Utilizing Reverberation Chambers as a Versatile Test Environment for Assessing the Performance of Components and Systems

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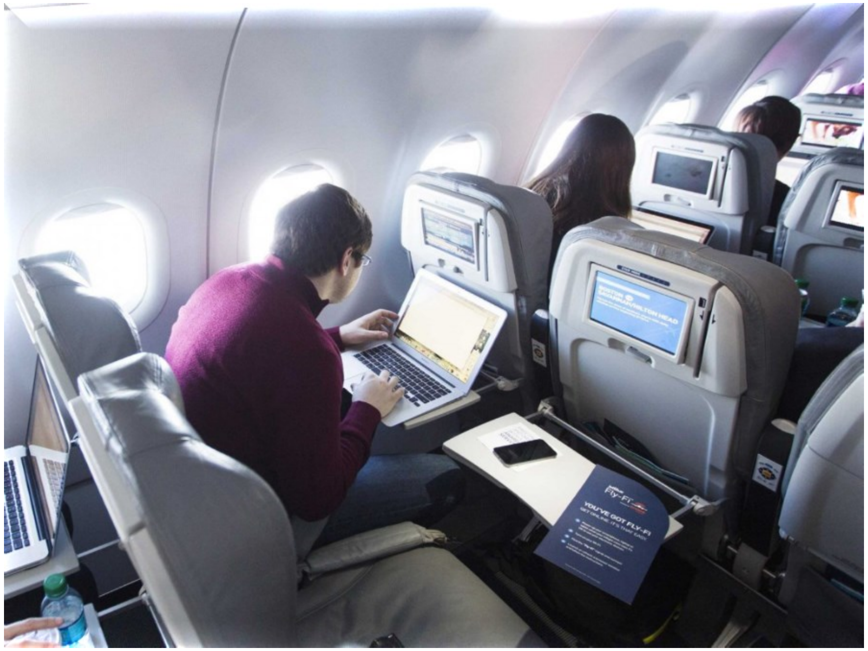
Overview

Growing need to evaluate the EM environment



http://www.businessinsider.com/r-faster-wi-fi-on-flights-leads-to-battle-in-the-sky-2014-14

- Certification
- System performance prediction/validation
- Model Validation
- Portable Electronic devices
- Wireless Sensor Networks

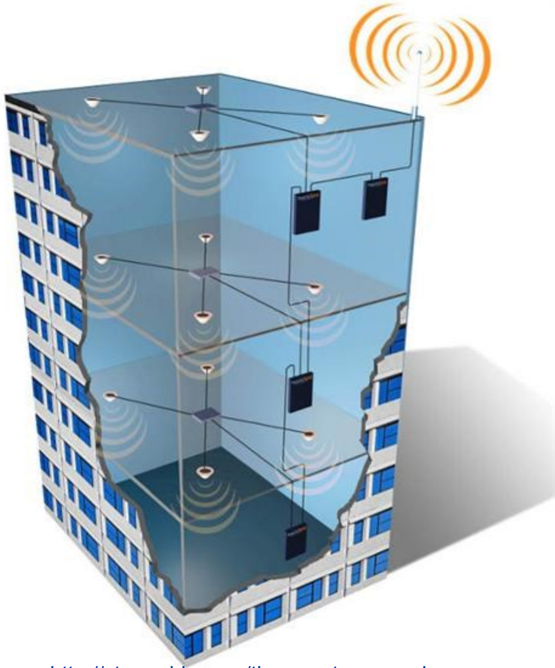
Overview

- **Some Complex Environments**
  - **Tunnels**
  - **Ships**
  - **Buildings**
  - **Aircraft**
  - **Factories**

http://www.forbes.com

http://www.theguardian.com

http://hothardware.com/News/Gogo-Inflight-Internet-Turns-1-Looks-To-Bring-WiFi-To-More-Planes/



http://xtreamblu.com/the-way-to-expand-your-wifi-signal-for-larger-office-buildings/

Agenda

- Reverberation Chambers
  - Overview
  - Discrete Frequency Stirring
- Metrology Application of Reverberation Chambers
  - Probe Calibration
  - Antenna Efficiency
- Measurement Applications
  - Component Shielding
  - Aircraft Shielding
  - Bulk Absorption
  - Field Mapping
  - Wireless propagation measurements

What is a Reverberation Chamber?

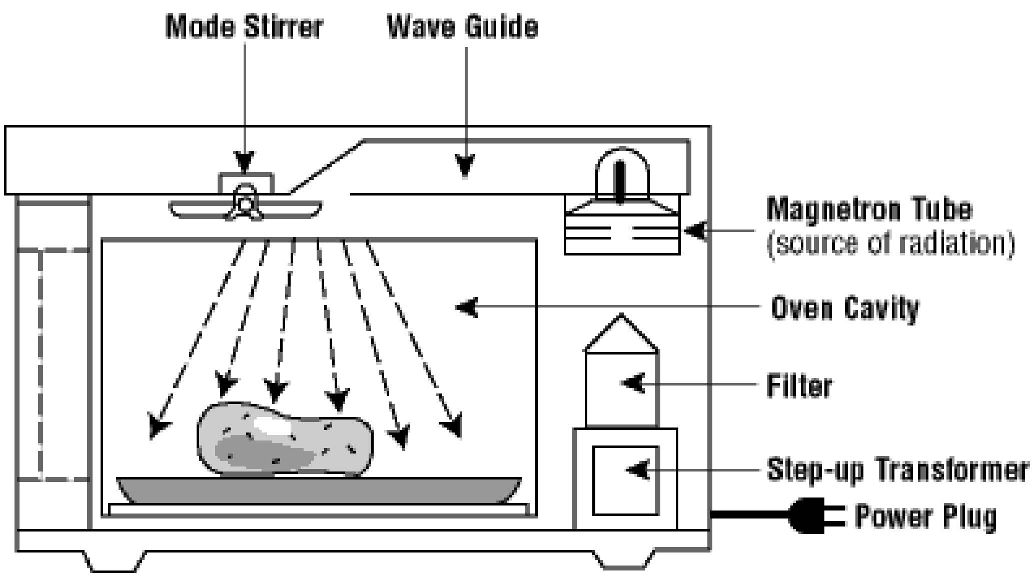
- **Shielded enclosure / cavity in which the test electromagnetic environment is <u>statistically</u>:**
  - Isotropic
  - Randomly polarized
  - Homogeneous

Permitted Modes

$$f_{lwh}(MHz) = 150\sqrt{\left(\frac{l}{L}\right)^2 + \left(\frac{w}{W}\right)^2 + \left(\frac{h}{H}\right)^2}$$

Lowest allowable mode

$$f_{110}(MHz) = 150\sqrt{\left(\frac{1}{L}\right)^2 + \left(\frac{1}{W}\right)^2 + \left(\frac{0}{H}\right)^2}$$



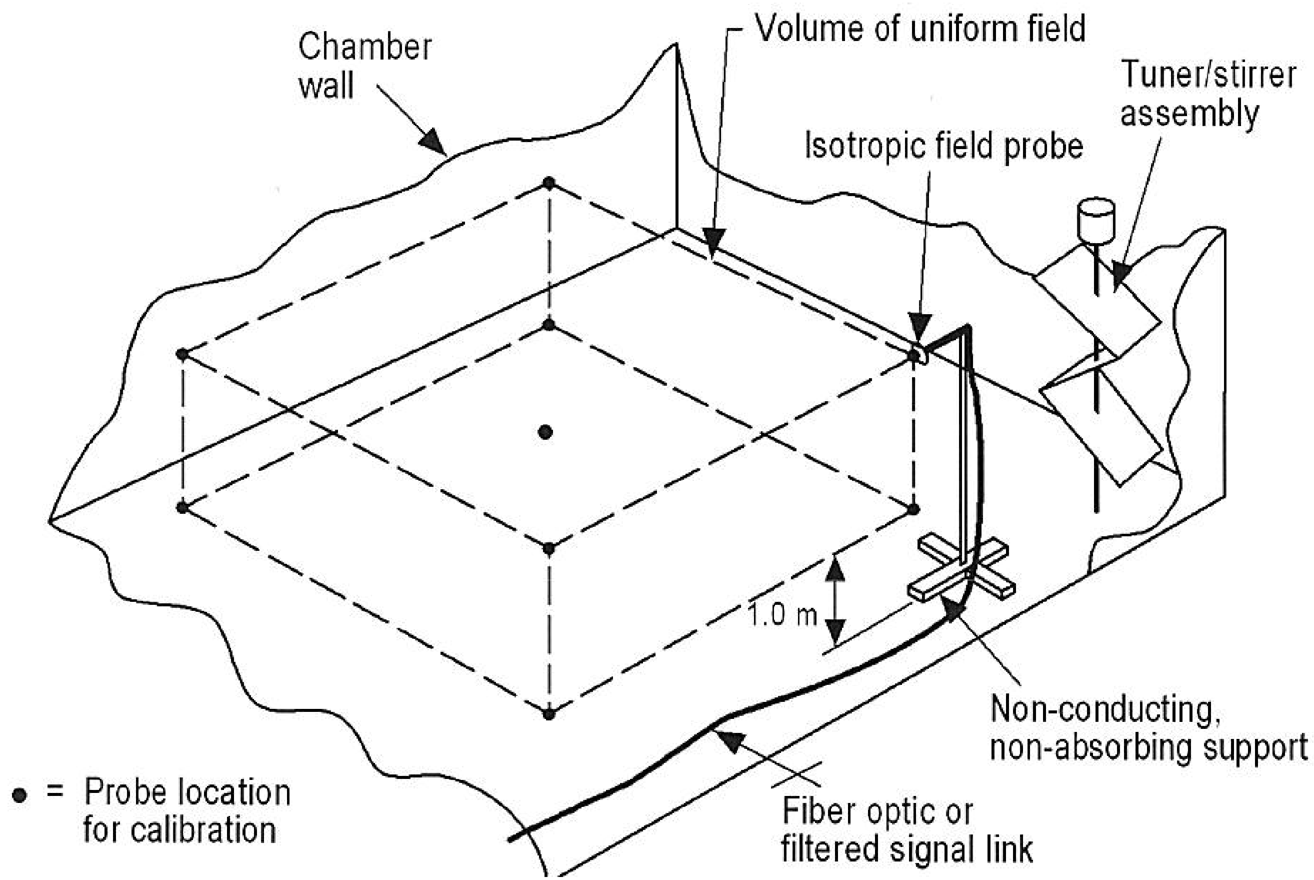
http://www.ccohs.ca/oshanswers/phys_agents/microwave_ovens.html

What is a Reverberation Chamber?

Independent Samples

* **Independent (non-correlated) and complex cavity modal structures key to reverberation chamber operation.**
  - Provides variability in cavity field structure necessary to obtain isotropy and random polarization.
  - Necessary for statistical analysis of data sets
* **Boundary conditions at successive tuner positions may be correlated**
  - Tuner dimensions too small with respect to:
    - Wavelength
    - Chamber dimensions
  - Tuner geometry too symmetric
  - Tuner step size too small

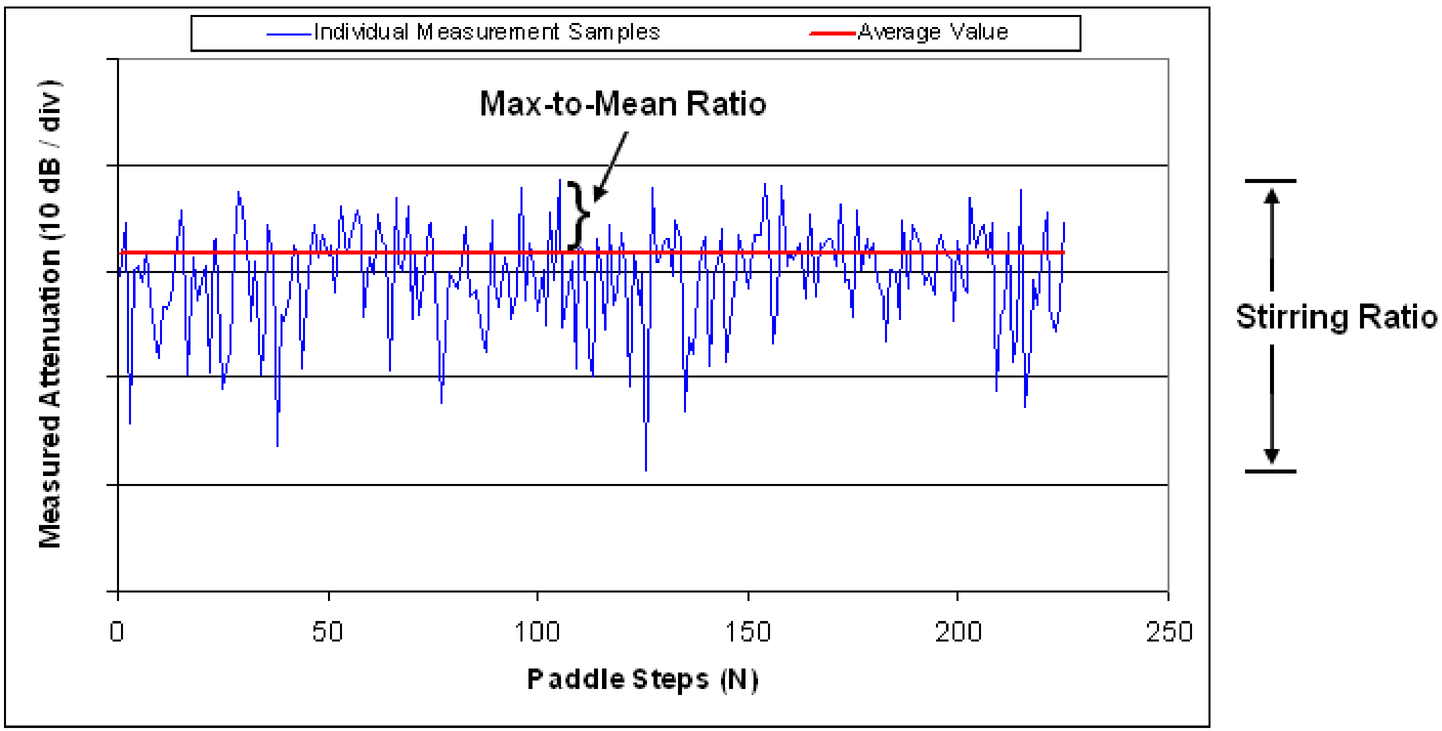
What is a Reverberation Chamber?



What is a Reverberation Chamber?

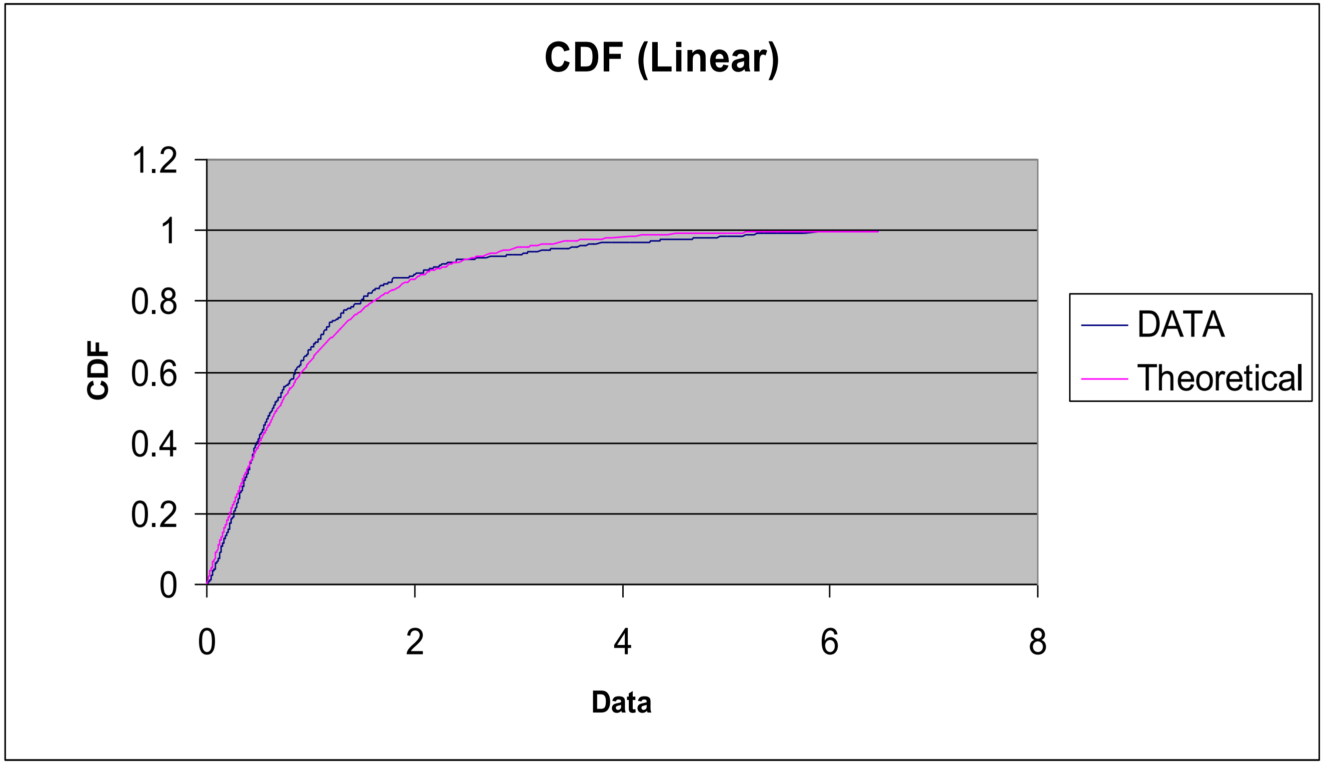
Measured MS data from Small Met Chamber @ 3 GHz…

Take this data at each frequency of interest



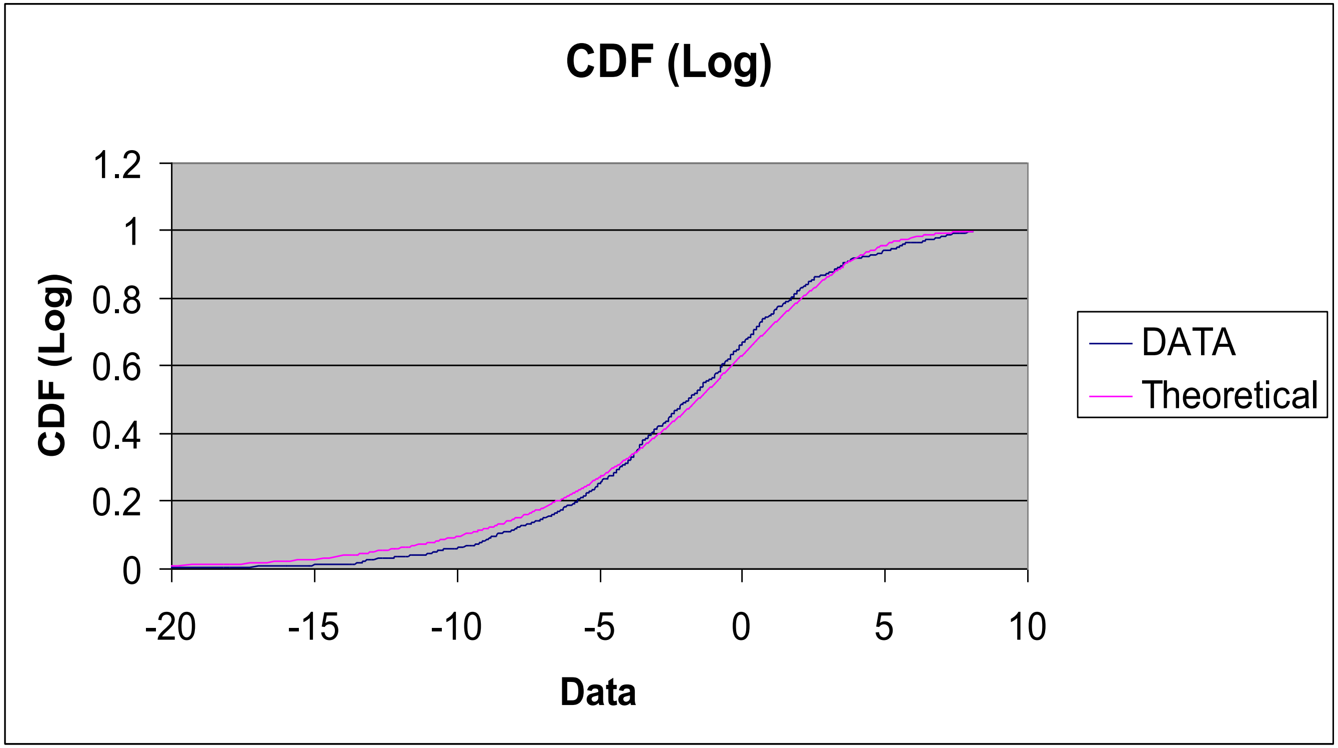
What is a Reverberation Chamber?

