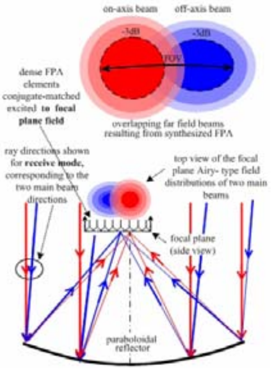
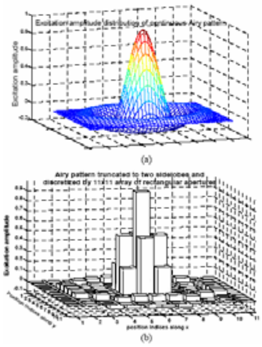
CHALMERS

Tutorial lecture:
Measurements of the mutual coupling and radiation efficiencies of dense wideband arrays in reverberation chamber
(AND NOISE TEMPERATURE!)

Per-Simon Kildal
www.kildal.se
Chalmers University of Technology

Schematic of FPA feed & Airy Pattern





Main results of collaboration with Marianna Ivashina

- Two submitted journal articles (IEEE Trans. Antennas Propagat., 2007):
  - M. Ng Mou Kehn, M. V. Ivashina, P.-S. Kildal, and R. Maaskant, "**Coupling efficiency** of wideband dense focal plane array feeds for reflector antennas – Part I: Definitions and experimental study on a hypothetical hard waveguide array"
  - M. V. Ivashina, M. Ng Mou Kehn, P.-S. Kildal, and R. Maaskant, "**Coupling efficiency** of wideband dense focal plane array feeds for reflector antennas – Part II: Experimental Study of Vivaldi Array"
- Two papers at The Second European Conference on Antennas and Propagation (EuCAP 2007), Edinburgh, 11 - 16 November 2007.
  - P.-S. Kildal, M. Franzén, M. Ivashina and W. van Cappellen, "Measurement of **embedded element efficiencies** of wideband dense arrays in reverberation chamber"
  - M. V. Ivashina, M. Ng Mou Kehn, Per-Simon Kildal, "Optimal number of elements and element spacing of wide-band focal plane arrays for a new generation radio telescope"

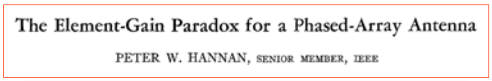
Outline

- My summary of and comments to efficiency, noise calculations and terminology
  - Subefficiencies
  - The coupling efficiency
  - Noise matching
  - Active reflection coefficient
- Measurements in reverberation chamber
  - Radiation efficiency
  - Coupling efficiency
  - Receive sensitivity & noise temperature

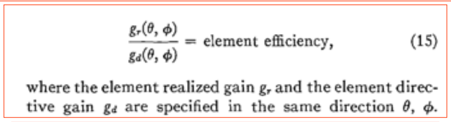
Summary of preliminary expected subefficiencies

Name of (sub)efficiency	Explaination	FPA-fed reflectors
Polarization	Cross pol. On axis	negligible
Spillover	Picks up noise. High sidelobes	> -0.3 dB
BOR1	Higher order phi-variations	Not known yet
Polarization sidelobe	Normally not significant	> -0.2 dB
Illumination taper	Due to taper. Trade-off against spillover	> -1.0 dB
Phase	Normal not significant.	> -0.1 dB
Illumination (product of above)	Pproduct (sum in dB) of the above 4 efficiencies	> -1.3 dB
Unblocked aperture eff.	Product (sum in dB) of all efficiencies above	< -0.5 dB, > -1.4 dB
Blockage, multiple scattering **Reflector in near-field of feed**	Of the form abs(1+delta)**2 May be for scattering pattern of feed	may be large
Aperture efficiency	Product of main efficiencies above	?
Coupling	Depends on excitation destribution of array	> -1.3 dB (?)
Radiation efficiency	Due to absorption in antenna structure	?
Total antenna efficiency or **Total aperture efficiency**	if neglecting blockage and scattering	< -0.5 dB > -2.5 dB?

Element efficiency is known from Hannan 1964


The Element-Gain Paradox for a Phased-Array Antenna

PETER W. HANNAN, SENIOR MEMBER, IEEE

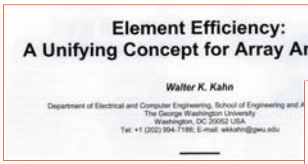

$$\frac{g_r(\theta, \phi)}{g_d(\theta, \phi)} = \text{element efficiency}, \qquad (15)$$

where the element realized gain g_r and the element directive gain g_d are specified in the same direction θ, ϕ.

