Power-balance in the time-domain for IEMI coupling prediction

J F Dawson

I D Flintoft, A C Marvin, M P Robinson, L Dawson

University of York, UK, e-mail: john.dawson@york.ac.uk

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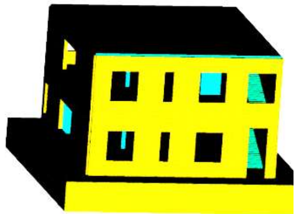
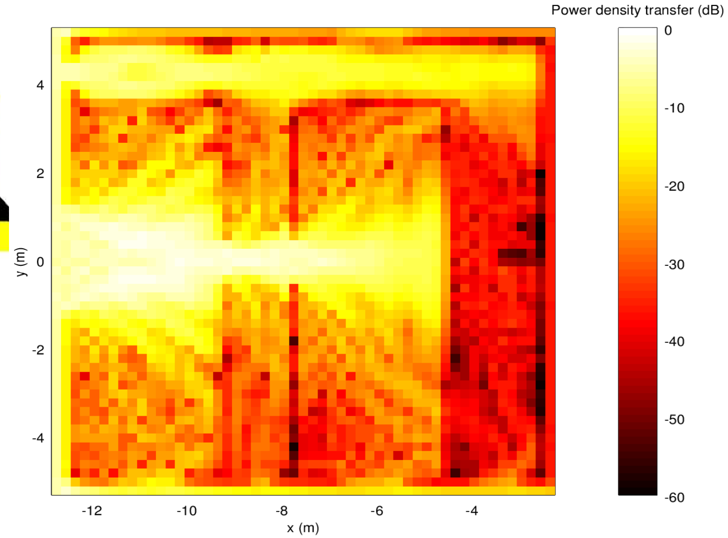
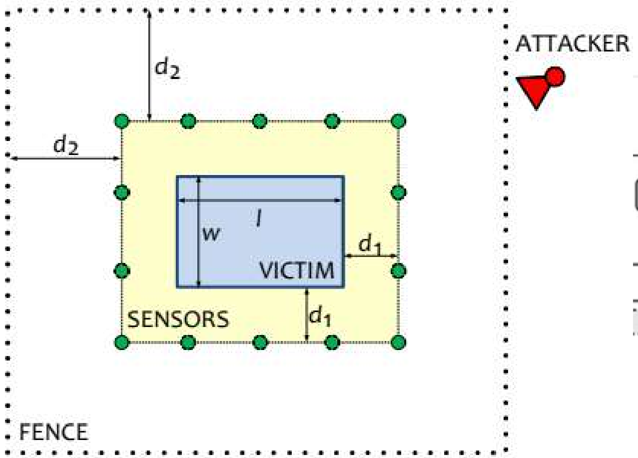
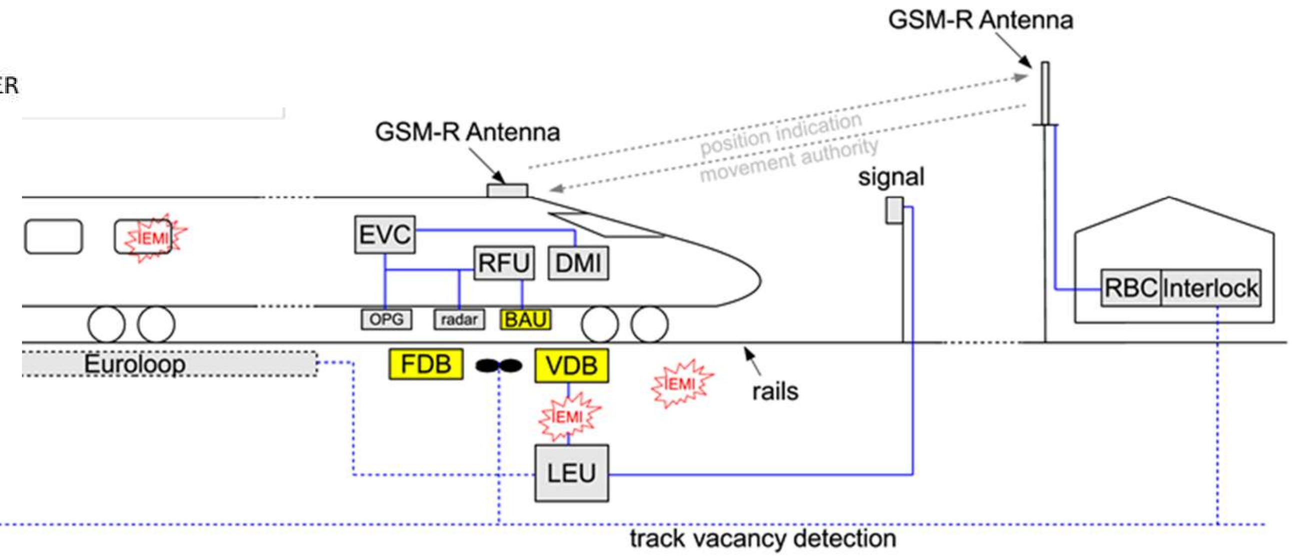
The STRUCTURES Project

- IEMI Coupling
- IEMI Detection
- System Vulnerability
- Guidelines & Standards
- Tools