Mean Norm Power (mW)



What is a Reverberation Chamber?

Mean Norm Power (dB)

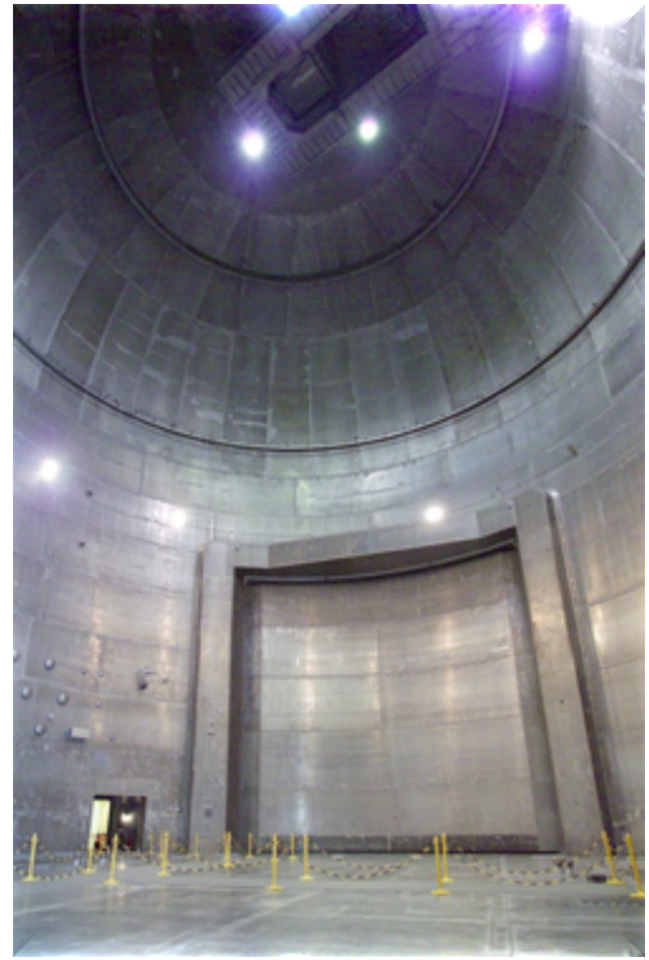


What is a Reverberation Chamber?

NIST Technical Note 1508 “Evaluation of the NASA Langley Research Center mode-Stirred Chamber Facility”

What is a Reverberation Chamber?

http://en.wikipedia.org/wiki/File:Magdeburg-reverberation_chamber.jpg



NASA Glen Research Facility

(100 ft Diameter 120 ft. Tall)

What is a Reverberation Chamber?

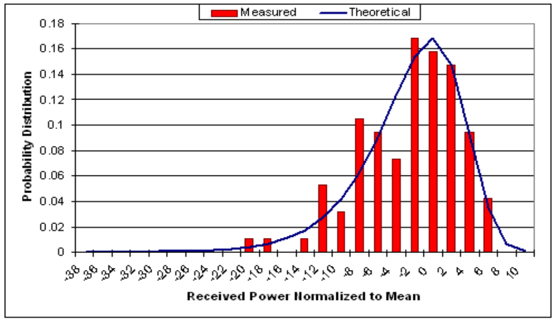
Photos courtesy of ETS-Lindgren

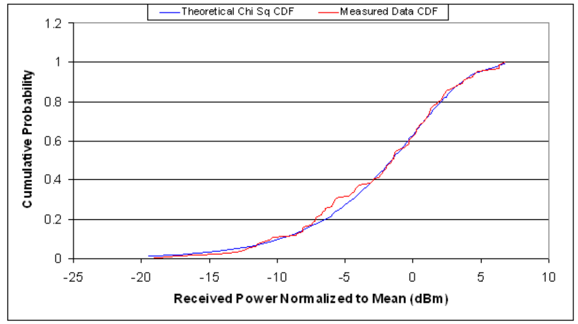
What is a Reverberation Chamber?

737-400 Inside Paint Hangar

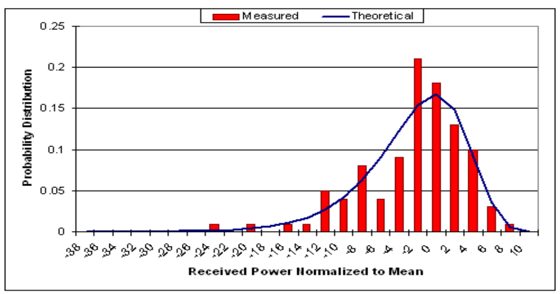
767-400 Inside Paint Hangar

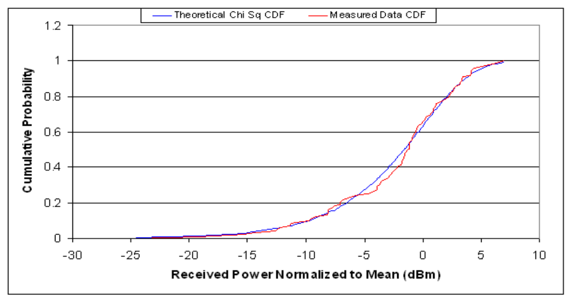
What is a Reverberation Chamber?



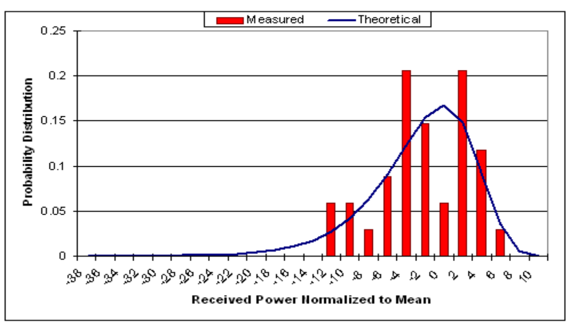


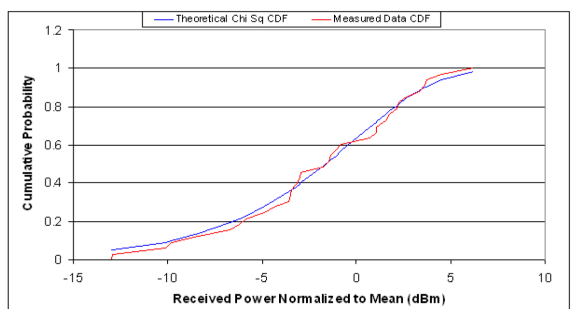
Reverb chamber





Paint hangar





Main passenger cabin

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  - Wireless propagation measurements

EMC SOCIETY

Background

Mechanical Mode Stir (MS)

- First proposed in 1968 as a statistical approach to field evaluation in shielded enclosures.
- Excitation of an electrically large, high-Q enclosure establishes a complex, random EM field.
- Perturbation of this field – by an electrically large, conductive paddle wheel for mechanical stir – results in a statistically uniform field.
- Investigated by Boeing in 1993 as a method for evaluating aircraft shielding.
- Used for HIRF testing in 1998 to support 757-300 cert.

"Small Metrology Chamber"

Background (cont.)

Frequency Stir (FS)

- Equivalency to mechanical mode stirring, first suggested in 1989.
- Field perturbation accomplished by changing the frequency of the excitation source.
- Frequency stir by the method of superimposed band-limited, white Gaussian noise (BLWGN) established in 1991 – adopted by Boeing a few years later and referred to as Gaussian Frequency Stir (GFS) method.
- GFS proposed as a viable approach for 757-300 HIRF testing.
- GFS used for 767-400 HIRF testing in 2000.

Motivation for Alternative Mode Stir Method

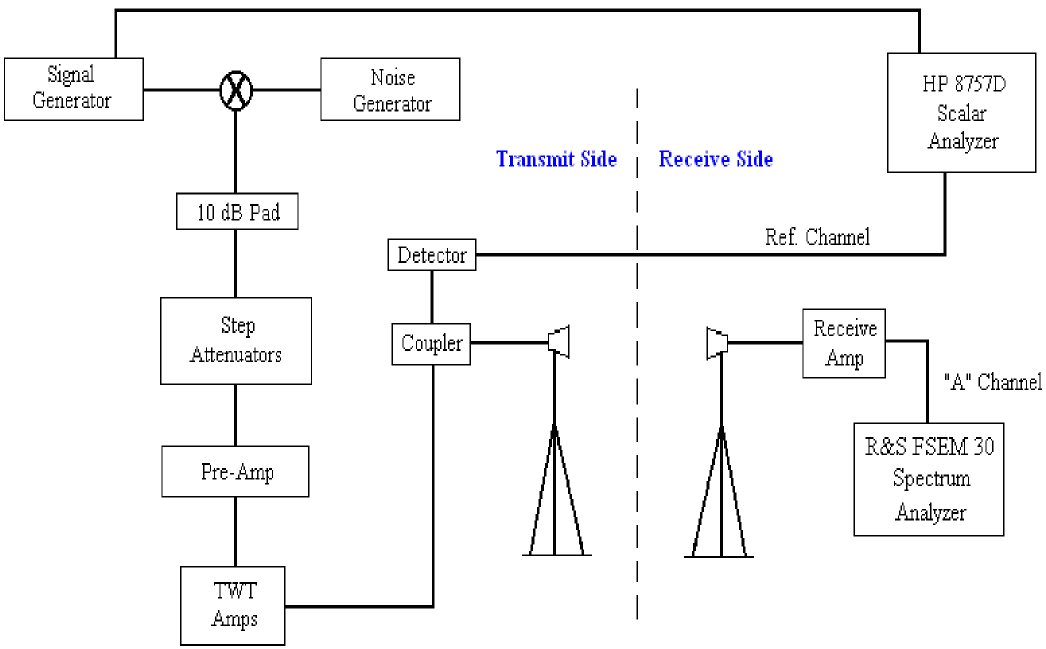
- **Why do we need another mode stir measurement method??**
  - Mechanical stir is very time (and therefore $$) intensive – must wait for complete paddle rotation, measuring the field after each small change in paddle position, at each frequency being measured.
  - Effective stirring with paddles can be a major concern with abnormally shaped cavities (i.e. a passenger cabin with seats & overhead bins).
  - GFS is equipment intensive = costly to maintain, difficult / costly to move around, higher measurement uncertainties.
  - GFS is a broadband measurement which reduces achievable dynamic range.
  - Loose statistical data with GFS.

GFS -- Gain speed vs. mechanical stir, but…

take some performance hits & loose statistical data!

Motivation for Alternative Mode Stir Method (cont.)

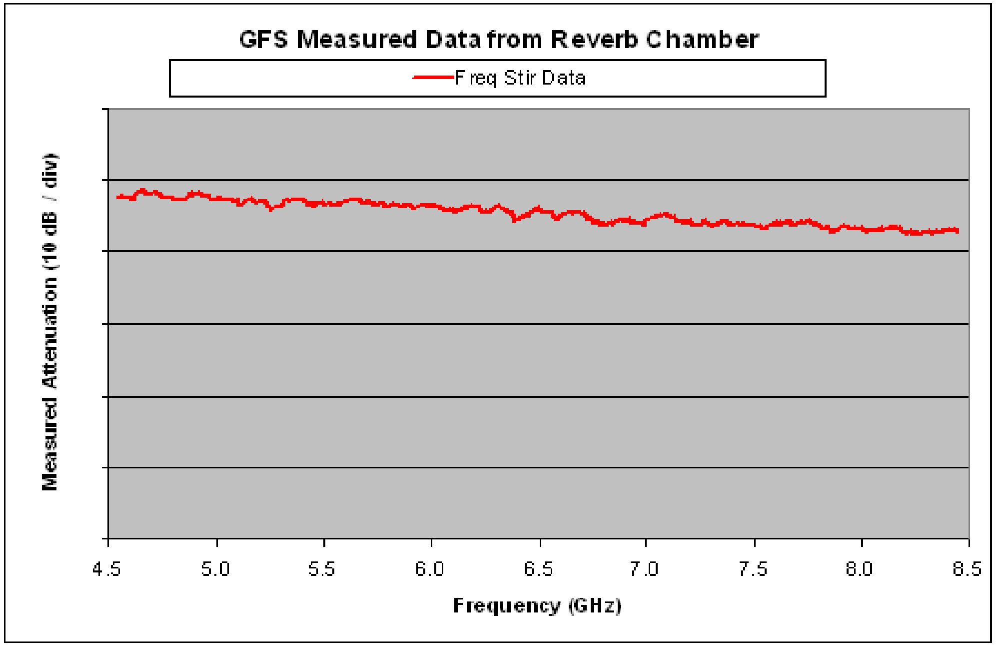
- **GFS is “equipment intensive”…**



GFS Block Diagram

Motivation for Alternative Mode Stir Method (cont.)

- **GFS measured data and processing…**



GFS method provides only the frequency stirred data – the average field values.

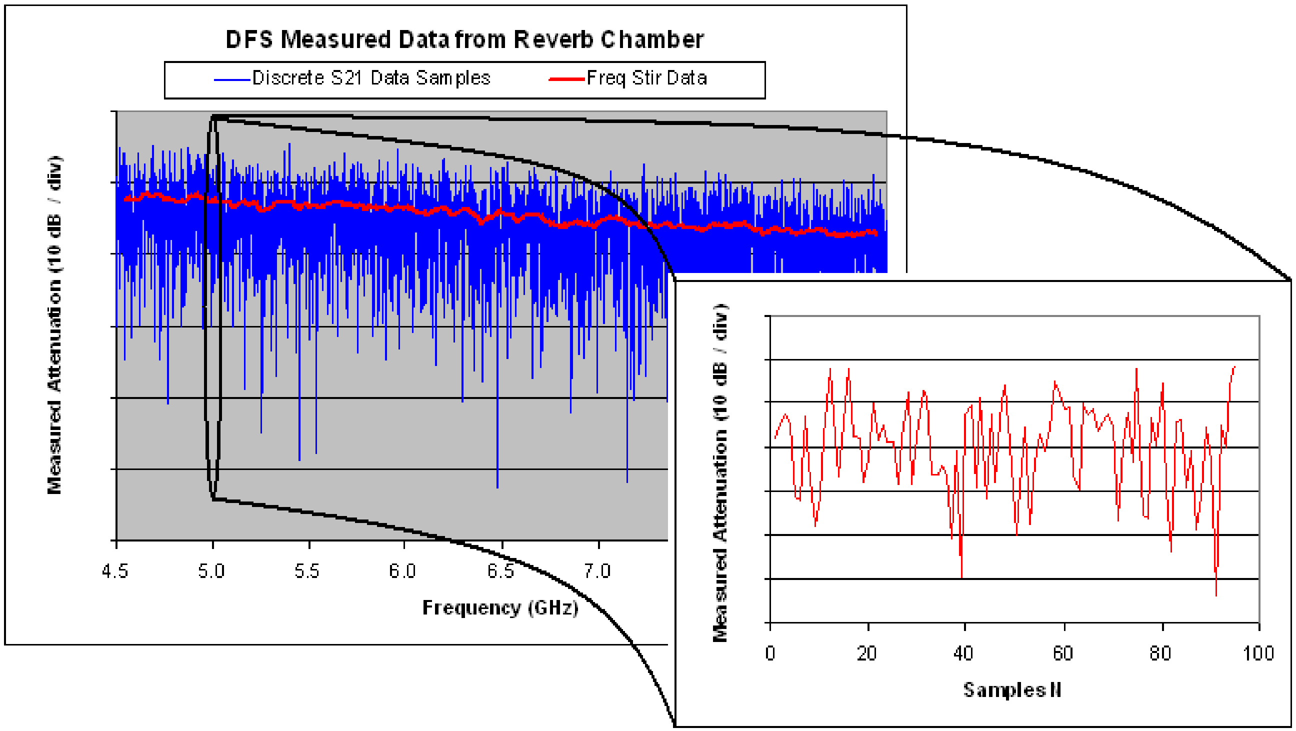
Further data processing and statistical analysis not possible.

Discrete Frequency Stirring

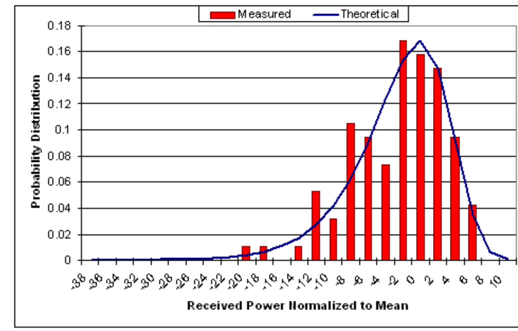
- The **Discrete Frequency Stir (DFS)** technique allows for better, faster, cheaper mode stir...
  - Electrical perturbation of cavity fields (no mechanical paddle need for stirring) – effected by frequency stepping a CW excitation source (narrow-band measurement = better dynamic range).
  - "Frequency stir" by averaging over stirring bandwidth – typically use 100 or 200 MHz stirring bandwidth above 1 GHz (need to consider sample size and frequency resolution)
  - Simple setup based on Agilent 8362 Precision Network Analyzer (PNA) – easy to move around large test article and easy to transport to remote test site
  - Fast data acquisition (50 to 80% faster than GFS) – reduce test time, save $$
  - Discrete measurement at each frequency step provides statistical data

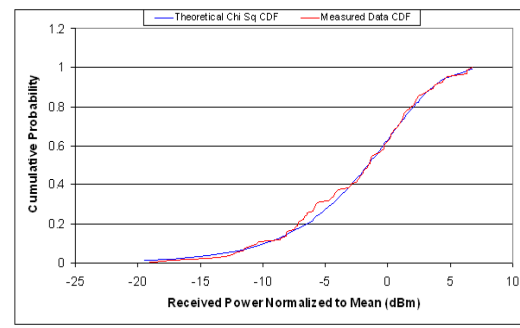
Discrete Frequency Stirring

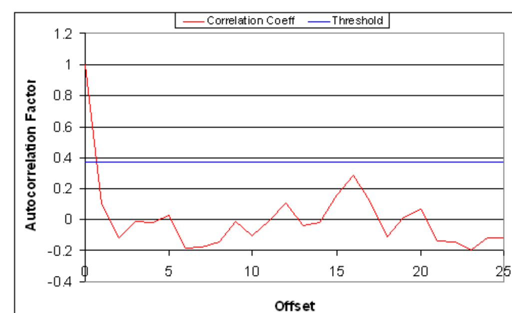
- **DFS measured data and processing…**



Statistical Analyses







Measurement of discrete data samples allows for further processing and statistical analysis

Discrete Frequency Stirring

- **Important characteristics to monitor with DFS:**
  - **Field Uniformity –** variation in average field values within a given cavity
    - Critical to measurement uncertainty
    - Driven by number (N_{ind}) of independent resonant modes excited within the stirring bandwidth (BW_{stir}) [7]
    - For a given cavity, total number (N) of modes within stirring bandwidth can be determined from Weyl's approximation as…

$$N = \frac{8\pi V}{c^3} f^2 BW_{stir}$$

    - Need to account for mode overlap due to non-zero resonant mode bandwidth (BW_Q) [7]

$$\Rightarrow \quad BW_Q = \frac{f}{Q}$$

    - In practice, N_{ind} will be limited as…

$$N_{ind} \leq \frac{BW_{stir}}{BW_Q}$$

Discrete Frequency Stirring

- **Important characteristics to monitor with DFS:**
  - **Sample independence**
    - Affects field uniformity as discussed on previous slide
    - Necessary for statistical analysis of data sets
    - Determined by Pearson's *r* autocorrelation check

$$r = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2}\sqrt{\sum_i (y_i - \bar{y})^2}}$$

where the *x*'s represent a data set and the *y*'s represent the same data set shifted by one so that x_2 has become y_1 and x_3 has become y_2, etc.

    - Uncorrelated when *r* is less than *1/e*

Discrete Frequency Stirring

– **Statistical Analysis…**

- To assess conformity of measured fields to theoretical field distributions for reverberation chambers.
- For a given frequency, only data samples within the stirring bandwidth are used for statistical analysis.
- Theoretical reverb chamber field distributions well established in literature: magnitude of individual field components (Ex, Ey, or Ez) is chi-distributed with 2 degrees of freedom; measured power is chi-square distributed with 2 degrees of freedom [8], [9].
- Chi-square probability distribution function (PDF) is:

$$f(p) = \frac{1}{2\sigma^2} e^{-p/2\sigma^2}$$

where σ is the std dev of underlying normal distributions [8].

