IETR

The electromagnetic reverberation chamber: a tool with multiple facets and applications

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Agenda

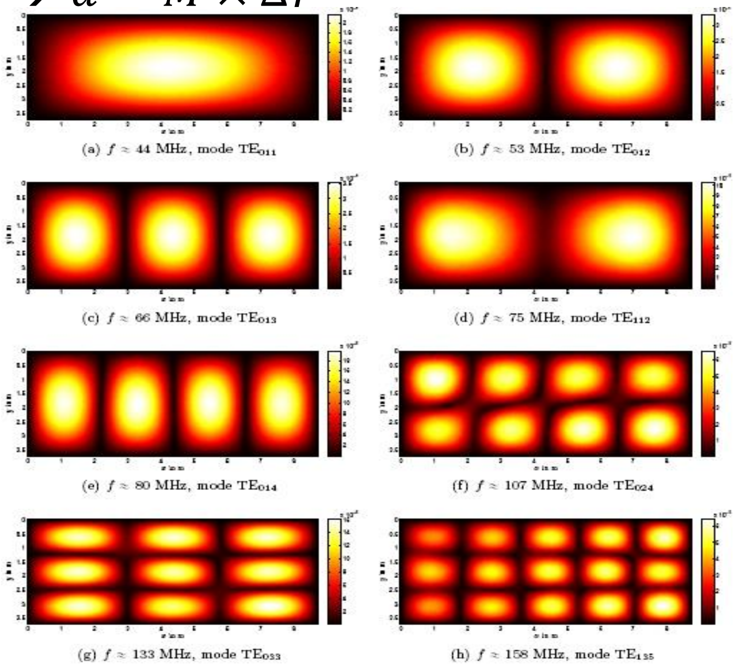
3-D overmoded cavities

- Multiple modes with significant excitation over a number of states

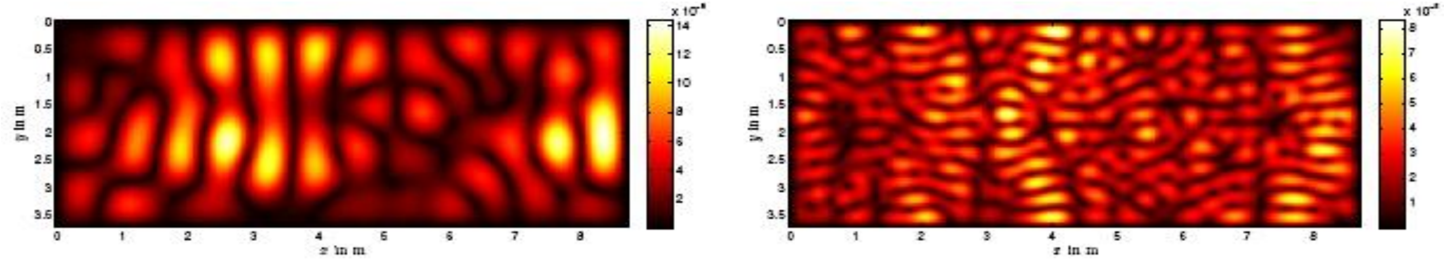
→ Mode density (M) $\approx 8\pi V \frac{f^2}{c}$

→ Composite Q-factor (Q) $= \frac{f}{\Delta f}$

→ $d = M \times \Delta f$ d=<<1



(a) $f \approx 44$ MHz, mode TE_{011}
(b) $f \approx 53$ MHz, mode TE_{012}
(c) $f \approx 66$ MHz, mode TE_{013}
(d) $f \approx 75$ MHz, mode TE_{112}
(e) $f \approx 80$ MHz, mode TE_{014}
(f) $f \approx 107$ MHz, mode TE_{024}
(g) $f \approx 133$ MHz, mode TE_{033}
(h) $f \approx 158$ MHz, mode TE_{135}



(i) $f \approx 263$ MHz (j) $f \approx 500$ MHz

E. Amador et. al, "Reverberation Chamber Modeling Based on Image Theory: Investigation in the Pulse Regime," in *IEEE Transactions on Electromagnetic Compatibility*, vol. 52, no. 4, pp. 778-789, Nov. 2010

Introduction to RC

Well overmoded / stirred cavity:

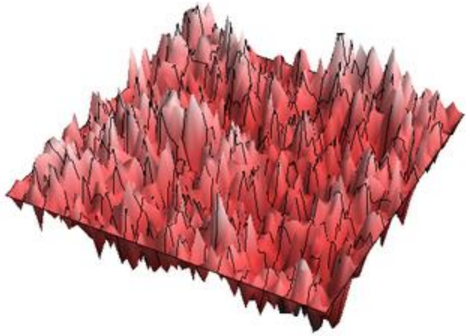
- Plane wave spectrum
- Hill's (asymptotical) model

$$e_{x,y,z}(t) = E_{x,y,z} e^{j\omega t}$$

$$E_{x,y,z} = E^{r}_{x,y,z} + jE^{r}_{x,y,z}$$

$$E^{r}_{x}, E^{r}_{y}, E^{r}_{z}, E^{i}_{x}, E^{i}_{y}, E^{i}_{z} \equiv v$$

$$Var(v) = \sigma_v{}^{2}$$



Gaussian « random » field

$$\mathrm{p}_n(v) = \frac{1}{\sqrt{2\pi}\,\sigma_v} e^{-\frac{1}{2}\frac{v^2}{\sigma_v^2}}$$

Introduction to RC

Antenna effective area $P_{rec} = A_{eff} \times P_{den}$

$$A_{\text{eff}} = \frac{\lambda^2}{4\pi}\eta m[D_\theta(\theta,\phi)\vec{\theta} + D_{phi}(\theta,\phi)\vec{\phi}] \qquad (23)$$

The same antenna is now under **a plane wave spectrum illumination.** Its effective area writes :

$$A_{\text{eff}} = \frac{\lambda^2}{4\pi}\eta m \int_0^{2\pi}\int_0^{\pi}[D_\theta(\theta,\phi)p_\theta(\theta,\phi)\vec{\theta}+D_\phi(\theta,\phi)p_\phi(\theta,\phi)\vec{\phi}]\sin\theta d\theta d\phi \qquad (24)$$

$p_\theta(\theta,\phi)$ and $p_\phi(\theta,\phi)$ are the probability distribution of the plane wave incidence for each polarization.

$$p_\theta(\theta,\phi) = p_\phi(\theta,\phi) = \frac{1}{4\pi} \qquad (25)$$

Receiving antenna $\frac{\lambda^2}{8\pi}\eta m$ (ensemble average) Transmitting antenna $\frac{\lambda^2}{4\pi}\eta m$

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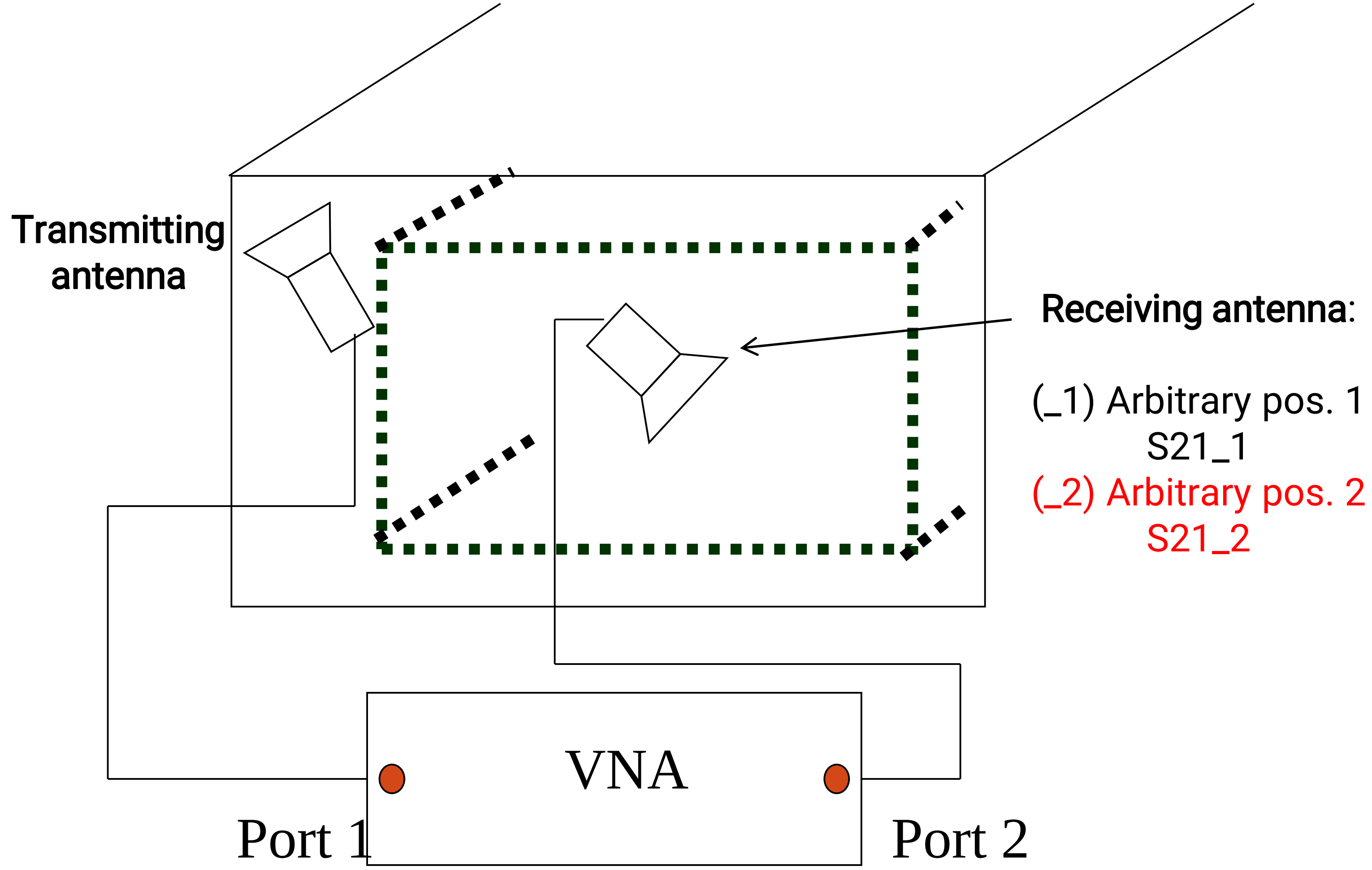
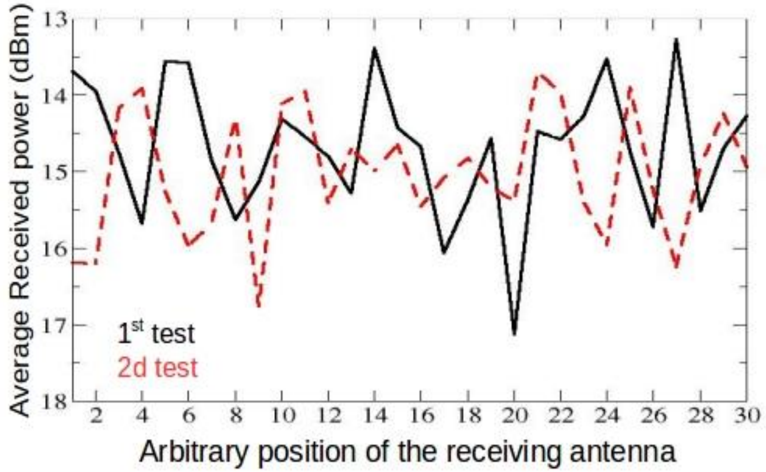
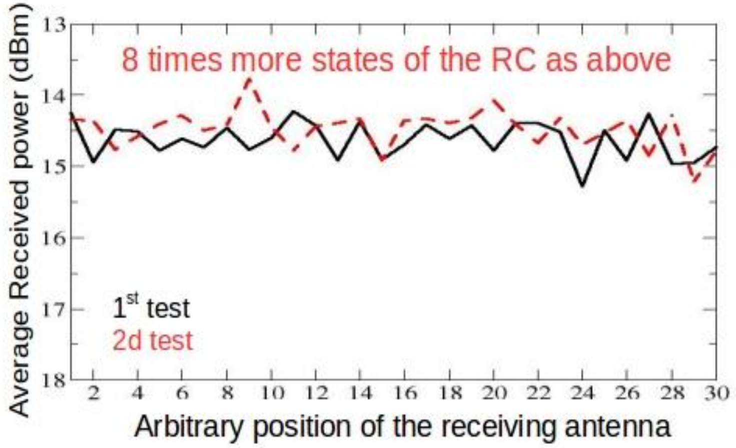
Receiving antenna $\frac{\lambda^2}{8\pi}\eta m$ (ensemble average)