This is the same as realized gain of the array per element divided by the directivity of the element.

It is also the same as the total radiated power by one singly-excited element divided by the maximum available power at the port of that element.

Others also focus attention on this now, in most recent issue of IEEE Antennas and Propagation Magazine:



Element Efficiency:
A Unifying Concept for Array Antennas

Walter K. Kahn

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The George Washington University
Washington, DC 20052 USA
Tel: +1 (202) 994-7186; E-mail: wkkahn@gwu.edu

$$\eta_m = \frac{P_m(radiated)}{P_m(available)} = 1 - \frac{P_m(reflected)}{P_m(available)}$$

$$= 1 - \frac{\sum_{n=1}^{N} |b_n|^2}{|a_m|^2} = 1 - \sum_{n=1}^{N} |S_{nm}|^2 .$$

Lower right curve equal to our appr. formula, based on Hannan

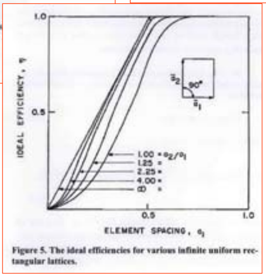


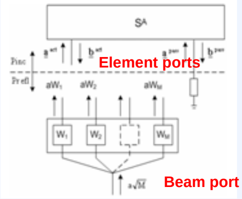
Figure 5. The ideal efficiencies for various infinite uniform rectangular lattices.

Definition of the coupling efficiency of the array

- Coupling efficiency in an array with arbitrary excitation of the elements.

$$\eta_{rad} = \frac{P_{rad}}{P_{inc}} = \frac{\sum_{m=1}^{M} |a_m|^2 - \sum_{n=1}^{N} |b_n|^2}{\sum_{m=1}^{M} |a_m|^2}$$

where - P_{inc} is the sum of the incident powers on all M active ports,
- $|a_m|^2$ is the power incident on an excited port m, and
- $|b_n|^2$ is the power leaving any port n.



Element ports

Beam port

- Coupling efficiency of the array is dependent on both S-par. and excitations.

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Marianna V. Ivashina

Coupling efficiency unifies all array concepts

- **FPA:**
  - General formula applies:
    total N ports, M excited ones
    a_n is forward wave on port n
    b_m is backward ………..
  - **Coupling efficiency**

$$\varepsilon_c = \frac{P_{rad}}{P_{inc}} = 1 - \frac{P_c}{P_{inc}}$$

$$= 1 - \left\{ \sum_{n=1}^{N} |b_n|^2 \Big/ \sum_{m=1}^{M} |a_m|^2 \right\}$$

- **Classical large phased arrays:**
  - Same formula gives then the known reflection efficiency due to impedance mismatch, i.e.
  - **Mismatch efficiency**

$$\varepsilon_c = 1 - |\rho|^2 , \quad |\rho| = |b_m| / |a_m|$$

$$\rho \quad is\ appr.equal\ \ for\ all\ m = 1,..., N$$

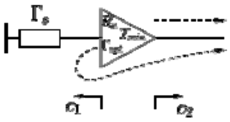
- **MIMO array for wireless comm.:**
  - sum of all powers coupled to non-excited ports and reflection on excited port, i.e.
  - **Embedded element efficiency**

$$\varepsilon_{c,m} = 1 - \sum_{n=1}^{N} |S_{nm}|^2$$

Terminology related to impedance mismatch and mutual coupling in arrays

- **Single excited element**
  - **Embedded element efficiency**
  - **Singly-excited element impedance**
- **Classical phased array**
  - **Mismatch efficiency**
  - ~~**Classical names: Active impedance (NOT good!)**~~
  - **Alternative common name introduced several years ago: Scan impedance (Good!)**
  - New alternative in line with FPA terminology:
    All-excited impedance
    Phased array-excited impedance
  - **These can in uniformly-excited array be measured both on element and beam ports**
- **FPA**
  - **Coupling efficiency**
  - **FPA-excited impedance, or beam port impedance**
  - **IMPORTANT: These can only be measured on beam ports**