Discrete Frequency Stirring

– **Statistical Analysis (cont.)…**

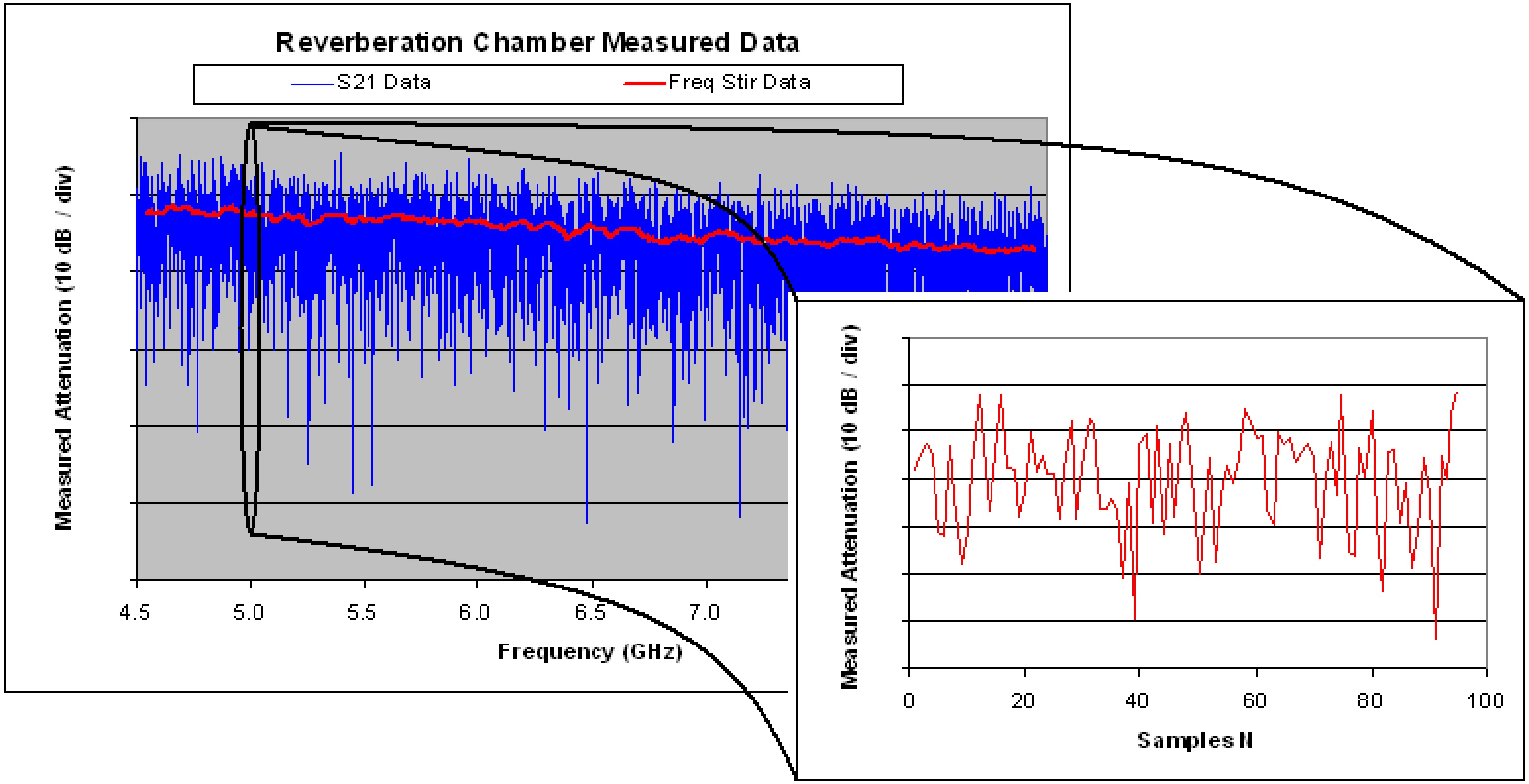
- Goodness of fit tests used to compare measured data distributions to theoretical distribution…
  - Chi-square test – calculate chi square statistic for assessment of binned, normalized data verses an integration of the theoretical probability distribution function
  - K-S test – assessment of maximum deviation from the theoretical cumulative distribution function
- Independent samples necessary for statistical analysis

Discrete Frequency Stirring

- **As an example, look at data from the Small Metrology Chamber comparing Mode Tuning to DFS measurement technique**
  - Chamber dimensions were 1.77 x 1.52 x 2.29 meters (length x width x height)
  - Resonant mode bandwidth was estimated to be less than 1 MHz across the 1-18 GHz measurement range
  - Frequency step size of 1.1 MHz was used, providing 95 measurement samples within stirring bandwidth of 100 MHz
  - Measurement samples verified to be independent
  - 1 Transmit, 3 Receive positions measured
  - Uniformity was ±1 dB

Discrete Frequency Stirring

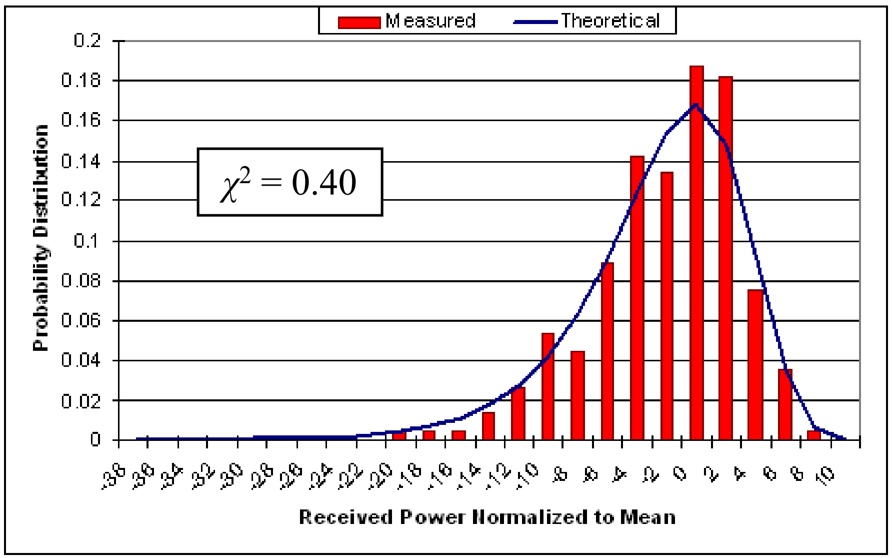
Small Metrology Chamber **measured data:**



Discrete Frequency Stirring

To compare, Small Met Chamber **field distribution using MT:**

Chi-square Test

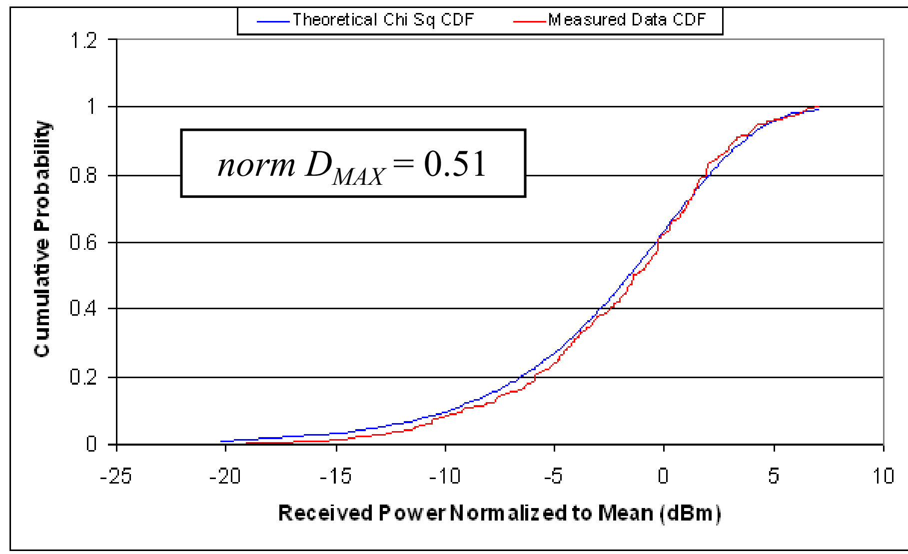


$Ave.\ \chi^2 = 0.84$

32% of data sets showed

$\chi^2 < 0.65$ (90% CL)

K-S Test



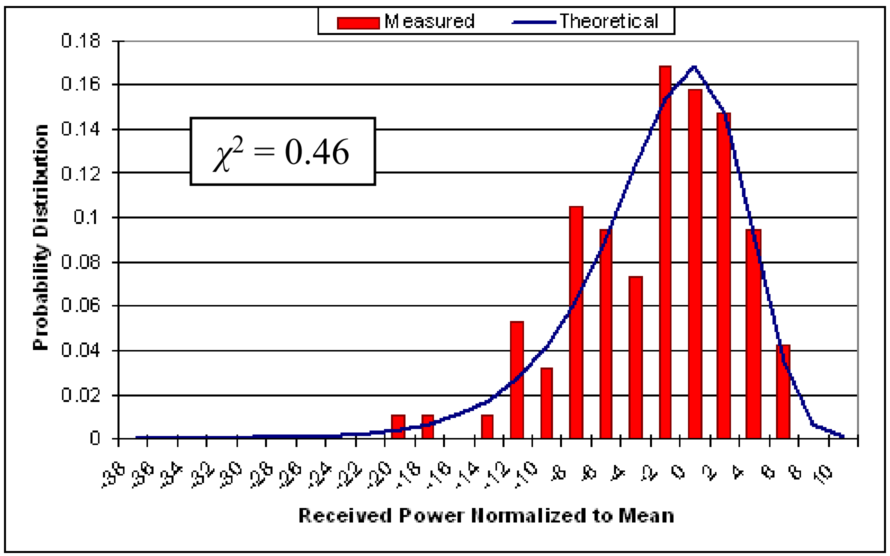
$Ave.\ norm\ D_{MAX} = 0.56$

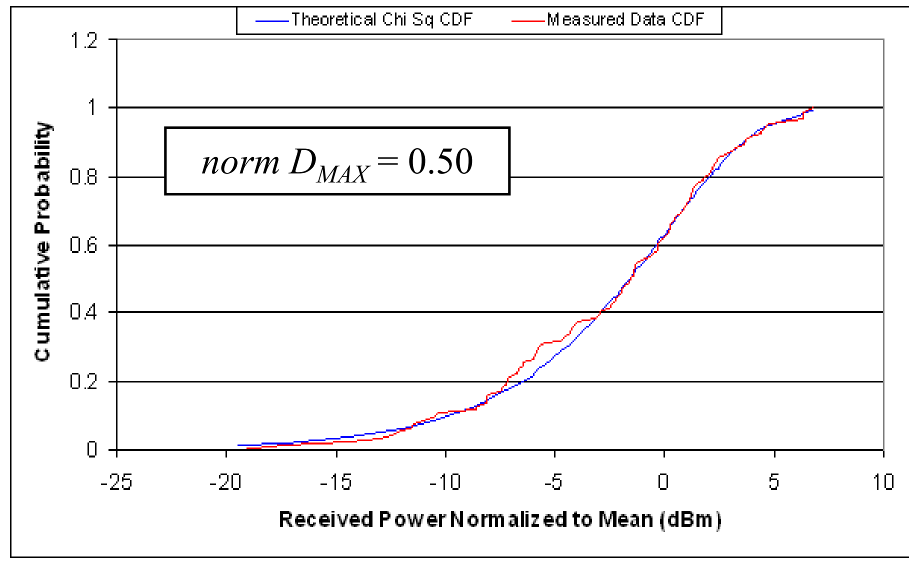
(Statistical data at 3 GHz shown; analysis done every 1, 2,…18 GHz)

Discrete Frequency Stirring

Small Met Chamber **field distribution using DFS:**

Chi-square Test **K-S Test**





$Ave.\ \chi^2 = 0.84$

50% of data sets showed

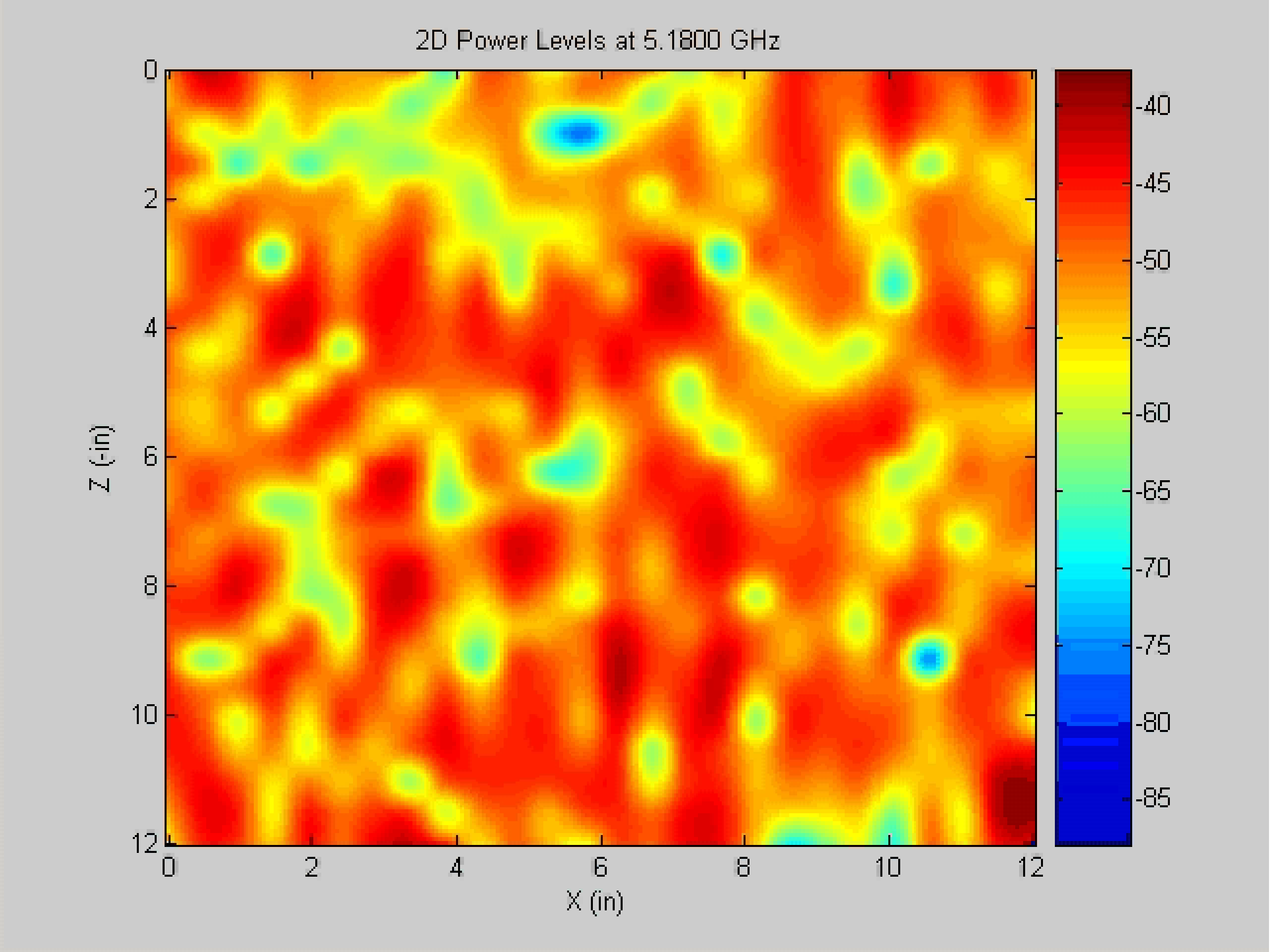
$\chi^2 < 0.65$ (90% CL)

$Ave.\ norm\ D_{MAX} = 0.53$

(Statistical data at 5 GHz shown; analysis done every 1, 2,…18 GHz)

Discrete Frequency Stirring

Measured data across 12” x 12” grid



Agenda

- Reverberation Chambers
  – Overview
  – Discrete Frequency Stirring
- **Metrology Application of Reverberation Chambers**
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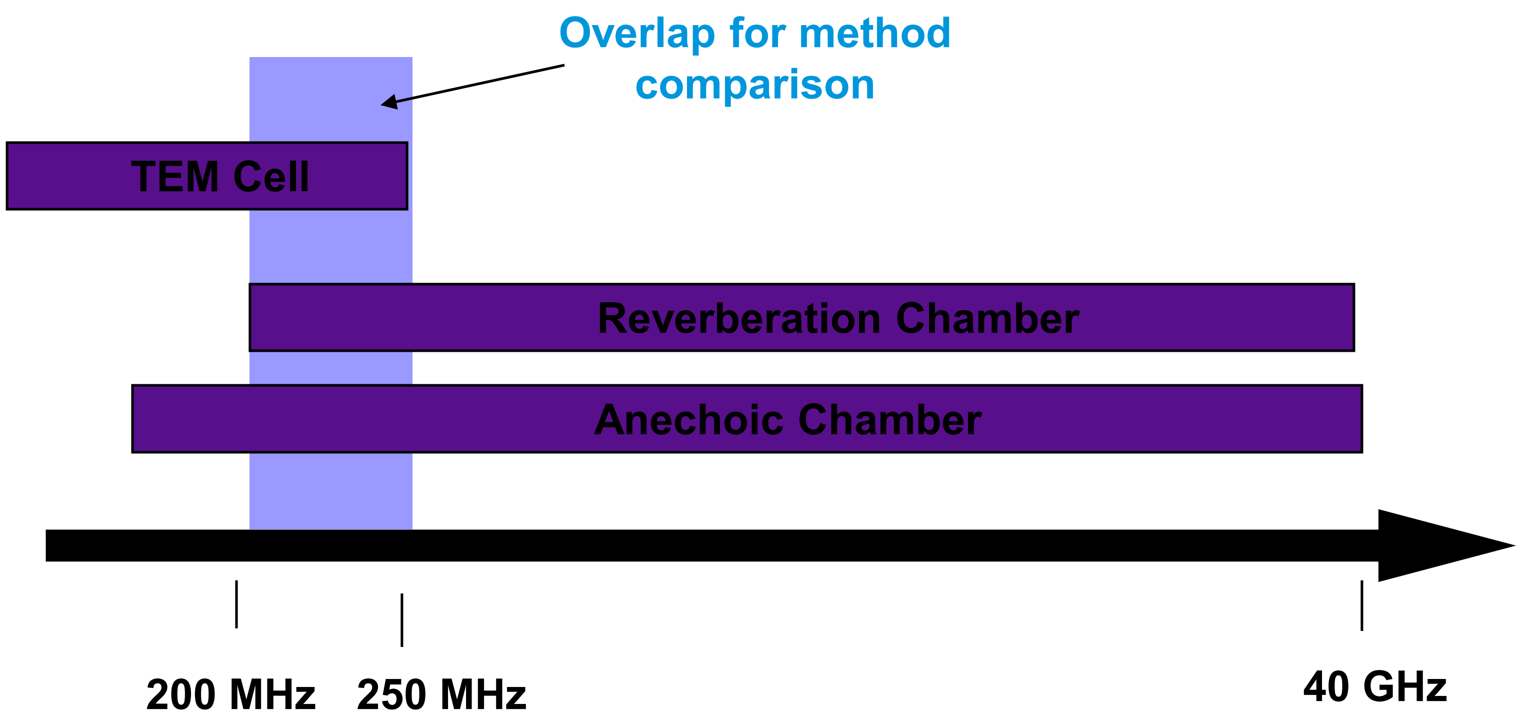
Metrology Applications of Reverberation Chambers

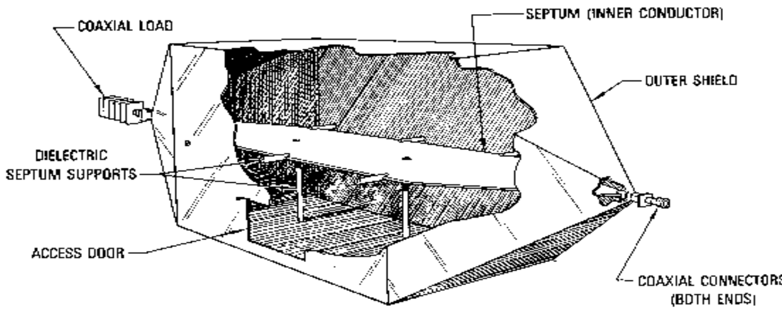


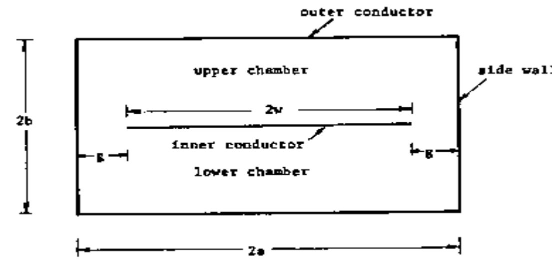
Metrology Applications of Reverberation Chambers

