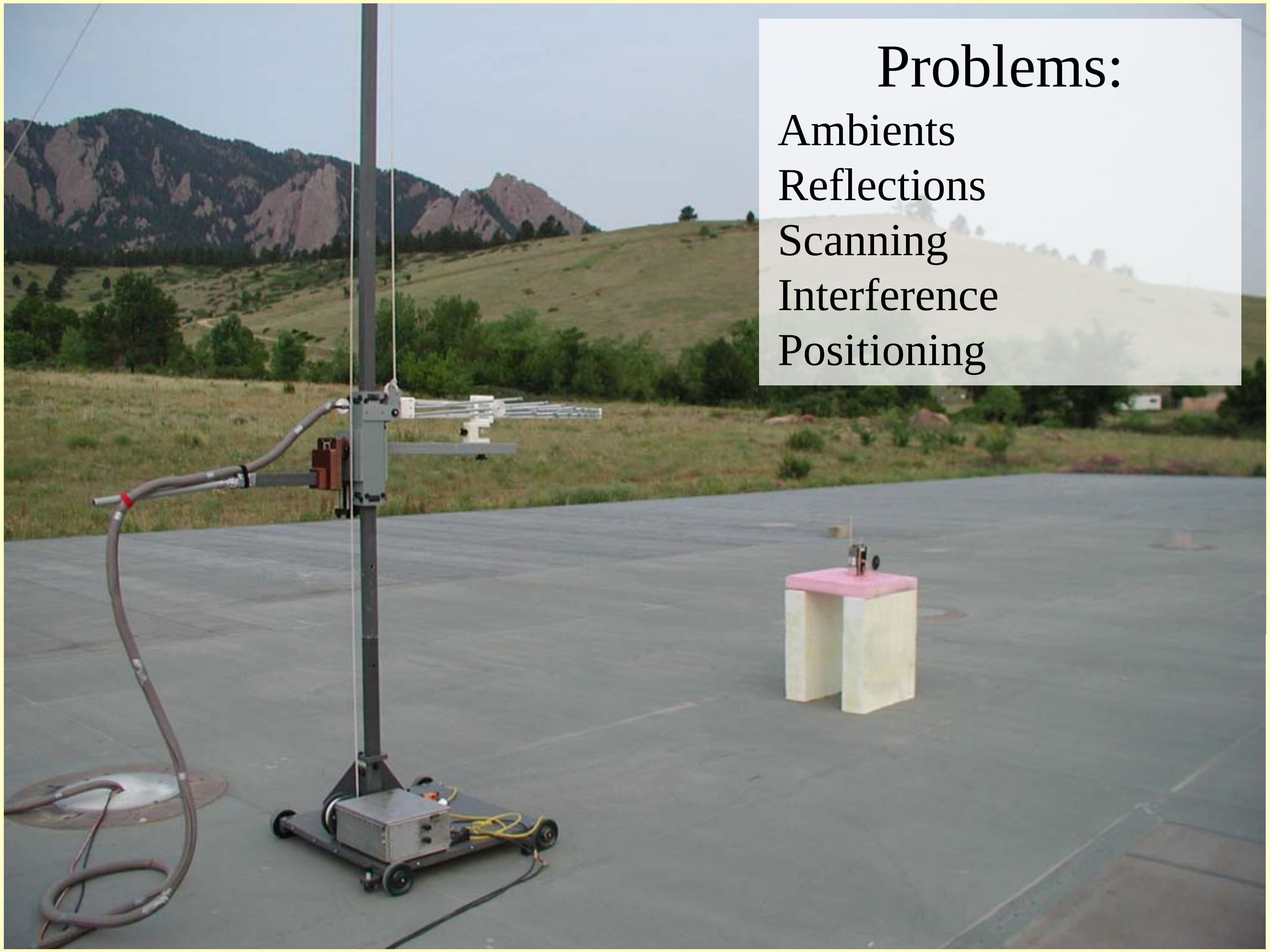
Reverberation Chambers for EM Applications

Christopher L. Holloway
John Ladbury, Galen Koepke, and Dave Hill
National Institute of Standards and Technology
Electromagnetics Division
Boulder, Colorado
303-497-6184, email: holloway@boulder.nist.gov

OPEN AREA TEST SITES (OATS)



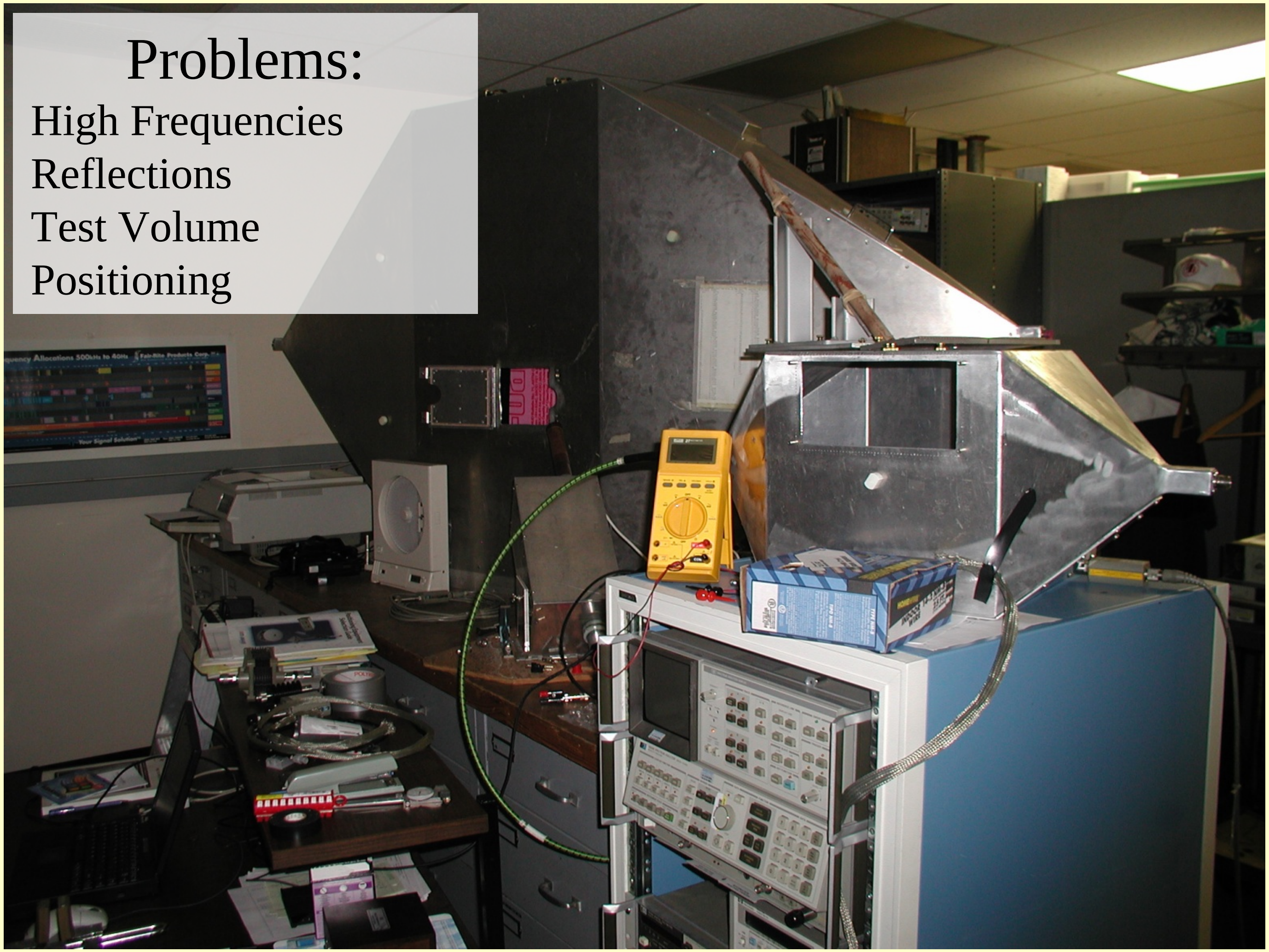
Problems:

Ambients
Reflections
Scanning
Interference
Positioning

TEM

Problems:

High Frequencies
Reflections
Test Volume
Positioning



GTEM

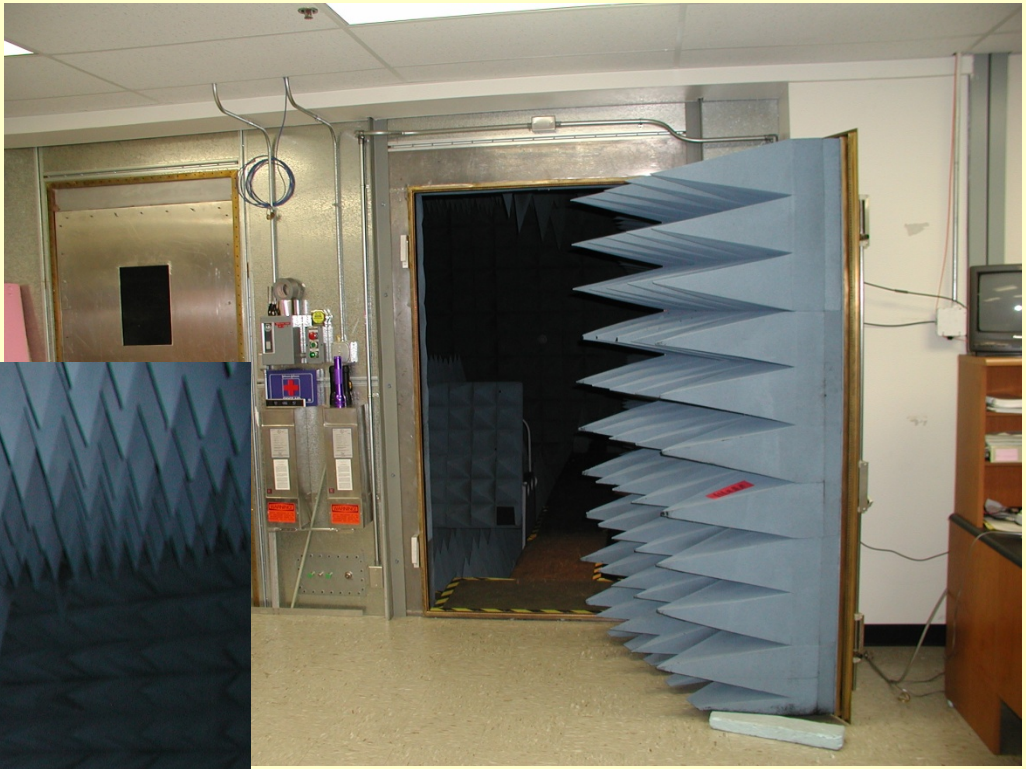
Problems:

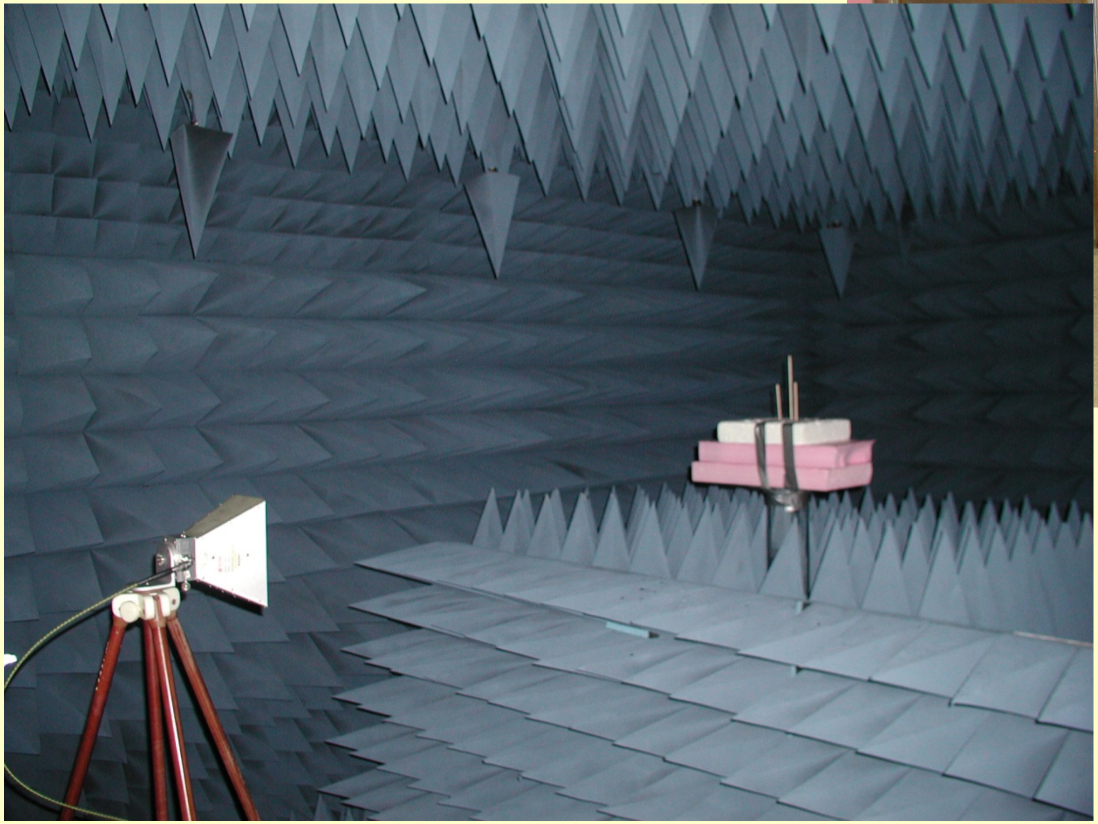
Test Volume
Uniformity Along Cell
Positioning

ANECHOIC CHAMBER

Problems:

Low Frequencies
Reflections
Positioning





REVERBERATION CHAMBER

Why use reverberation chamber?

The Classical OATS Measurements

The classic emissions test and standard limits (i.e, testing a product above a ground plane at a specified antenna separation and height) have their origins in interference problems with TV reception.

Emissions Test Standard Problem

One problem with the emissions test standard is that it is based on an interference paradigm (interference to terrestrial broadcast TV) that is, in general, no longer valid nor realistic today. *In a recent report, the FCC indicated that 85 % of US households receive their TV service from either cable, direct broadcast satellite (DBS), or other multichannel video programming distribution service, and that only a small fraction of US households receive their TV via direct terrestrial broadcast.*

Coupling to TV antennas designed to receive terrestrial broadcast may no longer be an issue.

EMC Environment Today

- In recent years, a proliferation of communication devices that are subject to interference have been introduced into the marketplace.

- Today, cell phones and pagers are used in confined offices containing personal computers (PCs). Many different products containing microprocessors (e.g., TVs, VCRs, PCs, microwave ovens, cell phones, etc.) may be operating in the same room.

- Different electronic products may also be operating within metallic enclosures (e.g., cars and airplanes). The walls, ceiling, and floor of an office, a room, a car, or an airplane may or may not be highly conducting.

- Hence, emissions from electric devices in these types of enclosures will likely be quite different from emissions at an OATS. In fact, the environment may more likely behave as either a reverberation chamber or a free space environment.

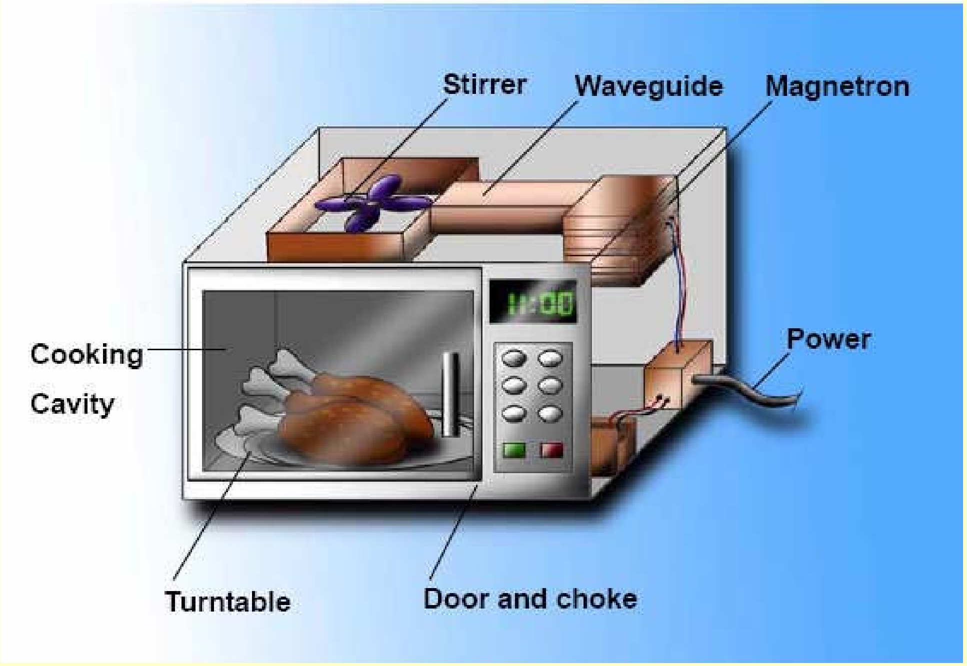
Where Should We Test?

- Thus, would it not be better to perform tests more appropriate to today's electromagnetic environment?

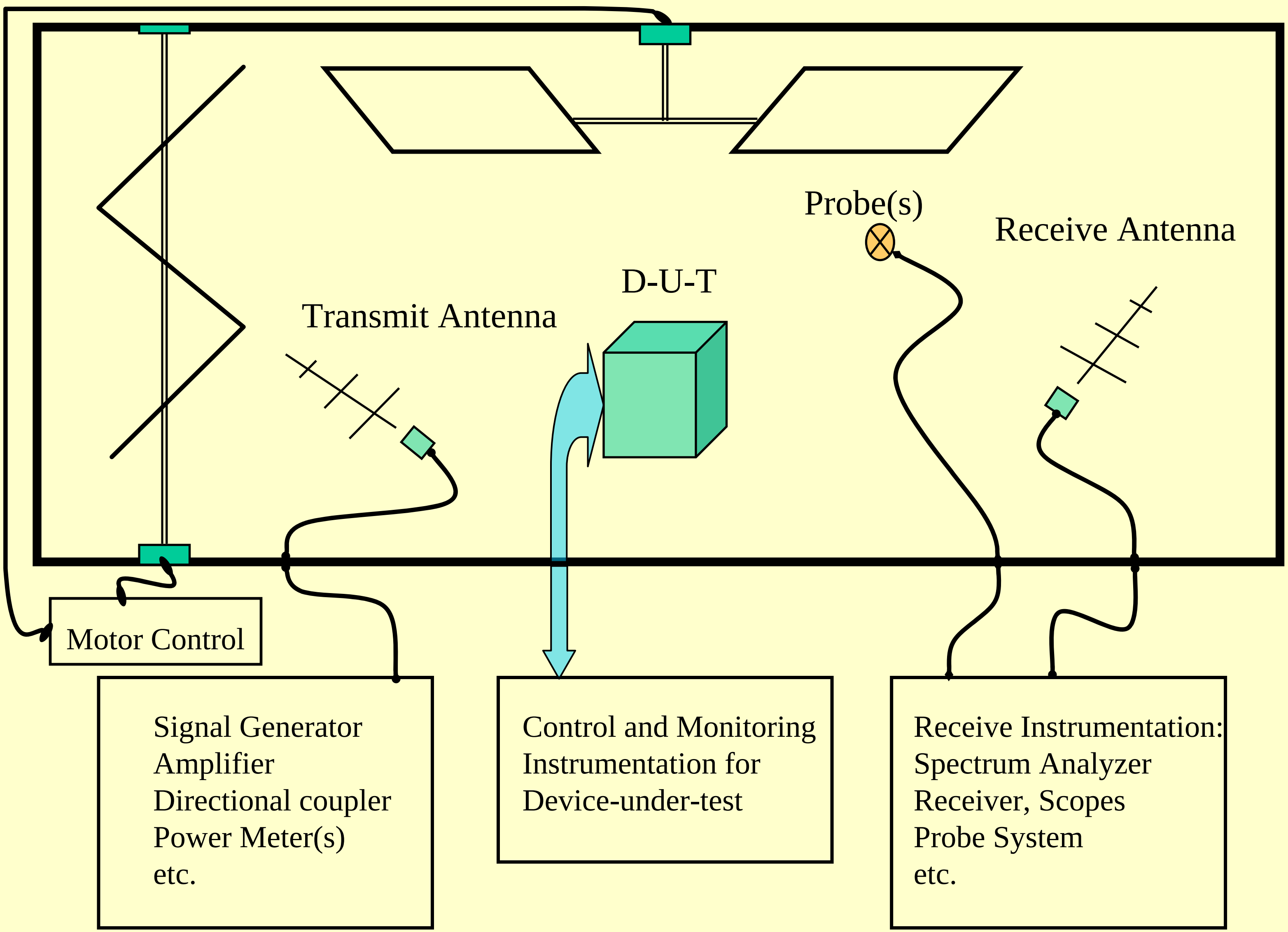
- Tests should be Shielded, Repeatable, Simple, Inexpensive, Fast, Thorough, …

Commercial Solutions…

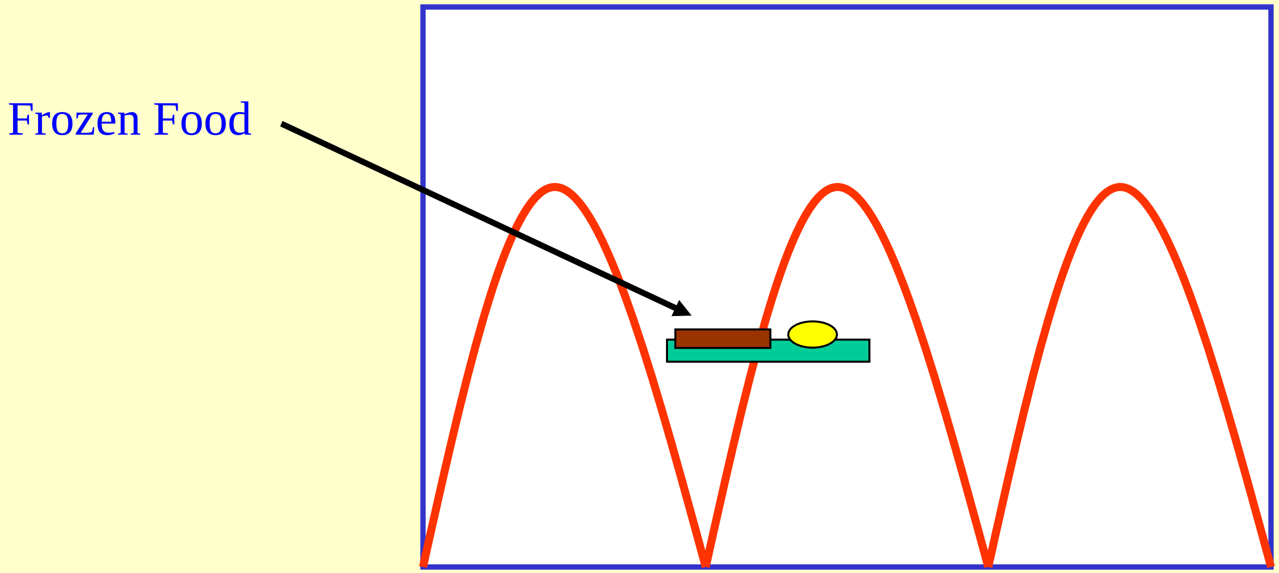
- Stirrer
- Turntable



Reverberation Chamber



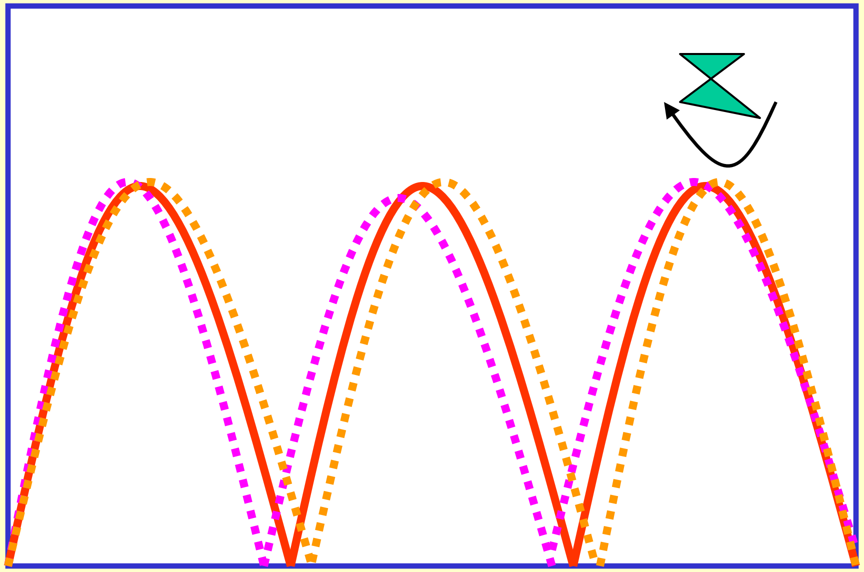
Fields in a Metal Box (A Shielded Room)



•In a metal box, the fields have well defined modal field distributions.