Rob Maaskant: Noise match for single antenna element receivers



$$T_{LNA} = T_{min} + \frac{4T_0 R_n}{Z_0} \frac{|\Gamma_s - \Gamma_{opt}|^2}{|1+\Gamma_{opt}|^2 (1-|\Gamma_s|^2)}$$

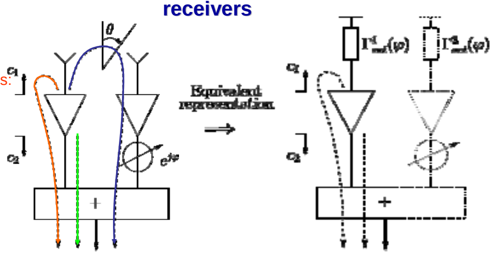
Noise Match if

$$\Gamma_{opt} = \Gamma_s$$

$$\Downarrow$$

$$T_{LNA} = T_{min}$$

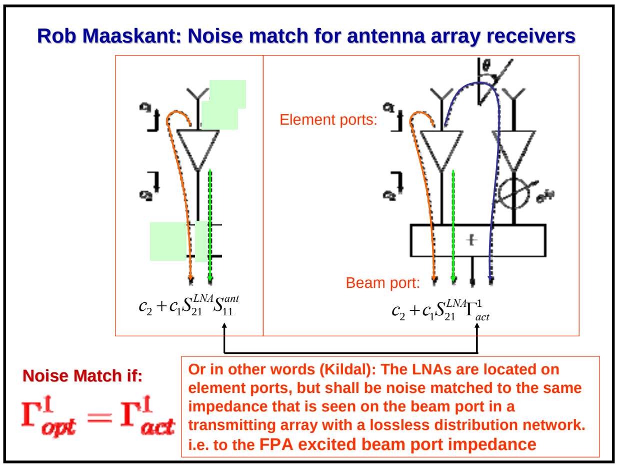
Rob Maaskant: Noise match for antenna array receivers



Element ports:

Beam port:

$$\begin{aligned} e_{tot} &= \text{Direct Part} + \text{Reflected Part} + \text{Coupled Part} \\ &= e_2 + e_1 S_{11}^{ant} S_{21}^{LNA} + e_1 S_{21}^{ant} S_{21}^{LNA} e^{j\varphi} \\ &= e_2 + e_1 S_{21}^{LNA} \left(S_{11}^{ant} + S_{21}^{ant} e^{j\varphi} \right) \\ &= e_2 + e_1 S_{21}^{LNA} \Gamma_{act}^{1}(\varphi), \end{aligned}$$



Rob Maaskant: Noise match for antenna array receivers

Element ports:

Beam port:

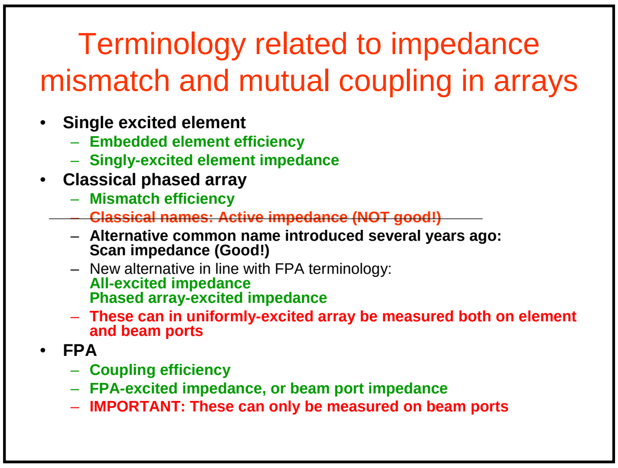
$c_2 + c_1 S_{21}^{LNA} S_{11}^{ant}$

$c_2 + c_1 S_{21}^{LNA} \Gamma_{act}^{1}$

Noise Match if:

$$\Gamma_{opt}^{1} = \Gamma_{act}^{1}$$

Or in other words (Kildal): The LNAs are located on element ports, but shall be noise matched to the same impedance that is seen on the beam port in a transmitting array with a lossless distribution network. i.e. to the FPA excited beam port impedance



