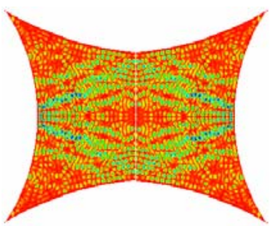
Prediction and Measurement of Induced Voltages and Currents in Complicated Metallic Enclosures

Steven M. Anlage, Sameer Hemmady,
Xing Zheng, James Hart, Chris Bertrand,
Tom Antonsen, Ed Ott



Statistical Methods Meeting
13 July, 2006

Research funded by the AFOSR-MURI and DURIP programs

Goal

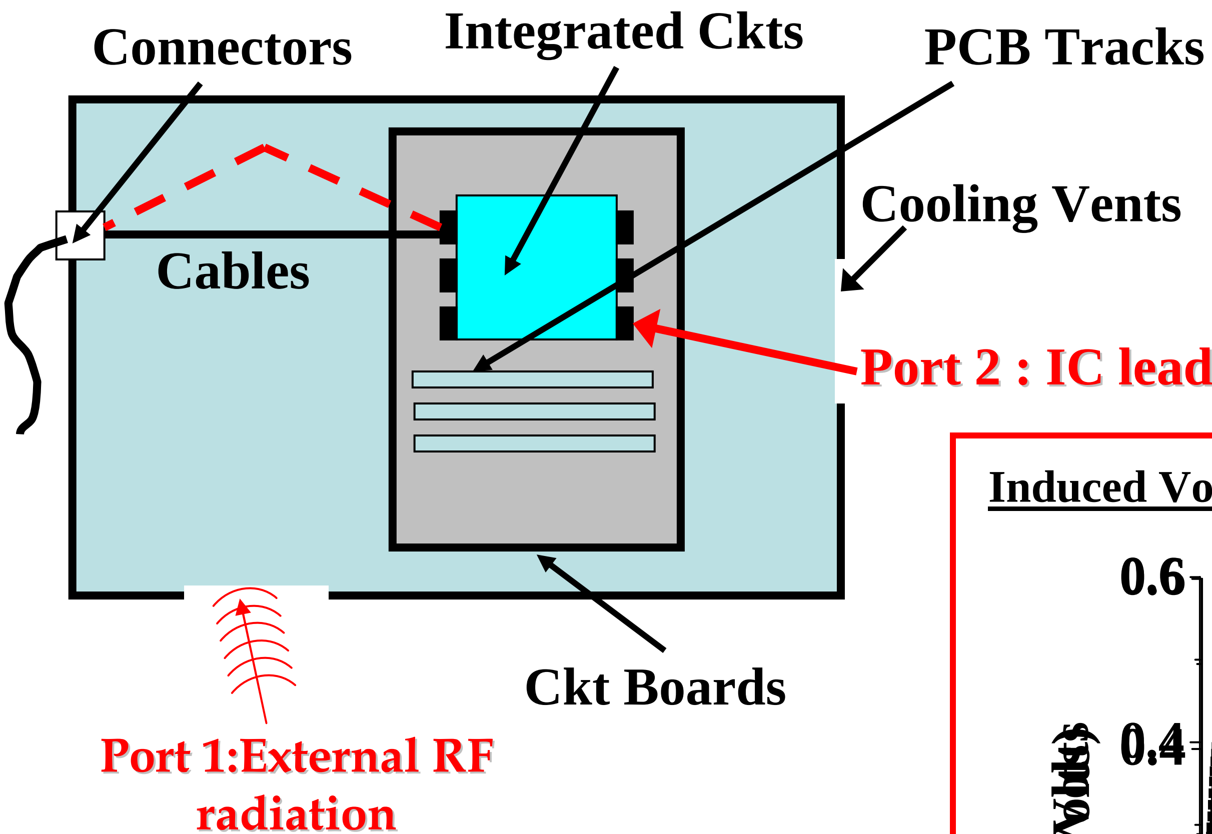
To develop a quantitative statistical understanding of induced voltage and current distributions in circuits inside complicated enclosures, based upon minimal information about the system

Target system information required:

- Volume
- Loss (1/Q)
- Frequency / Waveform of attack
- Radiation impedance of the relevant ports

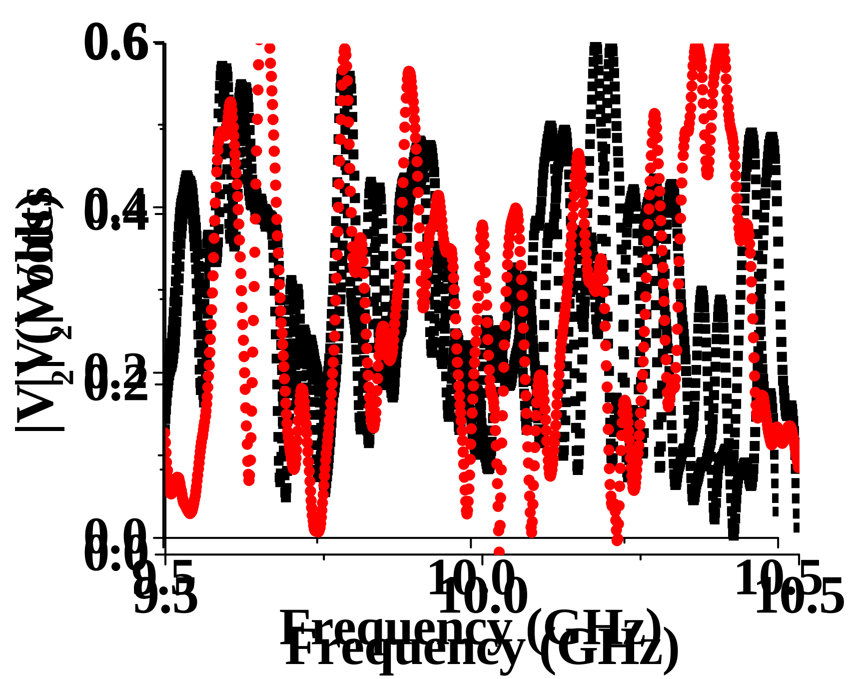
Random Coupling Model (RCM) Talks, Friday 14 July, Pecos (Free and open to all!)
8:00 AM Vic Granatstein, MURI Overview
8:20 AM Ed Ott, RCM Theory
8:50 AM Sameer Hemmady, RCM in Practice
9:15 AM Steven Anlage, GHz-Frequency Circuit Chaos
9:40 AM John Rodgers, Nonlinear HPM Effects