Locations in the chamber with very high field values
Locations in the chamber with very low field values

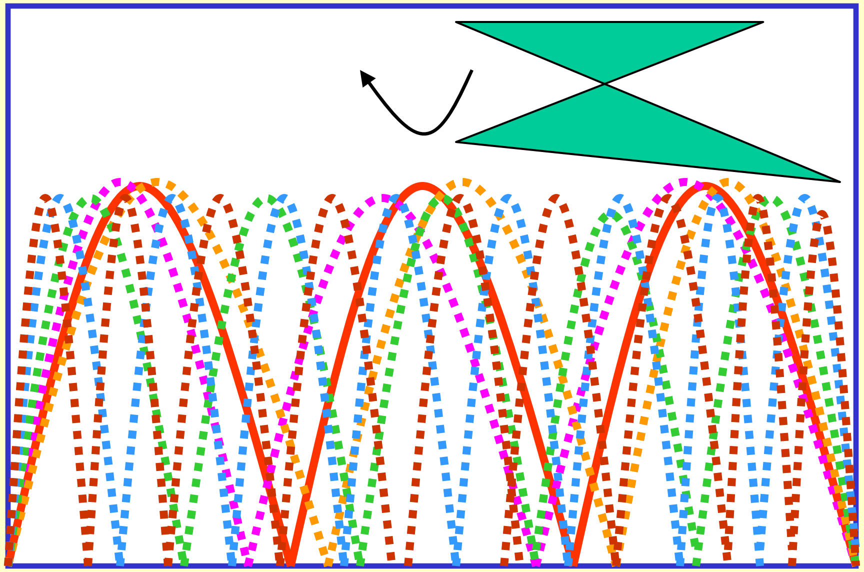
Fields in a Metal Box with Small Scatterer



In a metal box, the fields have well defined modal field distributions.

Small changes in locations where very high field values occur
Small changes in locations where very low field values occur

Fields in a Metal Box with Large Scatterer (Paddle)



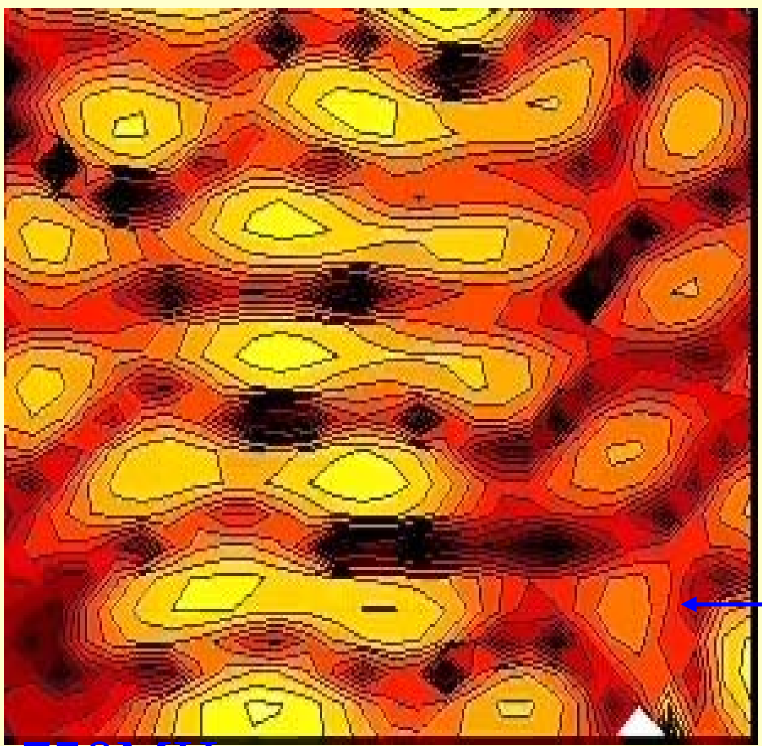
Large changes in locations where very high field values occur

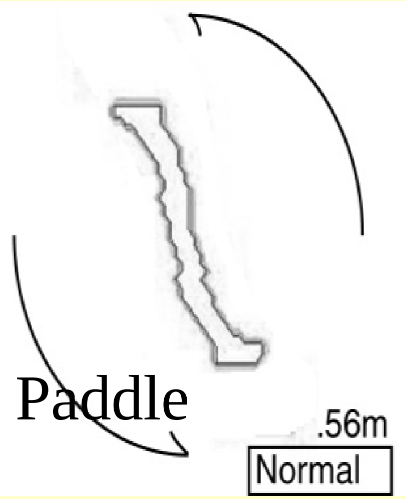
Large changes in locations where very low field values occur

In fact, after one fan rotation, all locations in the chamber will have the same maxima and minima fields.

Stirring Method

TIME DOMAIN

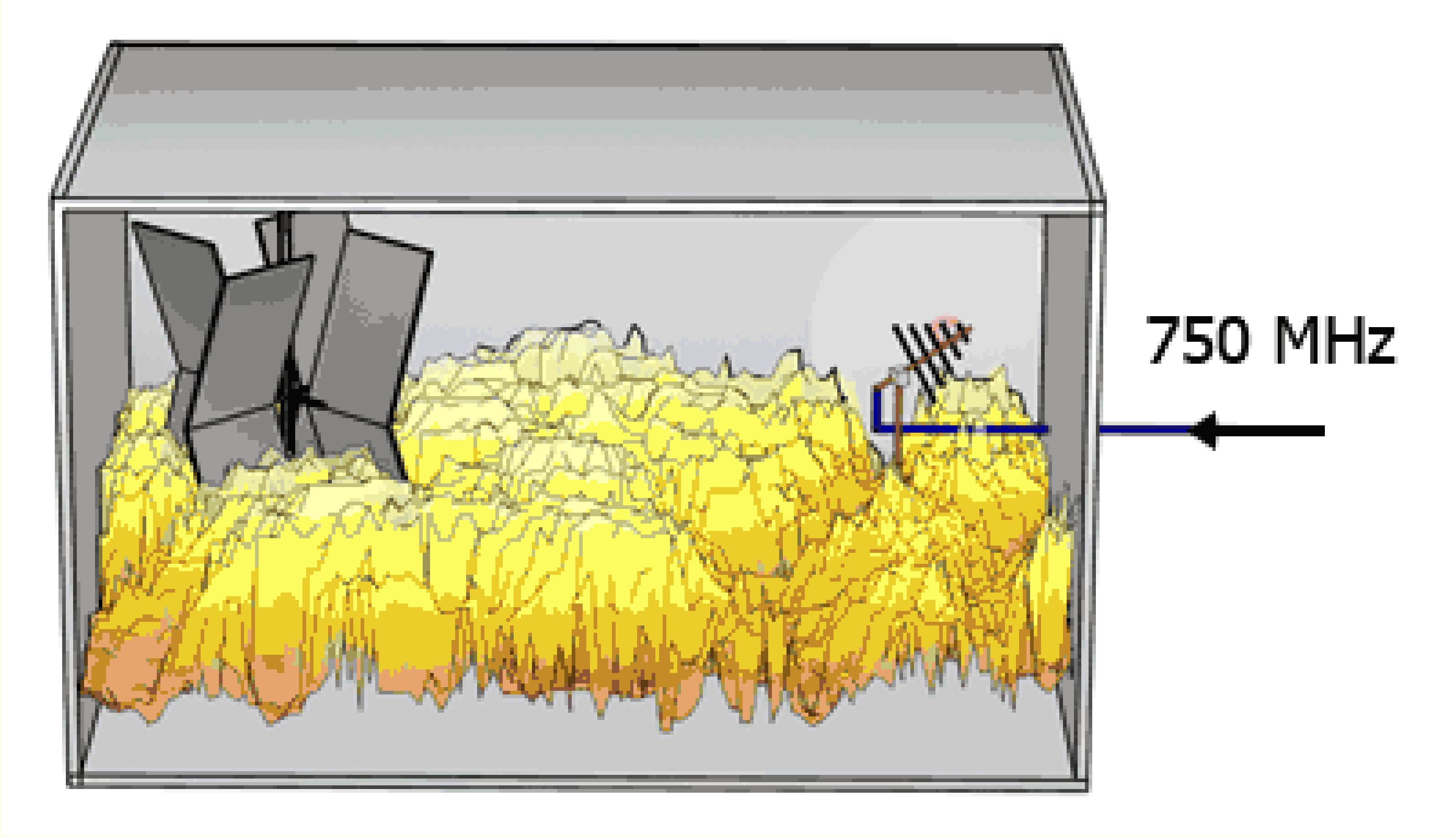




Click to play paddle rotation

750MHz

Field Variations with Rotating Stirrer



Reverberation Chamber: All Shape and Sizes

Small Chamber

Large Chamber

Moving walls

Reverberation Chamber with Moving Wall

Original Applications

- ***Radated Immunity***
  - components
  - large systems
- ***Radiated Emissions***
- ***Shielding***
  - cables
  - connectors
  - materials
- ***Antenna efficiency***
- ***Calibrate rf probes***
- ***RF/MW Spectrograph***
  - absorption properties
- ***Material heating***
- ***Biological effects***
- ***Conductivity and material properties***

Wireless Applications

- Radiated power of mobile phones
- Gain obtained by using diversity antennas in fading environments
- Antenna efficiency measurements
- Measurements on multiple-input multiple-output (MIMO) systems
- Emulated channel testing in Rayleigh multipath environments
- Emulated channel testing in Rician multipath environments
- Measurements of receiver sensitivity of mobile terminals
- Investigating biological effects of cell-phone base-station RF exposure

Fundamentals

- *A Reverberation Chamber is an electrically large, multi-moded, high-Q (reflective) cavity or room.*
- *Electromagnetic theory using mode or plane-wave integral techniques provides several cavity field properties (mode density, Q and losses, E^2, etc.)*
- *Changing boundary conditions, antenna or probe location, or frequency will introduce a new cavity environment to measure (sample)*
- *The composite effects of multiple cavity electromagnetic environments are best described by statistical models*

Sampling Considerations

- ***How many samples do we need****?*
  - time / budget constraints
  - acceptable uncertainties
  - standards may dictate
- ***Sampling rates may not be identical***
  - equipment-under-test
  - instrumentation
  - probes
- ***How long to dwell at each sample****?*

Sampling Considerations

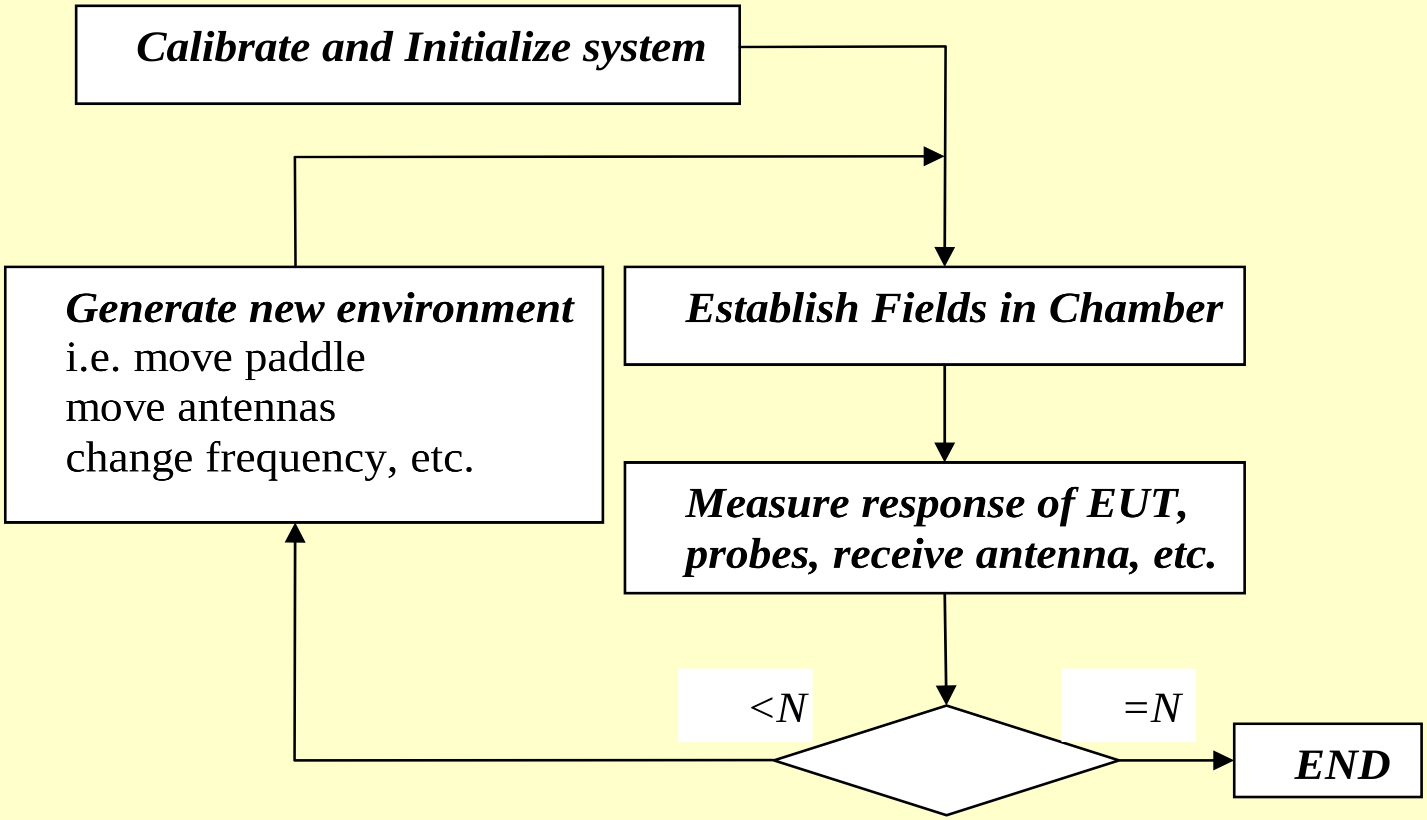
- ***How are samples generated****?*
  - change boundary conditions
  - change device-under-test and antenna locations
  - change frequency (bandwidth limits)
- ***Samples must be independent***
  - Changes are 'large enough'
- ***Measurement time proportional to number of samples*** *(time = $$)*

Sampling Considerations

Techniques to Generate Samples

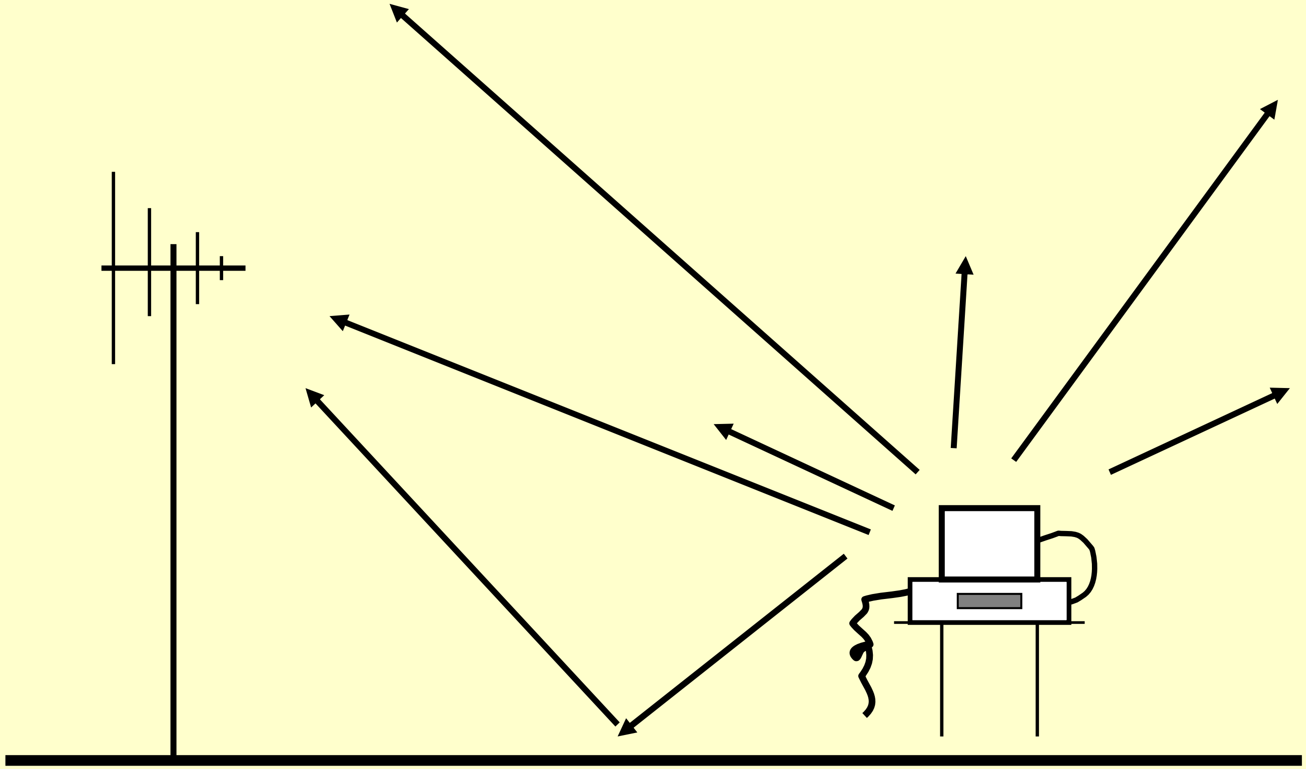
- ***Mechanical techniques***
  - Paddle(s) or Tuner(s)
    - stepped (tuned)
    - continuous (stirred)
  - Device-under-test and antenna position
  - Moving walls (conductive fabric, etc.)
- ***Electrical techniques*** *(immunity tests)*
  - Frequency stirring
    - stepped or swept
    - random (noise modulation)
- ***Hybrid techniques***

Measurement Procedures

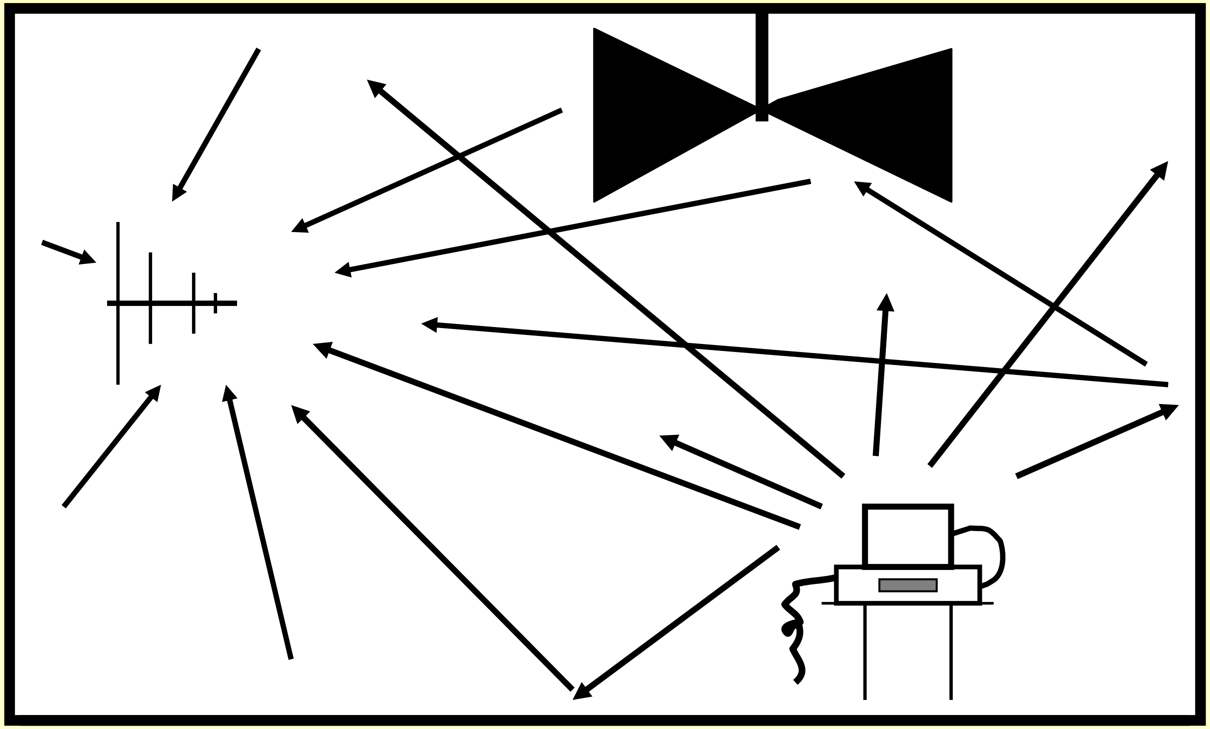


EM Applications

HIDING Emission Problems



YOU CANNOT HIDE IN
Reverberation Chamber



In reverberation chambers you cannot hide emission problems.