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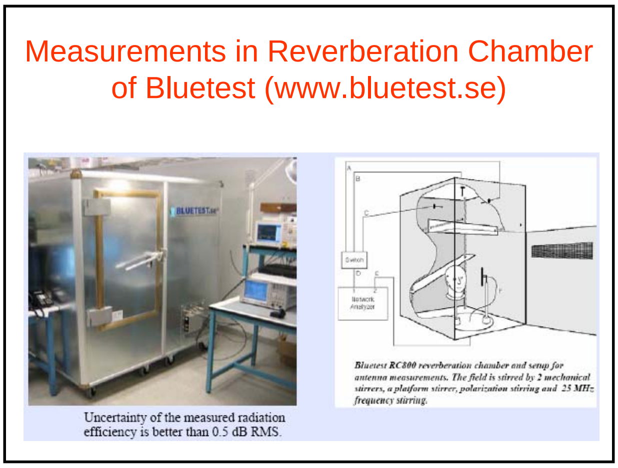
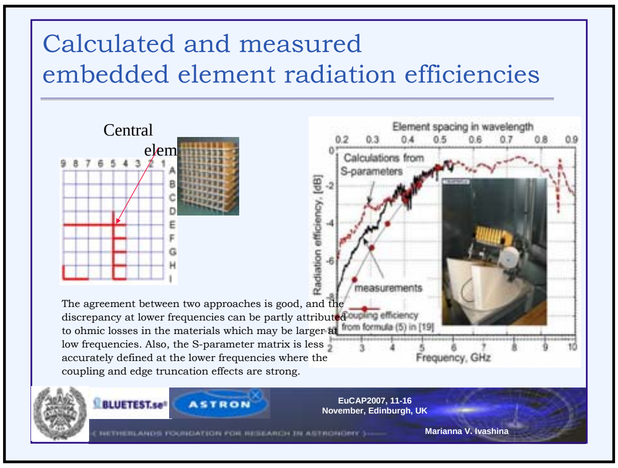


Measurements in Reverberation Chamber of Bluetest (www.bluetest.se)

Uncertainty of the measured radiation efficiency is better than 0.5 dB RMS.

Bluetest RC800 reverberation chamber and setup for antenna measurements. The field is stirred by 2 mechanical stirrers, a platform stirrer, polarization stirring and 25 MHz frequency stirring.



Calculated and measured embedded element radiation efficiencies

Central elem

The agreement between two approaches is good, and the discrepancy at lower frequencies can be partly attributed to ohmic losses in the materials which may be larger at low frequencies. Also, the S-parameter matrix is less accurately defined at the lower frequencies where the coupling and edge truncation effects are strong.

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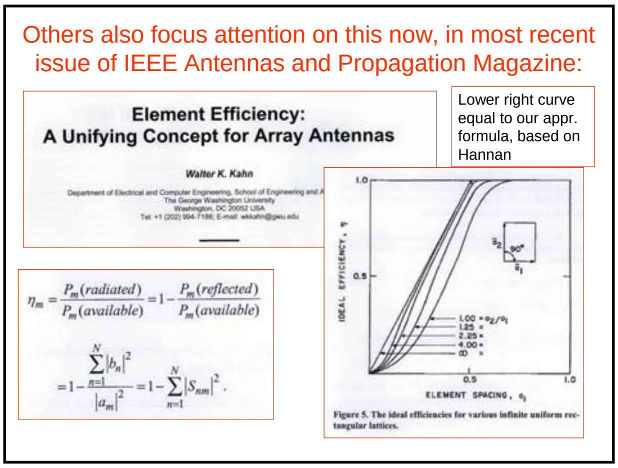

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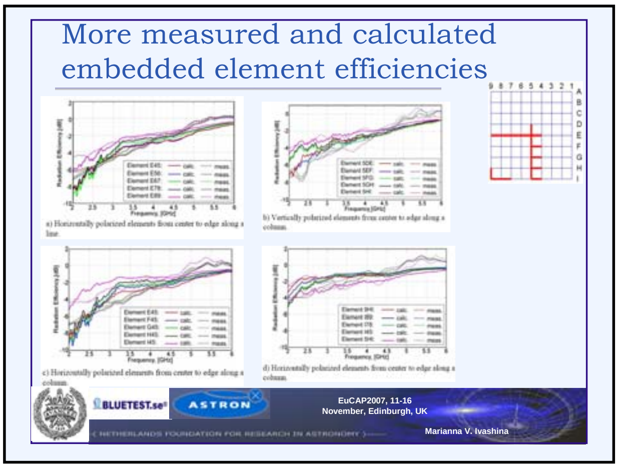

More measured and calculated embedded element efficiencies

a) Horizontally polarized elements from center to edge along a line.

b) Vertically polarized elements from center to edge along a column.

c) Horizontally polarized elements from center to edge along a column.

d) Horizontally polarized elements from center to edge along a column.