TEM Cell

- Transverse Electromagnetic Mode of Propagation (primary mode)
- Allow higher order modes of propagation higher frequencies (TE, TM)
- Work very well at low Frequencies

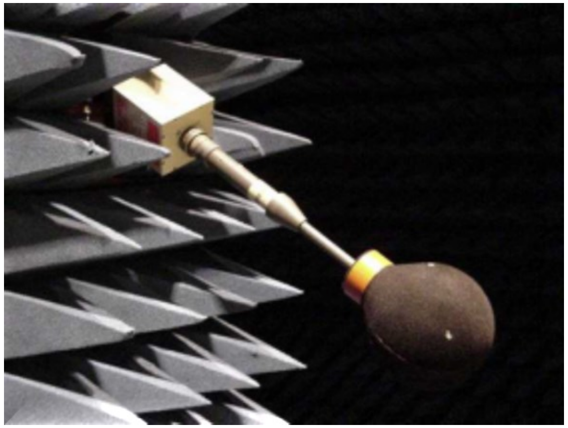
$$E = \frac{\sqrt{P * R}}{d} = \frac{V}{d} = \frac{Volts}{Meter}$$





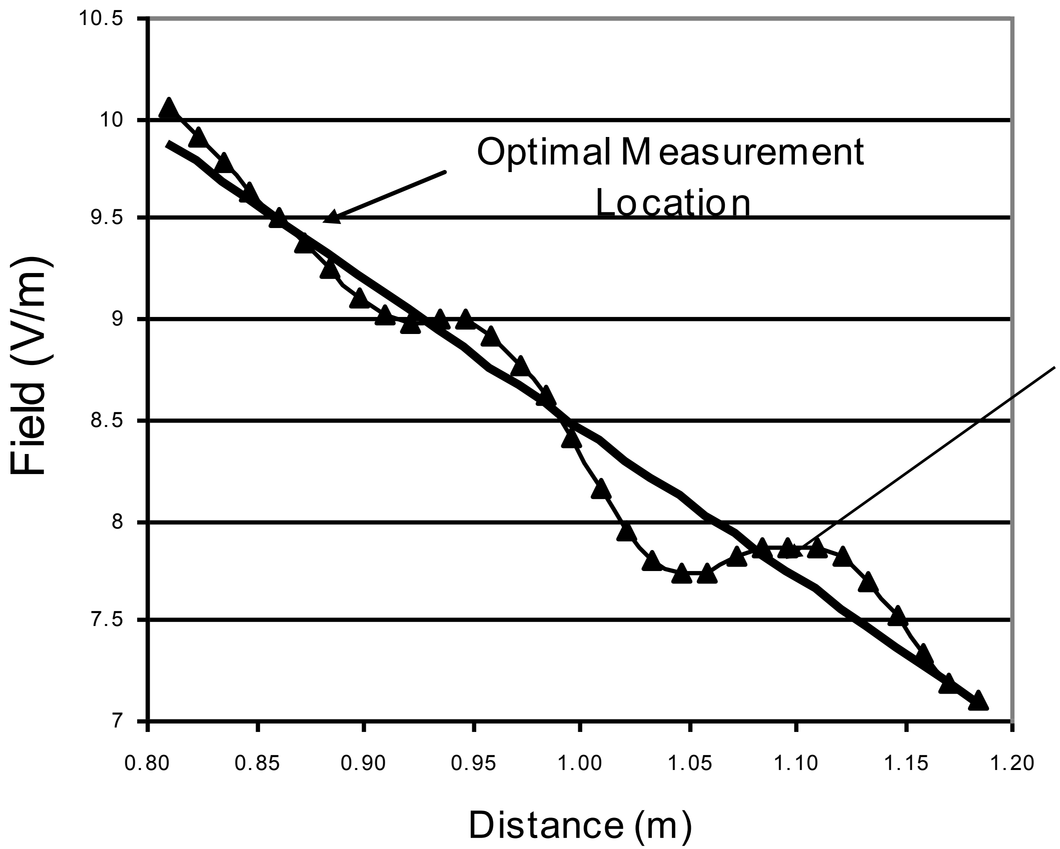
Metrology Applications of Reverberation Chambers

Gain Extrapolation Range



Metrology Applications of Reverberation Chambers

Optimal Distance determination for measurement point



Chamber Reflections

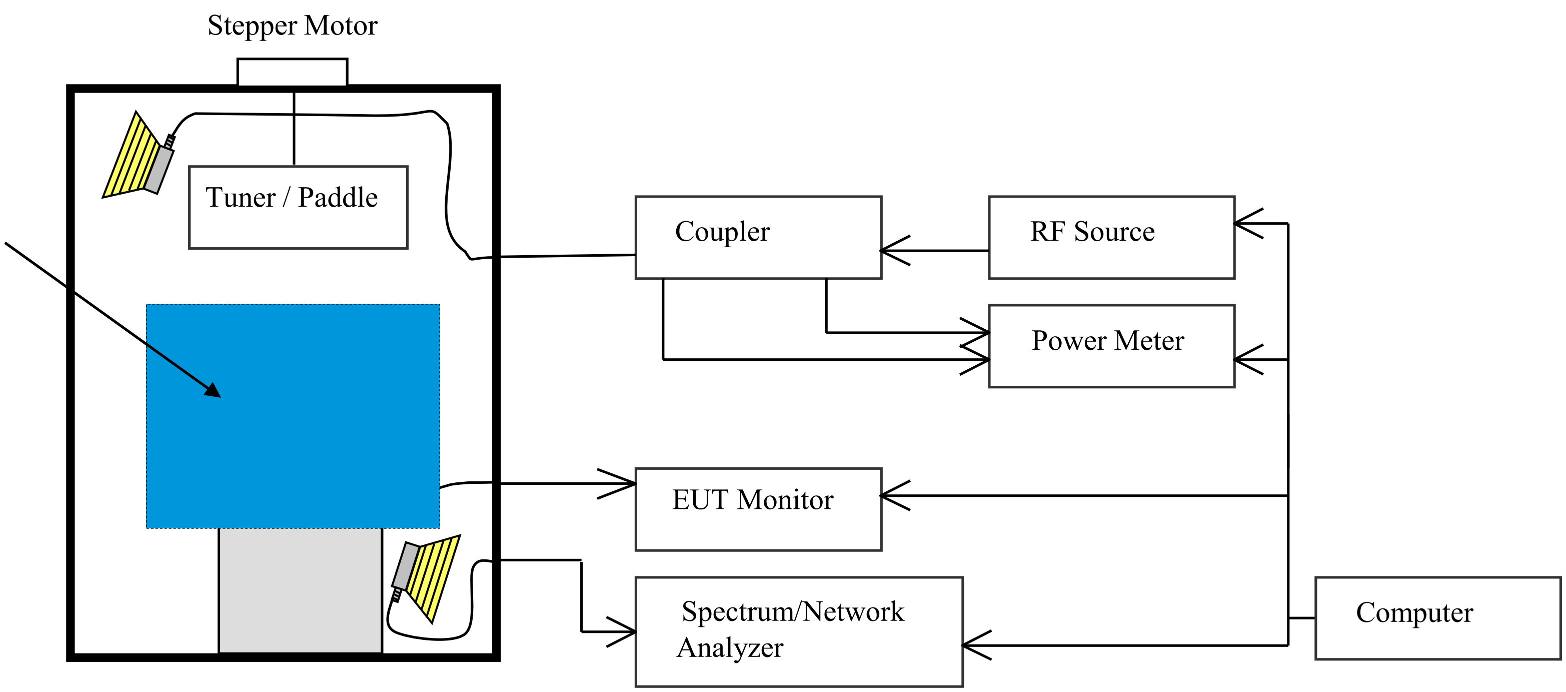
Metrology Applications of Reverberation Chambers

Reverb Chamber Method…

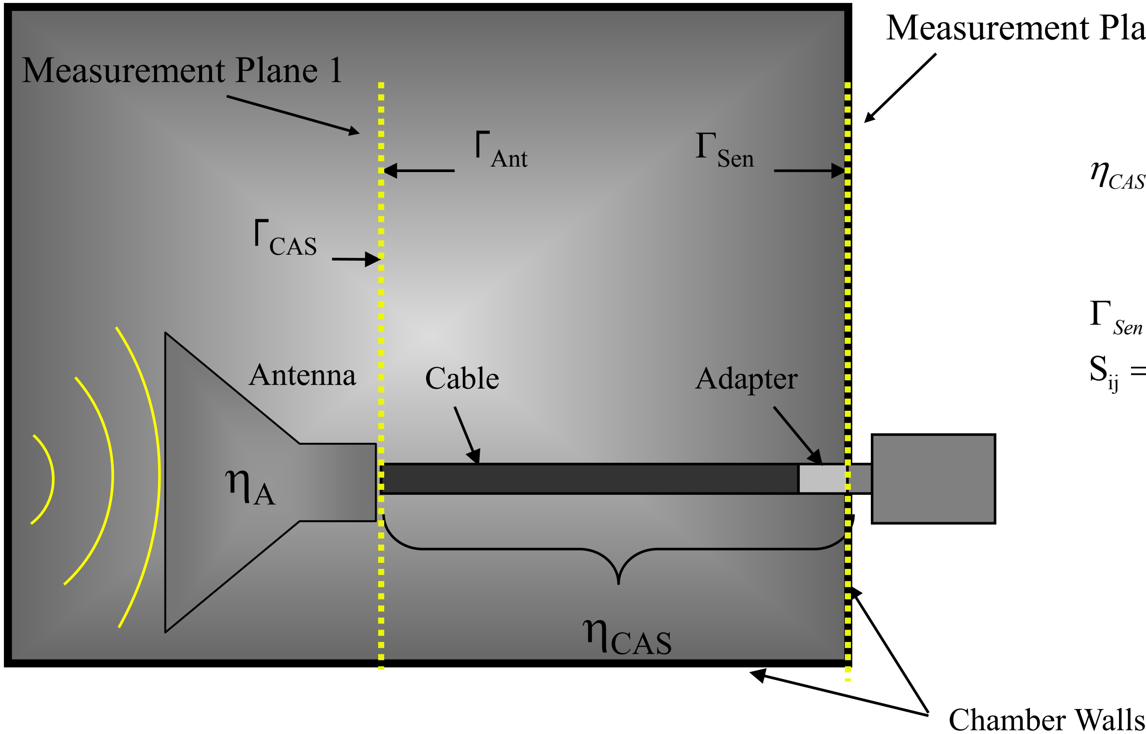
Metrology Applications of Reverberation Chambers

Working Volume

>λ/4 from Boundaries



Metrology Applications of Reverberation Chambers



Reverberation Chamber Block Diagram

$$\eta_{CAS} = \frac{|S_{21}|^2 (1 - |\Gamma_{Sen}|^2)}{|1 - S_{22}\Gamma_{Sen}|^2 - |(S_{12}S_{21} - S_{11}S_{22})\Gamma_{Sen} + S_{11}|^2}$$

Γ_{Sen} = Reflection coefficient of standard sensor

S_{ij} = S-parameter data for cable adapter combination

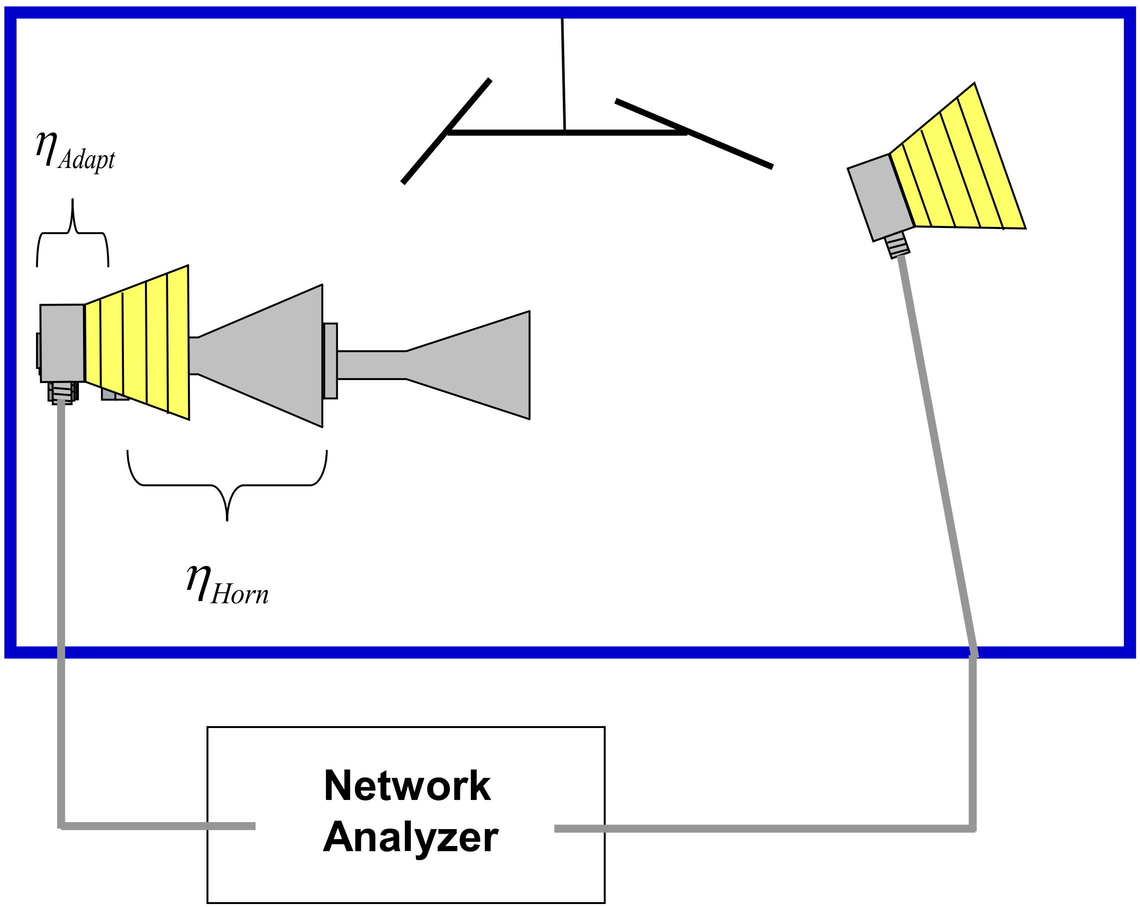
$$P_R = \frac{P_{Meas}}{\eta_A \eta_{CAS} \left(|1 - \Gamma_{CAS}\Gamma_{Ant}|^2 \right)}$$

$$\langle |E_T| \rangle = \frac{15\pi}{2\lambda} \sqrt{5\pi \langle |P_r| \rangle}$$

$$\langle |E_r| \rangle = \frac{4\pi}{\lambda} \sqrt{5\pi \langle |P_r| \rangle}$$

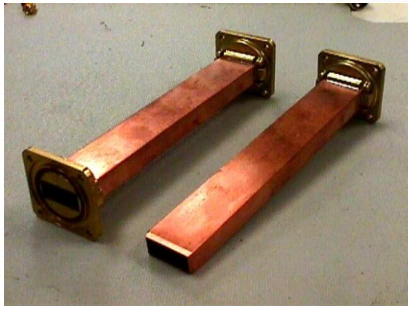
Metrology Applications of Reverberation Chambers

Antenna Efficiency



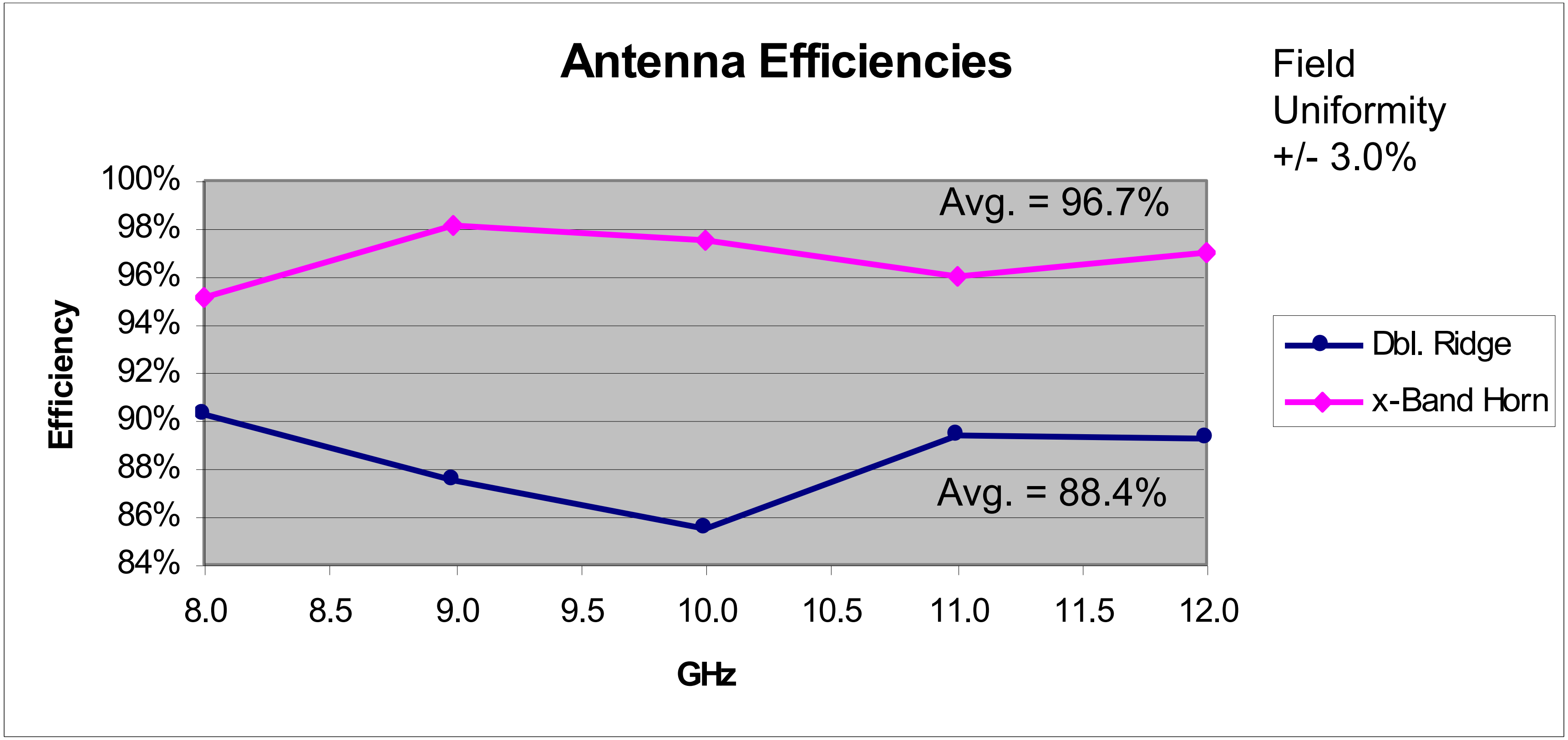
$$P_{COR} = \frac{\left\langle \left| S_{12} \right|^2 \right\rangle}{1 - \left| \left\langle S_{22} \right\rangle \right|^2}$$

$$\eta_{3115} = \frac{\bar{P}_{dr}}{\bar{P}_{wg}} \eta_{Horn} \eta_{adapt}$$



Antenna Efficiency

Antenna Efficiency



Antenna Efficiency

- Two-antenna approach

Total Efficiency

$$\eta_1^{total} = \sqrt{\frac{8\pi V}{f\lambda^3 e_b}\frac{\left\langle\left|S_{11,s}\right|^2\right\rangle}{\tau}},$$

$$\eta_2^{total} = \sqrt{\frac{8\pi V}{f\lambda^3 e_b}\frac{\left\langle\left|S_{22,s}\right|^2\right\rangle}{\tau}},$$

$$e_b = \sqrt{\left\langle\left|S_{11,s}\right|^2\right\rangle\left\langle\left|S_{22,s}\right|^2\right\rangle} \Big/ \left\langle\left|S_{21,s}\right|^2\right\rangle$$

Radiation Efficiency

$$\eta_1^{rad} = \sqrt{\frac{8\pi V}{f\lambda^3 e_b}\frac{\left\langle\left|S_{11,s}\right|^2\right\rangle_{cor}}{\tau}},$$

