

EMC Fundamentals and Computer Modeling

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EMC Definition

Electromagnetic Compatibility (EMC) is the ability of an electrical or electronic device or system to function satisfactorily in its intended electromagnetic environment (**Immunity**)

without introducing intolerable electromagnetic interference (EMI) to anything in that environment (**Emission**).

How does EMI happen?

Power density due to a 100 W transmitter
(isotropic radiator) in 100 km distance:

$$\frac{S}{[W / m^2]} = \frac{P}{4\pi r^2} \approx \frac{100}{1.26^{11}} \approx 0.8 \cdot 10^{-9} \Rightarrow S_{Transmitter} = 0.8 [nW / m^2]$$

What amount of power will produce the same
power density in a distance of 1 m?

$$\frac{P}{[W]} = S \cdot 4\pi r^2 \approx 0.8 \cdot 10^{-9} \cdot 12.6 = 1 \cdot 10^{-8} \Rightarrow P_{Noise} = 10 [nW]$$

Signal power: $P_{Signal} = V \cdot I = 5 \cdot 20 \cdot 10^{-3} [VA] = 100 [mW]$

$$\frac{P_{Noise}}{P_{Signal}} = 10^{-7}$$

Electromagnetic Basics

James Clerk Maxwell (1831 – 1879), Coulomb (1736-1806), Ampere (1775-1836), Faraday (1791-1867), Oersted (1777-1851) Volta (1745-1827), Gauss (1777-1855), Hertz (1857-1894), Marconi (1874-1937).



$$\nabla^2 \mathbf{E}_s - \gamma^2 \mathbf{E}_s = 0$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\mathbf{J} = \sigma \mathbf{E}$$



$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \cdot \mathbf{D} = \rho_v$$

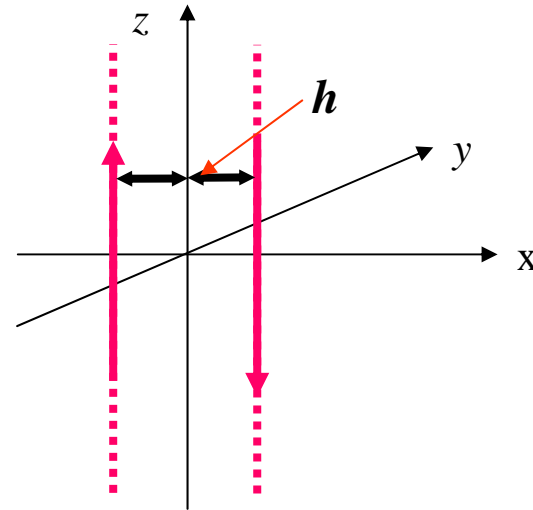
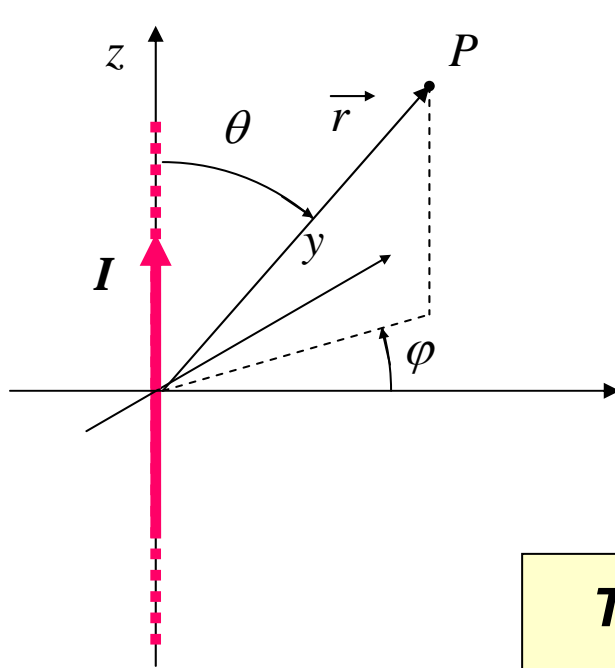


Electromagnetic Principles

Based on experiments by Coulomb (1736-1806), Ampere (1775-1836), Faraday (1791-1867), Oersted (1777-1851) and others the following observations have been made, which were then summarized by Maxwell (1831-1879) in his famous equations. Other names, worth mentioning are: Volta (1745-1827), Gauss (1777-1855), Hertz (1857-1894), Marconi (1874-1937).

- **Electric charges are associated with electric fields.**
- **Moving electric charges (currents) are associated with magnetic fields.**
- **Time varying electric fields are associated with changing magnetic fields.**
- **Time varying magnetic fields are associated with changing electric fields.**
- **This inter-dependence between varying electric and magnetic fields yields to wave propagation.**

Magnetostatic Field



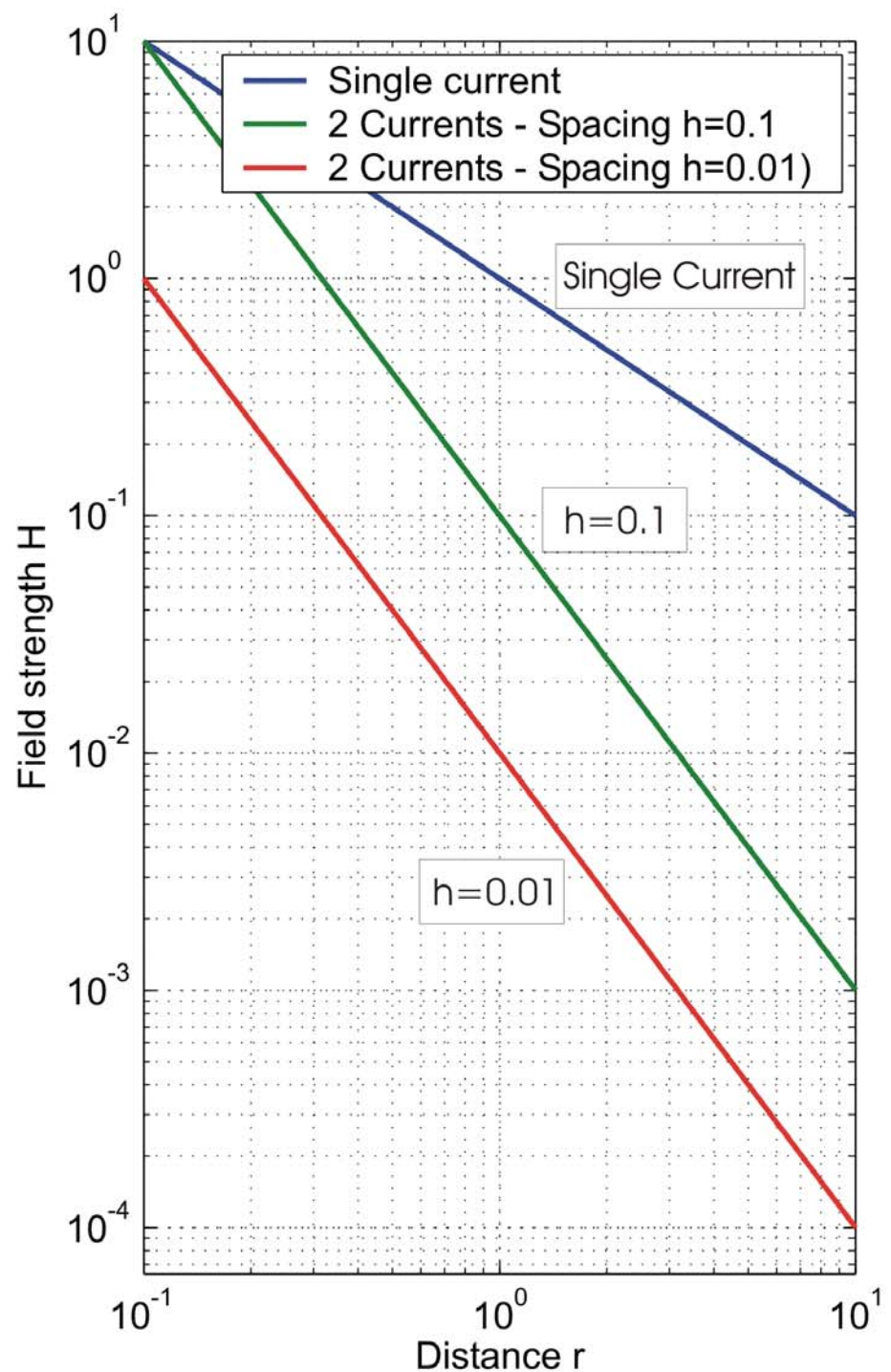
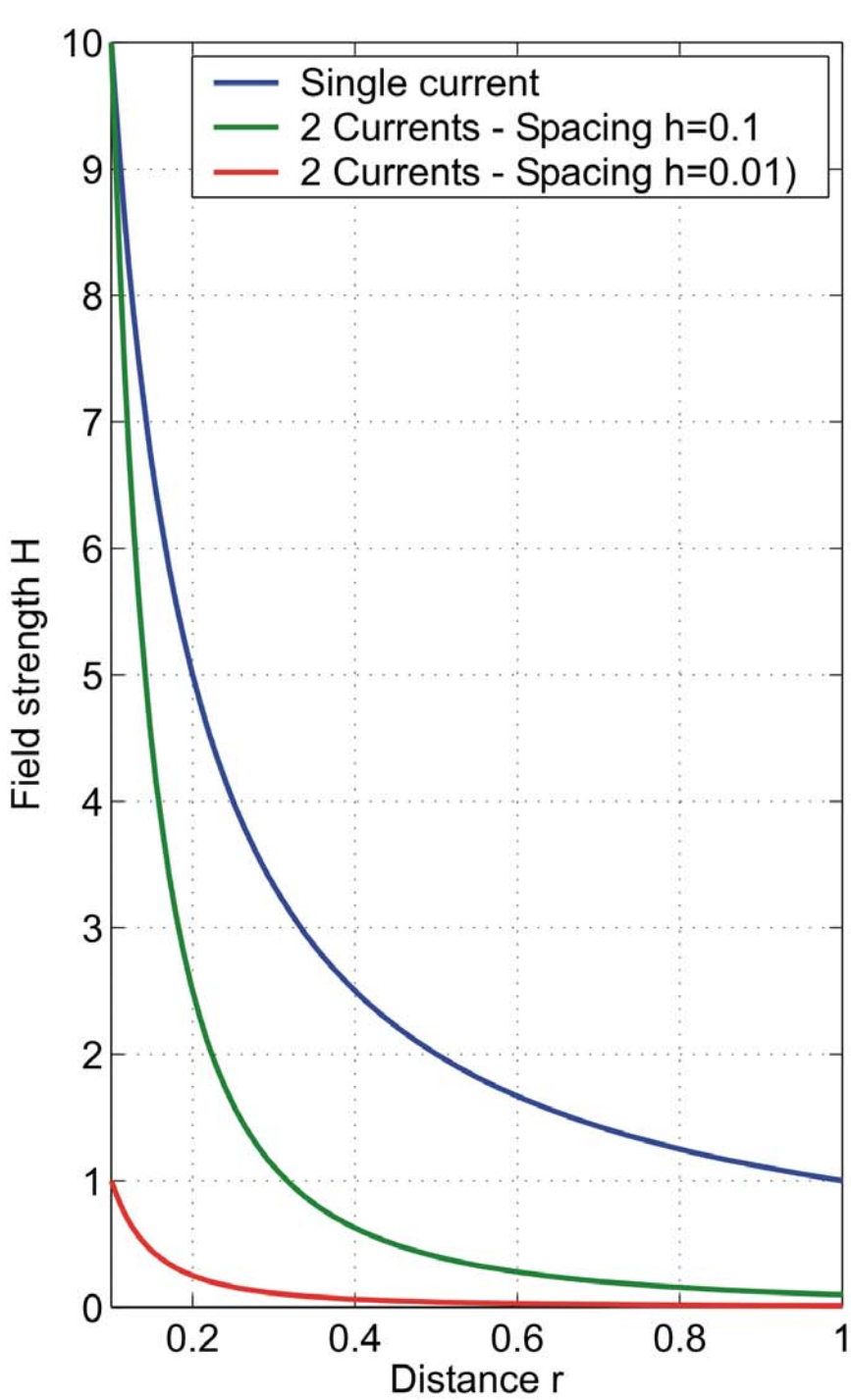
Ampere: $\oint_{loop} \vec{H} \cdot d\vec{l} = I_{enclosed}$

One line current: $|\vec{H}| = \frac{I}{2\pi r}$

Two parallel line currents

$$|\vec{H}| = \frac{I}{2\pi \cdot (r-h)} - \frac{I}{2\pi \cdot (r+h)}$$

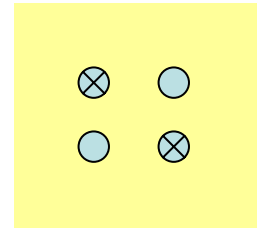
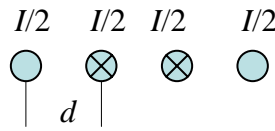
$$= \frac{I}{2\pi} \frac{(r+h) - (r-h)}{r^2 - h^2} \approx \frac{I}{2\pi} \frac{2h}{r^2} \quad (\text{for } r \gg h)$$



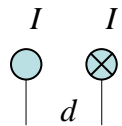
Magnetostatic Field



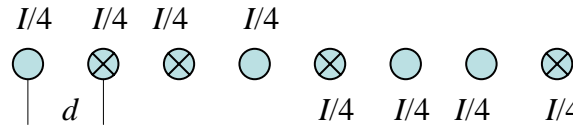
$$H \sim 1/r$$



$$H \sim 1/r^3$$



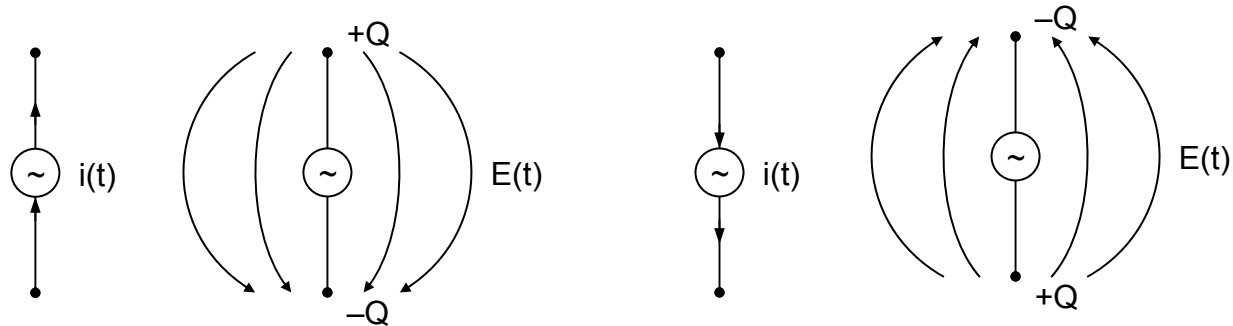
$$H \sim 1/r^2$$



$$H \sim 1/r^4$$

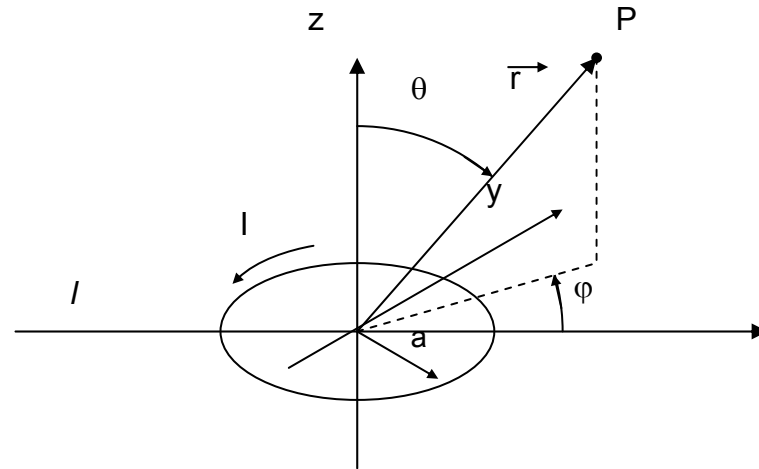
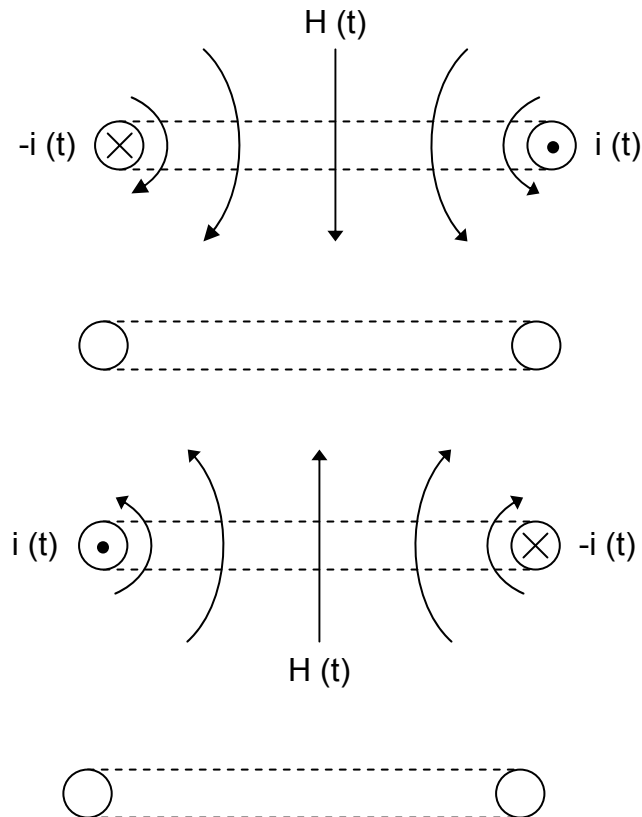
$$H(r) \sim \frac{d^{n-1}}{2\pi r^n} n! \prod_{i=1}^n 2^{i-1}$$

Hertzian Dipole - Principle

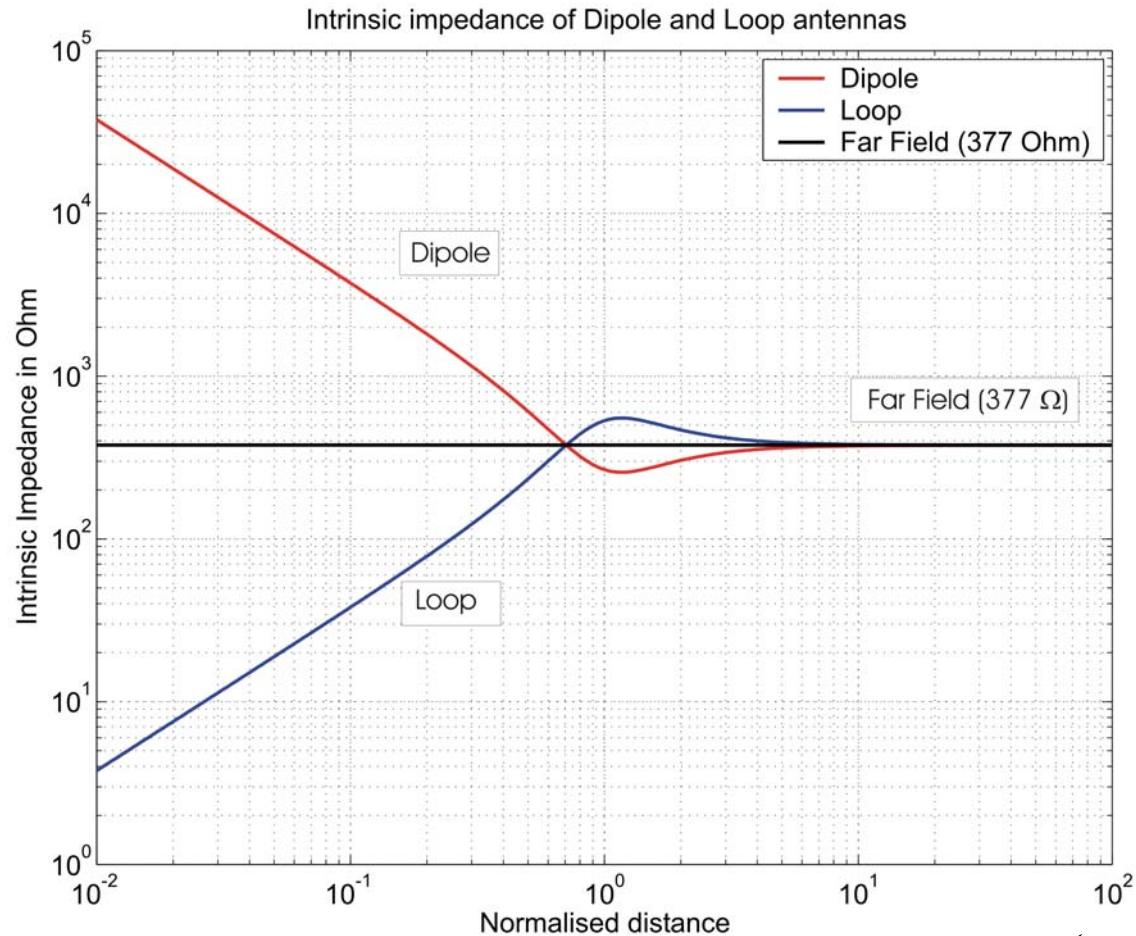


- As the electric charge changes, the electric field strength changes with time.
- A changing electric field is related to a spatial change of the magnetic field.
- As the current changes, the magnetic field strength changes with time.
- A changing magnetic field is related to a spatial change of the electric field.

Current Loop - Principle

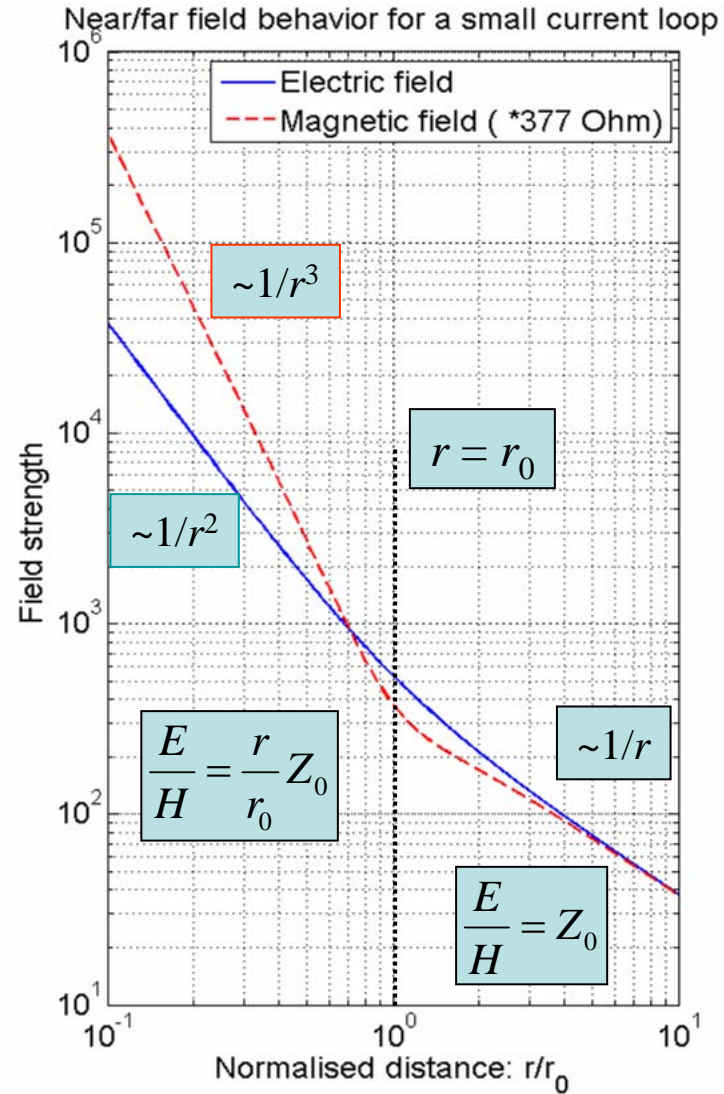
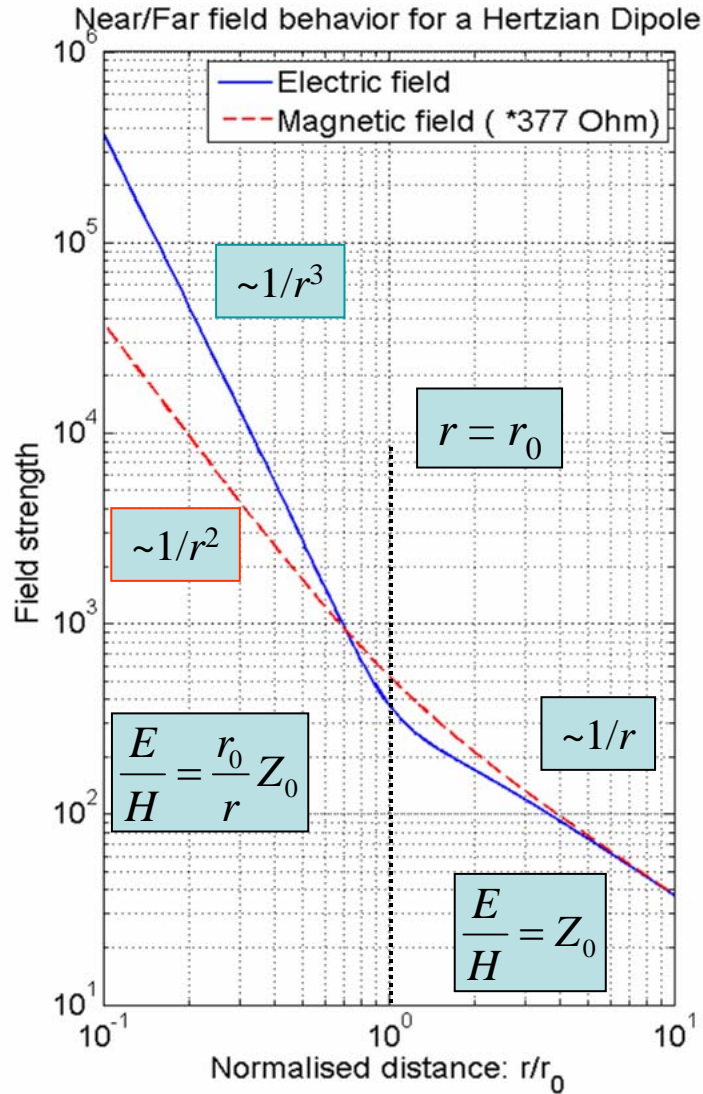


Intrinsic Impedance



$$\frac{r}{r_0} \left(r_0 = \frac{\lambda}{2\pi} \right)$$

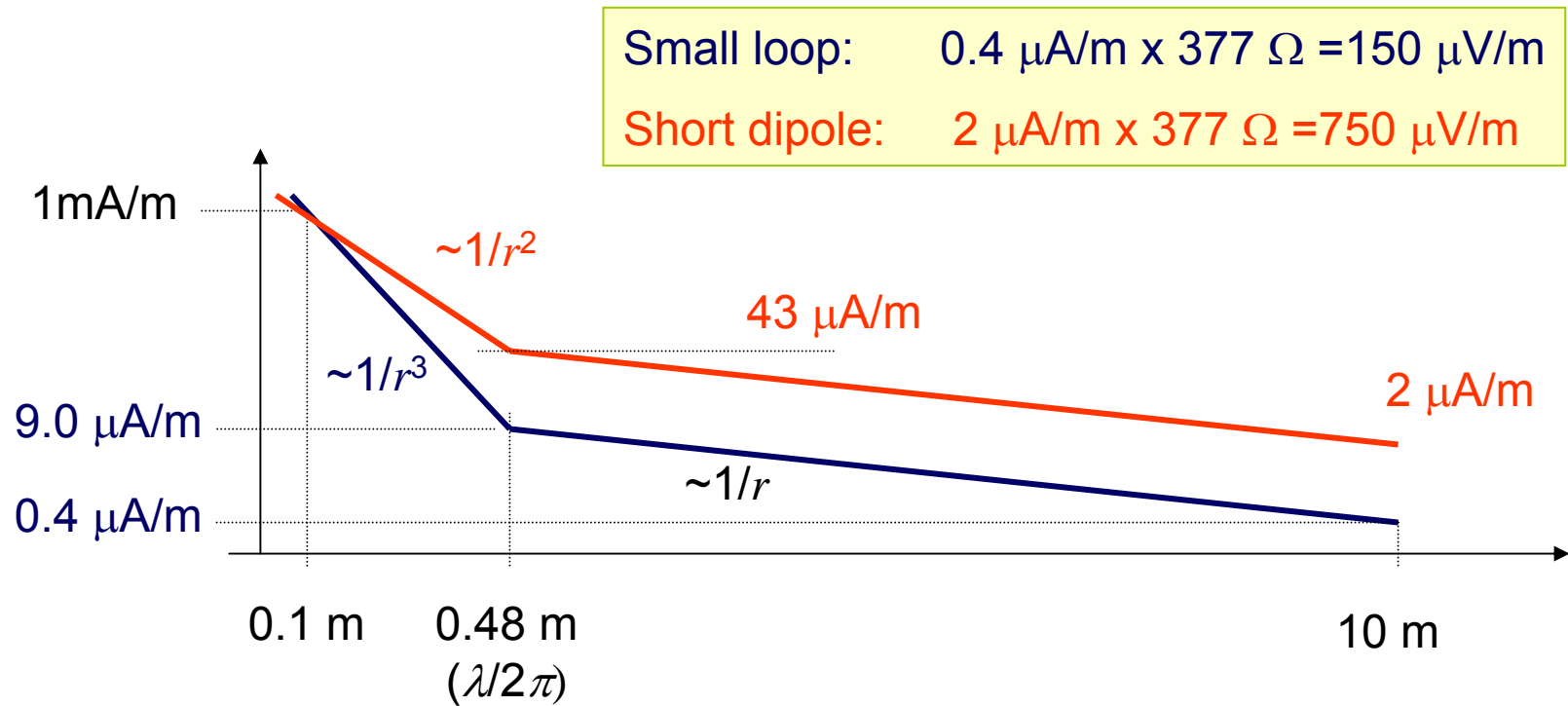
Near/Far field behaviour



Example:

H at 100 MHz in 0.1 m distance: 1 mA/m

What is the electric field in 10 m distance?



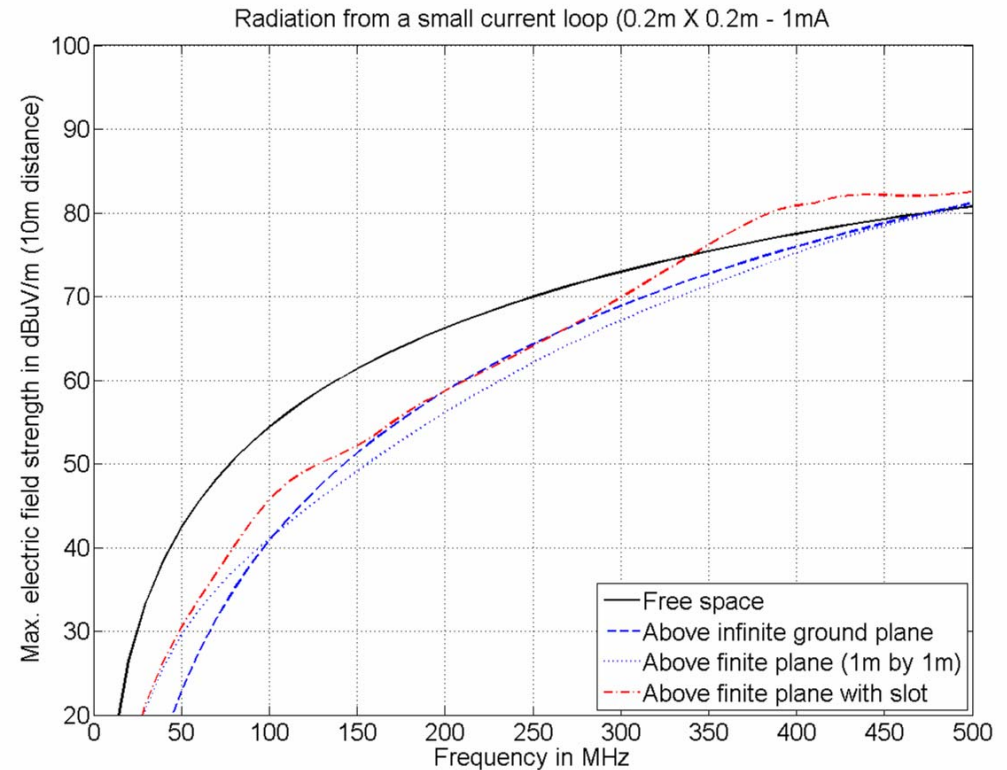
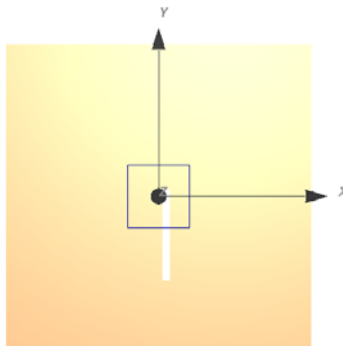
Example – Reduction due to Ground Plane (1)

Current loop (0.2m X 0.2m)
with uniform current of 1mA.