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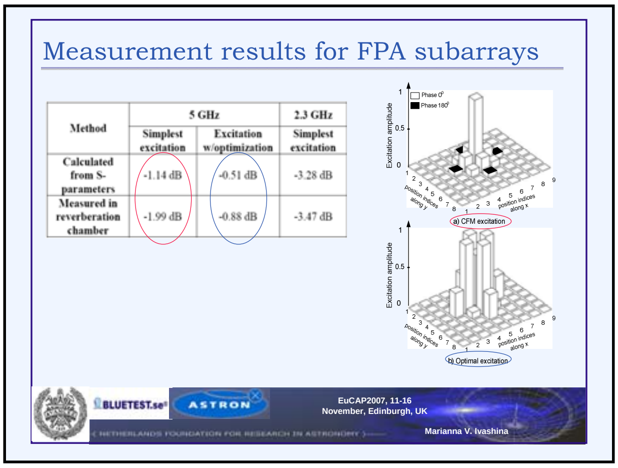

Measurement results for FPA subarrays

Method	5 GHz		2.3 GHz
	Simplest excitation	Excitation w/optimization	Simplest excitation
Calculated from S-parameters	-1.14 dB	-0.51 dB	-3.28 dB
Measured in reverberation chamber	-1.99 dB	-0.88 dB	-3.47 dB

a) CFM excitation

b) Optimal excitation

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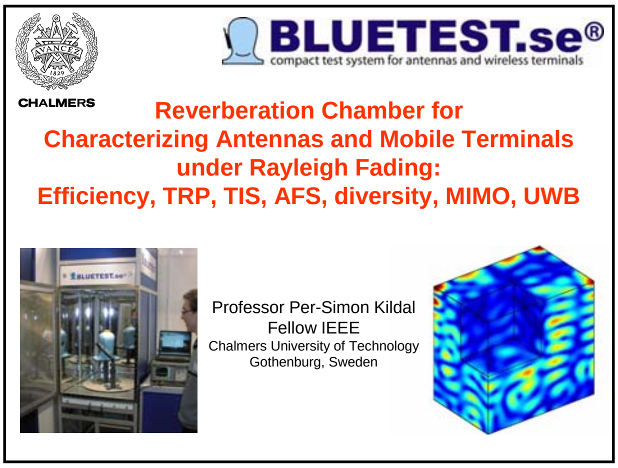
Conclusion

- Further studies of BOR1 efficiency, coupling efficiency, feed scattering and blockage needed
- Main goal is to optimize G/T, or equivalently total aperture efficiency over system noise temperature

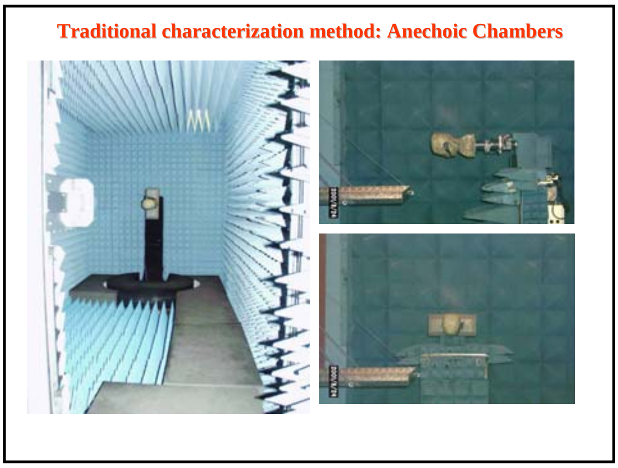
$$e_{tot} / T_{sys} = e_{ap} e_c e_{rad} / T_{sys}$$