Motivation for the Random Coupling Model



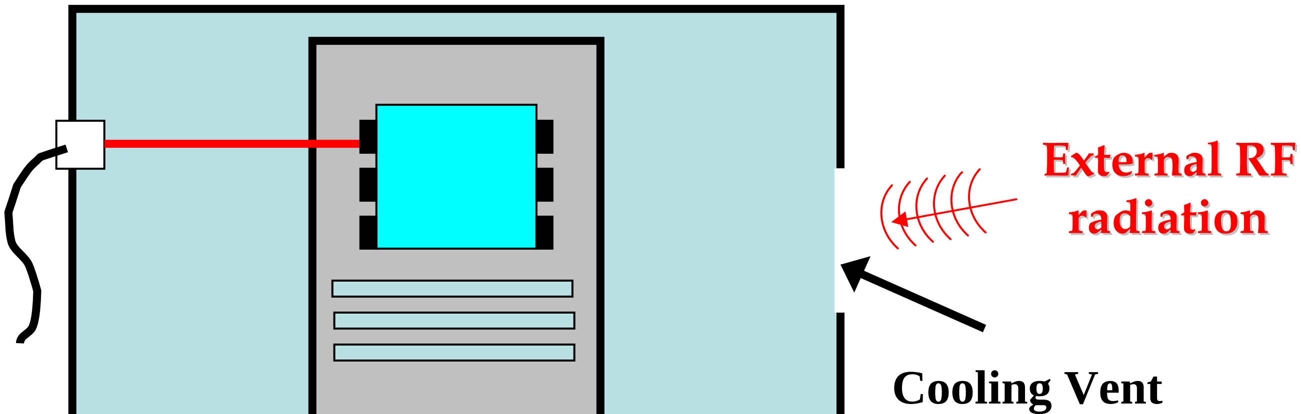
AMEREM Plenary
D. R. Wilton (312.4)
Made the case for statistical description from computation

Induced Voltages at Port 2 in a computer-box



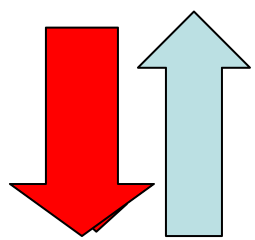
- Extreme sensitivity to system details makes numerical EM solutions based on Maxwell's equations impractical.
- Use Statistical Description !!

Our outlook on this problem:- Formulating the Random Coupling Model



▪ **Use <u>Universal</u> Properties of Wave Chaotic Systems to predict induced voltage <u>distributions</u> at specific locations inside the enclosure.**

Treat the computer-box as a wave-chaotic system



Chaotic Ray Trajectories

Related work: (Field distributions in reverberation chambers, etc.)

R. Holland and R. St. John, *Statistical Electromagnetics* (Taylor and Francis, Philadelphia, 1999).

D. A. Hill *et al.*, IEEE Trans. Electromag. Compat. **36**, 169 (1994).

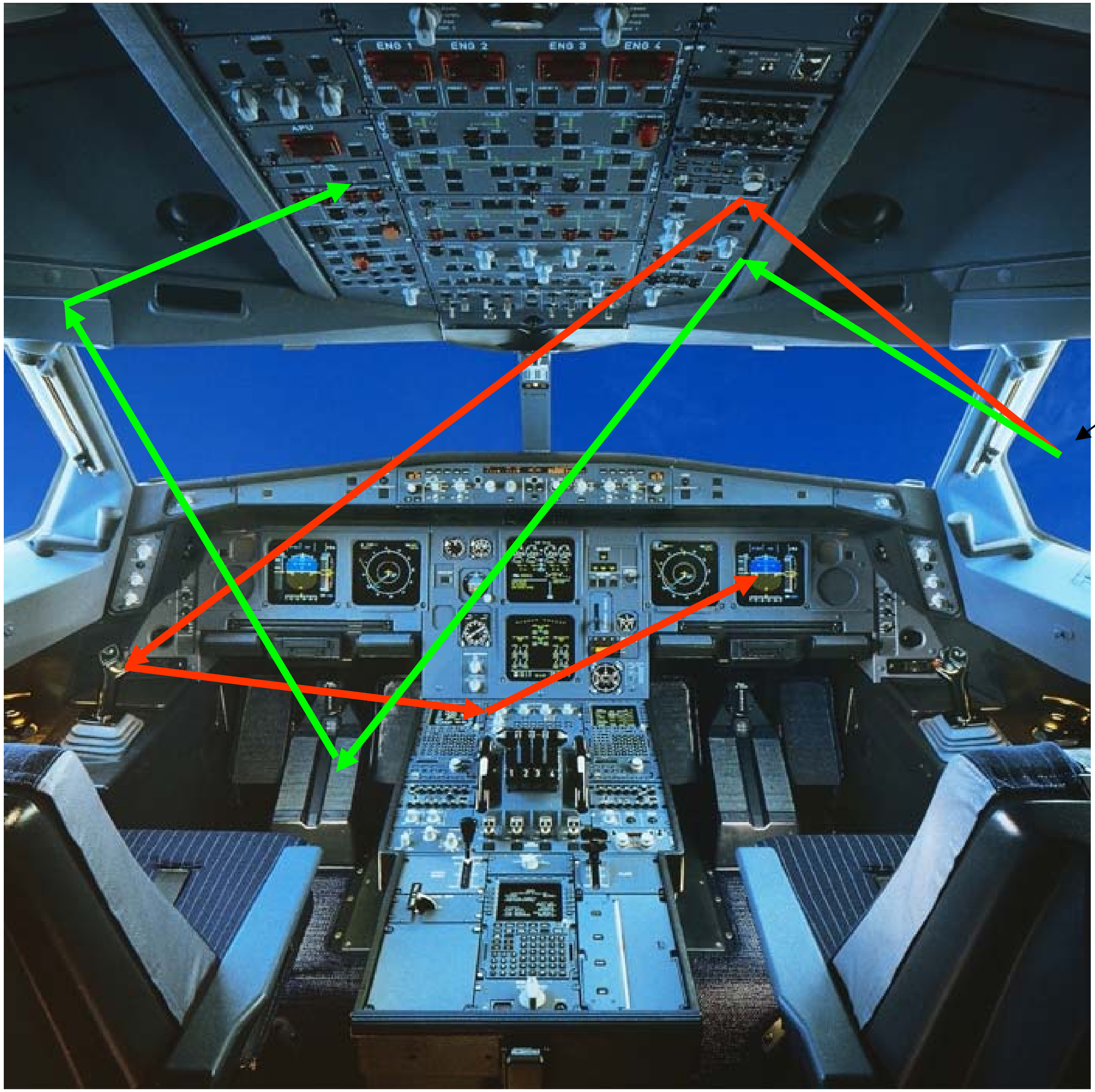
L. K. Warne *et al.*, IEEE Trans. Antennas Propag. **51**, 978 (2003).

C. Fiachetti and B. Michielsen, Electronics Lett. **39**, 1713 (2003).

and others…

What is Ray Chaos?