Transmitting antenna $\frac{\lambda^2}{4\pi}\eta m$

Introduction to RC



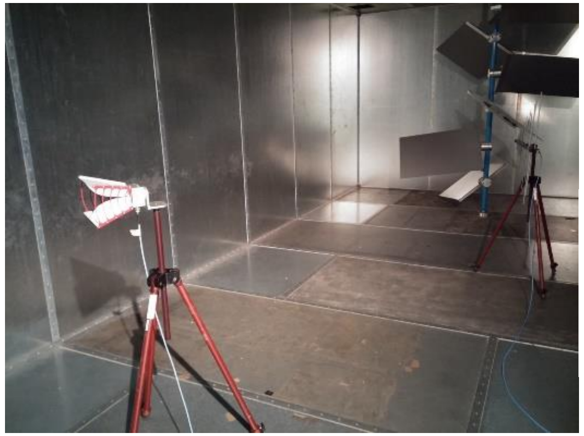




Antenna efficiency and antenna patterns in RC

Antenna efficiency from Q

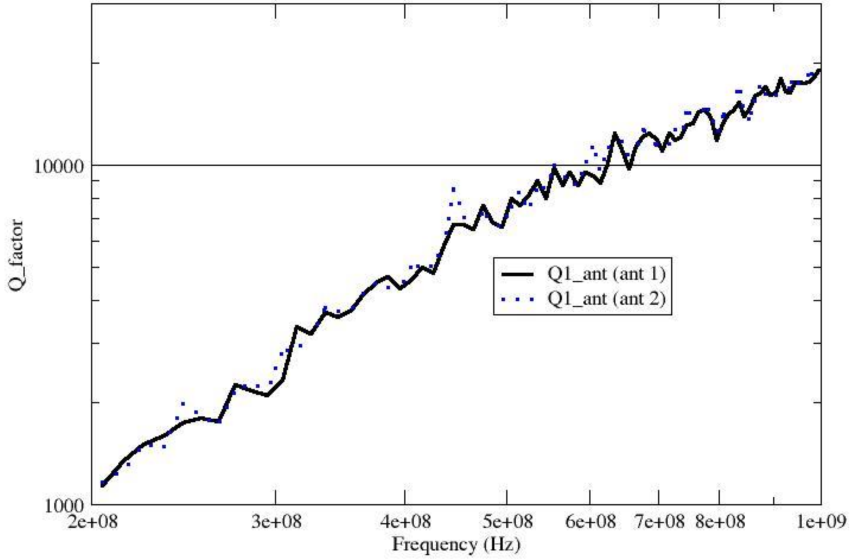
$$Q_{1ant} = \left\langle \left| S_{xx} - \langle S_{xx} \rangle \right|^2 \right\rangle \frac{Z_0 \omega \epsilon V}{(\lambda^2/4\pi)(1 - |\langle S_{xx} \rangle|^2)^2 \eta_x^2}.$$

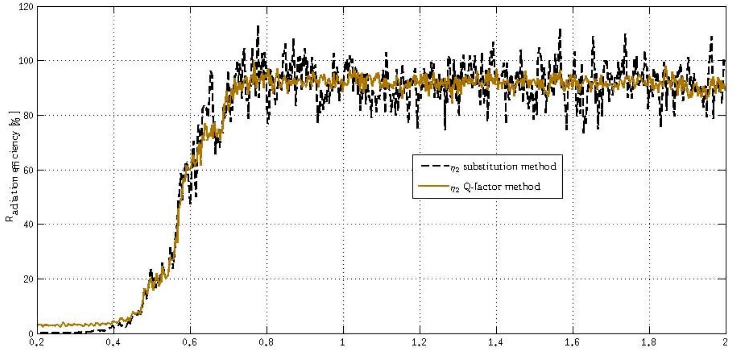


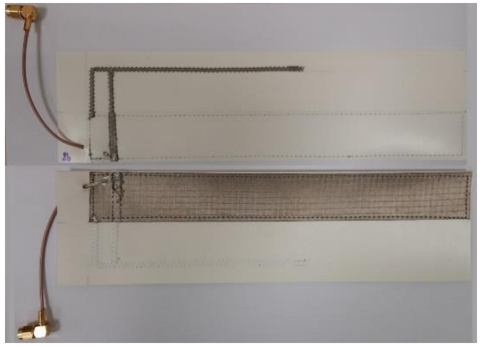
$$Q_x = \frac{Q_x^\#}{\eta_x^2}.$$

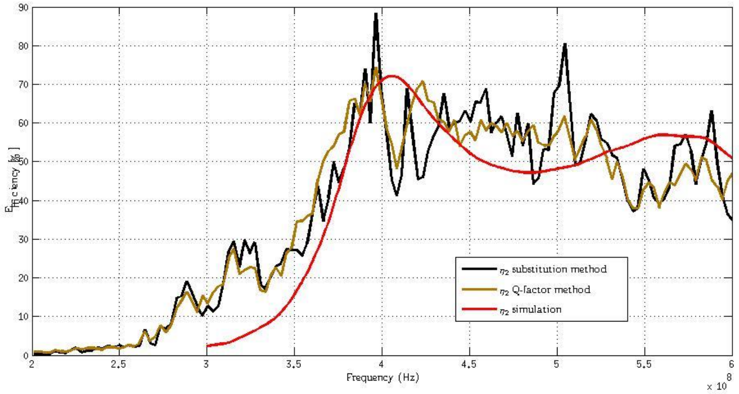
$$\eta_2 = \sqrt{\frac{Q_2^\#}{Q_1^\#}} \eta_1 = \sqrt{\frac{Q_2^\#}{Q_1}}$$

Q estimation at two identical antennas









P. Besnier, J. Sol, A. Presse, C. Lemoine, and A. -C. Tarot, “Antenna efficiency measurement from quality factor estimation in reverberation chamber,” in *Proc. Eur. Microw. Conf.*, 2016, pp. 715–718,

Antenna efficiency and antenna patterns in RC

Antenna efficiency: Without reference antenna

- Based on the difference between time domain and frequency domain estimation of Q
- The decay constant τ of the RC ($Q_{TD} = 2\pi f \ \tau$) is not dependent on η at **high enough frequencies**
- Can be applied for estimating efficency for 2 or 3 antennas at a time

Ref: C. L. Holloway, H. A. Shah, R. J. Pirkl, W. F. Young, D. A. Hill and J. Ladbury, "Reverberation Chamber Techniques for Determining the Radiation and Total Efficiency of Antennas," in IEEE Transactions on Antennas and Propagation, vol. 60, no. 4, pp. 1758-1770, April 2012

- Key role of (all) antenna stirring to reduce the bias estimation of reflection coefficients due to residual unstirred paths

Ref: W. Krouka, F. Sarrazin, J. Sol, P. Besnier and E. Richalot, "Biased Estimation of Antenna Radiation Efficiency Within Reverberation Chambers Due to Unstirred Field : Role of Antenna Stirring," in IEEE Transactions on Antennas and Propagation, vol. 70, no. 10, pp. 9742-9751,

Antenna efficiency: From backscattering measurements (i.e. without contact using 2 loading conditions)

Ref: W. Krouka, F. Sarrazin, J. d. Rosny, A. Labdouni and E. Richalot, "Antenna Radiation Efficiency Estimation From Backscattering Measurement Performed Within Reverberation Chambers," in *IEEE Transactions on Electromagnetic Compatibility*, vol. 64, no. 2, pp. 267-274, April 2022

