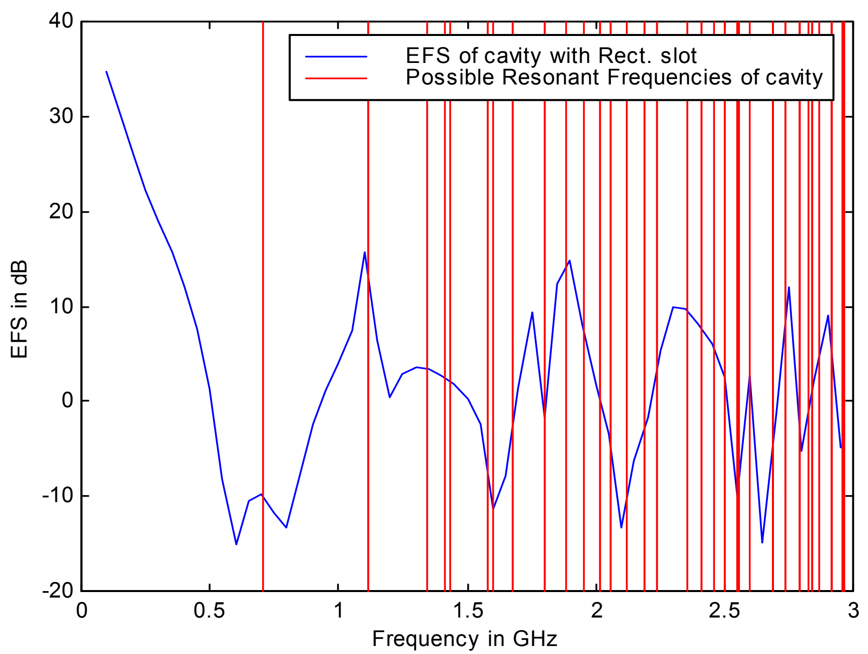




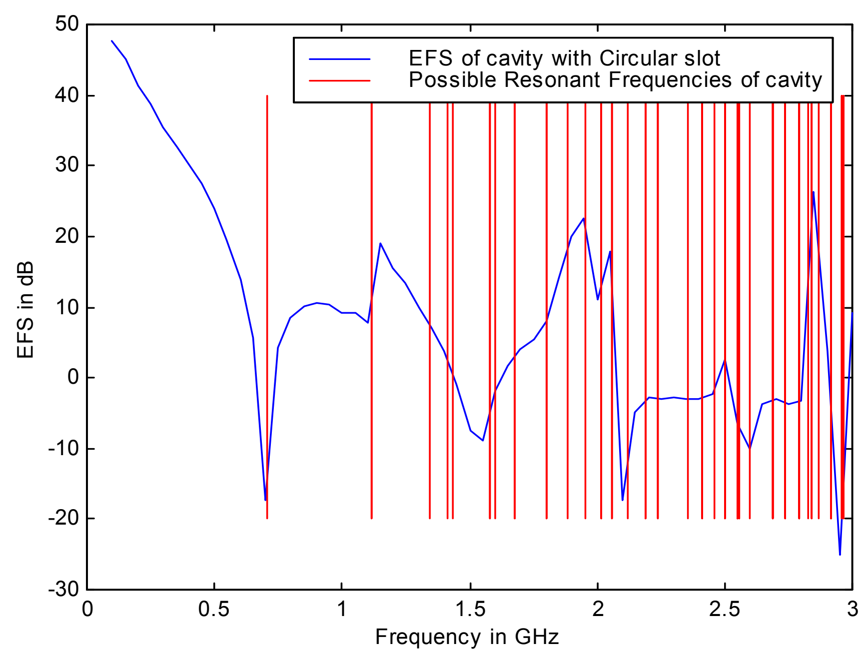
What is Important?

- Cavity resonances
- Slot resonances
- Resonances of other substructures (wires, other arbitrary apertures, protrusions)
- Interactions between Cavity, Slot and Wire resonances