- This is best done by optimizing geometry, FPA excitation, and FPA beam port impedance towards LNAs.
- The FPA excitation and system noise temperature MUST be characterized on the beam ports with all other ports matched-terminated (embedded case).
- Complex conjugate field matching can be used as initial solution before optimization
- Coupling efficiency can be measured in reverberation chamber
- We believe that also noise temperatures and noise figures can be measured in reverberation chamber

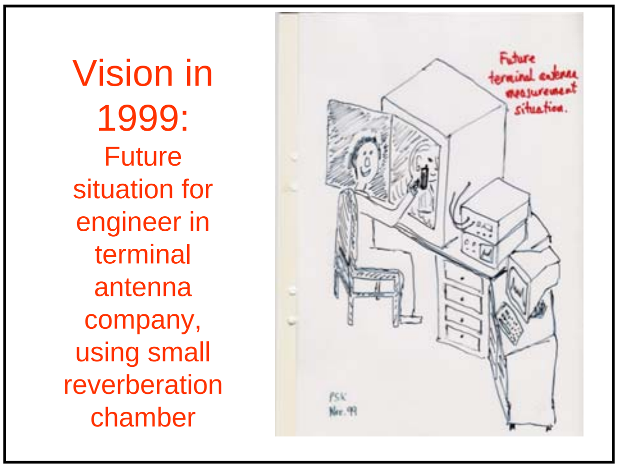


Reverberation Chamber for Characterizing Antennas and Mobile Terminals under Rayleigh Fading: Efficiency, TRP, TIS, AFS, diversity, MIMO, UWB

Professor Per-Simon Kildal
Fellow IEEE
Chalmers University of Technology
Gothenburg, Sweden



Traditional characterization method: Anechoic Chambers



Vision in 1999:

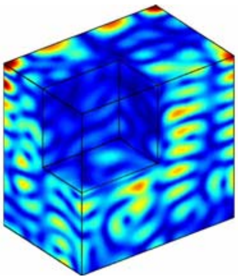
Future situation for engineer in terminal antenna company, using small reverberation chamber

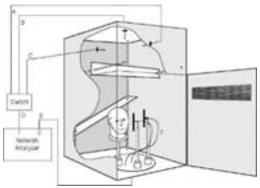
Spin-off company Bluetest at CeBIT 2002

With a reverberation chamber for operation down to 850 MHz

Simulated Electrical Field in cavity during stirring

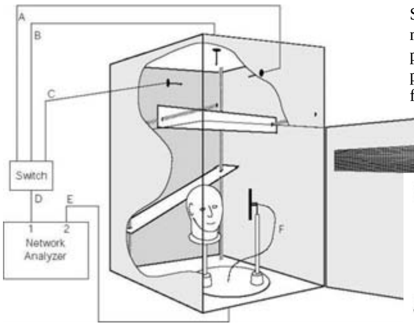
In-house MoM code
Cavity Green's functions

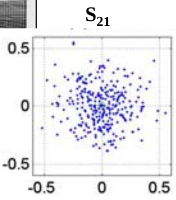




Reverberation chamber and set-up for antenna measurements

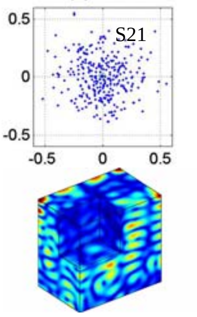
Stirring methods:
mechanical,
platform,
polarization and
frequency.

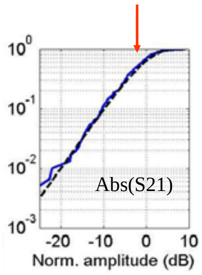




Cumulative probability distribution of fading

S21 is complex Gaussian distribution and envelope Rayleigh

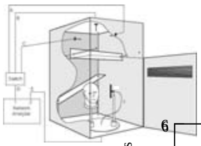




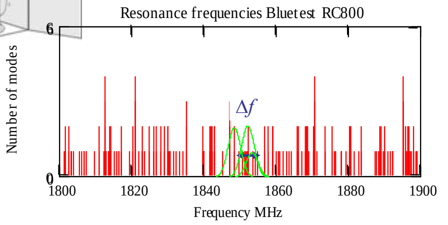
Measurements of antennas and active terminals for wireless