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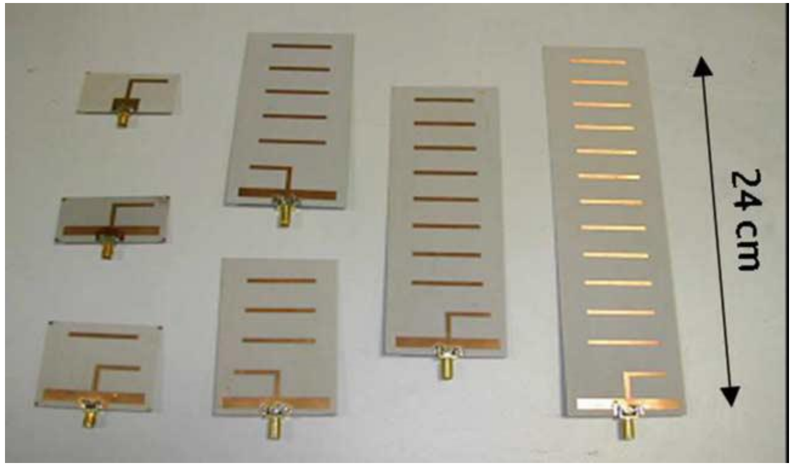
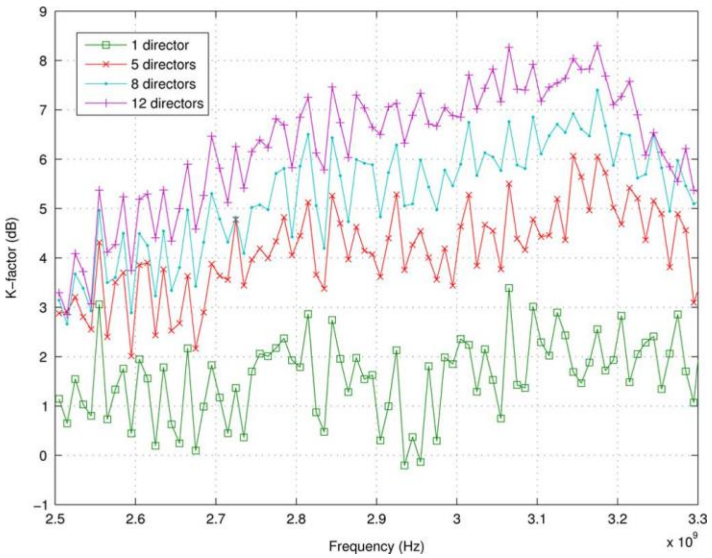
Antenna efficiency and antenna patterns in RC

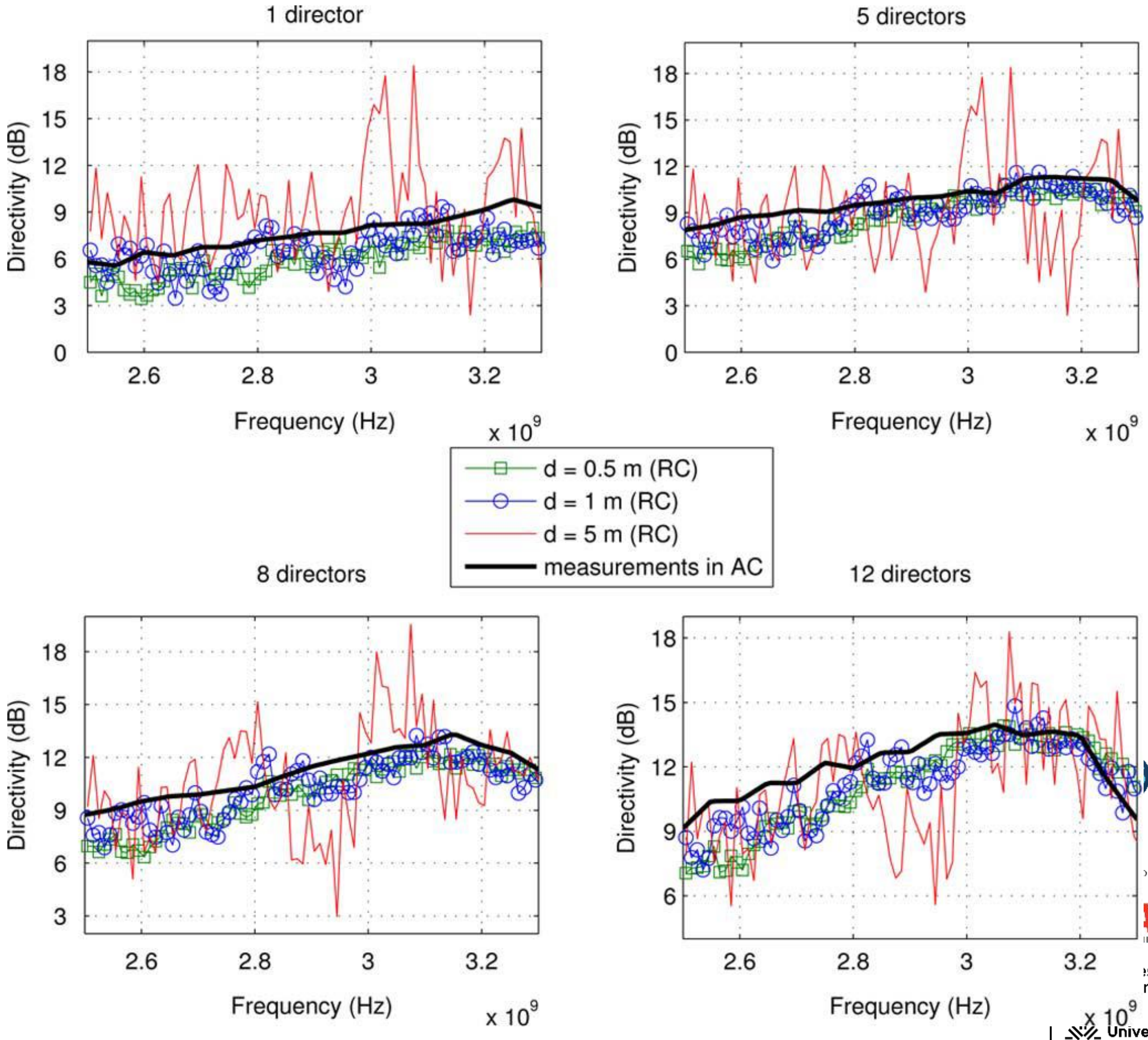
Antenna pattern





K factor
(Ricean channel)

$$K = \frac{v^2}{2\sigma^2}\cdot$$



C. Lemoine, E. Amador, P. Besnier, J. -M. Floc'h and A. Laisné, "Antenna Directivity Measurement in Reverberation Chamber From Rician K-Factor Estimation," in *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 10, pp. 5307-5310, Oct. 2013.

Average absorbing cross-section

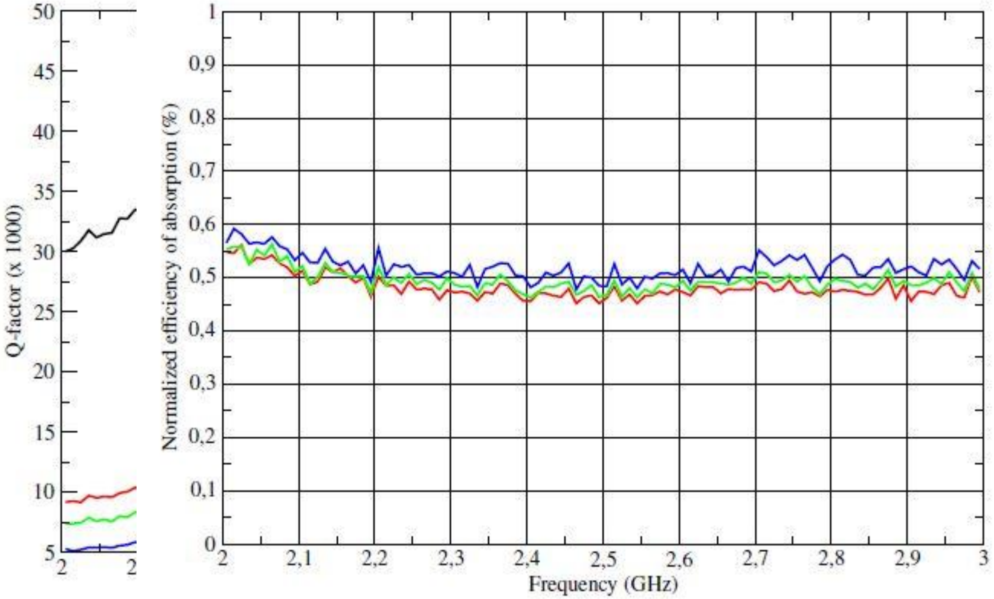
$$P_{d-obj} = \sigma_{abs} \frac{E^2}{Z_0}.$$

$$Q_{obj} = \frac{2\pi V}{\lambda} \frac{1}{\sigma_{abs}}.$$

$$\sigma_{abs} = \frac{2\pi V}{\lambda} \left(\frac{1}{Q_g^L} - \frac{1}{Q_g^0} \right).$$

$$\sigma_{abs} = \langle T \rangle \frac{A_{tot}}{2}.$$

$$\langle T \rangle = 2 \int_0^{\pi/2} \left[1 - \frac{|\Gamma_{TM}(\theta)|^2 + |\Gamma_{TE}(\theta)|^2}{2} \right] \cos(\theta) \sin(\theta) d\theta.$$