The Wave Chaos approach applies to systems that display Ray Chaos

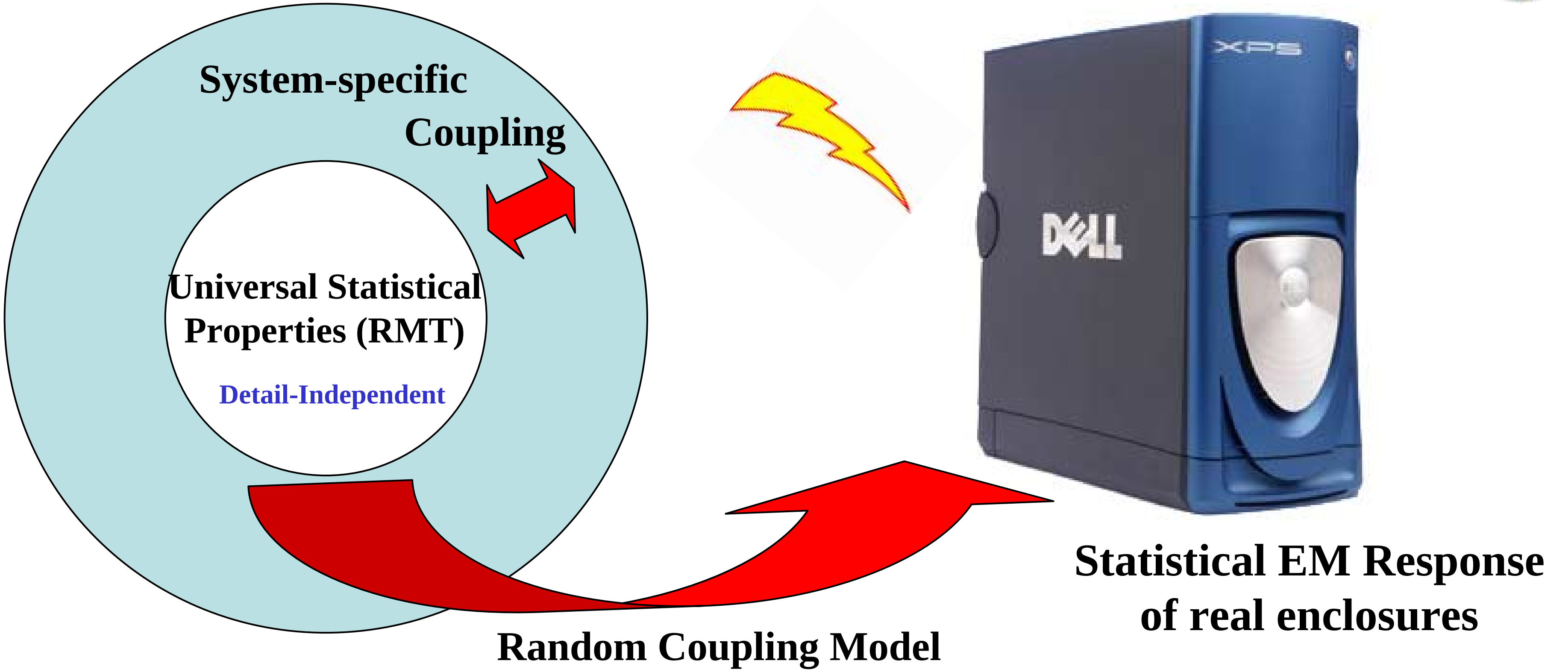


Consider Newtonian ray orbits (3D billiards)

Two incident rays with slightly different initial directions have rapidly diverging trajectories

Practical Implications for Real Life Problems

Bare Minimum Specifications for Induced-Voltage Statistics



What are the bare minimum specifications to accurately predict voltage Statistics?

<u>Minimum Information to predict PDF of induced voltages at an internal port:</u>

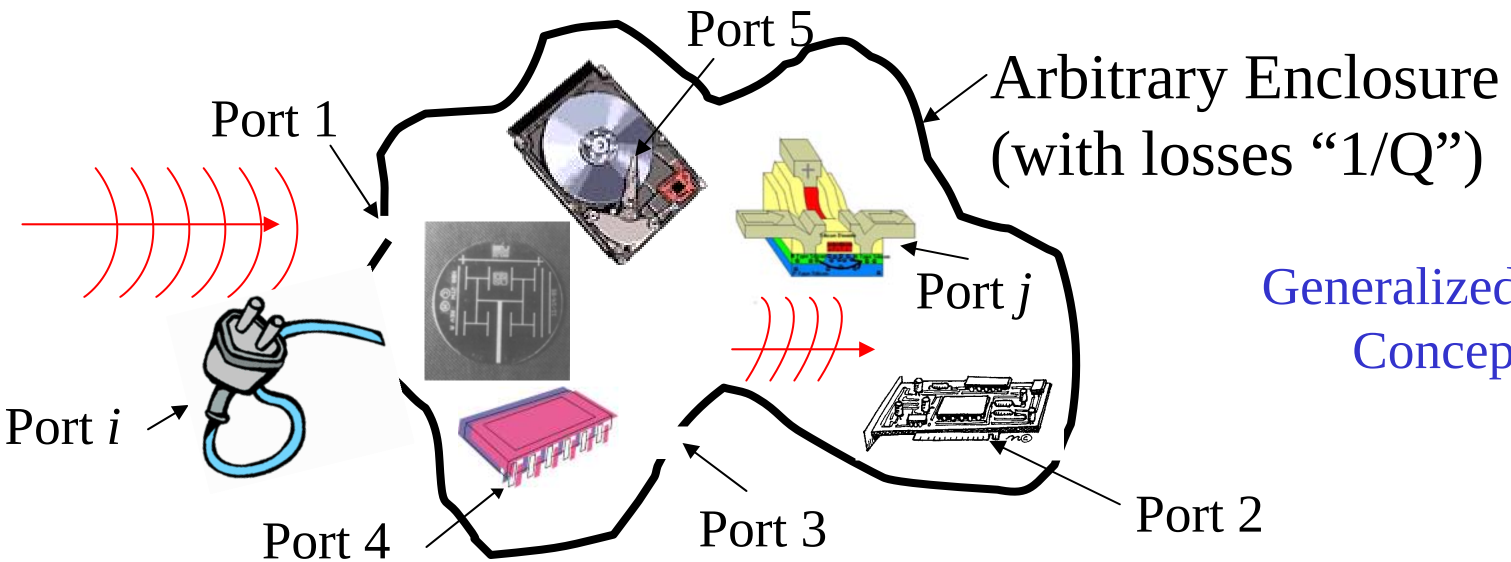
Frequency, Volume
Losses

$$\alpha = \frac{k^3 V}{2\pi^2 Q}$$

Radiation impedance of the ports
Radiated power Wave-form from port 1

Determine the shape and scales of the induced voltage PDFs

Induced Voltage Distributions for Objects in an Arbitrary Enclosure



Generalized Port Concept

Electromagnetics, **26** 3 (2006)
Electromagnetics, **26** 37 (2006)

Our approach treats all objects of interest as "ports"

Incident rf energy enters the enclosure through one or more ports

The energy reverberates and is absorbed by one or more ports inside the enclosure

Key quantities are the <u>radiation impedances</u> (Z_{Rad}) of the ports

Cavity Impedance has Mean + Fluc Parts

When applied to an ensemble of ray-chaotic cavities, the impedance becomes;

$$Z = \overline{Z} + \tilde{Z} = jX_{Rad} + (\rho + j\xi)R_{Rad}$$

Mean part ($\overline{Z}$) — Fluctuating part ($\tilde{Z}$)