FD Power Balance: Steady state

- Aperture electrically small – plane wave illumination
  - Polarisabilitities

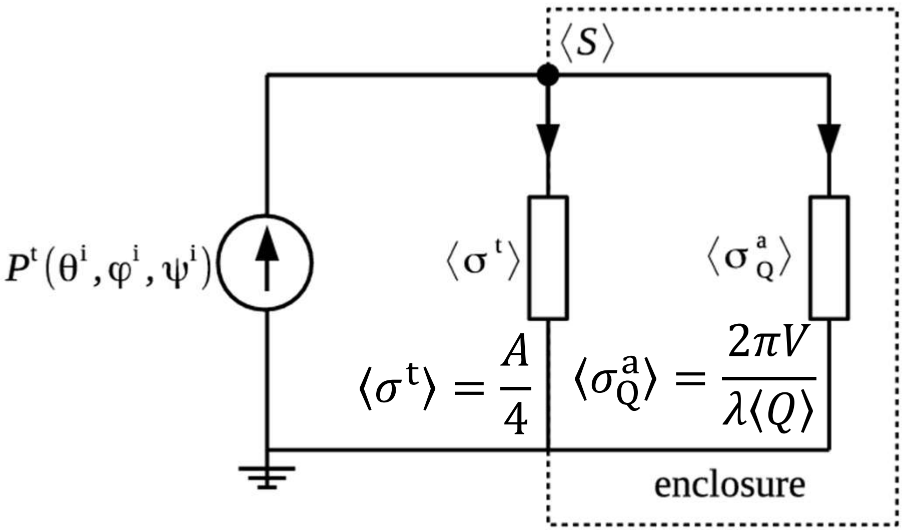
$$P^{\mathrm{t}}(\theta^{\mathrm{i}},\varphi^{\mathrm{i}},\psi^{\mathrm{i}}) = \frac{8\pi\eta_0}{3\lambda^2}\left(\omega^2\varepsilon_0^2\left|\overline{\overline{\boldsymbol{\alpha}}}_{\mathrm{e}}\cdot\mathbf{E}^{\mathrm{i}}\right|^2 + k^2\left|\overline{\overline{\boldsymbol{\alpha}}}_{\mathrm{m}}\cdot\mathbf{H}^{\mathrm{i}}\right|^2\right)$$

- Aperture electrically large – plane wave
  - PW GO model,

$$P^{\mathrm{t}} = A\frac{\mathrm{Re}[\mathbf{E}^{\mathrm{i}}\times\mathbf{H}^{\mathrm{i}}]}{2}\cdot\hat{\mathbf{z}} = A\left|S^i\right|\cdot\hat{\mathbf{z}}$$

$$\langle S\rangle = \frac{\langle|\mathbf{E}|^2\rangle}{2\eta_0} = \frac{3\langle|E_x|^2\rangle}{2\eta_0}$$

- Transfer function
  - $$H_E(f) = \frac{\sqrt{\langle|\mathbf{E}|^2\rangle}}{|E^i|} = \frac{\sqrt{\langle|\mathbf{H}|^2\rangle}}{|H^i|} = \sqrt{\frac{\langle S\rangle}{|S^i|}}$$



Fast Pulses: The JOLT

- BUT….

JOLT hyperband source
Far voltage ~ 5.3 MV
Pulse width ~ 100 ps

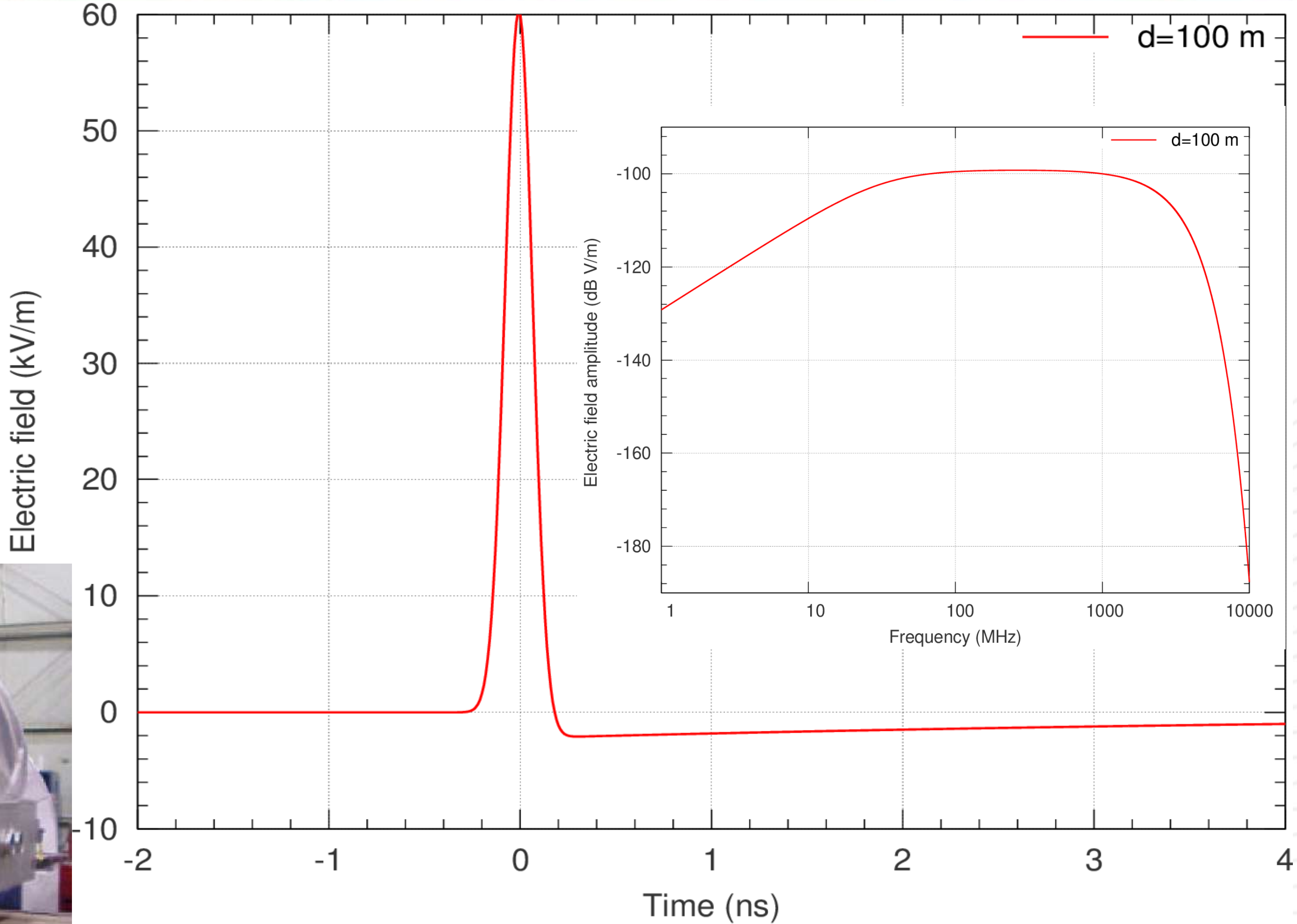
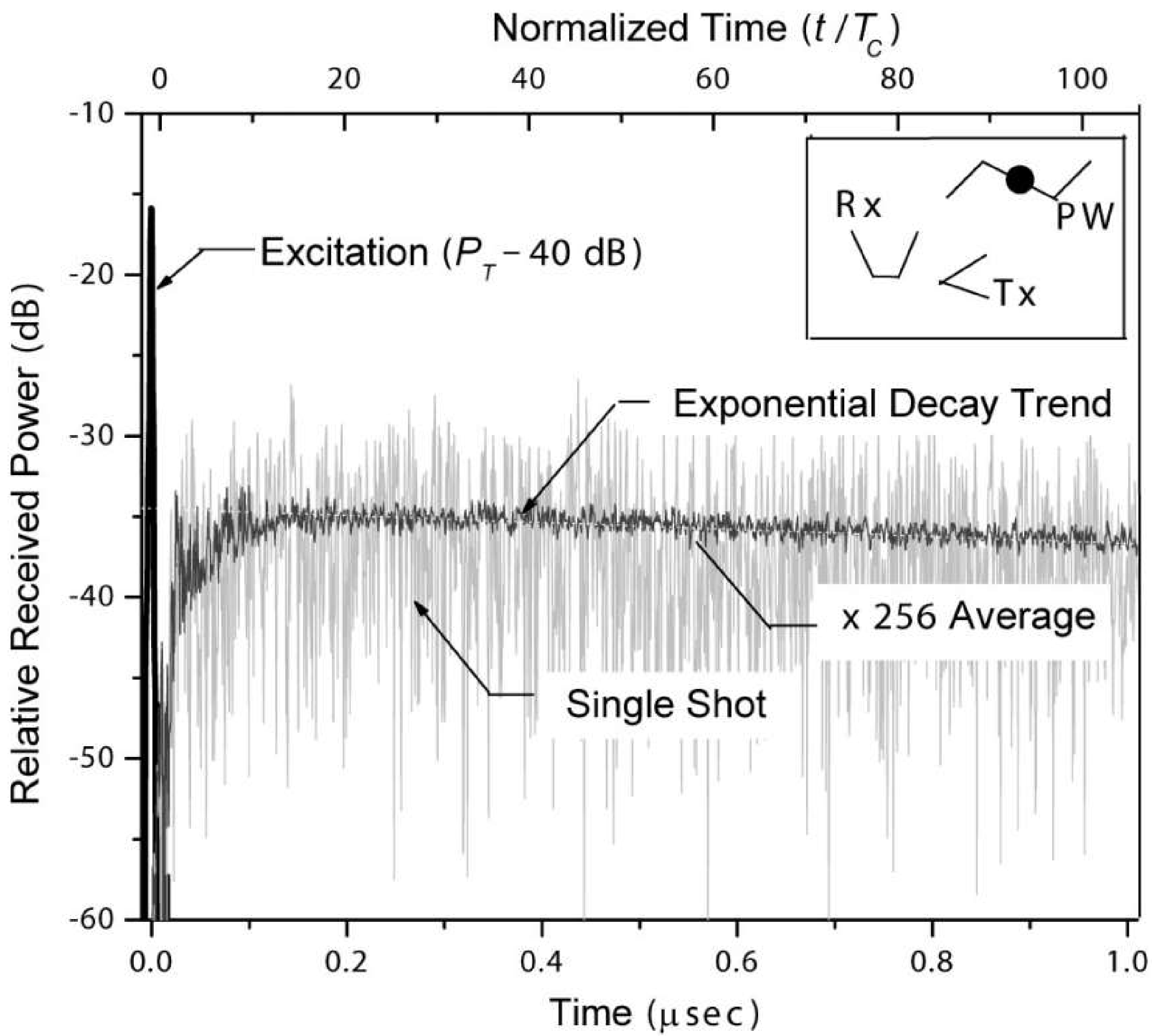