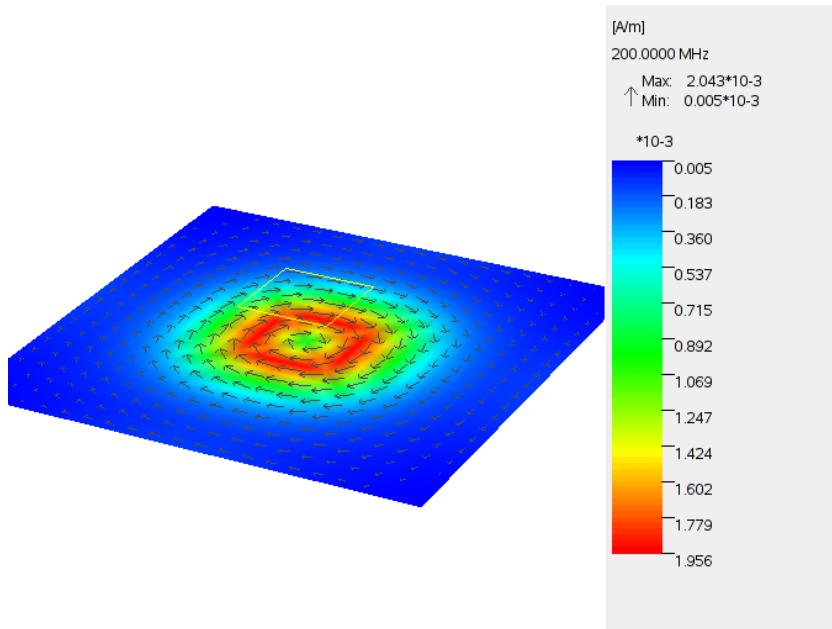


Maximum electric field in 10m distance for:

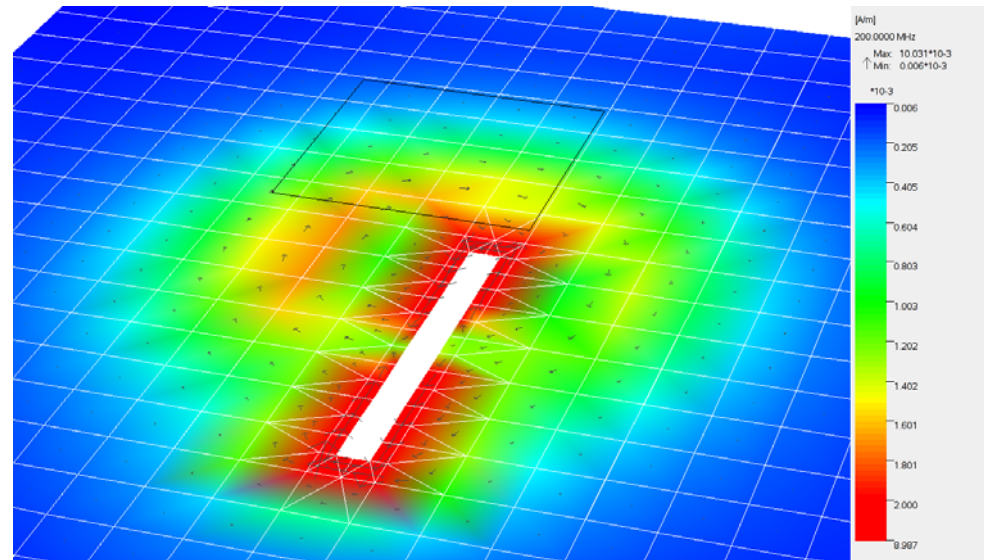
- Loop in free space
- Loop 0.1m above perfect, infinite ground plane
- Loop 0.1m above finite ground plane (1m X 1m)
- Slot in ground finite ground plane.



Example – Reduction due to Ground Plane (2)



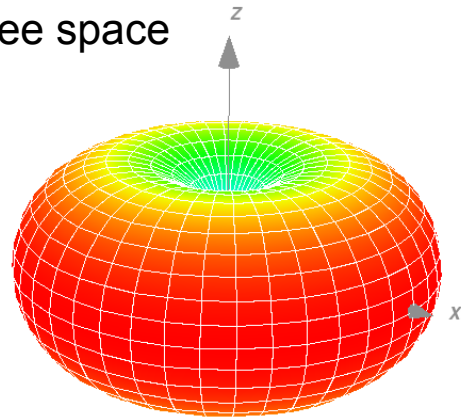
Current in ground plane (200 MHz)



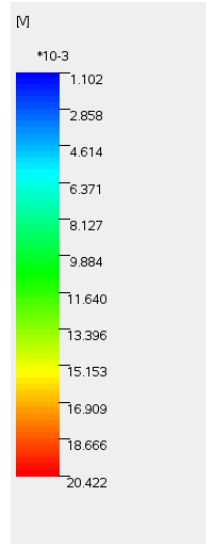
Current in ground plane with slot (200 MHz)
Note the high current density along the edges of the slot.

Example – Reduction due to Ground Plane (3)

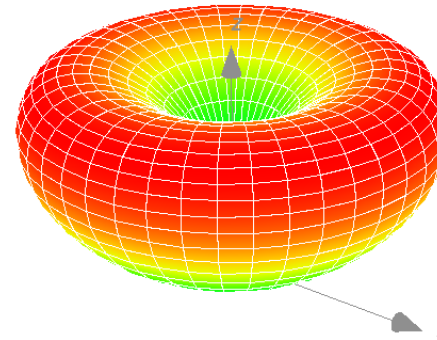
Free space



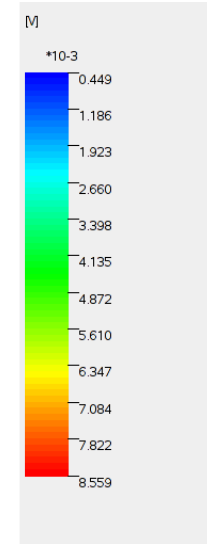
200.0000 MHz



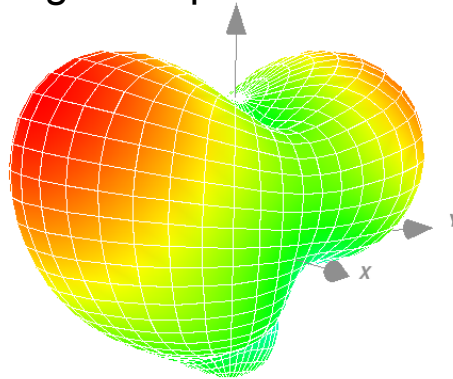
Infinite ground plane



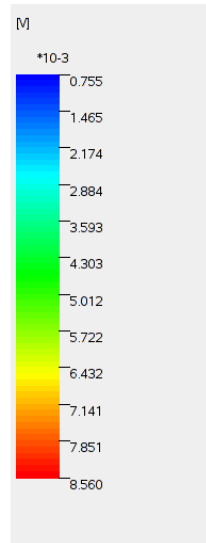
200.0000 MHz



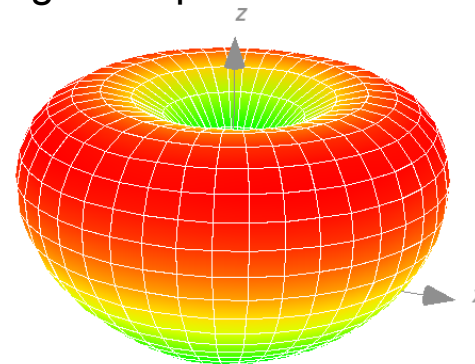
Slotted ground plane



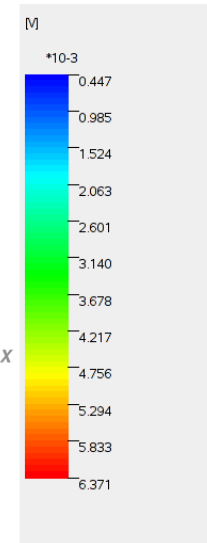
200.0000 MHz



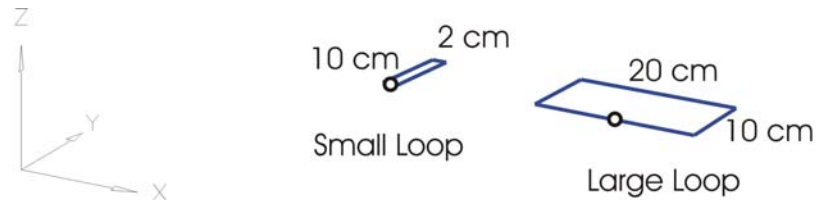
Finite ground plane



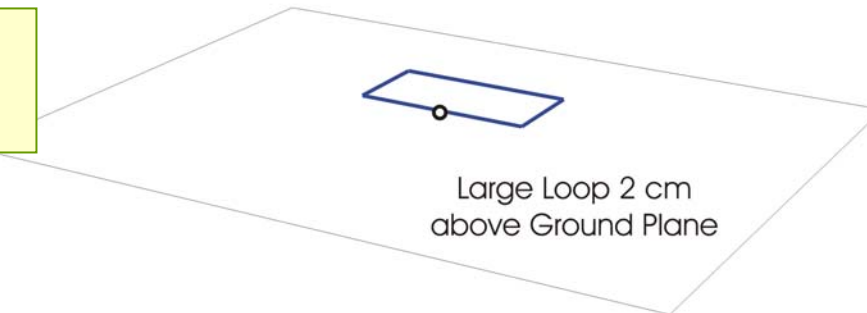
200.0000 MHz



Example: Fields due to current loop

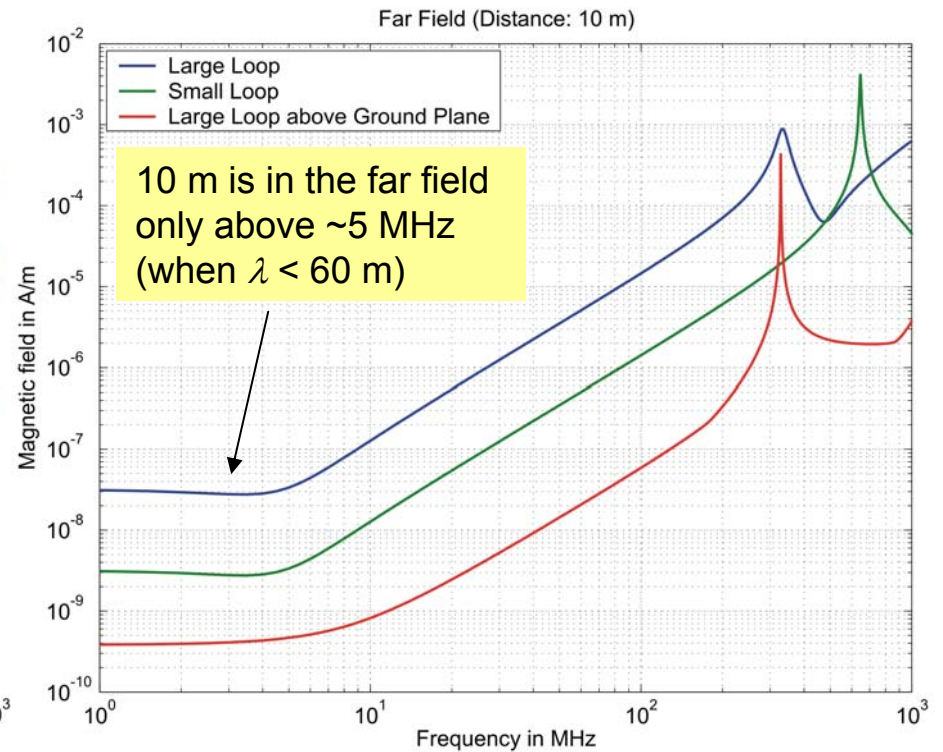
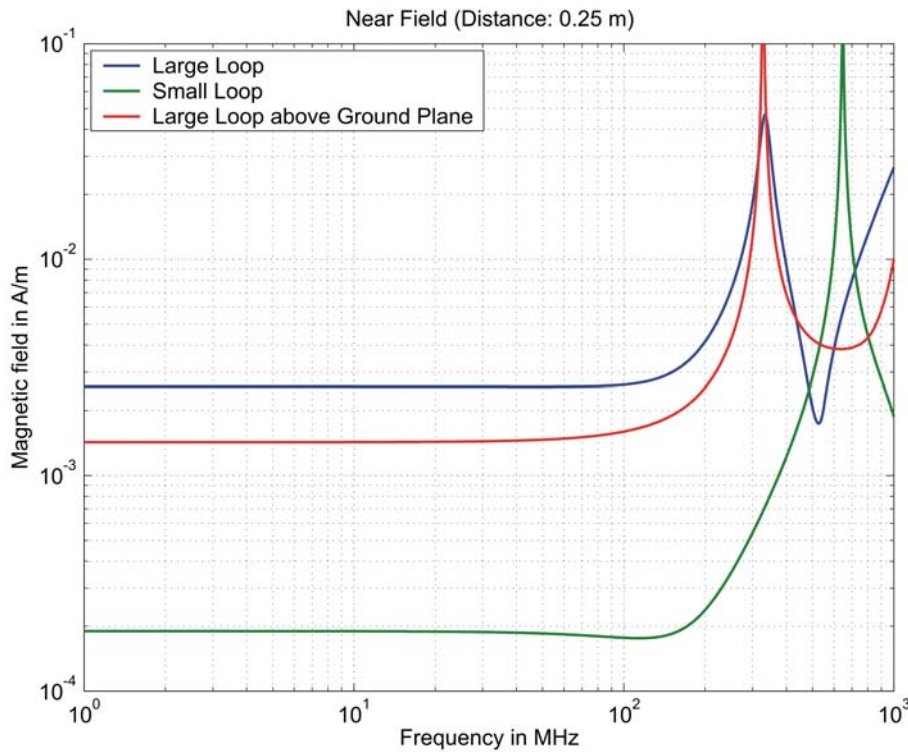
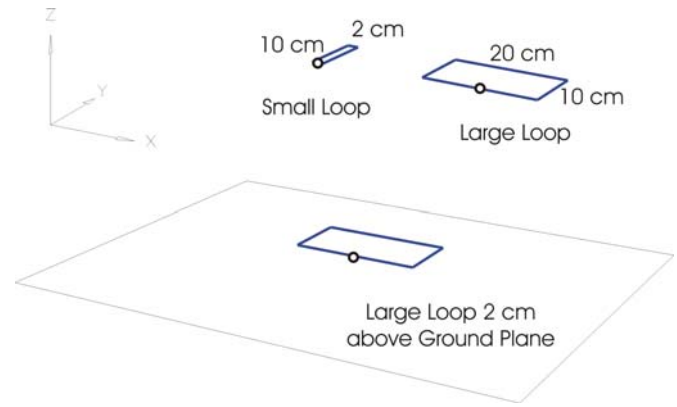


Excitation in each case:
Current source: 20 mA

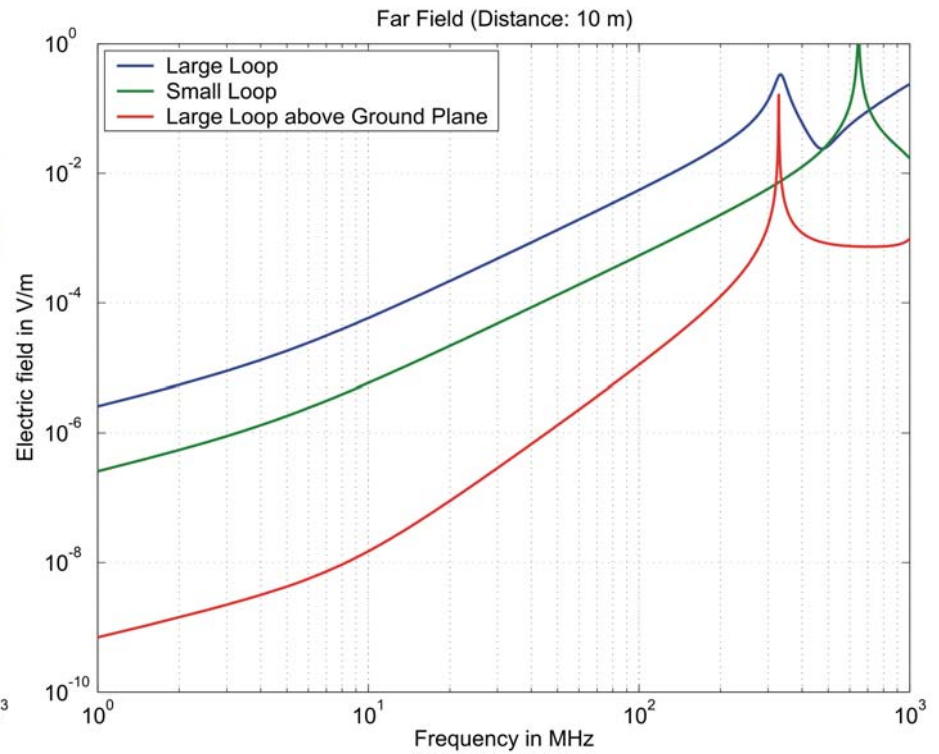
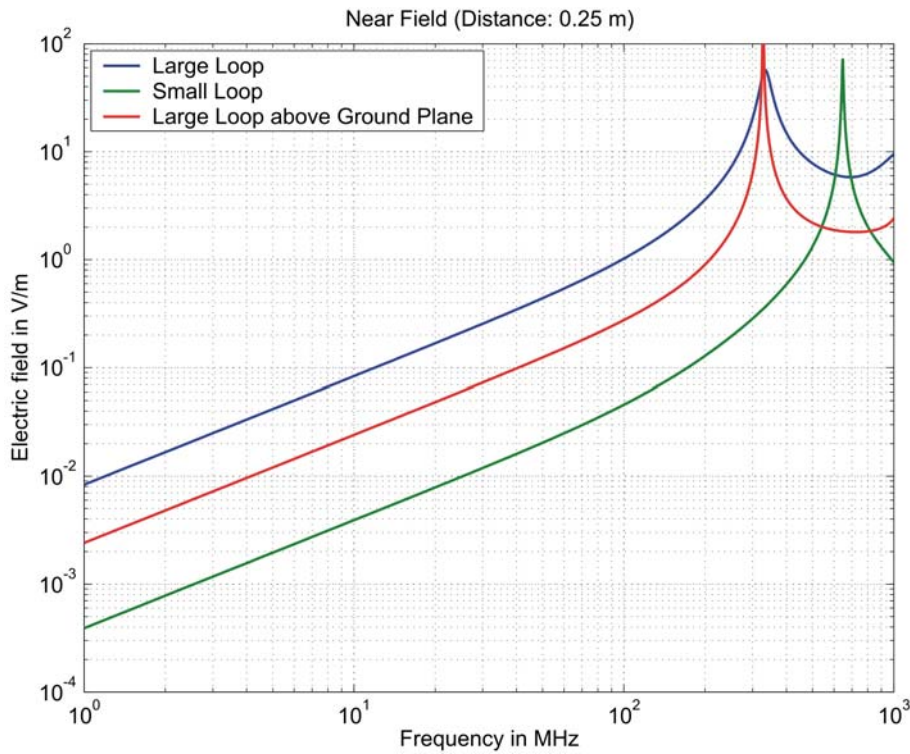
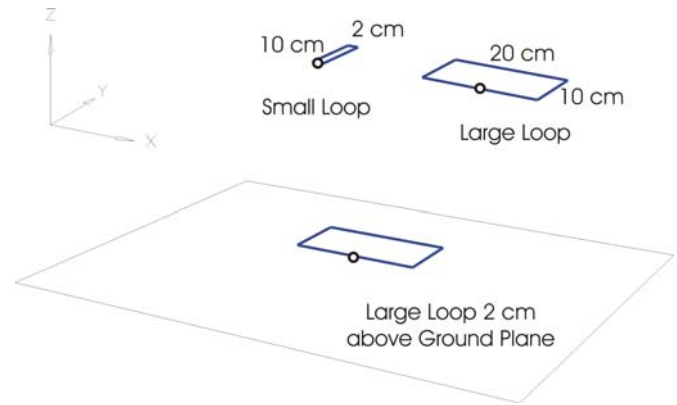


	Large loop (Reference)	Small loop (loop size: 10%)	Large loop over ground
Magnetic near field	100 %	8%	60 %
Magnetic far field	100 %	10 %	2 %
Electric near field	100 %	5%	30 %
Electric far field	100 %	10 %	0.3 %

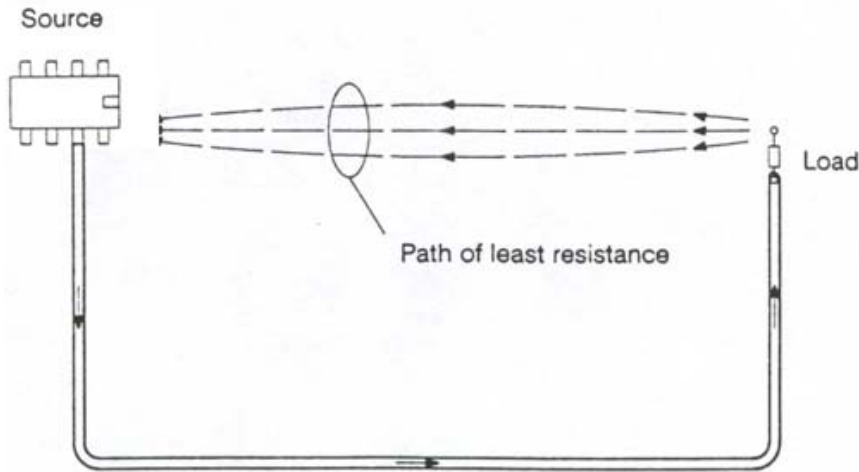
Example: Fields due to current loop



Example: Fields due to current loop



Current Return Path (1)

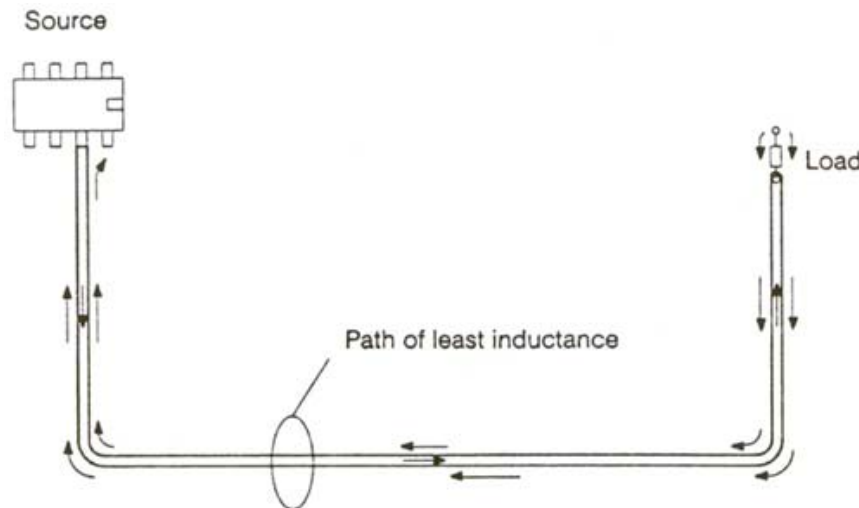


The return current will usually take the path of least **impedance!**

At low frequencies, this path will depend on the resistance characteristic of the structure.

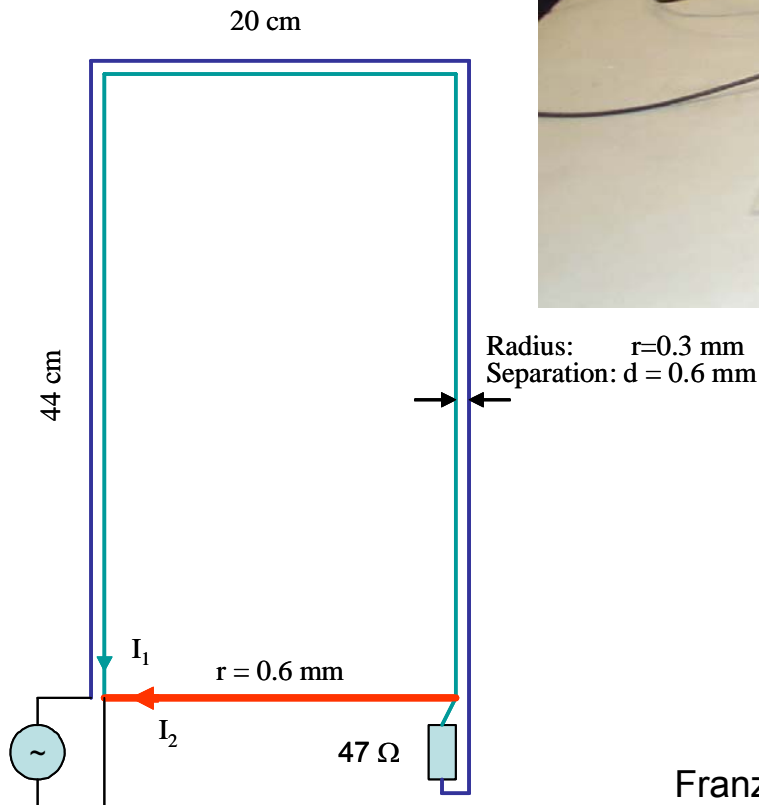
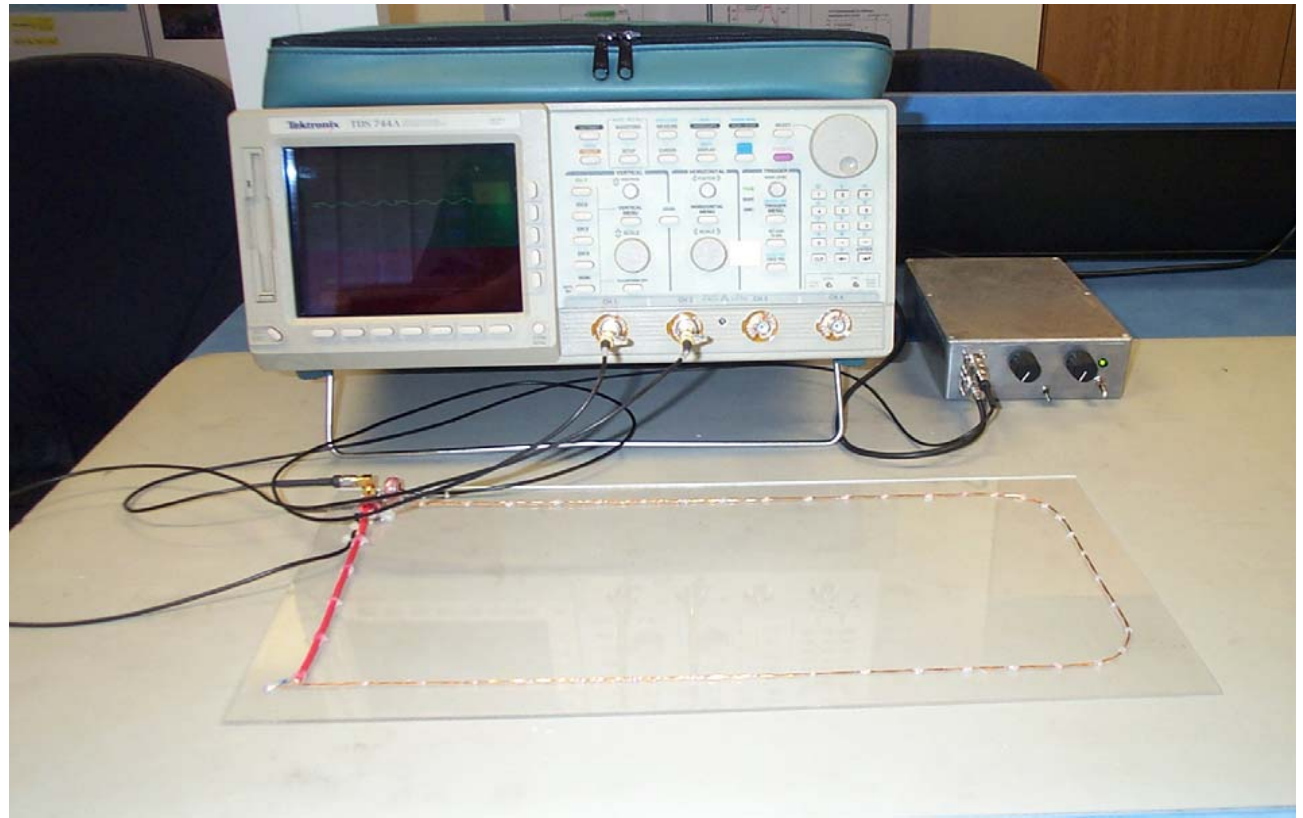
At high frequencies the impedance characteristics are dominated by inductances.

(At very high frequencies, also stray capacitances may play a role.)



Mother Nature sets up the return path in order to obtain the lowest possible impedance for the pair.

Current return path



Rough estimation to the current return path demonstration

The resistance is given by Ohm's law:

$$R = \frac{l}{\sigma A} \quad (l: \text{length}, \sigma: \text{conductivity}, A: \text{cross section})$$

For the inductance we use the formula for two thin parallel cylinders (two-conductor transmission line in free space)

$$L = \frac{\mu l}{\pi} \ln\left(\frac{d}{r}\right) \quad (l: \text{length}, \mu: \text{permeability}, d: \text{separation between conductors}, r: \text{radius})$$

We are aware that this inductance formula is not quite appropriate. Requirements for its use are that the distance between the conductors is much larger than the radius (not true for path 1) and that the conductors are much longer than their distance (not true for path 2). But let's use it anyway.

Path 1 (long thin wire):

$$l = (0.44 + 0.2 + 0.44)m = 1.08m, \quad r = 0.3mm, \quad d = 0.6mm$$

$$\sigma = 58 \cdot 10^6 \text{ Sm}^{-1}, \quad A = \pi r^2 \approx 0.28 \cdot 10^{-6} \text{ m}^2$$

$$R_1 = 67 \cdot 10^{-3} \Omega, \quad L_1 = 0.3 \cdot 10^{-6} \text{ H} \quad (1\text{MHz}: X_1 = \omega L_1 = 1.88 \Omega)$$

Path 2 (short thick wire)

$$l = 0.2m, \quad r = 0.6mm, \quad d = 200mm$$

$$\sigma = \text{Sm}^{-1}, \quad A = \pi r^2 \approx 1.13 \cdot 10^{-6} \text{ m}^2$$

$$R_2 = \frac{0.2}{58 \cdot 10^6 \cdot \pi \cdot (0.6 \cdot 10^{-3})^2} \left[\frac{m}{\text{Sm}^{-1} \text{m}^2} \right] = 3 \cdot 10^{-3} \Omega,$$

$$L_2 = \frac{4\pi \cdot 10^{-7} \cdot 0.44}{\pi} \ln\left(\frac{0.2}{0.3 \cdot 10^{-3}}\right) \approx 1.14 \cdot 10^{-6} \text{ H} \quad (1\text{MHz}: X_2 = \omega L_2 = 7.2 \Omega)$$

At low frequencies we expect the current to split according to resistance:

$$\frac{I_1}{I_2} = \frac{R_2}{R_1}; \quad I_2 = 22 \cdot I_1$$

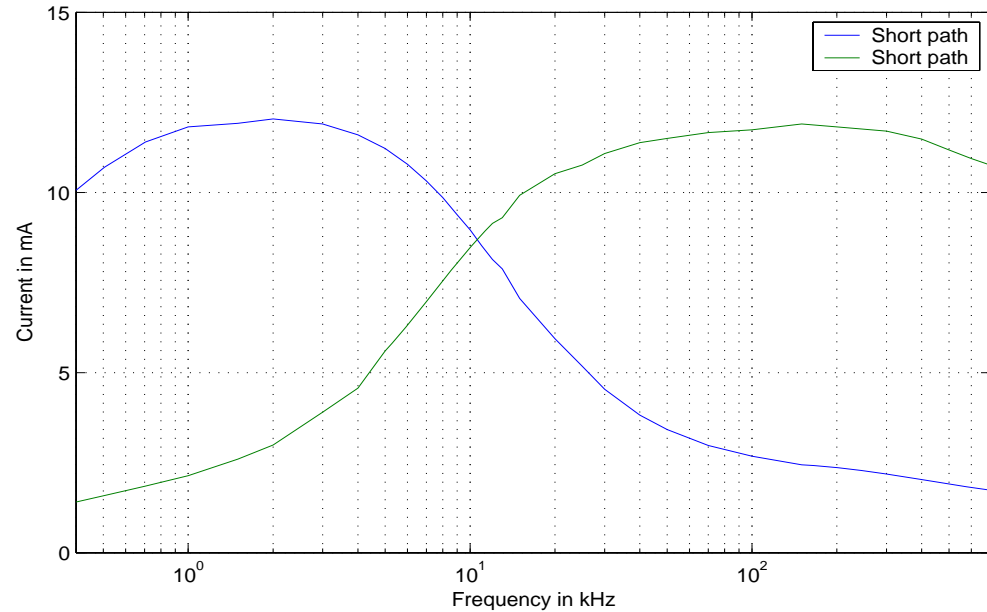
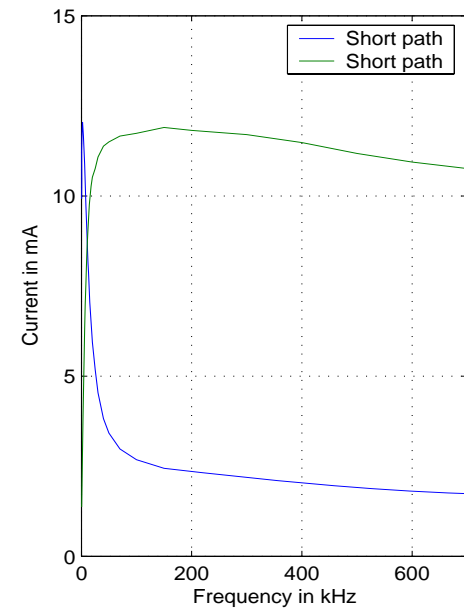
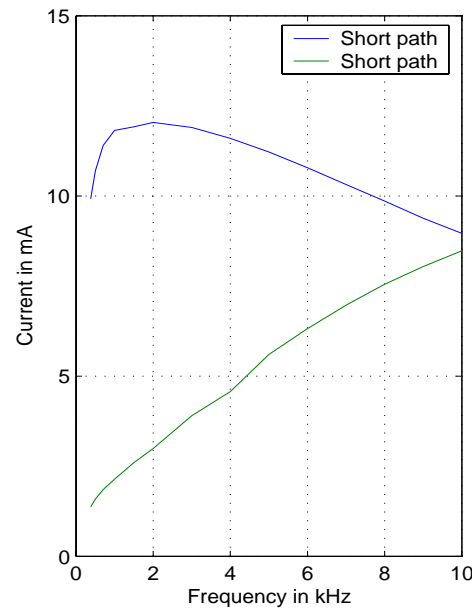
At high frequencies the current ratio should be governed by inductances:

$$\frac{I_1}{I_2} = \frac{L_1}{L_2}; \quad I_1 = 4 \cdot I_2$$

The frequency with an equal current split is expected at:

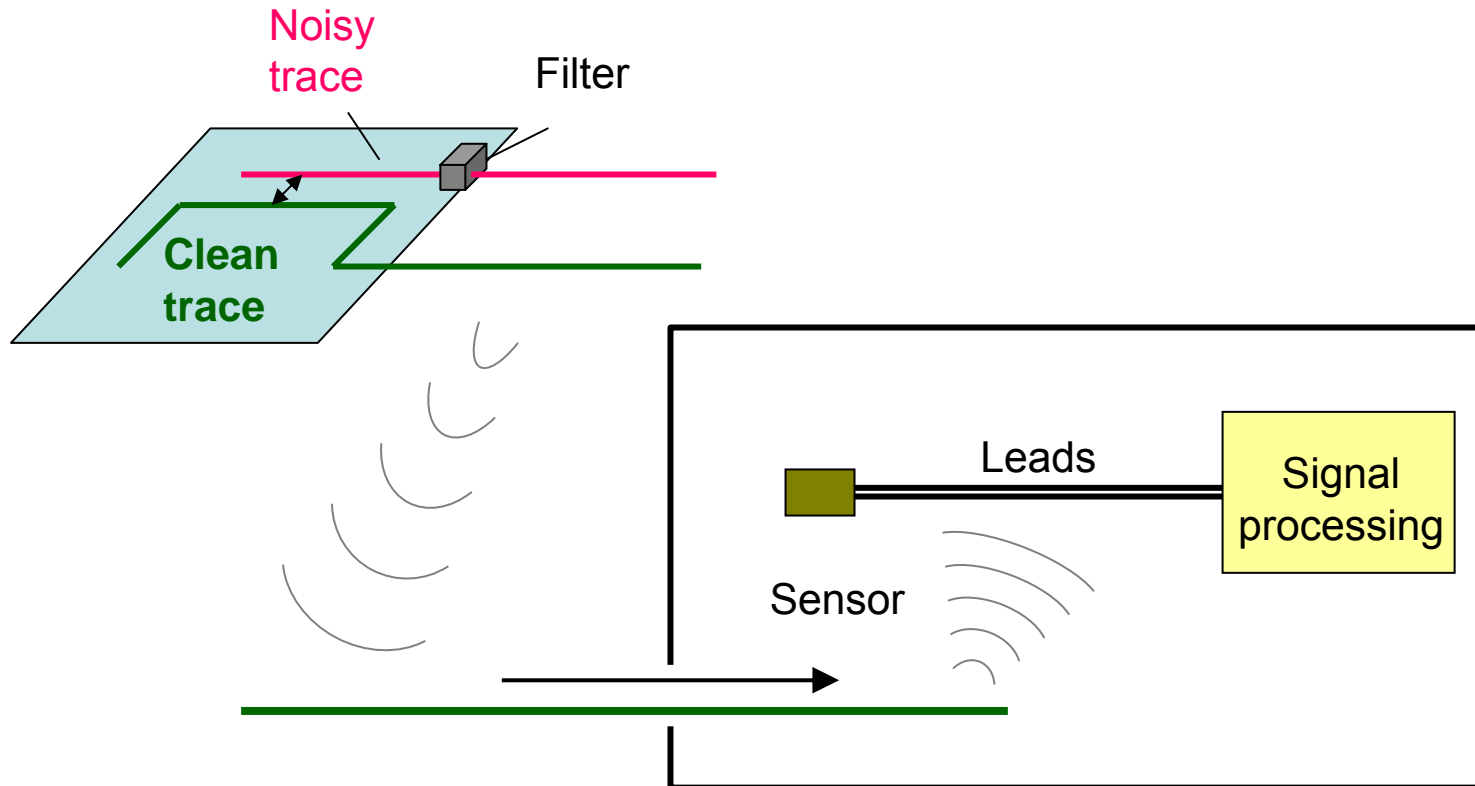
$$|R_1 + j\omega L_1| = |R_2 + j\omega L_2| \Rightarrow R_1^2 + \omega^2 L_1^2 = R_2^2 + \omega^2 L_2^2$$

$$\omega = \sqrt{\frac{R_1^2 - R_2^2}{L_2^2 - L_1^2}} \approx \sqrt{\frac{4.35 \cdot 10^{-3}}{1.2 \cdot 10^{-12}}} \text{ s}^{-1} \approx 61,000 \text{ s}^{-1}, \quad f = \frac{61,000}{2\pi} \text{ Hz} \approx 9.7 \text{ kHz}$$



EM Coupling Phenomena

Coupling path (example)

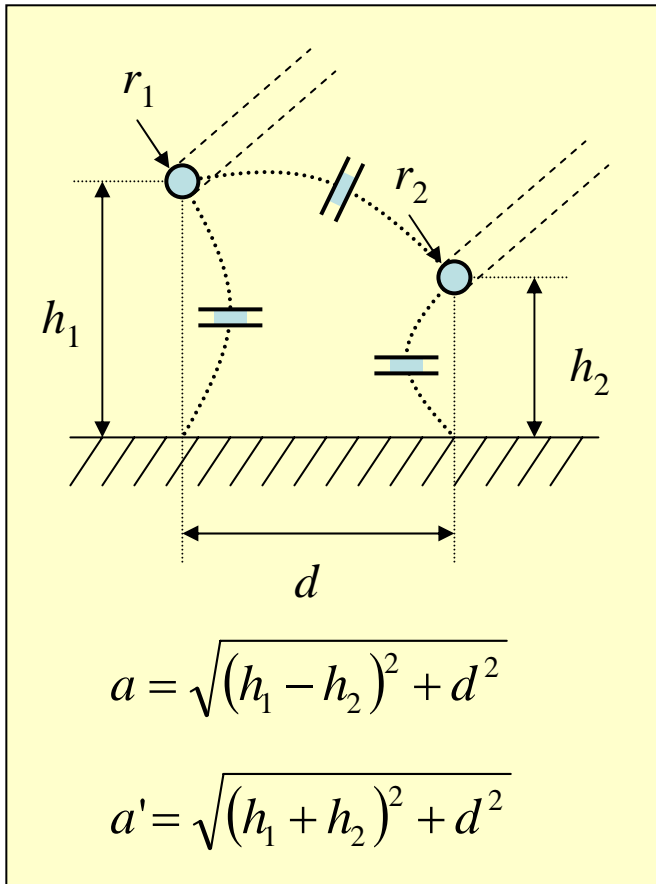


Capacitive Coupling

General remarks

- Coupling due to voltages (electric fields);
- Assumption: electrically short conductor (much shorter than a wavelength);
- Uniform voltage along the conductors;
- Critical parameter: capacitance;
- Most effective for high impedance circuits (source and sink).

Capacitive coupling - Model

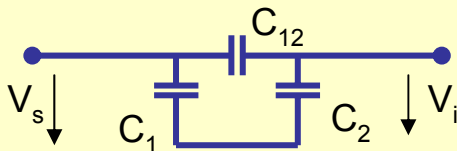


Per-unit-length capacitances for two cylindrical conductors above a perfect ground plane

$$C'_1 = 2\pi\epsilon \frac{\ln(2h_2 / r_2) - \ln(a' / a)}{\ln(2h_1 / r_1) \cdot \ln(2h_2 / r_2) - \ln^2(a' / a)}$$

$$C'_2 = 2\pi\epsilon \frac{\ln(2h_1 / r_1) - \ln(a' / a)}{\ln(2h_1 / r_1) \cdot \ln(2h_2 / r_2) - \ln^2(a' / a)}$$

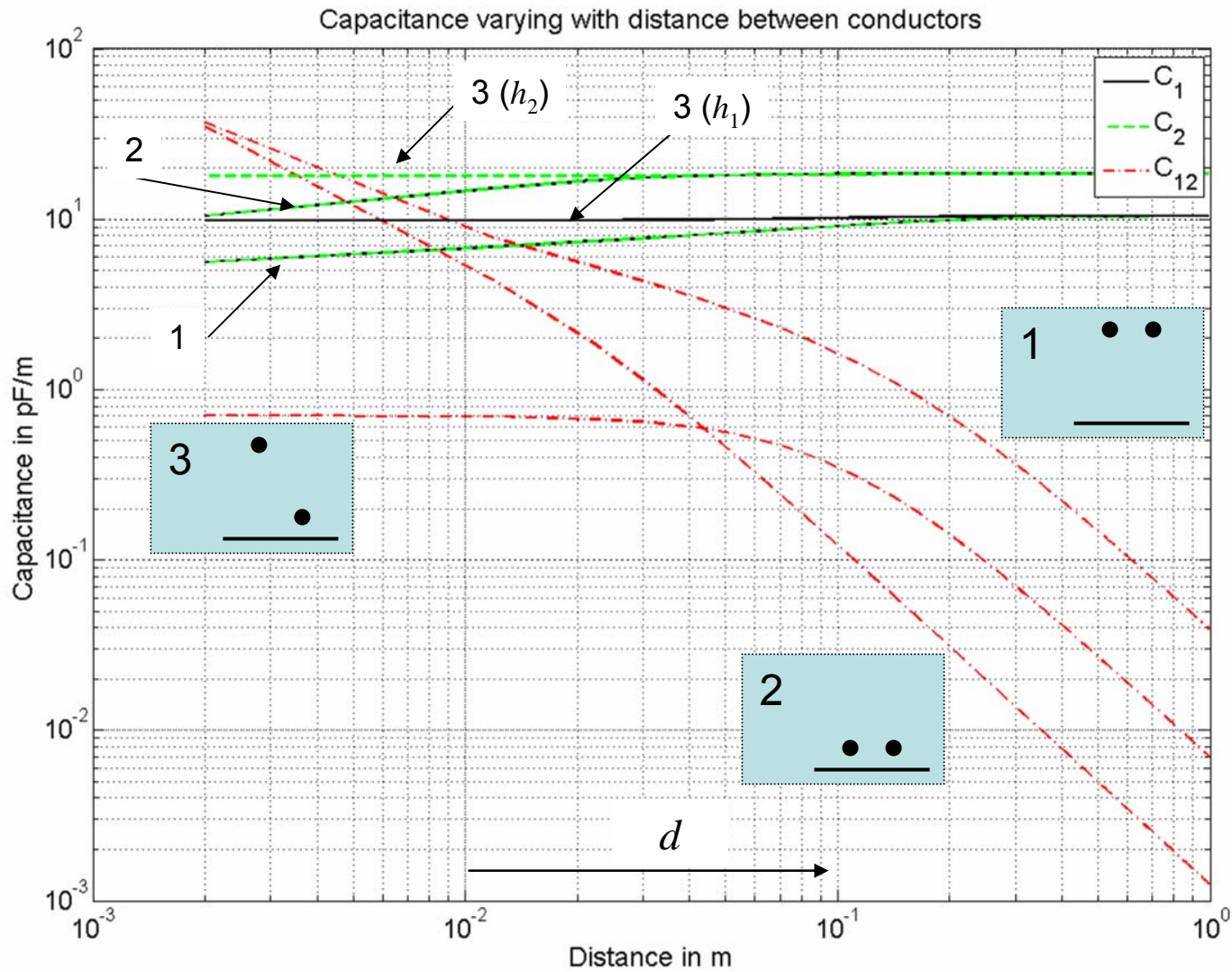
$$C'_{12} = 2\pi\epsilon \frac{\ln(a' / a)}{\ln(2h_1 / r_1) \cdot \ln(2h_2 / r_2) - \ln^2(a' / a)}$$



$$C_{eff} = C_{12} + \frac{C_1 C_2}{C_1 + C_2}$$

Note: The use of not grounded land can increase the coupling!

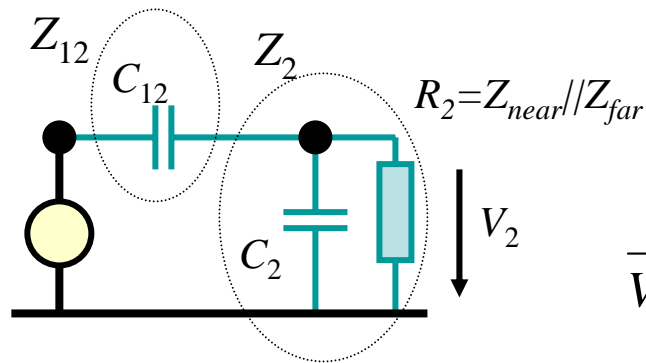
Capacitive coupling - Influence of distance



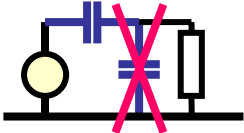
$$r_1 = r_2 = 1 \text{ mm}$$

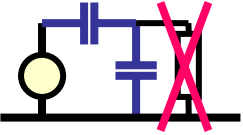
- 1) $h_1 = h_2 = 0.1 \text{ m}$
- 2) $h_1 = h_2 = 0.01 \text{ m}$
- 3) $h_1 = 0.1 \text{ m}$,
 $h_2 = 0.01 \text{ m}$

Capacitive coupling – Asymptotic behaviour (1)



$$\frac{V_2}{V_{Source}} = \frac{Z_2}{Z_2 + Z_{12}} = \frac{j\omega C_{12} R_2}{1 + j\omega(C_2 + C_{12})R_2}$$

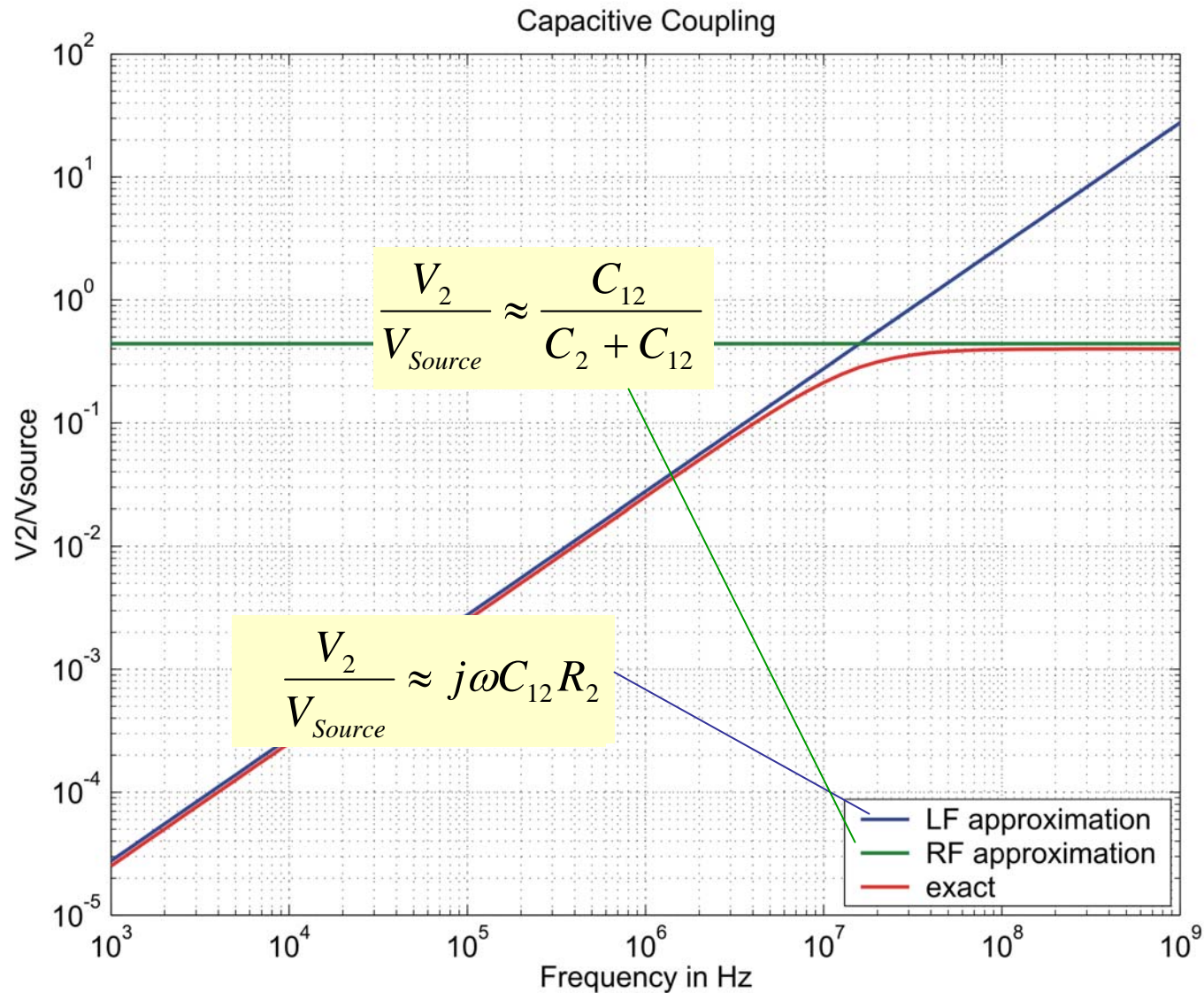
Low Frequency:  $\left(R_2 \ll \frac{1}{\omega C_2} \right) \Rightarrow Z_2 \approx R_2 \Rightarrow \frac{V_2}{V_{Source}} \approx j\omega C_{12} R_2$

High Frequency:  $\left(R_2 \gg \frac{1}{\omega C_2} \right) \Rightarrow Z_2 \approx \frac{1}{j\omega C_2} \Rightarrow \frac{V_2}{V_{Source}} \approx \frac{C_{12}}{C_2 + C_{12}}$

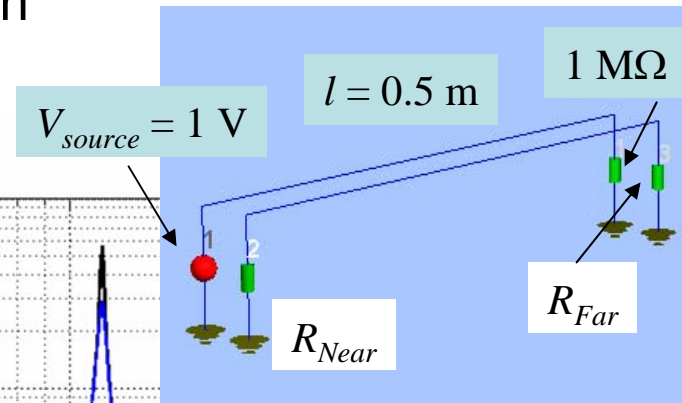
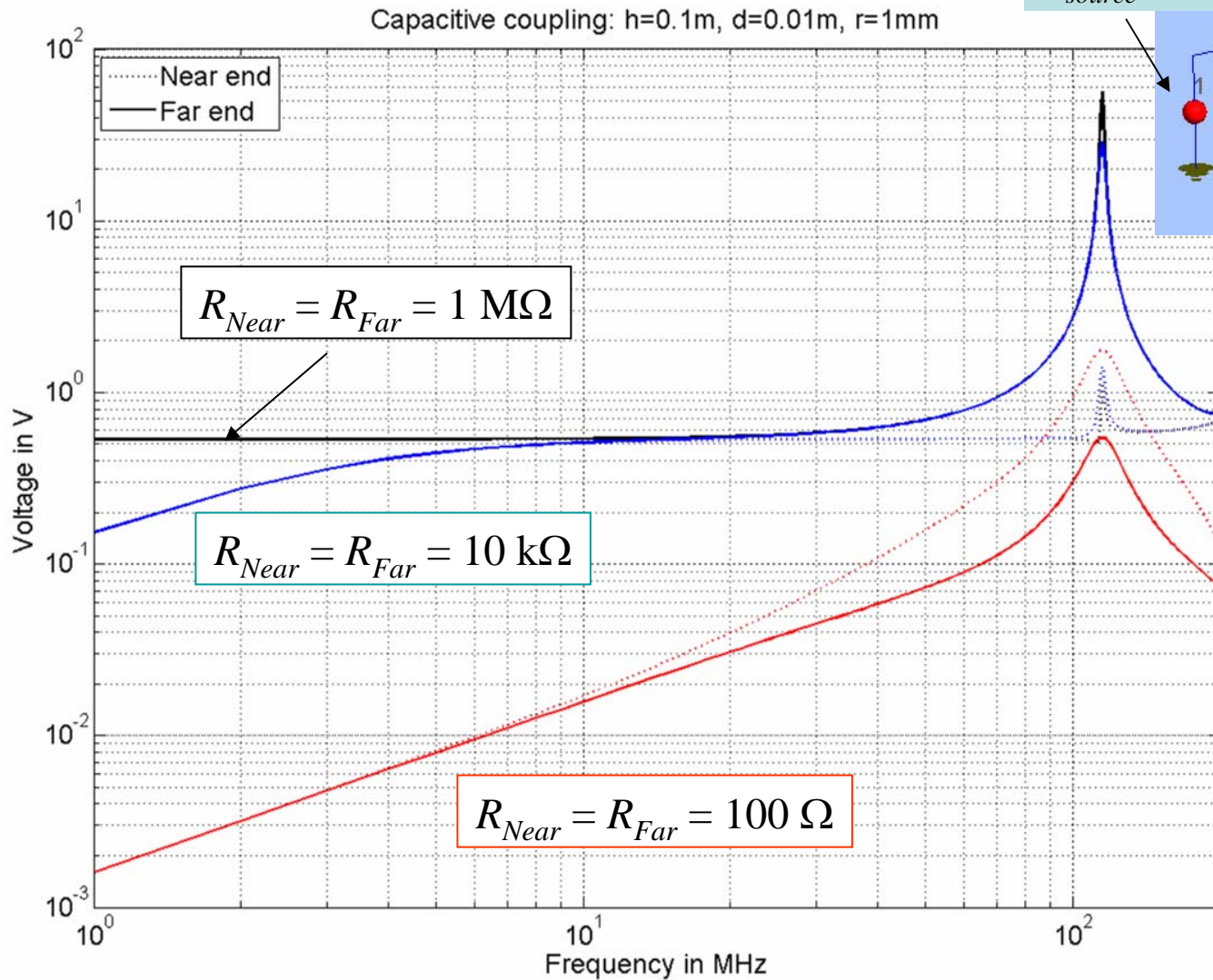
To reduce capacitive coupling:

- decrease C_{12} (increase distance, decrease cross section)
- increase C_2 (decrease distance to ground, increase cross section)

Capacitive coupling – Asymptotic behaviour (2)



Capacitive coupling - Influence of termination

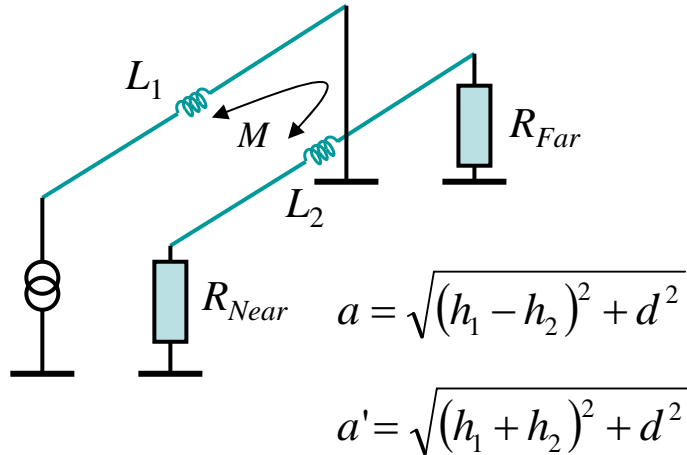


Inductive Coupling

General remarks

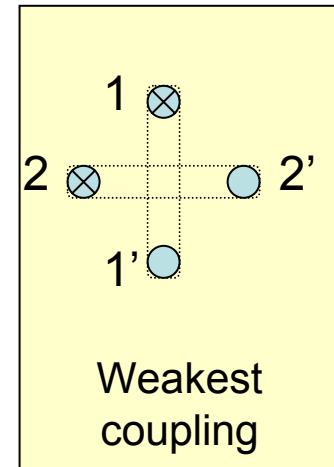
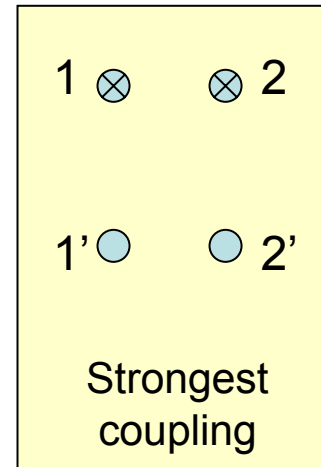
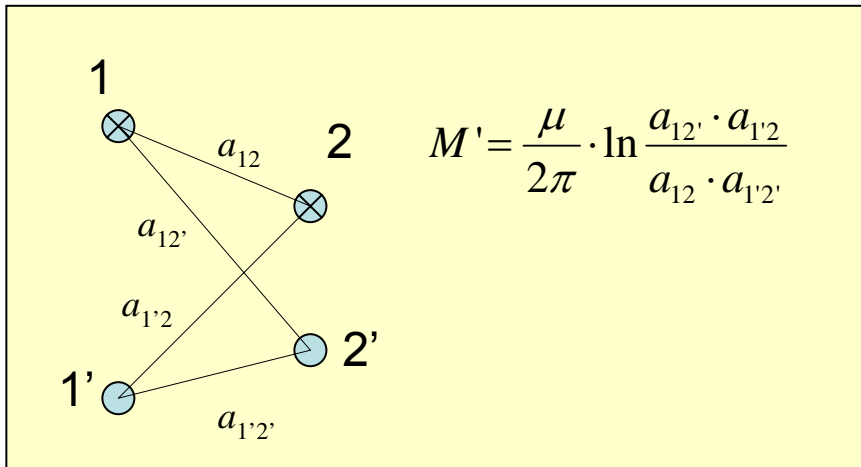
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- Uniform current along the conductors;
- Critical parameter: inductance;
- Most effective for low impedance circuits (source and sink).

Inductive coupling – Model (1)



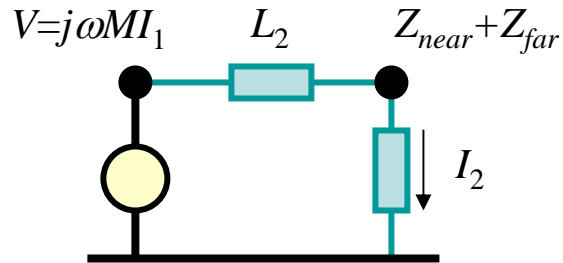
Per-unit-length inductances for two cylindrical conductors above a perfect ground plane

$$L_1' = \frac{\mu}{2\pi} \ln \frac{2h_1}{r_1}; \quad L_2' = \frac{\mu}{2\pi} \ln \frac{2h_2}{r_2}; \quad M' = \frac{\mu}{2\pi} \cdot \ln \frac{a'}{a}$$



Inductive coupling – Model (2)

Coupling model: simple – ideal current source driving circuit 1



Low Frequency:

$$(R_2 \gg \omega L_2)$$

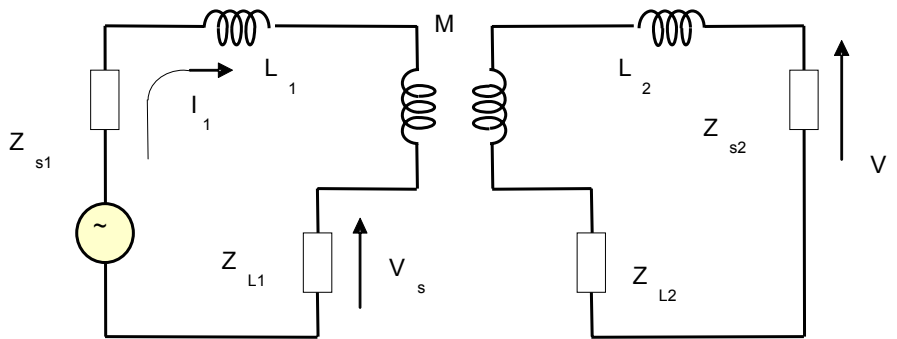
$$\Rightarrow \frac{I_2}{I_1} \approx \frac{j\omega M}{R_2}$$

High Frequency:

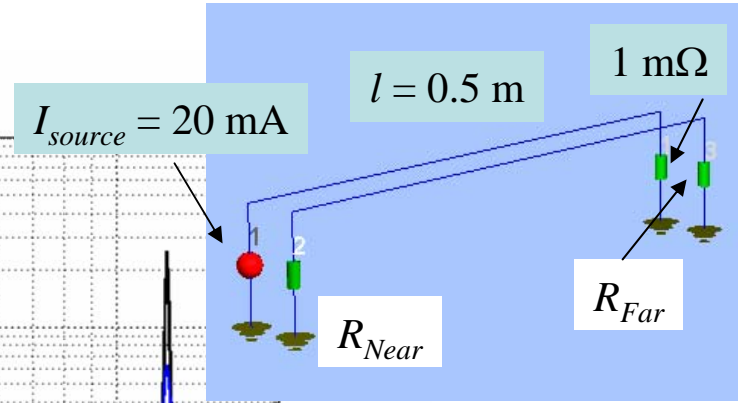
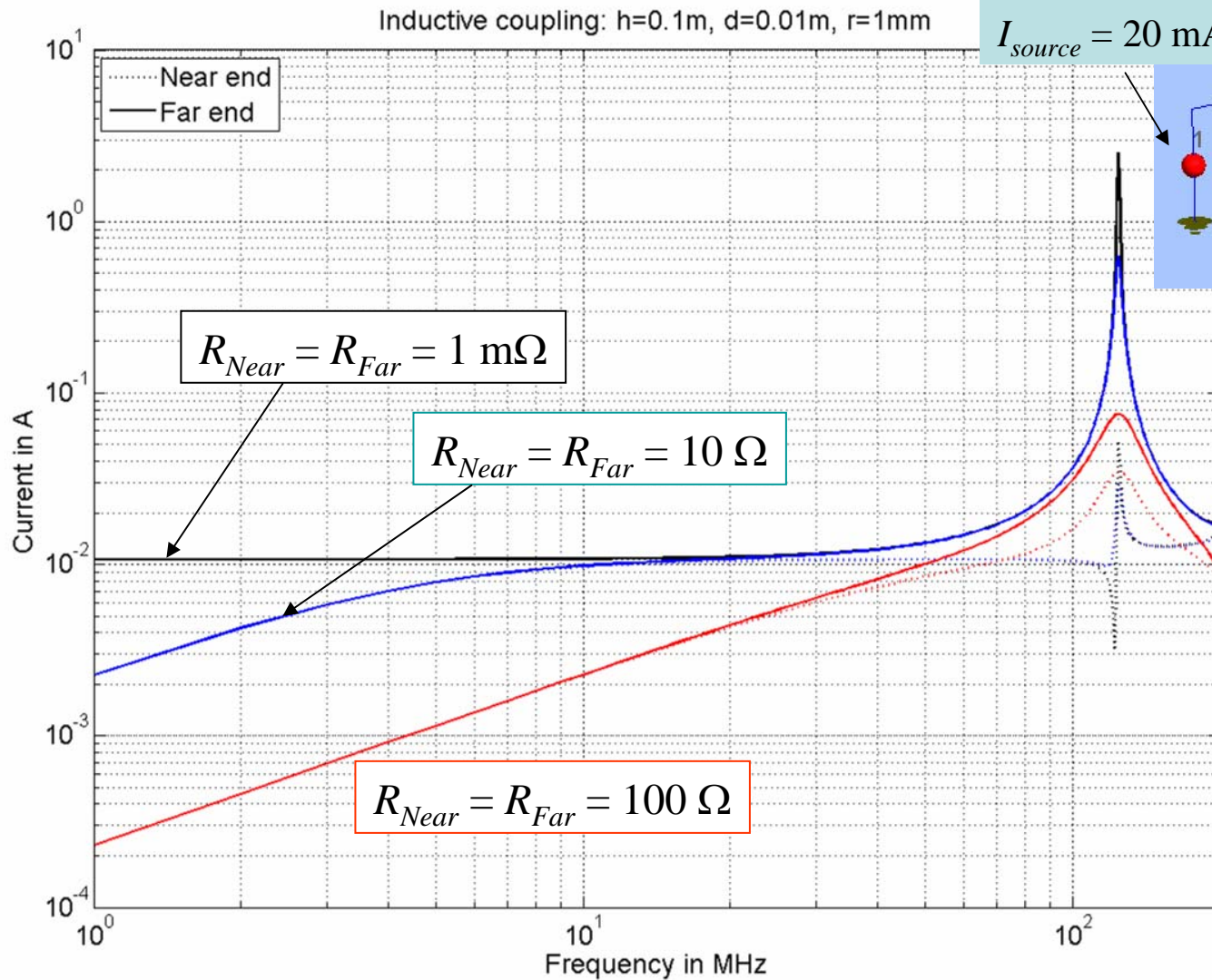
$$(R_2 \ll \omega L_2)$$

$$\Rightarrow \frac{I_2}{I_1} \approx \frac{M}{L_2}$$

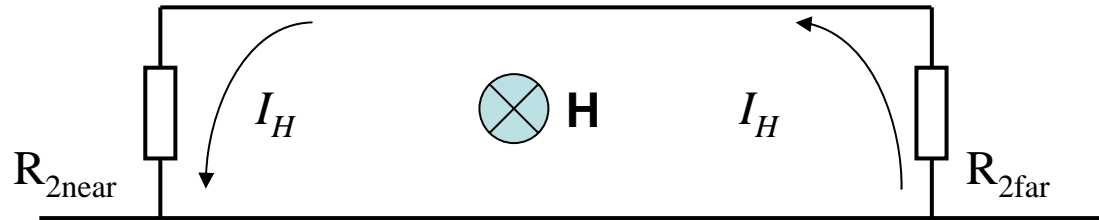
Coupling model: considering real current/voltage source driving circuit 1



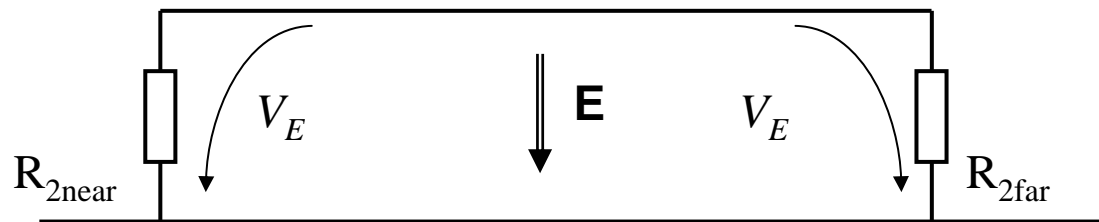
Inductive coupling - Influence of termination