$\langle\rho\rangle = 1$
$\langle\xi\rangle = 0$

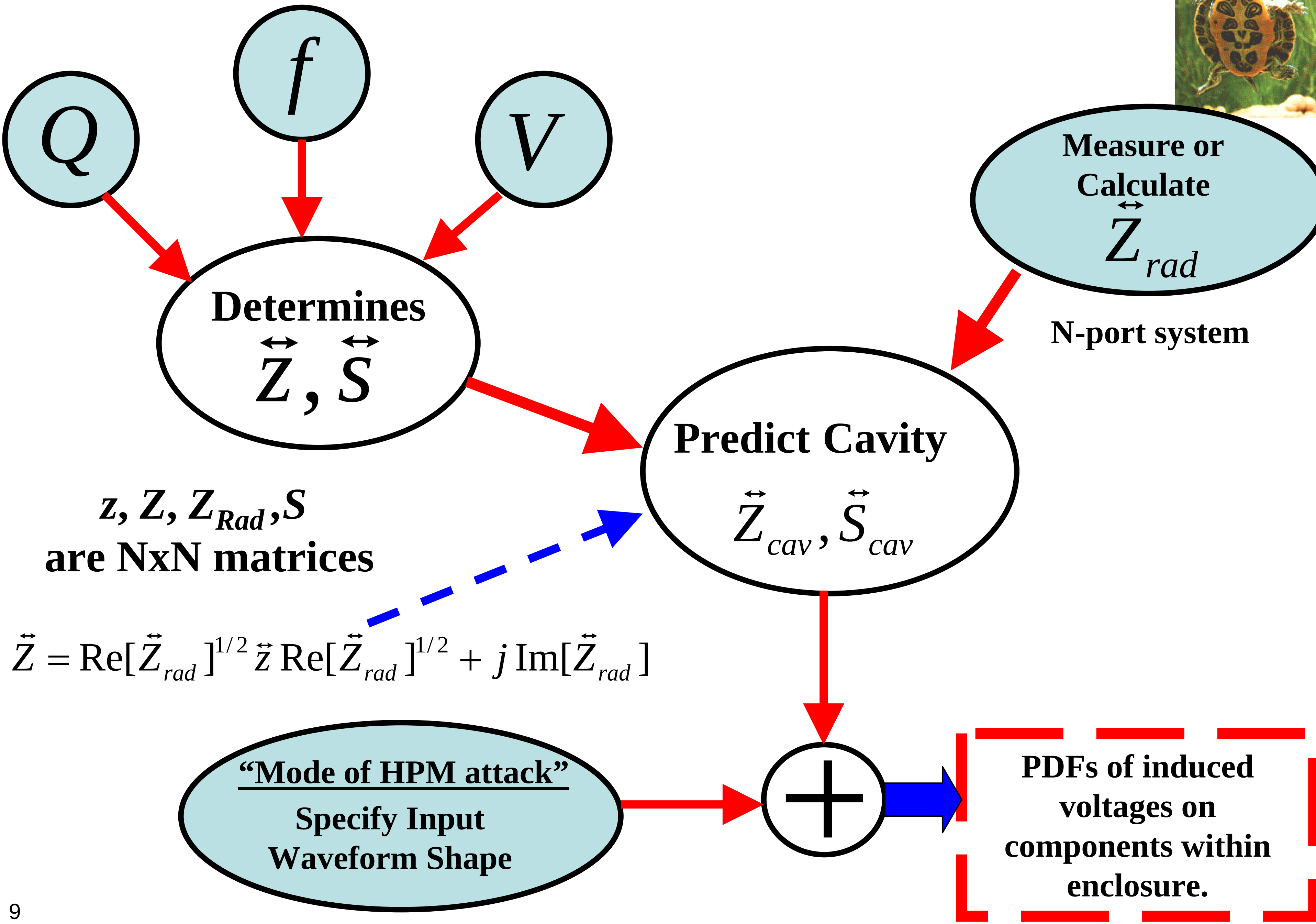
$$z = \rho + j\xi = \frac{Z - jX_{Rad}}{R_{Rad}}$$

Normalized impedance
"perfect coupled"
ρ, ξ distributions depend only on loss

Two measurements are required: 1) *Z* of chaotic system; 2) Z_{Rad}

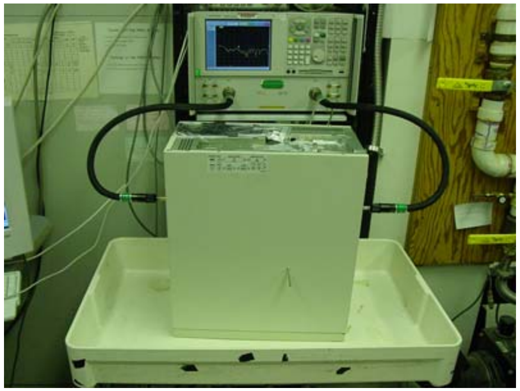
Loss Parameter: $\dfrac{k^2}{\Delta k_n^2 Q} \sim \dfrac{\mathrm{Im}[\omega_0]}{\Delta\omega}$ (sometimes called α)

“Terrapin algorithm” for *a priori* prediction of Induced Voltage PDFs

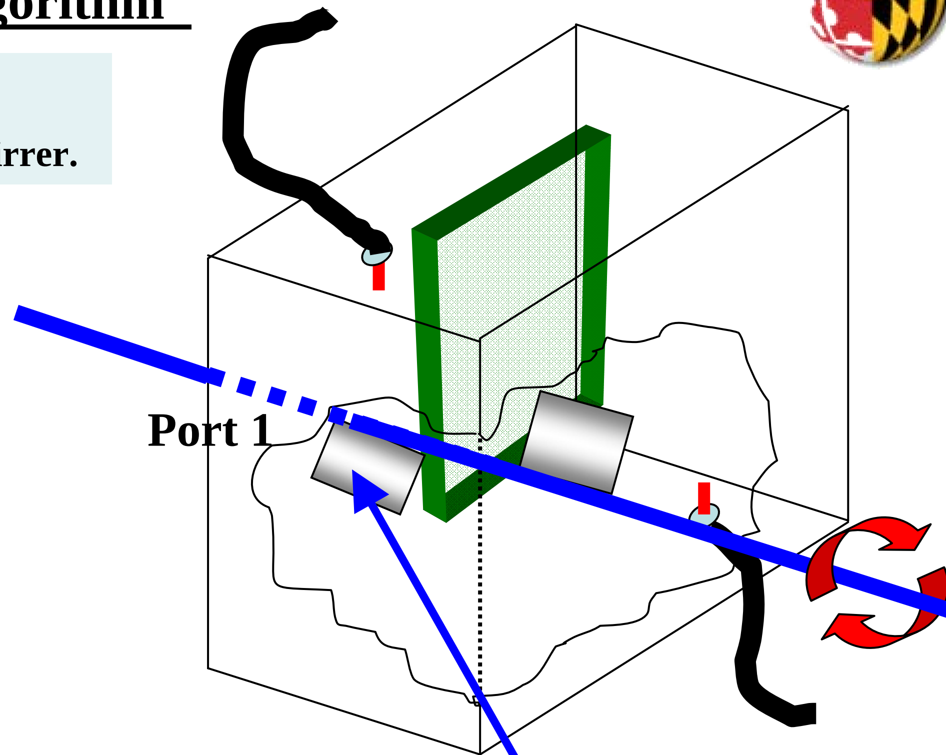


“3D Real-World” Test of the Random Coupling Model and the “Terrapin Algorithm”

- Frequency Range: 2GHz to 20 GHz (λ<<L)
- Ensemble Averaging over ~20 positions of the mode-stirrer.