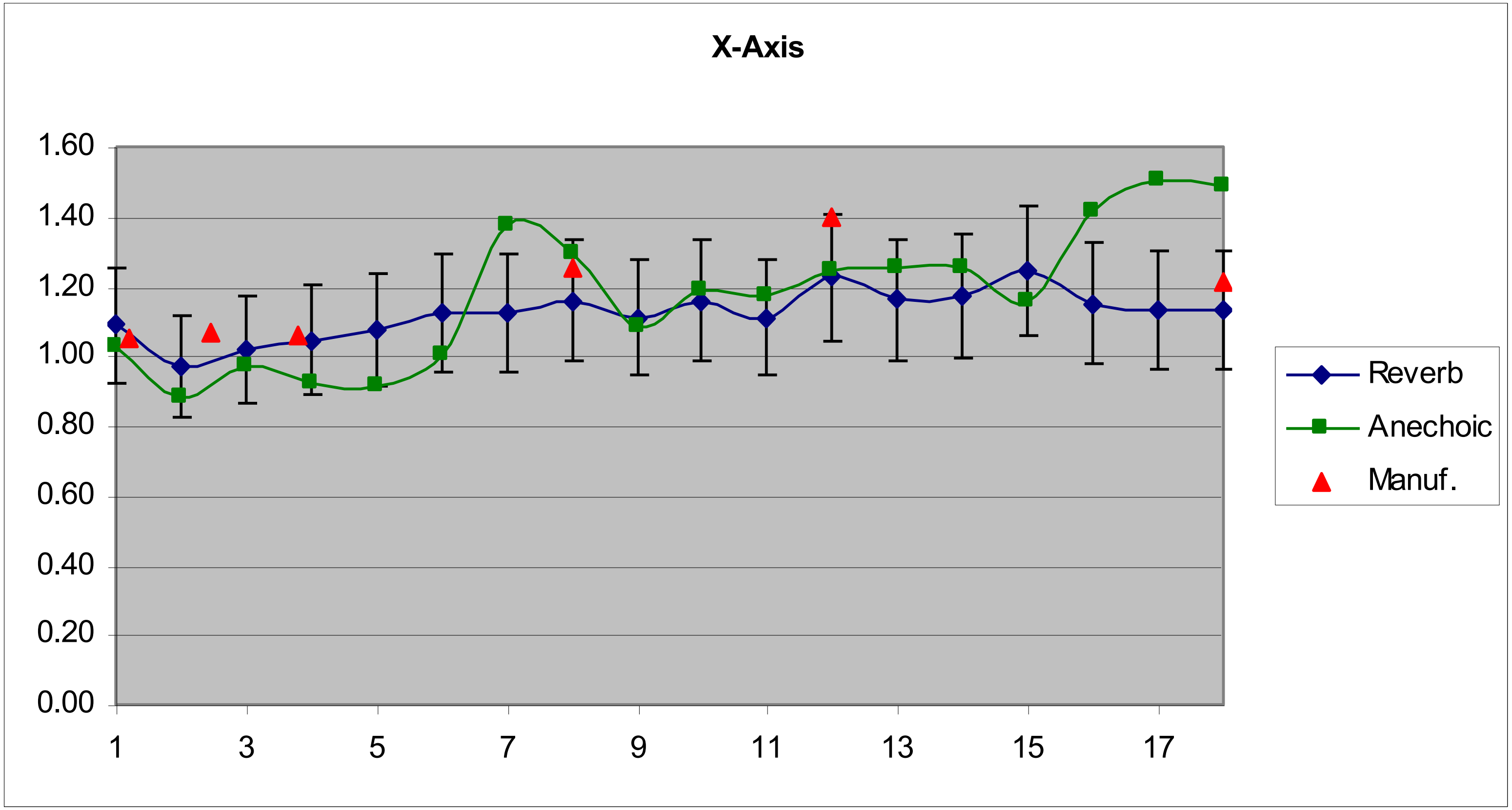
$$\eta_2^{rad} = \sqrt{\frac{8\pi V}{f\lambda^3 e_b}\frac{\left\langle\left|S_{22,s}\right|^2\right\rangle_{cor}}{\tau}},$$

$$\left\langle\left|S_{nn,s}\right|^2\right\rangle_{cor} = \left\langle\left|S_{nn,s}\right|^2\right\rangle / (1 - |\langle S_{nn}\rangle|^2)^2$$

HOLLOWAY, CL., SHAH, HA., PIRKL, RJ., YOUNG, WF., HILL, DA., and LADBURY, JM., Reverberation chamber techniques for determining the radiation and total efficiency of antennas, IEEE Trans. Antennas Propag., Apr. 2012, vol. 60 no. 4, pp. 1758-1770.

Antenna Efficiency

Probe Calibration Summary



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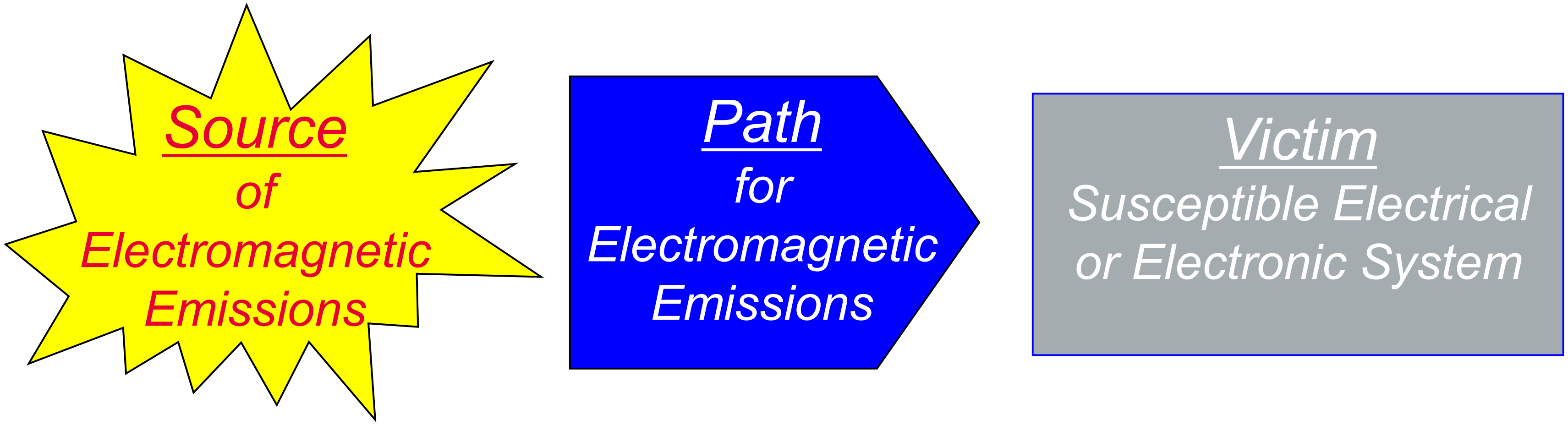
Factors in Electromagnetic Compatibility



An effective EMC approach controls:

– The source of electromagnetic emissions

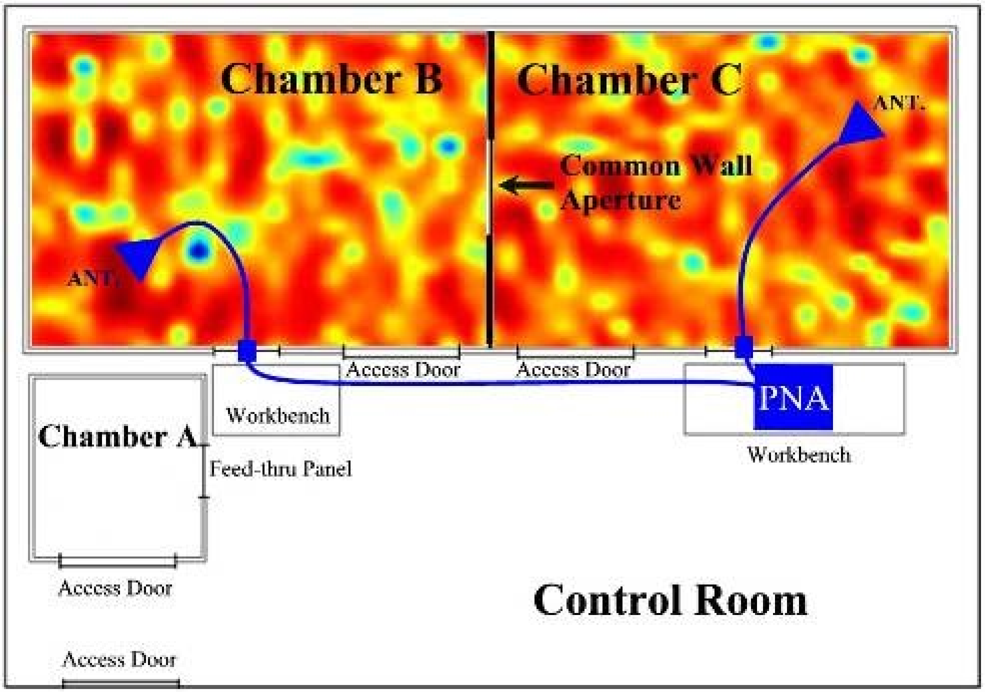
– The immunity of potential victim systems, and

– The path for EM emissions between the source and victim systems

Measurement Applications

Component Shielding

- **Using Reverb Chamber measurement technique (DFS technique) to measure RF shielding of aircraft components (i.e. windows)**



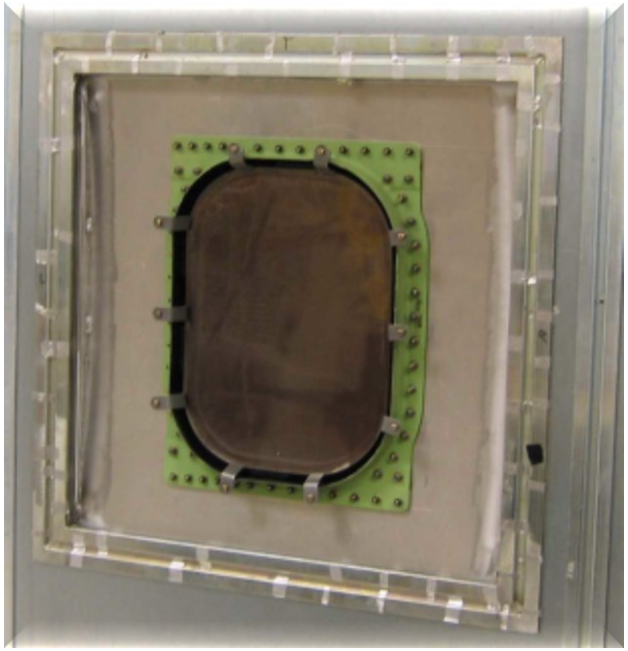
$$A_{ref} = \frac{P_{R,ref}}{P_{T,ref}}$$

$$A_{treatment} = \frac{P_{R,treatment}}{P_{T,treatment}}$$

$$SE_{treatment} = 10 \cdot \log\left(\frac{A_{ref}}{A_{treatment}}\right)$$

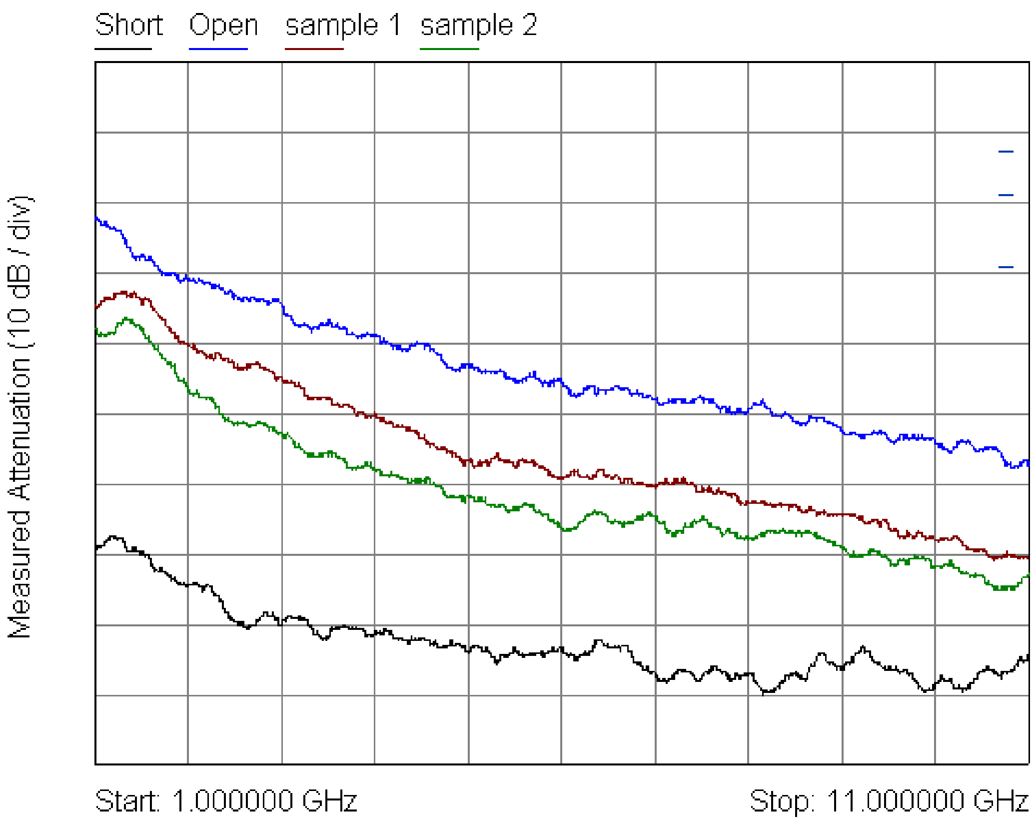
Measurement Applications

Component Shielding



Measurement Applications

Component Shielding



- Open-to-Short reveals useable dynamic range
- Sample-to-Open comparisons reveal sample shielding
- Data from metrology lab room showed good agreement to ideal reverb chamber setup

Agenda

- Reverberation Chambers
  - Overview
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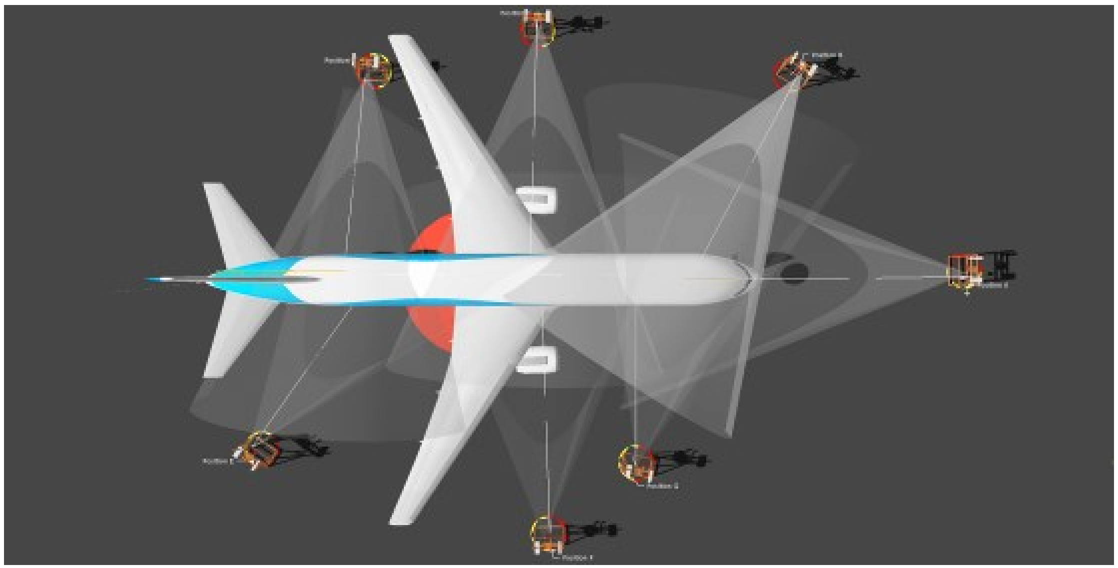
  - Aircraft Shielding
  - Bulk Absorption
  - Field Mapping
  - Wireless propagation measurements

Measurement Applications – Aircraft Shielding

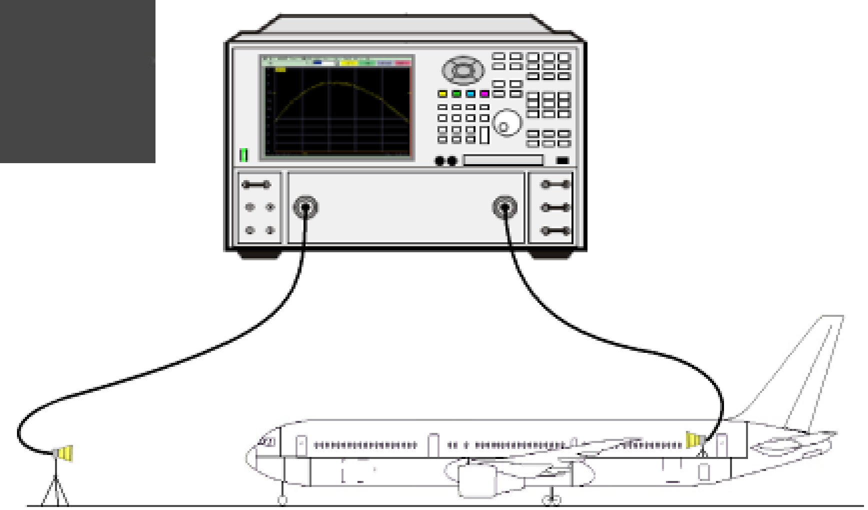
- 3 distinct types of measurements were made during the aircraft test (all utilizing the DFS measurement technique)
  - Reverberant (Reverb) Shielding Measurements
  - Direct Illumination Shielding Measurements
  - Reverberant (Reverb) Attenuation Measurements

Measurement Applications – Aircraft Shielding



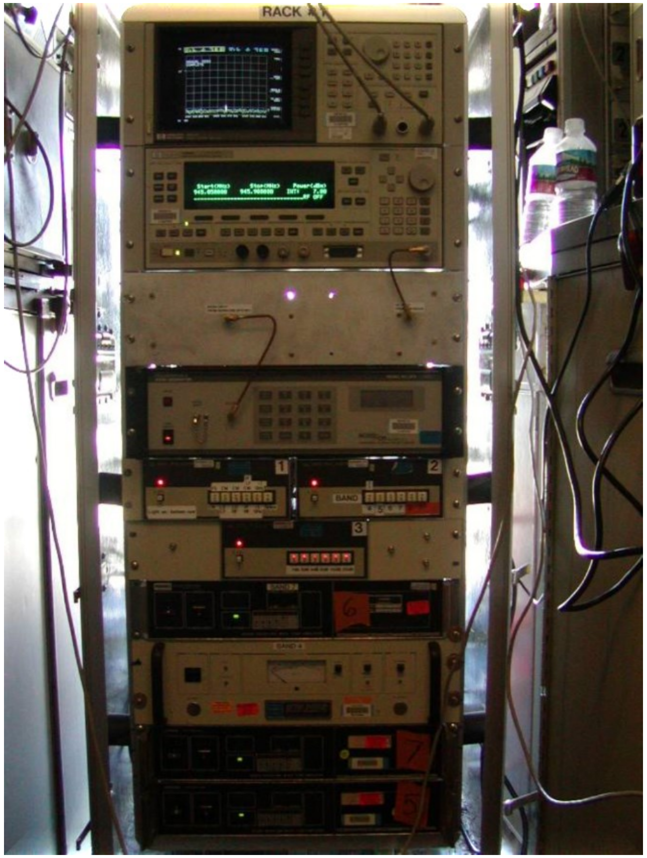
High Intensity Radiated Fields (HIRF) Certification Testing:

Greater than 200 meters of cables



Measurement Applications – Aircraft Shielding

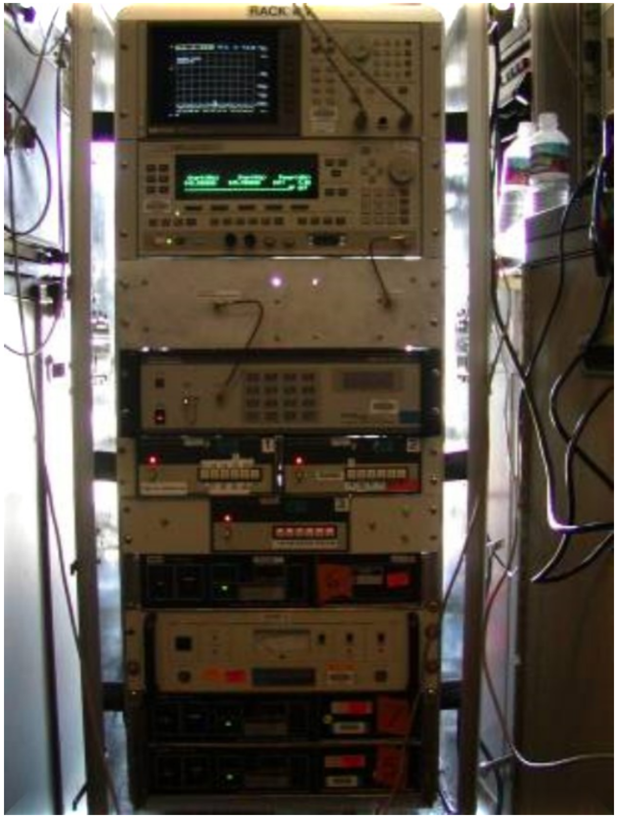
High power shielding measurement system…