Inductive coupling: Current at both ends is the same



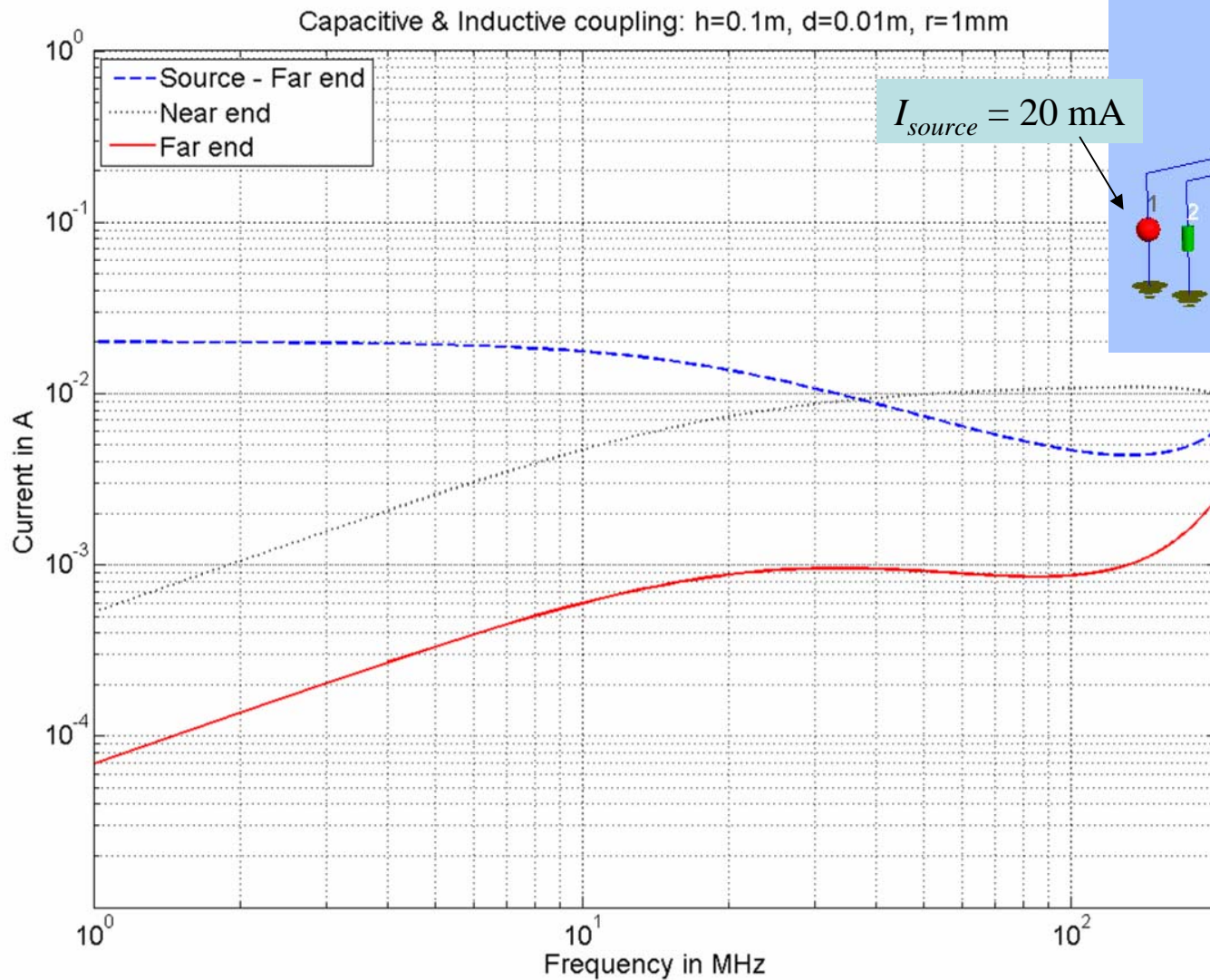
Capacitive coupling: Voltage at both ends is the same



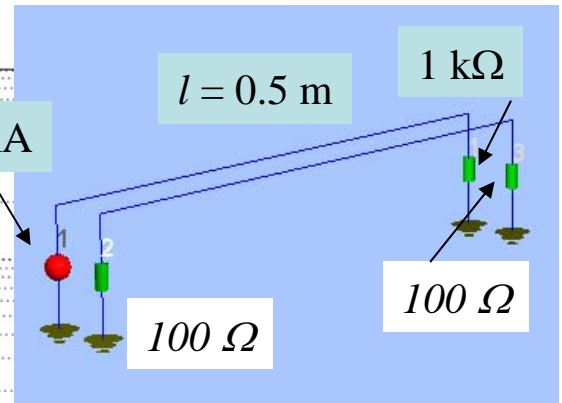
$$V_{2near} = V_E + R_{2near} \cdot I_H$$

$$V_{2far} = V_E - R_{2far} \cdot I_H$$

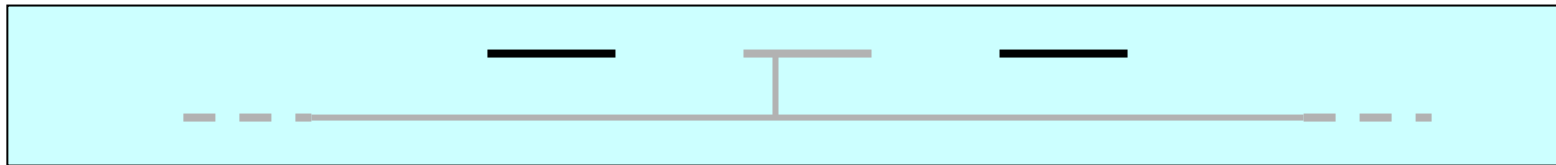
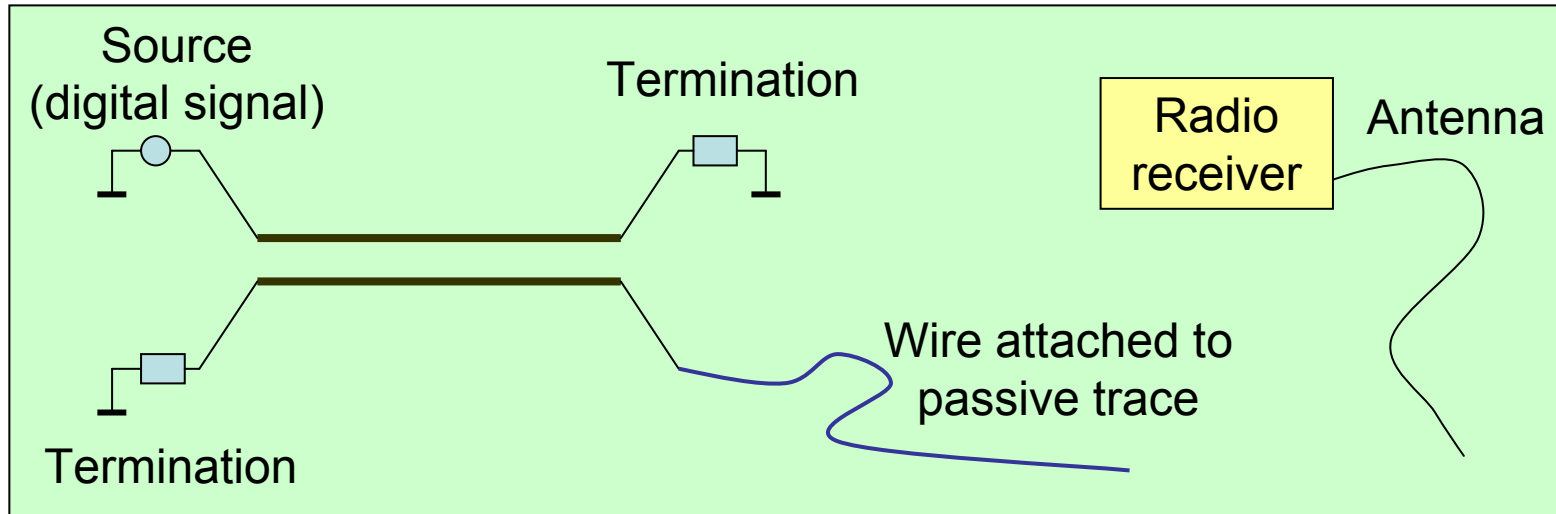
Example – Capacitive and inductive coupling



$I_{source} = 20\text{ mA}$



EM Coupling (Demo)



Variants: Distance between traces
Ground plane: no / yes
Shielding trace: no / yes (not grounded) / yes (grounded)

EM Coupling (Demo)

Measurement setup

Function generator
 $R_G = 50 \Omega$
 $f = 18.9 \text{ MHz}$

Source trace
Oscilloscope
 $R_l = 50 \Omega$



50Ω
Termination

Sink trace
Oscilloscope
 $R_l = 50 \Omega$

EM Coupling

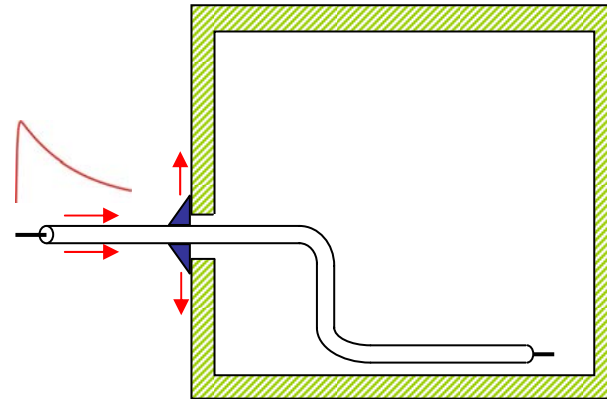
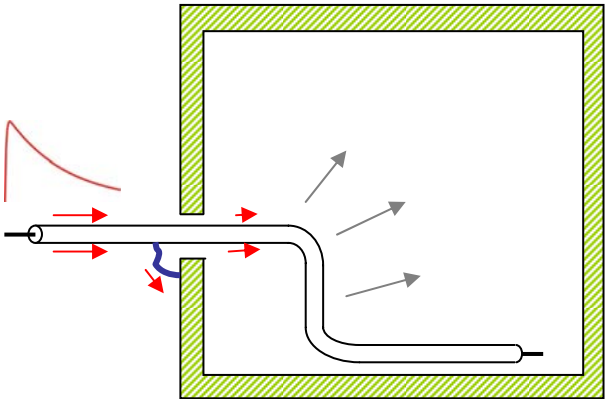
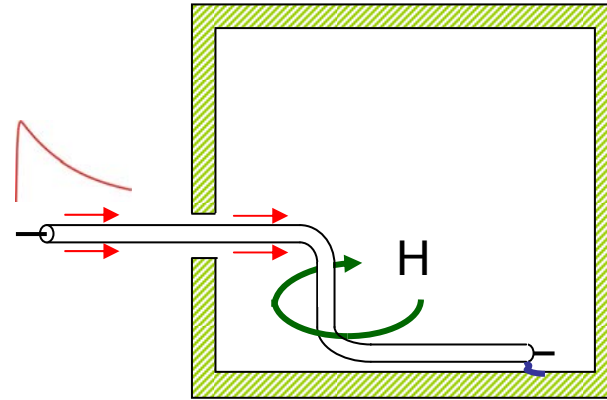
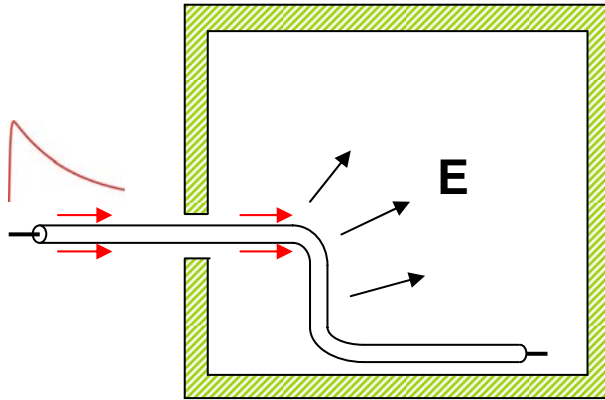


PCB No.	Trace width	Distance between traces	Land fill between traces, width	Reference plane beneath traces
	mm	mm	mm	
1	0.25	0.25	Nothing	No
2	0.25	2.5	Nothing	No
5	0.25	2.5	Floating, 2.0	No
6	0.25	2.5	Grounded at both ends, 2.0	No
11	0.25	0.25	Nothing	Yes
12	0.25	2.5	Nothing	Yes
15	0.25	2.5	Floating, 2.0	Yes
16	0.25	2.5	Grounded at both ends, 2.0	Yes

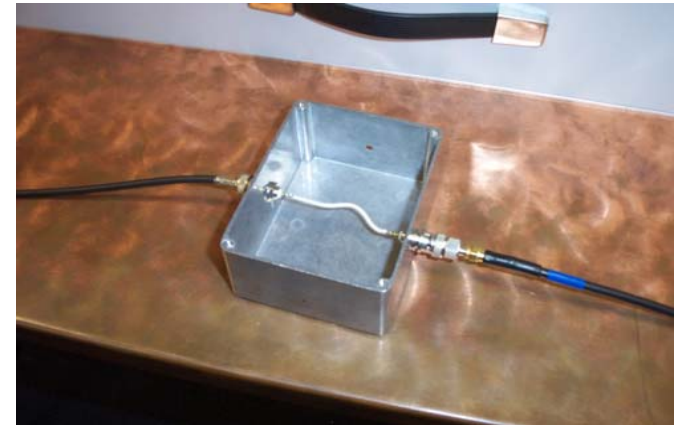
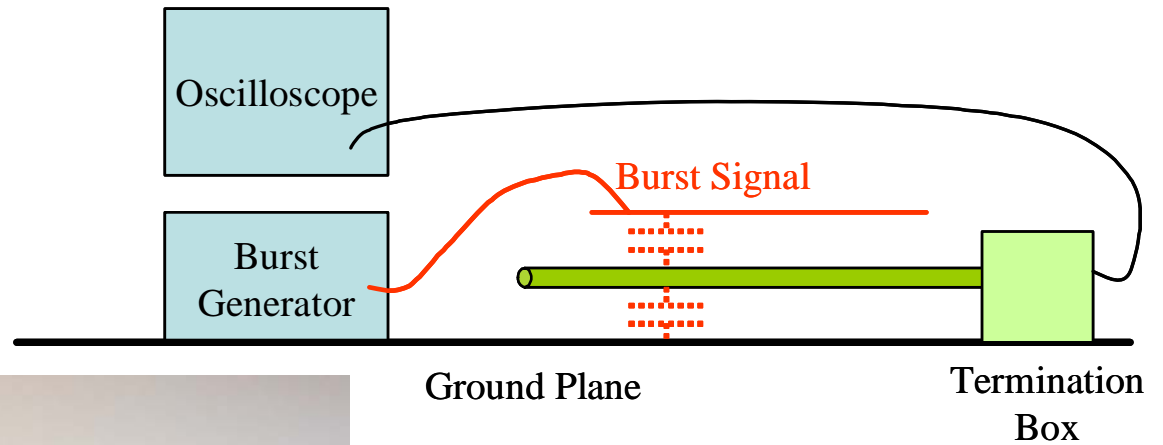
	PCB No.	Rise time for source trace	Fall time for source trace	Maximum voltage on sink trace	Interference to 94.5FM Radio with the shown setup
		Ns	Ns	mV	
Base line	1	6.7	7.2	340	Yes
Distance increased	2	6.6	7.0	260	Yes
Floating trace	5	6.5	6.9	275	Yes
Trace grounded	6	5.5	5.6	16	No
Base line	11	5.5	5.8	120	Yes
Distance increased	12	5.5	5.6	35	No
Floating trace	15	5.5	5.7	48	No
Trace grounded	16	5.4	5.4	4.5	No

Grounding

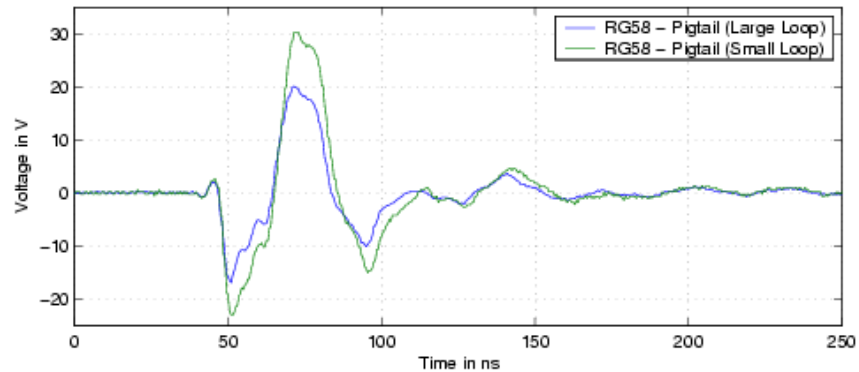
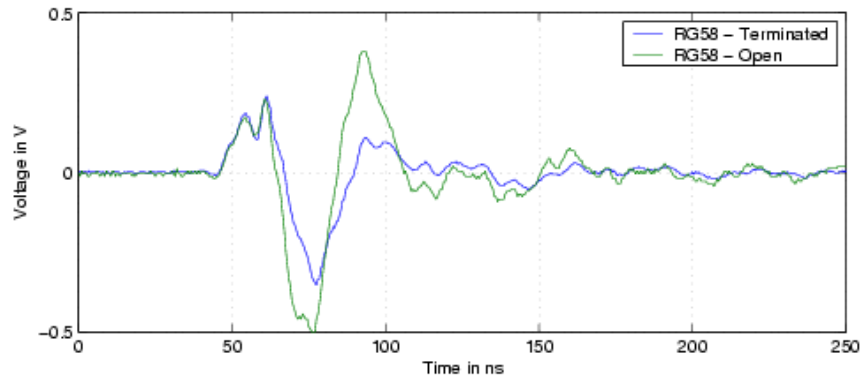
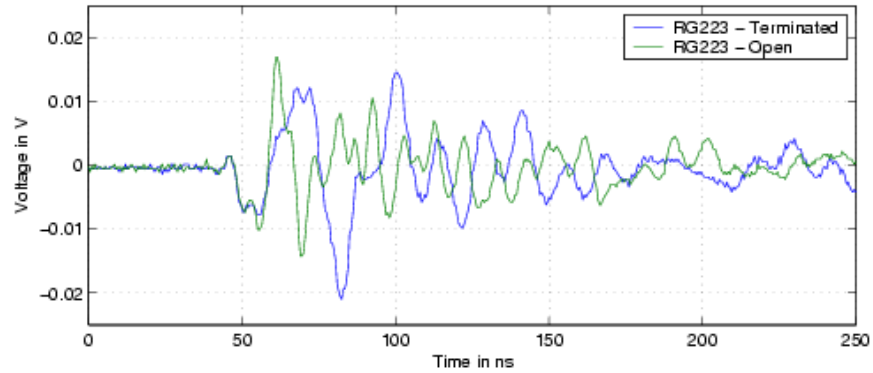
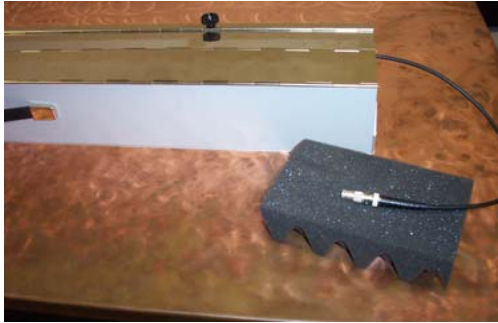
Cable screen termination



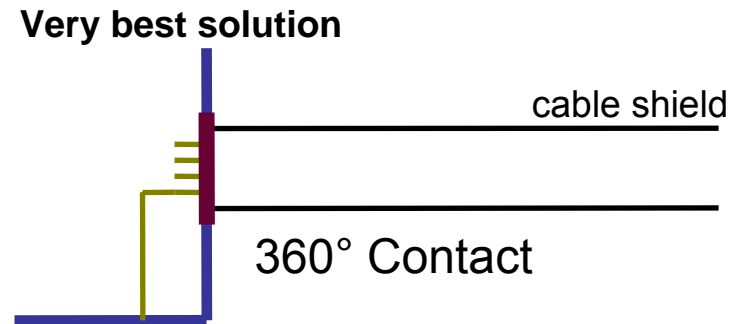
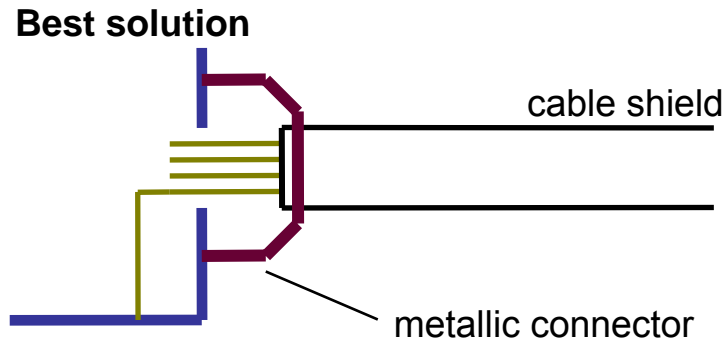
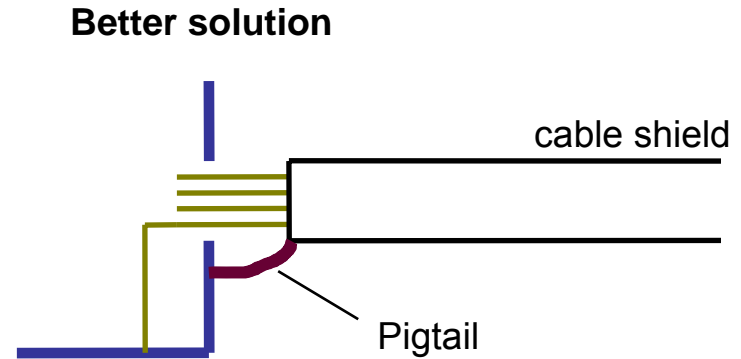
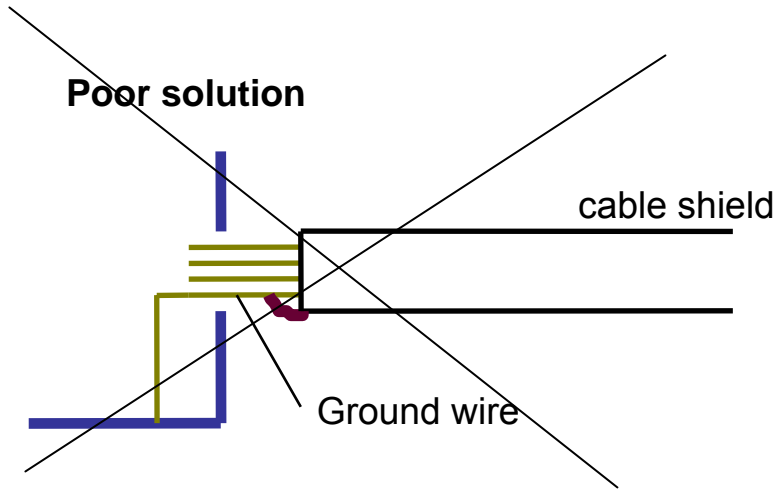
Grounding of Cables



Grounding of Cables



Grounding

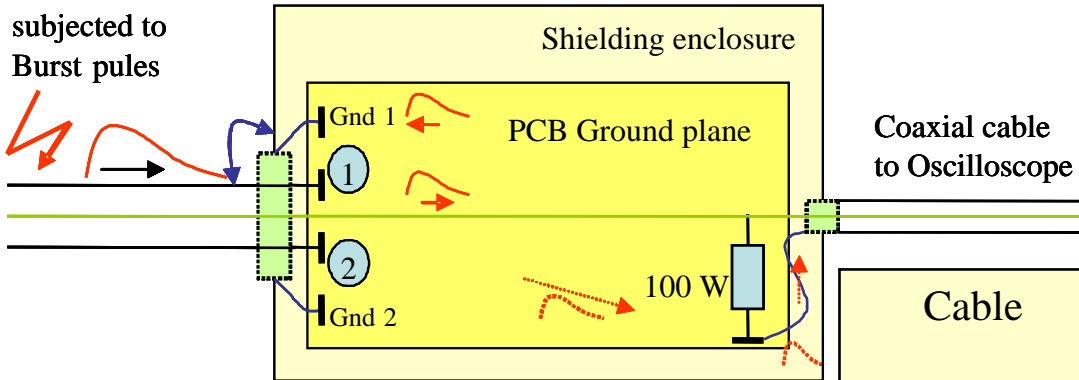


Cable Screen and PCB Grounding



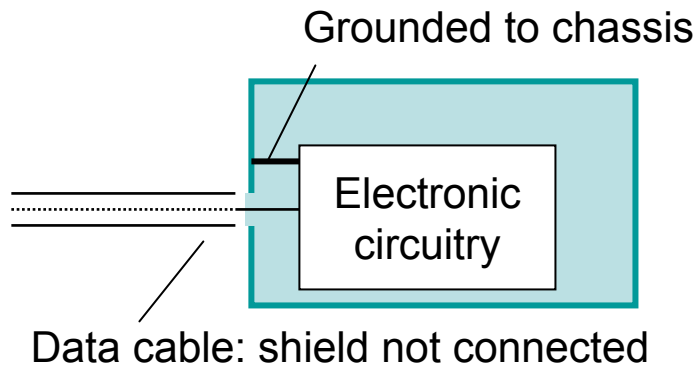
Cable Screen and PCB Grounding

Shielded cable
subjected to
Burst pulses

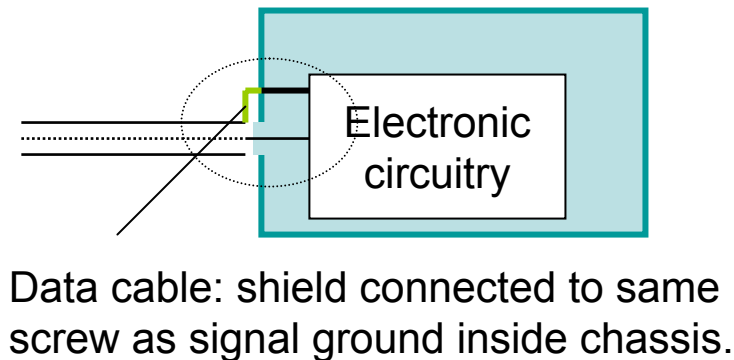


Cable	Box	Maximum voltage Pk-Pk
1 pin grounded	Grounded at far end	31 V
	1 near ground connection	17 V
2 pins grounded	Grounded at far end	25 V
	1 near ground connection	11 V
1 pin grounded	2 near ground connection	16 V
	2 short ground connections	14 V
2 pins grounded	2 near ground connections	9 V
	2 short ground connections	7 V

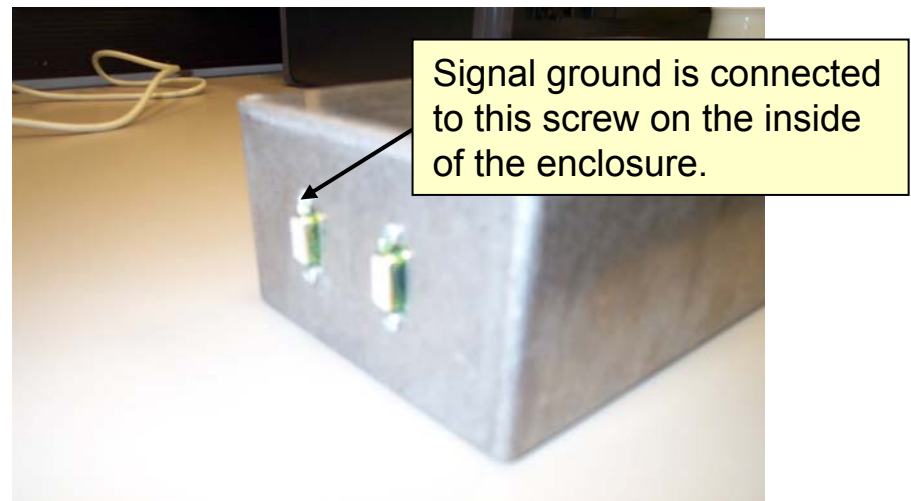
Grounding of Cable Screen



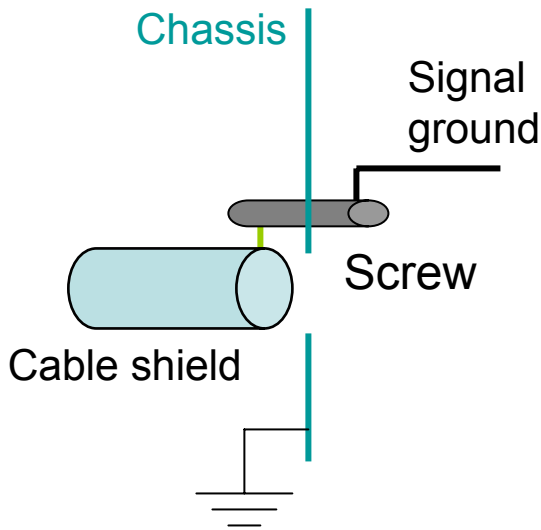
Failed radiated emission test due to radiation from data cable!



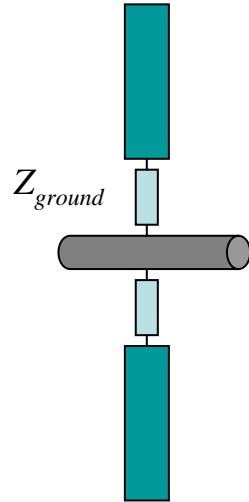
**Passed emission test.
Failed Electrical Fast Transient Test (Burst)!**



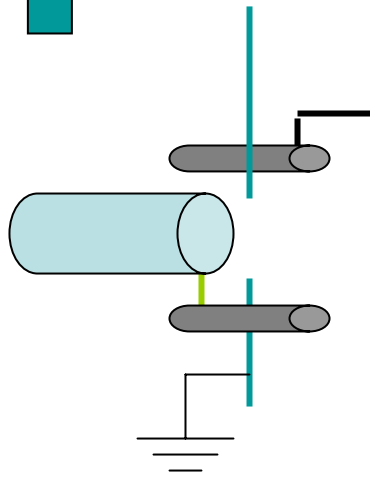
Grounding of Cable Screen



Chassis is considered 'ground'. A disturbance on the cable screen should be diverted to ground and not affect 'signal ground' on the inside!



Hypothesis: There is a small impedance between chassis and the screw. Only the (major) part of the disturbance flows to ground, a small portion continues on to signal ground. This small portion, however, is sufficient to upset to electronic circuitry.

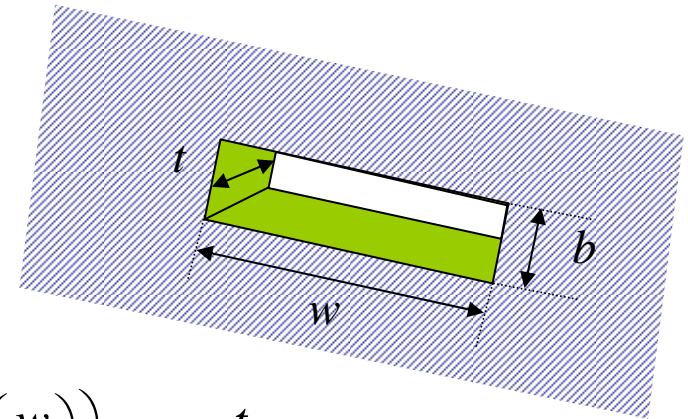


The screw had been chosen as a grounding point for convenience. Its primary purpose was the hold the connector. The cable screen was temporarily connected to the second screw on the connector.

**Passed emission test.
Passed Burst Test!**

That confirmed the thesis! In the final version of the product a dedicated grounding point for 'signal ground' was chosen.

Shielding degradation due to openings



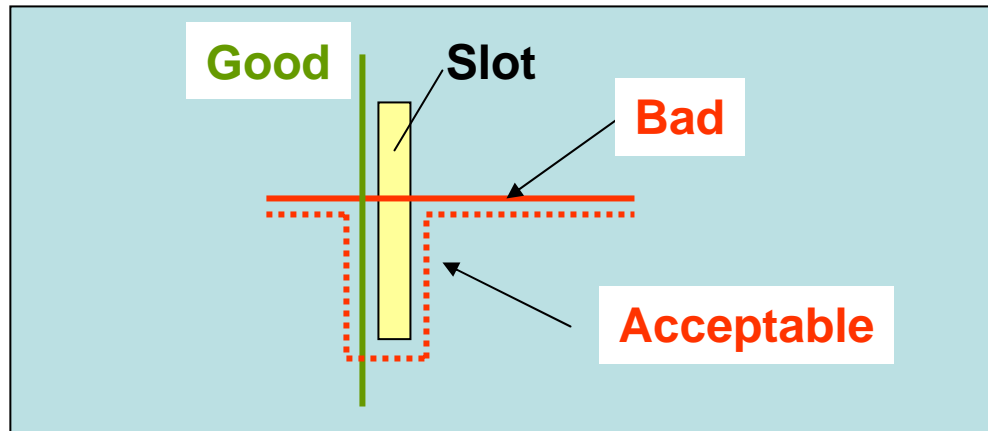
$$a_s [dB] \approx 100 - 20 \log_{10} \left(\frac{w}{\text{mm}} \cdot \frac{f}{\text{MHz}} \right) + 20 \log_{10} \left(1 + \ln \left(\frac{w}{b} \right) \right) + 30 \cdot \frac{t}{w}$$

Far field reflection term : $100 - 20 \log_{10} \left(\frac{w}{\text{mm}} \cdot \frac{f}{\text{MHz}} \right)$

'Fatness' factor (0 dB for $w=b$): $20 \log_{10} \left(1 + \ln \left(\frac{w}{b} \right) \right)$

Absorption term - Waveguide below cut-off frequency:
(not significant if $w \gg t$): $30 \cdot \frac{t}{w}$

Conductors passing slots



The direction of current flow is known when the source is the current along a conductor. A mirror current is flowing underneath the conductor.

Conductors should never cross slots!

