Wave Chaos for CDE Applications
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4/26/2016
Program Vision

Develop ability to predict spatial and temporal distribution of EM energy in complex environments

• Assess risk of EM interference
• Improve electronics designs
• Direct energy in complicated environments
• Detect changes in environments
• Send secure signals

Simple cavity with a) chaotic and b) regular trajectories and associated eigenmodes
Wave Chaos Studies for CDE/UMD/ T. Antonsen

**Objective/Description**
Apply wave chaos concepts to predict and control the distribution of HPM in enclosed spaces

**Payoffs/Key Technologies**
Protect electronics, send secure signals, direct energy.

**Schedule/Milestones**
- FY14 – Complete RCM, nonlinear time reversal on graphs
- FY15 – Transition models to NRL
- FY16 – Develop procedure for melding CEM and RCM

**POC**
T. M. Antonsen Jr, S. Anlage, E. Ott, J. Rodgers

Students: B. Addissie, B. Xiao, A. Farasatul, T.Koch, J-H Yeh, B. Taddesse

Collaborator: G. Gradoni (U. Nottingham)

Institutional Financial POCs: J. Gorski, J. Fields

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- Nonlinear reconstruction at nonlinear element
Maryland Team - Faculty

- Wave Chaos and EMC (ONR, AFOSR)
- Electronic Devices (AFOSR)
- Optoelectronics (ONR, AFOSR)

Steve Anlage  Tom Antonsen  Neil Goldsman
Ed Ott  John Rodgers (NRL, UMD)  Edo Waks
Students and Post-docs

• Present Students
  Wave Chaos (ONR)

• Recent Post-docs
  Gabriele Gradoni,
  U. Nottingham, UK

Bo Xiao  Trystan Koch  Bisrat Addissie
Faranstul Adnan  KeMa  Ziyuan Fu
Min Zhou  Alan Liu
# Program Recognition / Accomplishment

<table>
<thead>
<tr>
<th>Program</th>
<th>Performer/Organization</th>
<th>Researcher</th>
<th>Description of Award / Recognition</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Antonsen, Thomas</td>
<td>2016 IEEE John R. Pierce Award for excellence in vacuum electronics</td>
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<tr>
<td></td>
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<td>Gradoni, Gabriele</td>
<td>Elected international Early Career Representative (ECR) of Commission E, URSI, for the triennium 2014-2017</td>
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<td>Gradoni, Gabriele</td>
<td>Secured faculty position at University of Nottingham</td>
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## Scorecard for FY 2015

<table>
<thead>
<tr>
<th>Program</th>
<th>Total # for Program</th>
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<tbody>
<tr>
<td>Conference Papers</td>
<td>2</td>
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<tr>
<td>Journal Articles</td>
<td>2</td>
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<tr>
<td>Students Supported</td>
<td>3</td>
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<tr>
<td>Degrees Granted</td>
<td>0</td>
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<tr>
<td>Patents Awarded</td>
<td>0 Distribution (see cover slide)</td>
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UMD Wave Chaos / HPM Efforts

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<thead>
<tr>
<th>FY13</th>
<th>FY14</th>
<th>FY15</th>
<th>FY16</th>
<th>FY17</th>
<th>FY18</th>
<th>FY19</th>
<th>FY20</th>
<th>FY21</th>
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<td>Wave Chaos Studies for CDE Applications</td>
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<td>HPM Resistant Optical Interconnects for Robust Integrated Electronics (Waks)</td>
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<td>HPM Effects: Electromagnetic Coupling to Enclosures (Anlage)</td>
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<td>Coming Soon</td>
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<td>AFOSR Center of Excellence with UNM</td>
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<td>Telecom Italia - travel</td>
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ONR

Coming Soon

Joint Program with University of Nottingham
Propagating electromagnetic signals through complex built-up structures – Resilience of electronic components in the presence of EM noise and environmental uncertainty
2015 Progress

- Statistics of Voltages on Networks
- Departures from RCM Theory
- Measuring RCM parameters
- Irradiation of Cavities through Apertures
What is Wave Chaos?