Reverberation chambers will find problems.

Unethical Practices

- *The current measurement methodologies of a product can easily miss radiation problem of a products.*
- That is, energy propagation in a direction that a received antenna would miss.
- Not to suggest that companies would be unethical, but we have been told the individuals have setup products for emission measurements in such a manner to ensure that emission problems would not be detected.

Unethical Practices

- Secondly, not to suggest companies are unethical once can, but we have also been told that some individual have lists of OATS around the world with their corresponding ambient noise sources.

- Thus, if one had a product that has an emission problem at frequency “x”, and it is known that one particular OATS at some site in the world as a ambient noise problem at the same frequency “x”, then a product could be tested and possible certified on the OATS, in which the product emission problems would not showing up.

One Possible Solution

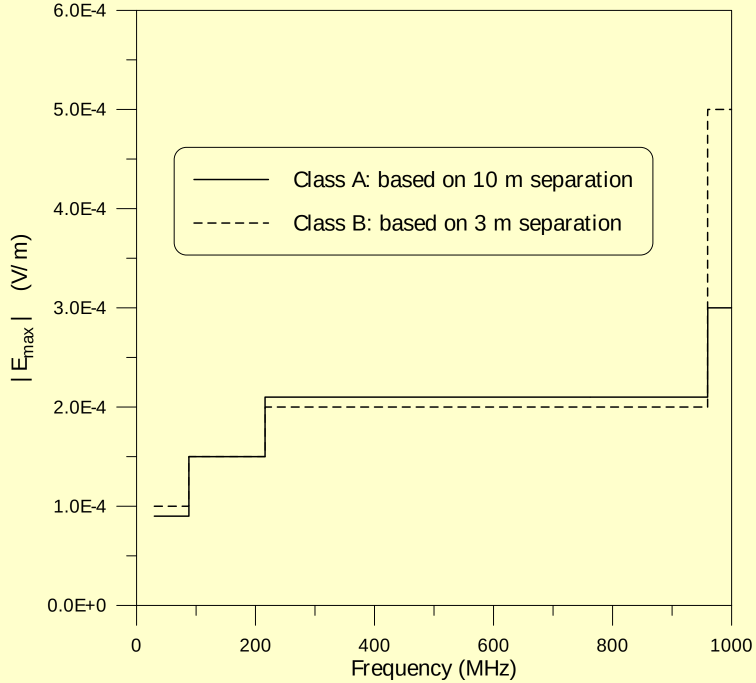
- These two possible ways of hiding emission problems cannot be accomplished in a reverberation chamber.
- In reverberation chambers you <u>cannot hide</u> emission problems.
- Reverberation chambers will find problems.
- If reverberation chambers are to be used, new standards are needed.

EMISSION LIMITS

•Devices and/or products are tested for emissions to ensure that electromagnetic field strengths emitted by the device and/or product are below a maximum specified electric (E) field strength over the frequency range of 30 MHz to 1 GHz.

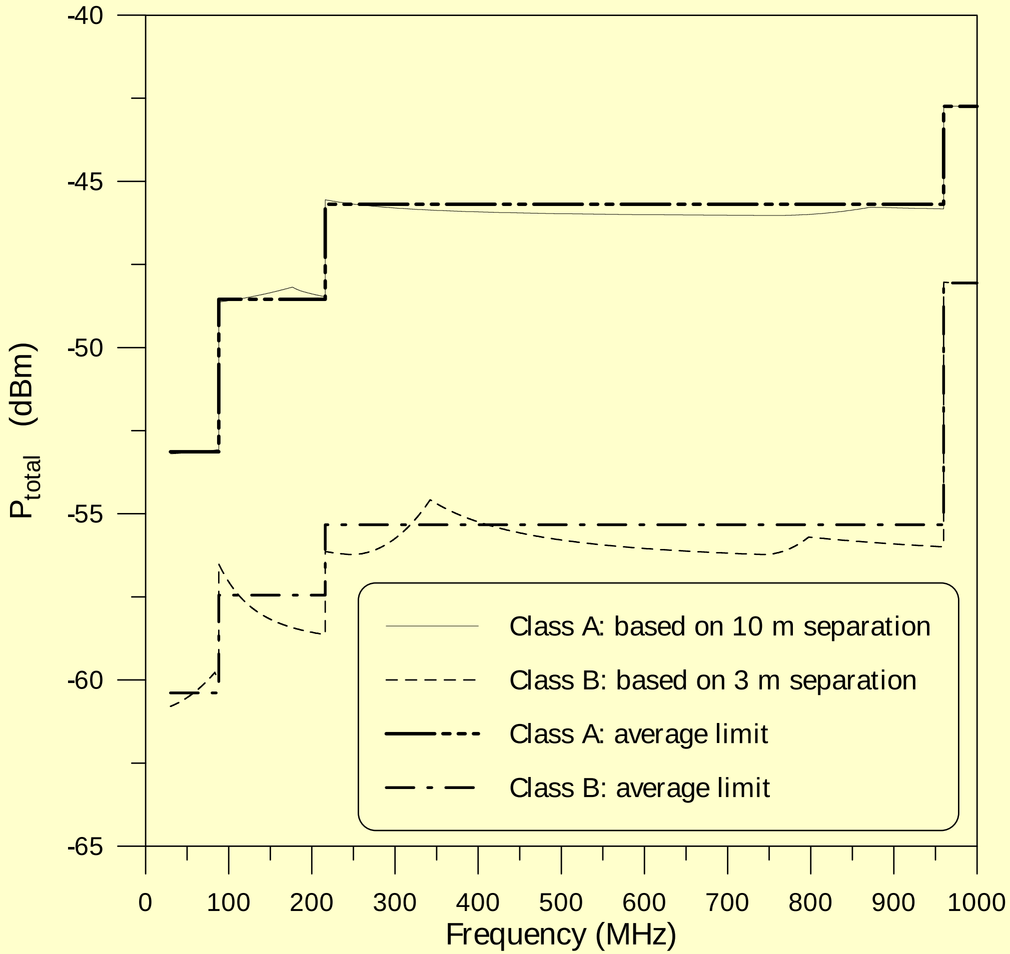
•These products are tested either on an open area test site (OATS) or in a semi-anechoic chamber.

•Products are tested for either Class A (commercial electronics) or Class B (consumer electronics) limits, Class A equipment have protection limits at 10 m, and Class B equipment have protection limits at 3 m.



Total Radiated Power for Reverberation Chambers

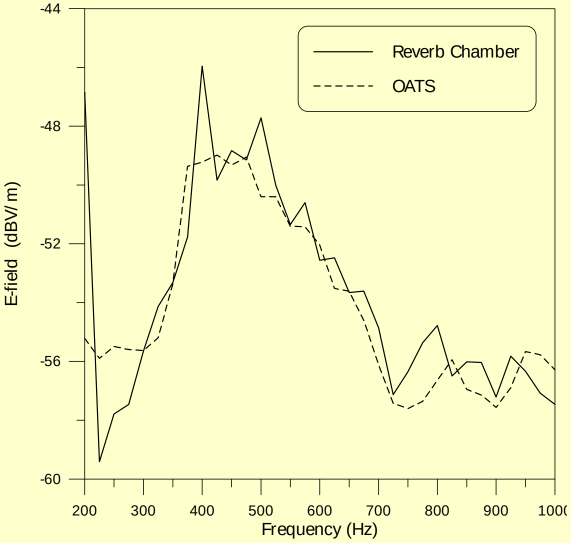
Holloway et al., IEEE EMC Symposium

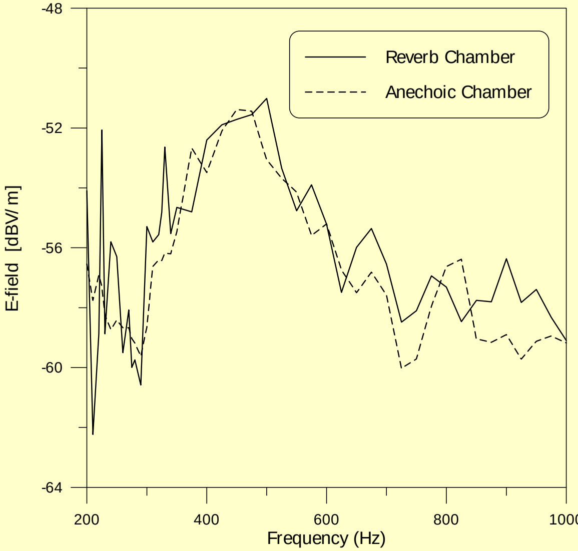


Emission Measurements

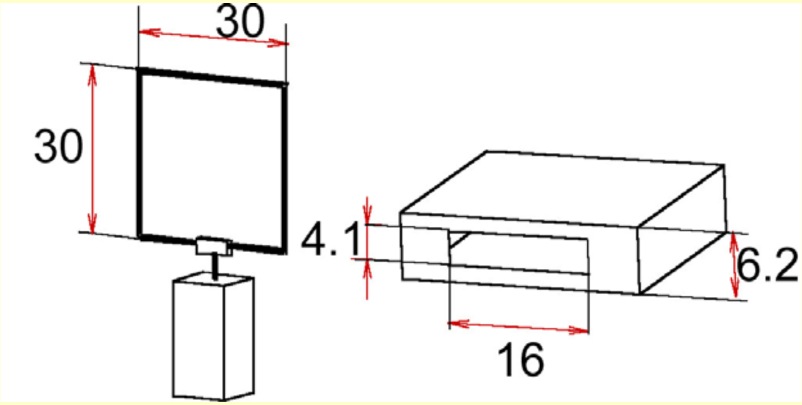
Relate total radiated power in reverberation chambers to measurements made on OATS with dipole correlation algorithms.

Spherical Dipole

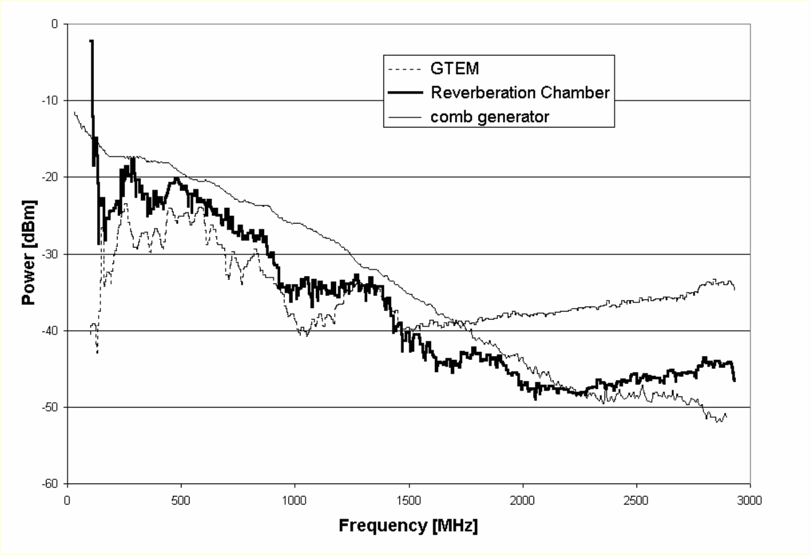




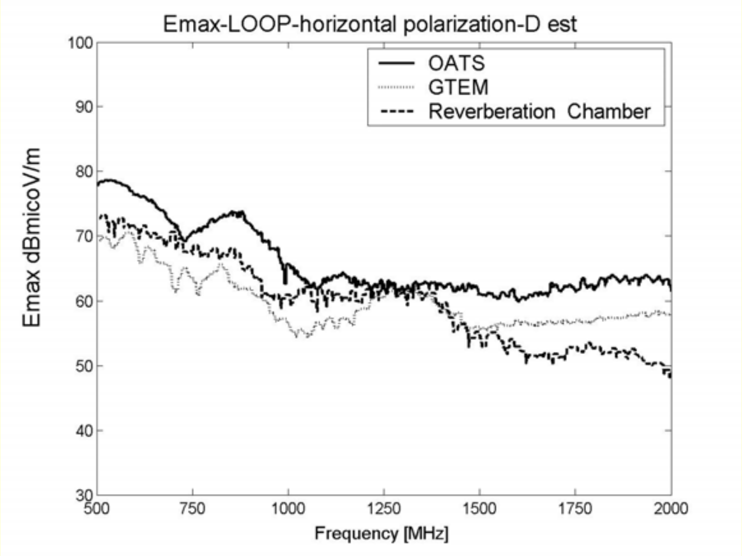
Emissions Measurements of Devices



Total Radiated Power Comparison

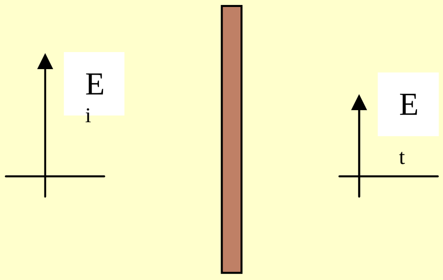


Max Field Comparison



Shielding Properties of Materials

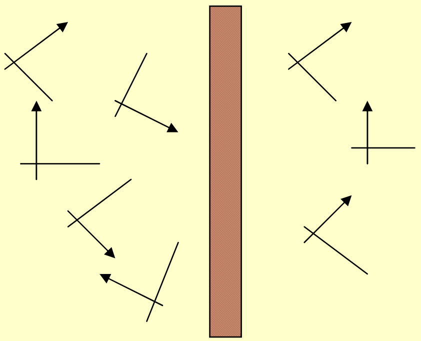
The conventional methods uses normal incident plane-waves, i.e., Coaxial TEM fixtures.



$$SE = -10 Log_{10}\left(\frac{P_t}{P_i}\right)$$

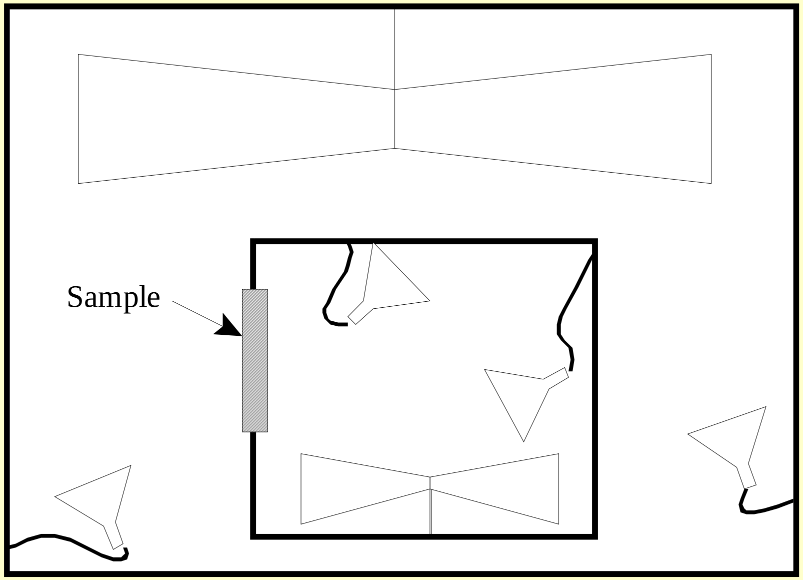
<u>However, these approaches determine SE for only a very limited set of incident wave conditions.</u>

In most applications, materials are exposed to complex EM environments where fields are incident on the material with various polarizations and angles of incidence.



Therefore, a test methodology that better represents this type of environment would be beneficial.

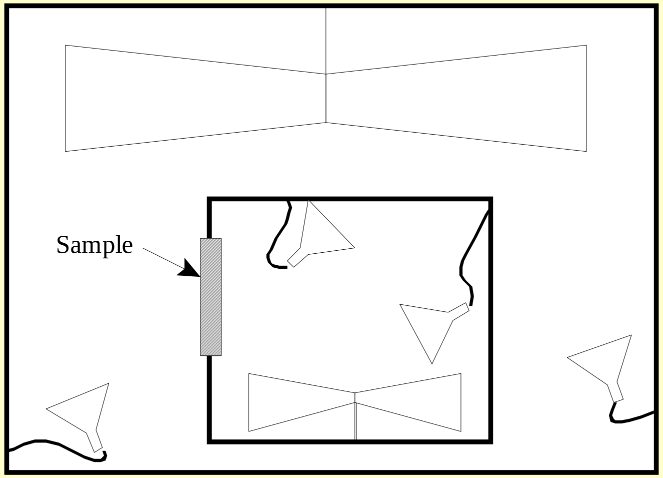
Nested Reverberation Chamber



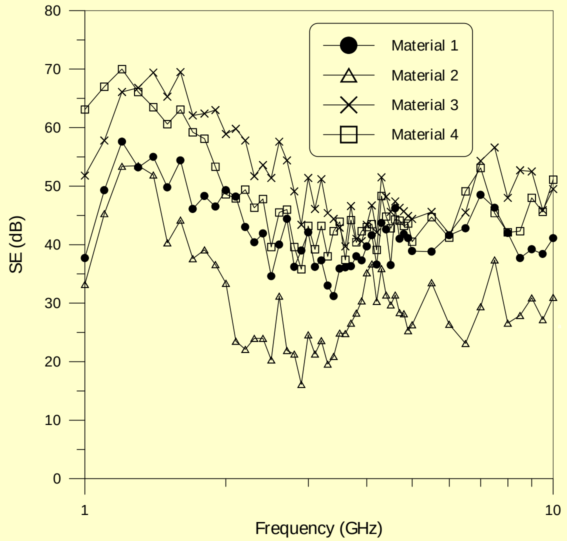
Nested Reverberation Chamber

C.L. Holloway, D. Hill, J. Ladbury, G. Koepke, and R. Garzia, “Shielding effectiveness measurements of materials in nested reverberation chambers,” *IEEE Trans. on Electromagnetic Compatibility*, vol. 45, no. 2, pp. 350-356, May, 2003.

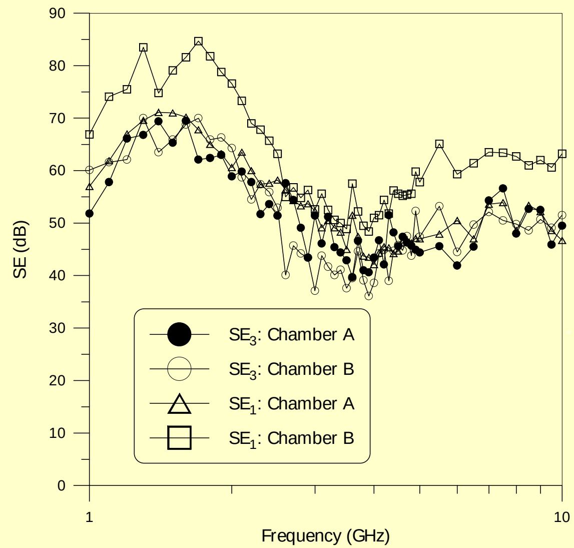
$$SE_3 = -10 Log_{10}\left(\frac{P_{r,in,s}}{P_{r,in,ns}} \frac{P_{r,o,ns}}{P_{r,o,s}} \frac{P_{rQ,in,ns}}{P_{rQ,in,s}} \frac{P_{tx,in,s}}{P_{tx,in,ns}} \right)$$



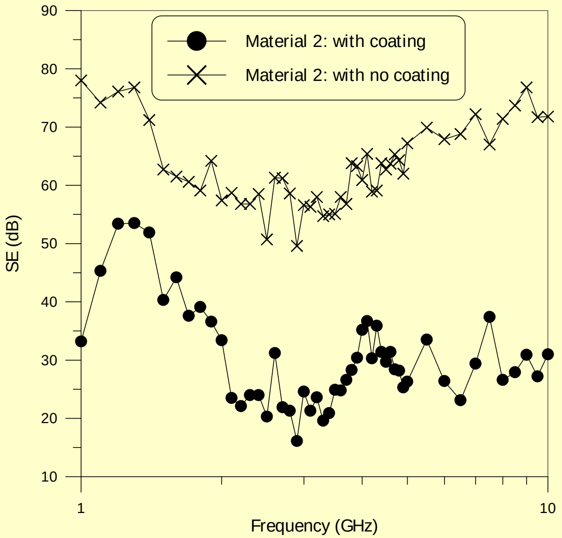
Nested Reverberation Chamber



Different Materials



Different Chamber Sizes



Edge Effects

Loading Effects: Rat in a Cage

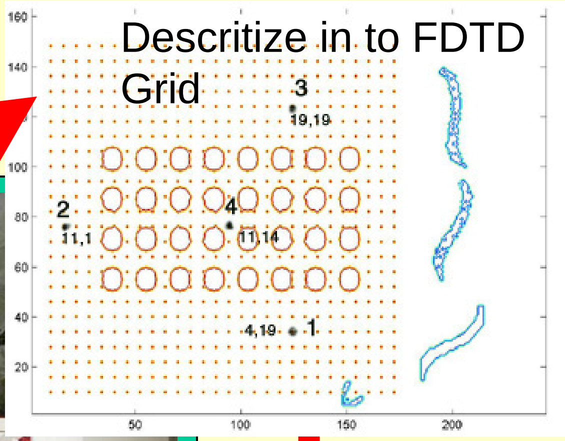
Research Goal

- To provide a way to gain intuition into loaded chamber responses to better help measurements

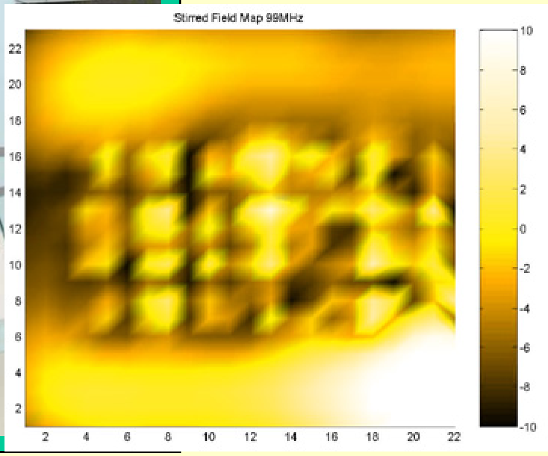
- Ultimately correlate measured and modeled data, and use models to predict what we cant measure.