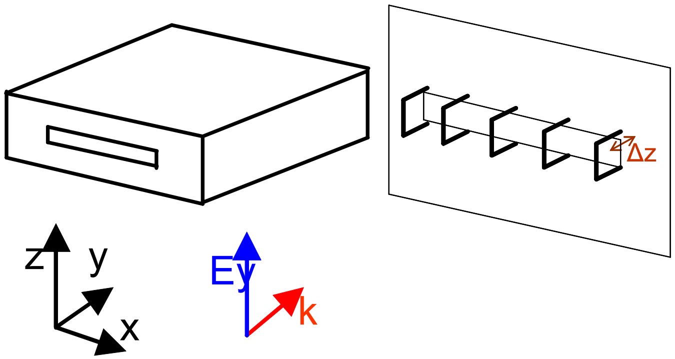
Rectangular slot

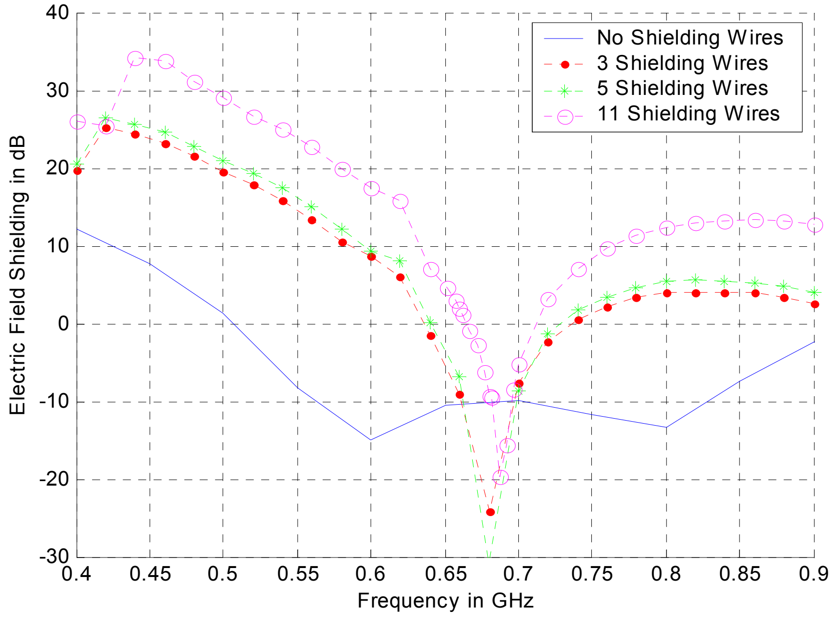


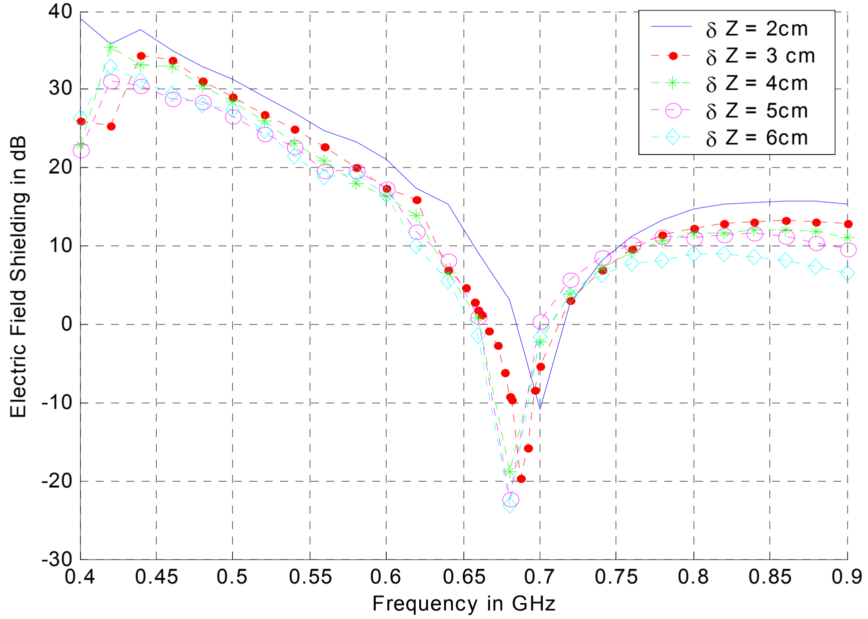
Circular slot



Reducing Coupling: Shielding Wires



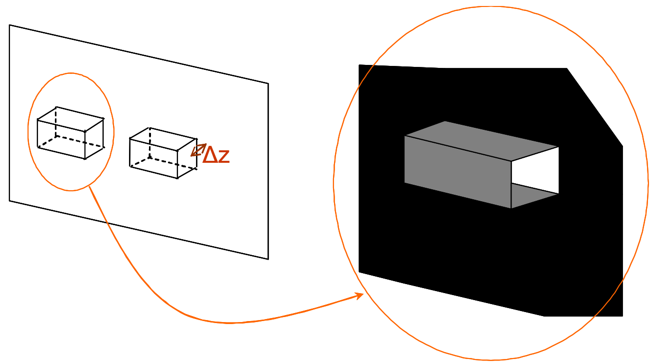


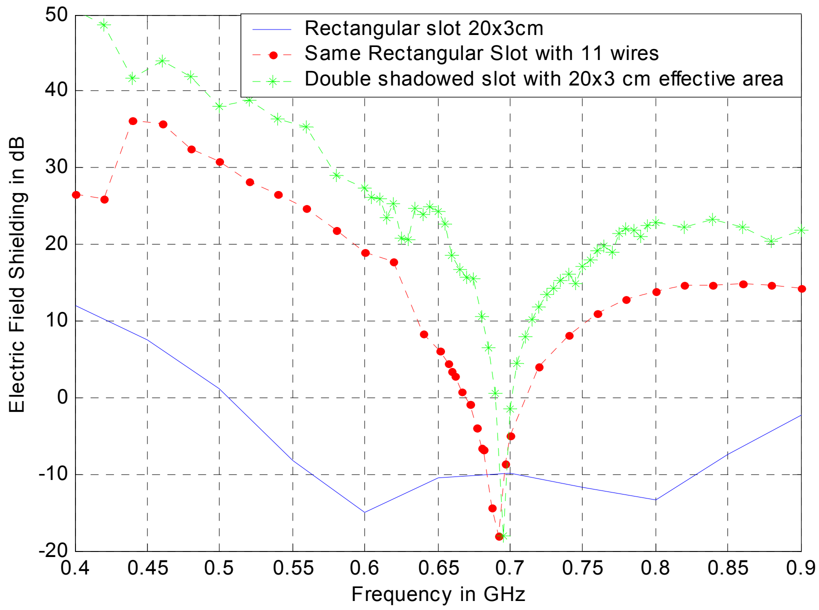


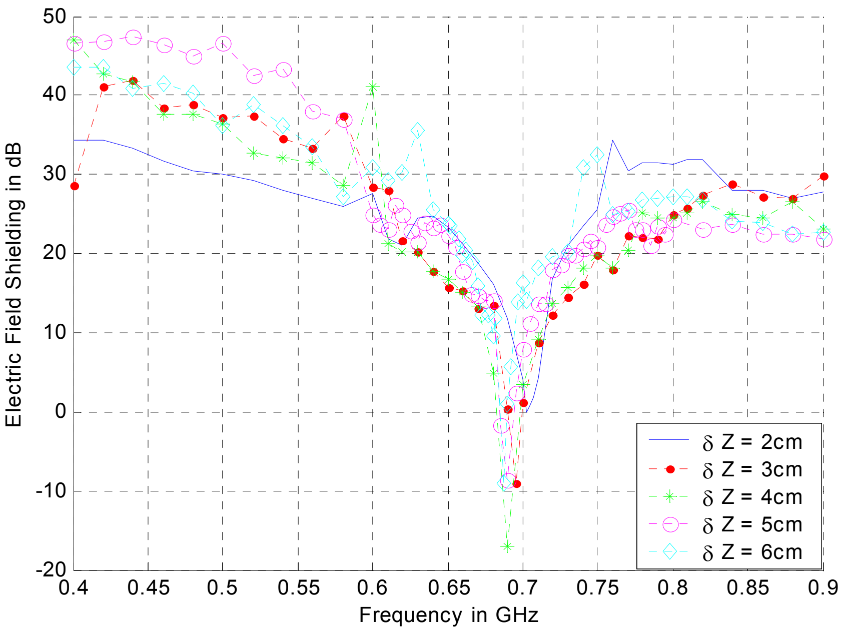
Variation in Number of Wires with ΔZ = 3cm