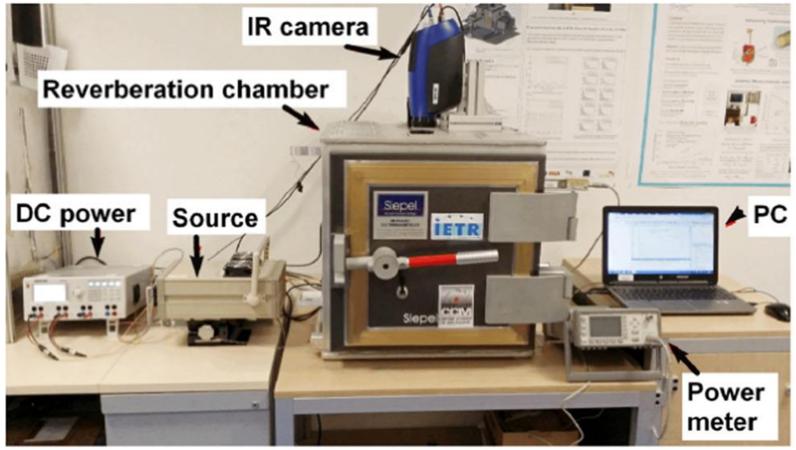


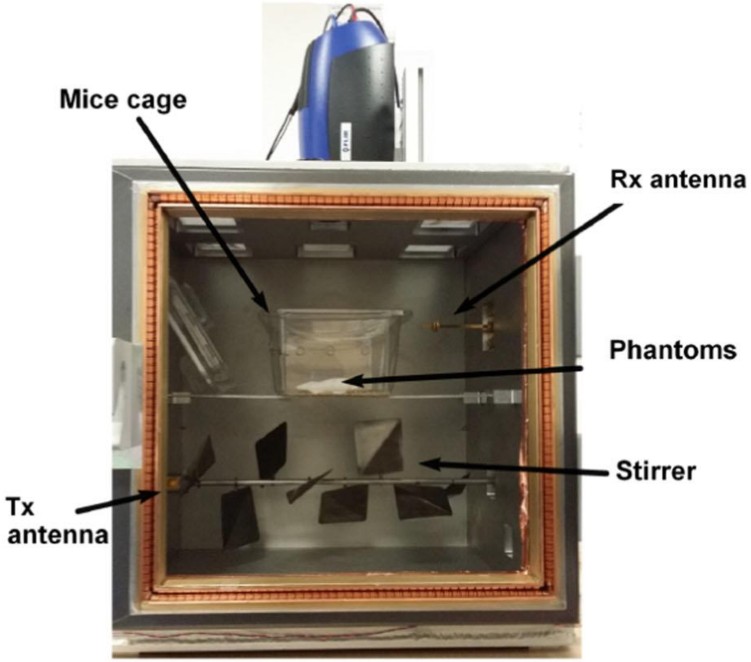
Dosimetry

$$\frac{\rho C}{k_t}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} - \frac{V_s}{k_t}(T - T_b) + \frac{q(x,y,z,t)}{k_t},$$

$$q(z) \simeq \frac{\langle S_0 \rangle \bar{T}_p}{\delta}[\exp(-2z/\delta) + \exp(-2(L_z - z)/\delta)].$$

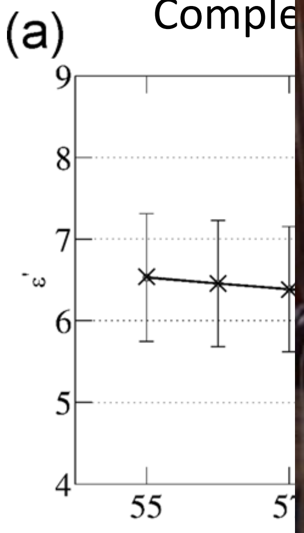
(1D)

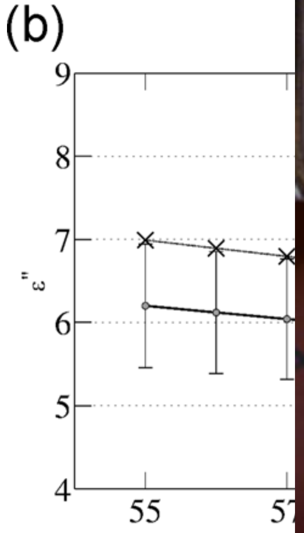


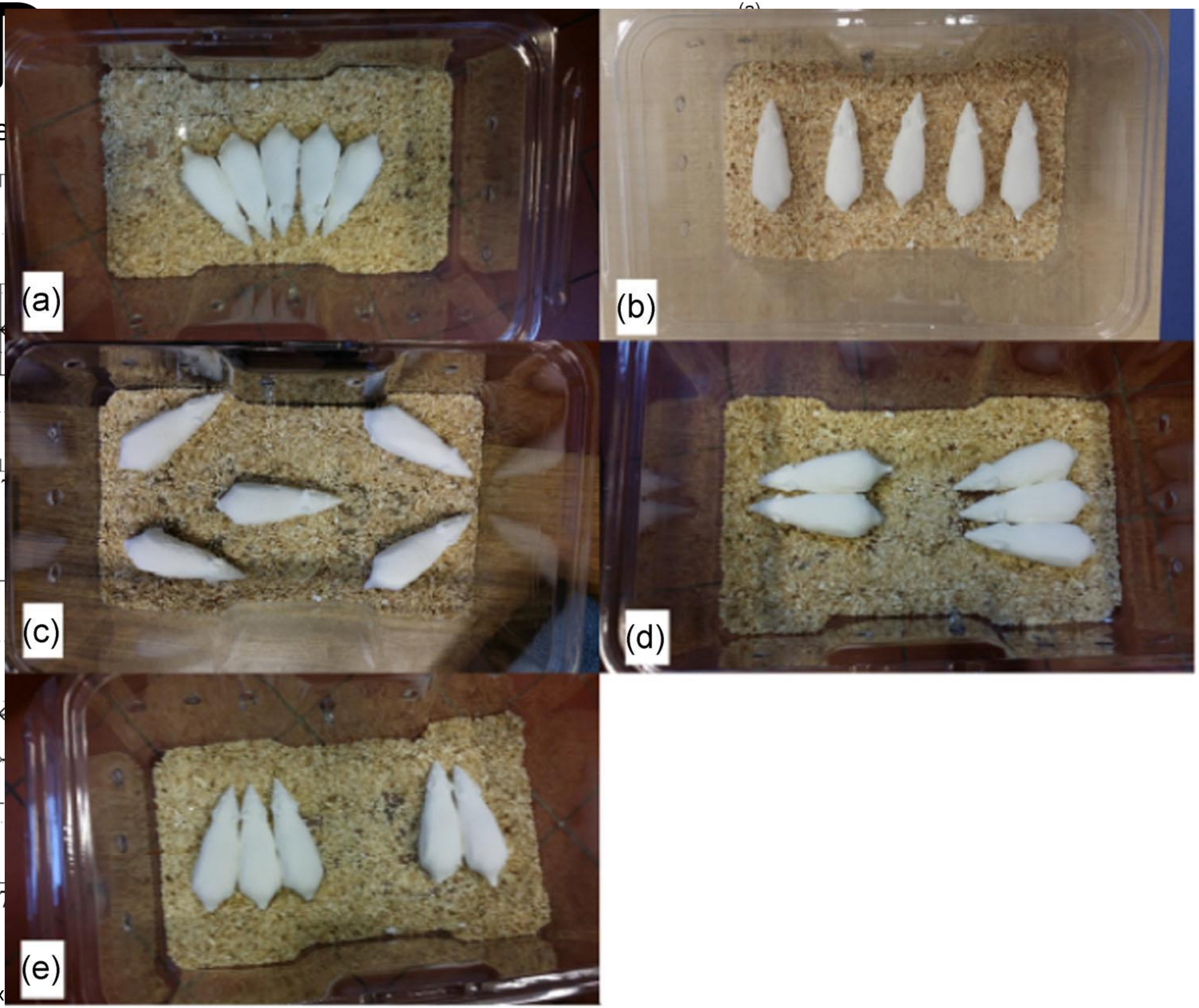


Khadir Fall, A. et al. (2020), Exposure Assessment in Millimeter-Wave Reverberation Chamber Using Murine Phantoms. Bioelectromagnetics, 41: 121-135