Measurement Applications – Aircraft Shielding

- **Fiber optic port extenders allowed us to go from…**

This… **to this!**

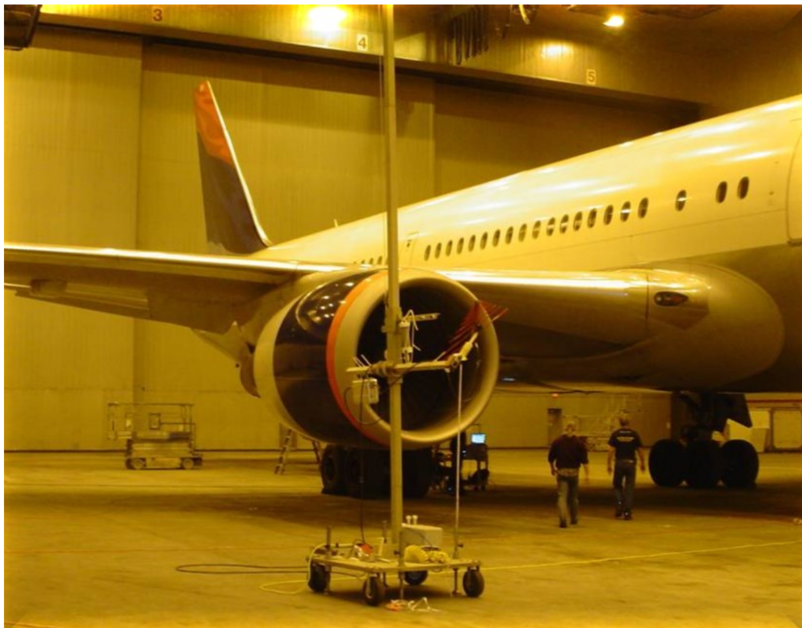


and still improve on…

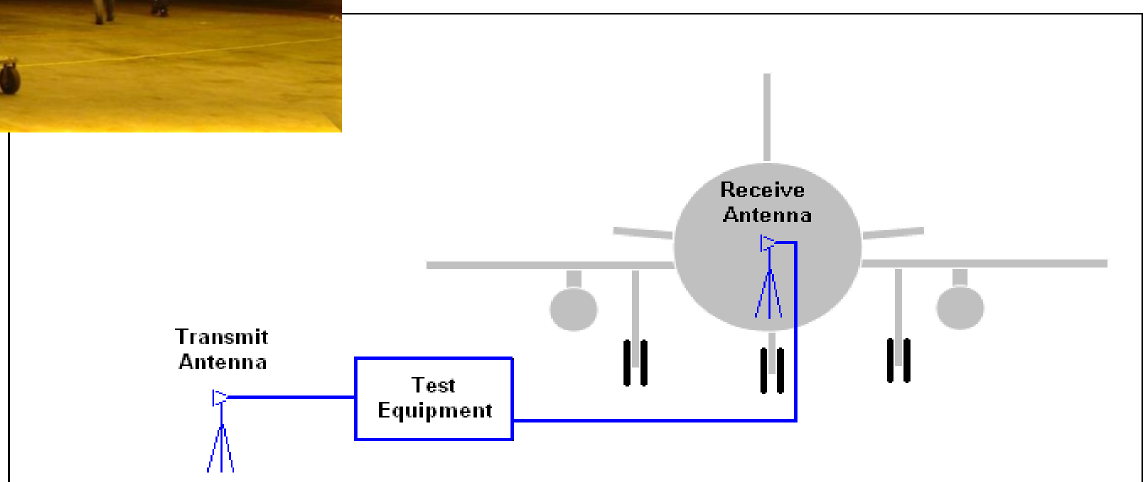
- Dynamic range
- Measurement accuracy/uncertainty

Measurement Applications – Aircraft Shielding

Measurement Applications – Aircraft Shielding



- Reverb shielding measurements utilize a “nested” chamber approach – paint hanger used as outer chamber, aircraft fuselage considered to be the inner chamber
- Shielding number produced is an average over all incident angles and polarizations



Measurement Applications – Aircraft Shielding

- Reverb shielding number determined by comparing empty hanger attenuation (or insertion loss) to the “aircraft inserted” attenuation (Tx antenna outside the aircraft, Rx antenna inside the aircraft).
- Hanger insertion loss requires measurement system to have a large dynamic range.

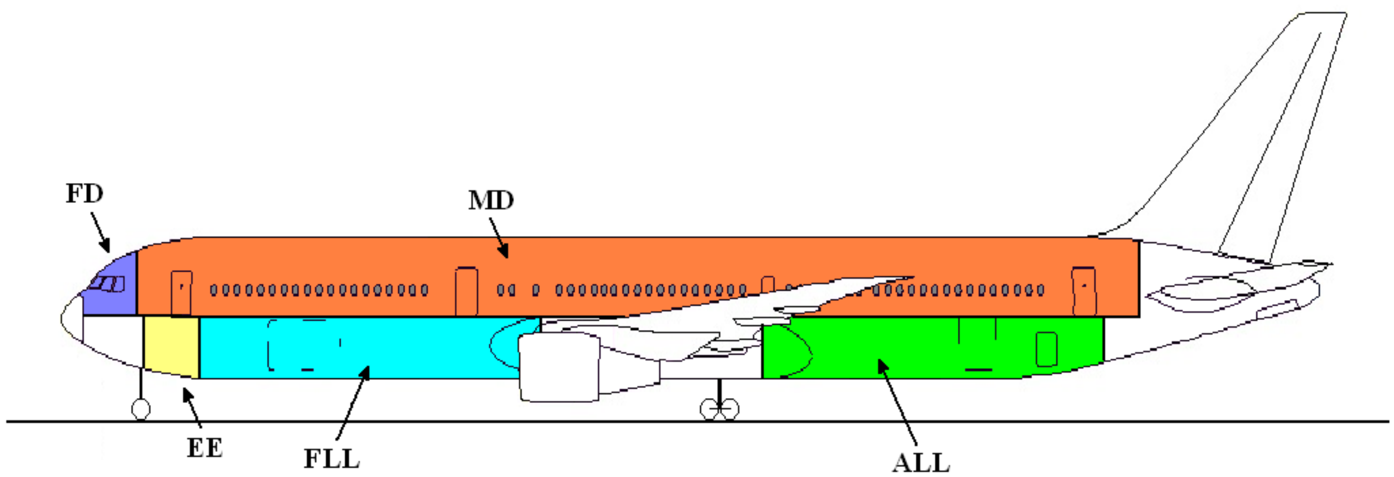
$$A_{ref} = \frac{P_{R,ref}}{P_{T,ref}}$$

$$A_{aircraft} = \frac{P_{R,aircraft}}{P_{T,aircraft}}$$

$$SE_{aircraft} = 10 \cdot \log\left(\frac{A_{ref}}{A_{aircraft}}\right)$$

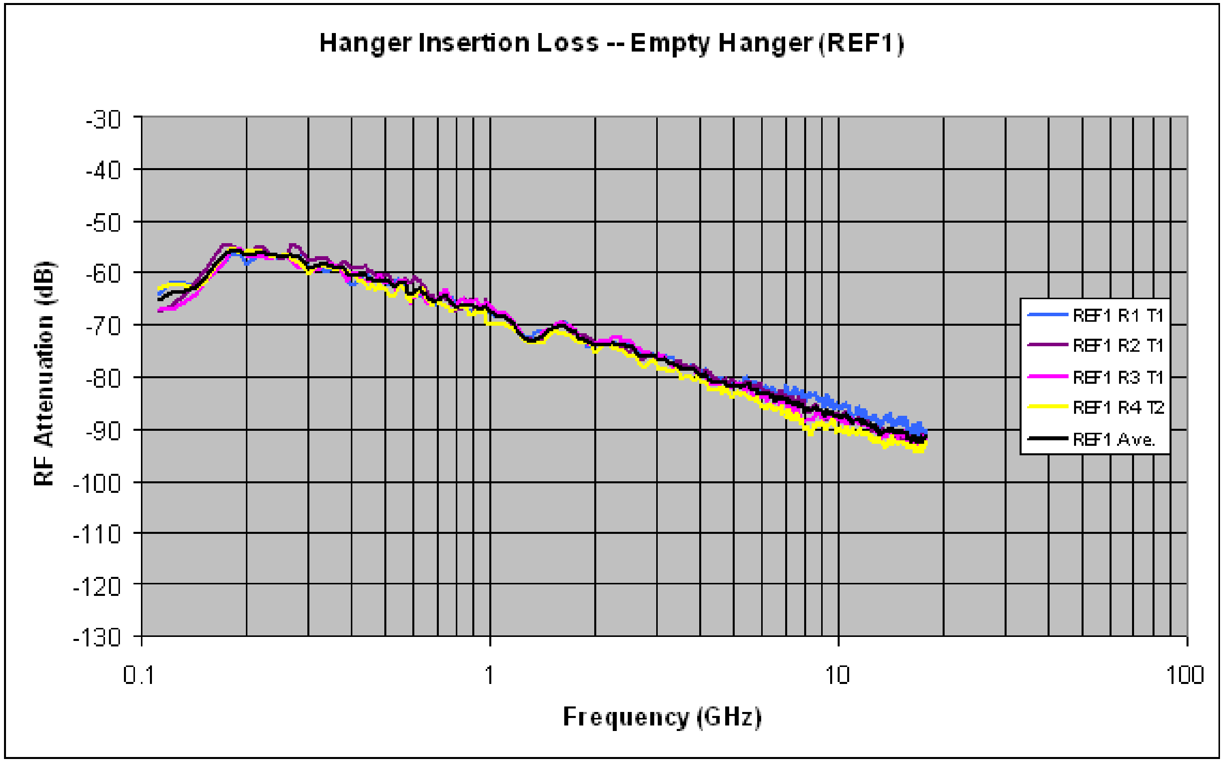
Measurement Applications – Aircraft Shielding

- Measurement points…
  - 2 Tx, 3 Rx points per aircraft area
  - Aircraft pressure hull divided into 5 aircraft areas: Main Deck (passenger cabin), Flight Deck, EE Bay, Forward Cargo Bay, and Aft Cargo Bay



Measurement Applications – Aircraft Shielding

- **Hanger Insertion Loss for empty hanger (REF1) and for hanger with aircraft (REF2)…**



Measurement Applications – Aircraft Shielding

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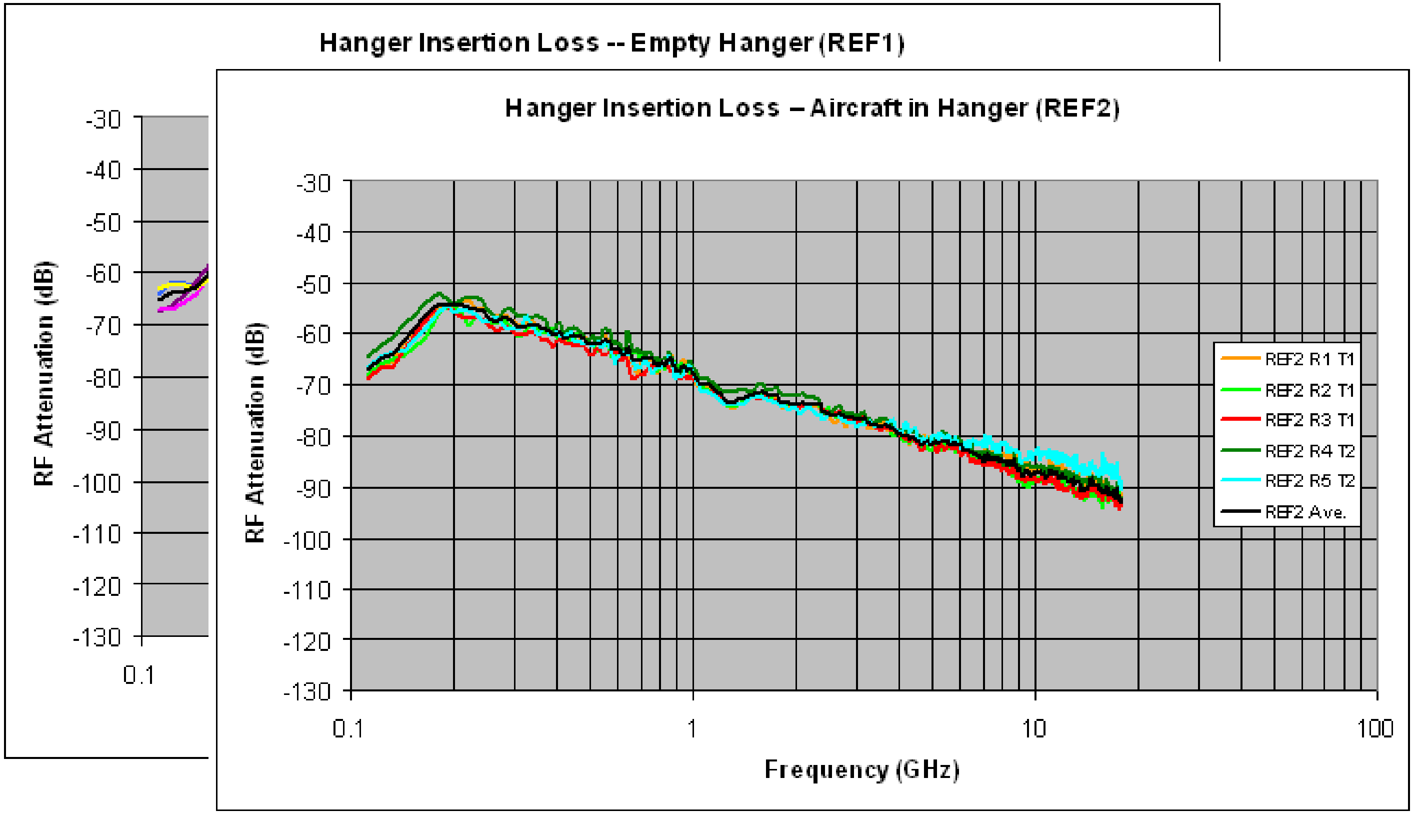
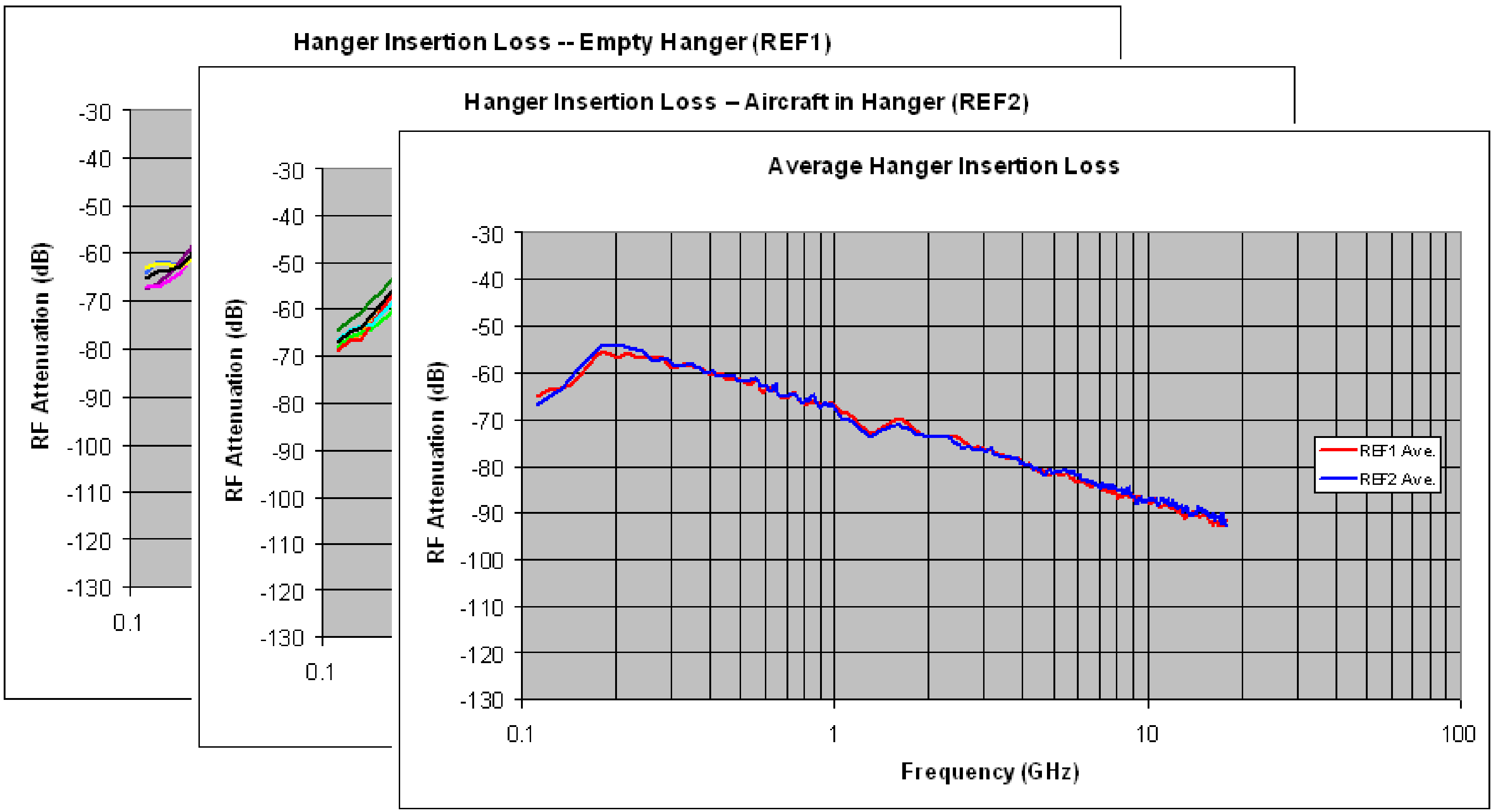


EMC SOCIETY

Measurement Applications – Aircraft Shielding

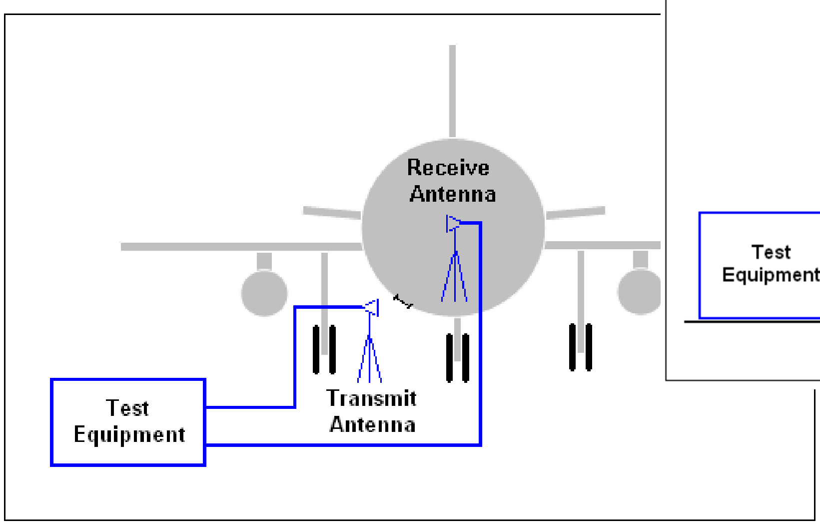
- **Hanger Insertion Loss for empty hanger (REF1) and for hanger with aircraft (REF2)…**