- Develop a fast and efficient numerical code to explore multiple chamber topologies. (FDTD)

Take Real System

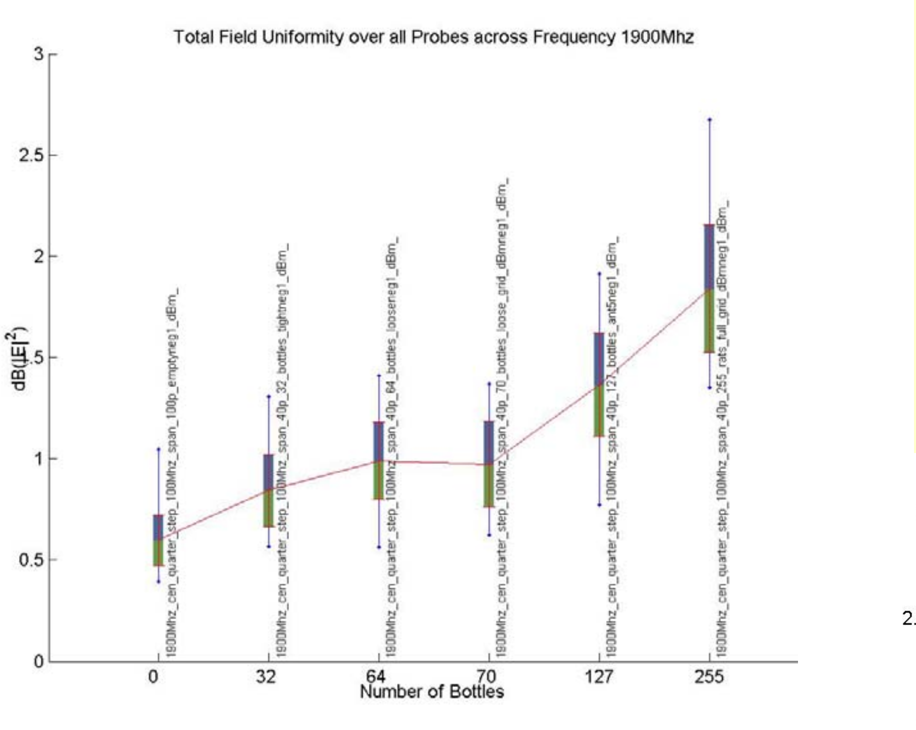


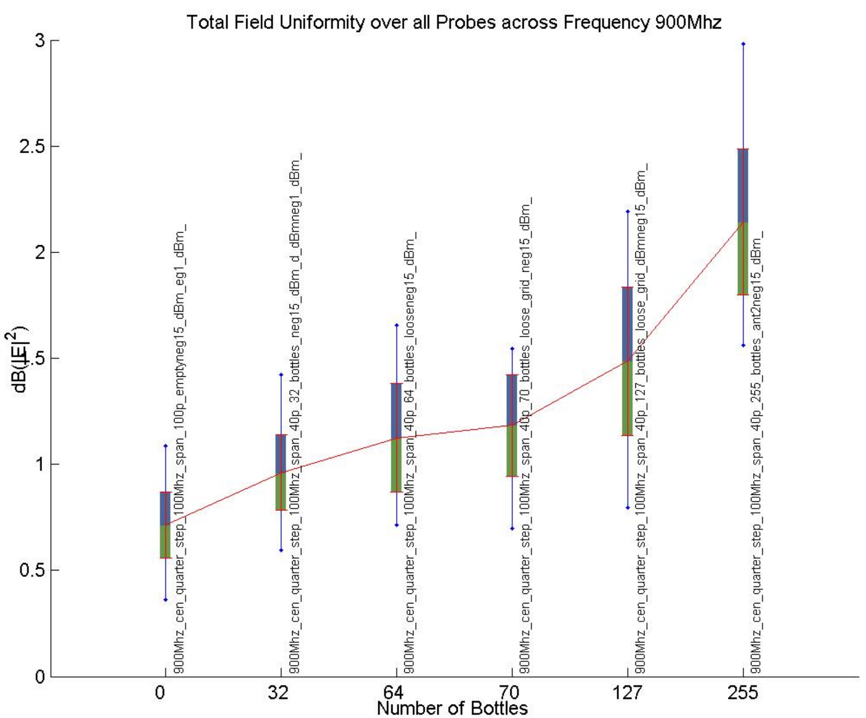
Simulate



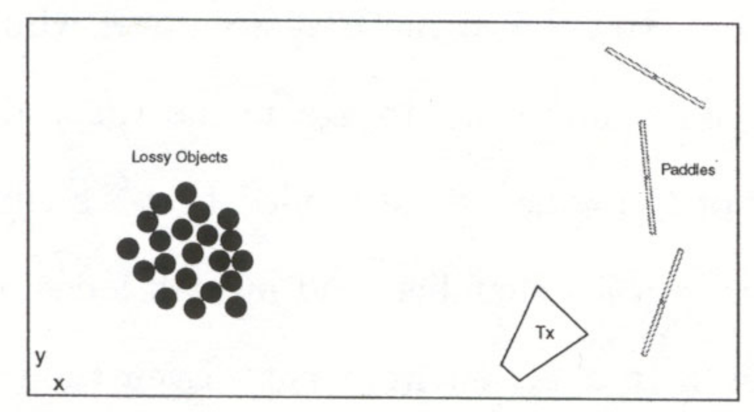
Predict Stirred Fields Computationally to give us **insight into chamber measurements** in a loaded environment

Measurements of Fake Rats

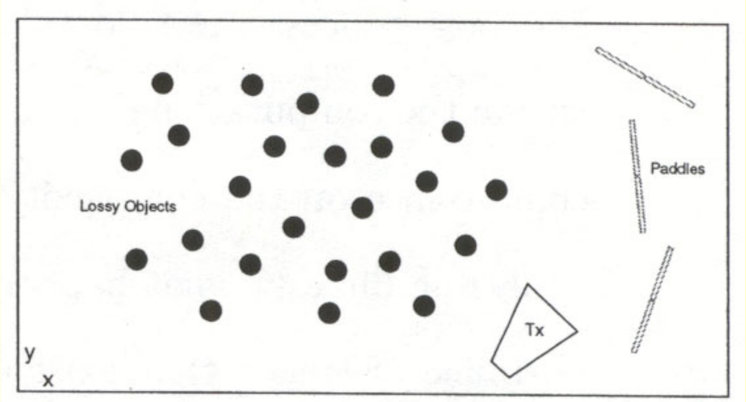




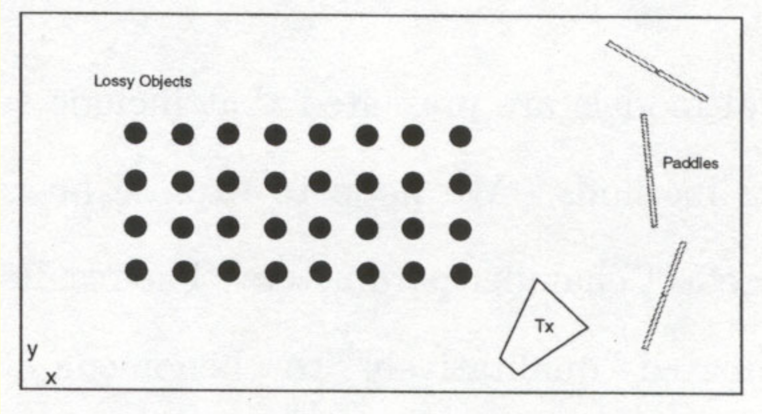
Lossy Body Configuration



Large Lossy Body

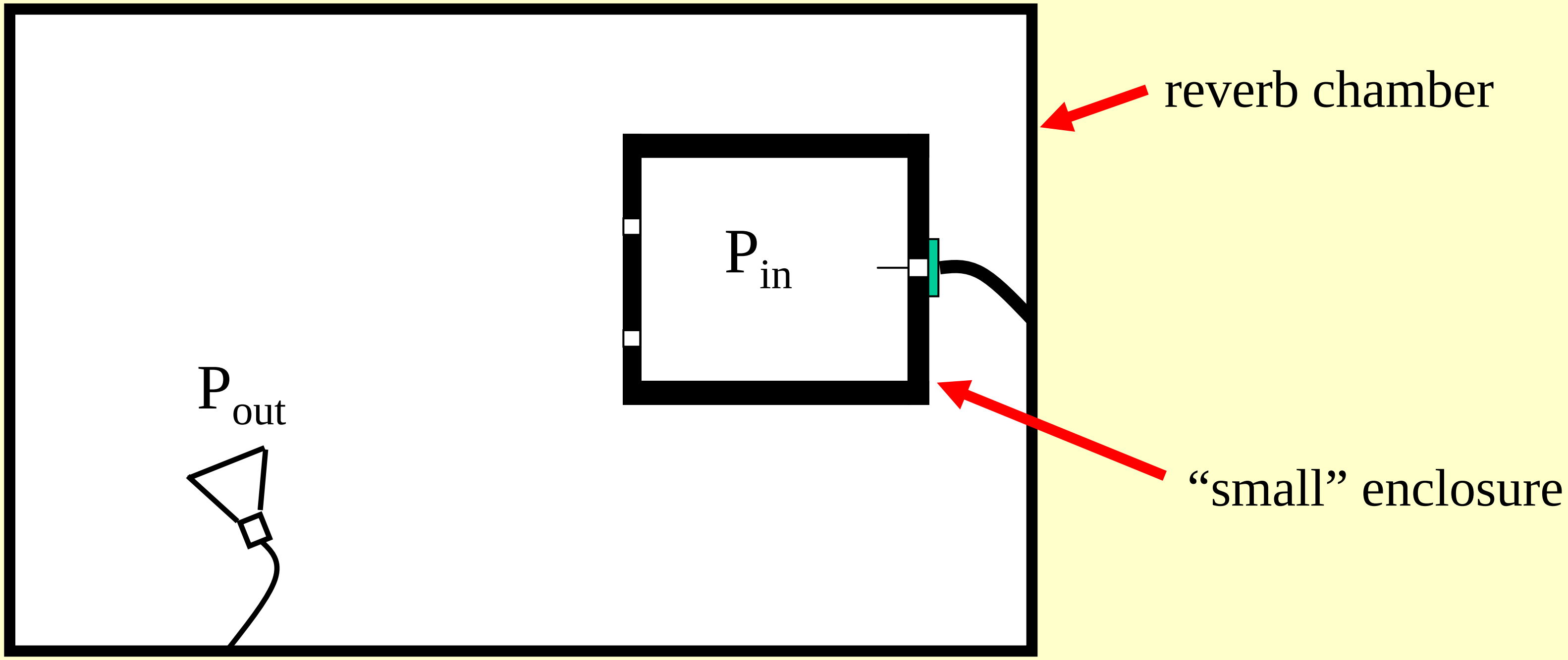


Distributed Lossy Bodies



Periodic Lossy Bodies

Measuring Shielding for “small” Enclosures



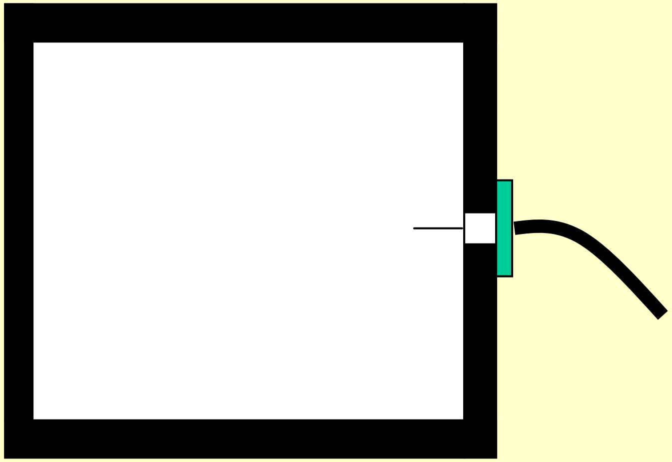
SE= -10 Log(P_{in}/ P_{out}): with frequency stirring

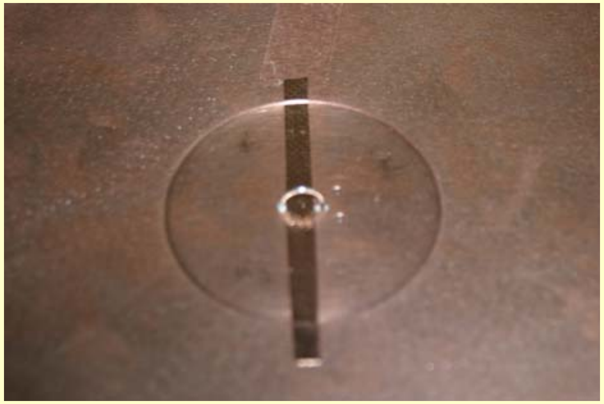
Problem with “small” Enclosures: Measuring the Fields Inside

- The “rule-of thumb” for antennas positioning in a chamber is ½ wavelength from the wall. This is because the tangential component of the E-field is zero are the wall.

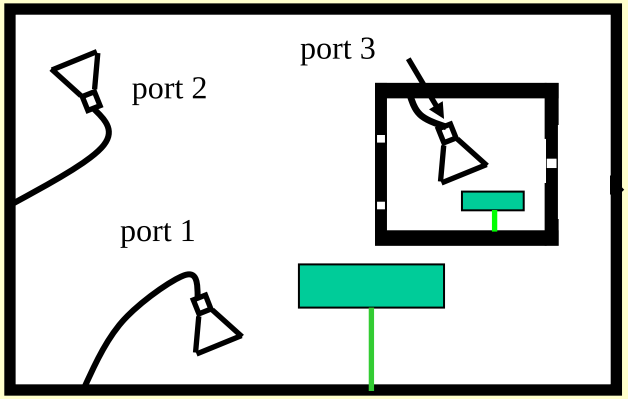
- However, Hill (IEEE Trans on EMC, 2005) has recently shown that the statistics for the normal component of the E-field at the wall are the same for the field in the center of the chamber.

Thus, small monopole (or loop) probes attached to the wall can be used to determine the power in the center of a “small” enclosure.

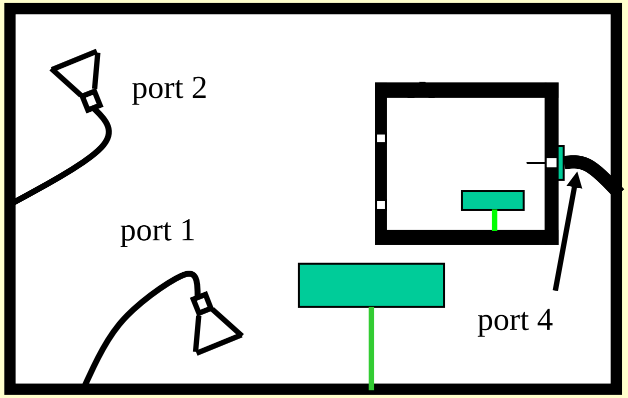




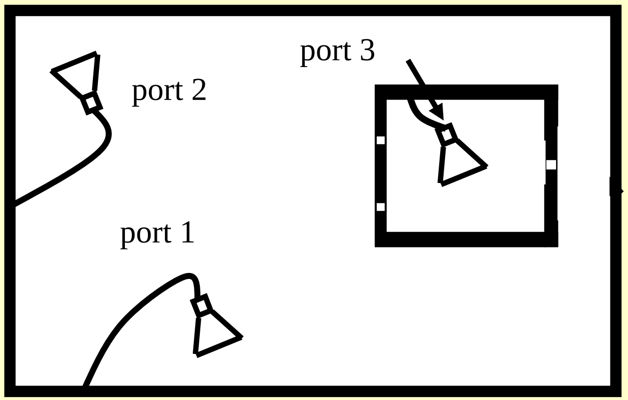
Comparison with Different Reverberation Chamber Approaches



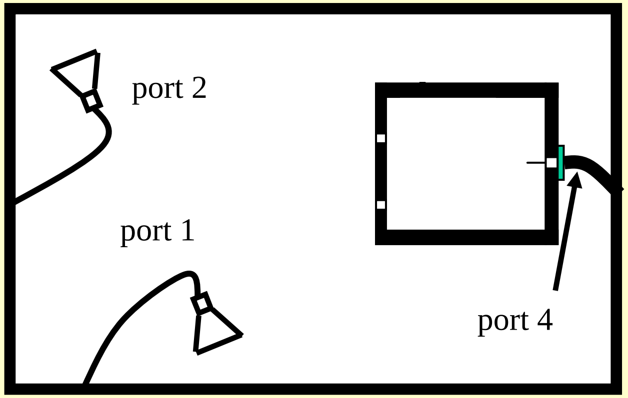
Mode-Stirred with a Horn Antenna: SE => S_{31}



Mode-Stirred with a Monopole Antenna: SE => S_{41}

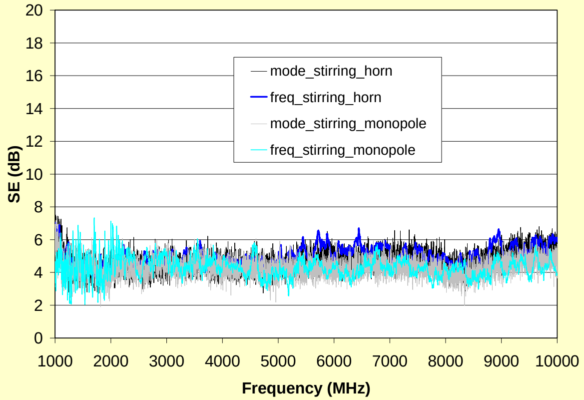


Frequency Stirring with a Horn Antenna: SE => S_{31}

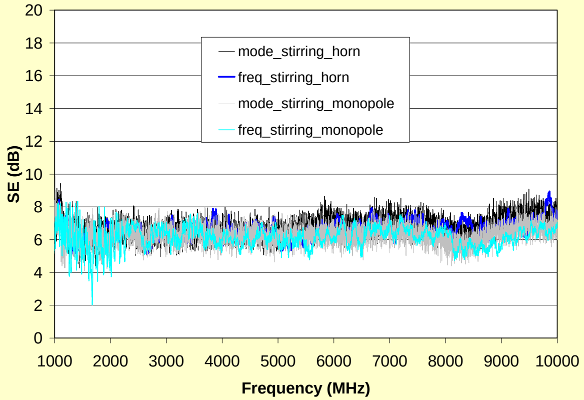


Frequency Stirring with a Monopole Antenna: SE => S_{41}

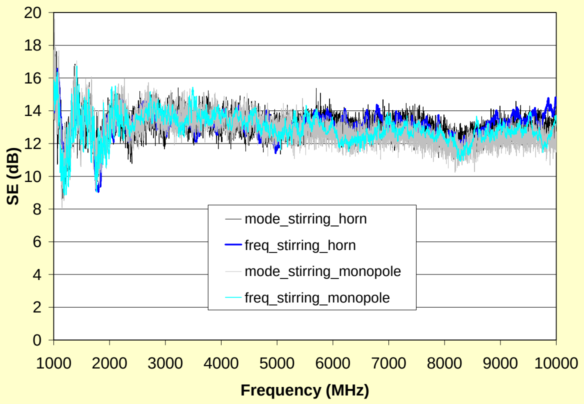
Comparison with Different Approaches



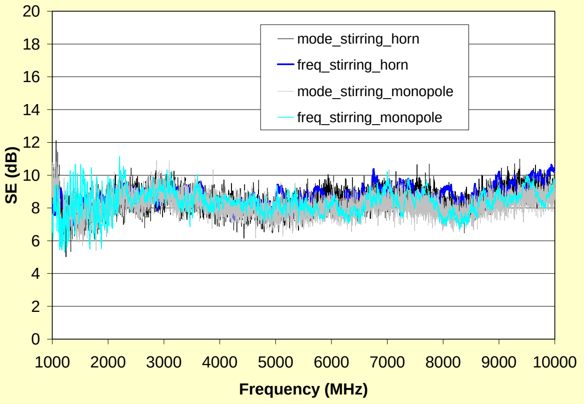
(a) open aperture



(b) half-filled aperture

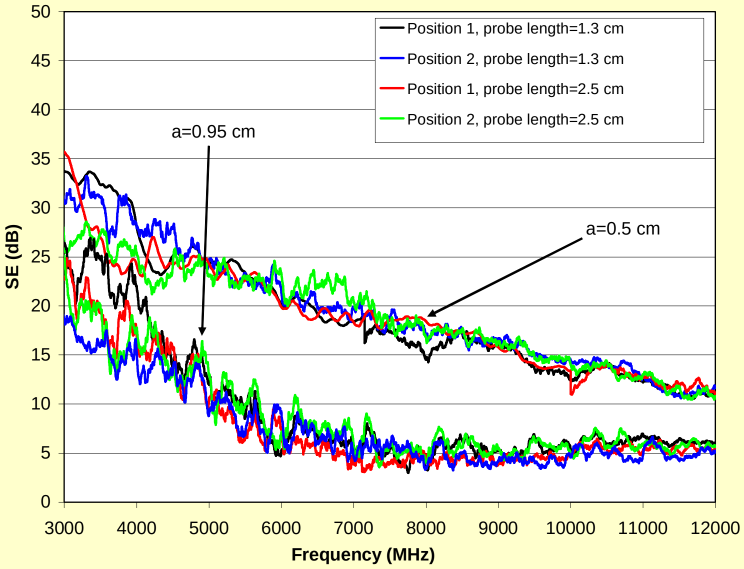


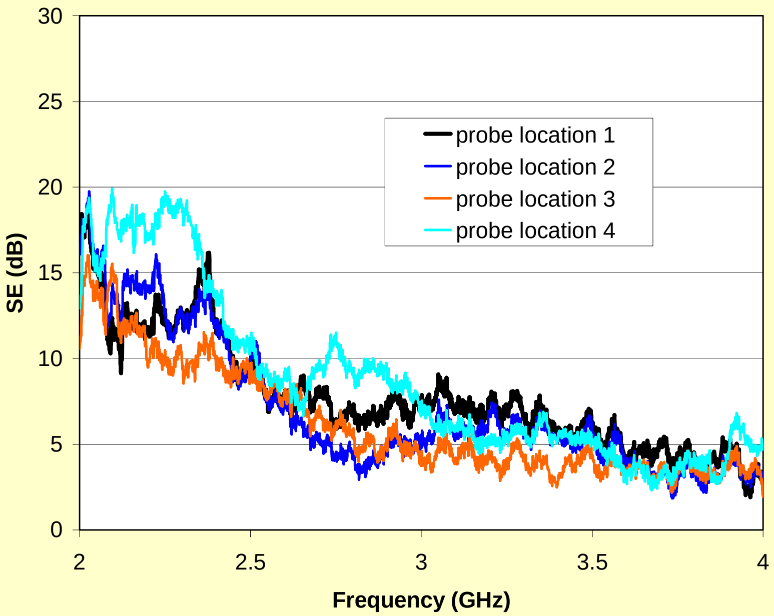
(c) narrow slot aperture



(d) generic aperture

Different Probe Lengths and Locations





Antenna Measurement:

NIST Reverberation Chamber and Experimental Set-up

Dual-Ridged Horn used as receive antenna

Antenna Under Test (AUT)

Two paddles used

Experimental Results to Compared to Horn Antenna

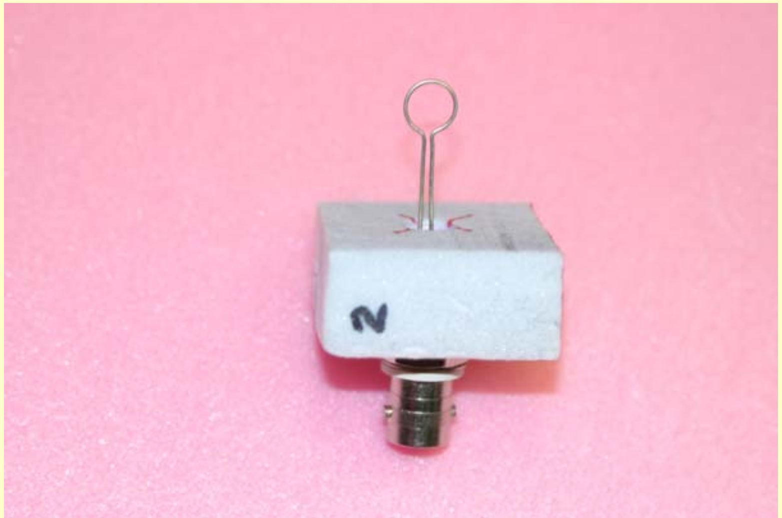
Results presented here are for relative total radiated power (*RTRP*) referenced to either a Horn or to a small Loop. For a Horn we have:

$$Total\ Radiated\ Power = \frac{P_{AUT}}{P_{Horn}}$$

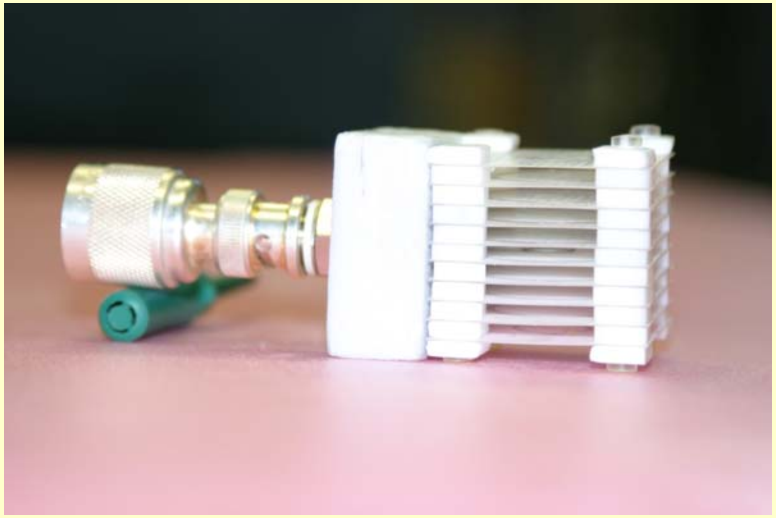
where P_{AUT} is the received power in the chamber when transmitting on the antenna under test (AUT), and P_{Horn} is the received power in the chamber when transmitting on the horn. All antennas were connected to a 50 ohm cable, so results include both mismatch and efficiency (ohmic loss) effects.

If we assume the horn is the “best” antenna available, then these measurements will show how “well” an antenna is performing.

Ten-Layer Spherical 612 MHz Structure

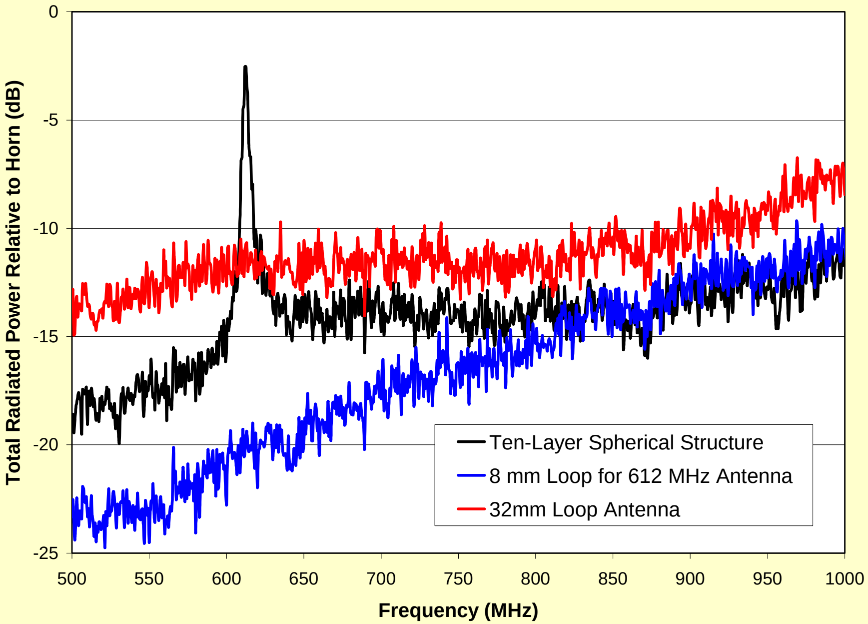


8 mm Loop for 612 MHz antenna

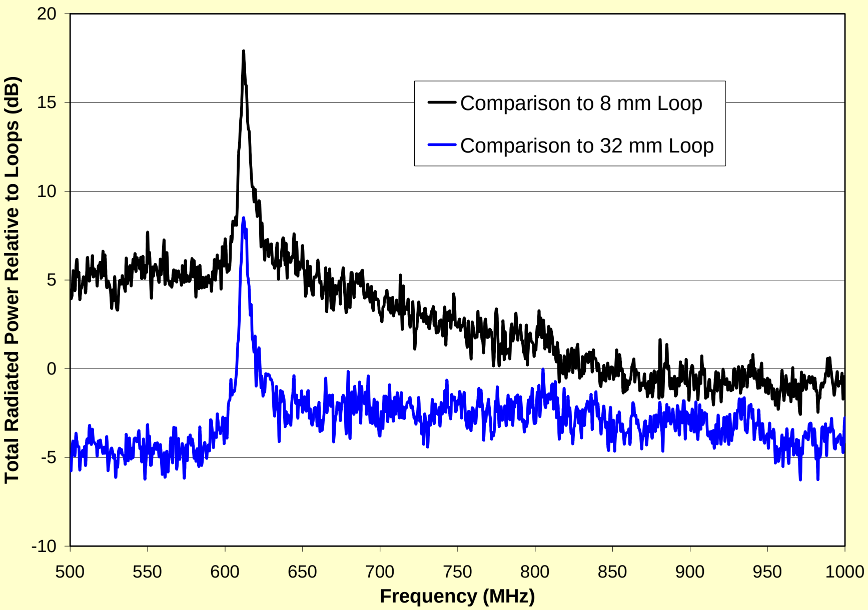


612 MHz antenna: loop with ten-layer spherical material

Ten-Layer Spherical 612 MHz Structure



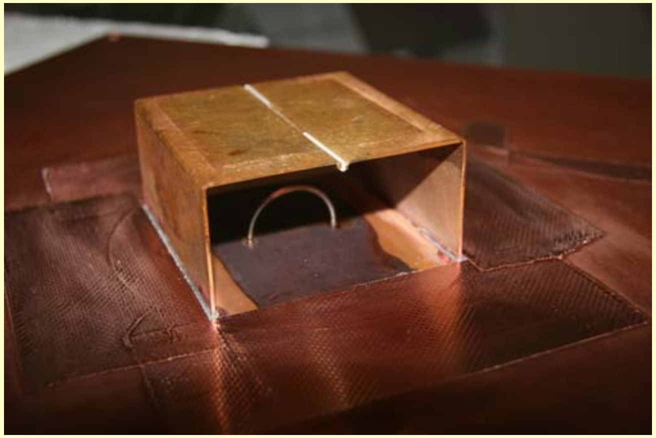
Comparison to Horn



Comparison to Loops

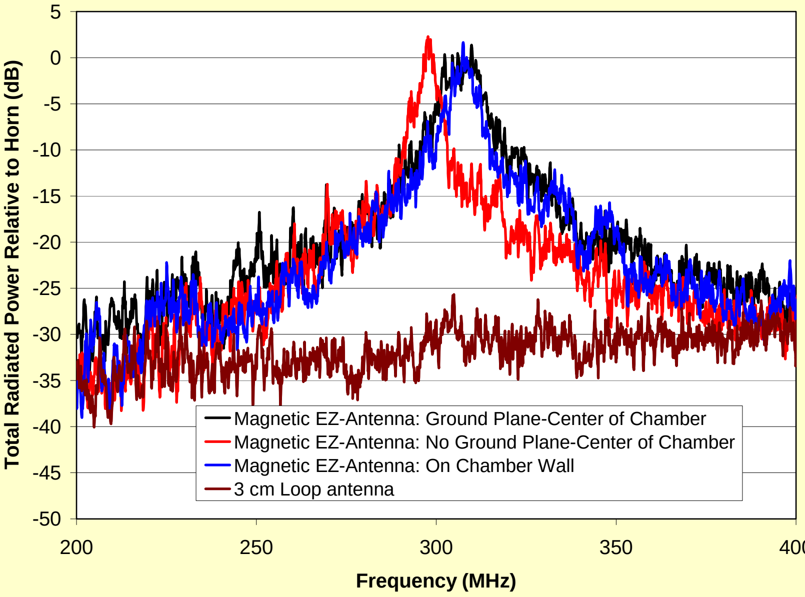
Magnetic Antenna

New Magnetic Antenna

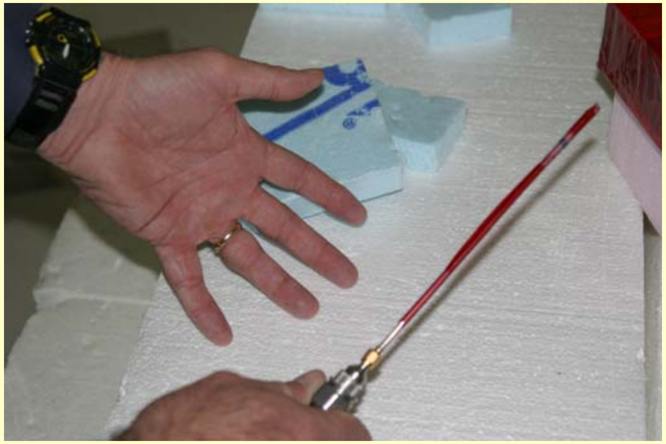


Comparison to Horn

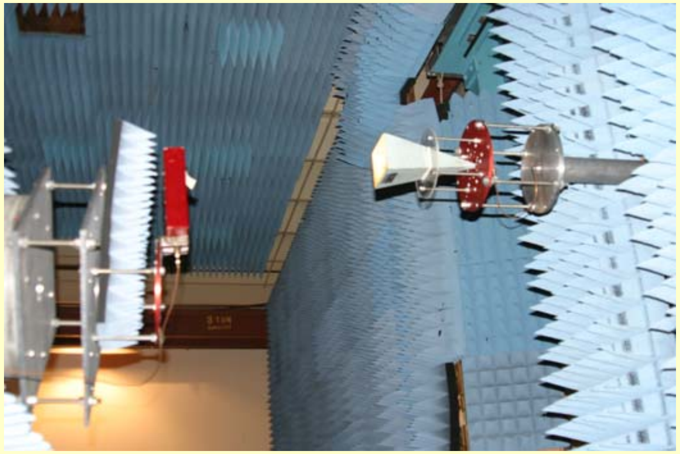
Loop Antenna

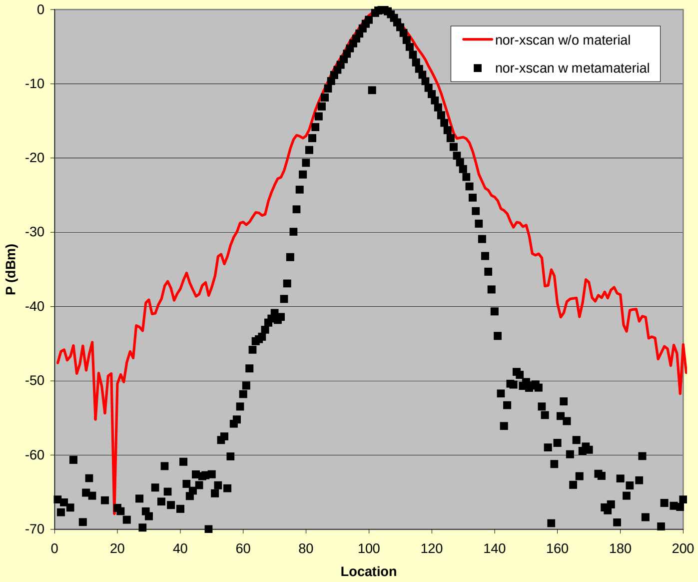


Can NOT Measurement Directivity

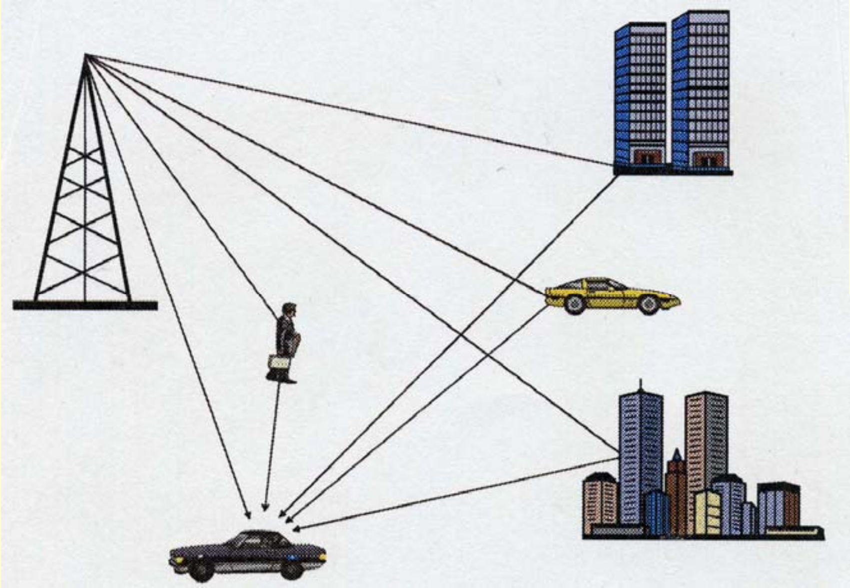


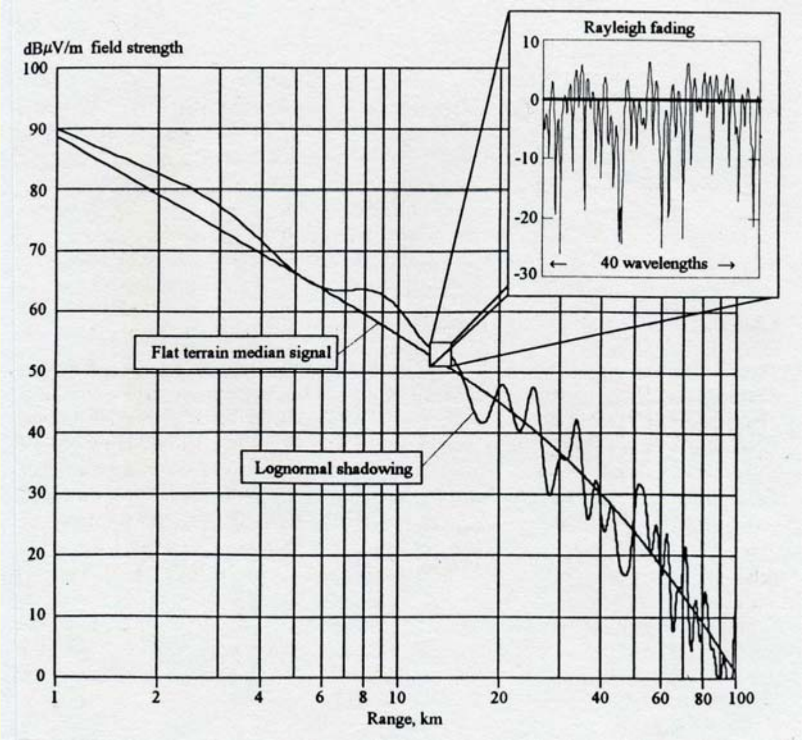
Near-Field Antenna Tests





Multipath Environments





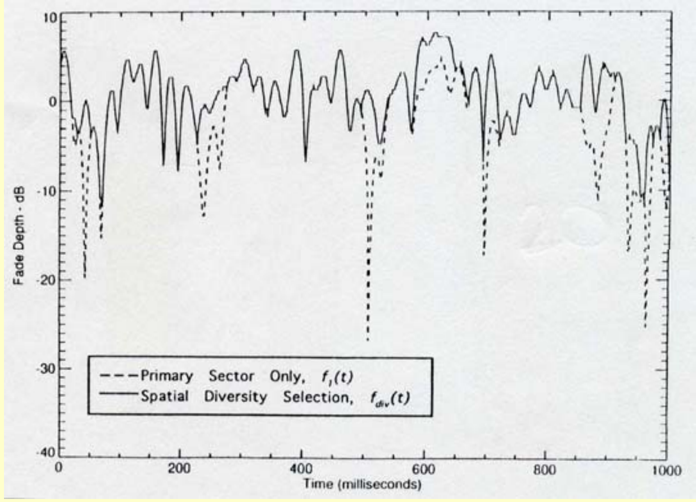
Multipath Environments

Extensive measurements have shown that when light of sight (LOS) path is present the radio multipath environment is well approximated by a **Ricean** channel, and when no LOS is present the channel is well approximated by a **Rayleigh** channel:

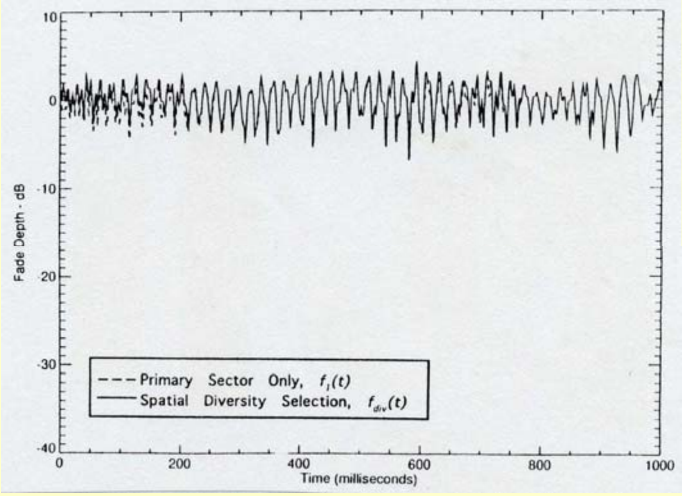
$$E = A_{LOS}\cos(2\pi f_c t) + \sum_{n=1}^{N} A_n \cos[2\pi(f_c + f_n)t + \phi_n]$$

The Amplitude of ***E*** is either Rayleigh or Ricean depending if a LOS path is present.