Photo taken from W. Radasky and E. Savage, "Intentional Electromagnetic Interference (IEMI) and Its Impact on the U.S. Power Grid" , Metatech Corporation

Time Response in Reverb

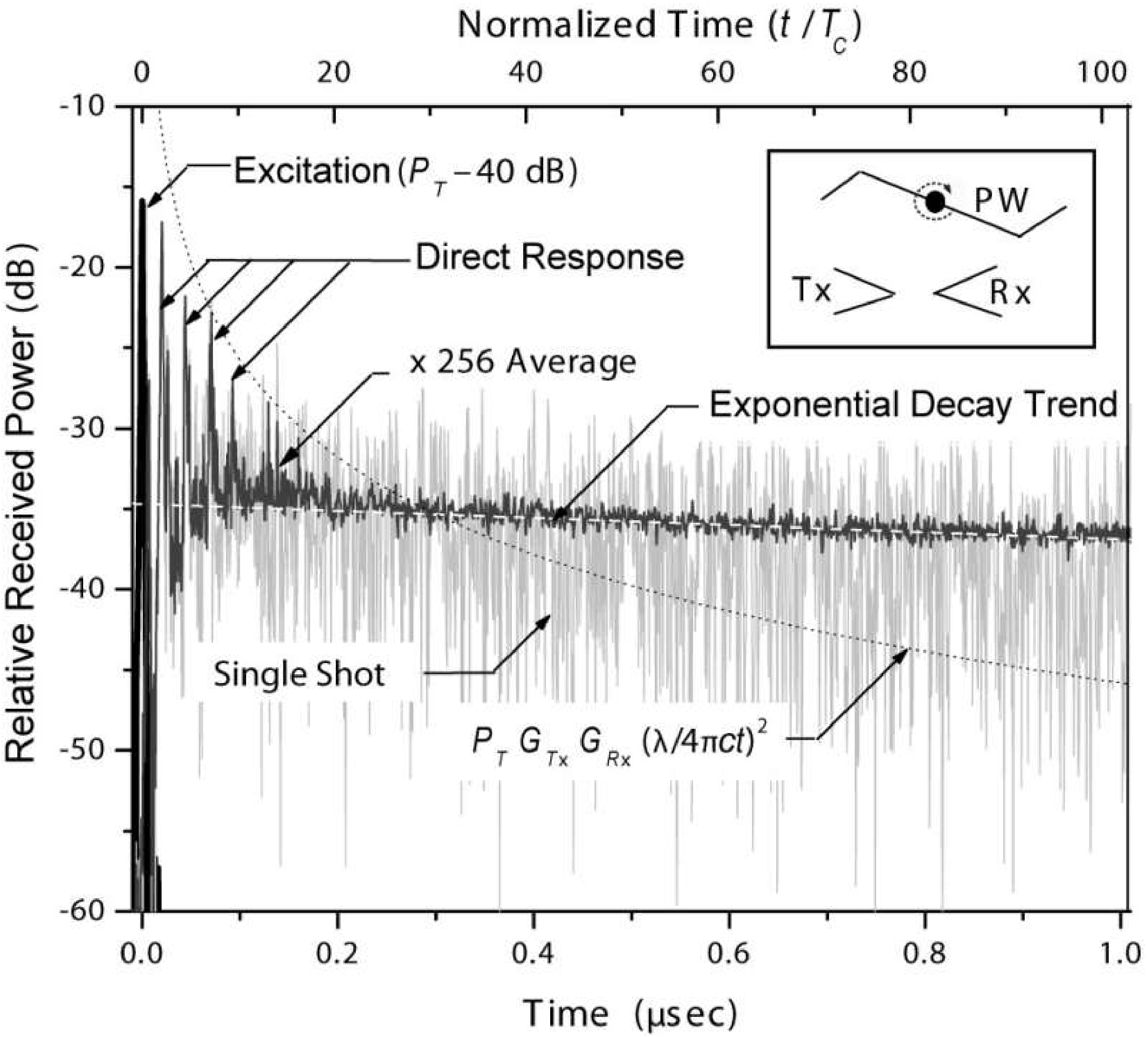
- Reverberant field
  - Build up
  - Exponential decay