– Wave propagation - linear phenomena
– (response is linearly proportional to excitation)
– Therefore - not chaotic
– In complex geometries field distribution are highly sensitive to: frequency and/or small perturbations
– Classical rays are chaotic - this affects the field solutions
– Statistical Properties Governed by Random Matrix Theory (RMT)

– Two incident rays with slightly different initial directions have rapidly diverging trajectories
Statistical Model of Z Matrix

The Random Coupling Model

Free-space radiation Resistance $R_R(\omega)$
$Z_R(\omega) = R_R(\omega) + jX_R(\omega)$

Losses

Other ports

Port 1

Port 2

$R_{R1}(\omega)$

$R_{R2}(\omega)$

$\omega_n$ - random spectrum
$w_{in}$- Guassian Random variables

Radiation Resistance $R_{Ri}(\omega)$

$\Delta\omega^2$ - mean spectral spacing

$Q$ -quality factor

$\Delta\omega^2 = \frac{\omega_{m}}{\sqrt{\sum_n \frac{w_n^2}{2}}} - \omega^2$
Statistics of Fields in Circuits

Quantum Graphs
Random Matrix Theory


Electromagnetic Topology
BLT Equations

Distribution of electromagnetic wave energy on networks, Tystan Koch and Ziyuan Fu
From Network to Graph

Electromagnetic topology is what matters.
Graph Scattering and Impedance

To model a transmission line network in a larger circuit, we add ports and examine the external scattering matrix.

We can write this as a function of the network's internal transmission and scattering properties.

\[ \vec{a}_{\text{in}} = T(k) \vec{a}_{\text{out}} \]
\[ \vec{a}_{\text{out}} = S \vec{a}_{\text{in}} \]

Since the impedance of the network is a function of the scattering, we have a closed-form expression for the impedance of a complicated network.

This allows us to examine the impedance and admittance matrices theoretically.
Experimental Scattering and Impedance

As expected, average resonance spacing is approximately frequency independent. Slight increase in resonance spacing attributed to frequency-dependent losses. Numerical examination of missing modes is ongoing.

\[ Z = \frac{R_{\text{net}} + i (X_{\text{net}} - X_{\text{rad}})}{R_{\text{rad}}} \]

Normalized by the radiation impedance at the calibration point.
Theoretical Scattering and Impedance

Impedance and scattering parameter calculated for a tetrahedral network.
Alternate Spacing Statistics

$s = \text{difference in adjacent frequencies}$

$P(s) \approx s^p$

Ensembles

$p=0$ Poisson
$p=1$ Gaussian Orthogonal
$p=2$ Gaussian Unitary
$p=3$ Gaussian Symplectic
1. Low Frequency: UG Student Alan Liu is measuring uniformity in phase of reflection coefficient.

2. Mixed Systems: Students Ke Ma and Bisrat Addissie are studying systems with both chaotic and nonchaotic orbits.

3. Direct orbits: Short orbits from transmitter to receiver studied by Bisratt Addissie
Lab Scale Measurements

Port 1 connected to radiating helical Antenna

2 Port Vector Network Analyzer

-Cylindrical Enclosure with scattering aluminum sheet suspended in the center, attached to a rotating rod

-Port 2 connected to circuit board loop trace antenna
Statistics of fields in systems with both regular and chaotic ray trajectories
Mixed Systems-phase space

- Boundary composed of four arcs
- Trajectory coordinates – s, \( \cos \theta \)
- Interlaced regular and chaotic regions, generic

Currently investigating properties of impedance
Mushroom Mixed System

- Trajectories and eigenfunctions
- Chaotic and regular regions of phase space well separated. Not generic.
- Statistics of impedance: mixture of regular and chaotic eigenfunction responses.
Experimental Effort

Quasi – 2D cavity
Short Orbit Modified RCM

J. Hart et al., PHYSICAL REVIEW E 80, 041109 (2009)

Original RCM:

$$Z_{cav} = j \text{Im}(Z_{rad}) + [R_{rad}]^{1/2} \cdot \xi \cdot [R_{rad}]^{1/2}$$

Modified RCM:

$$Z_{cav} = j \text{Im}(Z_{ave}) + [R_{ave}]^{1/2} \cdot \xi \cdot [R_{ave}]^{1/2}$$

Calculated in geometric optics limit:

$$Z_{ave} = j \text{Im}(Z_{rad}) + [R_{rad}]^{1/2} \cdot \xi \cdot [R_{rad}]^{1/2}$$

$$\left(\xi\right)_{mn} = \sum_{\text{ray paths} - b}^{\text{ray paths} - b} p_{b, mn} C_{b, mn} \exp[-jS_{b, mn}(\omega) - j\pi / 4]$$