Urban Environment



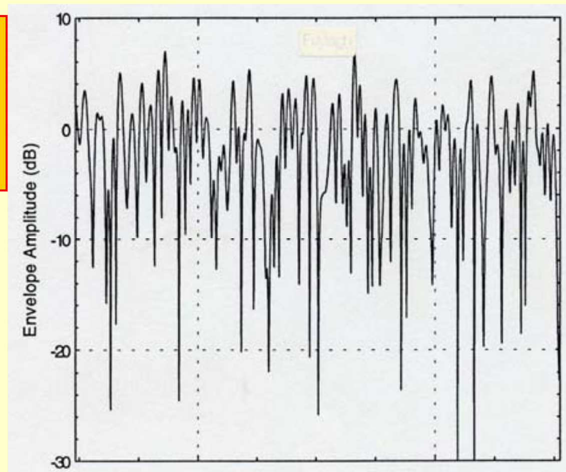
Rural Environment



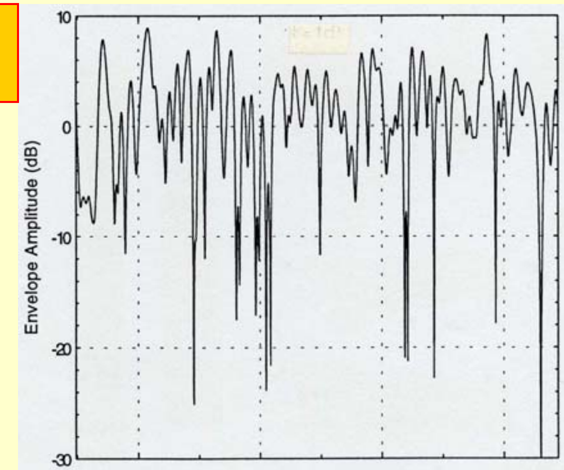
Ricean K-factor

k-factor: $k = \dfrac{\textit{direct component}}{\textit{scattered components}}$ or $K = 10\,Log(k)$

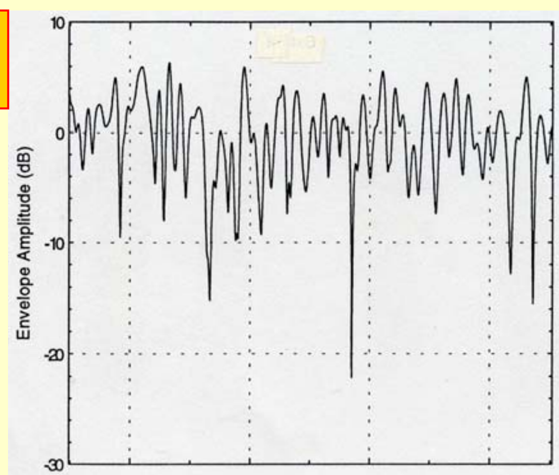
K= -∞ dB (Rayleigh)



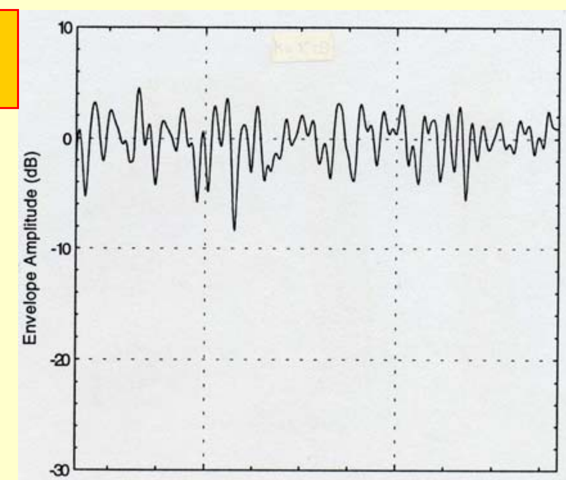
K=1 dB



K=4 dB

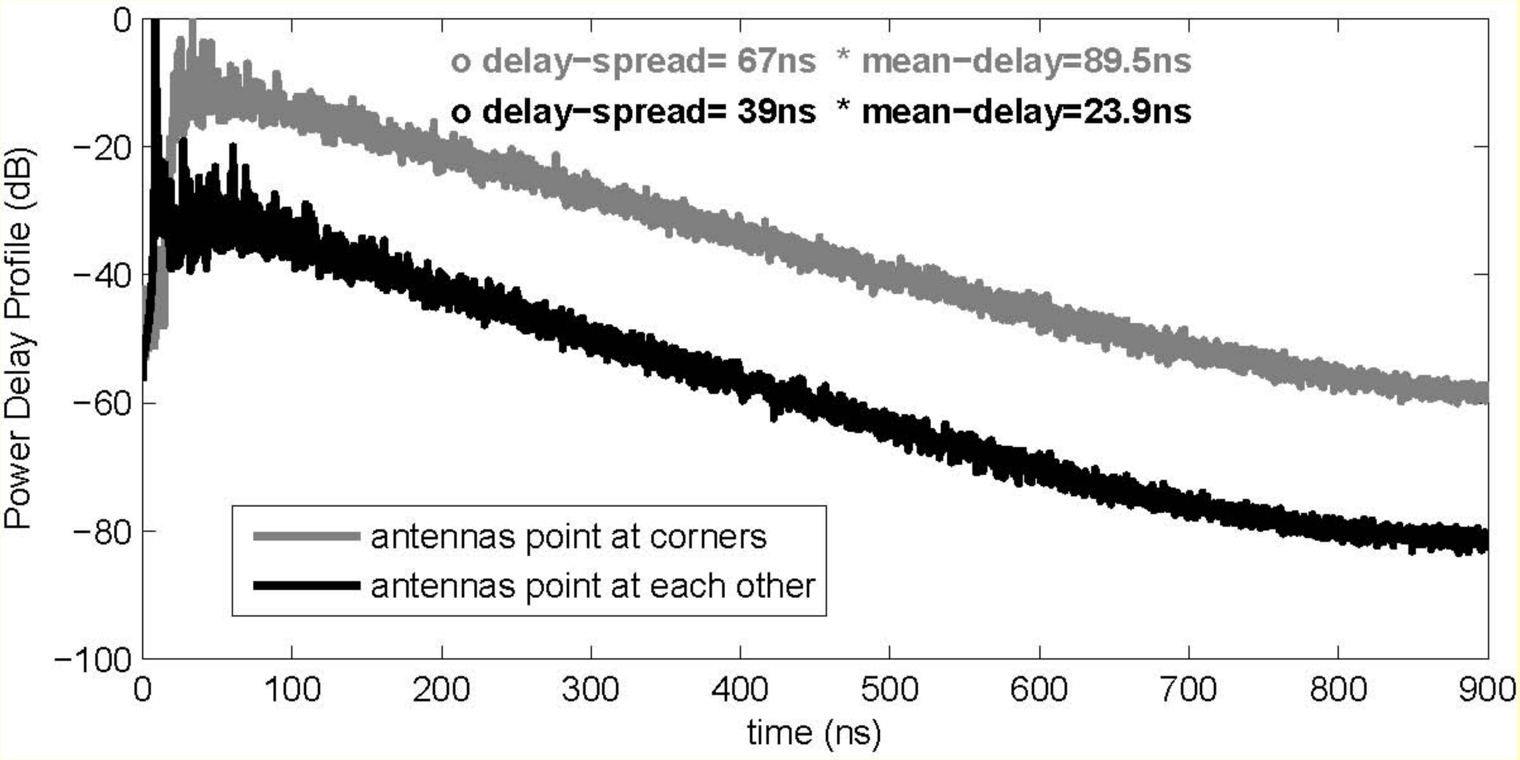


K=10 dB



Ricean K-factors and rms Delay Spreads

Besides chancing the K-factor, we need to vary its decay rate.

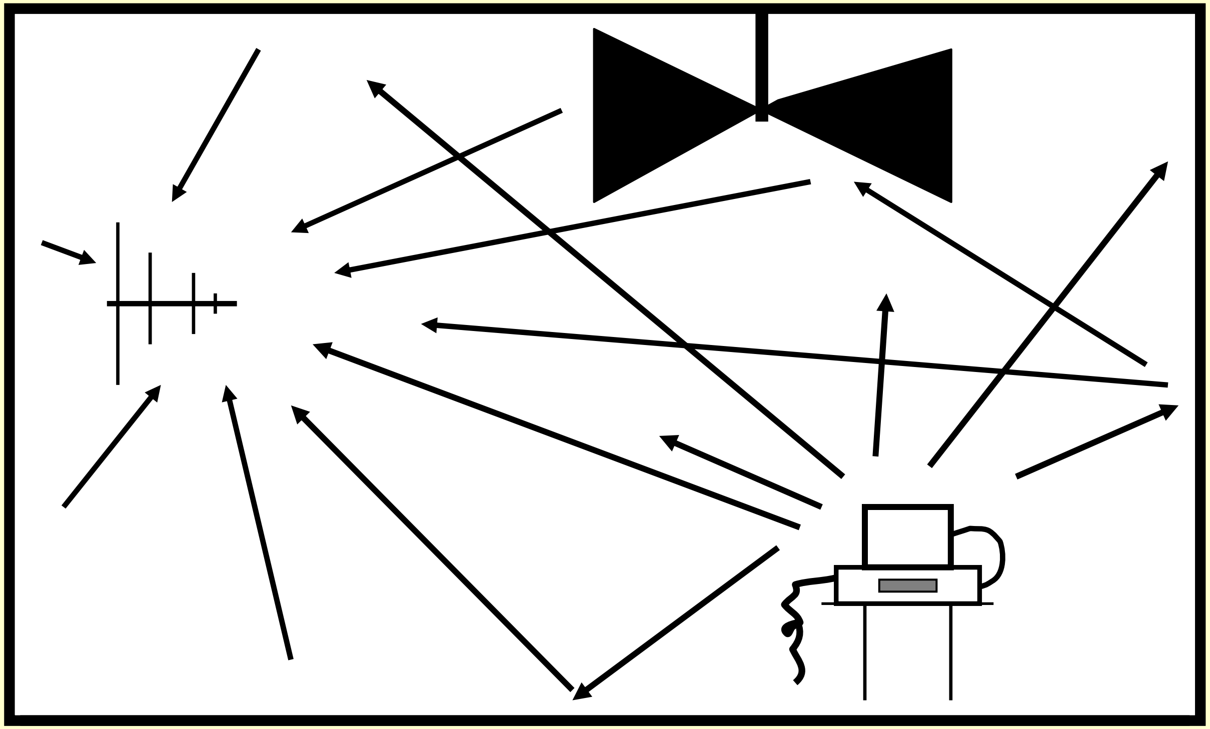


Standardization of Wireless Measurements

Can we use a reverberation chambers for a reliable and repeatable test facilities that has the capability of simulating any multipath environment for the testing of wireless communications devices?

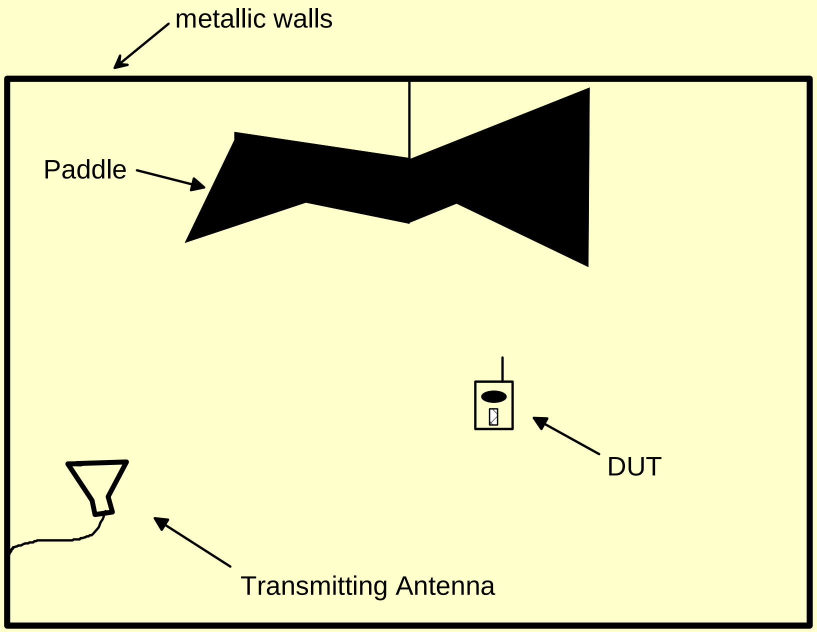
If so, such a test facility will be useful in wireless measurement standards.

Reverberation Chambers are Natural Multipath Environments



Typical Reverberation Chambers Set-up

Antenna pointing away from probe (DUT)

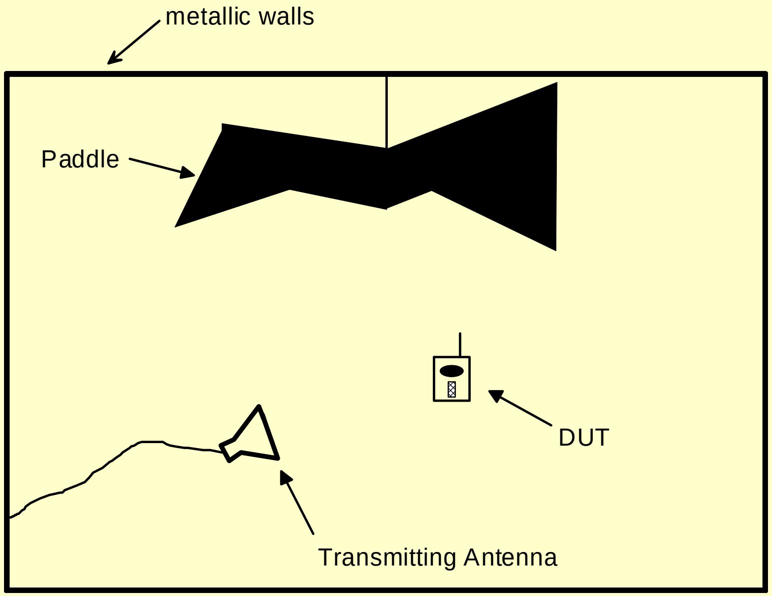


A Rayleigh test environment

Can we generate a Ricean environment?

Chamber Set-up for Ricean Environment

Antenna pointing toward (DUT)



We will show that by varying the characteristics of the reverberation chamber and/or the antenna configurations in the chamber, any desired Rician K-factor can be obtained.

Reverberation Chamber Ricean Environment

It can be shown: see Holloway et al, *IEEE Trans on Antenna and Propag.*, 2006.

$$K = \frac{3}{2}\frac{V}{\lambda Q}\frac{D}{r^2}$$

Note:

•We see that K is proportional to D. This suggests that if an antenna with a well defined antenna pattern is used, it can be rotated with respect to the DUT, thereby changing the K-factor.

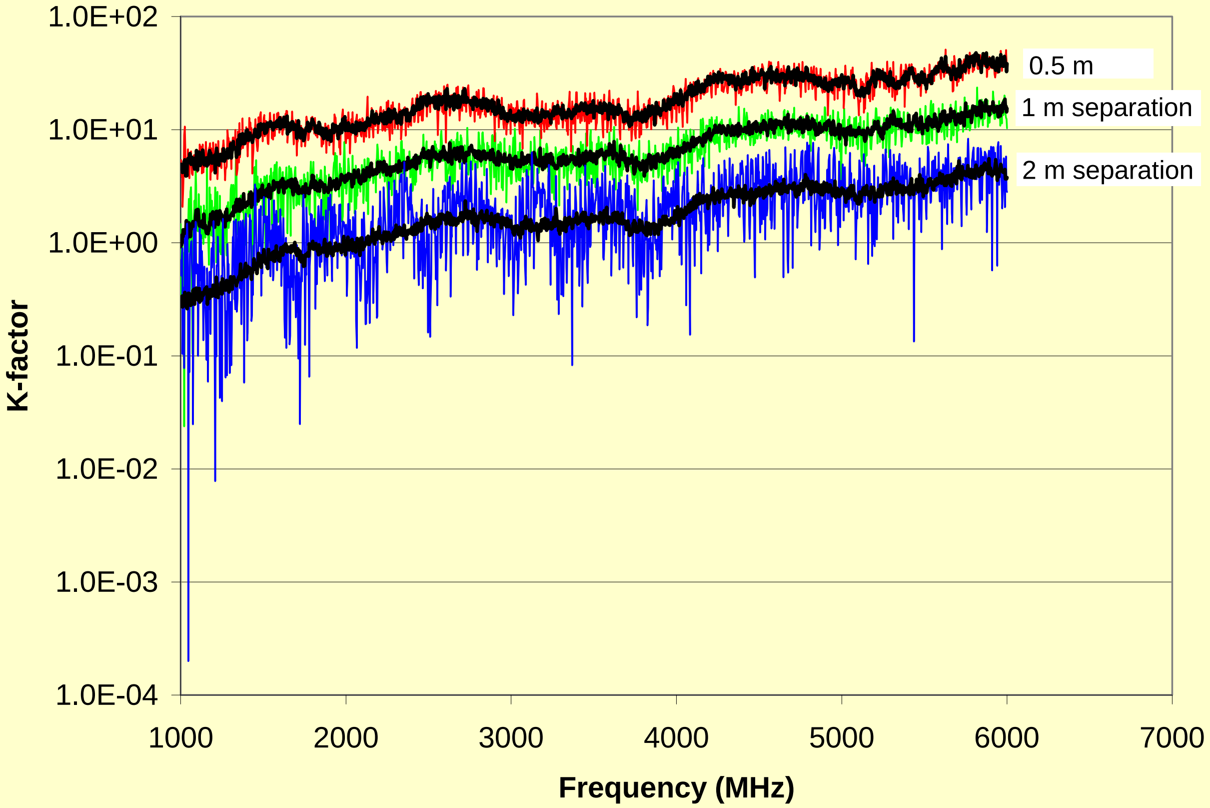
•Secondly, we see that if r is large, K is small (approaching a Rayleigh environment); if r is small, K is large. This suggests that if the separation distance between the antenna and the DUT is varied, then the K-factor can also be changed to some desired value.

•Next we see that by varying Q (the chamber quality factor), the K-factor can be changed to some desired value. The Q of the chamber can easily be varied by simply loading the chamber with lossy materials.

Also, if K becomes small, the distribution approaches Rayleigh.

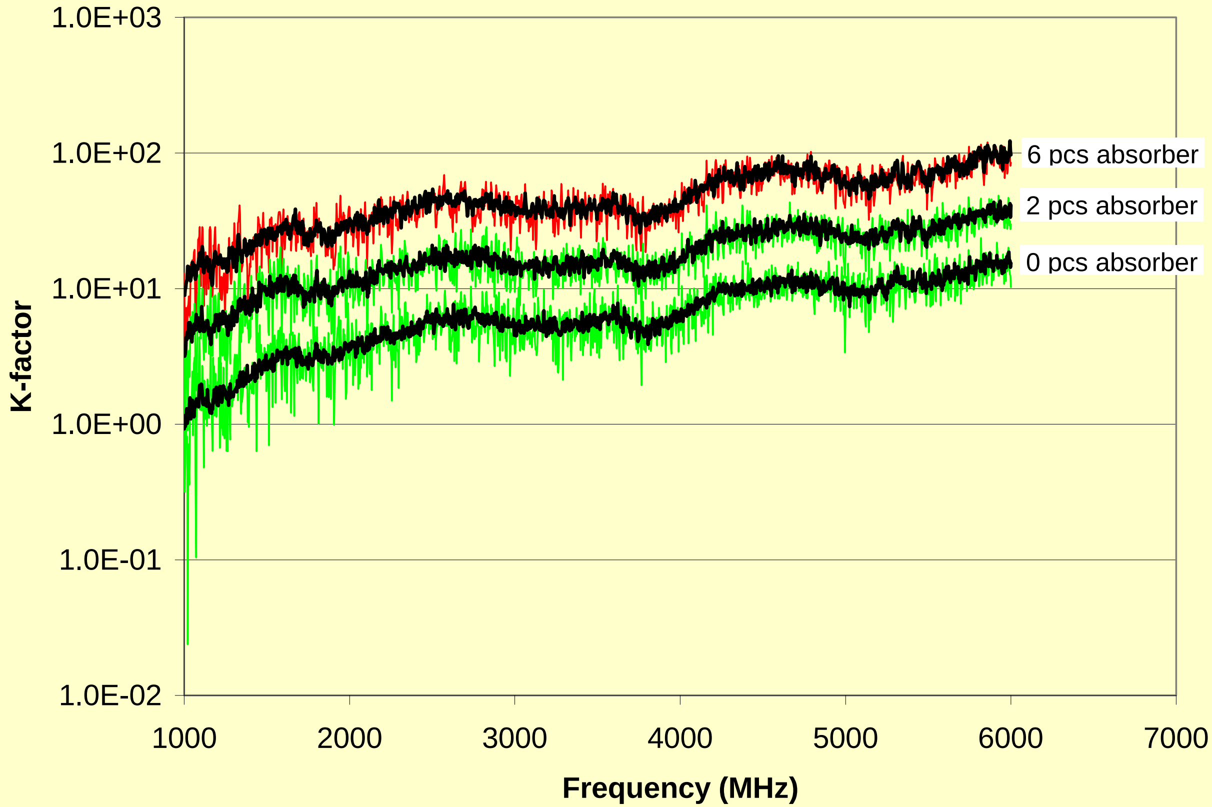
Thus, varying all these different quantities in a judicious manner can result in controllable K-factor over a reasonably large range.

Measured K-factor for Different Antenna Separation



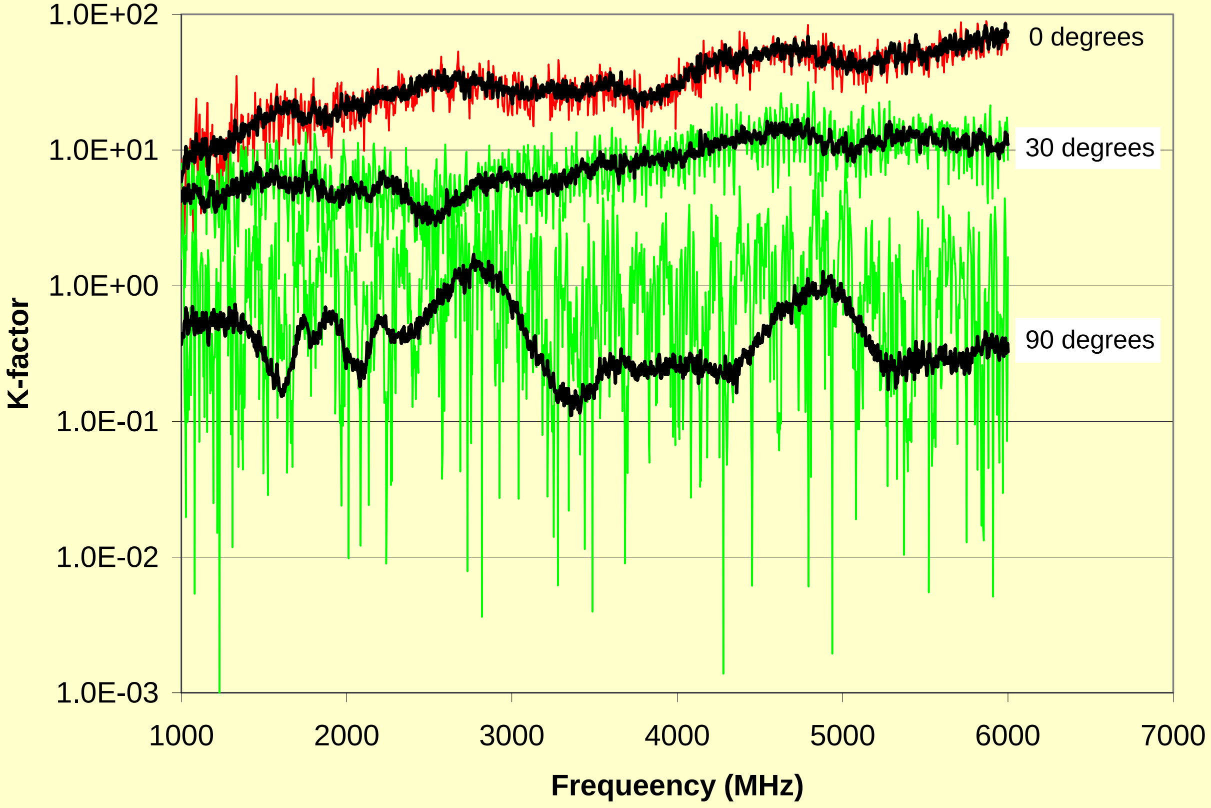
Each set of curves represents a different distance of separation. The thick black curve running over each data set represents the *K*-factor obtained by using d determined in the anechoic chamber.