Taken from: **Figure 2–4**, of Richardson, R. E. , "Reverberant Microwave Propagation" , *NAVAL SURFACE WARFARE CENTER DAHLGREN DIV VA , NAVAL SURFACE WARFARE CENTER DAHLGREN DIV VA , no. ADA501122* , OCT, 2008 , Available: http://www.dtic.mil/docs/citations/ADA501122

Time Response in Reverb

- Reverberant field
  - Build up
  - Exponential decay
- Direct path
  - Friis Equation
- Early reflections
  - Mean free path
  - Friis
  - Reflection loss

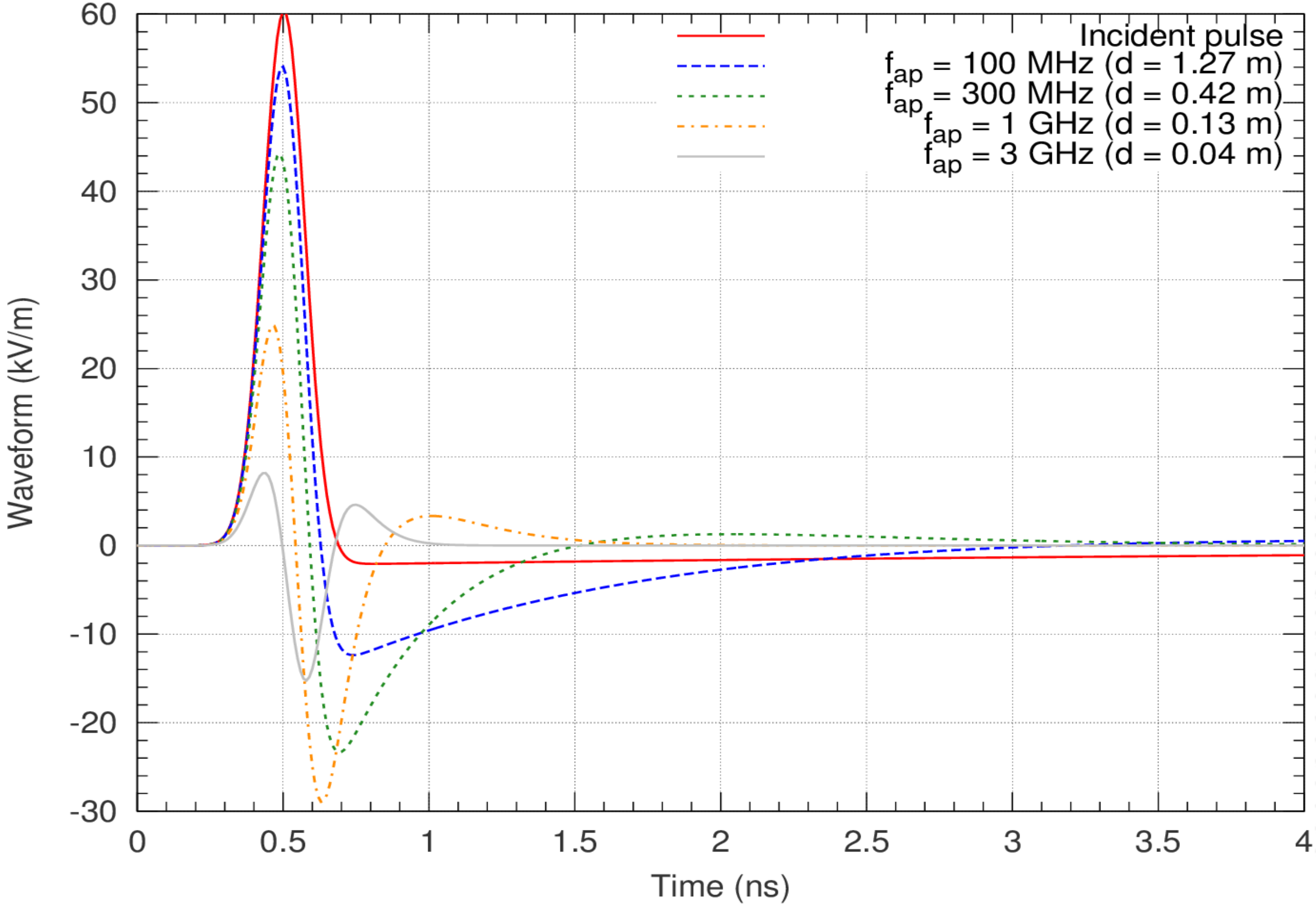


Taken from: **Figure 2–3**, of Richardson, R. E. , "Reverberant Microwave Propagation" , *NAVAL SURFACE WARFARE CENTER DAHLGREN DIV VA , NAVAL SURFACE WARFARE CENTER DAHLGREN DIV VA , no. ADA501122* , OCT, 2008 , Available: http://www.dtic.mil/docs/citations/ADA501122