Variation in Distance ΔZ of Wire from Slot

Reducing Coupling: Plate Shielding



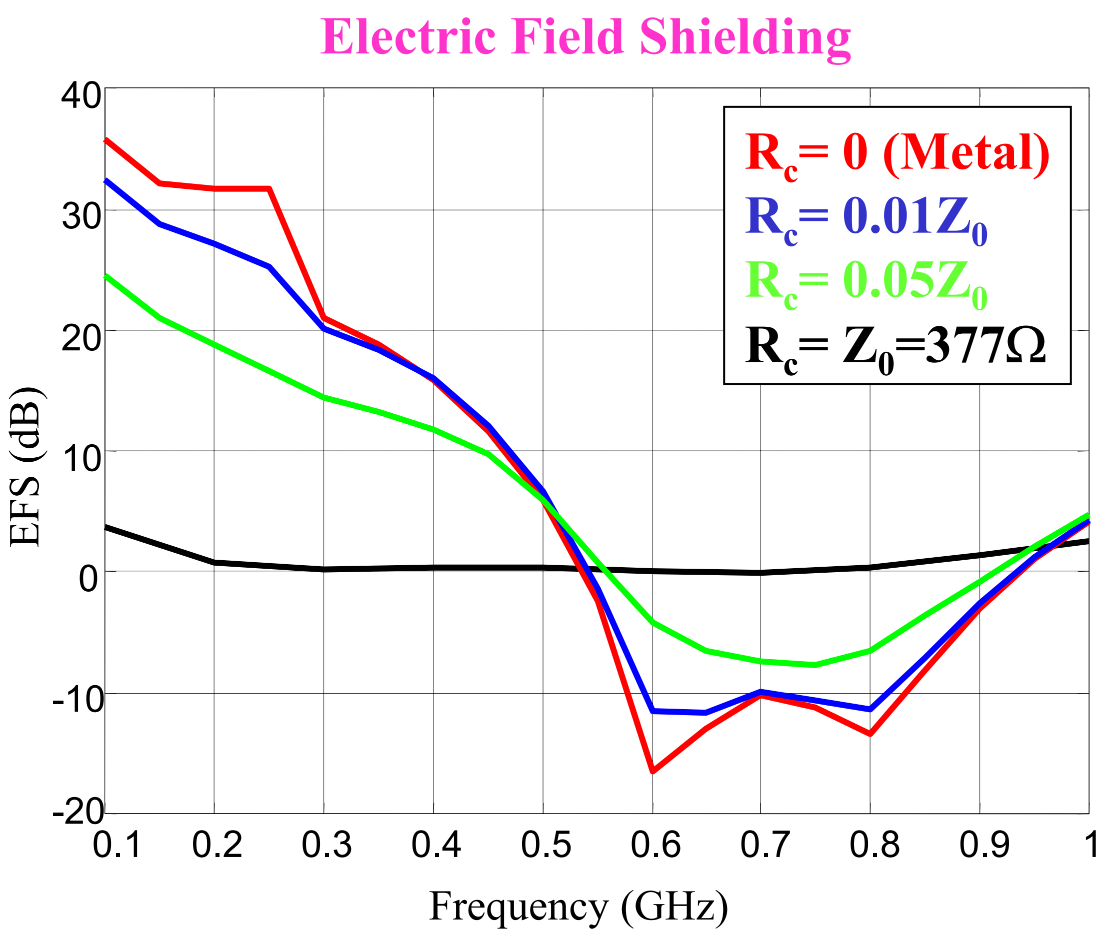


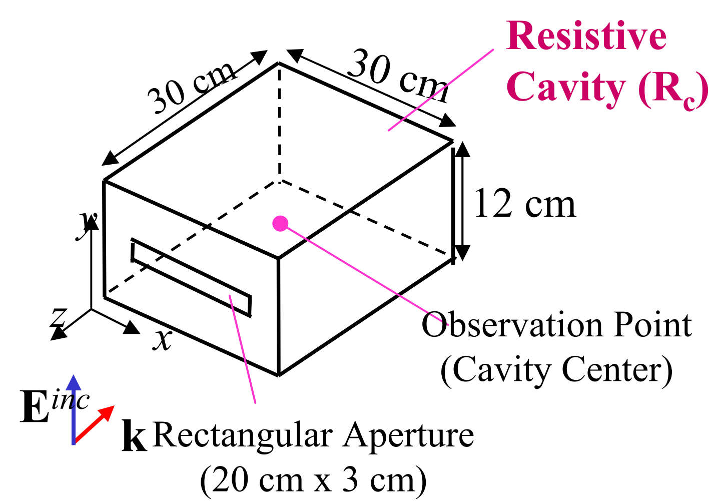


Comparison of slot shadowing with shielding wire array for ΔZ = 5cm

Variation in Distance ΔZ of PEC plate from Shadowed Slot

Effects of Cavity Loading

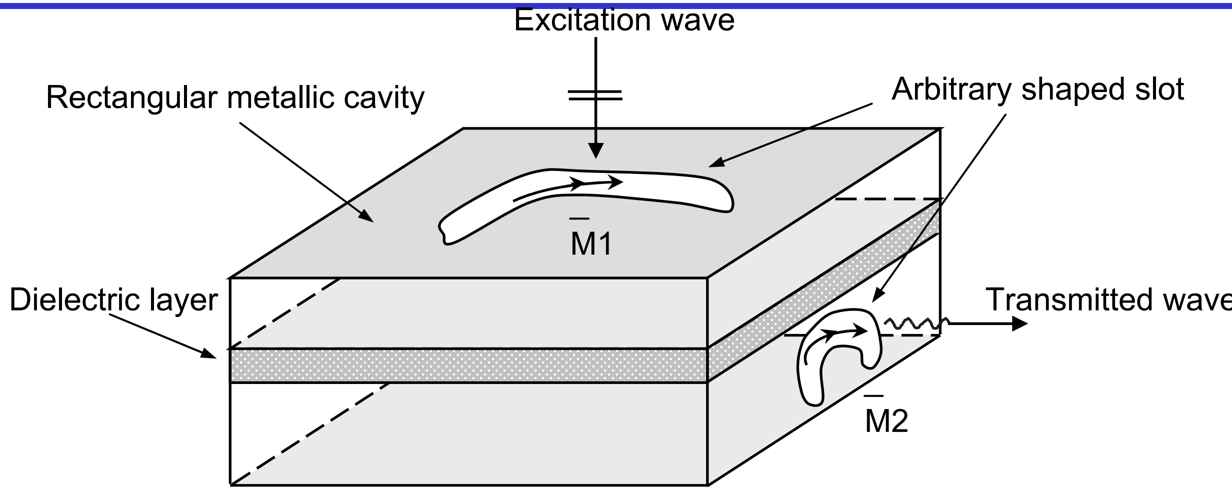




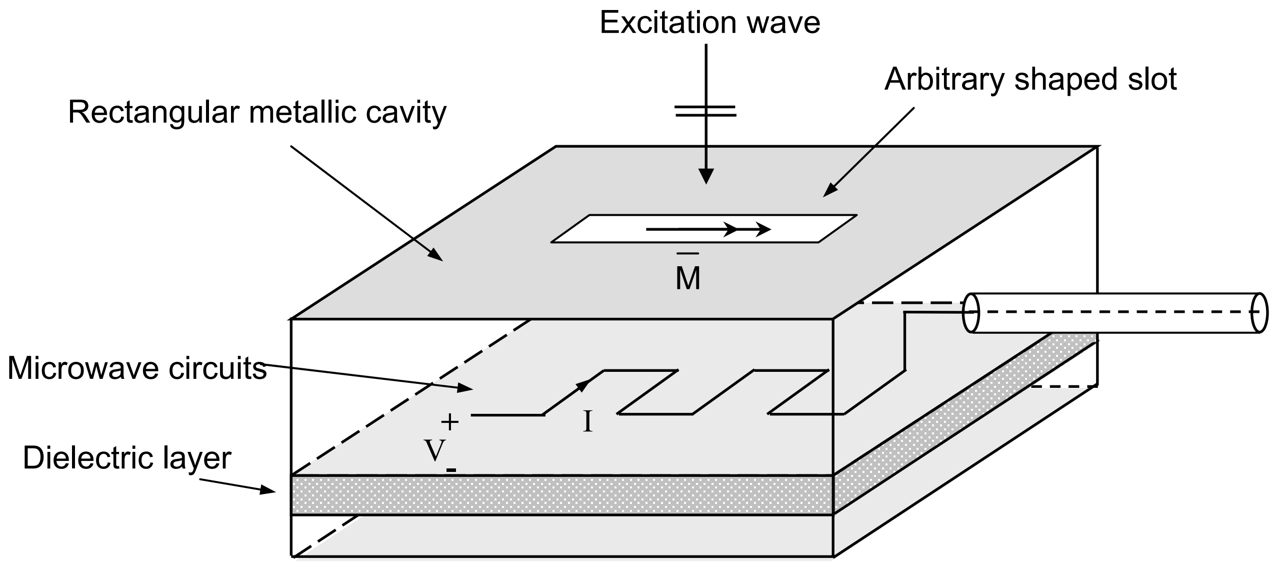
Methods to Improve Shielding

- Low cost shielding using wire grids across the aperture can reduce coupling by 5 to 20 dB over the frequency range around the slot and cavity resonance.
- Using PEC plates to ‘shadow’ slots leads to a larger improvement of 5 to 30 dB over the same frequency range.
- Both approaches work on attenuating the incident wave and reducing the slot resonance so as to reduce EMC coupling.
- Cavity resonance at 0.7 GHz acts to amplify the input signal by as much as 10-20dB.
- Cavity resonance can be further attenuated by a sheet of dielectric within the cavity interior.