Measured K-factor for Chamber Loading



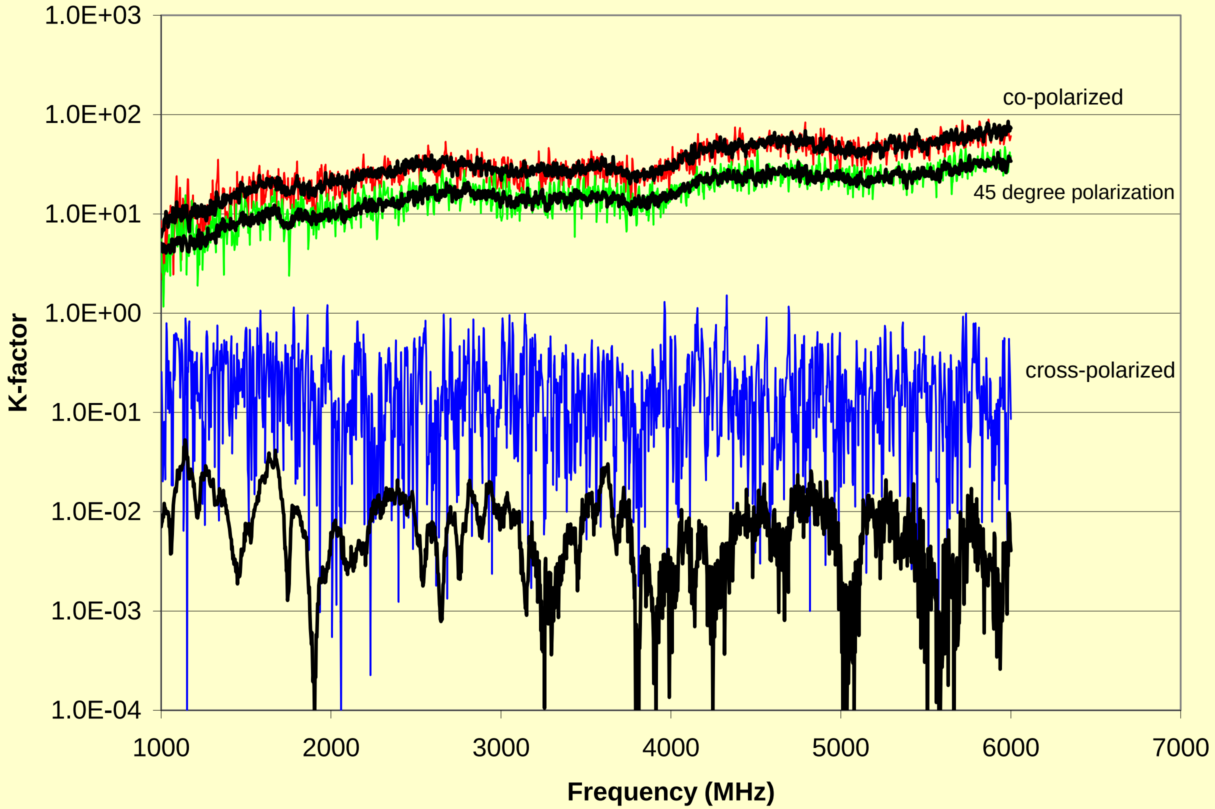
The thick black curve running over each data set represents the *K*-factor obtained by using d determined in the anechoic chamber.

Measured K-factor for Different Antenna Rotations



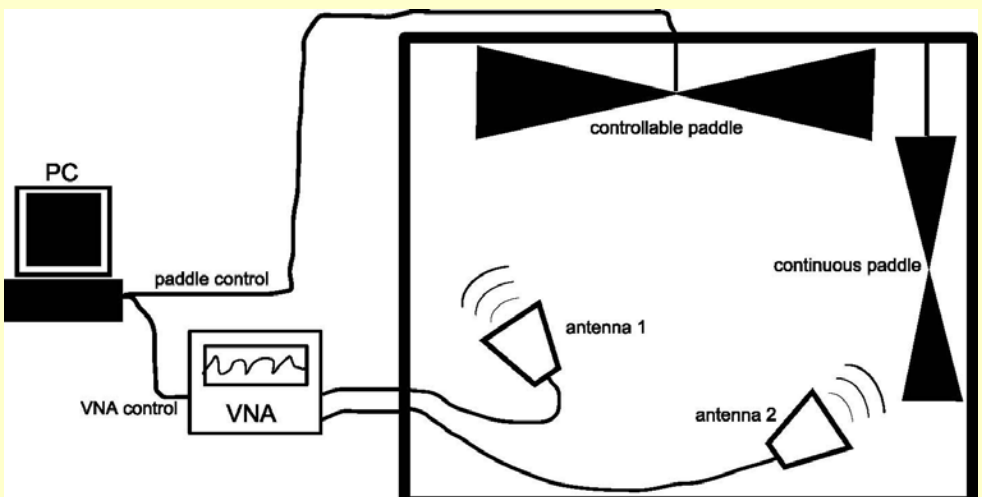
The thick black curve running over each data set represents the *K*-factor obtained by using d determined in the anechoic chamber. Each data set was taken at 1 m separation and with 4 pieces of absorber in the chamber.

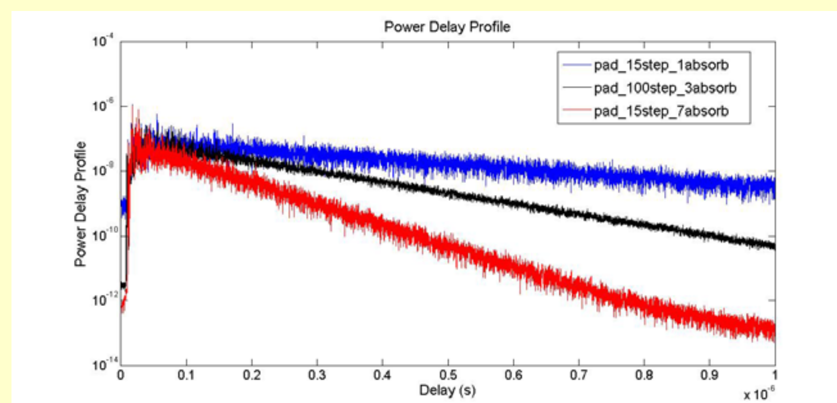
Measured K-factor for Different Antenna Polarizations



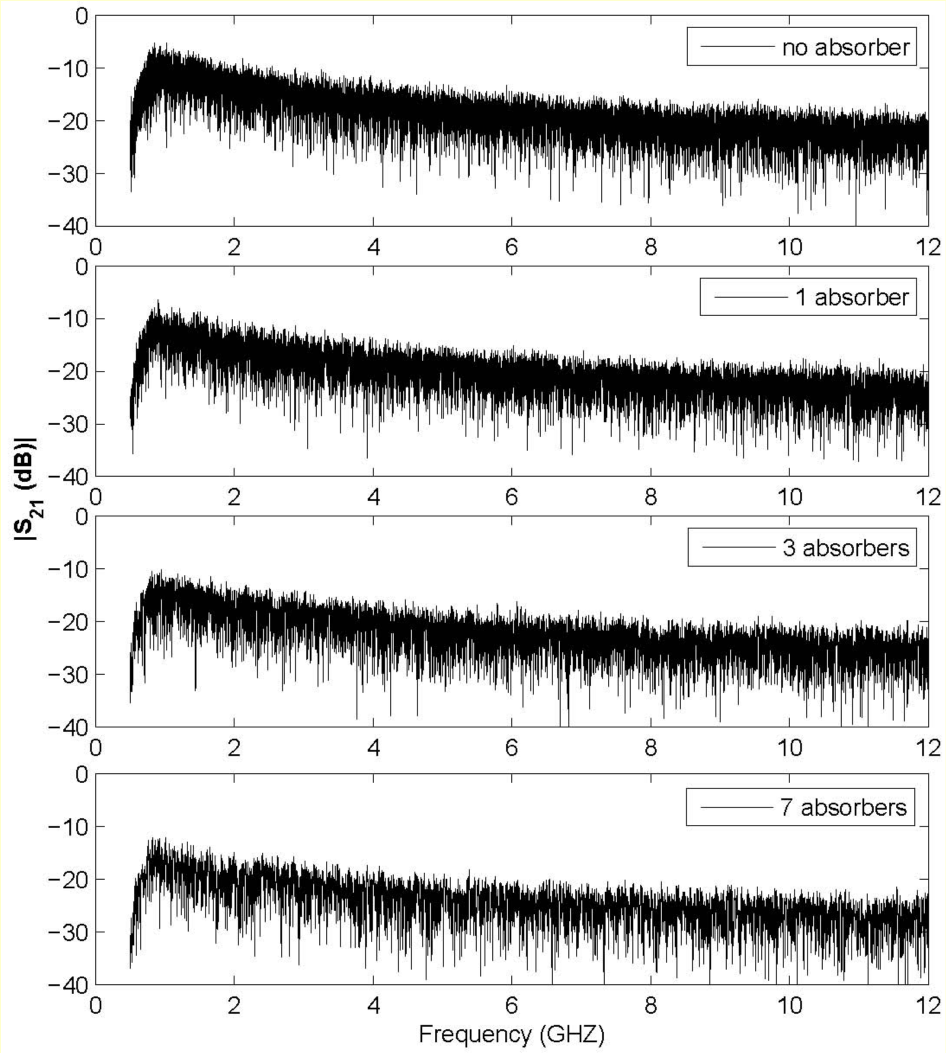
The thick black curve running over each data set represents the *K*-factor obtained by using d determined in the anechoic chamber. Each data set was taken at 1 m separation and with 4 pieces of absorber in the chamber.

Simulating Propagation Environments with Different Impulse Responses and rms Delay Spreads





S_{21} Measurements: Loading the Chamber



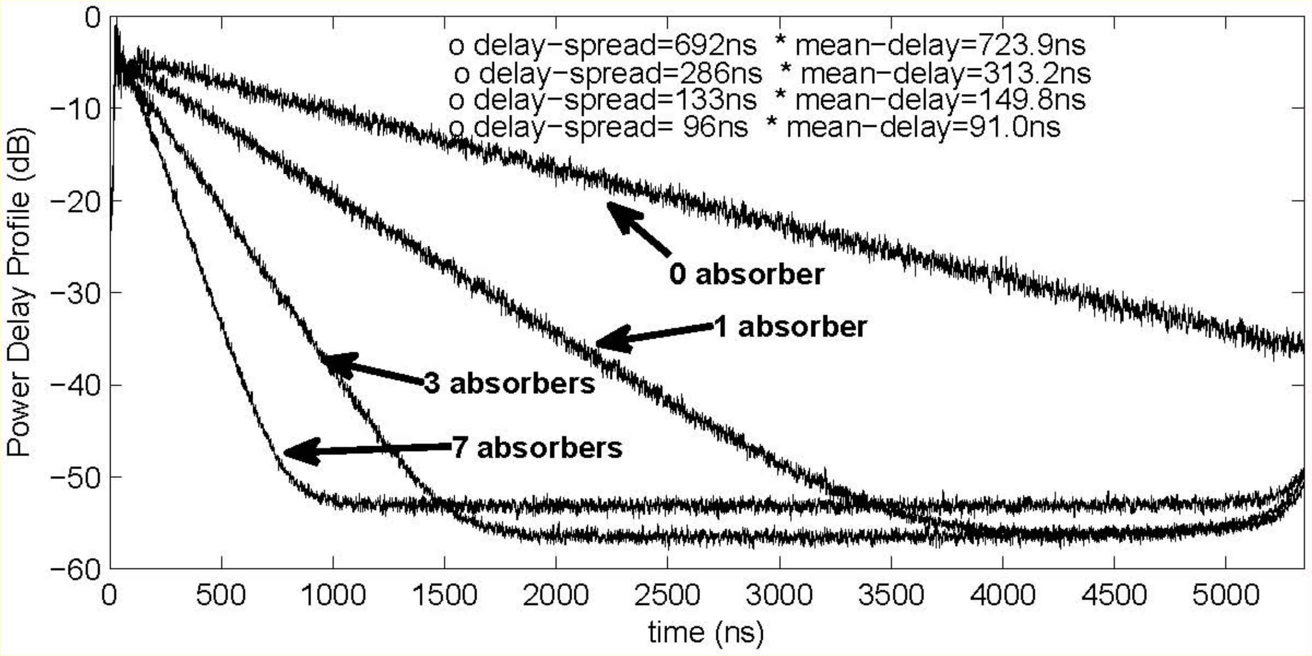
Impulse Responses and Power Delay Profiles

Power Delay Profile:

$$PDP(\tau) = \left\langle \left| h(t) \right|^2 \right\rangle$$

where *h(t)* is the Fourier transform of $S_{21}(\omega)$

Loading the Chamber



rms Delay Spreads

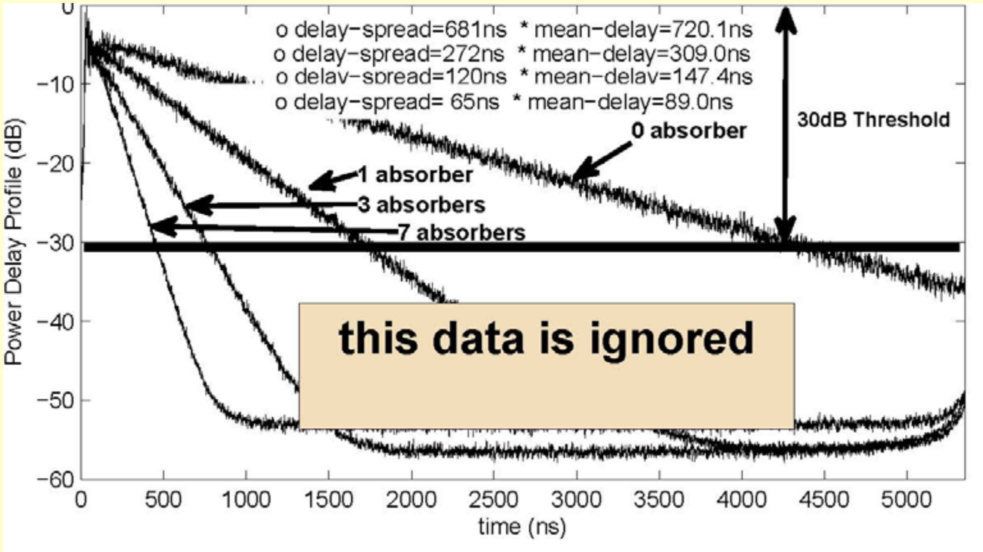
One characteristic of the PDP that has been shown to be particularly important in wireless systems that use digital modulation is the *rms* delay spread of the PDP:

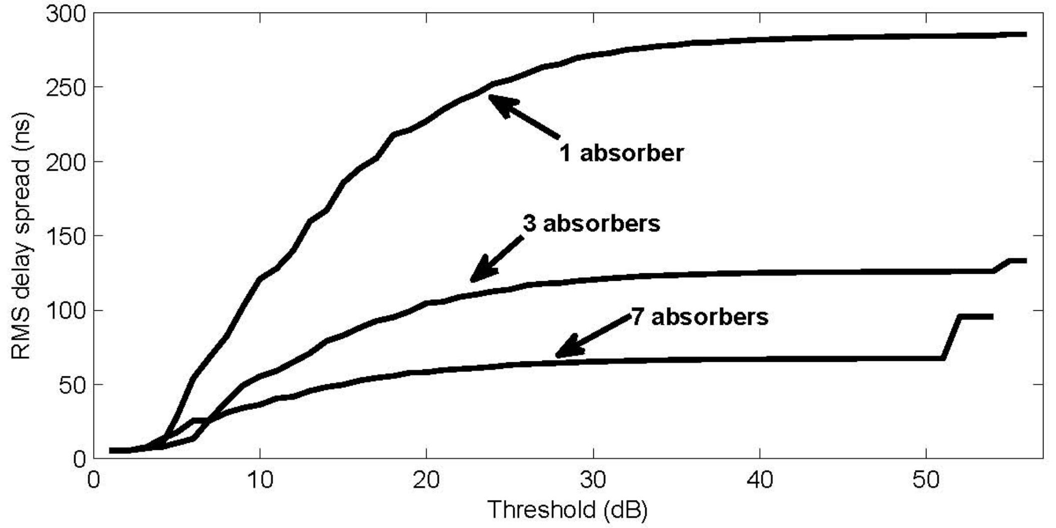
$$\tau_{rms} = \frac{\int_0^\infty (t-\tau_o)^2 P(t)\,dt}{\int_0^\infty P(t)\,dt}$$

where τ_o is the mean delay of the propagation channel, given by

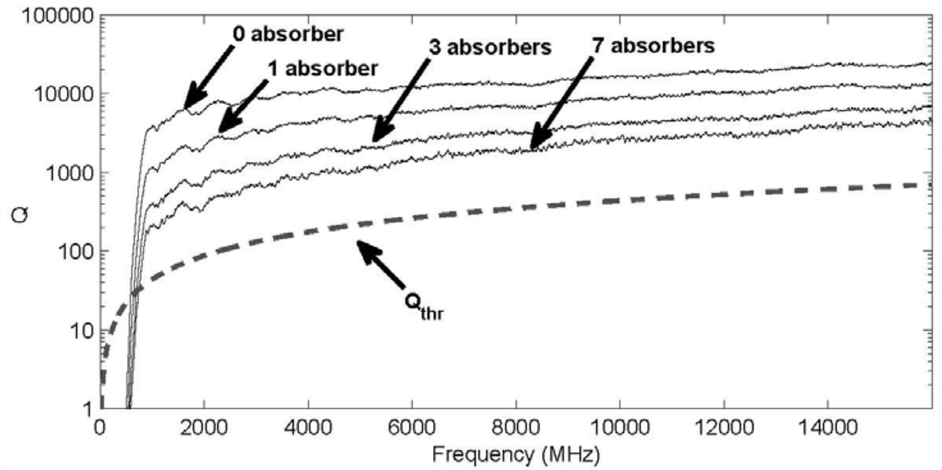
$$\tau_o = \frac{\int_0^\infty tP(t)\,dt}{\int_0^\infty P(t)\,dt}$$

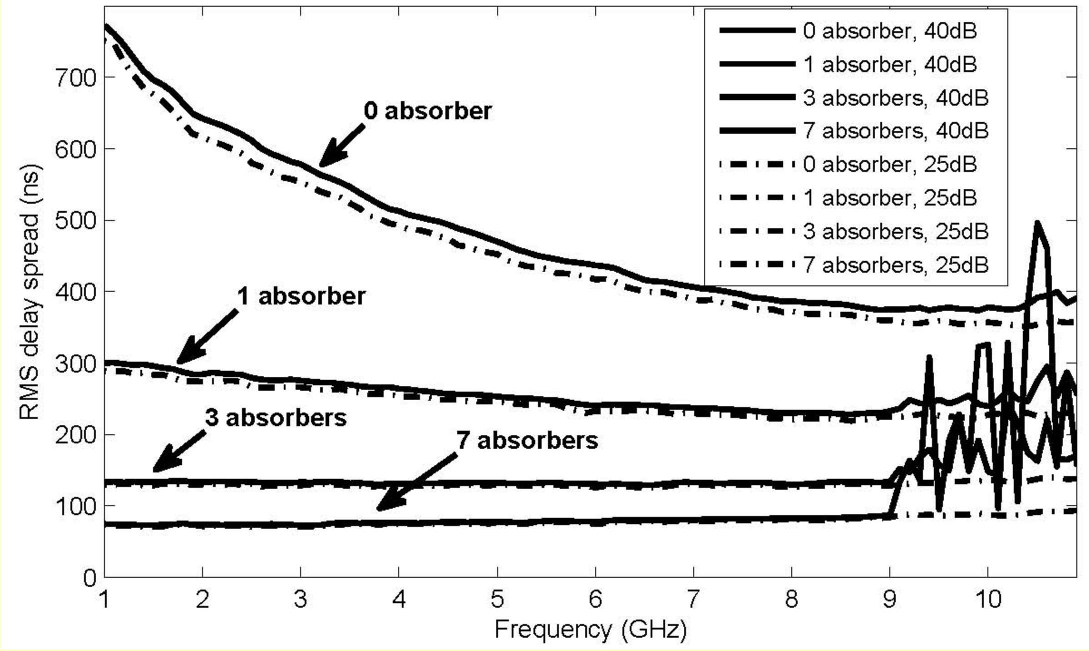
rms Delay Spreads vs Threshold Levels





Impulse Responses and rms Delay Spreads
(200 MHz band filter on S_{21} data)