Enclosure: PWB analysis (TD)

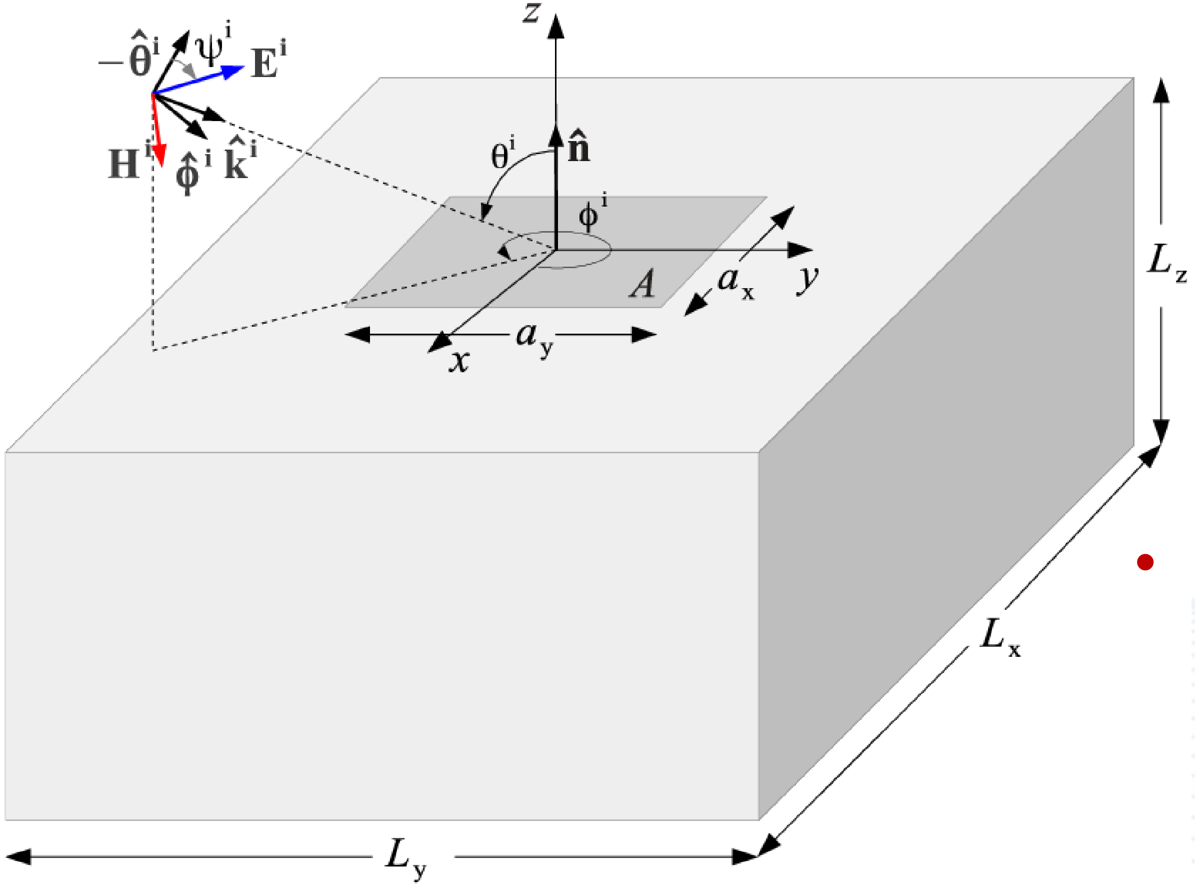
- Time domain energy balance
  - $\frac{\mathrm{d}\langle U\rangle}{\mathrm{d}t} + \frac{\langle U\rangle}{\tau_{\mathrm{enc}}} = \frac{\mathrm{d}\langle U\rangle}{\mathrm{d}t} + \Lambda_{\mathrm{enc}}\langle U\rangle = P^{\mathrm{t}}(t)$
- Power transmitted through aperture
  - $\frac{A}{\eta_0}\left[\int_0^t h_{\mathrm{ap}}(t-t')E_{\mathrm{pulse}}(t')\,\mathrm{d}t'\right]^2 \cos\theta^{\mathrm{i}}$
- Dispersion of aperture – filter
  - $H_{\mathrm{ap}}(s) = H_{\mathrm{ap}}^{\infty}\left(\frac{s}{s+\omega_{\mathrm{ap}}}\right)^2$
- Transfer function
  - $H_{E_{\mathrm{RMS}}} = \frac{\sqrt{\max_t[\langle|\mathbf{E}|^2(t)\rangle]}}{\max_t[E_{\mathrm{pulse}}(t)]}$

Enclosure: PWB analysis (TD)



Effect of dispersion on propagation of JOLT pulse for different cut-off frequencies