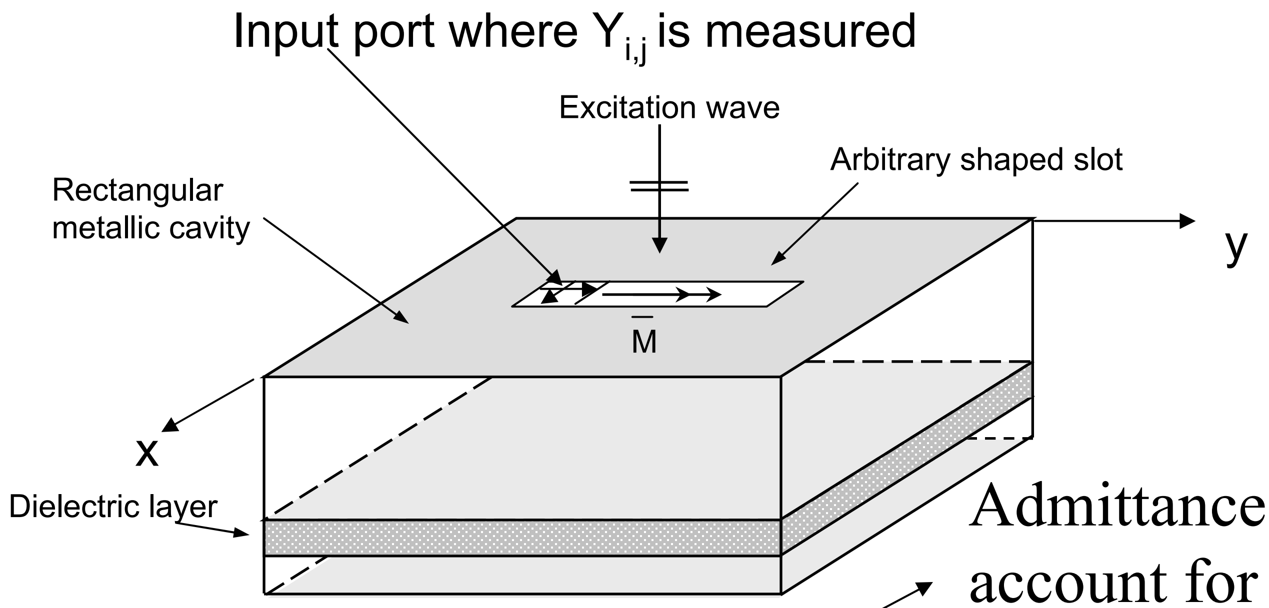
Semi Analytical Cavity Analysis



Why? To develop circuit models for incorporation into overall code



Port Analysis



Admittance matrix account for interior (a) and exterior (b)

$$\begin{bmatrix} M_{xo} \\ M_{yo} \end{bmatrix} = -\begin{bmatrix} Y^a_{xx} - Y^b_{xx} & Y^a_{xy} - Y^b_{xy} \\ Y^a_{yx} - Y^b_{yx} & Y^a_{yy} - Y^b_{yy} \end{bmatrix}^{-1} \begin{bmatrix} I^{inc}_x \\ I^{inc}_y \end{bmatrix}$$

This column is very small

How [Y] is derived?

- Interior Fields

$$C_{mn} = -\frac{8jY_o(\Delta x\Delta y)^2}{k_o\mu_b\, ab}\frac{1}{k_{mn}\tan(k_{mn}c)}$$

$$H_x^b = \sum_{m,n}\frac{C_{mn}}{(2\Delta x\Delta y)^2}\left[\varepsilon_n\left\{k_b^2 - \left(\frac{m\pi}{a}\right)^2\right\}\int_S M_x \sin(\frac{m\pi}{a}x')\cos(\frac{n\pi}{b}y')ds'\right.$$
$$\left. - \varepsilon_m\left(\frac{m\pi}{a}\right)\left(\frac{n\pi}{b}\right)\int_S M_y \cos(\frac{m\pi}{a}x')\sin(\frac{n\pi}{b}y')ds'\right]\sin(\frac{m\pi}{a}x)\cos(\frac{n\pi}{b}y)$$

$$H_y^b = \sum_{m,n}\frac{C_{mn}}{(2\Delta x\Delta y)^2}\left[-\varepsilon_n\left(\frac{m\pi}{a}\right)\left(\frac{n\pi}{b}\right)\int_S M_x \sin(\frac{m\pi}{a}x')\cos(\frac{n\pi}{b}y')ds'\right.$$
$$\left. + \varepsilon_m\left\{k_b^2 - \left(\frac{n\pi}{b}\right)^2\right\}\int_S M_y \cos(\frac{m\pi}{a}x')\sin(\frac{n\pi}{b}y')ds'\right]\cos(\frac{m\pi}{a}x)\sin(\frac{n\pi}{b}y)$$