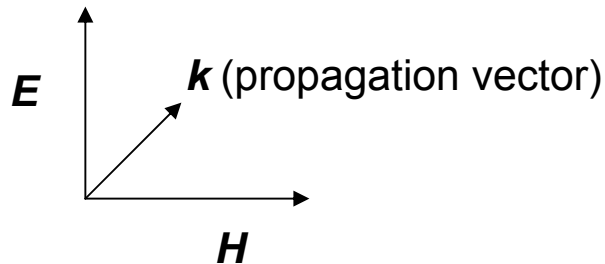
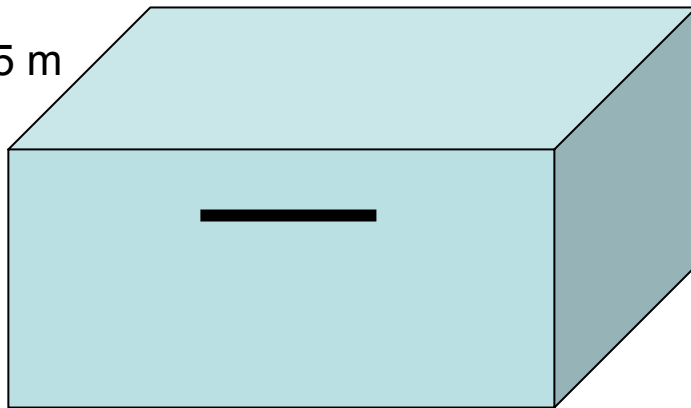
Example – Shielding Enclosure with Slot

A shielding box with a slot (slots) on its front side is hit by a plane wave

0.6 m

0.45 m

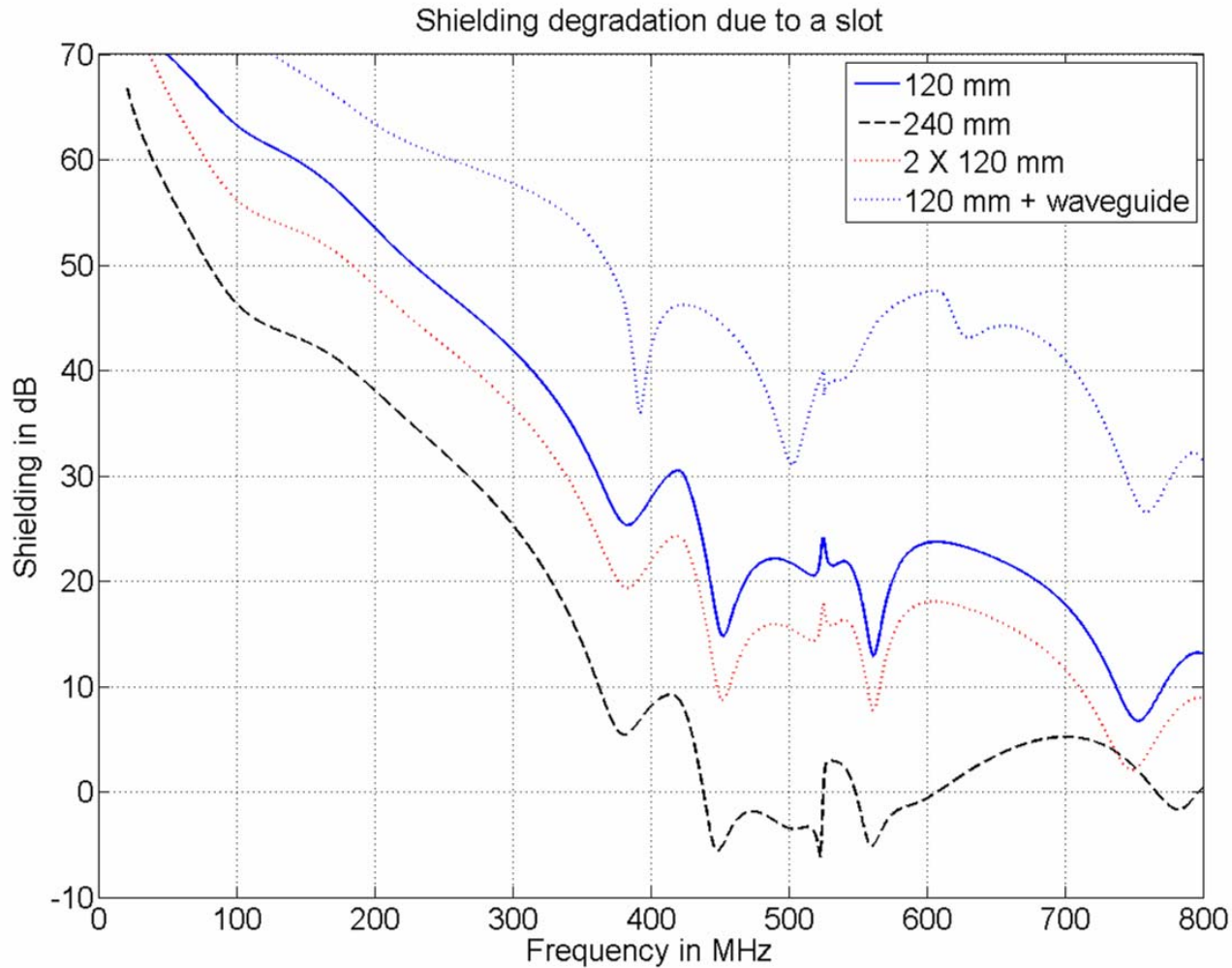
0.4 m



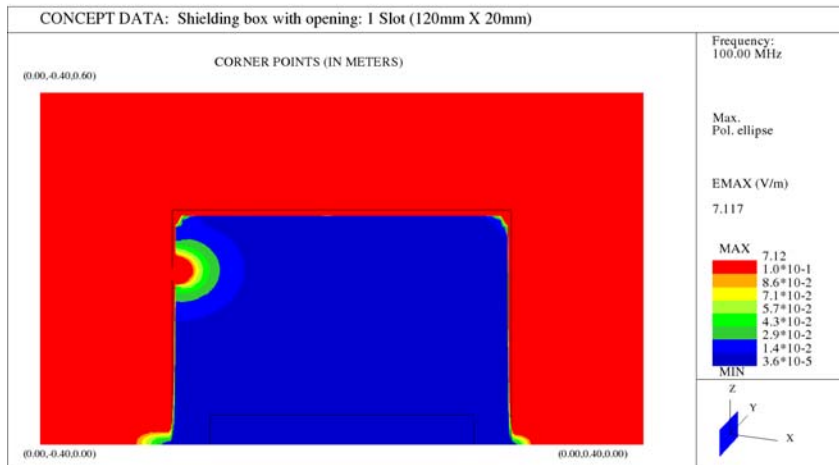
The field inside the box is simulated for four scenarios:

- Short slot (120mm by 10mm) in front side
- Long slot (240 by 10 mm) in front side
- Two slots (120mm by 10mm) in front side
- Short slot (120mm by 10mm) with 125mm long wave guide attached.

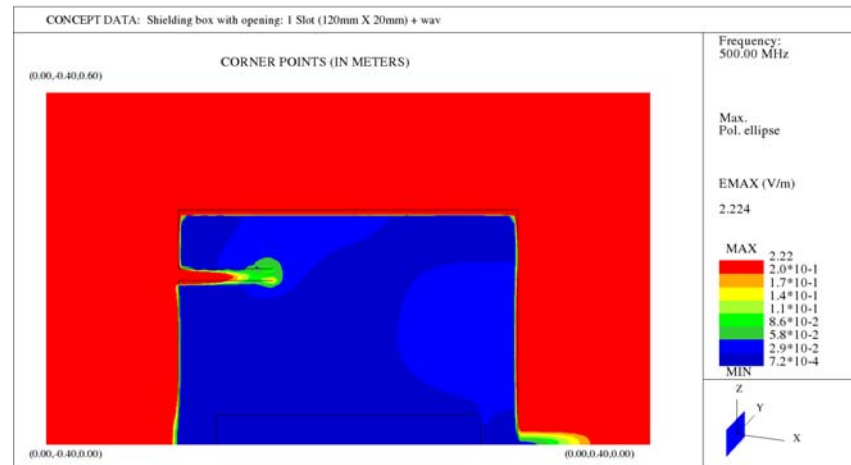
Example – Shielding Enclosure with Slot



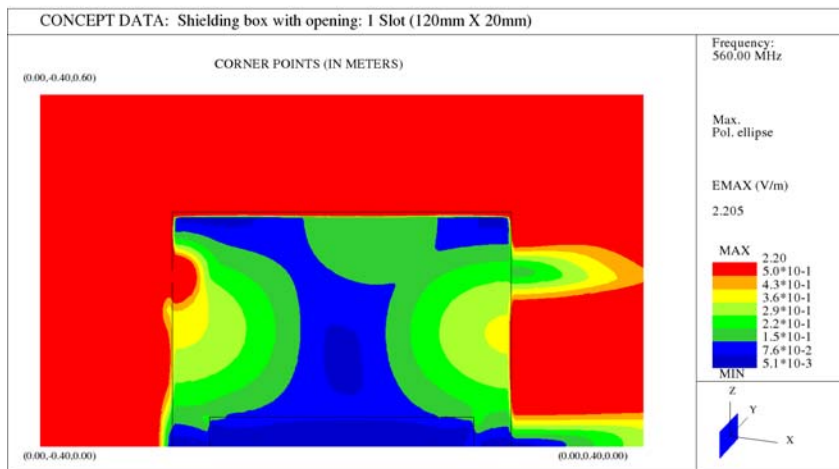
Example – Shielding Enclosure with Slot



120mm slot – 100MHz (high field strength concentrated around slot)



120mm slot with wave guide attached – 500MHz (field is attenuated along the wave guide)



120mm slot – 560MHz (field distribution governed by cavity mode)

Introduction

- Simulation is based on modelling, i.e. the transformation of a physical model into an abstract mathematical equation system which is then solved by a computer.
- This transformation is based on physics, in our case mainly on Maxwell's equations or derivations from them.
- Hopefully, the resulting numbers represent physical quantities of the original model.
- **Neglecting as many unimportant details** as possible speeds up simulation time and improves numerical stability.
- **Keeping all essential details** ensures usefulness (correctness) of the results.
- **Distinguishing between unimportant and essential** details makes up the wisdom of the simulation engineer.

Introduction

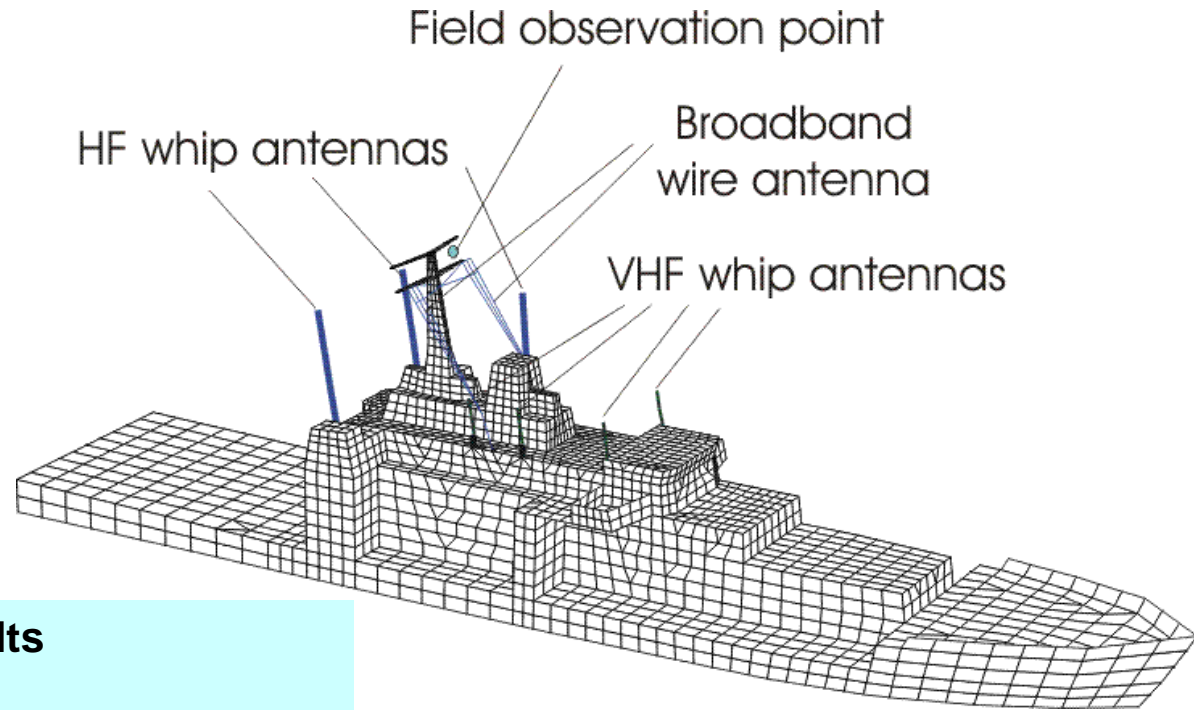
Reasons for a Simulation

- Prototype for measurements not available
 - Antenna arrangement on ship or aircraft during design phase
- Controlled variation of parameters not possible in measurements
 - Voltage induced by lightning strokes: comparison of different over-voltage protection devices
- Measurement set up interferes with the physical value of interest
 - Radiation from cables masks radiated emission from PCBs
- Physical value of interest not (easily) accessible to measurements
 - The field between power-ground planes on a PCB, or SAR values in a dielectric body

Example: No Prototype Available

Some Electromagnetic characteristics for a new ship must be known, **before** the first ship is built.

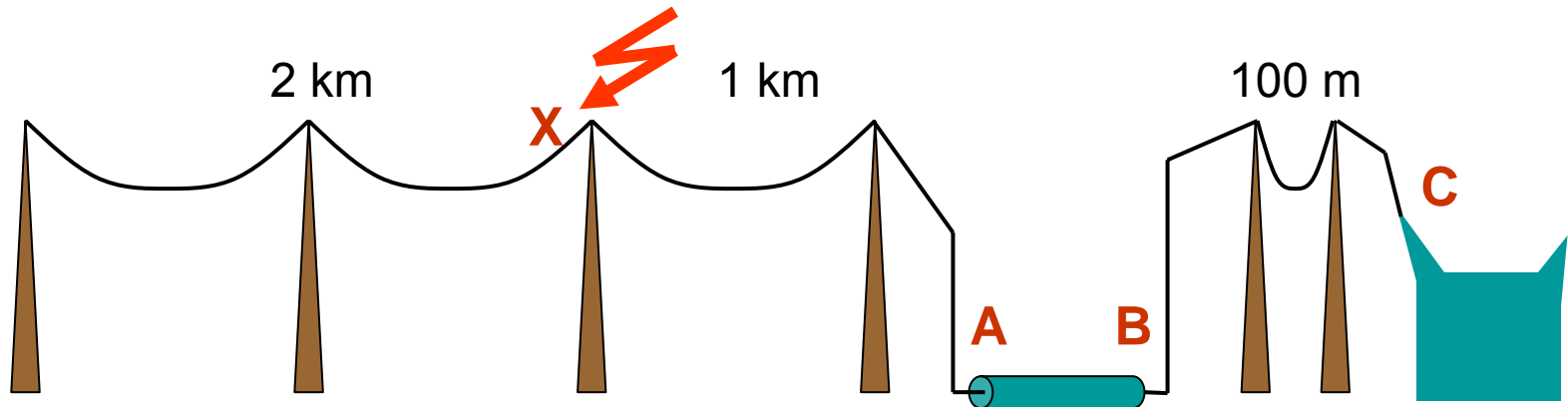
Changing the superstructure later is not possible, and even relocation of antennas may cause major problems (costs).



Simulation Results

- Active coupling between HF Antennas
- HF – VHF antenna coupling
- Field strength on selected top-deck areas
- Field strength in mast area
- Antenna input impedances
- Radiation patterns

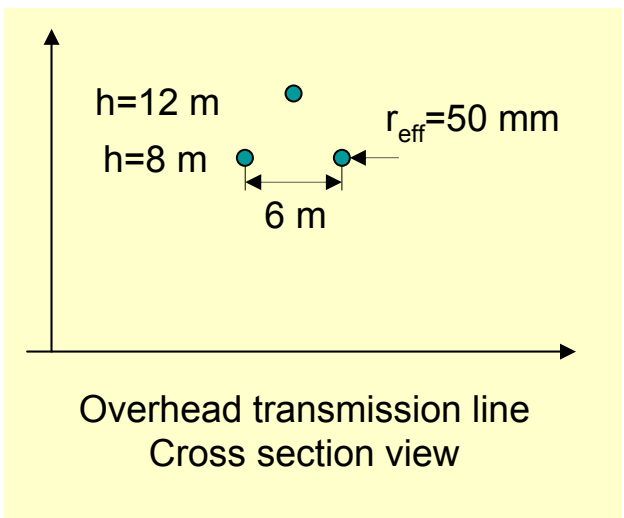
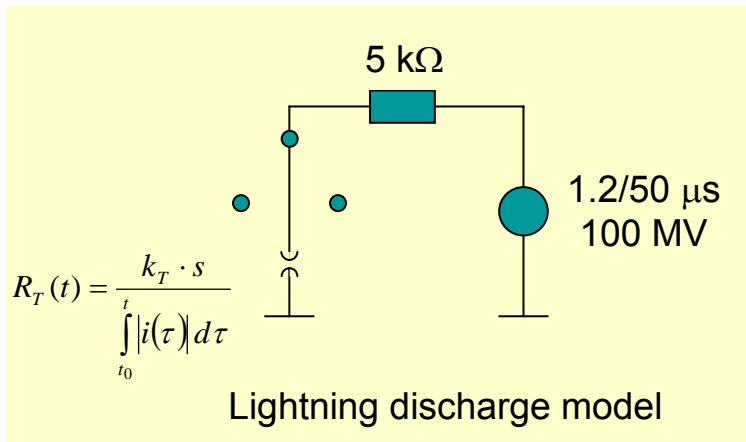
Example: No Control Over Parameters



3-phase overhead transmission line

3 x 1-phase cable
100 Ohm
Length: 200 m (1 μ s)

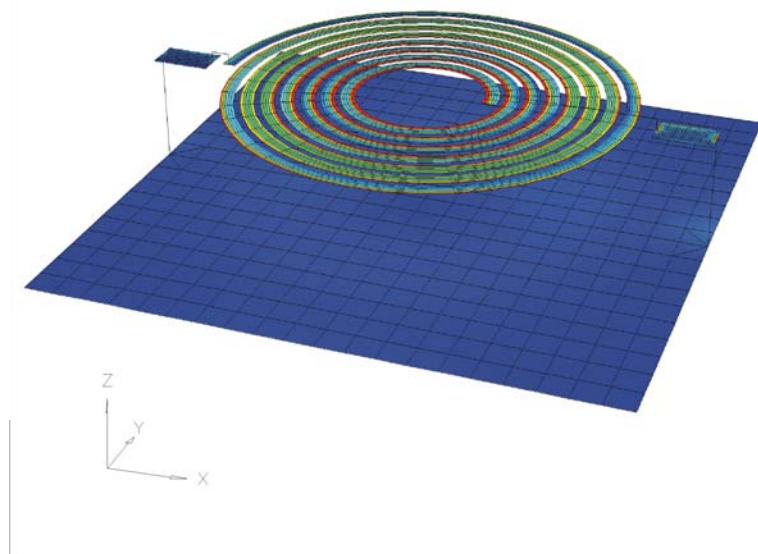
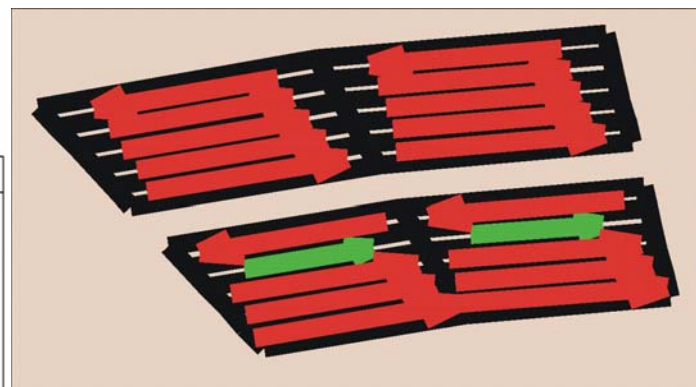
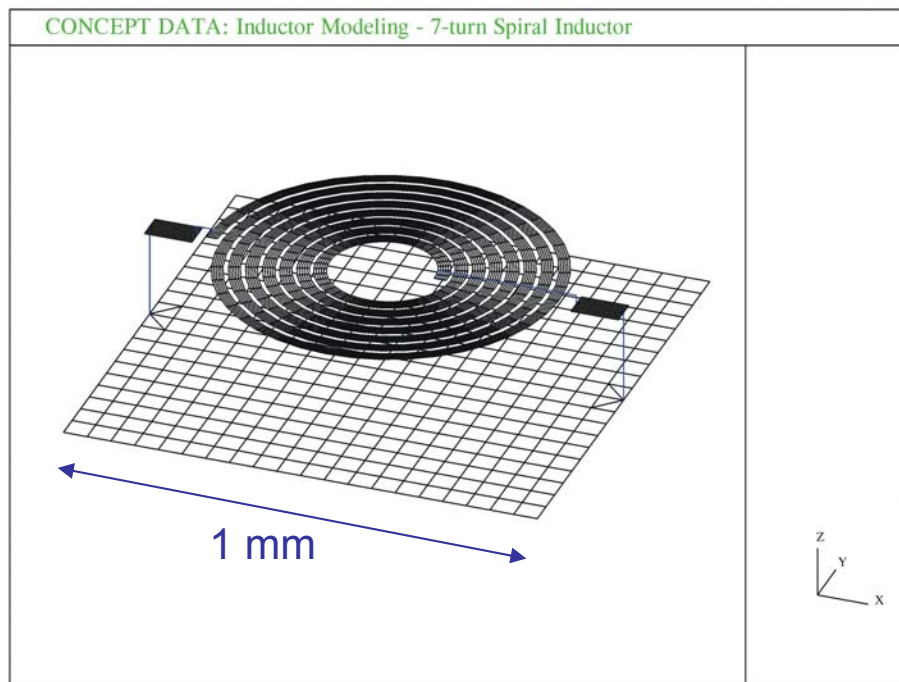
Transformer:
1 nF phase-ground
3 nF phase-phase



The cables A-B and the Transformer C have to be protected against lightning:

- Where to place a surge arrester, at A, B, C, or everywhere?
- What type of surge arrester should be used?

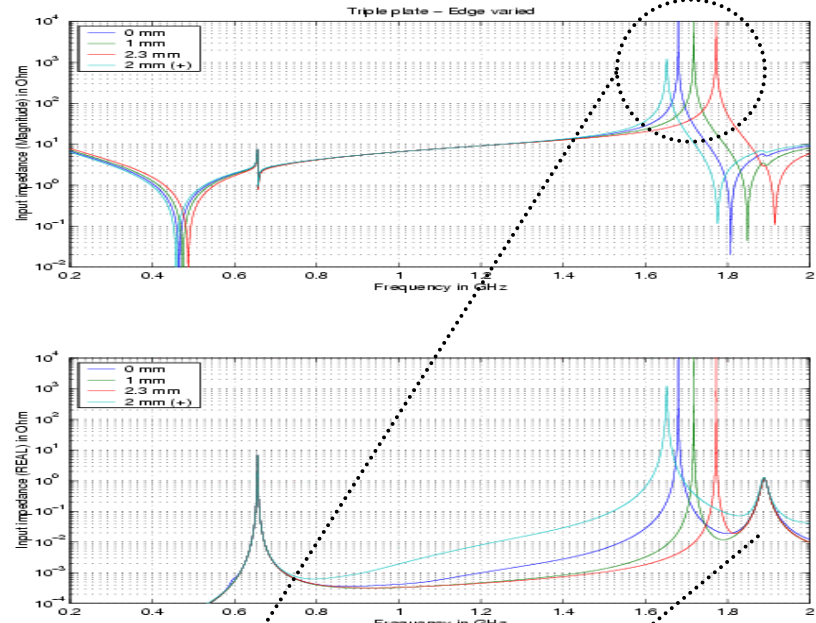
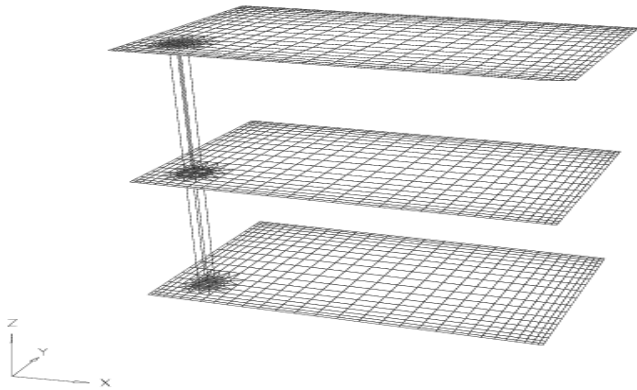
Example: Prototype expensive to manufacture and measurements not possible without interfering with the model



- Inductance value of spiral inductor
- Current flow on trace
- Magnetic field distribution around inductor

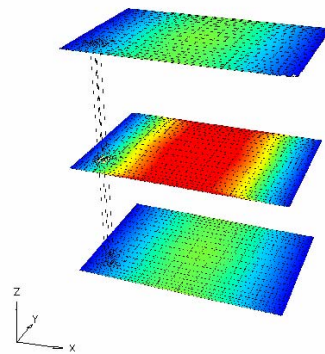
Example: Measurement results are difficult to interpret

CONCEPT-Data: Triple Plate Configuration

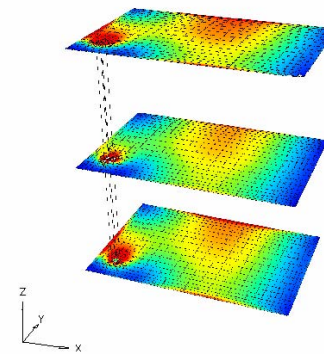


Triple plate configuration:
One resonance (1.68 GHz)
changes with size of centre
plane, the other (1.89 GHz)
doesn't. Why?

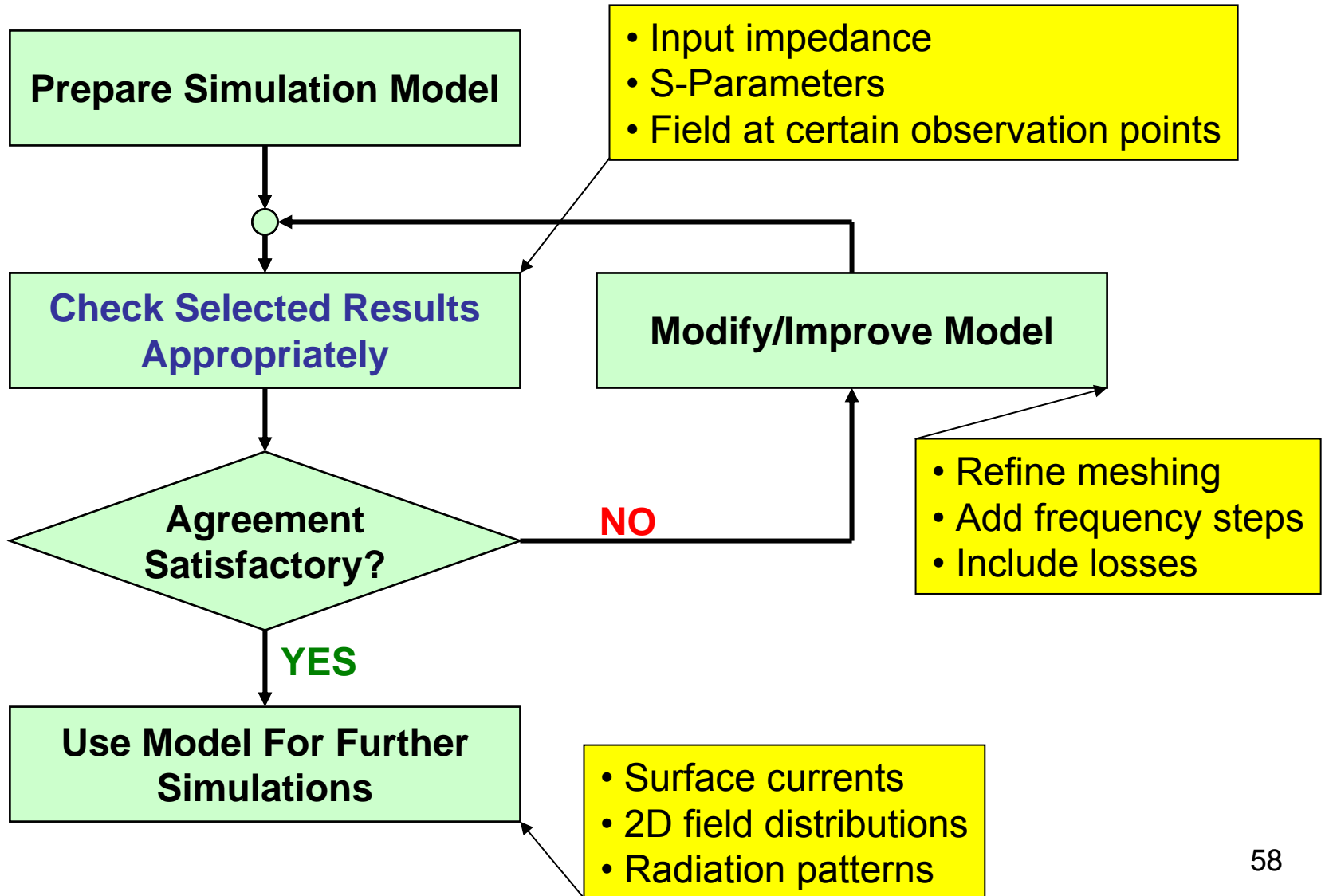
CONCEPT-Data: Current density - 1.68 GHz



CONCEPT-Data: Current density - 1.89 GHz

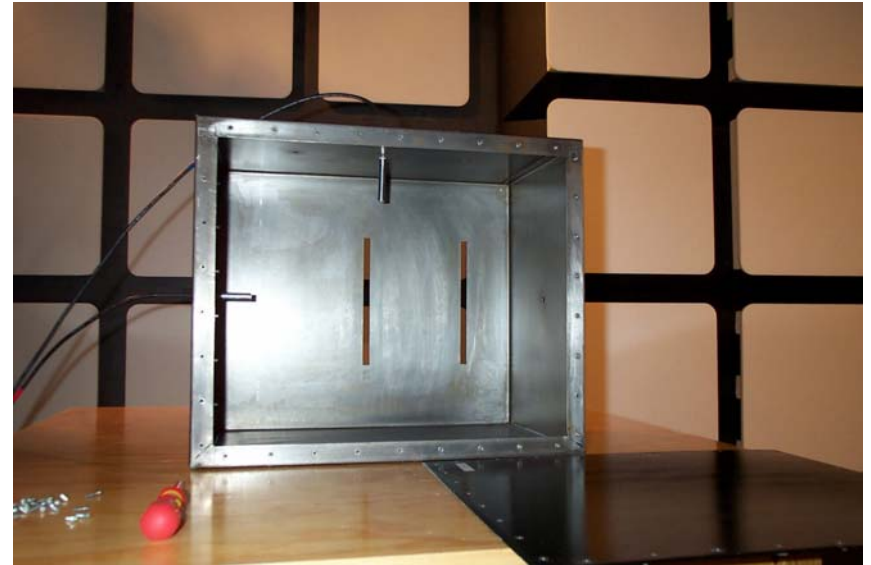
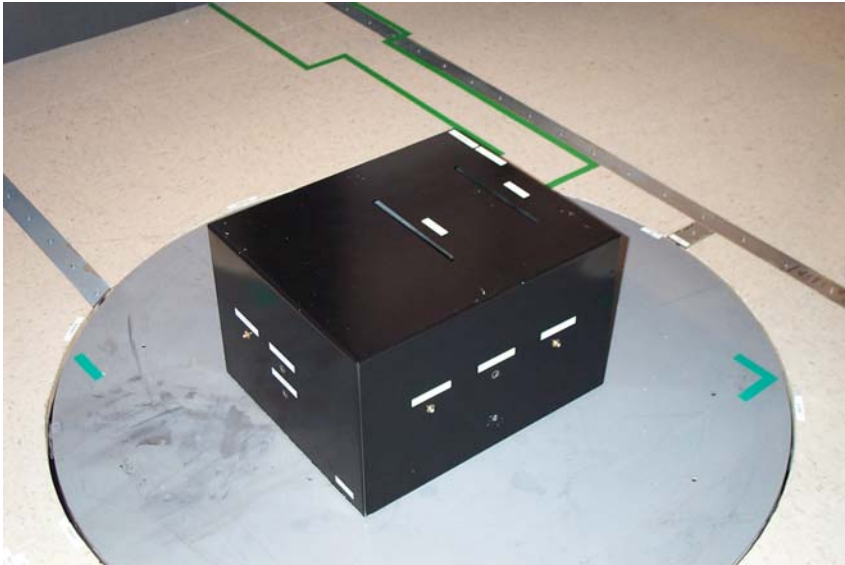