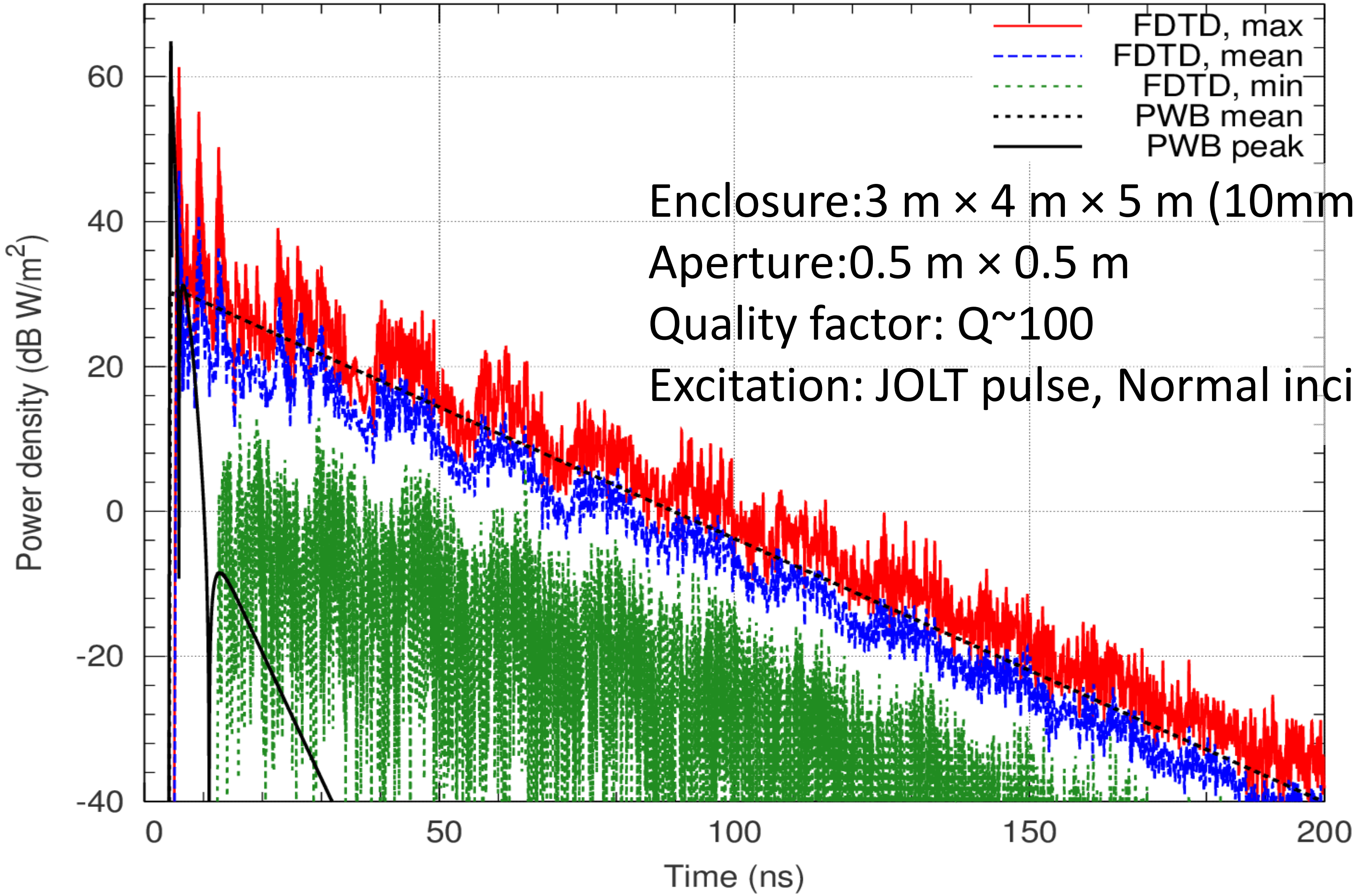
Enclosure with aperture



- Geometry & parameters:
  - Cuboid enclosure: L_x, L_y, L_z,
  - Rectangular aperture: a_x, a_y
  - Quality factor: <Q_{enc}(f)>
  - Plane-wave: E^i, θ^i, ϕ^i, ψ^i

- Analyses:
  - Power balance (CW, JOLT)

FDTD vs PWB (TD)



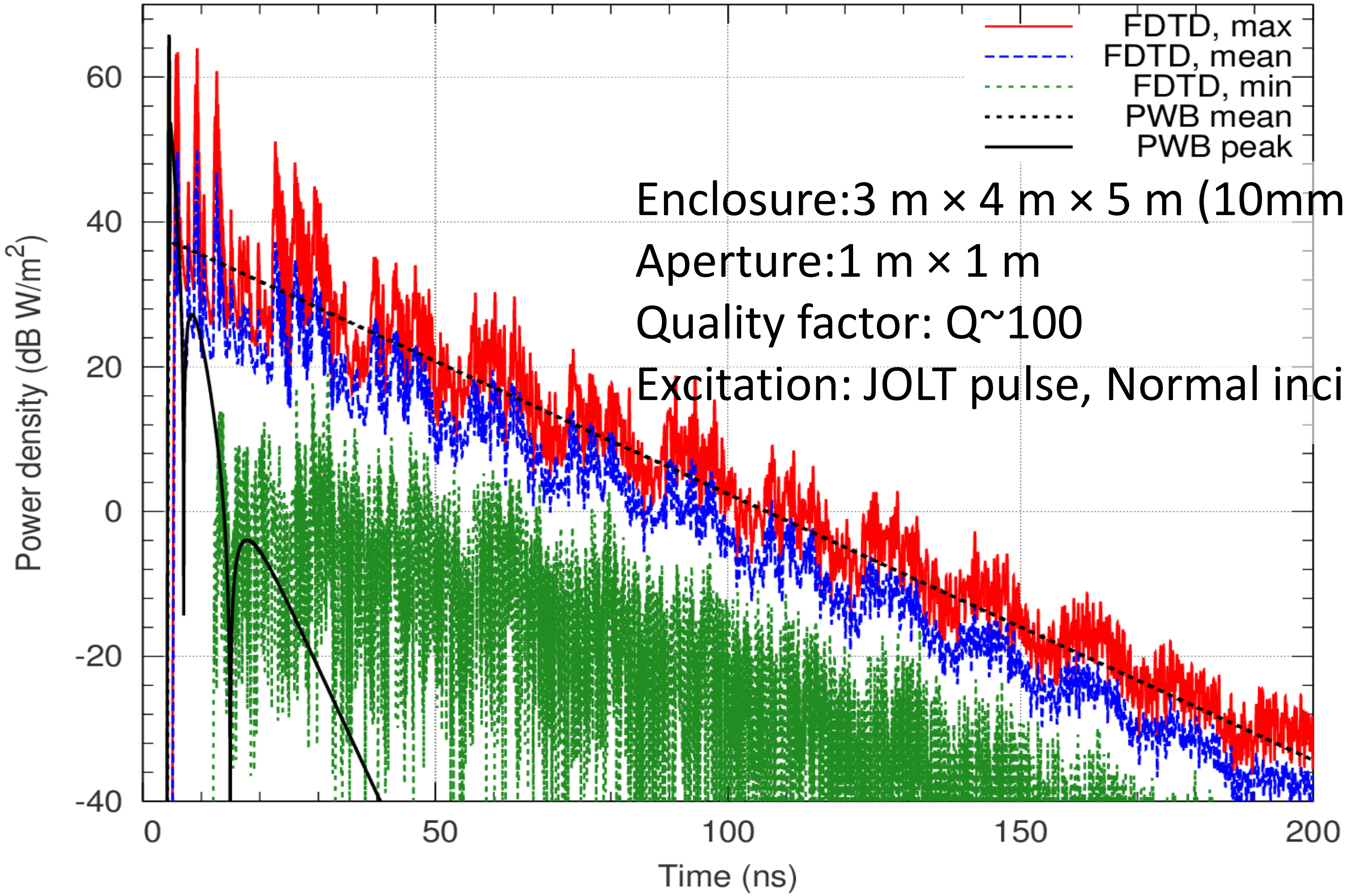
Enclosure:3 m × 4 m × 5 m (10mm mesh)