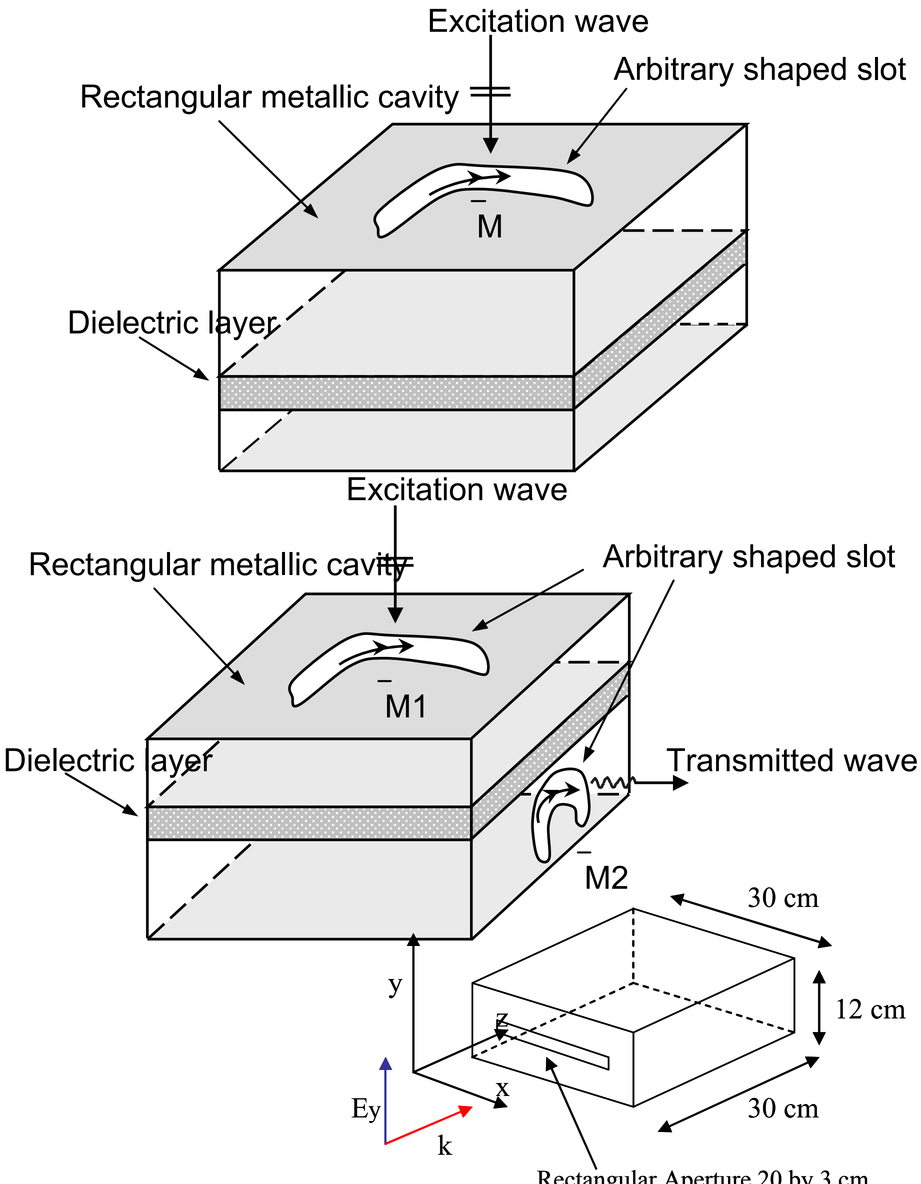
- Exterior Fields

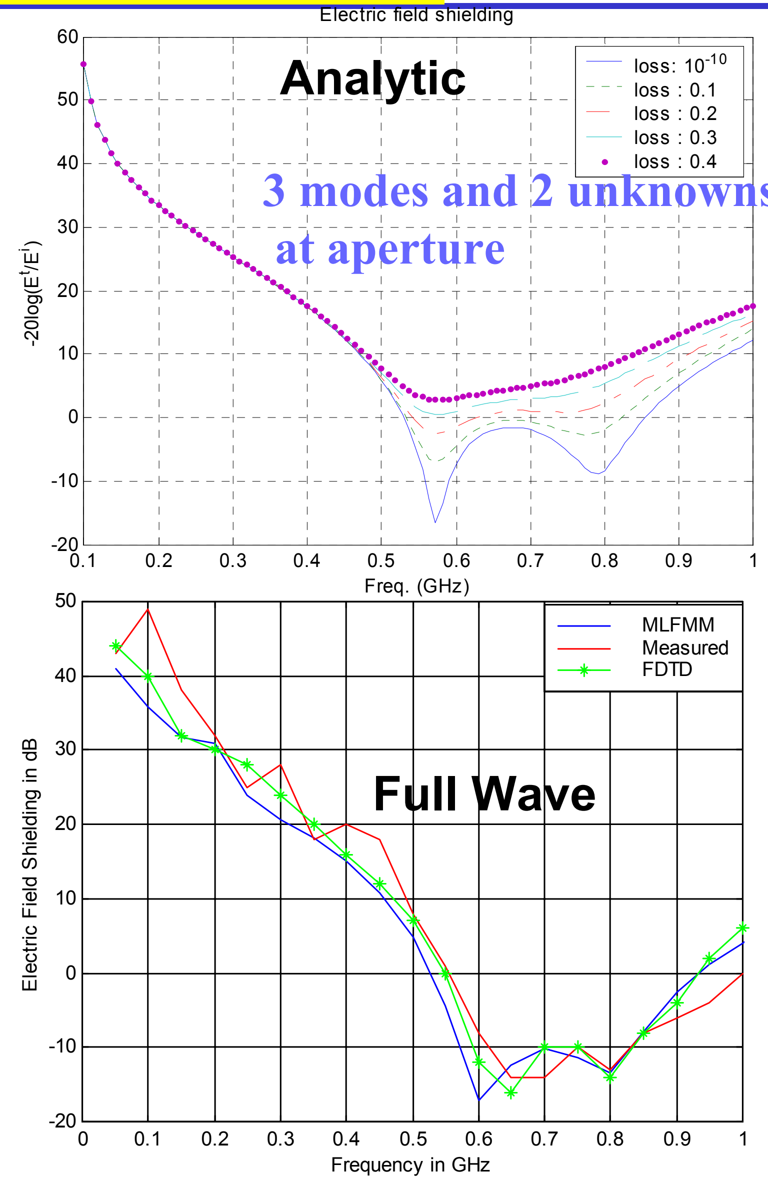
Free space GF

$$\overline{H}^a(\overline{r}) = -jk_0Y_0\int_S 2\overline{M}(r')\cdot\overline{\overline{\Gamma}}_0(\overline{r};\overline{r}')ds'$$

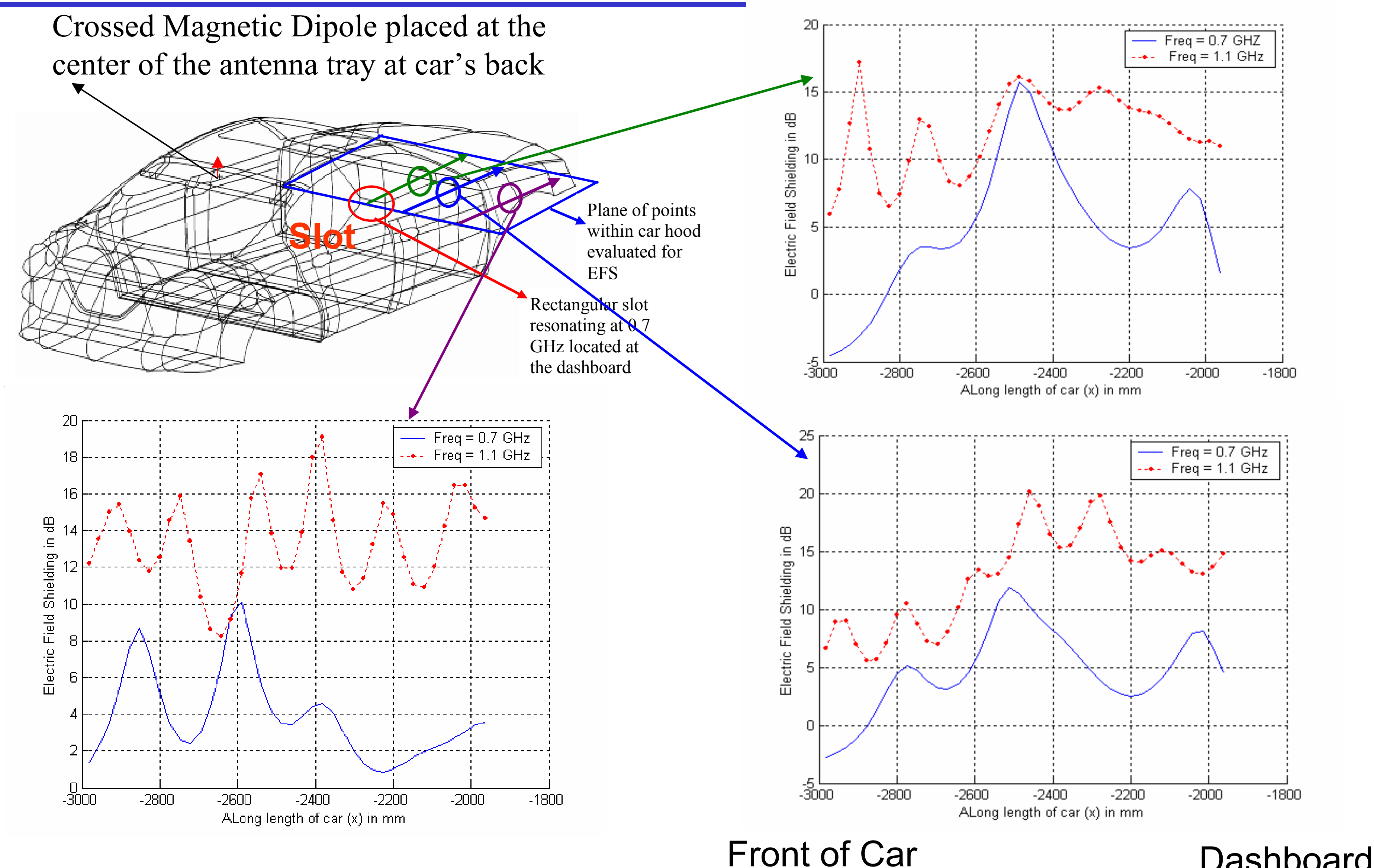
- Admittance matrix equation results by equating H fields at the aperture