Simulation Procedure



Simulation Procedure

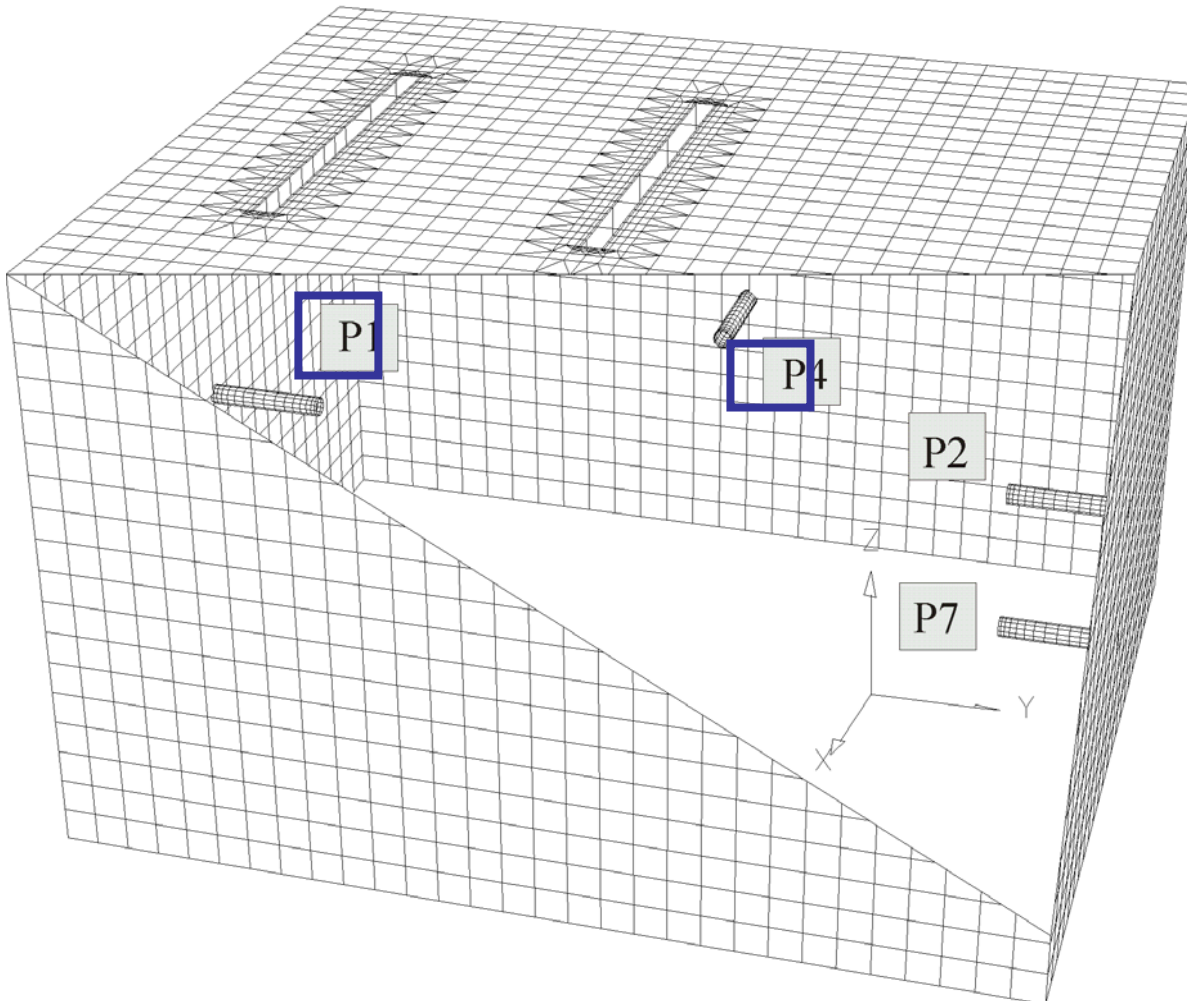
Generic Model – Empty Metal Box With Slots



- Pronounced resonance effects
- Electrically large openings
- Dimensions: 0.48m X 0.40m X 0.30m
- Interesting frequency Range: 2 GHz

Simulation Procedure

CONCEPT-Data: NED - Antennas at: P1, P2, P4, P7



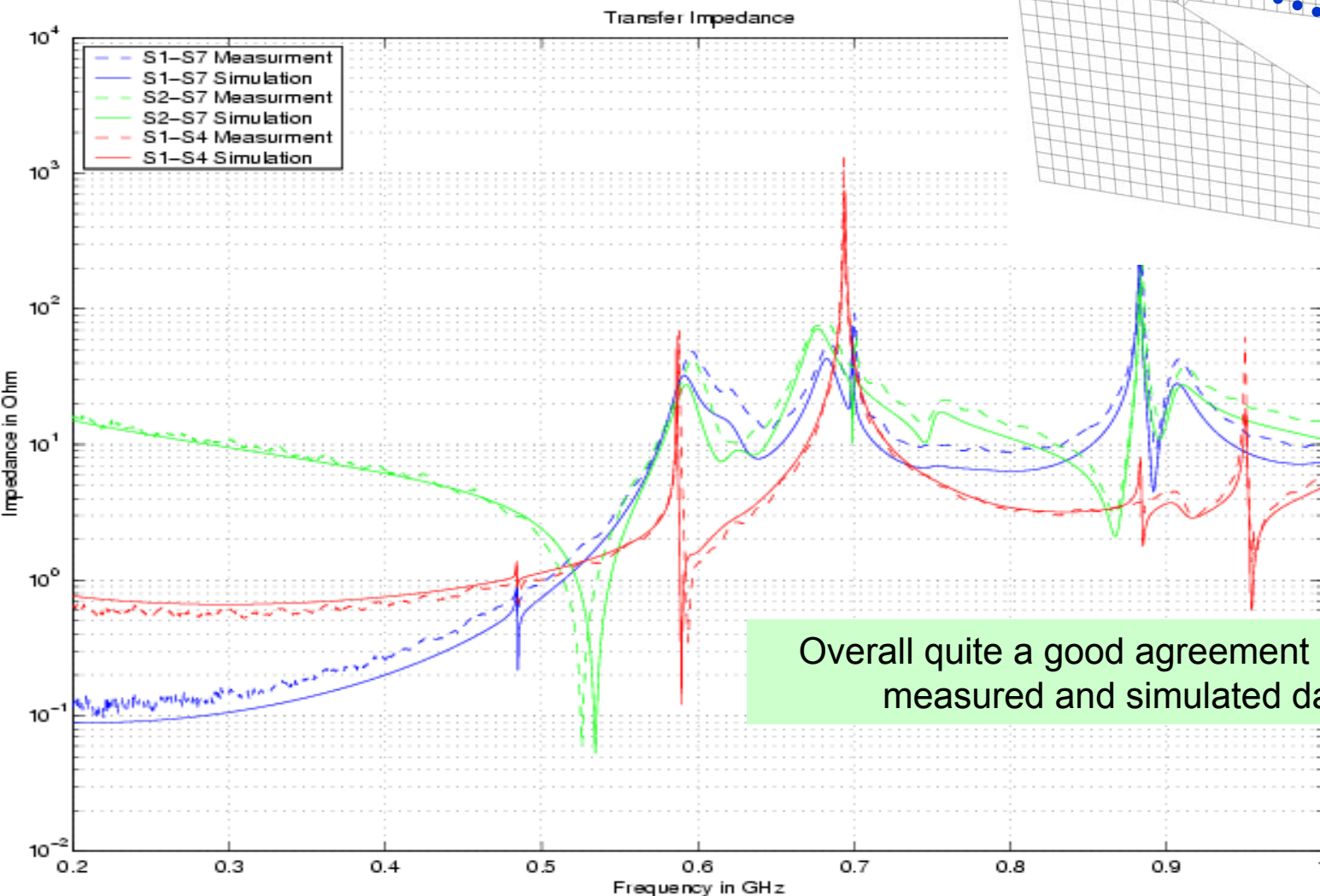
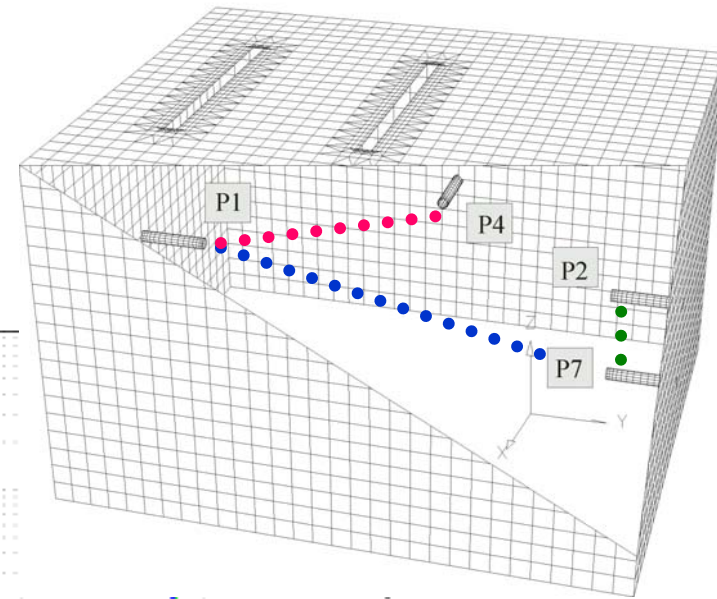
Input impedance

Indicator for relationship between electric and magnetic field and feeding/load current and voltage.

Transfer impedance

Indicator for relationship between electric and magnetic fields at both antenna positions.

Simulation Procedure

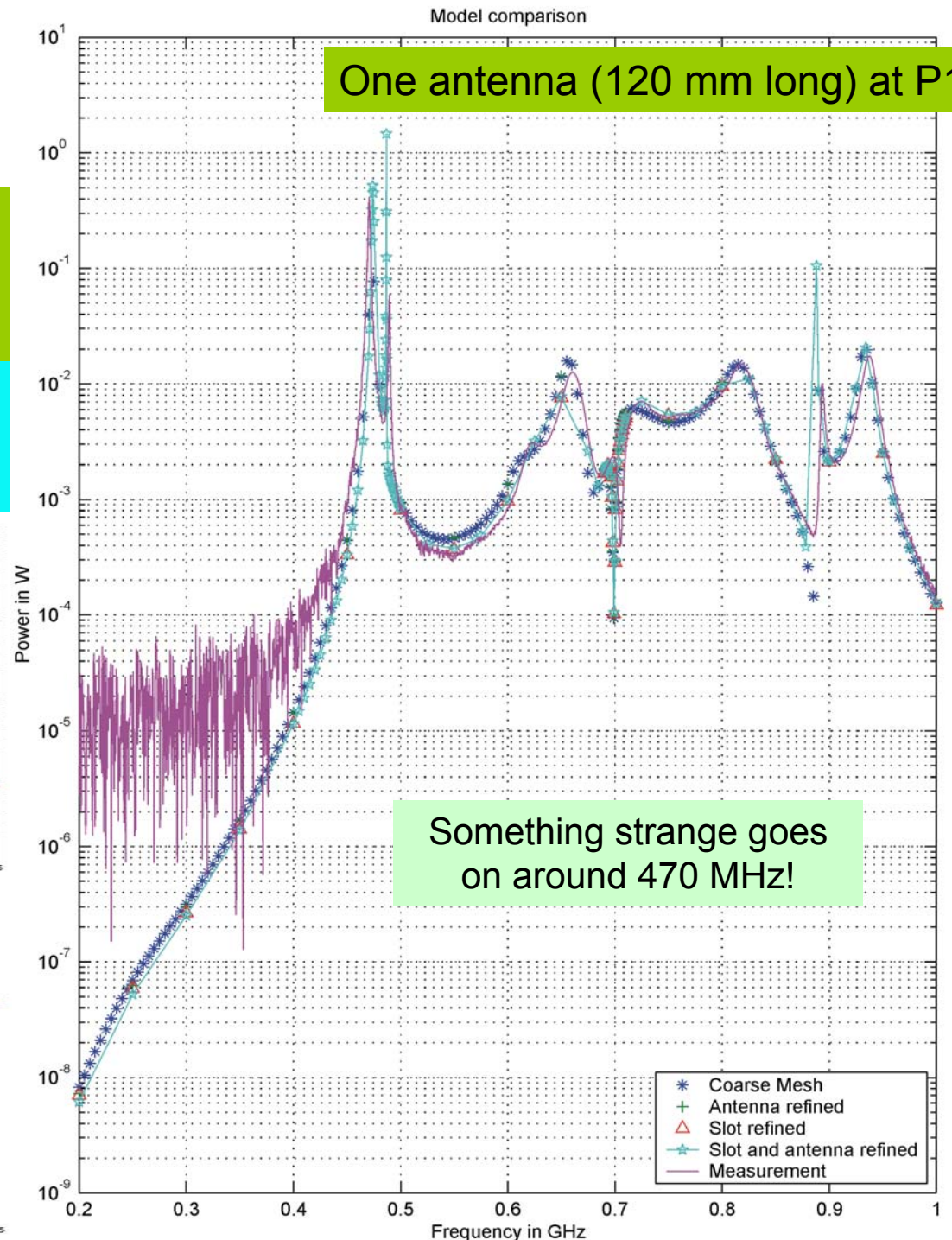
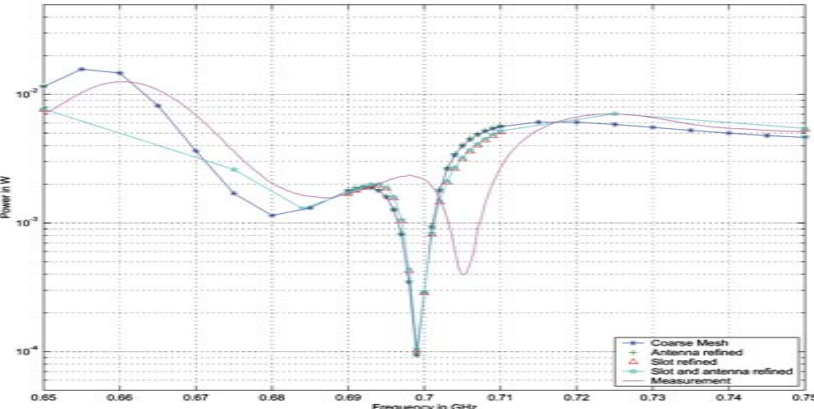
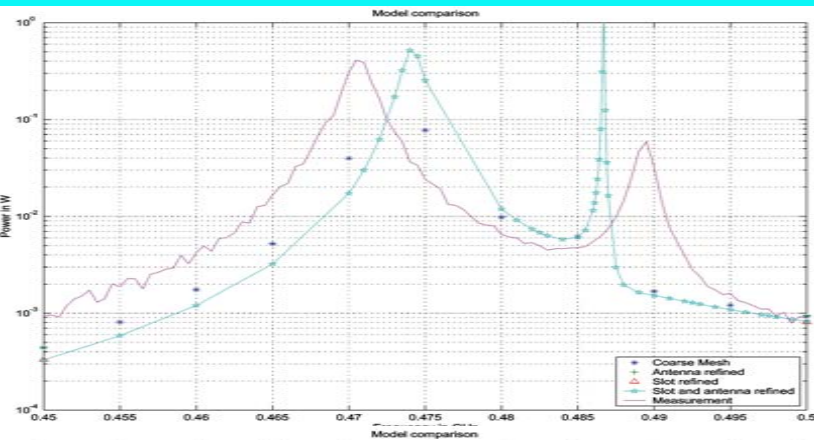


Overall quite a good agreement between measured and simulated data.

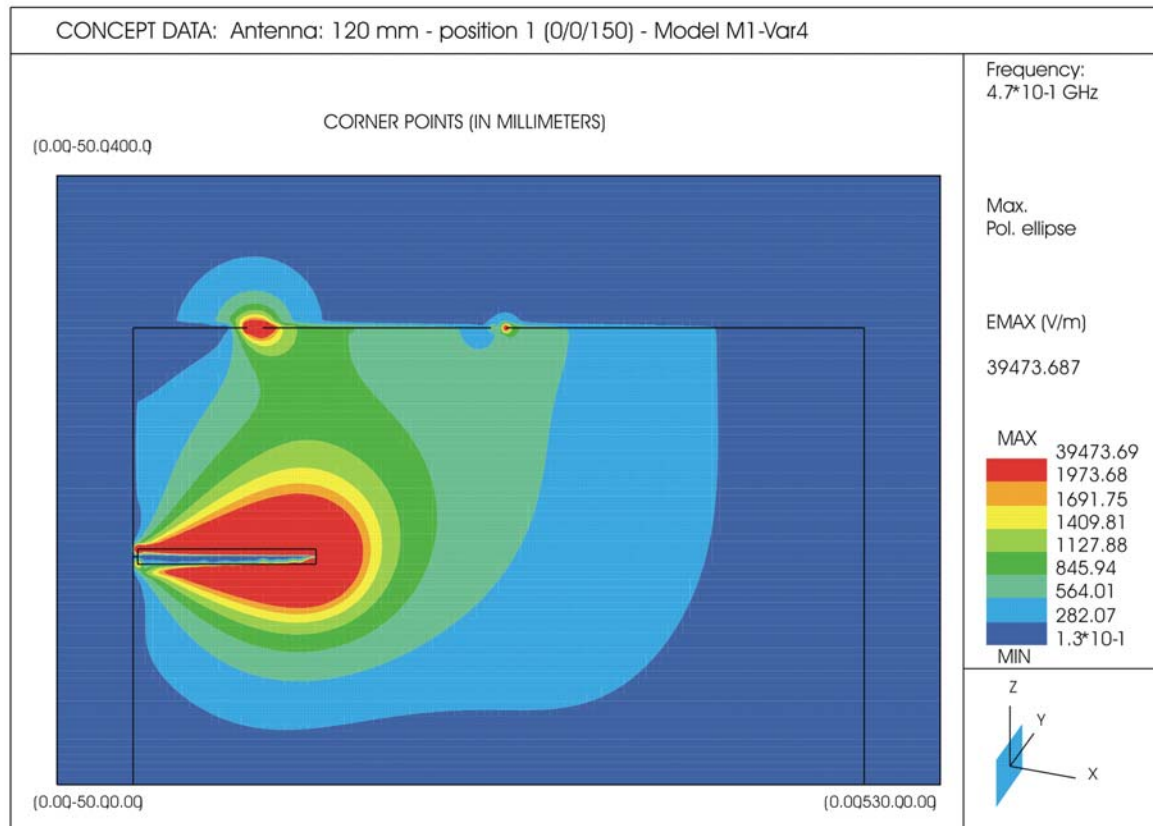
Power Budget

Measured Input Power
Simulated Radiated Power

$$\frac{p_{input}}{1W} = \frac{V}{1V} \cdot \frac{\text{Re}\{Z_{input}\}}{|Z_{input}|^2} \quad Z_{input} = Z_0 \cdot \frac{1+S_{11}}{1-S_{11}}$$

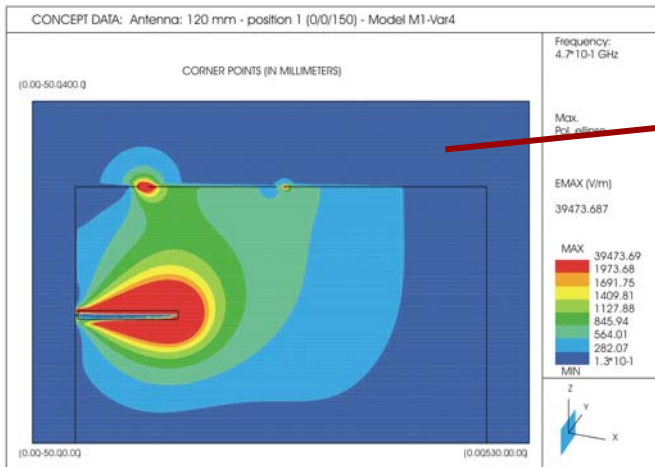


Simulation Procedure



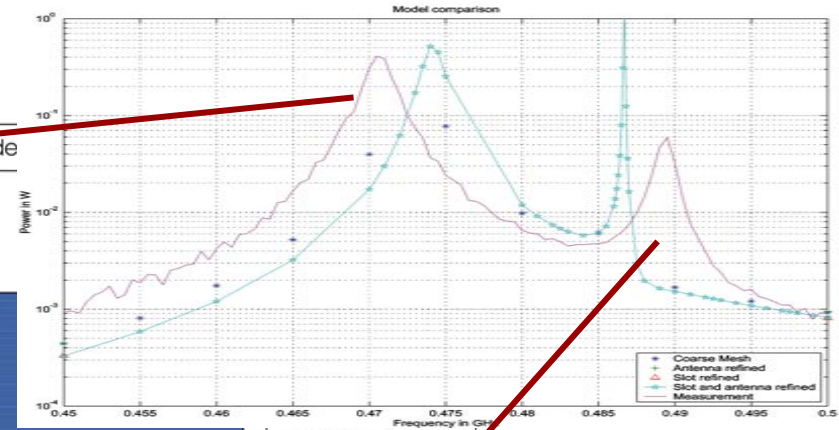
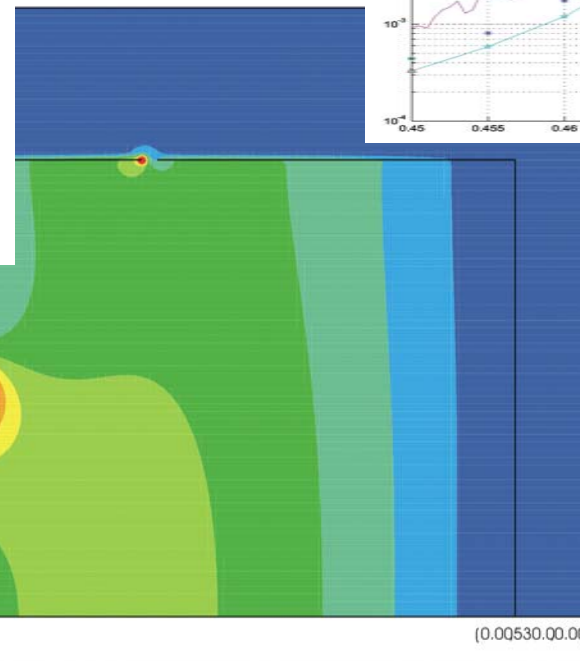
470 MHz: High field strength around slots leads to significant radiation – this is the dominant loss mechanism and modeling the box as perfect conductor is perfectly fine.

Simulation Procedure



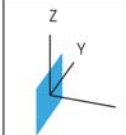
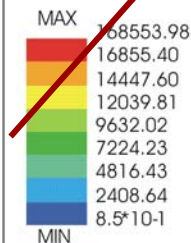
120 mm - position 1 (0/0/150) - Mode

CORNER POINTS (IN MILLIMETERS)



EMAX (V/m)

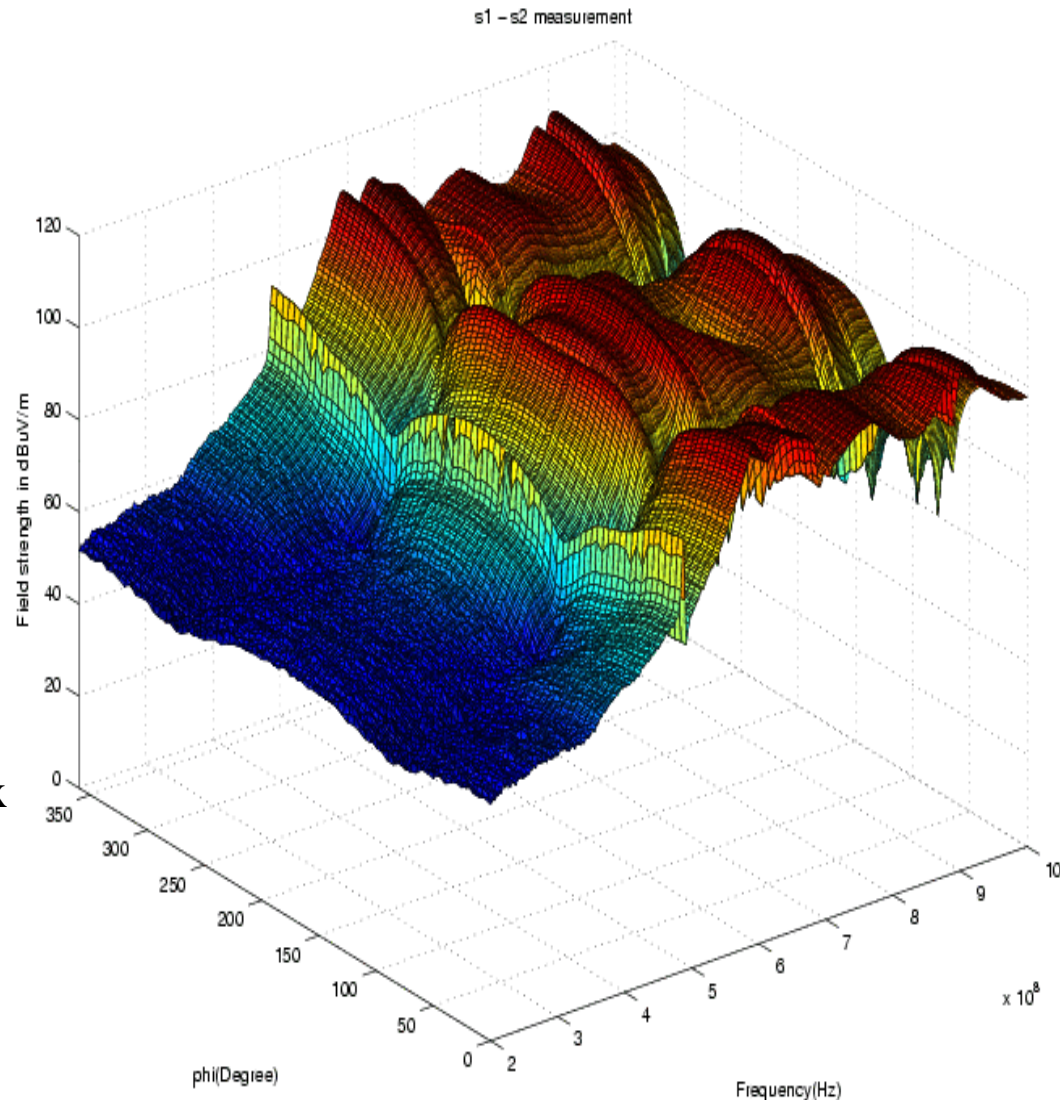
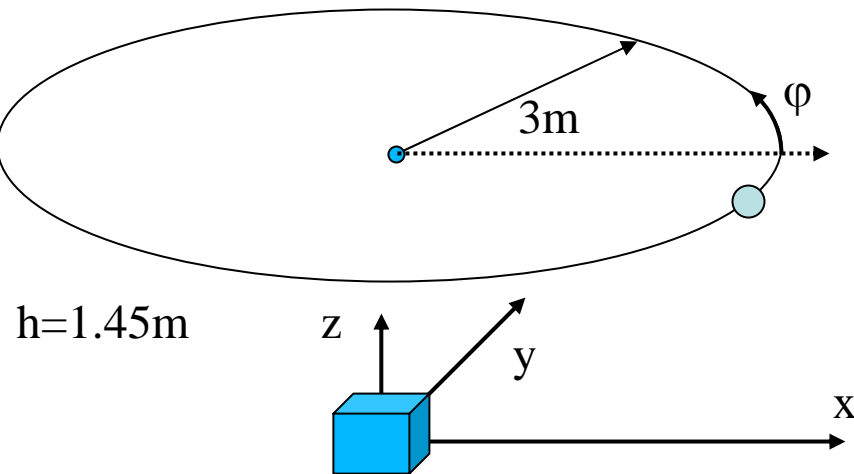
168553.984



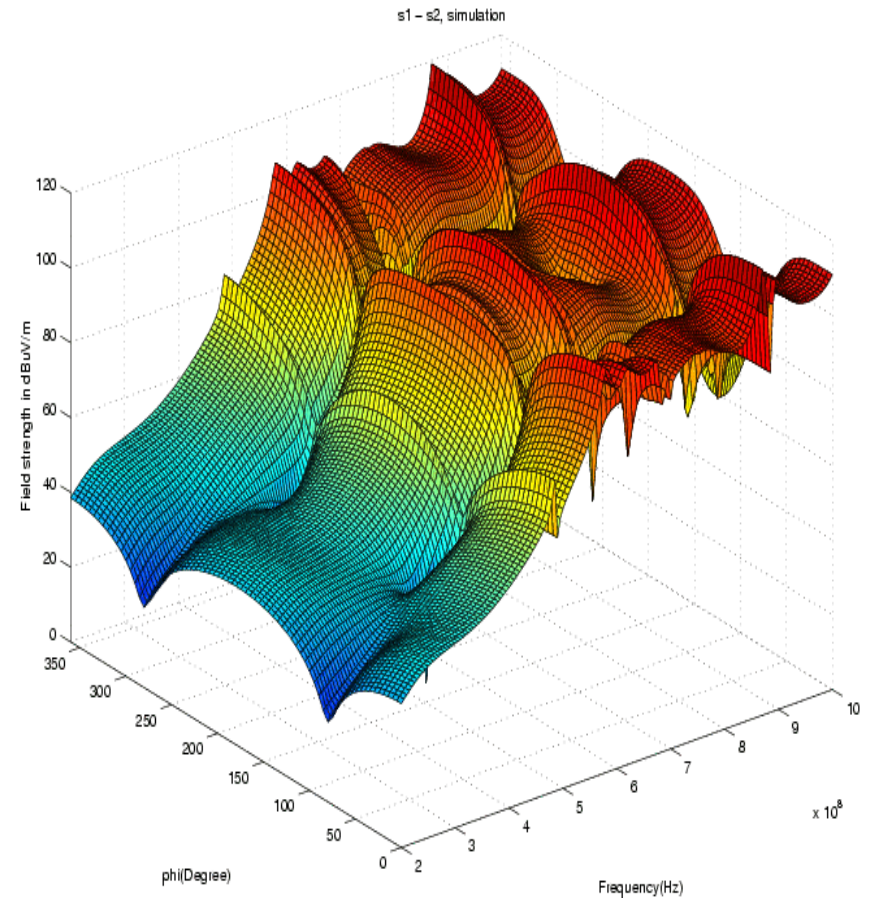
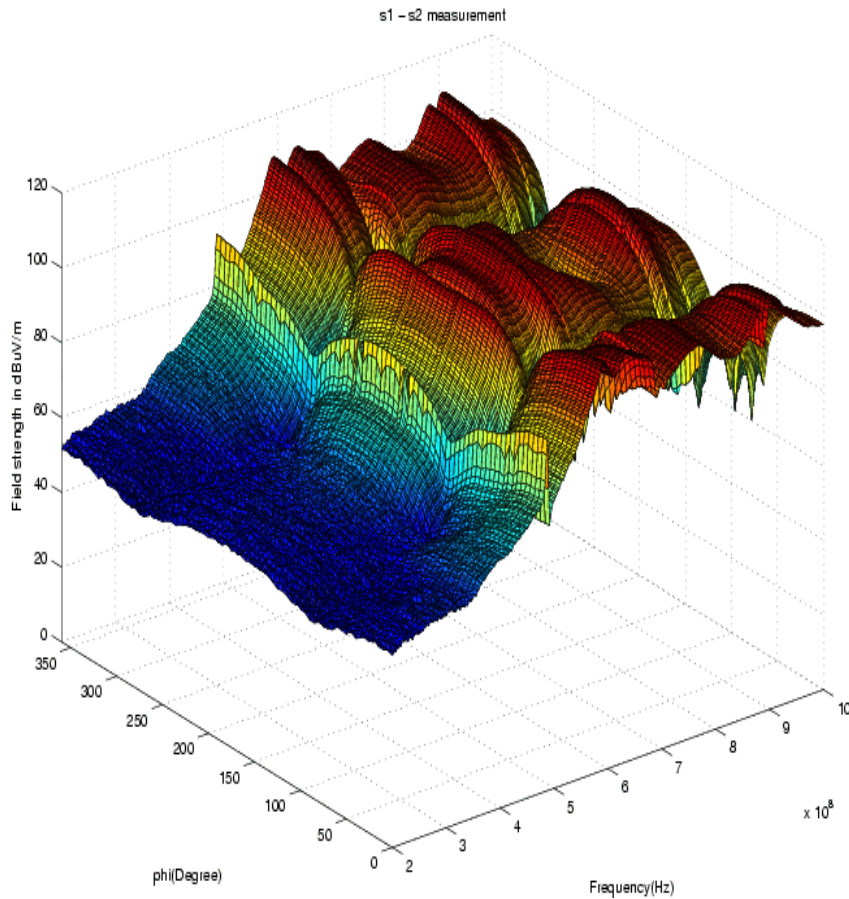
490 MHz: Low field strength around slots means little radiation – the dominant loss mechanism is now due to the finite conductivity of walls and is neglected in the model (note: finer meshing does NOT solve this problem!)

Simulation Procedure

Electric field strength
Vertical polarisation
Height: $h=1.45\text{m}$
Horizontal distance: 3m



Simulation Procedure



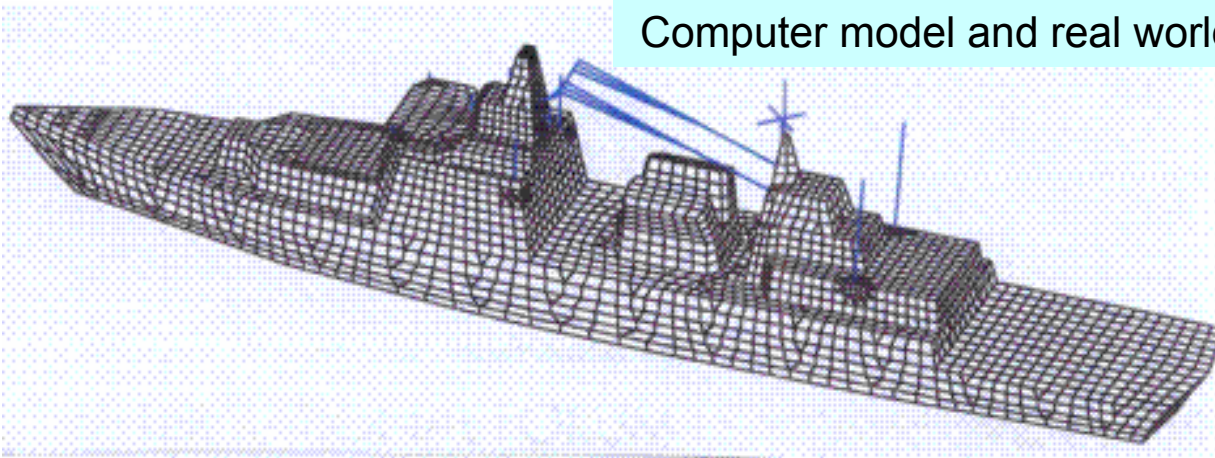
Now we have validated the model and can start the simulation in earnest!

Simulation Procedure

- Modelling and pre-processing
- Meshing
- Calculation
- Validation of results
- Post-processing

Modeling

Computer model and real world structure of German frigate.



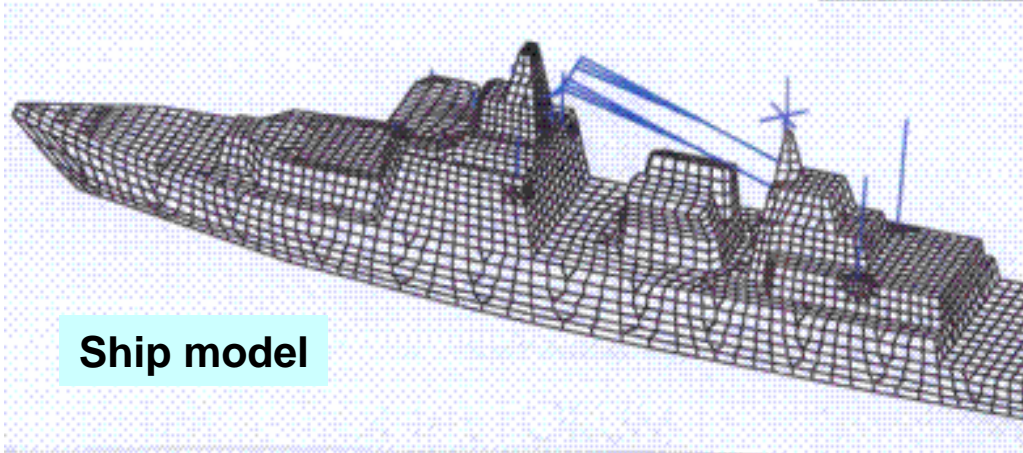
Total surface area: $A \cong 5000 \text{ m}^2$
Wavelength at 30 MHz: $\lambda = 10 \text{ m}$
Segments per λ : $n > 8$
Number of patches: $N > A/(\lambda/n)^2 = 3200$

- Some patches at corners and around feeding areas of antennas have to be significantly smaller.
- Wire segments for the antennas have to be added.
- Using rectangular patches there are about 2 unknowns per patch.