Aperture:0.5 m × 0.5 m

Quality factor: Q~100

Excitation: JOLT pulse, Normal incidence

FDTD vs PWB (TD)



Enclosure:3 m × 4 m × 5 m (10mm mesh)

Aperture:1 m × 1 m

Quality factor: Q~100

Excitation: JOLT pulse, Normal incidence

Enclosure: Scenarios

- Range of “real” scenarios
- Monte Carlo model for statistical view of each scenario

Scenario	L_x (m)	L_y (m)	L_z (m)	a_x (m)	a_y (m)	$\langle Q_{enc} \rangle$ (-)
Machine hall, WP7.2	10-20	3-6	10-20	2-3	2-3	10-20
Server/ICT room, WP7.3	3	2.5	3	0.5	0.5	200
Train cabin, WP7.4	2-3	1.8-2.5	2-5	1-1.8	0.8-1.5	50-200
Office, WP7.5	5	3	6	2.5	1	20
Aircraft cabin, WP7.6	2-4	2-4	5-15	0.2-0.4	0.2-0.4	50-300
Building, WP7.7	4	3	6	1	2.5	20
Parameter range	**2-20**	**2-6**	**2-10**	**0.2-3**	**0.2-3**	**10-300**

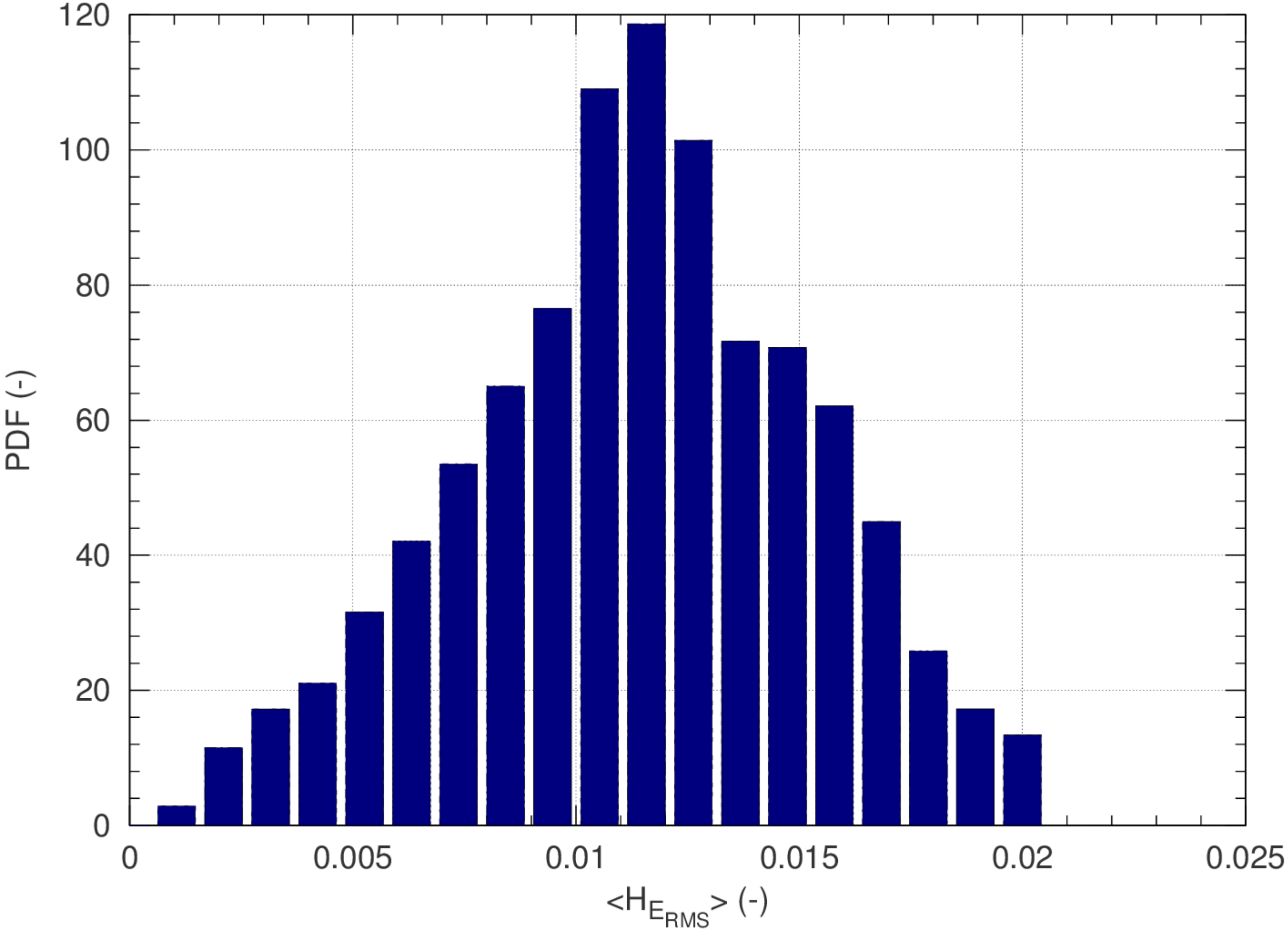
Monte Carlo simulation results

Scenario	CW 100 MHz		CW 300 MHz		CW 1 GHz		CW 3 GHz		CW 10 GHz		JOLT Pulse	
	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max
Machine hall	-24	-16	-26	-19	-28	-21	-31	-24	-34	-26	-2	0
ICT room Office Building	-18	-4	-13	-3	-16	-6	-18	-8	-21	-10	-3	0
Train cabin	-6	0	-7	-1	-8	-2	-11	-4	-14	-7	-2	0
Aircraft cabin	-35	-14	-24	-14	-26	-17	-28	-20	-32	-22	-3	-1

Mean and maximum transfer functions (in dB): $H_E(f) = \frac{\sqrt{\langle|\mathbf{E}|^2\rangle}}{|E^i|} = \frac{\sqrt{\langle|\mathbf{H}|^2\rangle}}{|H^i|} = \sqrt{\frac{\langle S\rangle}{|S^i|}}$ over 1000 sets of uniformly distributed random parameters over the ranges specified in previous slide plus random incidence angle.