Port Analysis Validation





Antenna to Slot Coupling in Systems

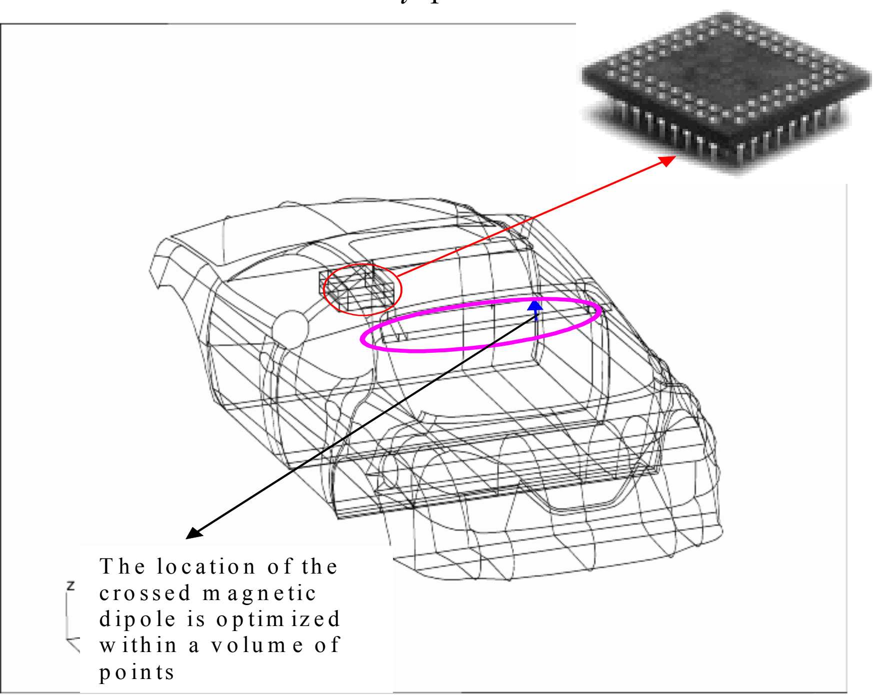


Slot is Resonating at 0.7 GHz

Optimization For EMC Applications: Minimize Coupling at Pre-Specified RF Circuit Location

Overall Objective Function

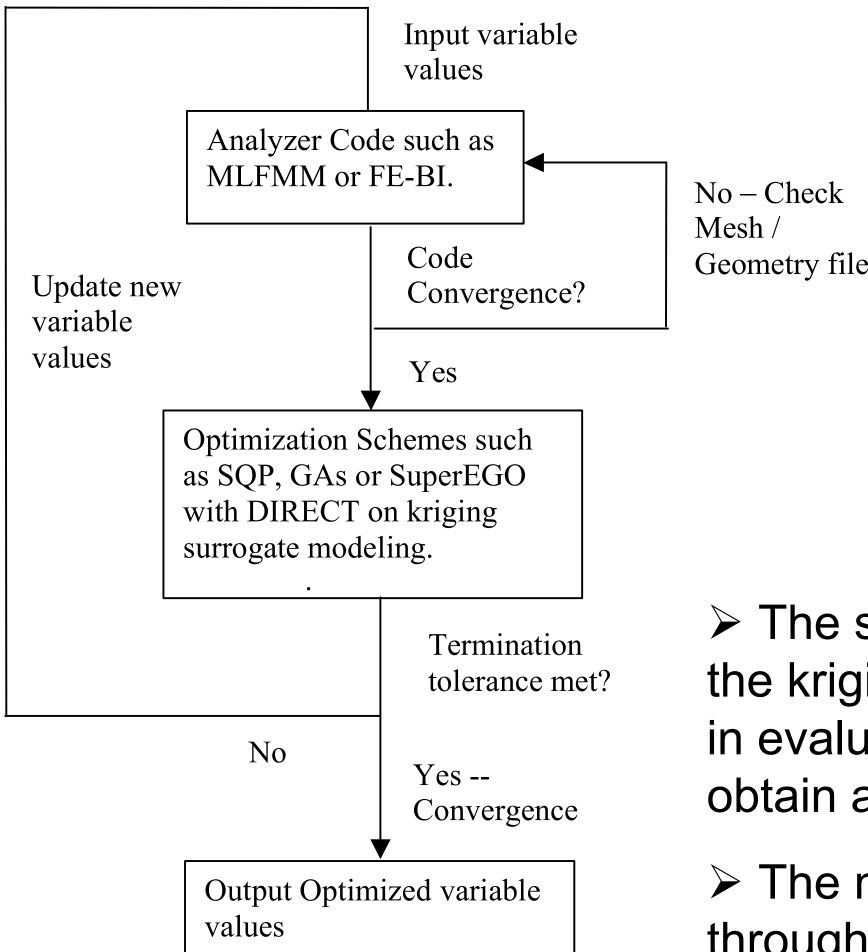
$$F(x,y,z)=\frac{\sum_{i=1}^{40}\left|E_i^{total}\right|^2}{\sum_{i=1}^{40}\left|E_i^{inc}\right|^2}$$



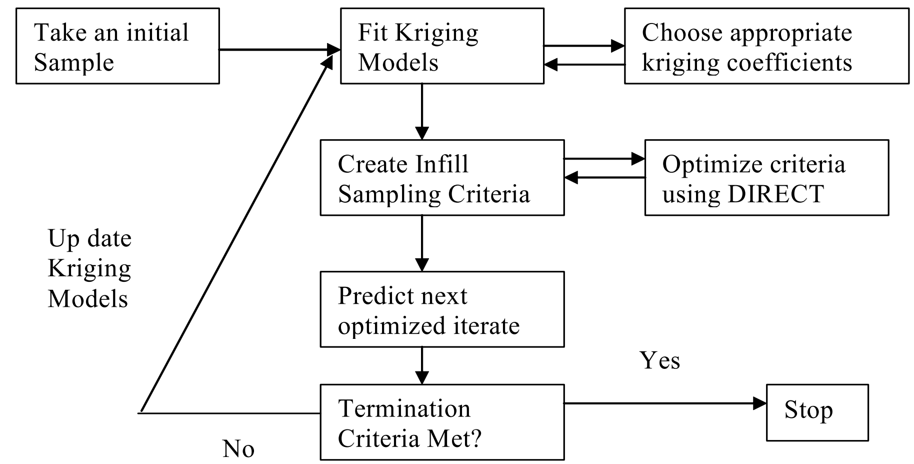
- Excitation is a pair of crossed Magnetic dipoles with orthogonal phase excitation at 0.7 GHz (same as cavity).
- Antenna location is to be optimized for a volume of points on the back of an automobile that minimizes the EM Coupling from the antenna to the 40 pins of a chip placed within a resonant cavity.
- Resonant cavity at 0.7 GHz housing the electronic chip amplifies incident fields.
- Different antenna locations can mitigate cavity modal excitation and reduce EM coupling.
- Design space bounds: $-70 \le x \le 70$,