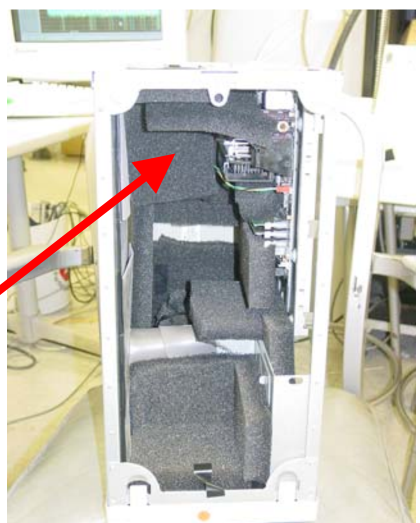


Experimental Setup [Cavity Case]



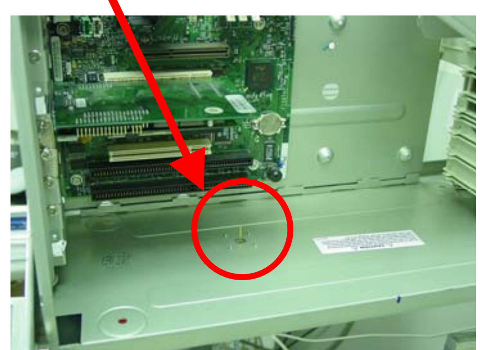
Port 2

Paddle-Wheel Mode-Stirrer



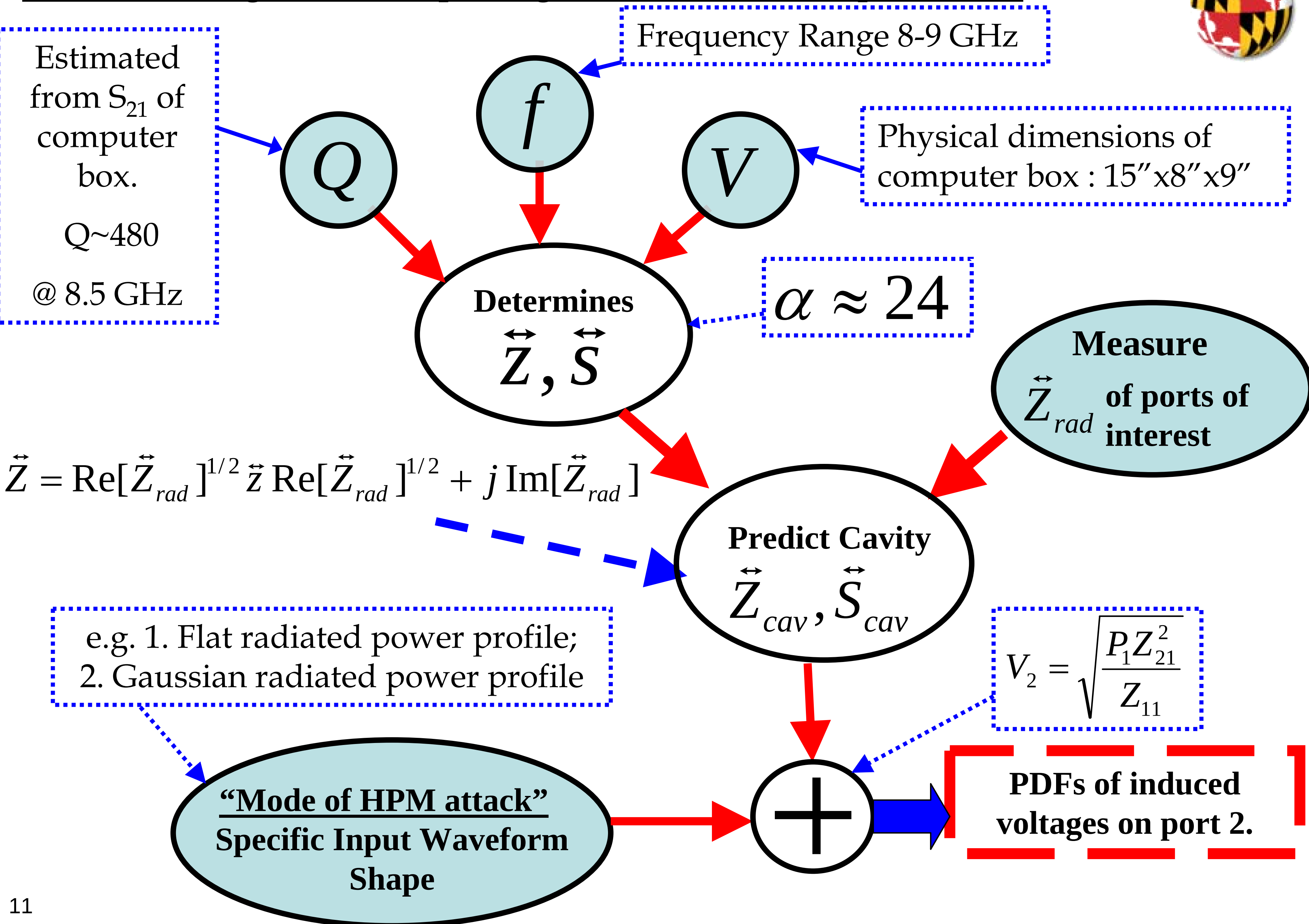
Microwave absorber

Port 2

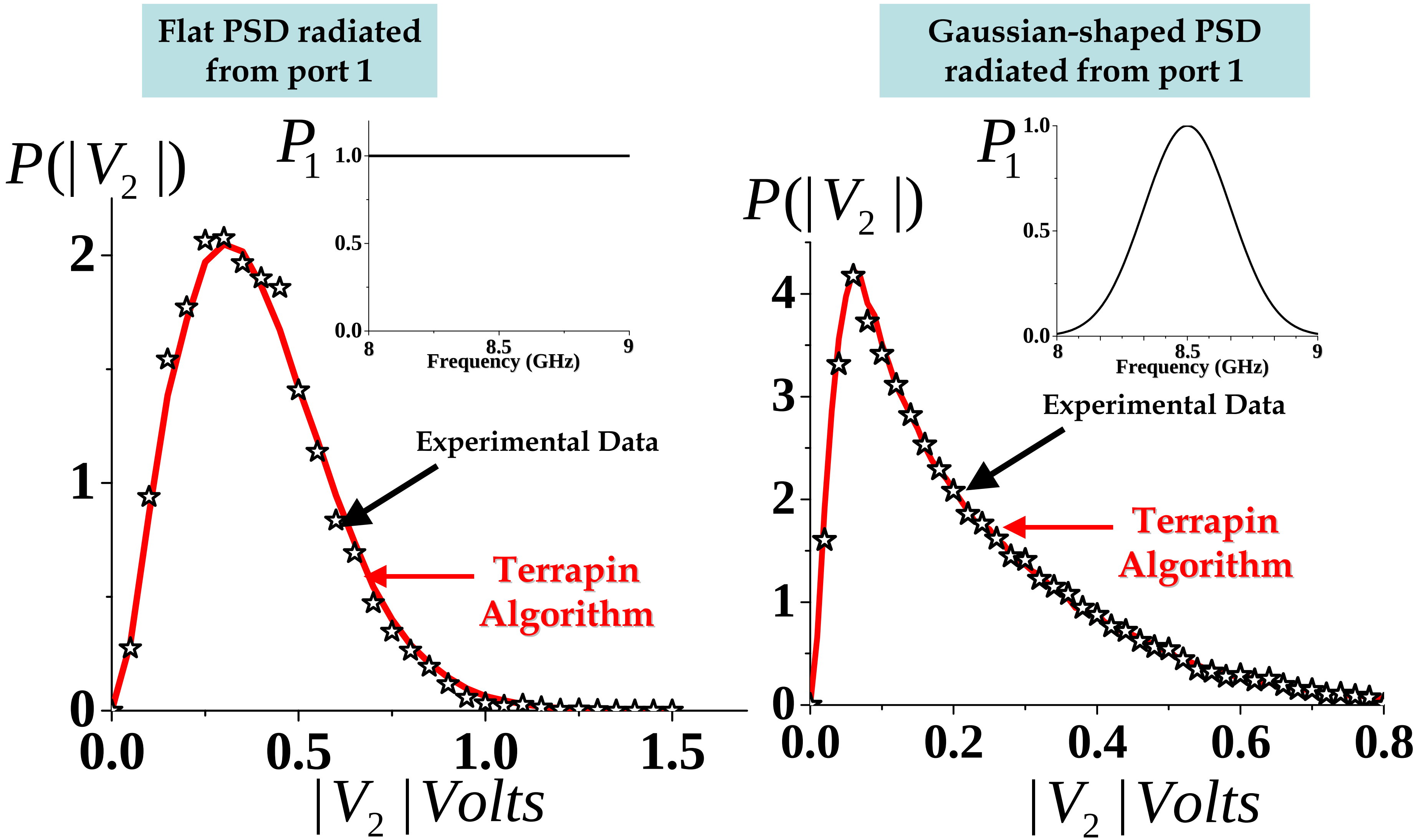


Port Radiation Measurement Setup

Tutorial: Using the "Terrapin Algorithm" on the computer-box:

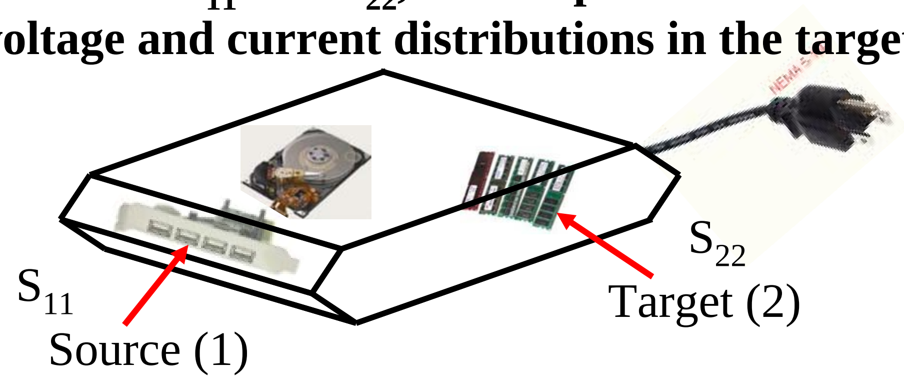


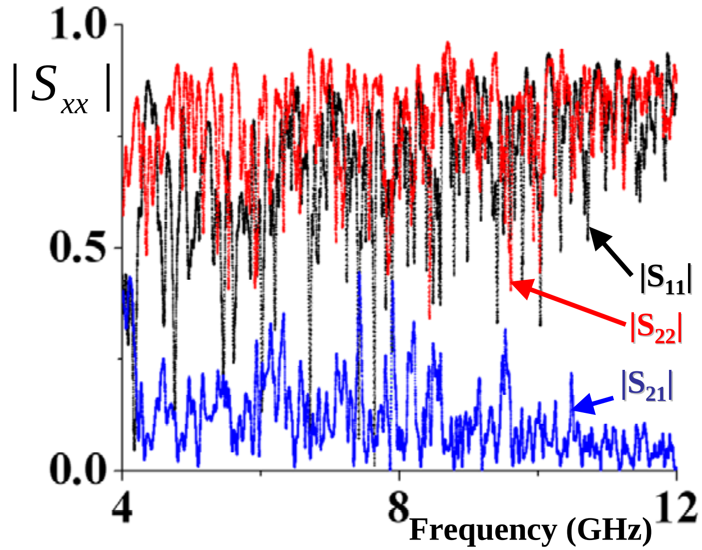