Comple

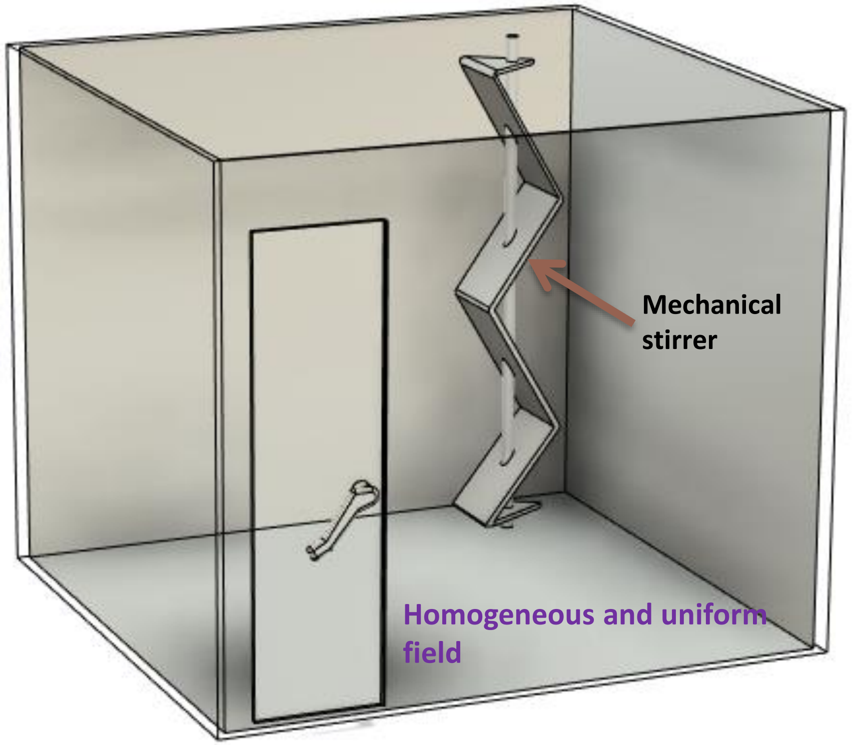


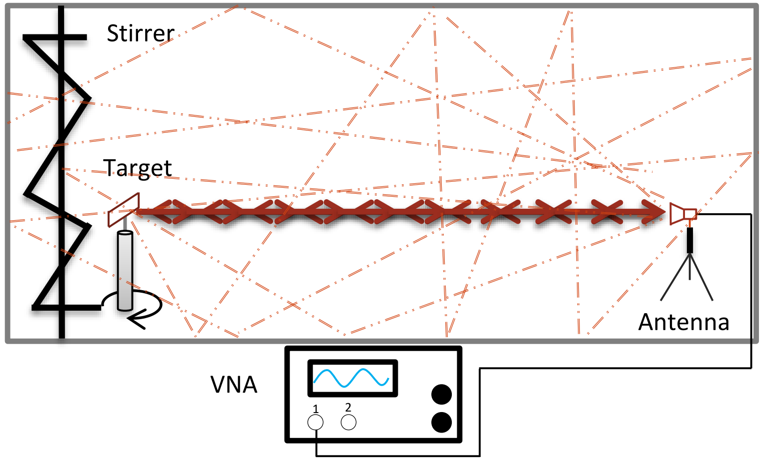




Khadir Fall, A. et al. (2020), Ex

Backscattering measurements





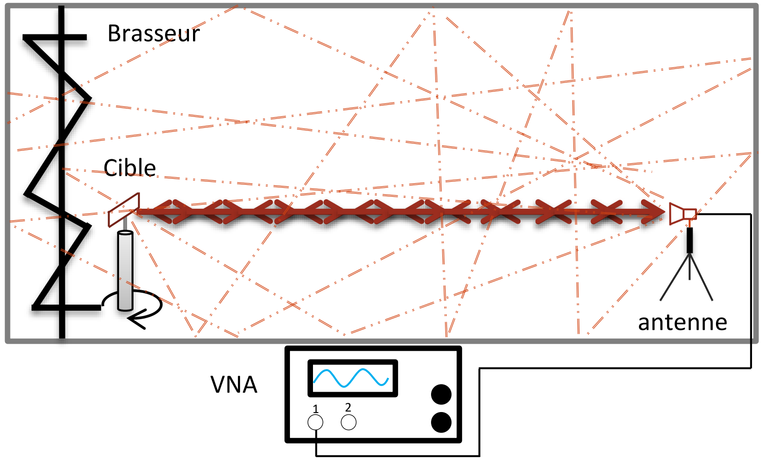
Multiple paths

LOS path extraction ?

Backscattering measurements

LOS path extraction ?

- K-factor estimation of Rice distribution [1], [2(for RCS)]
- Doppler effect (linear movement of the target [3])
- Time gating [4(for RCS)]



Another approach based on RC properties (IETR / ESYCOM collaboration)

[1] P. Besnier, C. Lemoine, J. Sol, J.-M.Floc'h, Radiation pattern measurements in reverberation chamber based on estimation of coherent and diffuse electromagnetic fields, IEEE Conference on Antenna Measurements and Applications (CAMA), Nov. 2014.

[2] A. Sorrentino, G. Ferrara, M. Migliaccio and S. Cappa, "Measurements of Backscattering from a Dihedral Corner in a Reverberating Chamber", ACES JOURNAL, vol. 33, no. 1, January 2018

[3] M. Á García Fernández, D. Carsenat and C. Decroze, Antenna Radiation Pattern Measurements in Reverberation Chamber Using Plane Wave Decomposition, IEEE Transactions on Antennas and Propagation, vol. 61, no. 10, pp. 5000-5007, Oct. 2013.

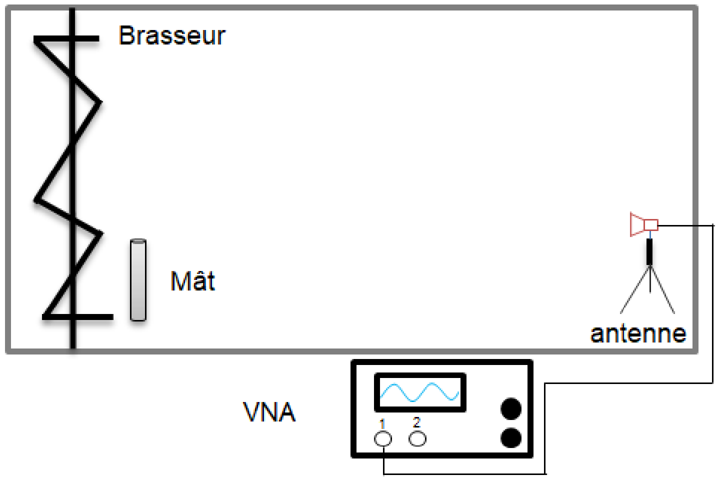
[4] A. Soltane, G. Andrieu and A. Reineix, Monostatic Radar Cross-Section Estimation of Canonical Targets in Reverberating Room Using Time-Gating Technique, 2018 Int. Symp . Electromagn. Compat. (EMC EUROPE), Amsterdam, pp. 355-359, 2018.

Backscattering measurements

Mesure dans la chambre à vide (sans la cible):

$$S(f_0,\alpha_{br}) = S_{EL}(f_0) + (1-|S_{EL}(f_0)|^2)\eta_{ant}[H(f_0,\alpha_{br}) + h_s(f_0,\alpha_{br})]$$

Espace libre — Rétrodiffusion CRBM — Réflexions spéculaires

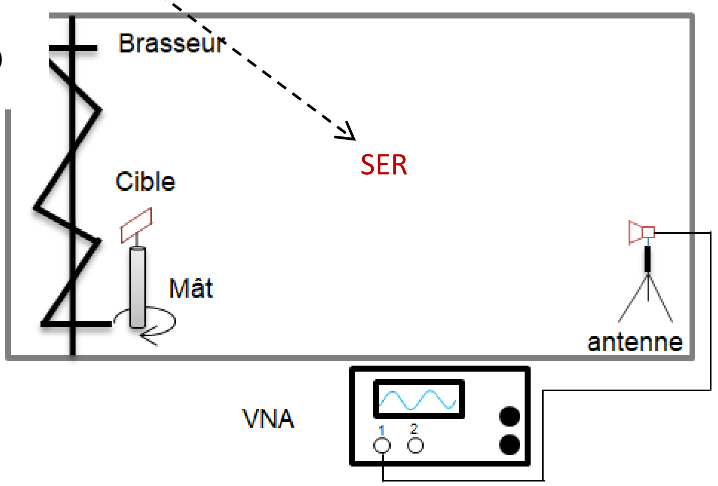


Mesure dans la chambre chargée (avec la cible):

$$S_c(f_0,\alpha_{br},\theta_c) = S_{EL}(f_0) + C(f_0)\sqrt{\sigma_c(f_0,\theta_c)} + (1-|S_{EL}(f_0)|^2)\eta_{ant}[H_c(f_0,\alpha_{br},\theta_c) + h_s(f_0,\alpha_{br})]$$

Espace libre — Onde balistique — Rétrodiffusion CRBM — Réflexions spéculaires

$$|C(f_0)| = \frac{G_{ant}(f_0)\lambda_0}{(4\pi)^{3/2}R^2}(1-|S_{EL}(f_0)|^2)$$



A. Reis *et al.*, "Radar Cross Section Pattern Measurements in a Mode-Stirred Reverberation Chamber: Theory and Experiments," in *IEEE Transactions on Antennas and Propagation*, vol. 69, no. 9, pp. 5942-5952, Sept. 2021.

Backscattering measurements

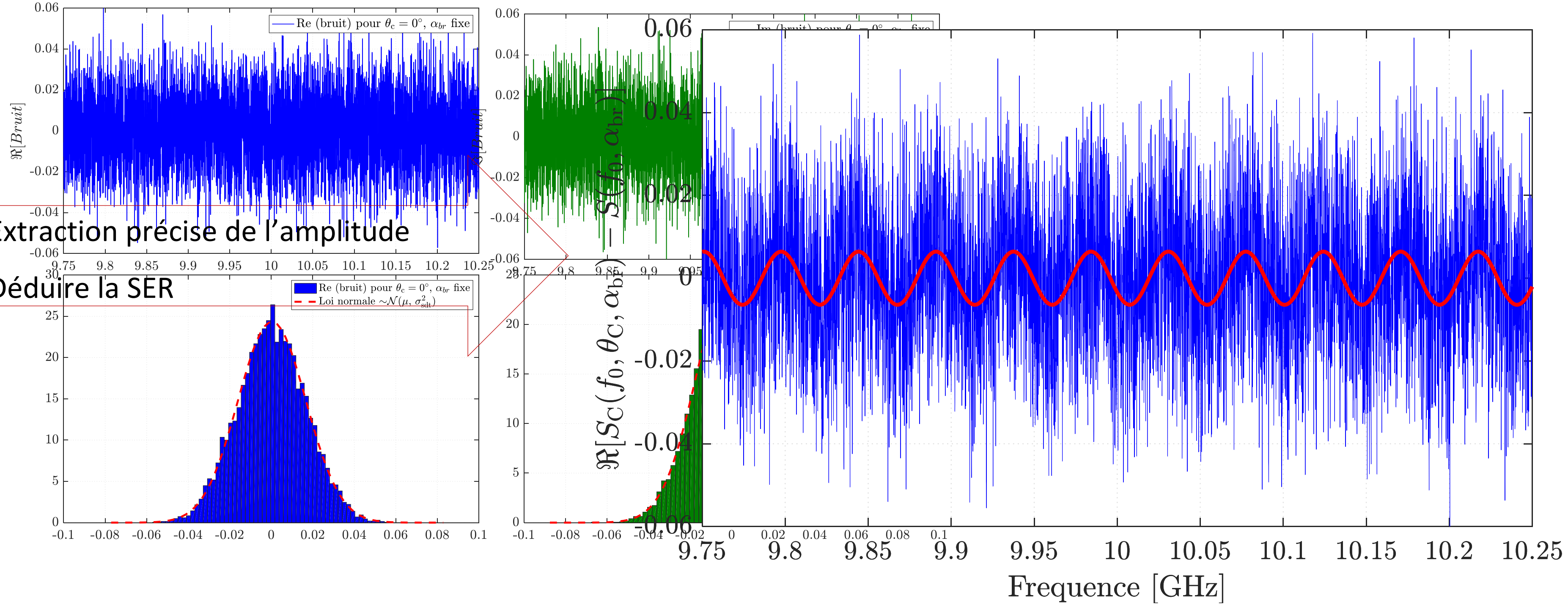
$$S_c(f_0,\alpha_{br},\theta_c) - S(f_0,\alpha_{br}) = (1-|S_{EL}(f_0)|^2)\eta_{ant}\left[H_c(f_0,\alpha_{br},\theta_c) - H(f_0,\alpha_{br})\right] + \sqrt{\sigma_c(f_0,\theta_c)} \times |C(f_0)| \times exp\left[-j\left(2\pi f_0\frac{2R}{c} - \phi_0\right)\right]$$