  $-500 \le y \le 0$ and $-80 \le z \le 48.57$

Optimization Algorithms



Flow Model of the superEGO Global Optimizer code

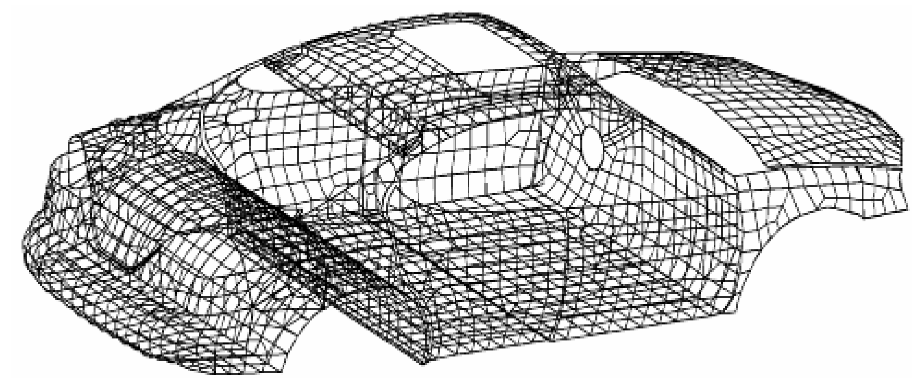


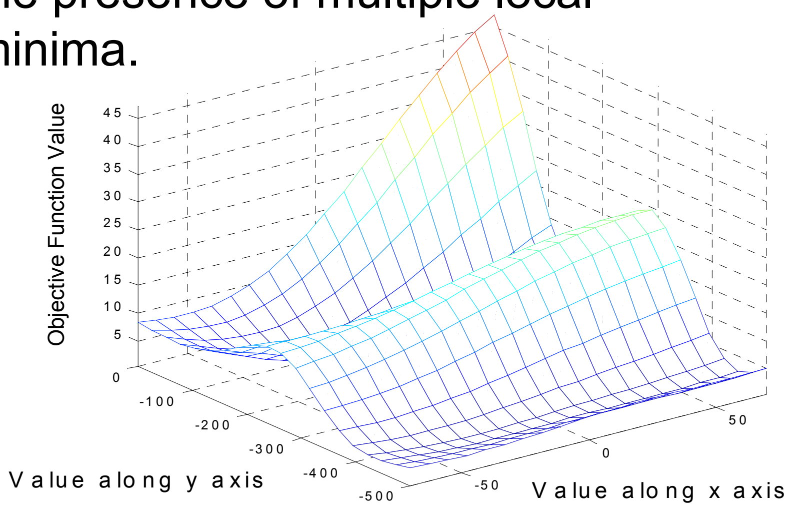
- The superEGO optimizer continually looks at the kriging meta-model to guide the optimizer in evaluating promising points with potential to obtain a low objective function.
- The next predicted design point is obtained through DIRECT to optimize an auxiliary model characterized by the choice of Infill sample criteria with kriging meta-modeling.

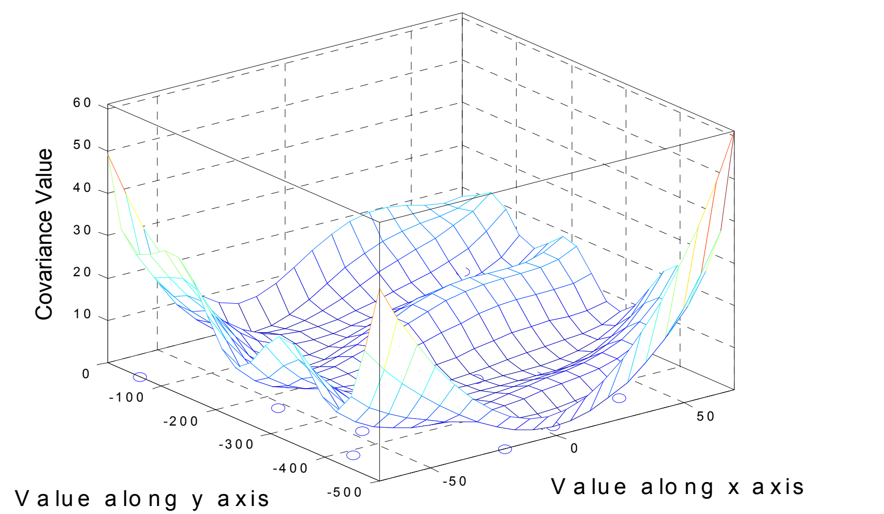
An Initial look at the suitability of the Kriging Metamodel and requirements of the MLFMM

- Automobile model has 26000 unknowns, MLFMM code takes up 310 MBytes of RAM and solves in slightly over 2 hours on an SGI platform.

- Initial Kriging Model obtained from a sparse randomly generated vector of 18 data sampling points indicates a Response Surface with the presence of multiple local minima.



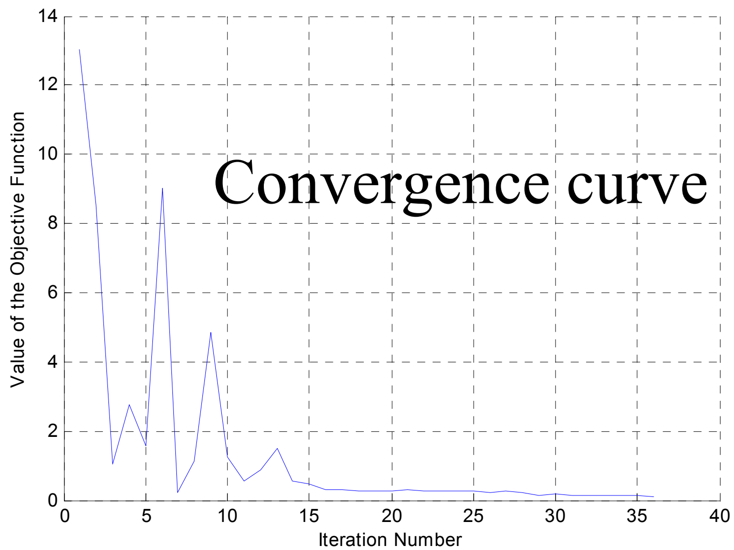


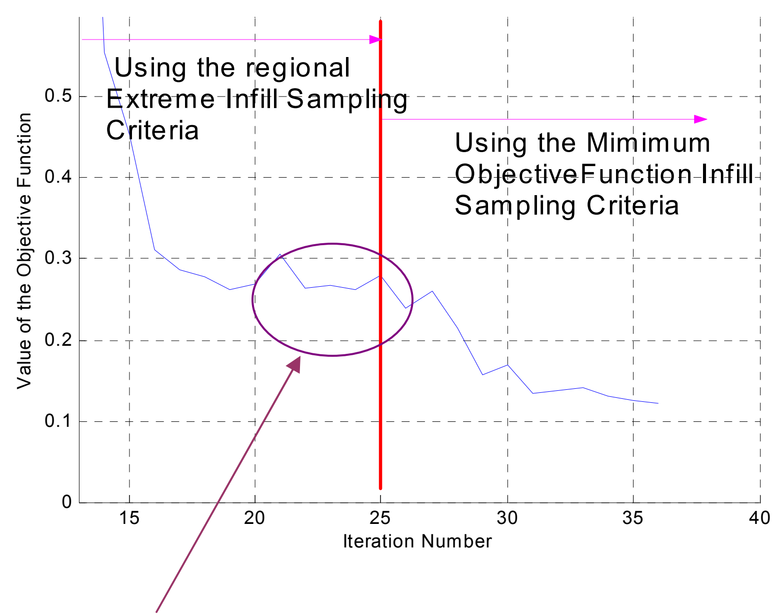


Convergence Rate of the superEGO optimization algorithm

➢ Optimizer found a global minimum solution within tens of iterations besides the initial sample size. This is a significant improvement compared to using Genetic Algorithms.