PDF of induced voltages on port 2 of computer-box for different power-spectral densities radiated at Port 1

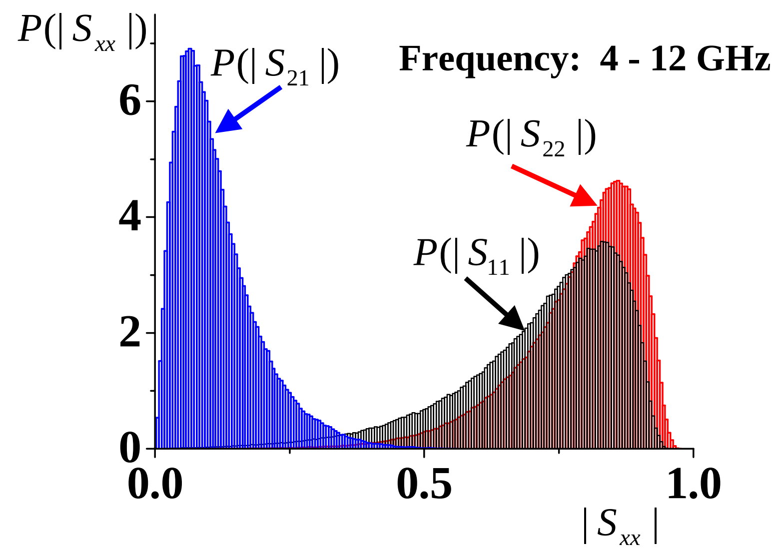


Variance of Voltage and Current Distributions on the Target

Given the variance of S_{11} and S_{22}, we can predict the variance of the induced voltage and current distributions in the target







$$Var(S_{12}) \approx \frac{1}{2}\sqrt{Var(S_{11})Var(S_{22})} \quad \text{(ONERA)}$$

Or :

$$Var(Z_{12}) = \frac{1}{2}\sqrt{Var(Z_{11})Var(Z_{22})} \quad \text{(Maryland)}$$