–Direct orbits lead to Rician Statistics
In terms of $S_{21}$

- Weak Direct Coupling
- Strong Direct Coupling

- $|S_{21}|$ has Rayleigh distribution (left, $K<<1$) and Rician distribution (right, $K\approx1$)

Lab Scale Measurements

Port 1 connected to radiating helical Antenna

2 Port Vector Network Analyzer

–Cylindrical Enclosure with scattering aluminum sheet suspended in the center, attached to a rotating rod

–Port 2 connected to circuit board loop trace antenna
Time Gating Method (TGM) – Determining Alpha

- The impulse response is analyzed to determine the composite decay rate from which $\alpha$ can be determined.
- In real-world cavities, the short orbits scatter at a rate due to non-ideal EM boundaries.
Measuring the Loss Parameter

- Objective: Using a single VNA measurement to compute the loss parameter $\alpha$

\[
\alpha = \frac{k^2}{\Delta k^2 Q}
\]

Reference wavenumber, $k = \frac{2\pi}{c} f$

Quality factor, $Q = 2\pi f \tau$
Where $\tau$ is time constant for energy decay in the cavity

Mean spacing between adjacent eigenvalues, $\Delta k^2 = \langle k_n^2 - k_{n-1}^2 \rangle$ is approximated by Weyl formula as $\frac{2\pi^2}{kV}$

Can we measure $\Delta k^2$ from $S_{11}$ measurement?
Finding $\Delta k^2$ from measurement

- **Stainless Steel Cylindrical Chamber**
- **Volume:** 1.92m$^3$
- **Quality Factor:** 40500

- **Antenna:** X-Band Standard Gain Horn Antenna
- **Frequency Range:** 9.5GHz – 11GHz
Overlapping Modes

Measurement

Identify Minima

Compute $\Delta k^2$

\[
\Delta f^2 = \langle f_{n+1}^2 - f_n^2 \rangle
\]

\[
\Delta k^2 = \Delta f^2 \left(\frac{2\pi}{c}\right)^2
\]

\[
\Delta k^2 \text{ (Weyl)} = \frac{2\pi^2}{kV} = 0.0479
\]

\[
\Delta k^2 \text{ (Counting)} = 4.45
\]
Exponential Amplification

$\Delta k^2 (\text{Exp. Amp.}) = 1.23$
Harmonic Inversion

• $S_{11}$ as superposition of Lorentzians.

$$S(f) = 1 - \sum_n \frac{a_n}{f - f_n + i\gamma_n}$$

$\Delta k^2$ (Harmonic Inversion) = 0.49

Jan Wiersig and Jörg Main, Phys. Rev. E 77, 036205  March 2008
• Alternative method is to compare pdf of $\xi$ and measured normalized impedance
  – Find $\alpha$ that minimizes the Mean Squared Error $= \text{mean}((\text{PDF}_R - \text{PDF}_{\text{Re}\{\xi(\alpha)\}})^2)$

• Example

<table>
<thead>
<tr>
<th>Port</th>
<th>$\alpha_{\text{Weyl}} = k^3 V / (2\pi^2 Q)$</th>
<th>Best Fit $\alpha$</th>
<th>Min(MSE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper Loop</td>
<td>24.6</td>
<td>23.7</td>
<td>7.7E-4</td>
</tr>
</tbody>
</table>
Statistics of voltages on circuit elements in cavities irradiated through apertures

What can one say without solving the full problem computationally?

Power enters cavity through aperture,

Distributes itself throughout,

Induces voltage on the terminals of an antenna.
Statement of Random Coupling Model (RCM)

– Cavity admittance:

\[
Y_{cav} = i \text{Im}(Y_{rad}) + \left[ \text{Re}(Y_{rad}) \right]^{1/2} \cdot \xi \cdot \left[ \text{Re}(Y_{rad}) \right]^{1/2}
\]

– Universal part: random normalized admittance

– System specific part:

– un-backed aperture admittance

– Find admittance matrix describing \( z>0 \)

\( Y_{ss'}(k_0 = \omega / c) = \sqrt{\frac{\varepsilon}{\mu}} \int \frac{d^3k}{(2\pi)^3} \frac{2i k_0}{k_0^2 - k^2} \bar{e}_s \cdot \Delta_2 \cdot \bar{e}_{s'} \)