➢ Using the Regional Extreme Infill Sampling criteria, local-global optimization scheme forces optimizer to find local minimum. Applying the Global optimization Infill scheme allows optimizer to find other global minimas.

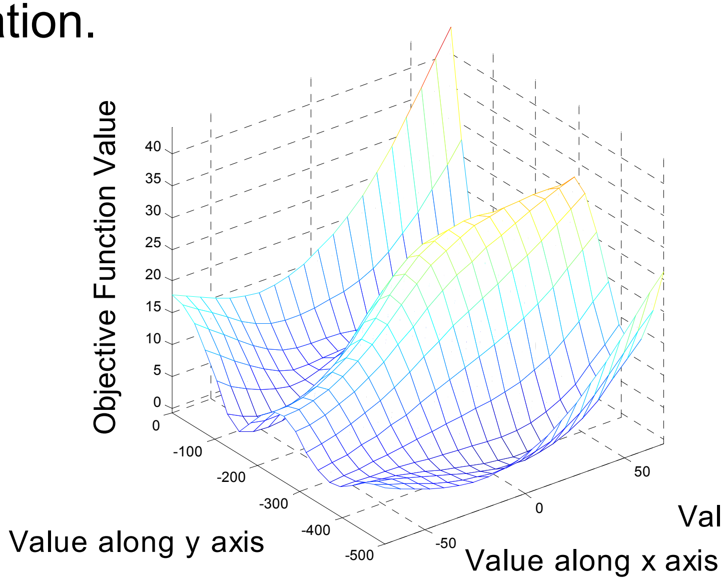


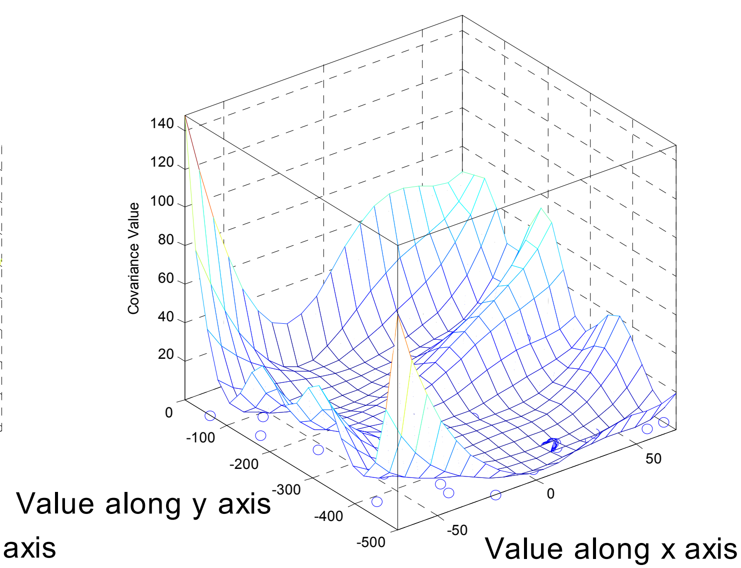


Region of local minimum Point

Final Optimized Antenna Position and Coupling Coefficient

- Antenna location at the center of the automobile gives F(x,y,z) = 13.3025
- Final Optimized Antenna position gives F(x,y,z) = 0.122057 (20.37 dB improvement compared to the center location) at the positions x = 24.19753 mm, y = -421.773 mm and z = -34.6448 mm.
- Final kriging metamodel plots show a slightly modified Response Surface Modeling (RSM) with continual update of the kriging model at each optimization iteration.



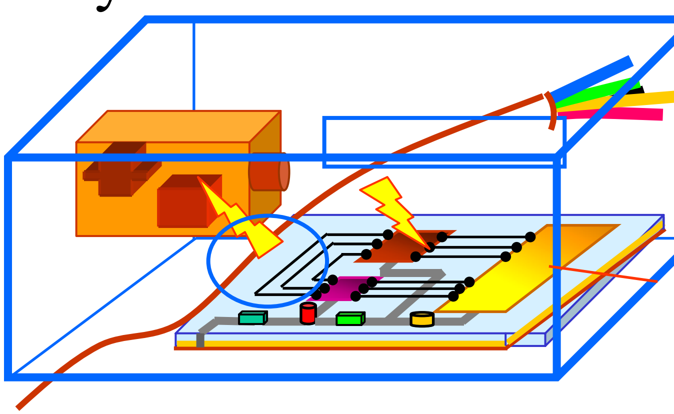


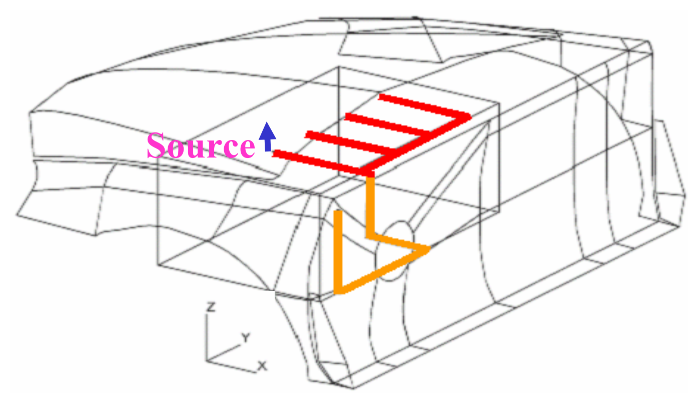
Accomplishments

- Phenomenology of cavity coupling
- Effects of wire penetrations and loading
- Simplified semi-analytical model for cavity
- Coupling in systems using general-purpose EMCAR code
- Optimization for coupling control in systems

Computational Tools

- MLFMM for coupling studies
- Hybrid (finite element, boundary/volume integrals) for modeling realistic systems

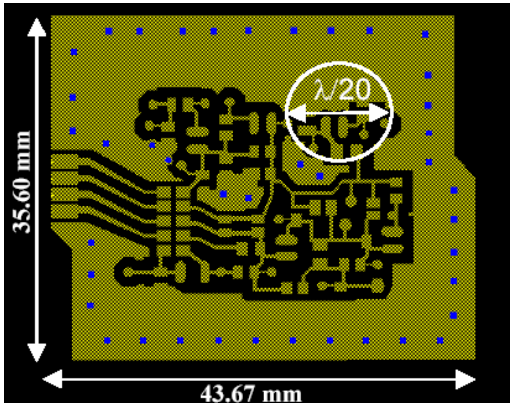




Next Steps

- Complete development of the hybrid FE-BI code with various Green's function domains.
- Further development of [Y] matrix model for integration
- **Modeling of realistic boards within enclosures**

Actual Interconnect



Interconnect Mesh