Rétrodiffusion CRBM

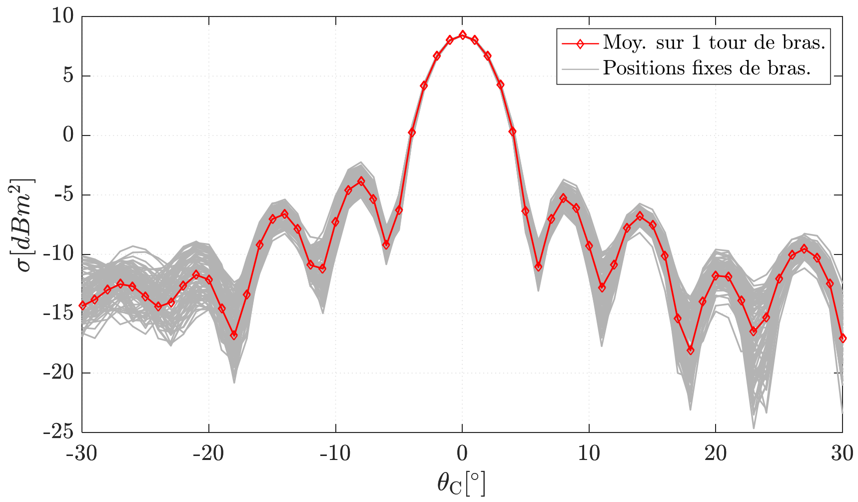
SER

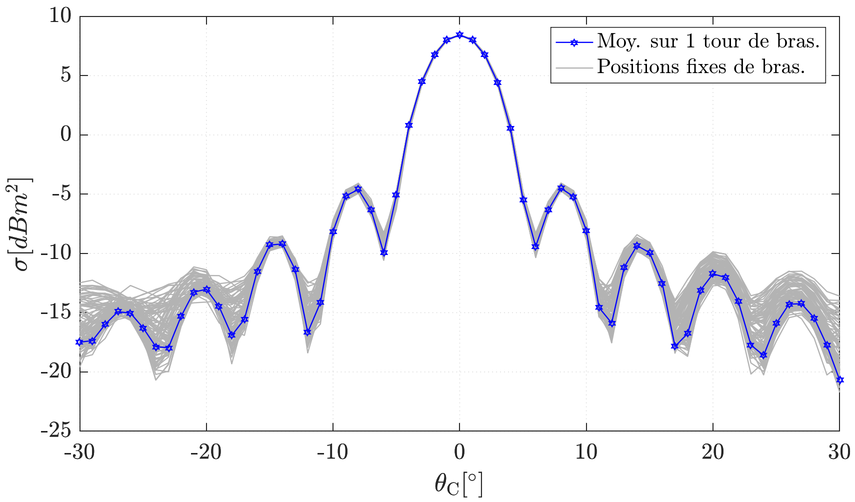
Amplitude onde balistique

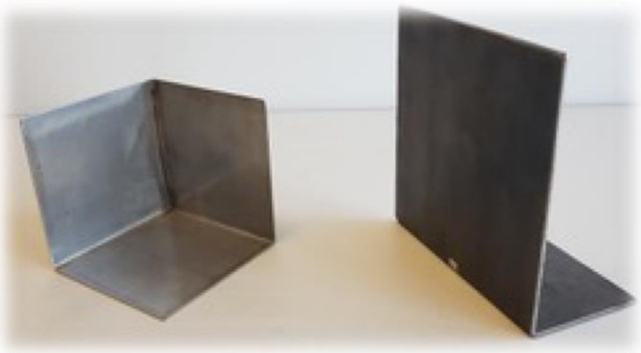
- Extraction précise de l'amplitude
- Déduire la SER

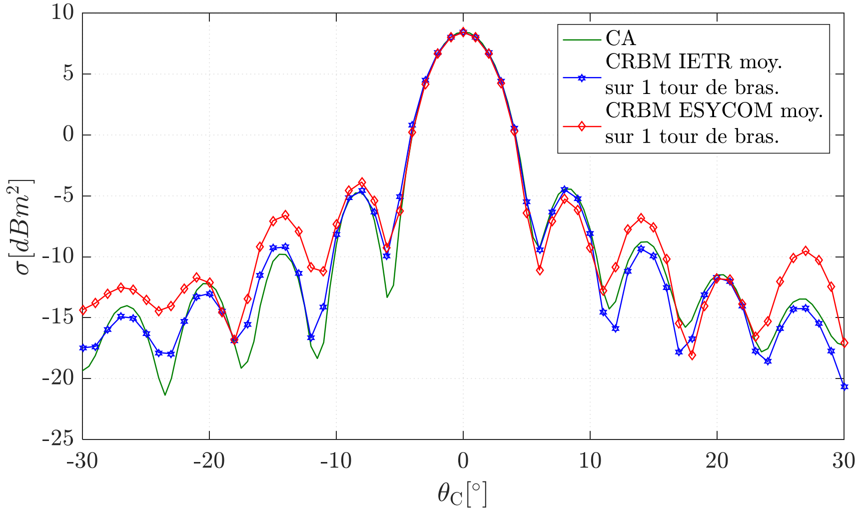


Backscattering measurements





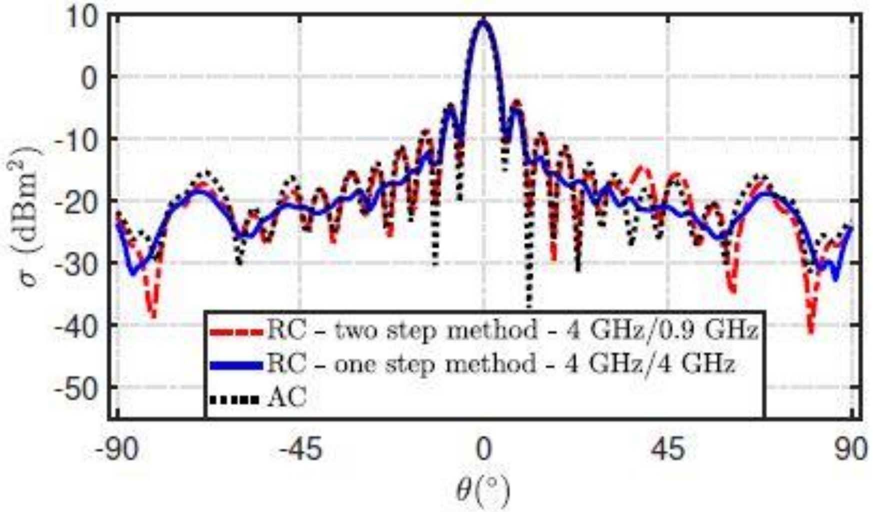




Backscattering measurements

Recent improvements

Quasi-monostatic configuration (no stirring)



Distance
+
Amplitude

Charlo, C., Méric, S., Sarrazin, F., Richalot, E., Sol, J., & Besnier, P. (2023). Advanced Analysis of Radar Cross-Section Measurements in Reverberation Environment. https://arxiv.org/abs/2303.08751

IETR Backscattering measurements

Antenna radar cross-section → Antenna pattern ?

$$\sqrt{\sigma_{\mathrm{ant}}} = \sqrt{\sigma_{\mathrm{s}}} + \sqrt{\sigma_{\mathrm{r}}}$$

Radiating mode

$$\sqrt{\sigma_{\mathrm{r}}} = \sqrt{\sigma_r^{\mathrm{max}}} \cdot |\Gamma_{\mathrm{L}}|$$

Measurements with two loads L1 and L2:

$$S_{\mathrm{L1}} = S_{\mathrm{FS}} + (1 - |S_{\mathrm{FS}}|^2)\eta_a H_{\mathrm{L1}} + \mathrm{C}\left(\sqrt{\sigma_{\mathrm{s}}} + \sqrt{\sigma_r^{max}} \cdot |\Gamma_{\mathrm{L1}}|\right)$$

$$S_{\mathrm{L2}} = S_{\mathrm{FS}} + (1 - |S_{\mathrm{FS}}|^2)\eta_a H_{\mathrm{L2}} + \mathrm{C}\left(\sqrt{\sigma_{\mathrm{s}}} + \sqrt{\sigma_r^{max}} \cdot |\Gamma_{\mathrm{L2}}|\right)$$