\( E_t = \sum_s V_s e_s(x_\perp) \)

\( H_t = -\sum_s I_s n \times e_s(x_\perp) \)

\( I_s = \sum_{s'} Y_{ss'}(k_0) V_{s'} \)
Net power transmitted by an aperture $A = 0.25 \text{ m by } 0.02 \text{ m}$ in free space, for an external plane wave of $h_{\text{inc}} = 1 \text{ mA/m}$. ($I \cos \theta A = 0.66 \times 10^{-6} \text{ W}$)
Power Coupled to a Cavity

- Frequency

Net Transmitted Power [W]

Moderate Loss

Low Loss

Real Net Power [W]

800 realizations, 600 cavity modes,
\( \Delta f = 10 \text{ MHz}, \alpha = 1.0 \)

\( P_{ \text{rad} } \)

\( P_{ \text{avg} } \)

\( \langle P_{ \text{cav} } \rangle \)

800 realizations, 600 cavity modes,
\( \Delta f = 10 \text{ MHz}, \alpha = 0.1 \)

\( P_{ \text{rad} } \)

\( P_{ \text{avg} } \)

\( \langle P_{ \text{cav} } \rangle \)
Terminal power in the Gigabox

Z. Drikas, J. Gil Gil (NRL), G. Gradoni

$\theta = 0$

$-\frac{\pi}{4} \leq \varphi \leq \frac{\pi}{4}$

$\varphi = \frac{\pi}{4}$

$\varphi = -\frac{\pi}{4}$

$P_{T,\text{ant}} \sim 16 \; -\text{dBm}$

$P_{L,\theta,\varphi} = \left\langle P_L(\text{pos, freq}) \right\rangle_{\text{pos}}_{\text{freq}}$

$\sim 1.2 - 1.7 \text{dB diff}$

$\theta = 0$
Combining RCM with Computational EM

w/Zhen Peng UNM still underway

Must choose a surface where matching of three solutions can be made.

\[ (Y^> + Y^<) \cdot V = 2I^{\text{inc}} \]

RCM Prescription

\[ Y^{cav} = i \text{Im}(Y^{rad}) + [G^{rad}]^{1/2} \cdot \xi \cdot [G^{rad}]^{1/2} \]
Transition Details

• Future Transitions
  – Procedures to measure RCM parameters can be transferred to NRL and other DoD labs. Will allow for characterization of structures with unknown contents/dimensions (1 year for B. Addissie to complete PhD.)
  – Combining RCM with CEM (Zhen Peng UNM) will provide a tool for computing system specific parameters for RCM (2-3 years) CEM Tool transitioned to NRL and DoD users.

• NRL: TEW group, Jesus Gil, Zack Drikas, T. Andreadis

• John Rodgers now at NRL
Proposed Efforts FY17 and Beyond

–New Ideas / Opportunities

• See next presentation by S. Anlage
Upcoming Major Activities

• AFOSR Center of Excellence: Science of Electronics in Extreme Environments

• UNM/UMD collaboration
  – Field Coupling
  – Circuits
  – Devices
  – First Year Review, June 15, 2016 College Park, MD

• Joint Program with U. Nottingham DEA and RCM

• STTR with XL corporation

• NSF proposal with Zhen Peng
A Statistical Model for the Excitation of Cavities Through Apertures
By: Gradoni, G; Antonsen, TM; Anlage, SM; Ott, E, IEEE TRANSACTIONS ON ELECTROMAGNETIC COMPATIBILITY, Volume: 57 Issue: 5 Pages: 1049-1061, DOI: 10.1109/TEMC.2015.2421346, Published: OCT 2015

Random coupling model for the radiation of irregular apertures
By: Gradoni, G; Antonsen, TM; Ott, E, RADIO SCIENCE, Volume: 50 Issue: 7 Pages: 678-687, DOI: 10.1002/2014RS005577, Published: JUL 2015
Conference Proceedings & Presentations


Conference presentations

• Antonsen, Gradoni, Anlage, and Ott, Statistical model for coupling EM energy through apertures, AMERAEM 2014, Albuquerque NM.
Program Success Stories

• Collaboration with TEW group at NRL

• Graduated PH D Students
  – Jen Hao Yeh Laboratory for Physical Sciences
  – Bini Tadesse Intel
Status Update on FY16 Funding

• Grant funds were exhausted on 2/29/16
Back-up
To be filled in but not presented