Monte Carlo PWB FD simulation

– PDF of relative amplitudes for CW (Machine hall)



L: 10-20m

W: 10-20m

H: 3-6m

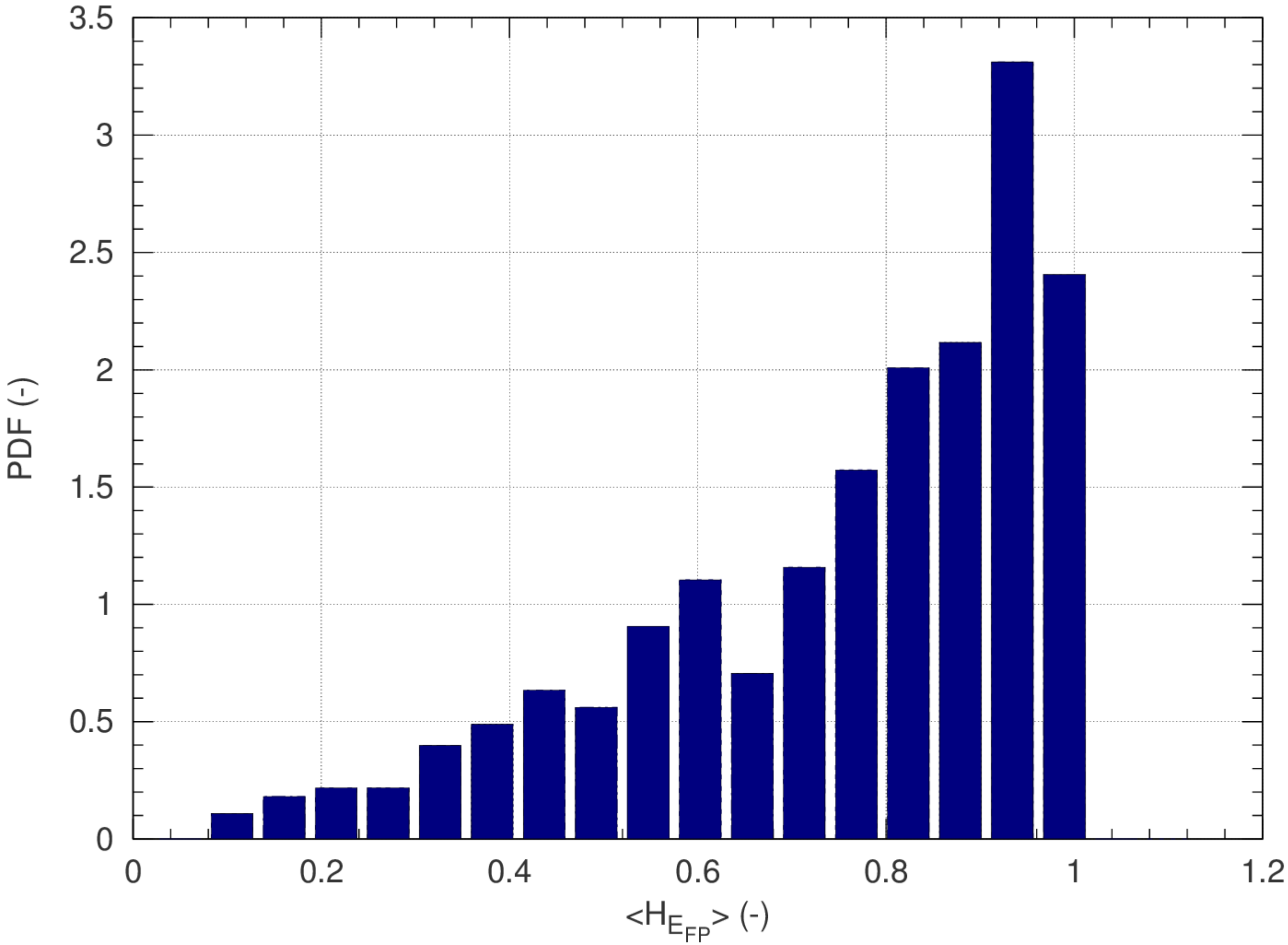
a_x: 2-3

a_y: 2-3m

Q: 10-20

Monte Carlo PWB TD simulation

– PDF of relative coupling for JOLT Pulse (Machine hall)



L: 10-20m

W: 10-20m

H: 3-6m

a_x: 2-3

a_y: 2-3m

Q: 10-20

Concluding remarks

- Power balance can estimate time-domain coupling but must include direct first pulse
  - Possibly should include other initial reflections
  - Not included here but may be significant
- Possible to do fast parametric/ Monte Carlo models
- Results show significant difference in attenuation between pulse/transient and CW steady state
  - Should think about CW turn on transient ?

The END

Bibliography

Additional material beyond the references in the abstract

The STRUCTURES project
"STRUCTURES Strategies for The impRovement of critical infrastrUCTUre Resilience to Electromagnetic attackS" , Available: http://www.structures-project.eu/

Time domain measurements in reverb chamber:
Richardson, R. E. , "Reverberant Microwave Propagation" , *NAVAL SURFACE WARFARE CENTER DAHLGREN DIV VA* , *NAVAL SURFACE WARFARE CENTER DAHLGREN DIV VA , no. ADA501122* , OCT 2008. , Available: http://www.dtic.mil/docs/citations/ADA501122

Results:
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