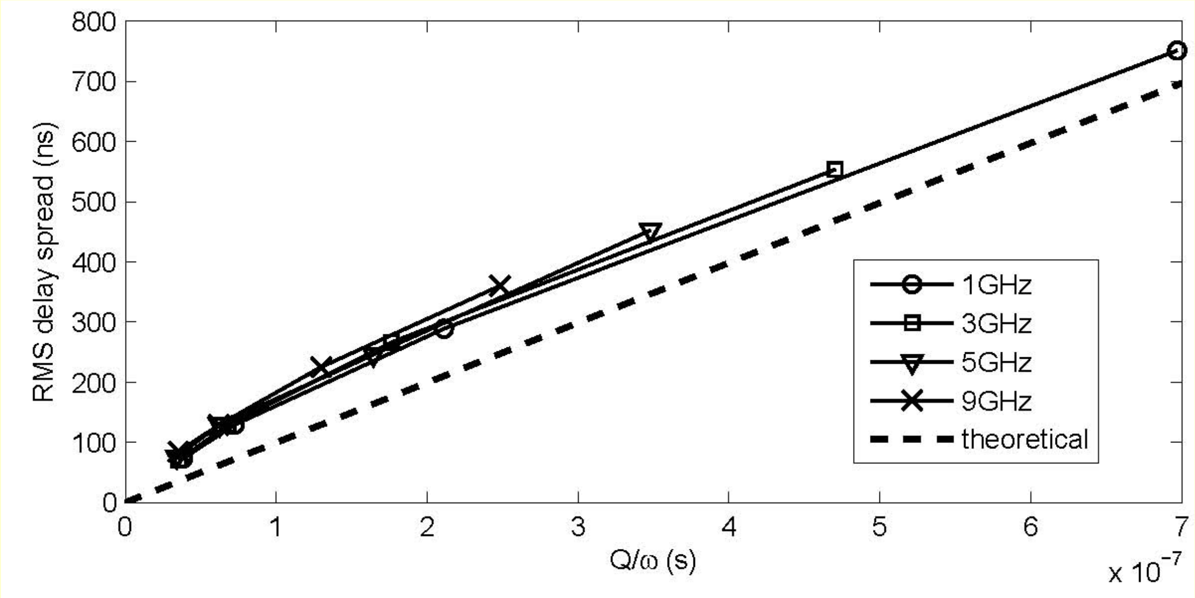




rms Delay Spreads from Q measurements

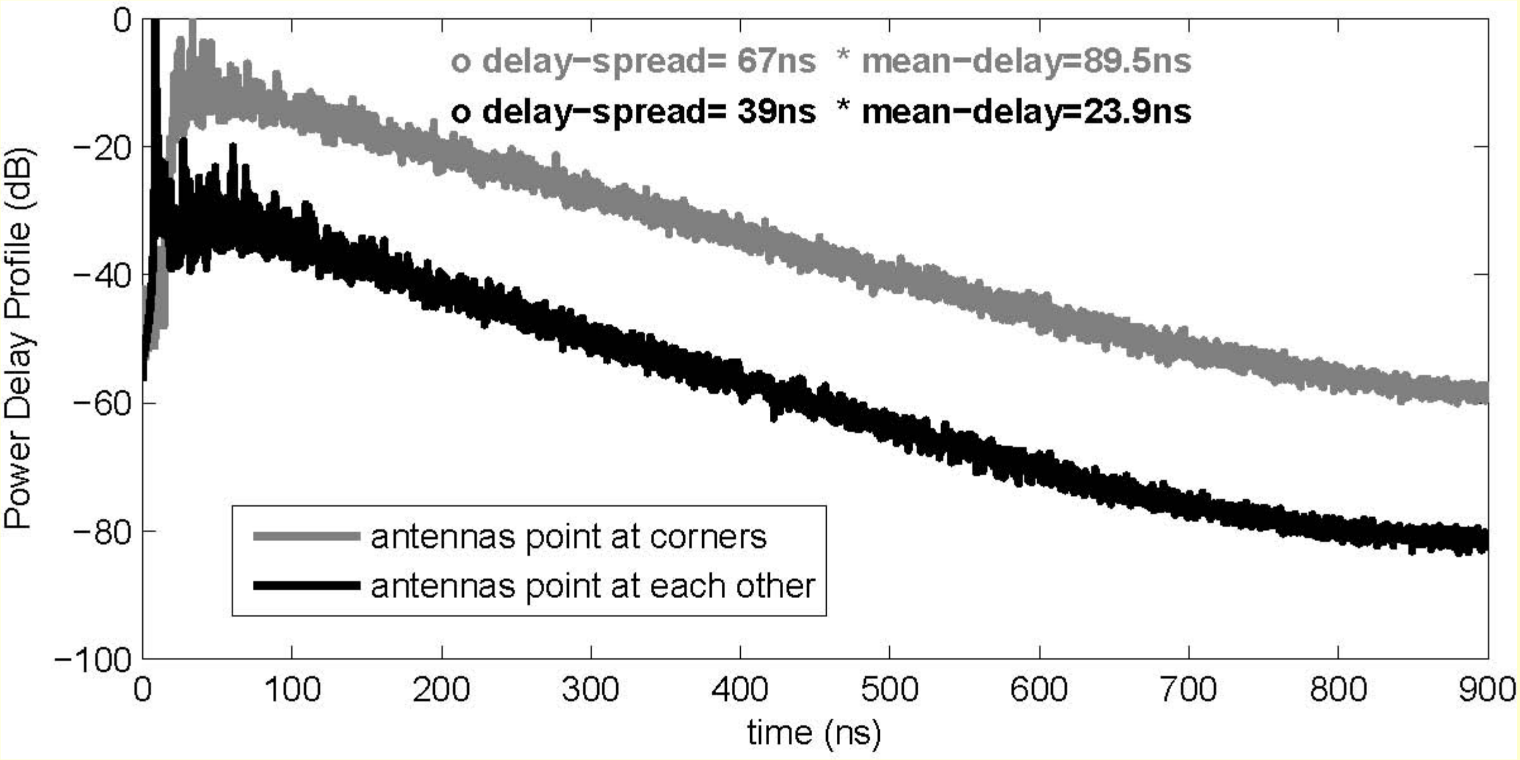
$$\tau_{rms} = \frac{Q}{\omega}\sqrt{\frac{2\alpha\,\mathbf{ln}(\alpha) - \mathbf{ln}^2(\alpha)\varepsilon - 2\alpha + 2}{(1-\alpha)+K} - \frac{(\alpha\,\mathbf{ln}(\alpha)+1-\alpha)^2}{((1-\alpha)+K)^2}}$$

where K is the k-factor and α threshold.

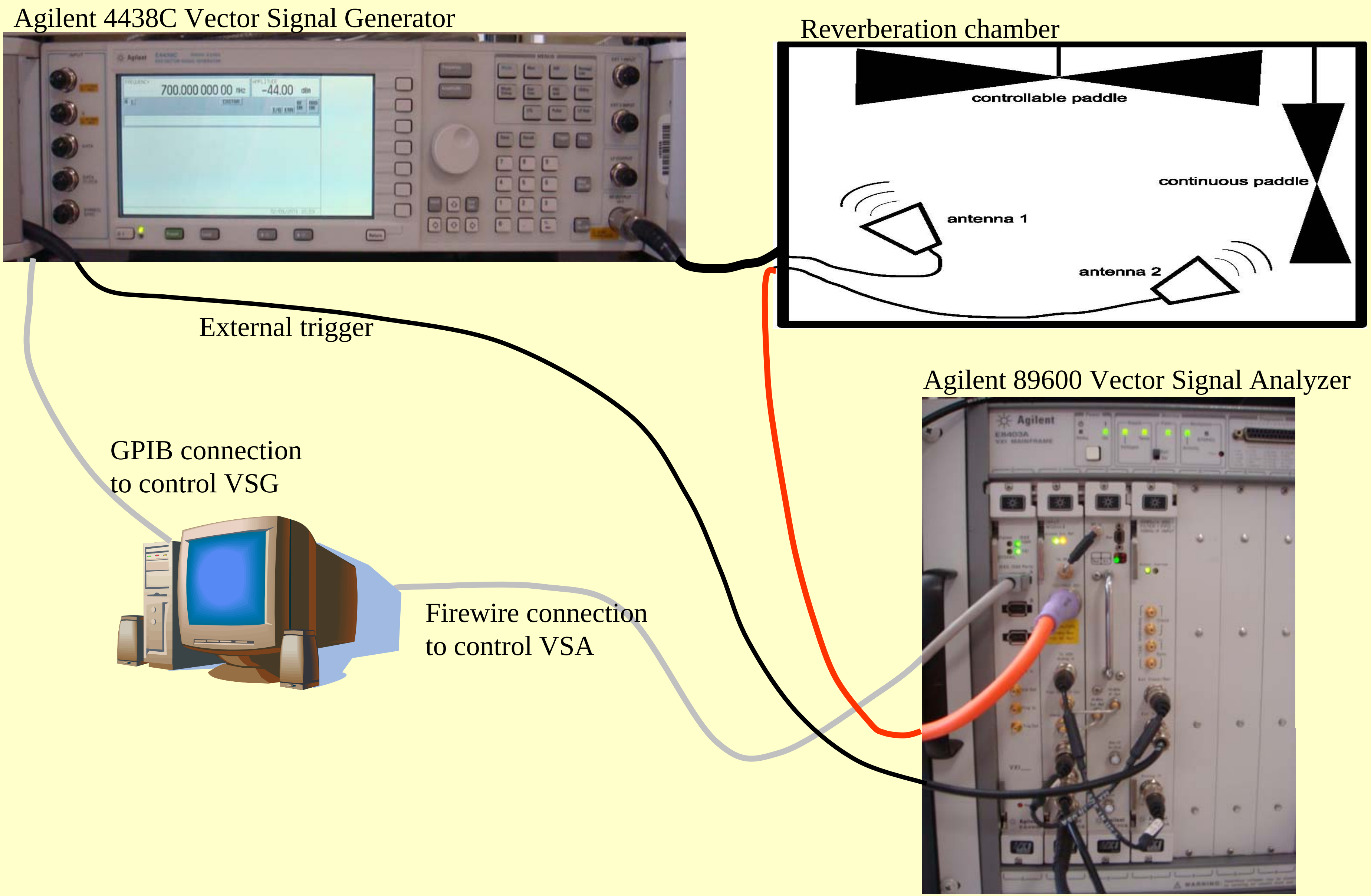


Thus, once we have *Q*, we can estimate τ_{rms}

Impulse Responses and rms Delay Spreads for Different Ricean K-factors

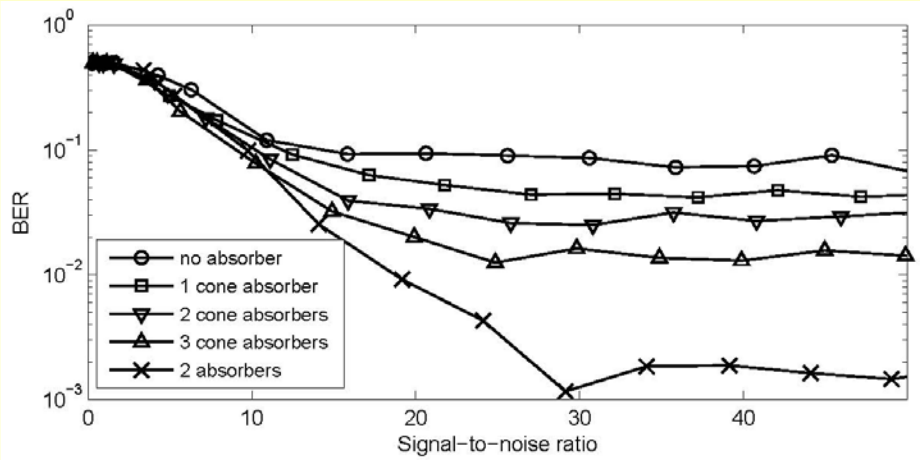


BER Measurements - setup

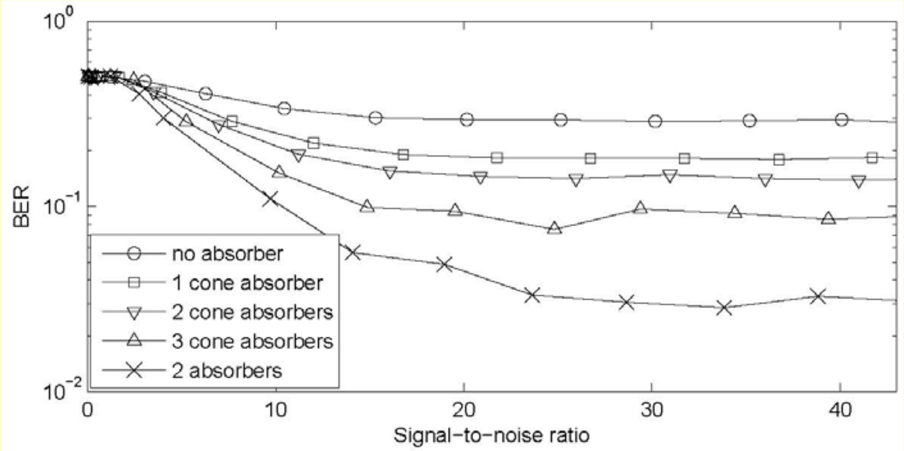


BER Measurements

BER for a 243 ksps BPSK signal

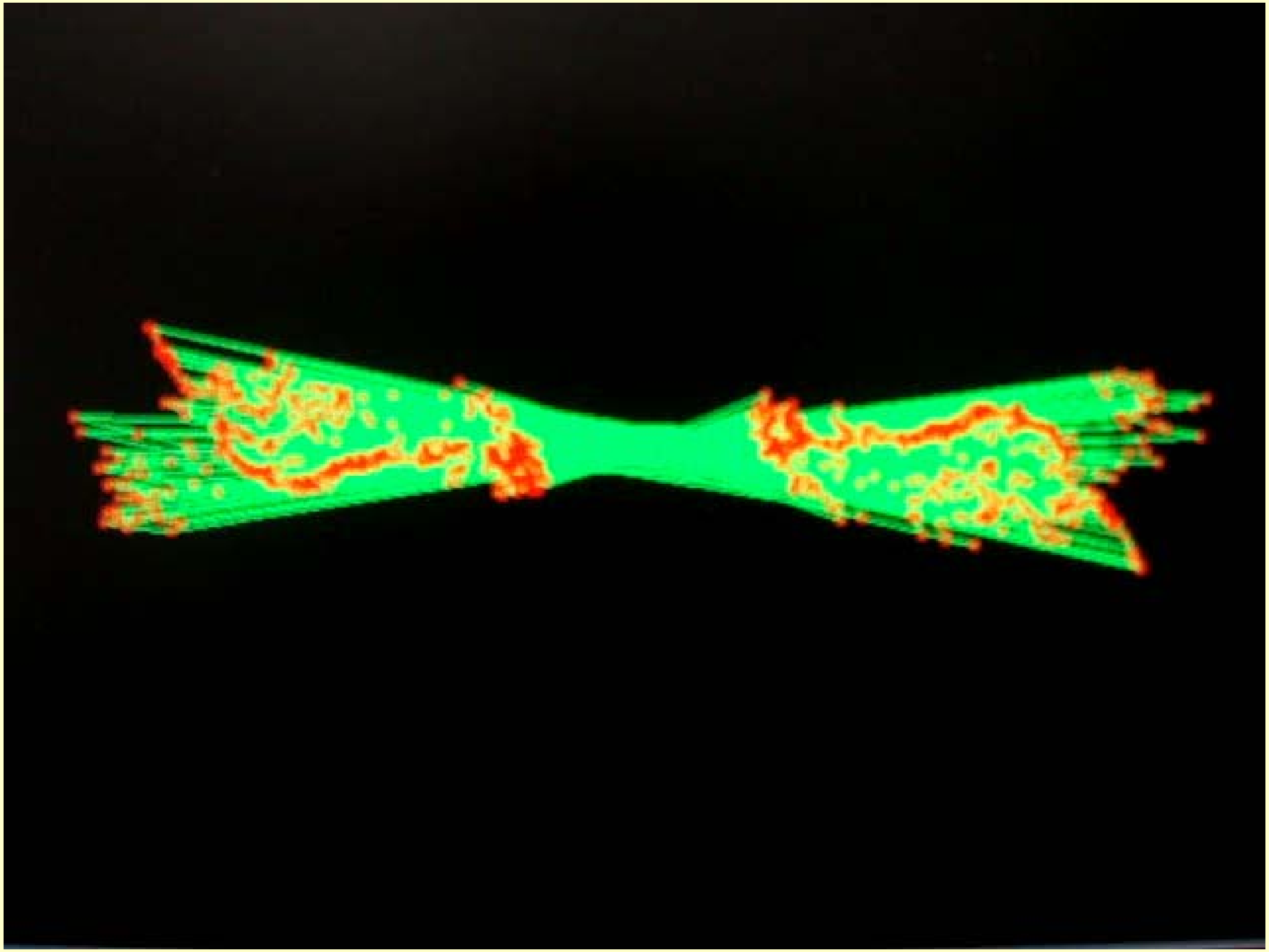


BER for a 786 ksps BPSK signal



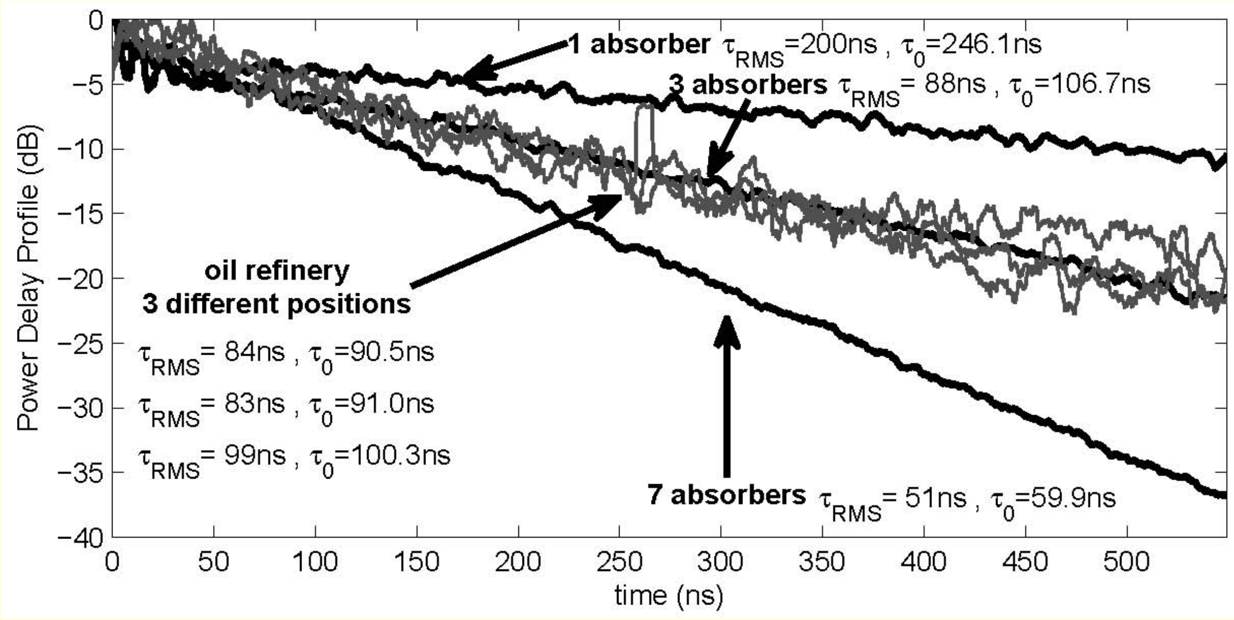
BER Measurements

Demodulated 768ksps BPSK signal in I-Q diagram



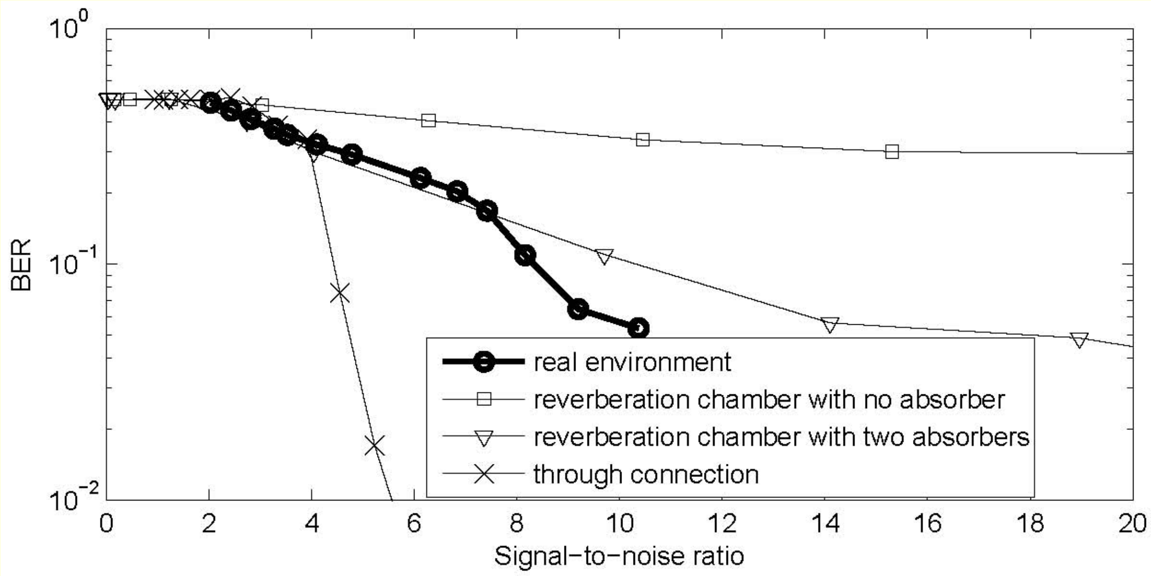
How Well Can we Simulate a Real Environment?

Power Delay Profile in an oil refinery.



How Well Can we Simulate a Real Environment?

BER measurement in a laboratory.



Wireless Measurements

1. **Reverberation chambers represent reliable and repeatable test facilities that have the capability of simulating any multipath environment for the testing of wireless communications devices.**

2. **Such a test facility will be useful in the testing of the operation and functionality of the new emerging wireless devices in the future.**

3. **Such a test facility will be useful in wireless measurements standards.**

Summary

- Reverberation chamber measurements are thorough and robust.
- Proper sampling techniques reduce measurement uncertainties
- Statistical models help minimize the number of samples required

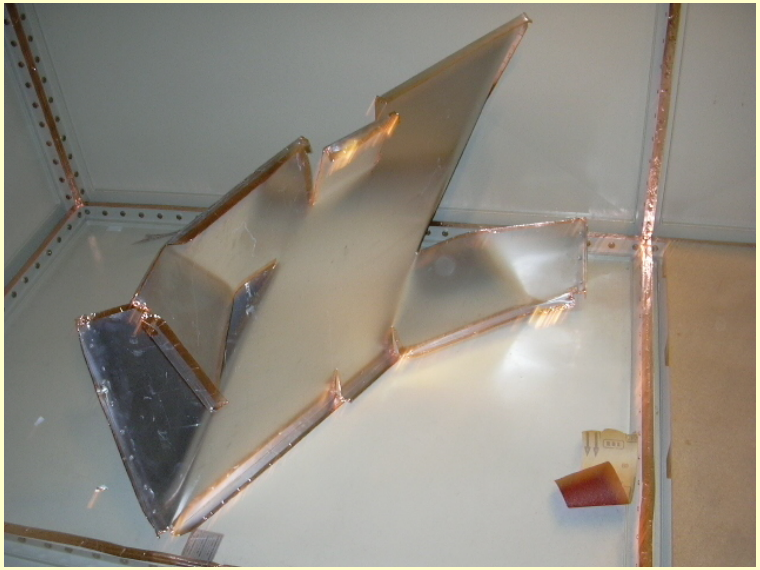
Summary

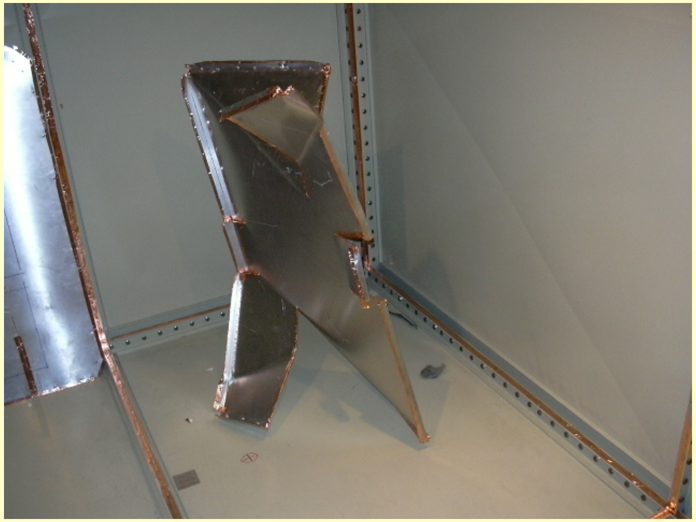
- Reverberation chambers capture radiated power (total within the measurement bandwidth)
- Results are insensitive to EUT placement in the chamber
- Results are independent of EUT or antenna radiation pattern
- Enclosed system free from external interference

Rome’s Old Chamber

Rome’s New Chamber

Rome's New Chamber





Reverberation Chamber Standards

- **International Standard IEC 61000-4-21:** *Testing and measurement techniques – Reverberation chamber test methods*