Estimated number of unknowns: $K \cong 10,000$
Memory requirements (MoM): $\text{Mem} = 16 \cdot K^2 = 1.6 \text{ GB}$

Modeling

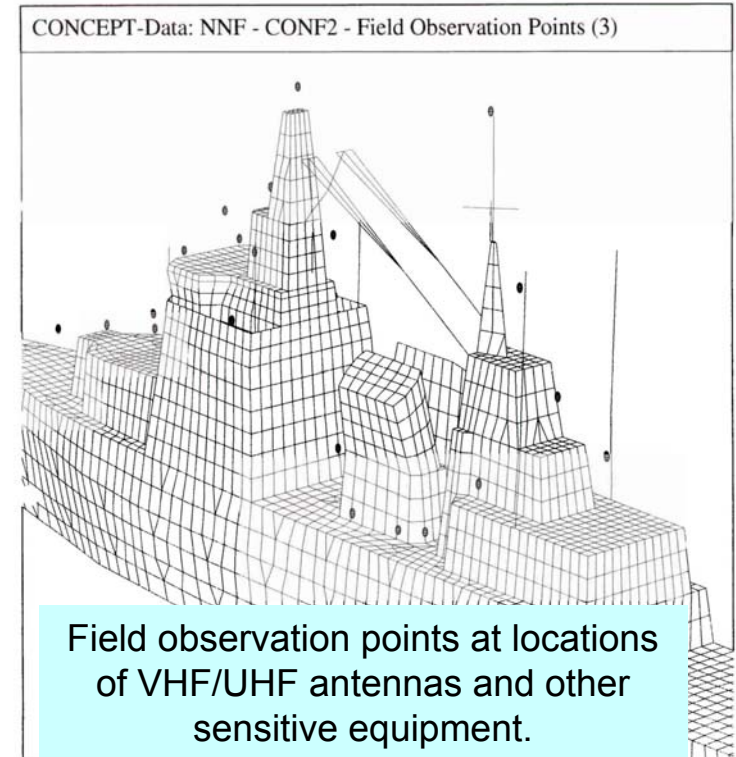
Example: HF Antenna System Simulation



Ship model

Sea modelled as perfect ground plane:

- Acceptable for antenna input impedances and antenna-to-antenna coupling;
- Critical for precise propagation analysis close to the sea surface.



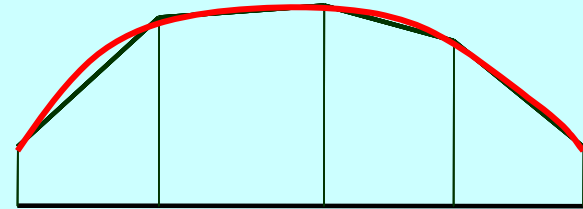
Field observation points at locations of VHF/UHF antennas and other sensitive equipment.

Mixing large patches on flat surface areas and tiny VHF and UHF antennas can cause numerical stability problems. Therefore a two-step approach is used to calculate the impact of HF antennas on small objects: electric and magnetic fields are calculated at appropriate observation points (neglecting the sink); then the impact of these fields is investigated. An eventual field distortion due to mounting structures is taken into account in the second step.

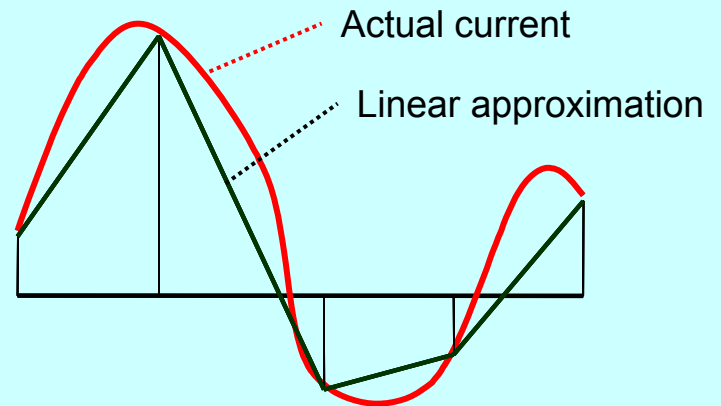
Meshing

- Most numerical field simulation methods, e.g. Finite Elements, Finite Differences, or Method of Moments, are based on meshing of the structure.
- This implies that basic electromagnetic quantities, such as potentials, or line and surface currents, are described piecewise of simple functions (constant or linear for instance).
- In order to obtain correct results the approximation must represent the actual distribution 'reasonably' good.
- The following examples are based on Method of Moments simulations using CONCEPT II. This code uses linear basis functions for line and patch currents.
- Typical meshing requirements are:
 - 8-12 segments per wavelength for large, smooth surfaces;
 - Finer meshing around points where the current is distorted, e.g. small holes, wires over surfaces, edges, antenna feed points.

Smooth current distribution: Linear approximation fits quite well.

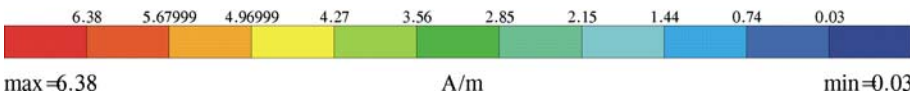
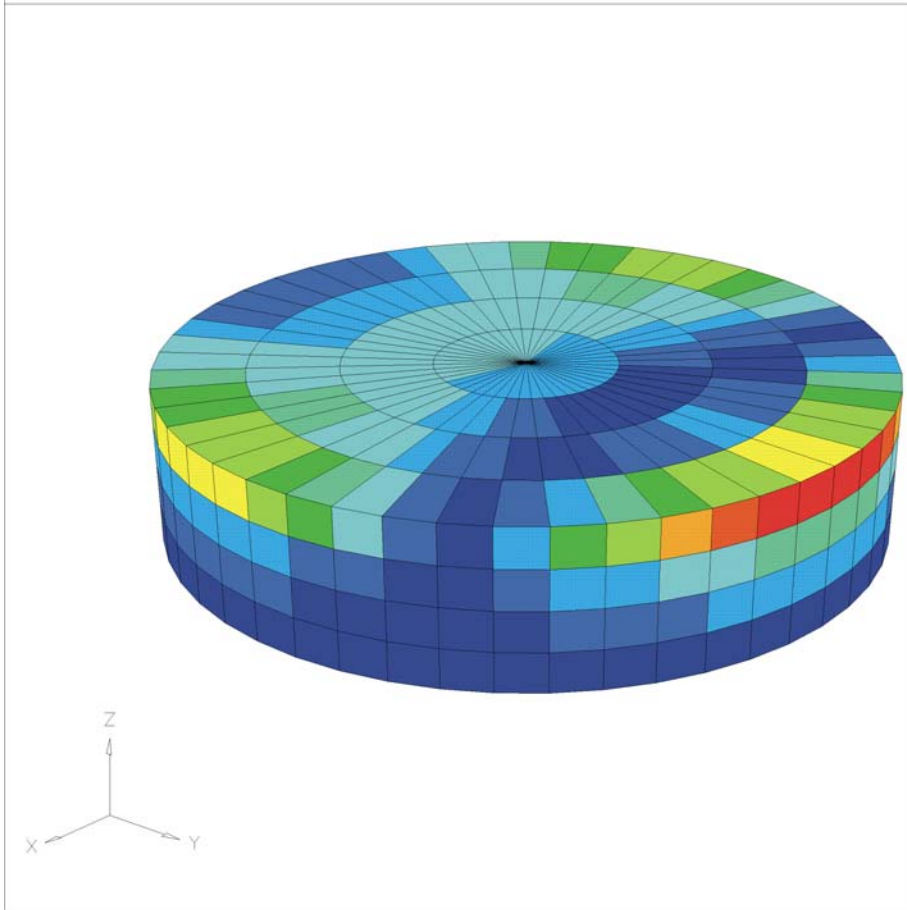


Rapid spatial variation of current: Finer segmentation (meshing) is required.

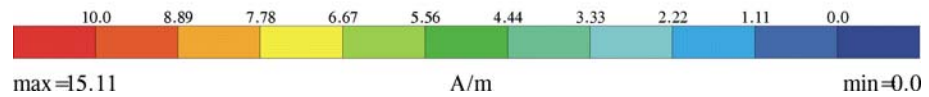
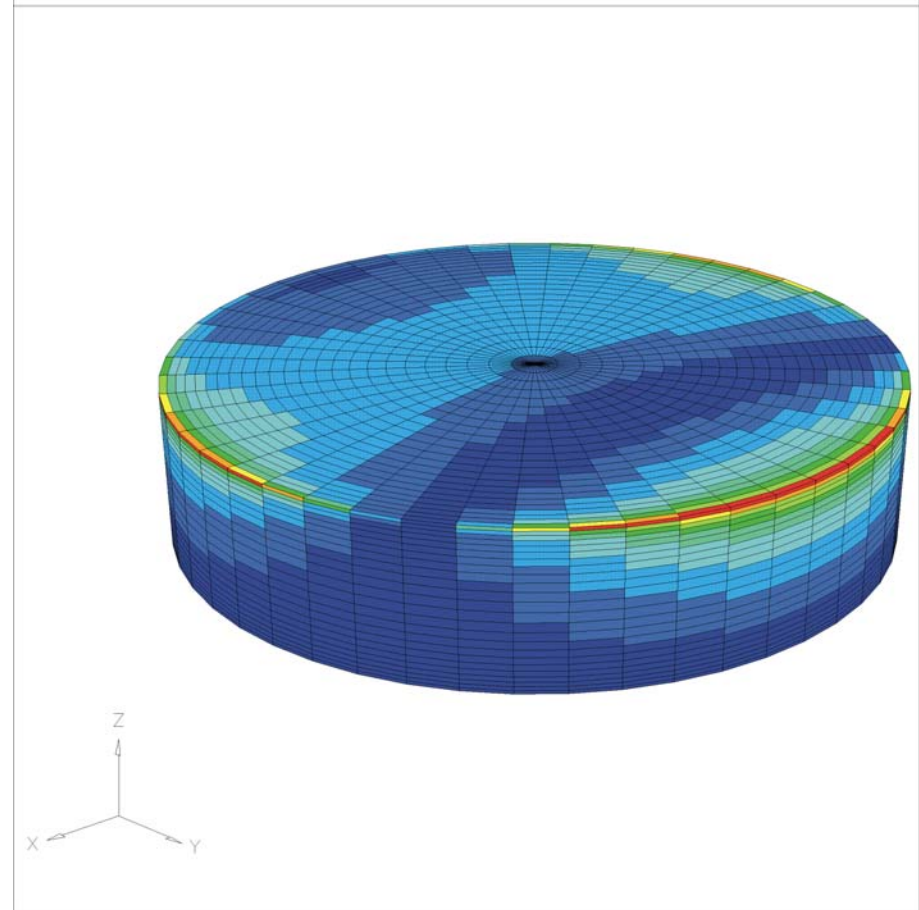


Current density on a 'pill box' with coarse and fine meshing

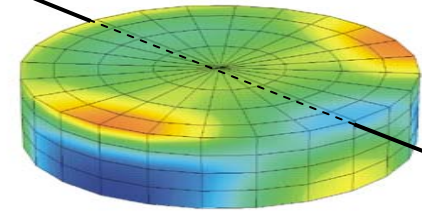
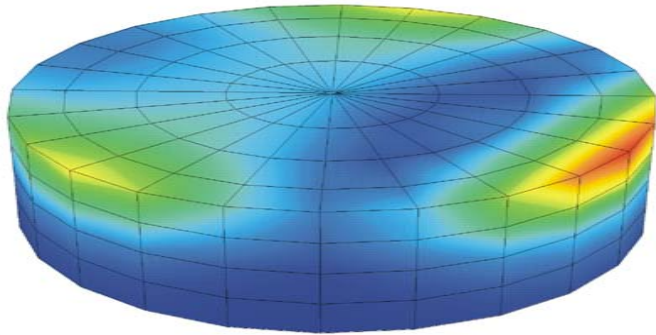
CONCEPT-Data:Electrical Charge Distribution - 500 MHz



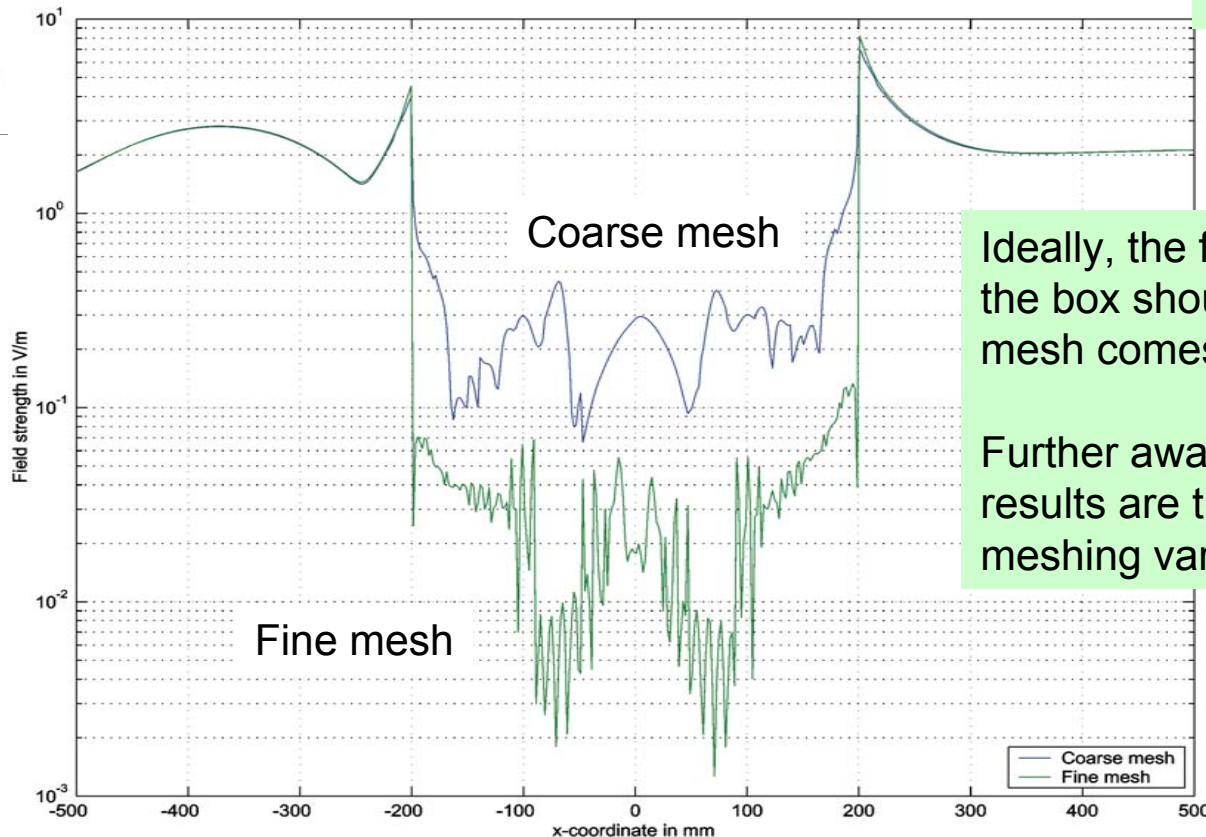
CONCEPT-Data:Electrical Charge Distribution - 500 MHz



Careful: Just because a program shows you a smooth current or charge distribution doesn't necessarily mean that the results are more accurate.



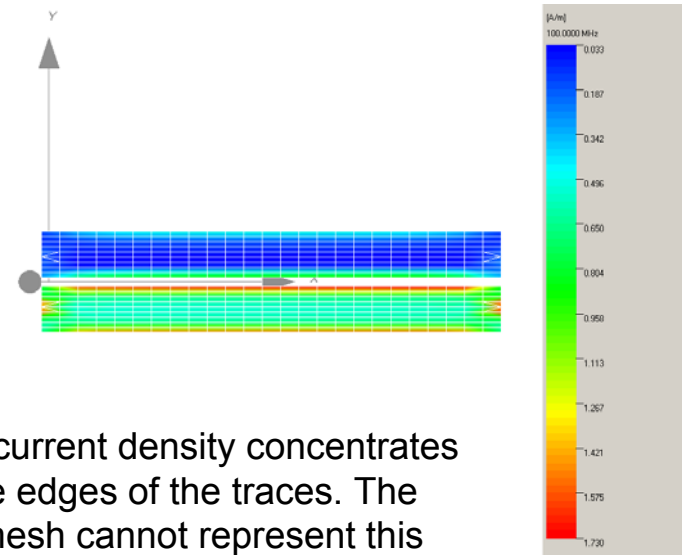
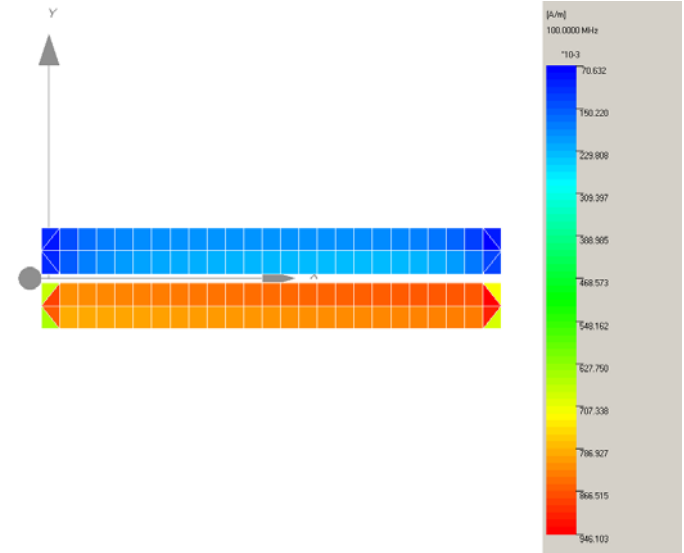
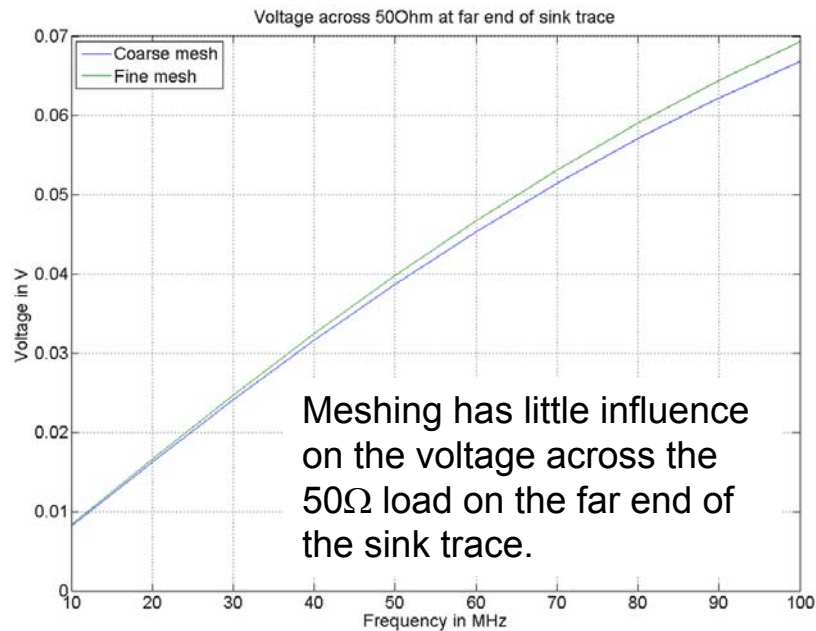
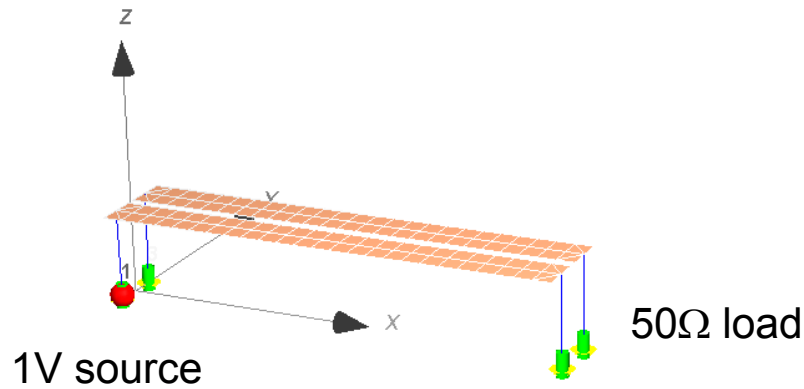
Field observation line just underneath the lid



Ideally, the field strength inside the box should be zero. The finer mesh comes closer to this result.

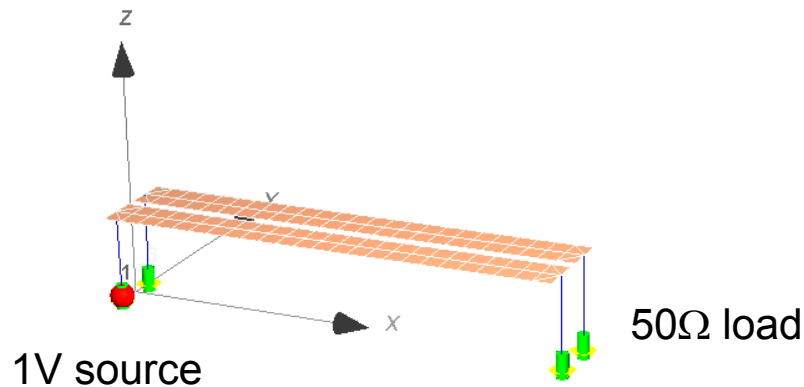
Further away from the box the results are the same for the two meshing variants.

Influence of meshing

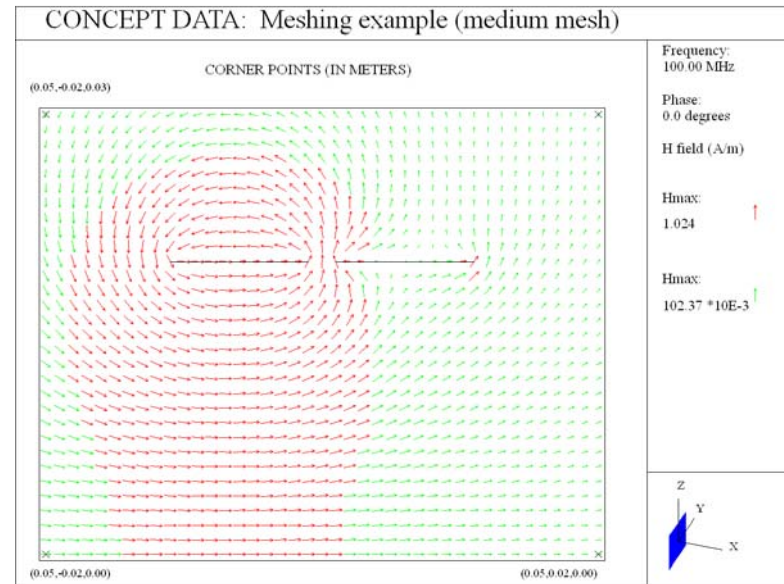
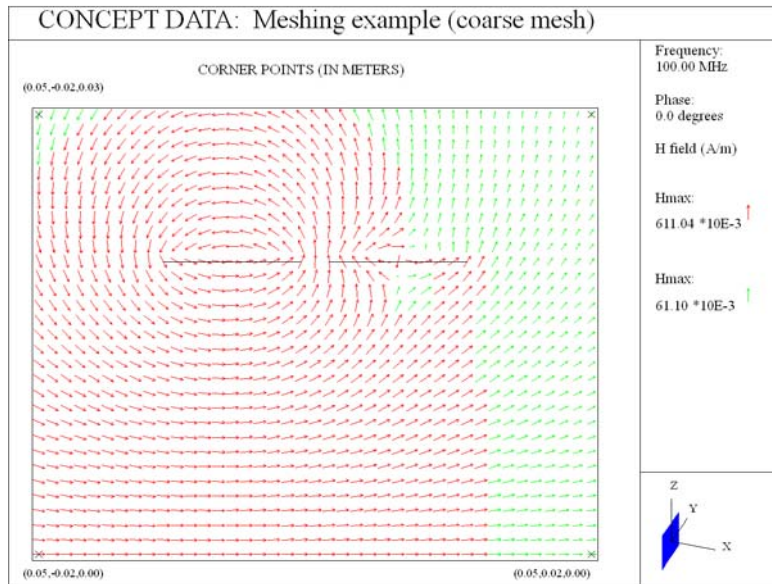


Surface current density concentrates along the edges of the traces. The coarse mesh cannot represent this behaviour.

Influence of meshing



The coarser mesh does not give the correct field strength values close to the traces. Distance of field observation points from a surface should be at least one patch dimension.

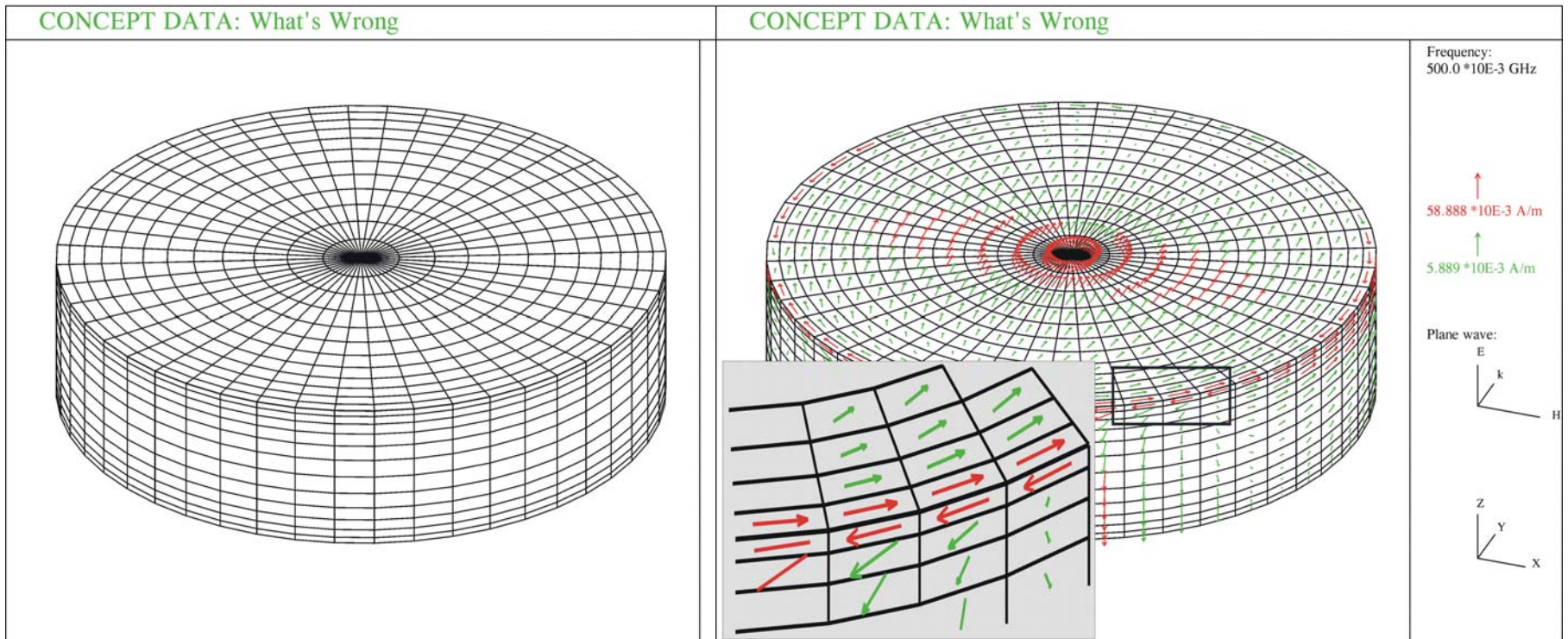


Meshing - summary

- What are the 'primary results' for the particular method (surface current, potential)?
- What are the implicit assumption for these results (typically constant or linear over one patch)?
- Can the mesh approximate the actual distribution with reasonable accuracy?
- For Method of Moment:
8 – 12 patches per wavelength along smooth surfaces
Finer mesh size around inhomogeneous parts such as feeding points, edges, small gaps etc.

Validation

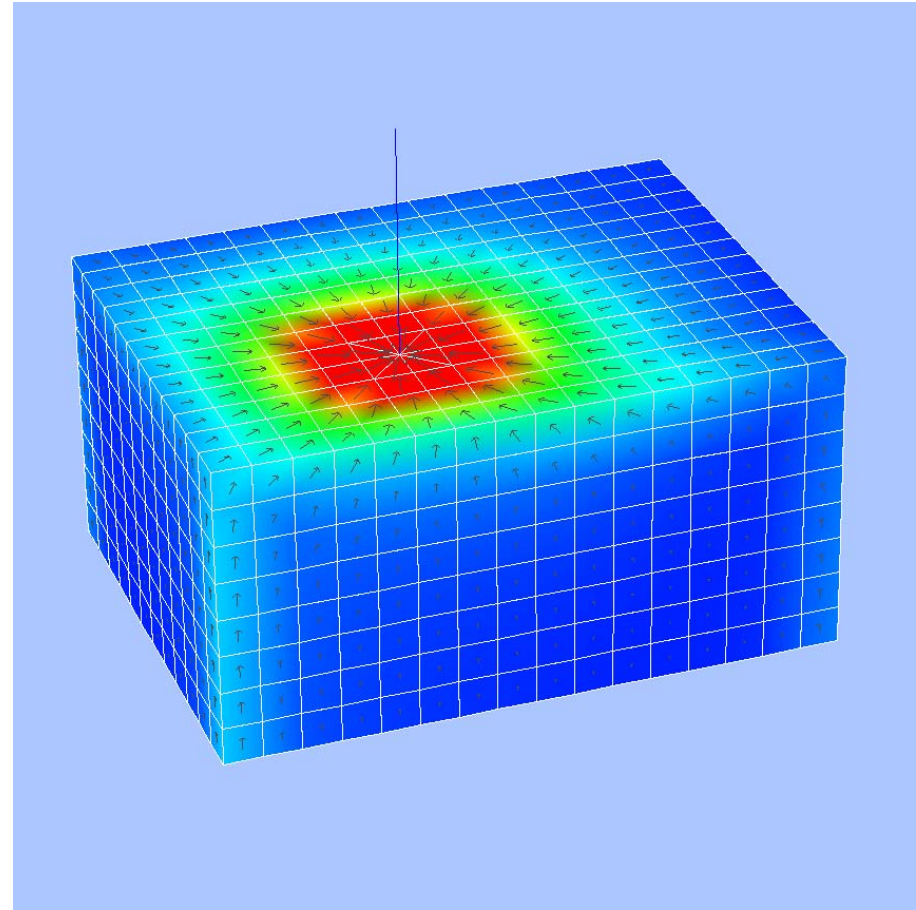
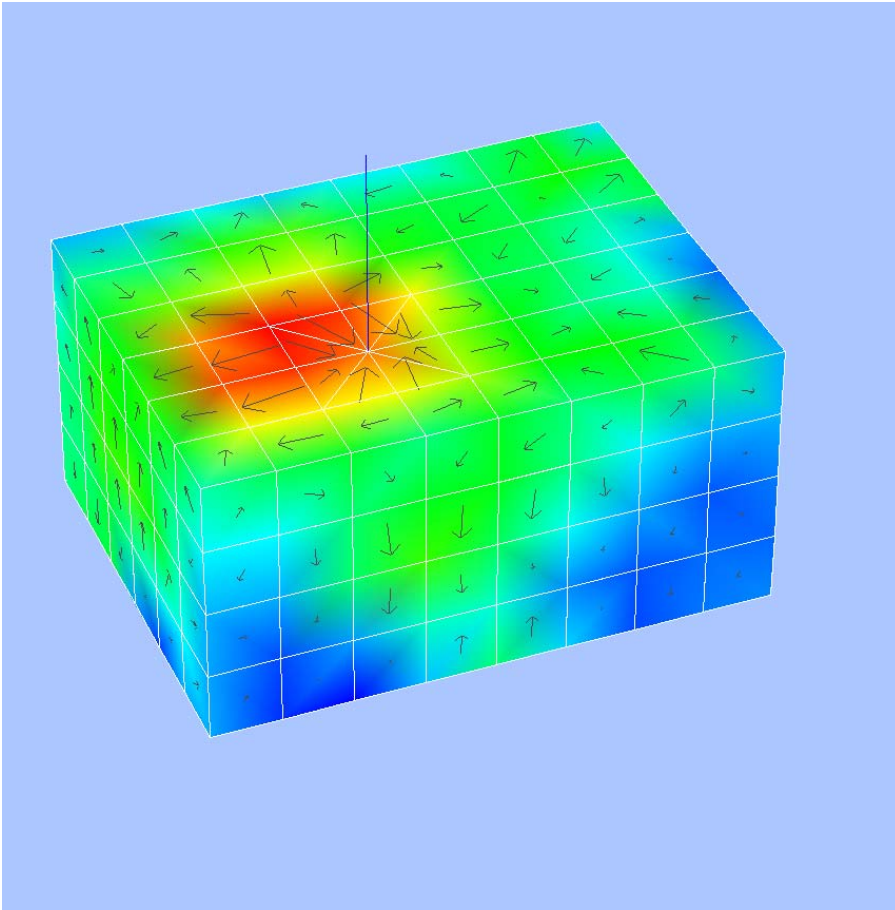
Sometimes, errors in input data are difficult to spot, and become obvious only after the simulation.



A simulation code might provide the option to test for nodes that are only a tiny bit apart, and suggest that they should actually be identical: but maybe they these nodes are really different? How could the program guess what the user wanted to simulate?