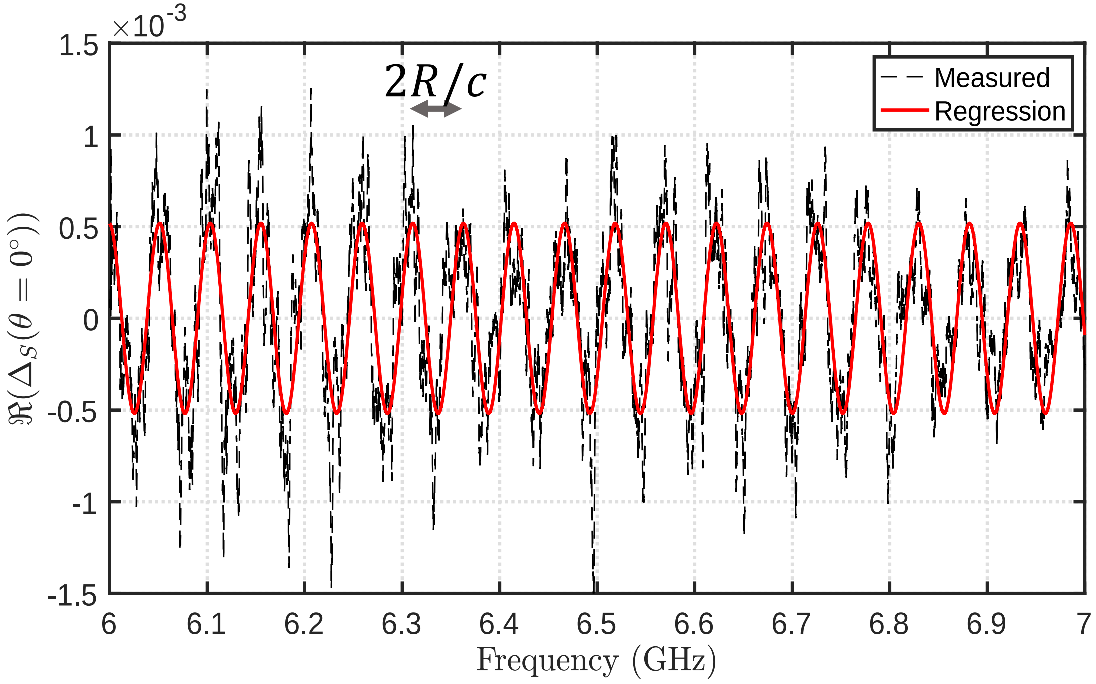
$$S_{\mathrm{L1}} - S_{\mathrm{L2}} = (1 - |S_{\mathrm{FS}}|^2)\eta_a (H_{\mathrm{L1}} - H_{\mathrm{L2}}) + \mathrm{C}\sqrt{\sigma_r^{max}} \cdot (|\Gamma_{\mathrm{L1}}| - |\Gamma_{\mathrm{L2}}|)$$

Backscattering measurements

$$S_{L1} - S_{L2} = (1 - |S_{FS}|^2)\eta_a(H_{L1} - H_{L2}) + |C|\sqrt{\sigma_r^{max}}(|\Gamma_{L1}| - |\Gamma_{L2}|)\ exp\frac{-j2\pi f 2R}{c}$$

$$\Delta_S = \sqrt{\sigma_r^{max}}\ exp\left(-j2\pi f\frac{2R}{c}\right) + noise$$

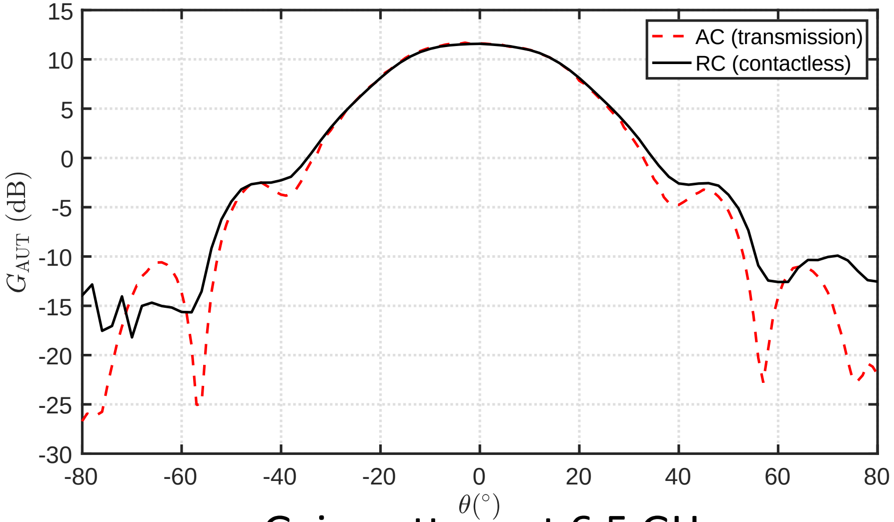
72 stirring positions
+
sinusoidal regression



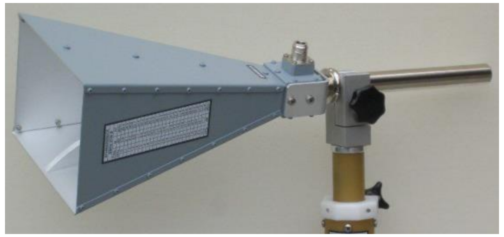
Backscattering measurements

Validation ESYCOM RC 19 m^3

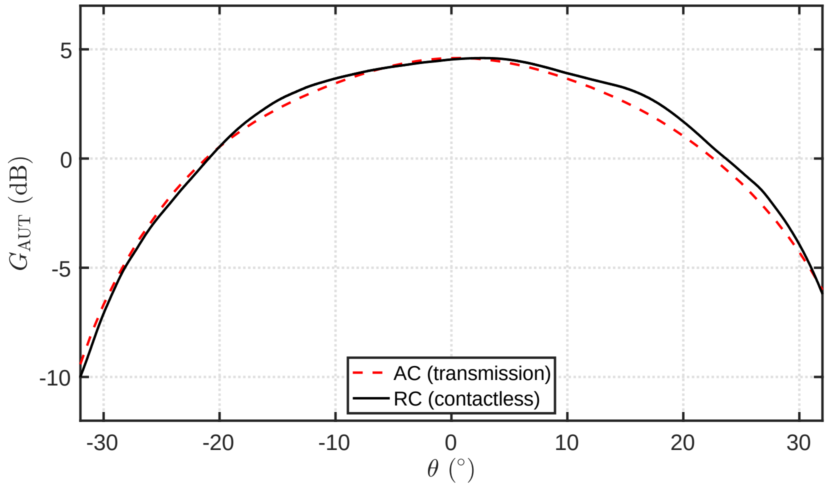
Fréquency: [6-7] GHz



Gain pattern at 6.5 GHz



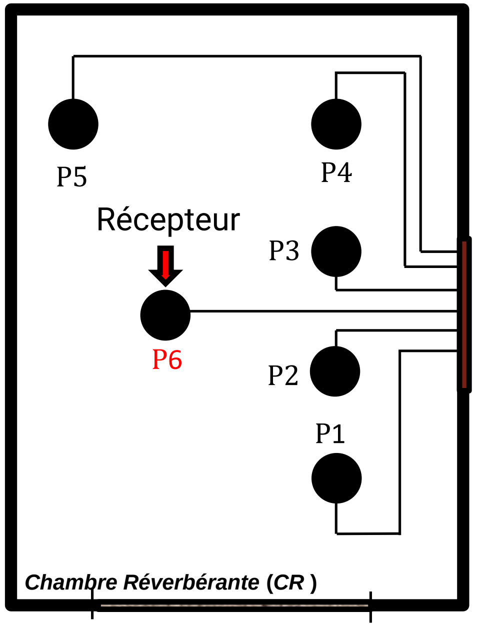
Fréquency: [3-4] GHz

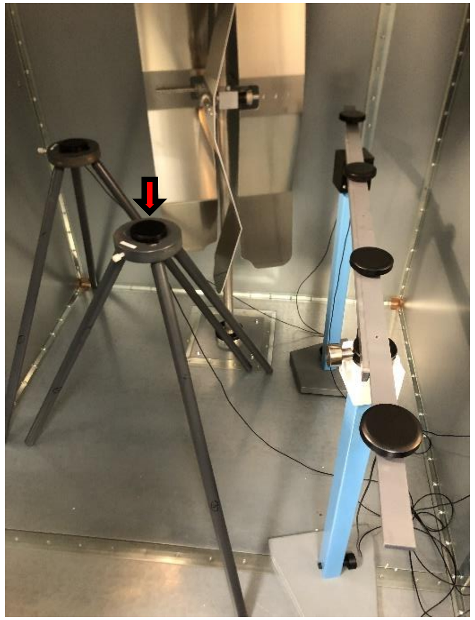


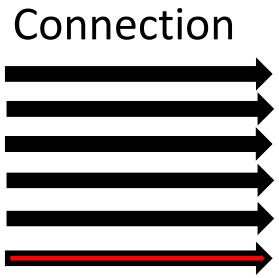
[5] A. Reis, F. Sarrazin, P. Besnier, P. Pouliguen and E. Richalot, "Contactless Antenna Gain Pattern Estimation From Backscattering Coefficient Measurement Performed Within a Reverberation Chamber," in *IEEE Transactions on Antennas and Propagation*, vol. 70, no. 3, pp. 2318-2321, March 2022, doi: 10.1109/TAP.2021.3111184.