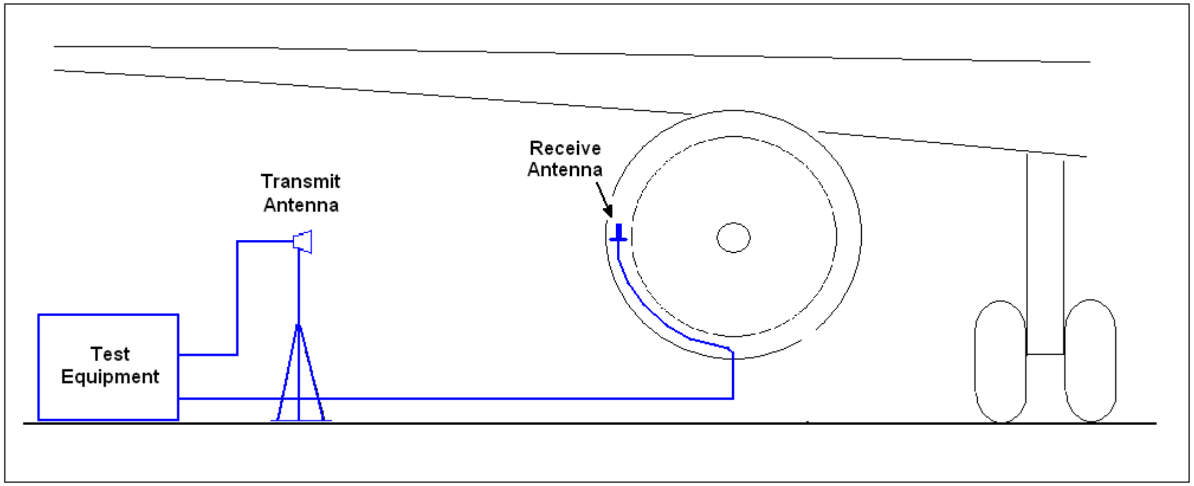


Measurement Applications – Aircraft Shielding

– Directly illuminate device under test with transmit antenna; can be used to directly illuminate apertures of concern

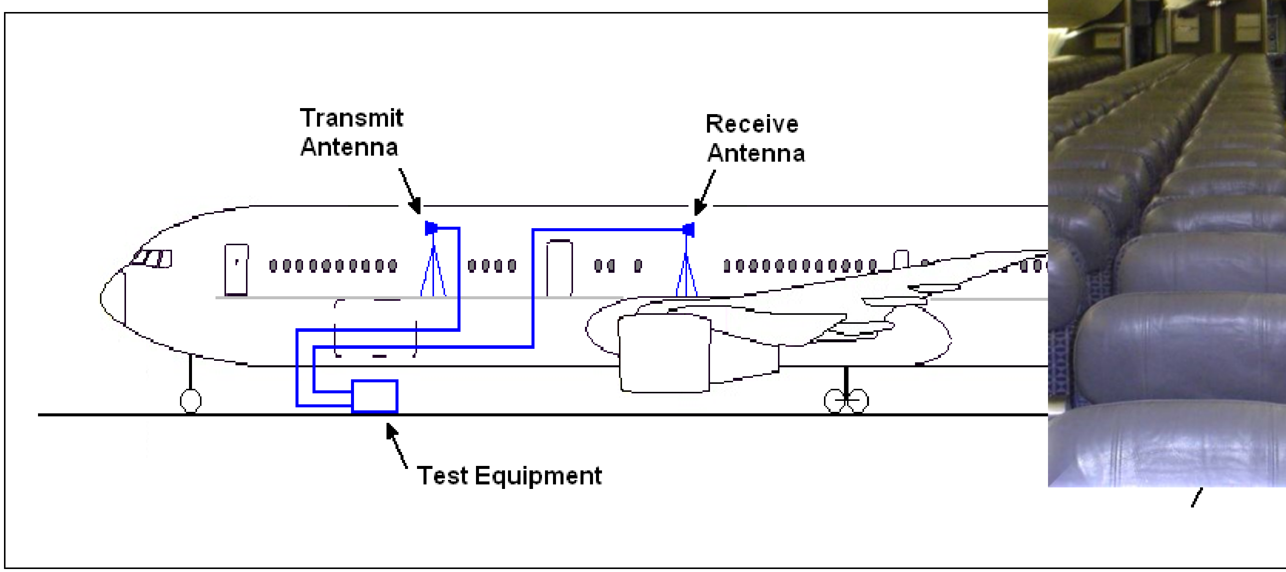
– Can be used to determine a worst case shielding number





Measurement Applications – Aircraft Shielding

- Measurement of antenna-to-antenna gain / attenuation when both transmit and receive antennas are located inside the device under test
- Provides an indirect assessment of cavity Q and can reveal changes to internal cavity electrical characteristics



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  - Aircraft Shielding
  - **Bulk Absorption**
  - Field Mapping
  - Wireless propagation measurements

Measurement Applications

Bulk Absorption

- Using Reverb Chamber measurement technique (DFS technique) to quantify RF absorption characteristics of complex objects
- Engineering problem: Ideally analyze wireless IFE with airplane full of passengers and luggage
- Not feasible for long-term detailed testing
- Looking for alternative to represent loading of the aircraft by passengers

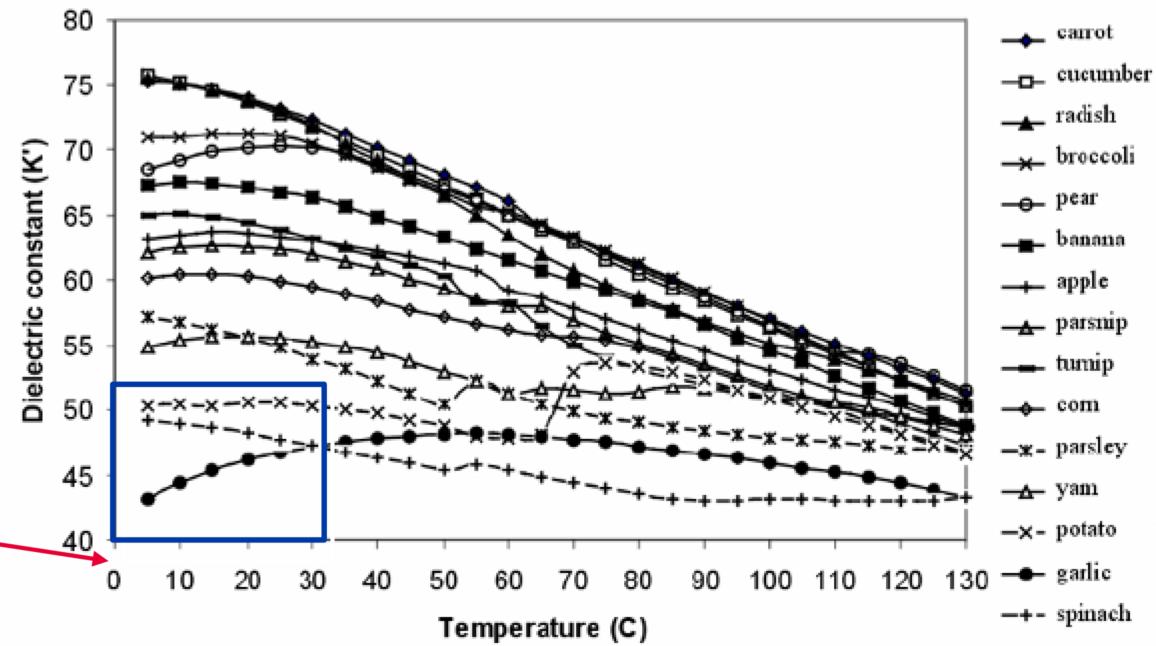
SYNTHETIC
PERSONNEL
USING
DIELECTRIC
SUBSTITUTION

Measurement Applications

Bulk Absorption

Dielectric Constants at 2450 MHz

ε $_r$ for human head is about 39; higher for other tissues (IEEE 1528-2003)



"Dielectric Properties of Vegetables and Fruits as a Function of Temperature, Ash, and Moisture Content," O. SIPAHIOGLU AND S.A. BARRINGER, JOURNAL OF FOOD SCIENCE—Vol. 68, Nr. 1, 2003

Measurement Applications

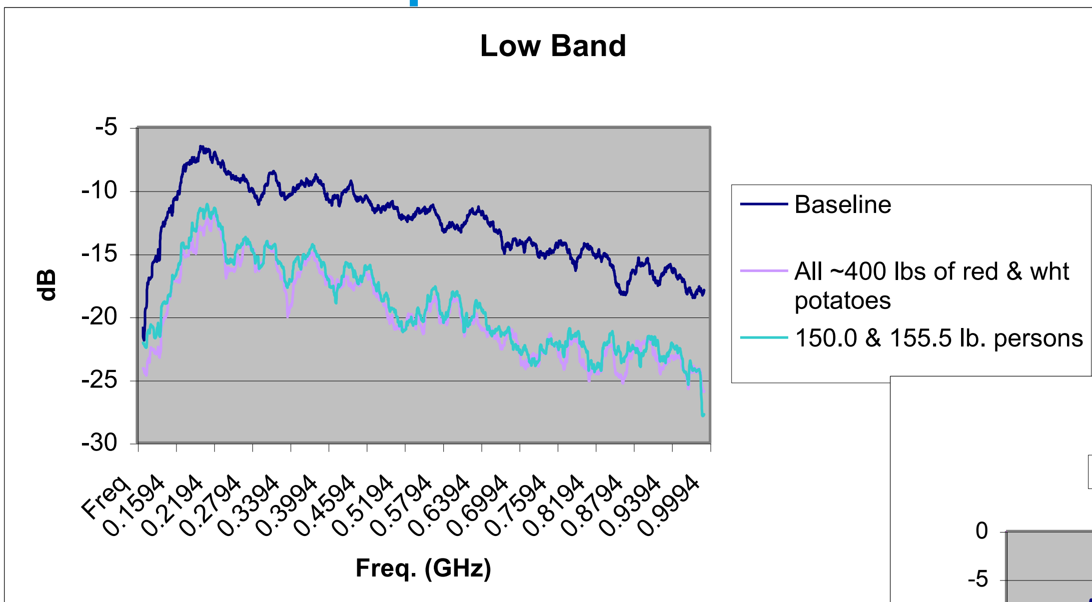
Bulk Absorption

Comparing Potatoes to People…

- Starch content is a key parameter for RF Absorption
- Tested 2 types of potatoes: Russets (high starch), Reds (low starch)

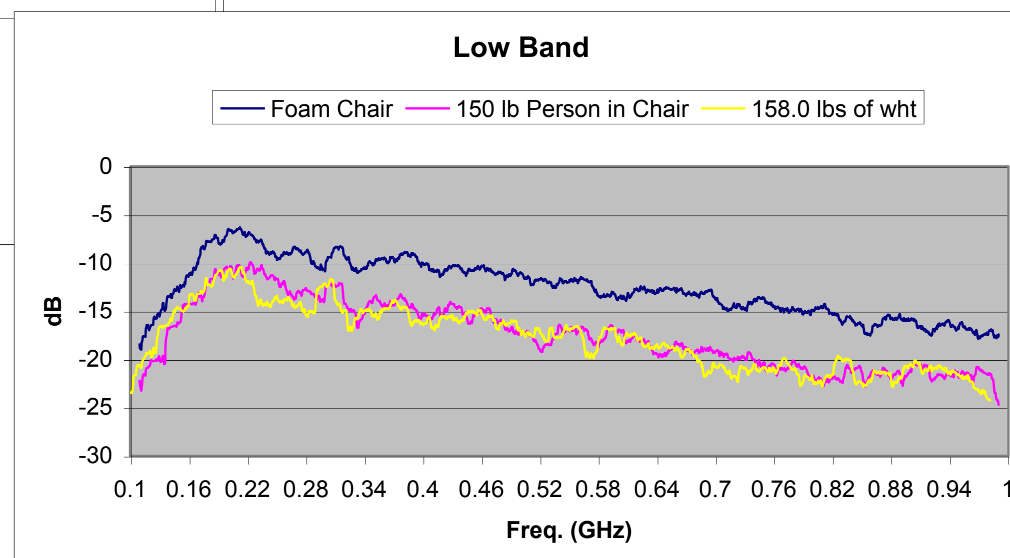
Measurement Applications

Bulk Absorption



Potatoes vs. People

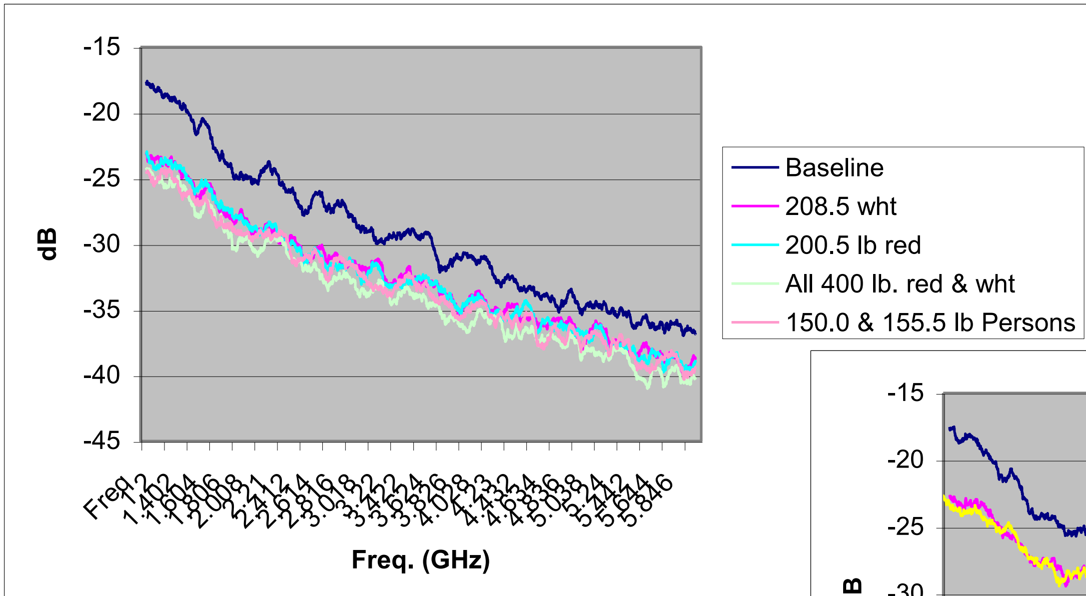
100 to 1000 MHz



Note: Based on correlation calculations between frequency points, we were likely over-sampling the chamber below 150 MHz

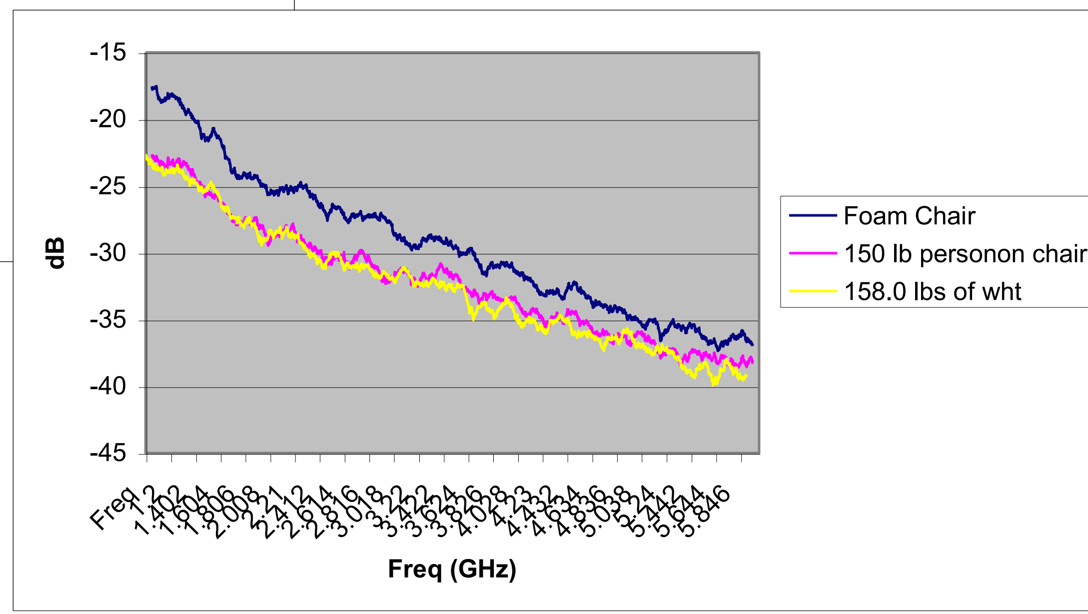
Measurement Applications

Bulk Absorption



Potatoes vs. People

1 to 6 GHz



Measurement Applications

Bulk Absorption

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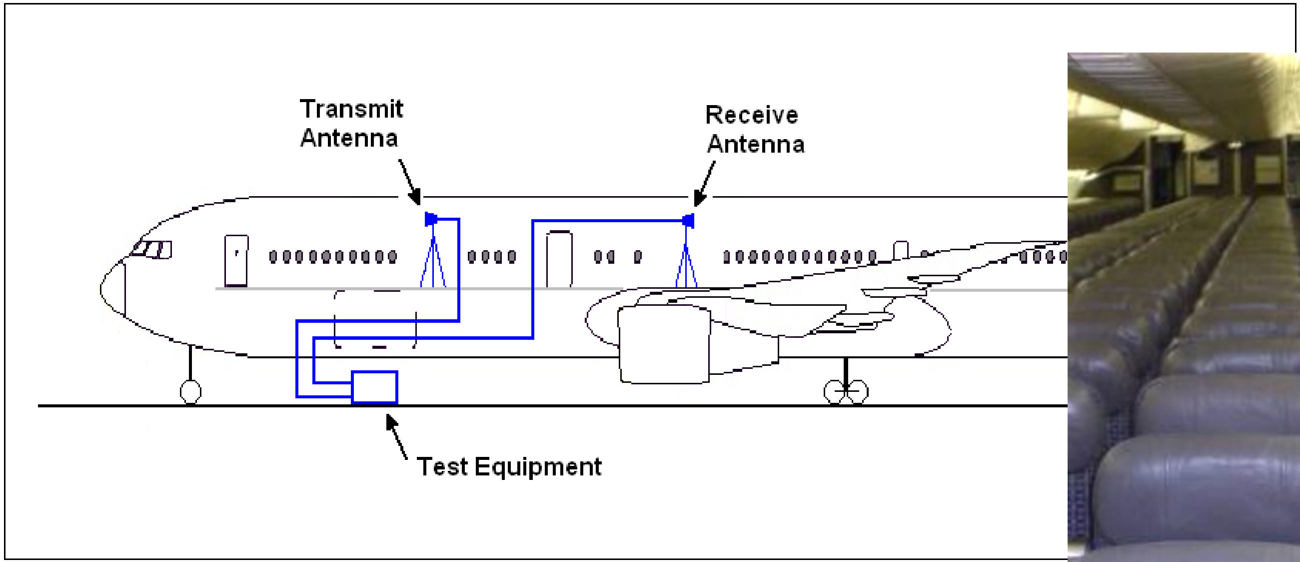
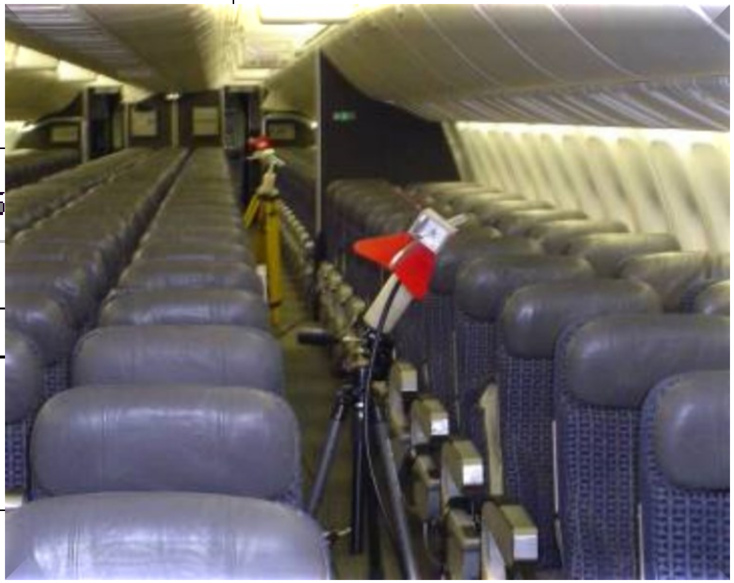
Measurement Applications

Cavity Field Mapping

- Measurement of antenna-to-antenna coupling when both transmit and receive antennas are located inside the test article (aircraft, in our case)
- Provides an indirect assessment of cavity Q and can reveal changes to internal cavity electrical characteristics
- Similar measurements can be used to provide wireless channel characterization