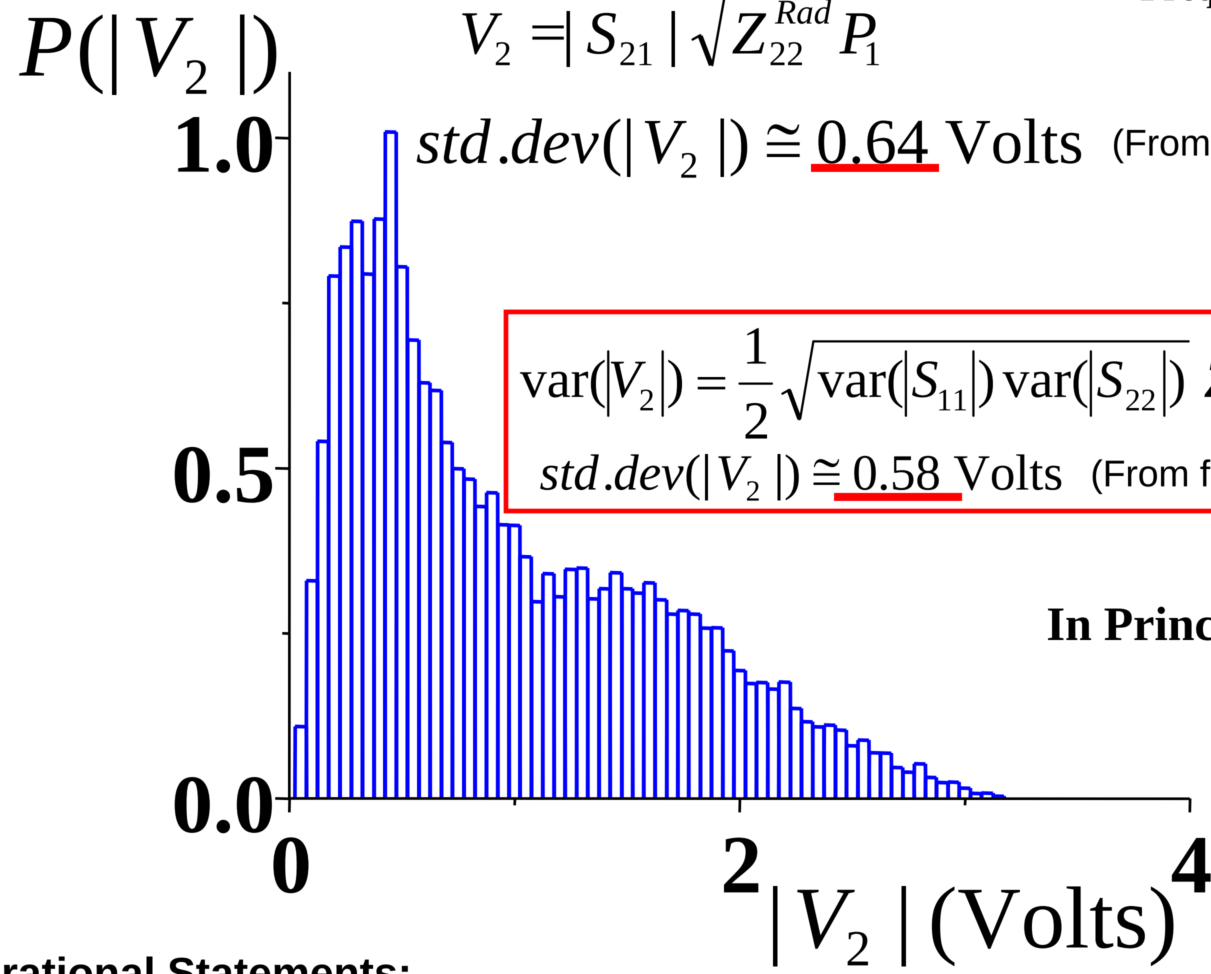
Phys. Rev. E 73, 046208 (2006)

PDF of Induced Voltages on Port 2 with 1 Watt Radiated by port 1:

Frequency: 5-6 GHz

$$V_2 = |S_{21}| \sqrt{Z_{22}^{Rad} P_1}$$

$$std.dev(|V_2|) \cong \underline{0.64} \text{ Volts}$$ (From Histogram)



$$\text{var}(|V_2|) = \frac{1}{2}\sqrt{\text{var}(|S_{11}|)\,\text{var}(|S_{22}|)}\; Z_{22}^{Rad} P_1$$

$$std.dev(|V_2|) \cong \underline{0.58} \text{ Volts}$$ (From formula)

In Principle: No need to measure in transmission!

Operational Statements:

Measure Var(Z_{11}) of the target <u>to quantify its degree of susceptibility to HPM attack</u>

Minimizing Var(Z_{11}) of the target is a strategy for <u>minimizing damage from HPM attack</u>

Phys. Rev. E 73, 046208 (2006)

Random Coupling Model Web Site / CD

http://www.csr.umd.edu/anlage/RCM/index.htm

Contents:

Introduction to the Random Coupling Model (RCM)

Computer Code (MatLab) <Terrapin RCM Solver v1.0 - by special request>

- **Generate predictions of induced-voltage PDFs (Speed: ~ 5 minutes)**
- **"Normalize" data to find universal S, Z statistics**

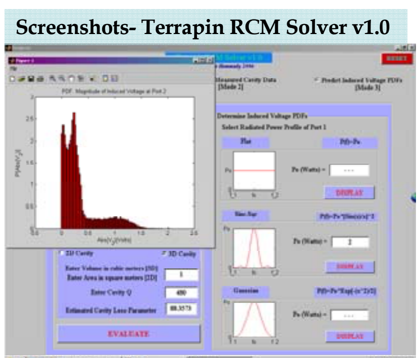
Tutorial on using the code

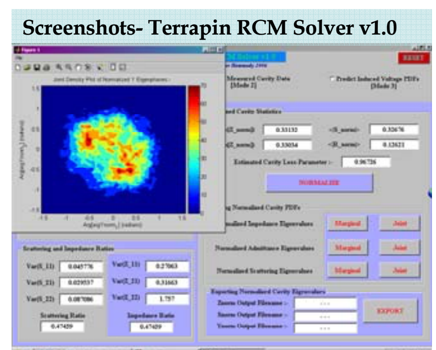
Example data and calculations

Frequently Asked Questions and Answers about the RCM

Caveats and limitations of the model

All of our publications and selected talks





We encourage others to pick up our model, TEST it, and USE it in your applications

We are happy to help you understand and use the model! (anlage@umd.edu)

Random Coupling Model: CAVEATS

What could possibly go wrong?

You need to predict the outcome of a specific measurement in a specific situation
The RCM provides only statistical predictions

Strong periodic contributions to the ray dynamics (e.g. short periodic orbits from parallel planes)
Can lead to deviations from RCM predictions: Scars, perhaps "Freak Waves"
Solutions: Mixed-dynamics systems heavily studied in quantum chaos
Scar identification: Antonsen, *et al*., Phys. Rev. E 51, 111 (1995)
New method to identify and account for system-specific short periodic orbits

When do you NOT want to use this model?