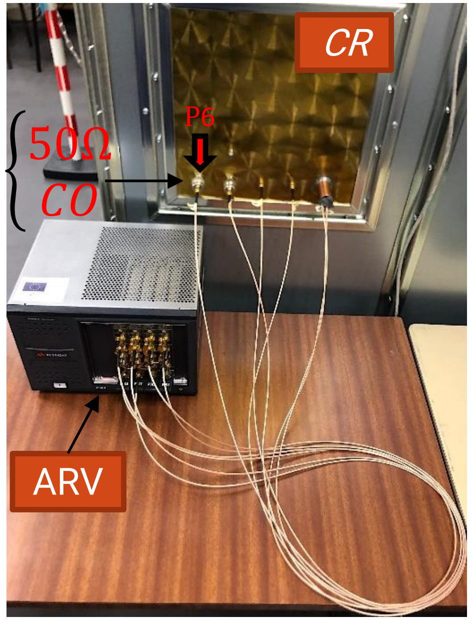
Focalization

Focalization upon detection of the modification of the backscattered field
(opérateur de Wigner-Smith généralisé)



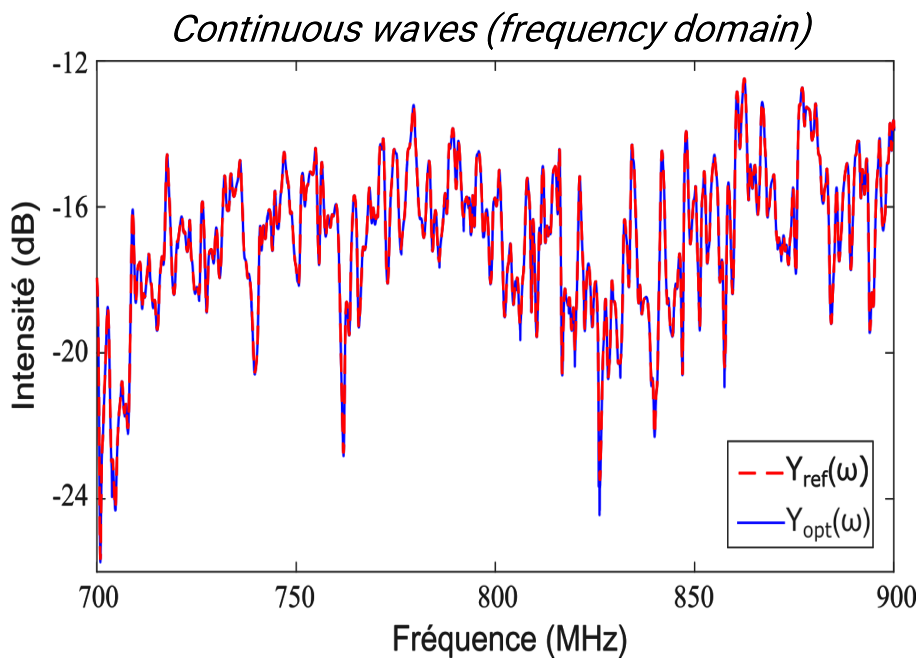






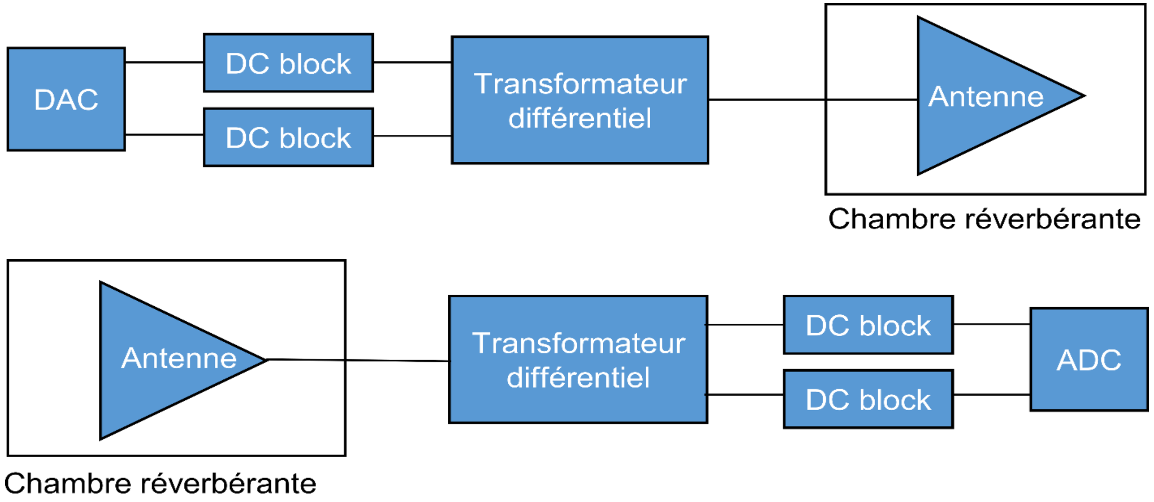
- Impedance modification: 50 Ω (S_1) and CO (S_2) ➔ $Q_\alpha = -iS_1^{-1}(S_1 - S_2)$
- Diagonalization of Q_α➔ q_i with the highest $|\lambda_i|$ -> Most sensitive to the change
- Injection de q_i à l'émission ➔ focalisation

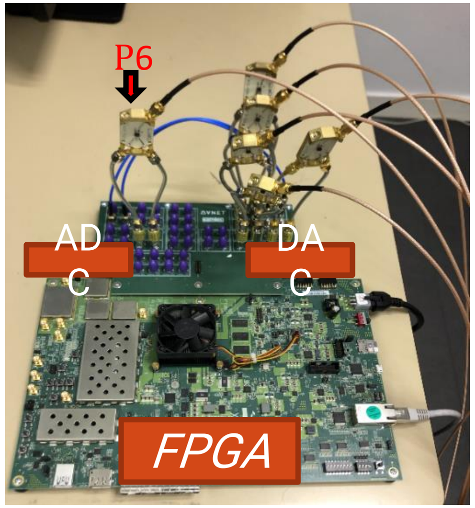
Focalization

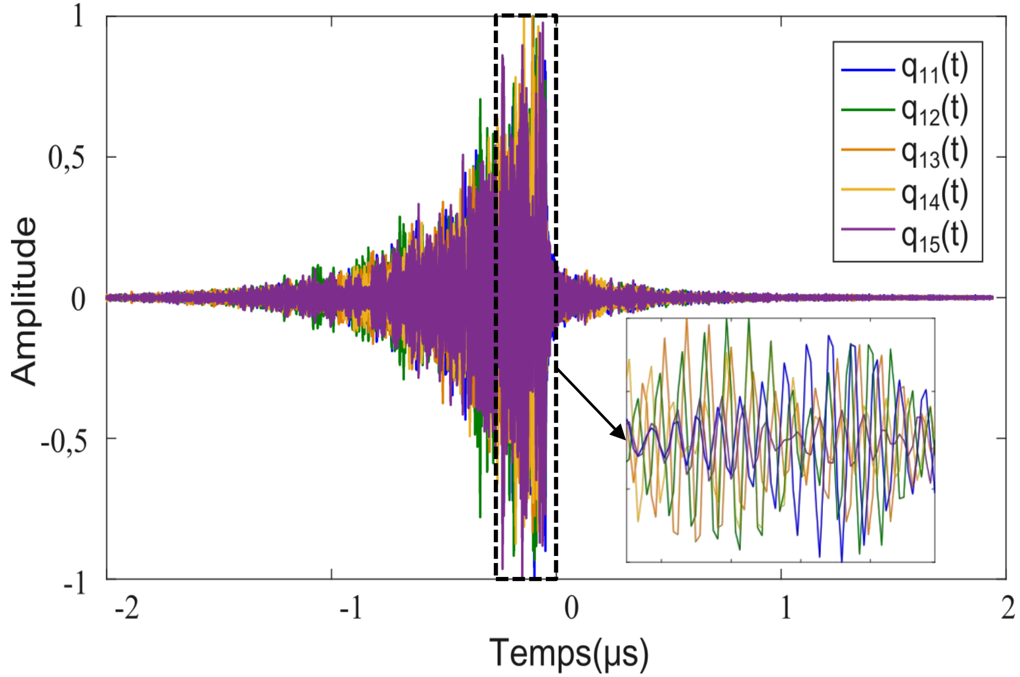


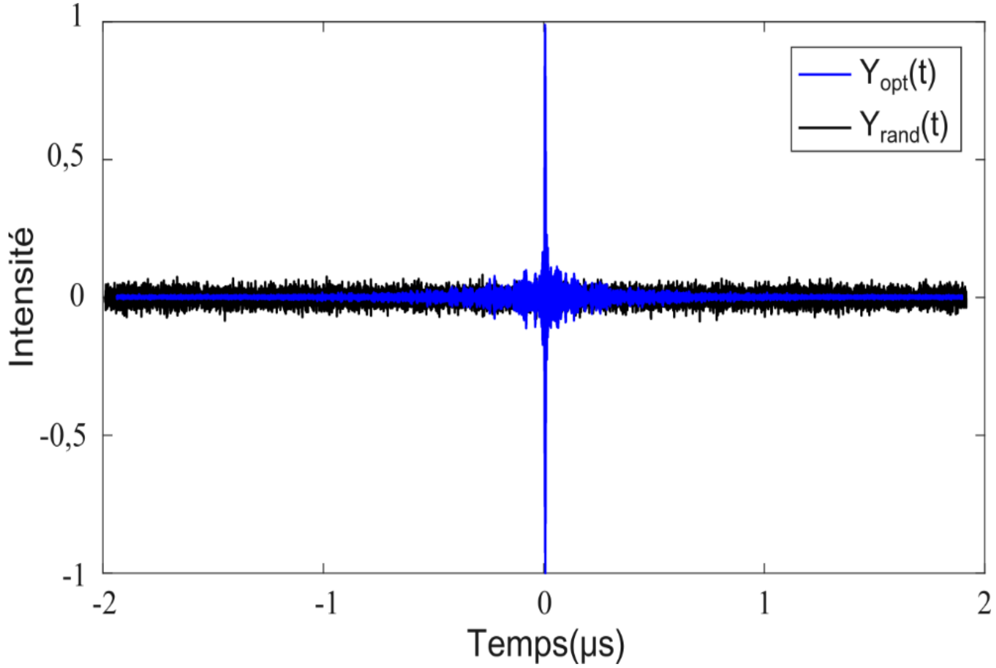
- $Y_{ref}(\omega) = \left|\psi_{ref}(\omega)t(\omega)\right|^2 = \|T\|^2$, PHASE CONJUGATION
- $Y_{opt}(\omega) = \left|\psi_{opt}(\omega)T(\omega)\right|^2$, avec $\psi_{opt} = q_1^T$; WSG FOCALIZATION

Focalization (time domain, in situ)









K. B. Yeo, C. Leconte, P. del Hougne, P. Besnier and M. Davy, "Time Reversal Communications With Channel State Information Estimated From Impedance Modulation at the Receiver," in *IEEE Access*, vol. 10, pp. 91119-91126, 2022

Conclusion

How to conclude this ?

- Impossible !
- Research within the scope of RCs or diffuse (chaotic) field environments are still extended
- This presentation is only a sample
- Many more stimulating research areas involving
  - Wavefront shaping / RIS
  - Noise correlation
  - … /…

IETR

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