Quantity	Anechoic chamber	Reverberation chamber
Size	🟥	🟩
Price	🟥	🟩
Measurement time	🟥	🟩
Radiation pattern	🟩	🟥
Radiation efficiency	🟩	🟩
Total radiated power TRP	🟩	🟩
Receiver sensitivity TIS	🟩	🟩
Average fading sensitivity AFS	🟥	🟩
Diversity gain (active terminals)	🟥	🟩
MIMO capacity, opportunistic scheduling and more (active terminals)	🟥	🟩

Excitation of multiple resonances
stirring and finite bandwidth makes many modes excited of cavity modes



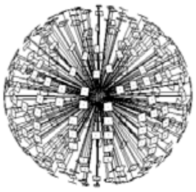
$$f_{ijk} = 150\sqrt{\left(\frac{i}{L}\right)^2 + \left(\frac{j}{W}\right)^2 + \left(\frac{k}{H}\right)^2}\ [\mathrm{MHz}]$$



Angles of incidence of plane waves in 0.8m x 1.1m x 1m chamber (GSM 900 band)

$$\varphi = \arctan\left(\frac{\frac{\pi n_b}{b}}{\frac{\pi n_a}{a}}\right)$$

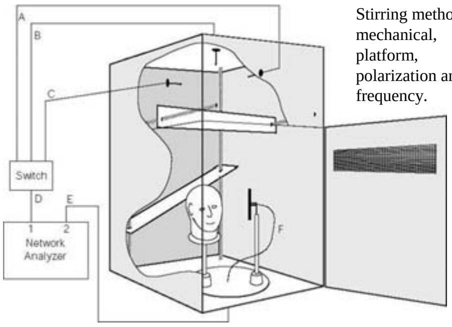
$$\theta = \arctan\left(\frac{\sqrt{\left(\frac{\pi n_b}{b}\right)^2 + \left(\frac{\pi n_a}{a}\right)^2}}{\frac{\pi n_c}{c}}\right)$$



Conclusion: Reverberation chambers corresponds to isotropic multipath environment with uniform distribution of wave directions in both azimuth and elevation.

From Kent Rosengren, Intenna AB

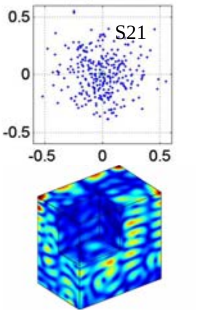
Reverberation chamber and set-up for antenna measurements

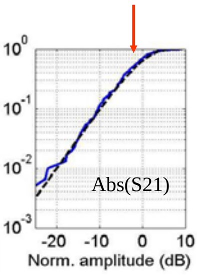


Stirring methods: mechanical, platform, polarization and frequency.

Cumulative probability distribution of fading

S21 is complex Gaussian distribution and envelope Rayleigh





Data extraction for reflection coefficient and radiation efficiency (averaging over stirring positions and frequency)

- Free space reflection coefficient of AUT:

$$\overline{S_{22}} = \frac{1}{N}\sum_{n=1}^{N} S_{22}^{(n)}$$

- Relative received power of AUT:

$$P_{AUT} = \frac{1}{N}\sum_{n=1}^{N} \frac{\left|S_{21}^{(n)}\right|^2}{\left(1-\left|\overline{S_{11}}\right|^2\right)\left(1-\left|\overline{S_{22}}\right|^2\right)}$$

- Radiation efficiency:

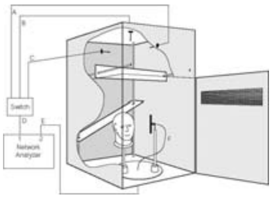
$$e_{rad} = \frac{P_{AUT}}{P_{ref}}\left(1-\left|\overline{S_{22}}\right|^2\right)$$

- P_{ref} is relative received power of reference antenna

Power transfer function is proportional to radiation efficiency (Hill, 1994)