Enclosure Q ~ 1. No reverberation, no chaos, very lossy

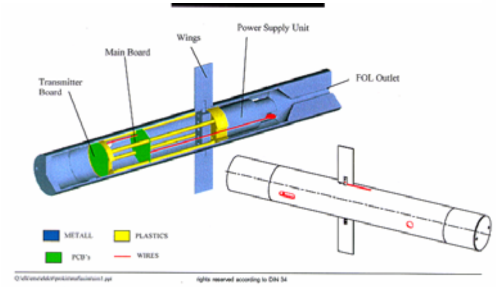
Enclosure size NOT much larger than wavelength λ. Direct numerical solution not sensitive to details
Rule of thumb: enclosure dimension > about 5-10 λ
Remember: Dielectrics inside the enclosure increase it's effective size

Our Vision for the Future… Extensions, Improvements, etc.

• **Random Coupling Model shows very promising signs... But still in its infancy.**

• **Further Experimental Validation of the RCM**
• **GENEC device**
• **Mode-Stirred Chamber tests**
• **Other antenna configurations (apertures, bundle of cables, etc.)**
• **Non-Reciprocal Media as a way to mitigate EM "Hot Spots"**

GENEC Hardware

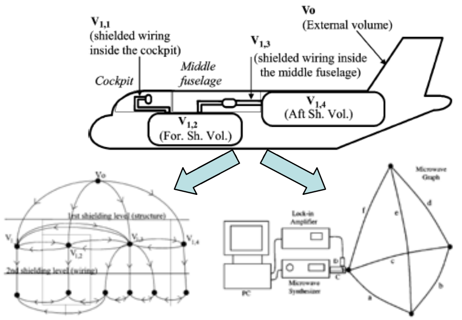


Mode-stirred chamber at ONERA

• **Transfer the Model and it's predictive capabilities to the END User:**
  • **Created a code (Terrapin RCM Solver 1.0) to make predictions of induced voltages**
  • **Educate the User in the strategy and execution of predictions**

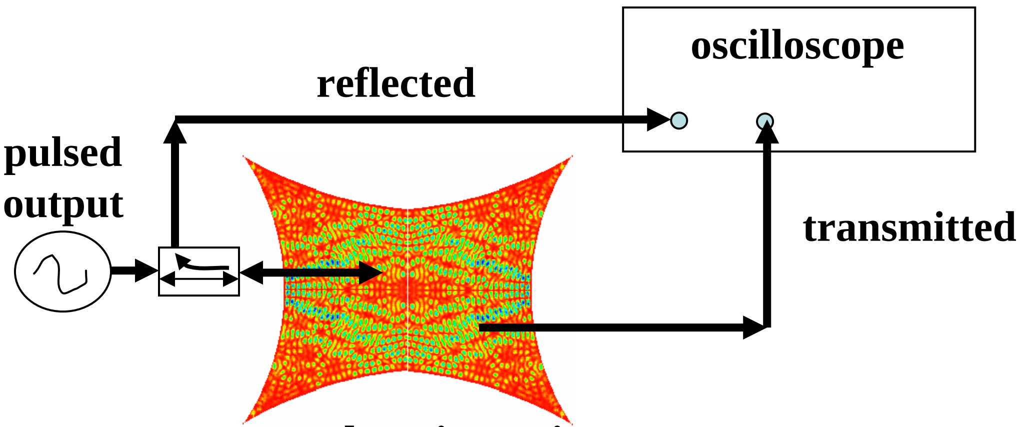
• **Extend RCM to Pulsed Time-Domain Measurements:**
  • **Compelling Theoretical Work – Hart, Antonsen, Ott**
    • **Time-Reversed Attack (see Ed Ott's talk tomorrow!)**
  • **Experimental work is encouraging**

• **Connect RCM to the EM Topology Approach:**
  • **Quantum graphs and chaos on networks**

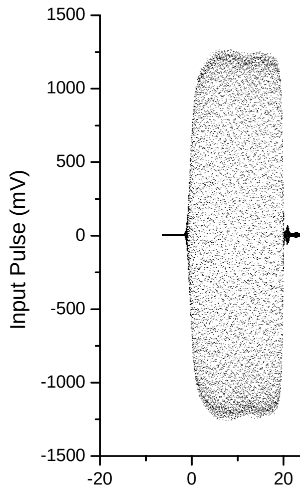


EMC topology **Quantum Graphs**

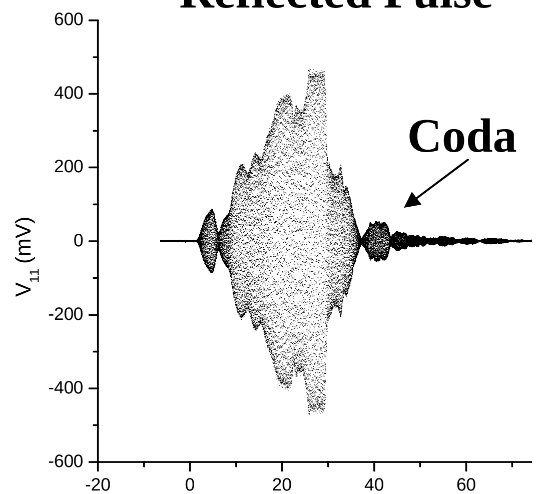
Time Domain Results



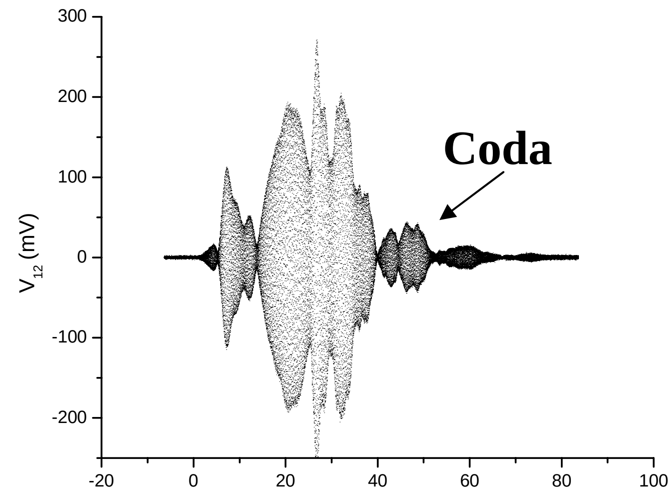
Incident Pulse
10 ns long @ 7.68 GHz



Reflected Pulse



Transmitted Pulse



Time (ns)

Conclusions

We have developed a Random Coupling Model (based on RMT) to make statistical predictions of induced voltages in complicated enclosures

Experimental tests of many basic 1 port and 2-port predictions have confirmed that the approach is correct in 2D and 3D.

Frequency, Volume
Losses
Radiation impedance of the ports

$$\left.\begin{array}{l}\text{Frequency, Volume} \\ \text{Losses}\end{array}\right\} \frac{k^2}{\Delta k^2 Q}$$

Radiation impedance of the ports } Determine the Z, S PDFs

Clear strategies to engineer the PDFs to suit one's purpose

We encourage everyone to try it!

Random Coupling Model User's Guide + Code:

http://www.csr.umd.edu/anlage/RCM/index.htm

anlage@umd.edu