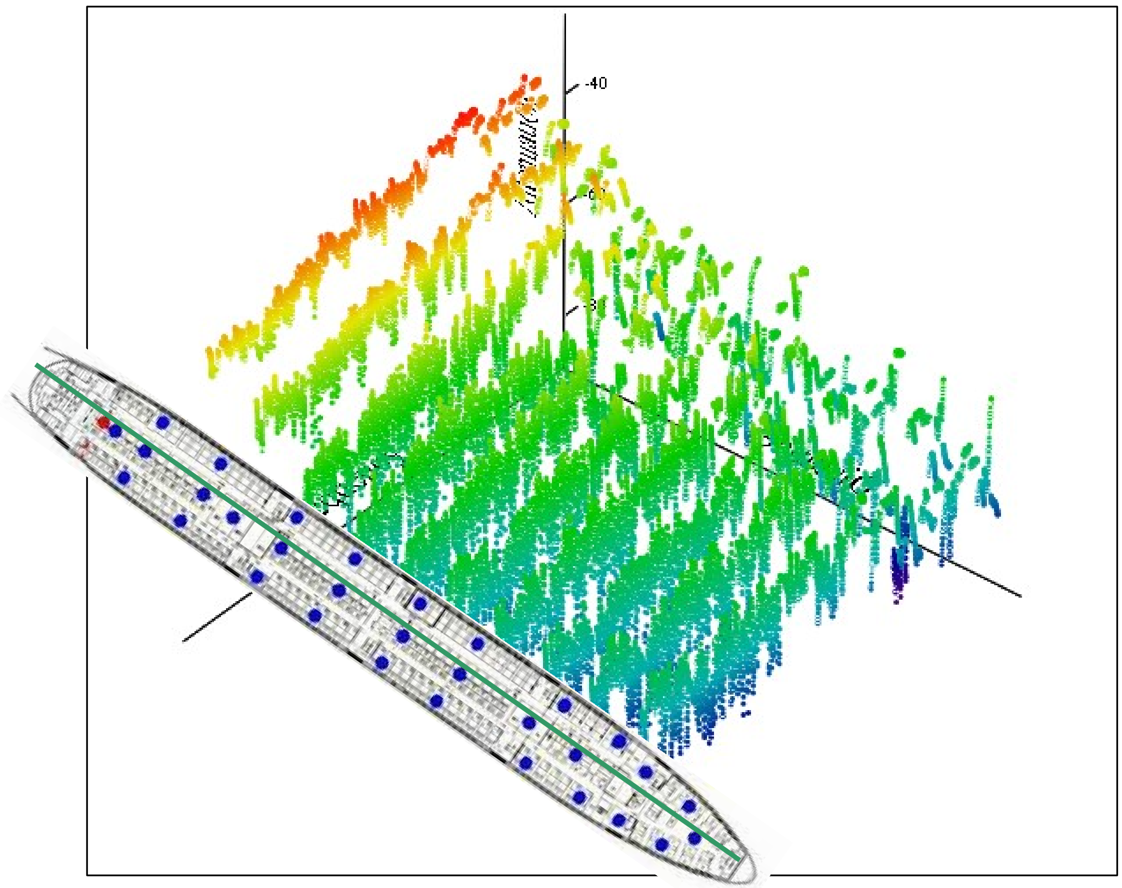




Measurement Applications

Cavity Field Mapping

- **Results from cavity field mapping…**

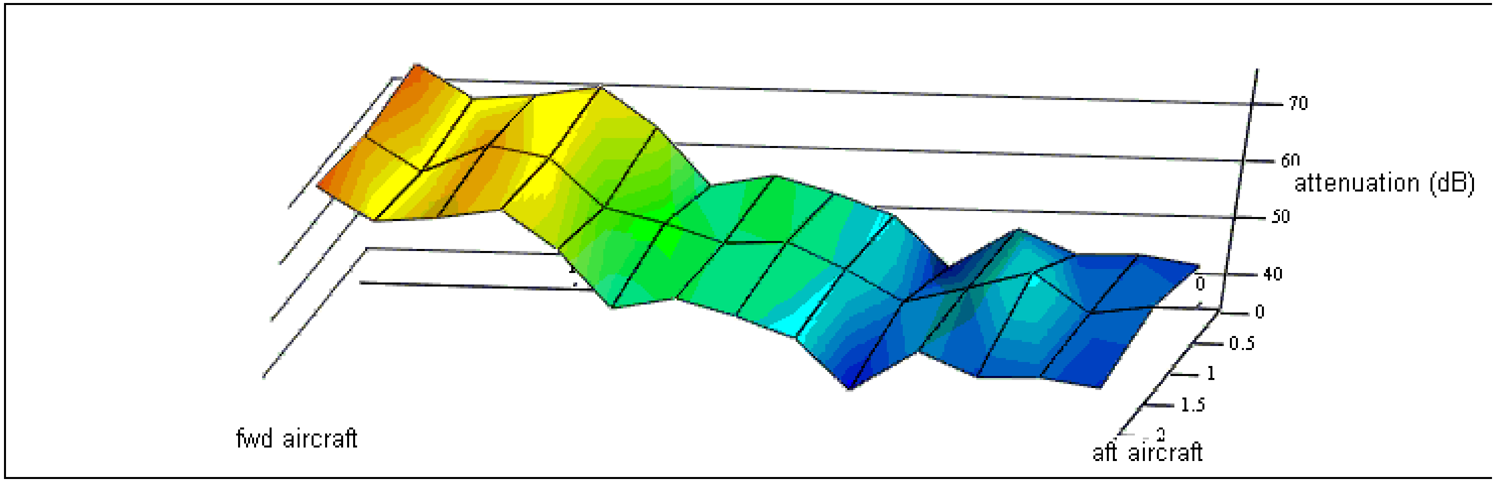


Measurement Applications

Cavity Field Mapping

- **More results from inside a large passenger cabin…**

$$\textbf{Frequency} = \left(1.403 \times 10^{9}\right)$$



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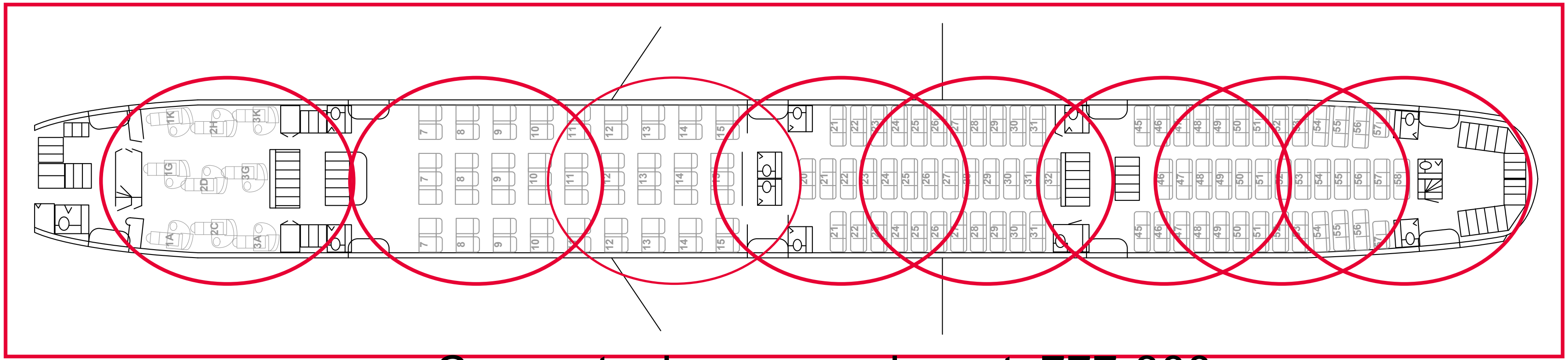
Measurement Applications

Wireless propagation measurements

Deliver DVD quality streamed unicast video to every seat

- **Airplane is high multipath environment, but with curved boundary surfaces, how correlated will multipath be?**
- **Need Coverage, Delay Spread, Angle of Arrival / Departure statistics to build a good Airplane MIMO channel model**
  - Optimize installation locations
  - Optimize antennas types, orientations, spacing
  - Optimize radio designs

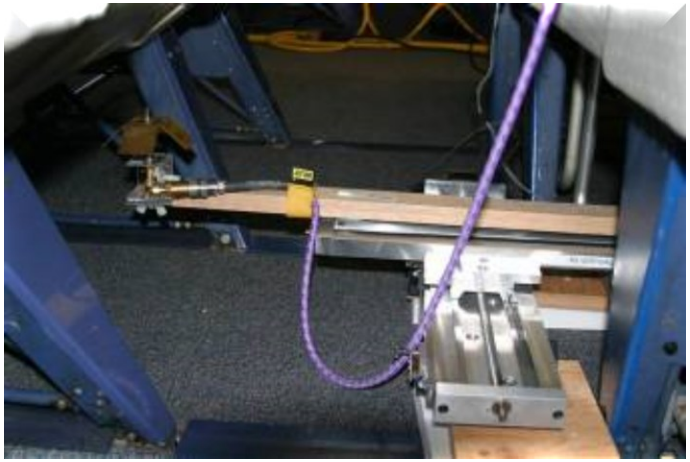


Conceptual coverage layout, 777-300

Measurement Applications

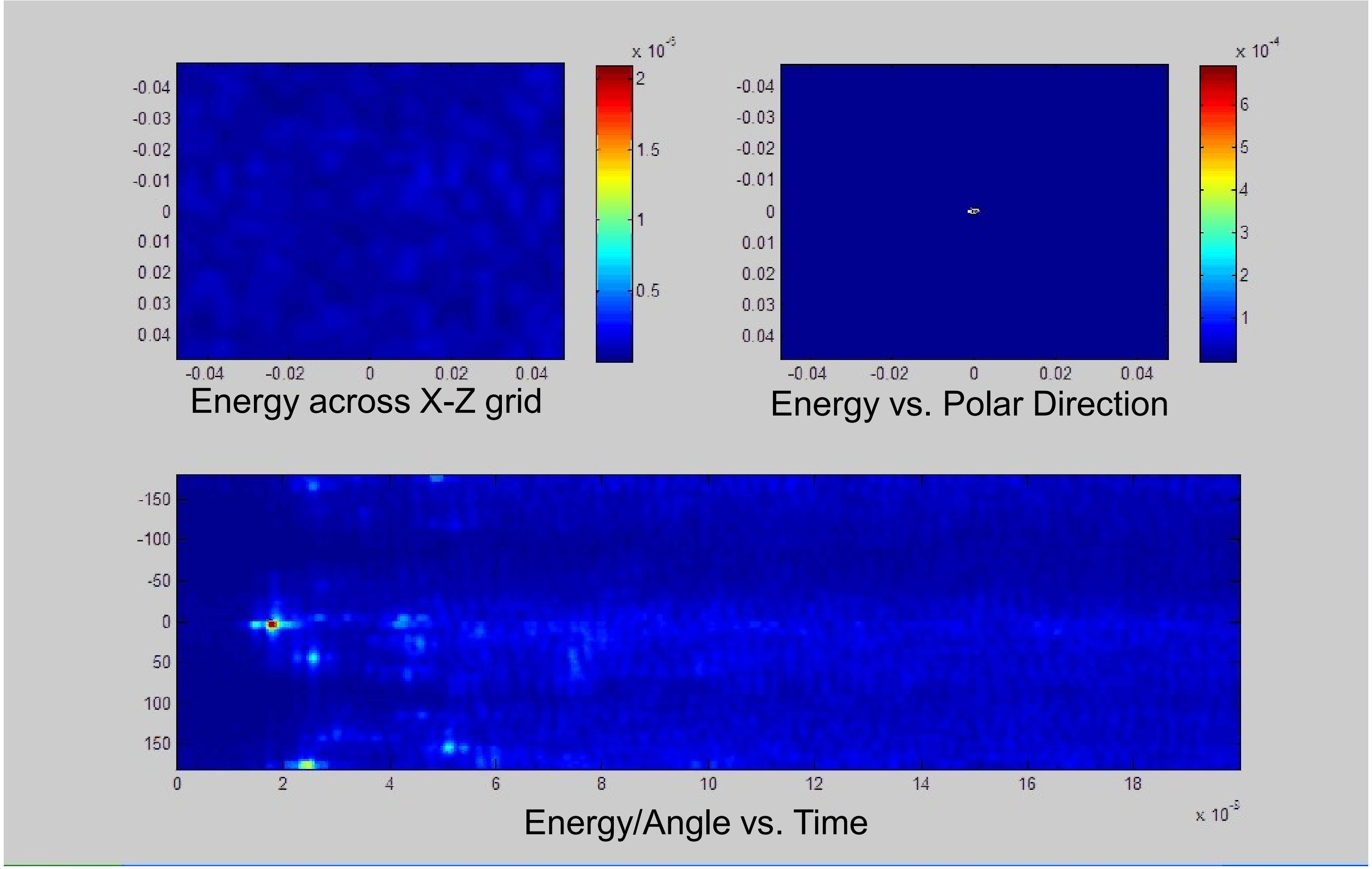
Wireless propagation measurements

Channel Sounding Translation Stages



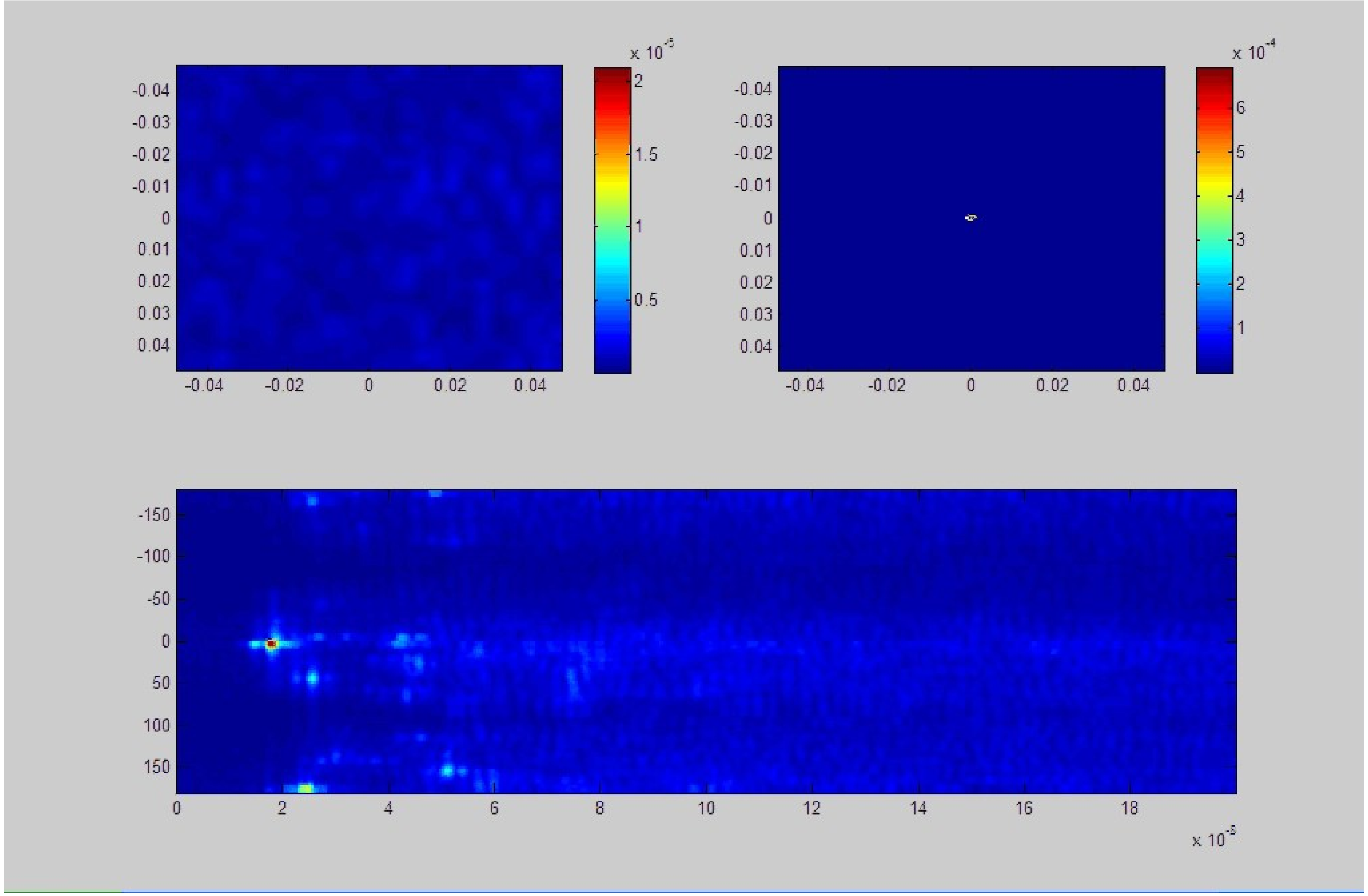
Measurement Applications

Wireless propagation measurements



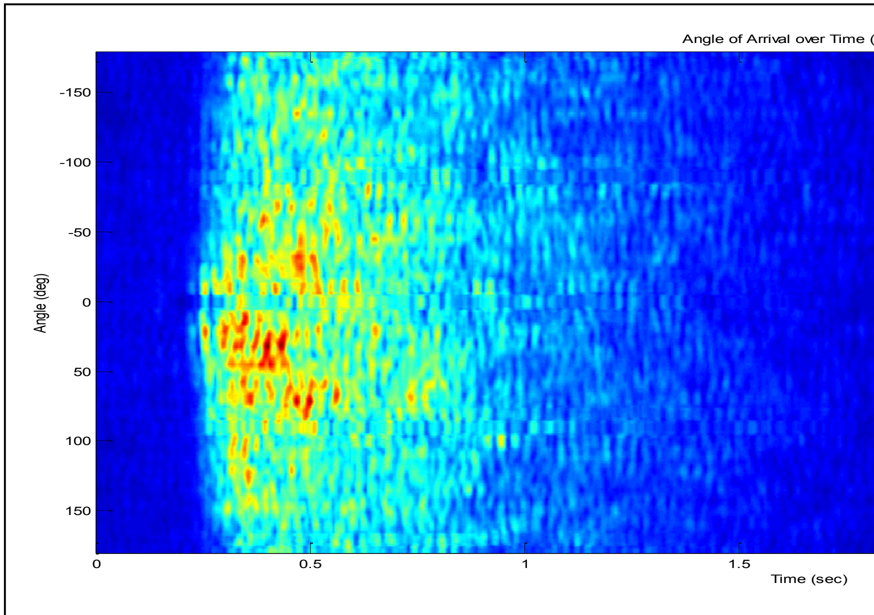
Measurement Applications

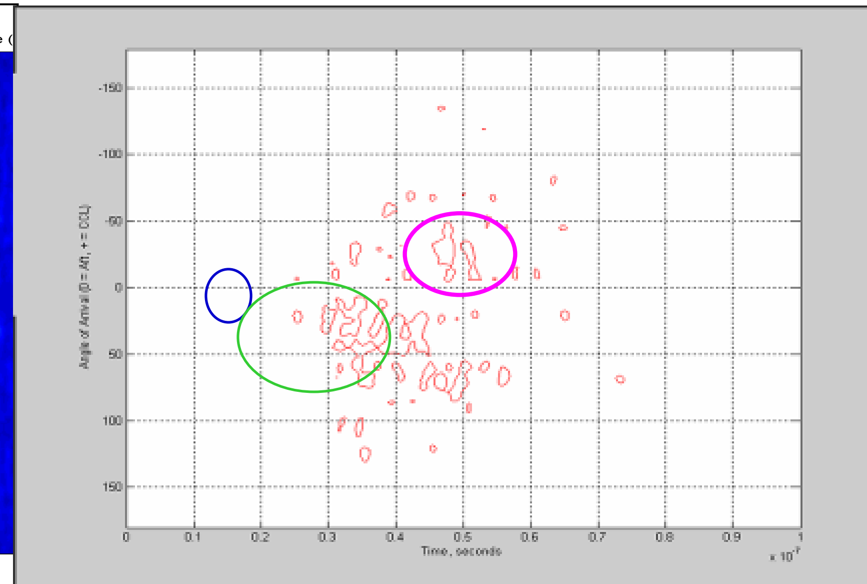
Wireless propagation measurements



Measurement Applications

Wireless propagation measurements





Example Angle Spectrum
DC-10 Seat 51E

Summary

- Reverberation chambers can be used to calibrate field probes with comparable uncertainties to Anechoic chambers
- Frequency, Spatial and Mode averaging reduce Field uniformity to level sufficient to measure antenna efficiency.
- Probe calibrations in reverberation chamber appear to be more repeatable than anechoic chamber method.
- Discreet Frequency Stirring reduces test times and is well suited for stirring aircraft
- Nested chambers approach is useful for characterizing odd shaped objects
- Statistical methods used in the lab can be utilized for evaluation of EM environment onboard aircraft

Discussion