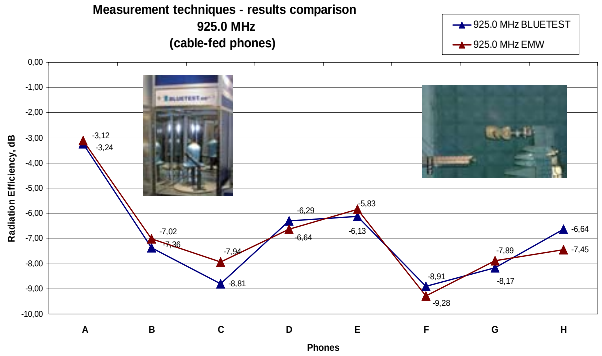
$$G_{\text{chamber}} = \frac{P_r}{P_t} = \frac{c^3 e_{rad1} e_{rad2}}{16\pi^2 V f^2 \Delta f}$$

$$Q_{\text{chamber}} = f/\Delta f$$

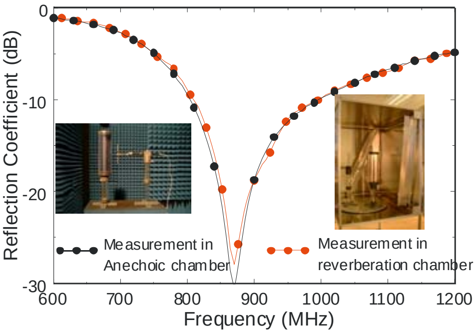


Thereby we can measure radiation efficiency and radiated power

Validation against anechoic chamber Example: 925 MHz, 8 phones, 1 pos.

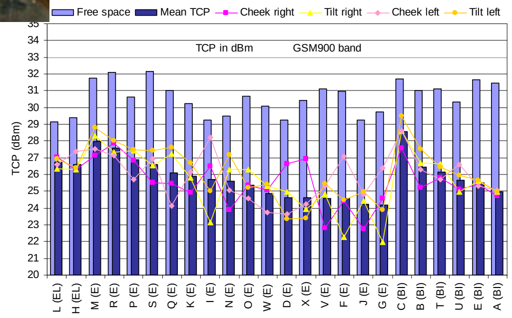


Measurements of free space antenna impedance Example: Dipole 10 mm from cylinder surface

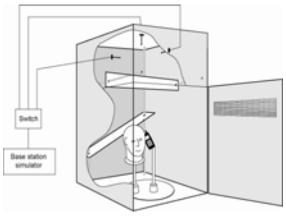


Measured radiated power of 20 phones in 5 positions (free space + CENELEC)

Example of results for radiated power 20 phones, 5 positions, 900 MHz



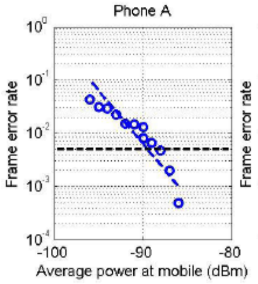
Measuring receiver sensitivity of GSM and CDMA phones

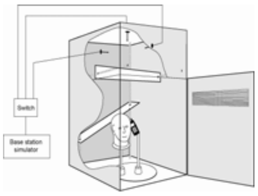


- FER = Frame Error Rate
- Corresponds to BER = Bit Error Rate
- TIS = Total Isotropic Sensitivity
- AFS = Average fading sensitivity

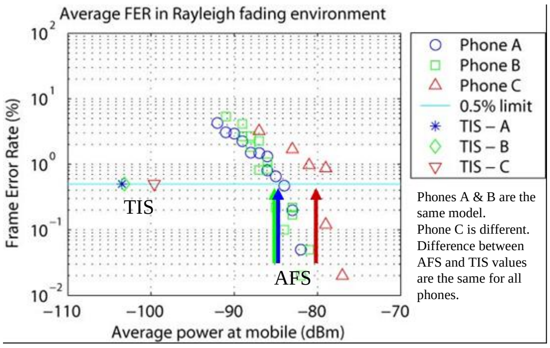
With Kyocera

Determining AFS at 0.5% FER (Average Fading Sensitivity)



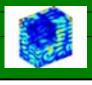


Comparison between TIS and AFS sensitivities



Phones A & B are the same model. Phone C is different. Difference between AFS and TIS values are the same for all phones.

Measurements of antennas and active terminals for wireless

Quantity	Anechoic chamber	Reverberation chamber
Size	🟥	🟩
Price	🟥	🟩
Measurement time	🟥	🟩
Radiation pattern	🟩	🟥
Radiation efficiency	🟩	🟩
Total radiated power TRP	🟩	🟩
Receiver sensitivity TIS	🟩	🟩
Average fading sensitivity AFS	🟥	🟩
Diversity gain (active terminals)	🟥	🟩 
MIMO capacity, opportunistic scheduling and more (active terminals)	🟥	🟩