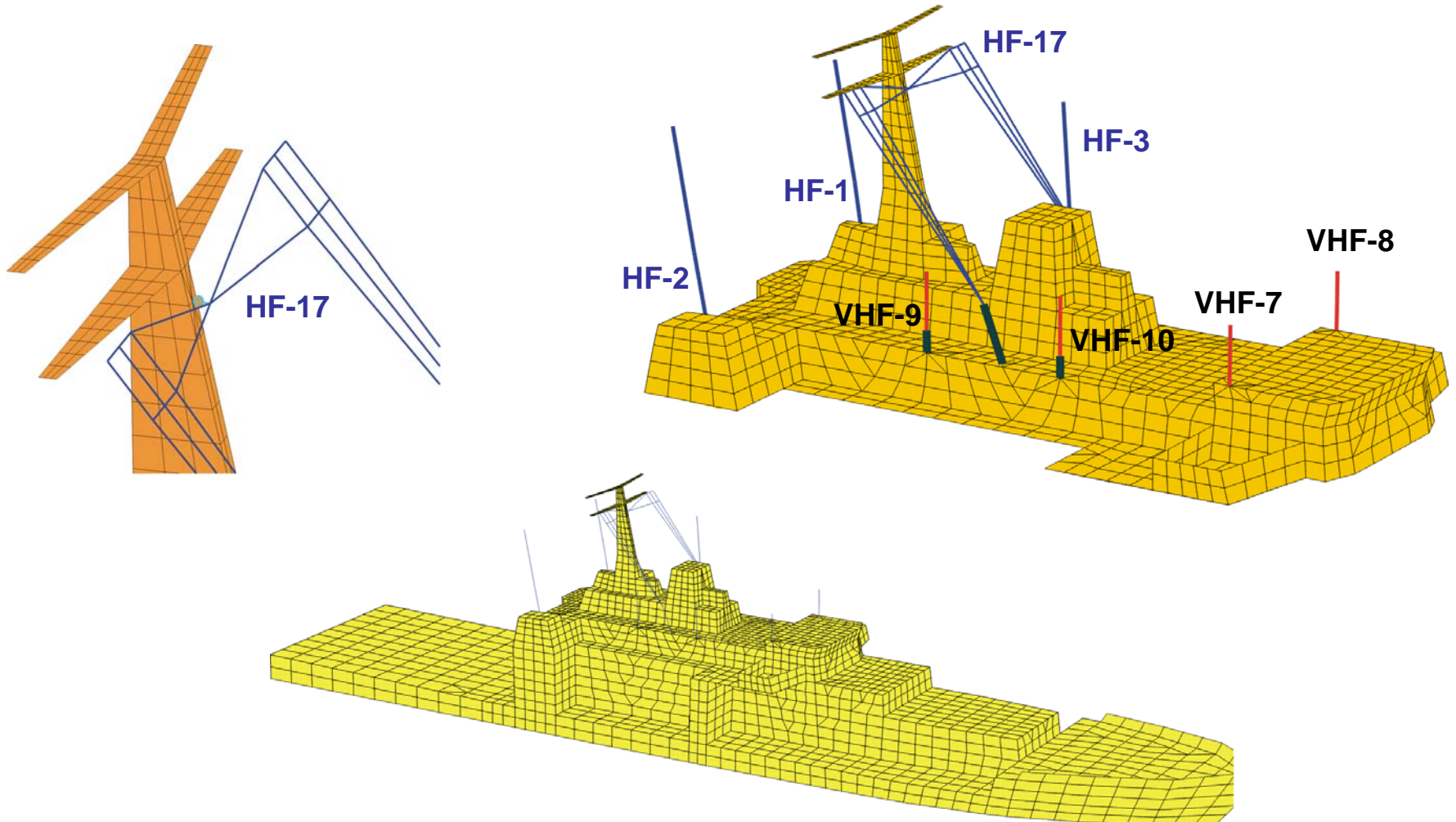
Validation

Surface current density (magnitude and direction)
for coarse and fine mesh

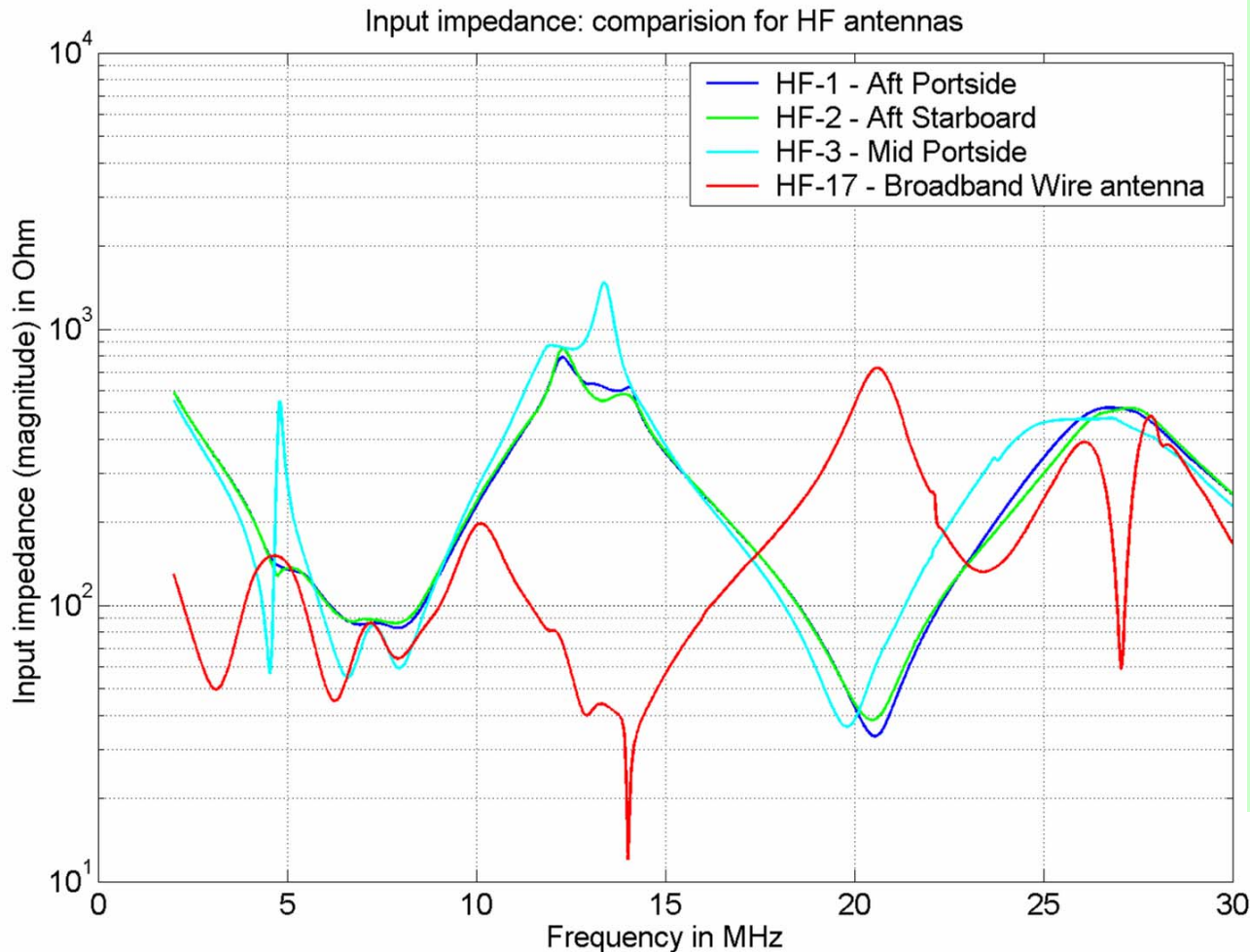


Example I – Top-Deck Antenna Arrangement

CONCEPT-Data: HF - Model

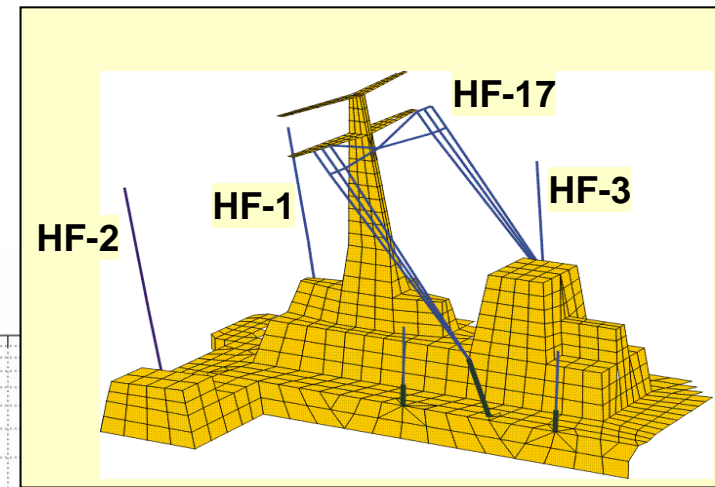
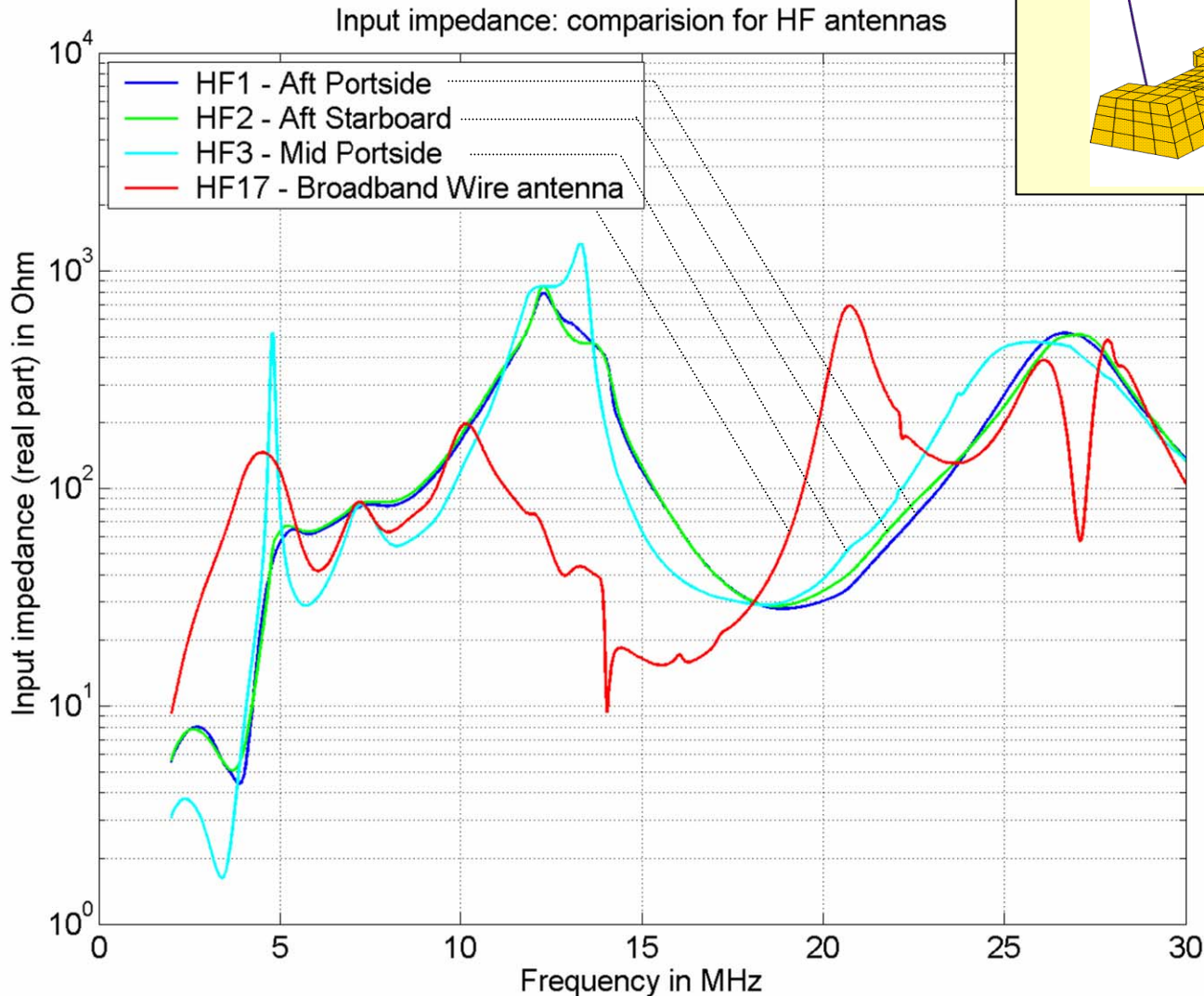


HF Antenna Input Impedance



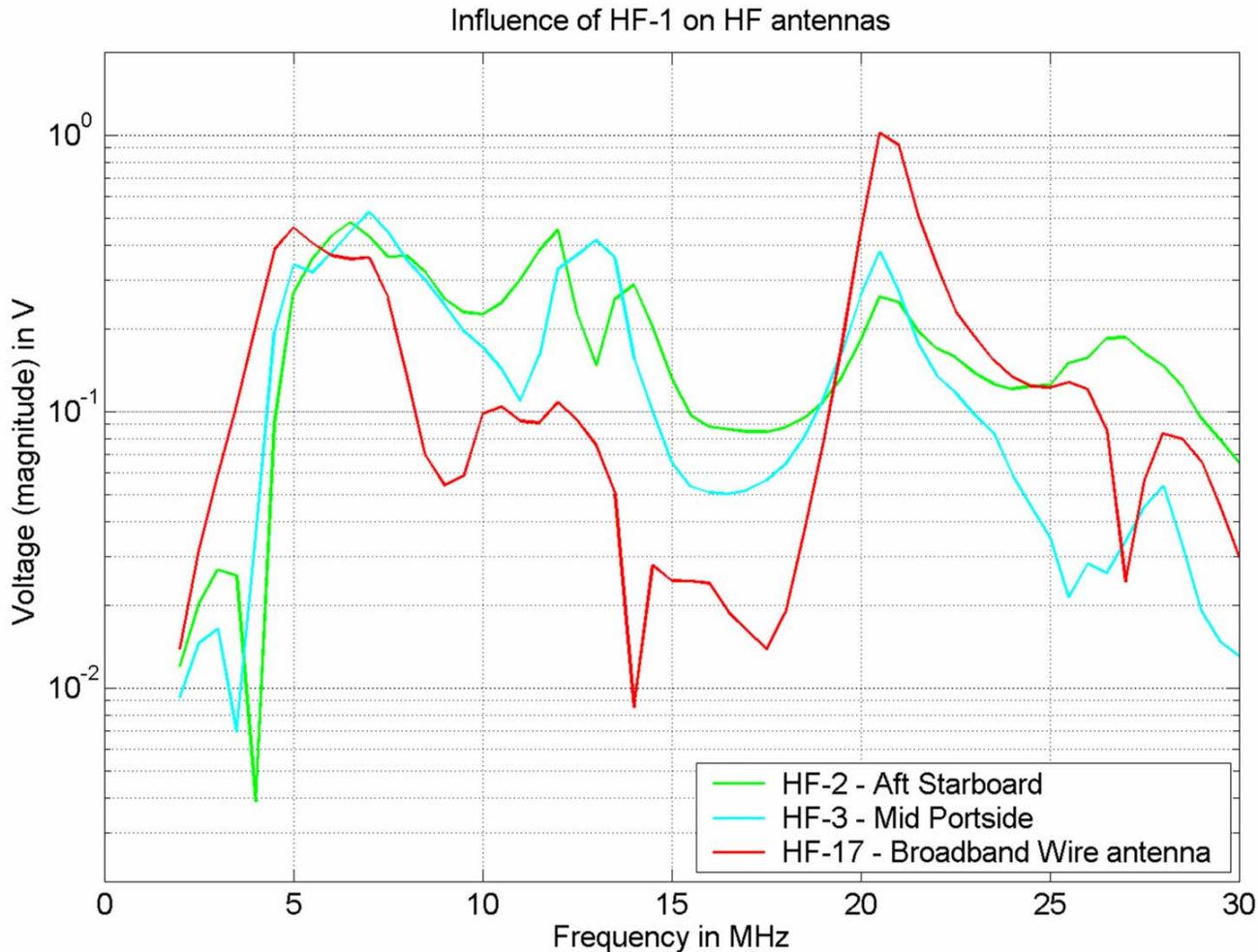
- The ship itself forms an essential part of the HF antenna system. The input impedances for HF antennas depend therefore very much on the location on the platform, not only on the geometry of the actual aerial.
- In particular at low frequencies large parts of the ship form the ground plane for HF antennas, and currents induced there when feeding the antenna, contribute significantly to the overall radiation.
- Information about HF antenna input impedances can be used to design matching networks, and are also important input data for coupling calculations.

Comparison of HF Antenna Input Impedances (Real Part)



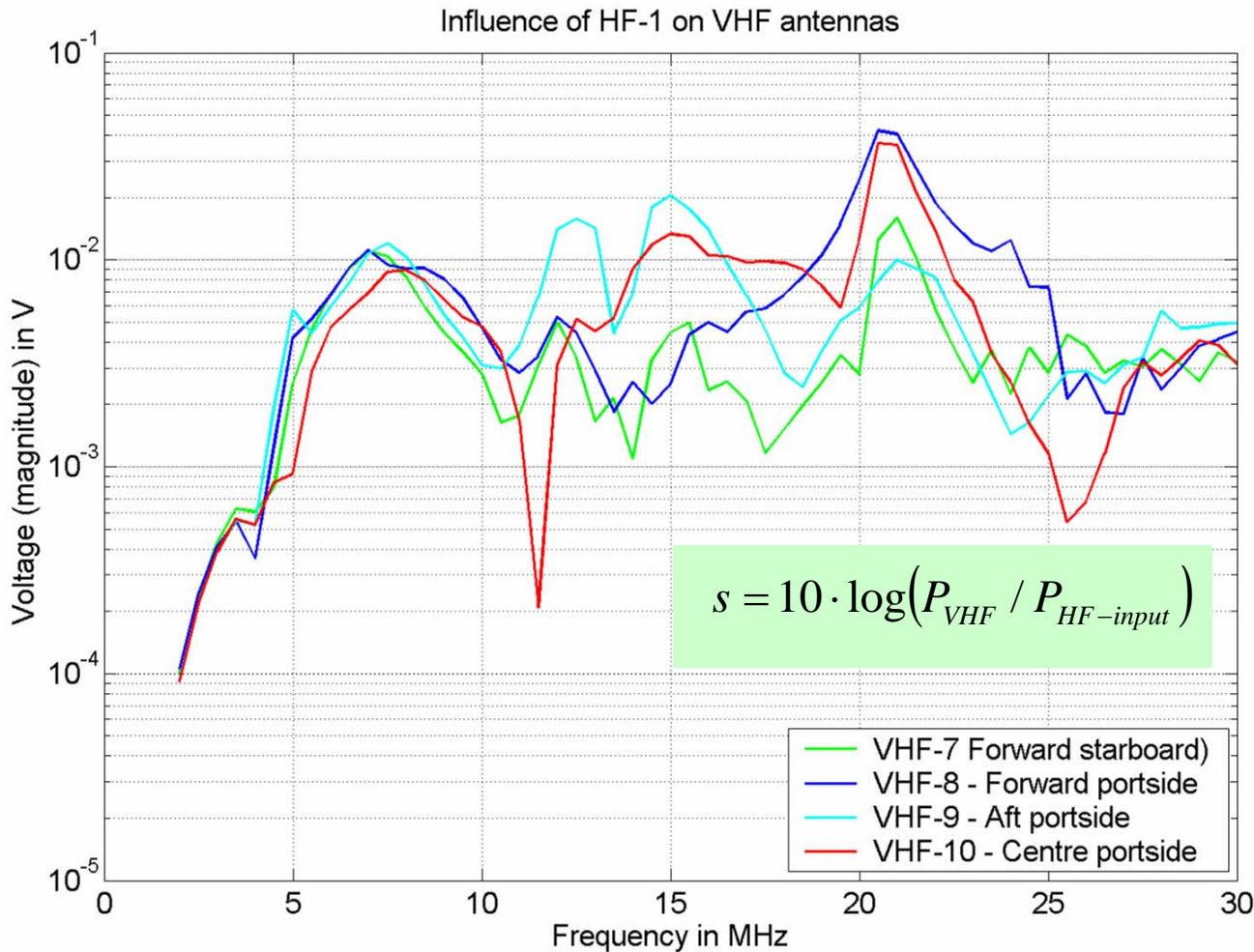
- Input impedances for antenna HF-1 and HF-2 are almost identical due to their symmetric location;
- Input impedance for HF-3 is similar as for HF-1 and HF-2 due to the same dimensions;
- Input impedance for HF-17 is significantly different due to the profoundly different geometry characteristics.

HF Antenna Terminal Voltage



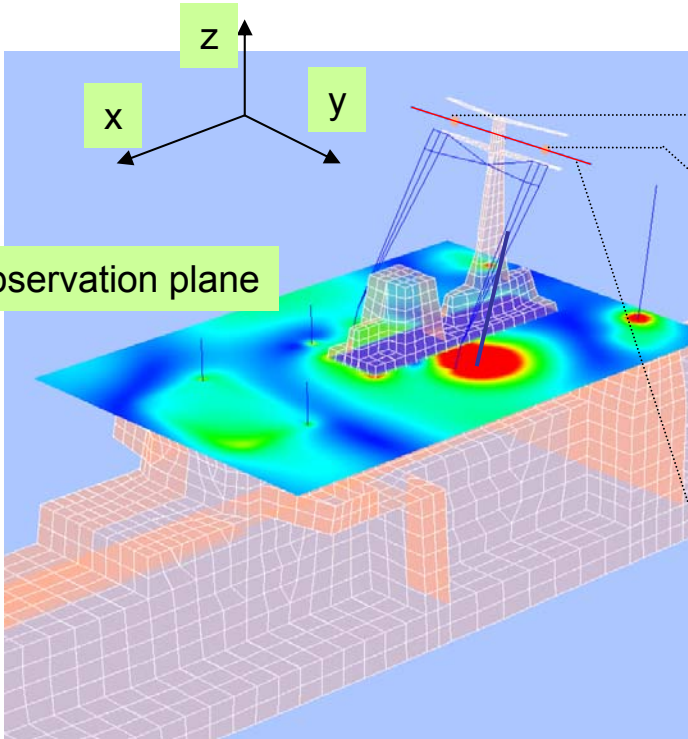
- Voltages coupled in nearby other HF antennas must be known in order to predict maximum coupling parameters.
- This provides input data for the specification of filter requirements and determines simultaneous operation capabilities.
- **Leaving the terminals of non-transmitting HF antennas open provides data for transfer impedances**
- **Knowing the complete impedance matrix for the HF antenna system allows comprehensive coupling calculations without repeating field simulations.**

VHF Antenna Terminal Voltage

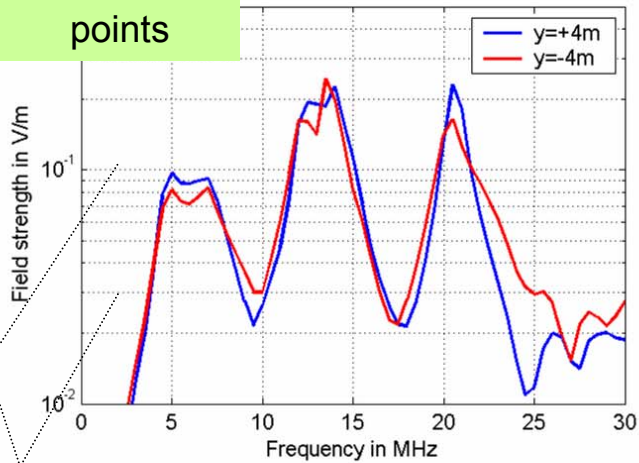


- Voltages coupled in nearby other VHF antennas must be known in order to predict maximum coupling parameters.
- This provides input data for the specification of filter requirements and determines simultaneous operation capabilities.
- Other than for HF antennas the termination of VHF antennas is typically not varied, and they should be terminated with their nominal impedance.

Field Strength Values



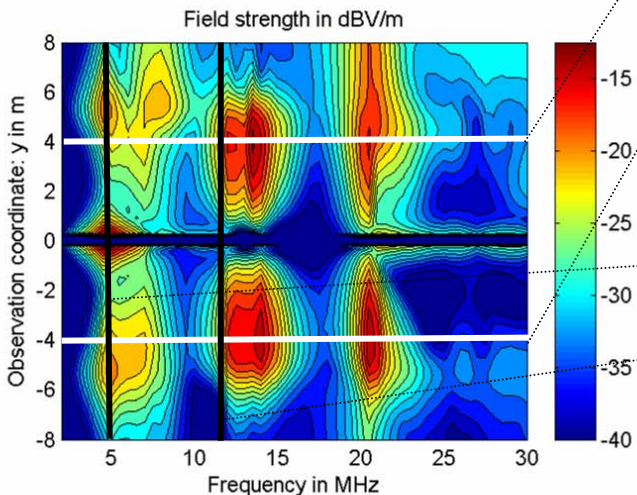
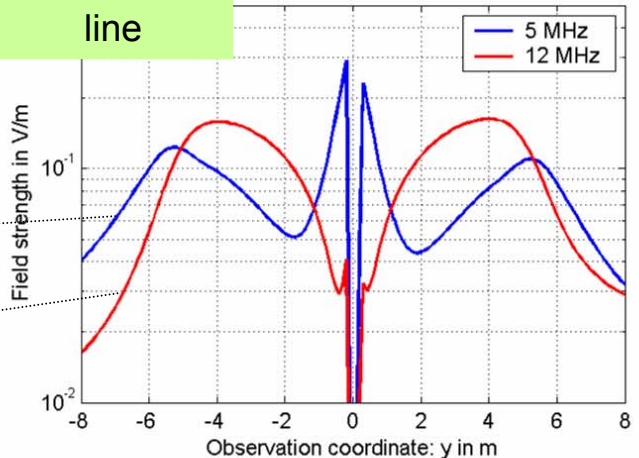
Observation points



Field strength values at observation points may be used to determine frequencies for which comprehensive 2-D plots should be generated.

Field strength values on 2-D planes may be used to determine the values for which points should be used for further analysis.

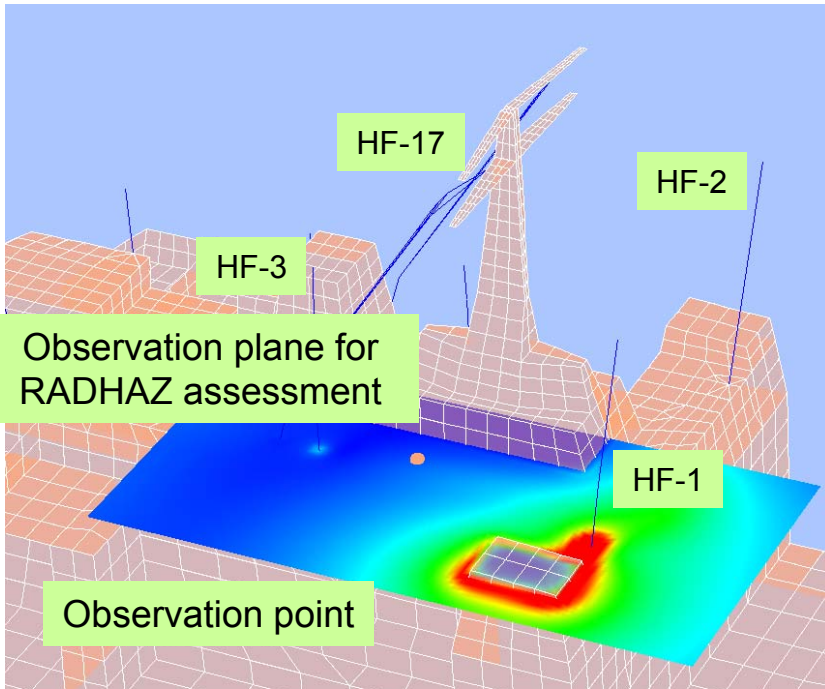
Observation line



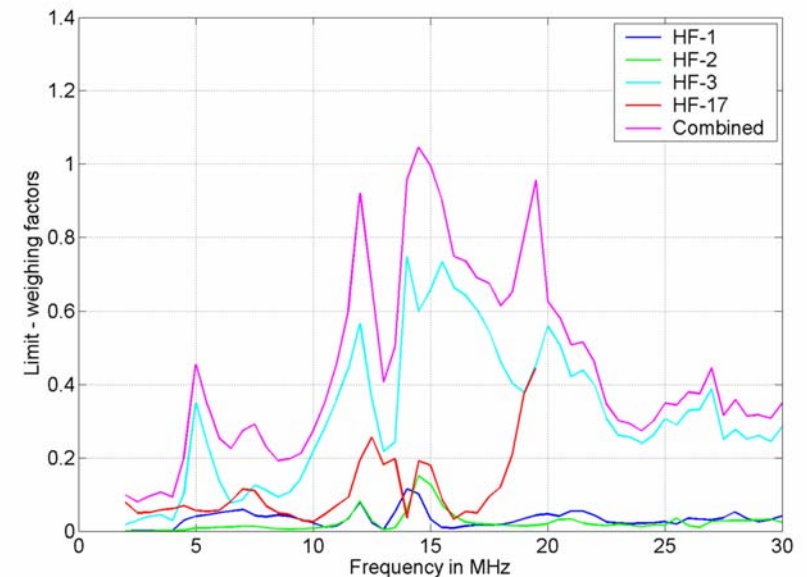
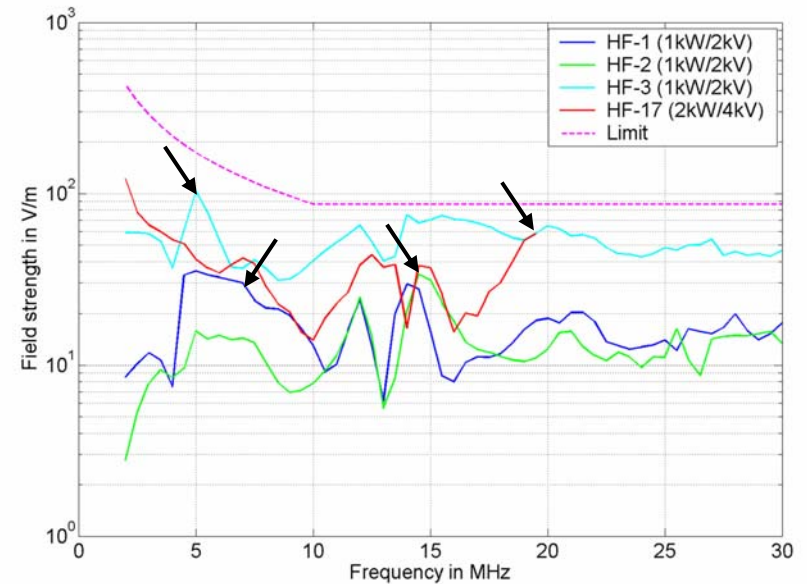
Superposition of Field Strength

- HF antennas can produce high electric and magnetic fields in their vicinity and therefore be RADHAZ concern.
- According to most relevant standards the effect of multiple sources must be considered.
- In most cases, the field produced by HF antennas decreases quite fast with increasing distance, and the RADHAZ zone around each antenna is only marginally affected by contributions from other antennas.
- Sometimes however, an influence can not be ruled out and transmission scenarios involving multiple transmitters must be investigated. This can be done in several steps:
 - For each antenna to be included in the assessment a transmission frequency and load impedance is selected;
 - Based on the termination and source conditions a feeding current for each antenna is calculated;
 - The field strength at an observation point produced by each antenna, due to the actual feeding current is determined;
 - The field strength contribution from each antenna is weighted in accordance to the limit value for the respective frequency, and all weighing factors are combined.

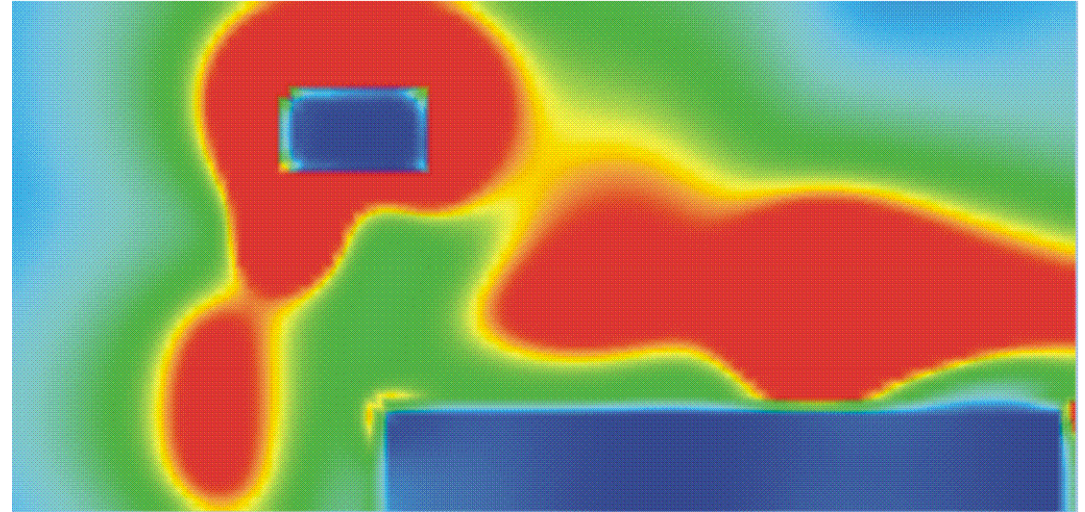
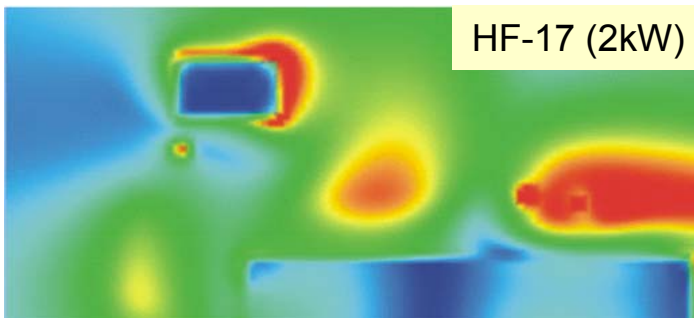
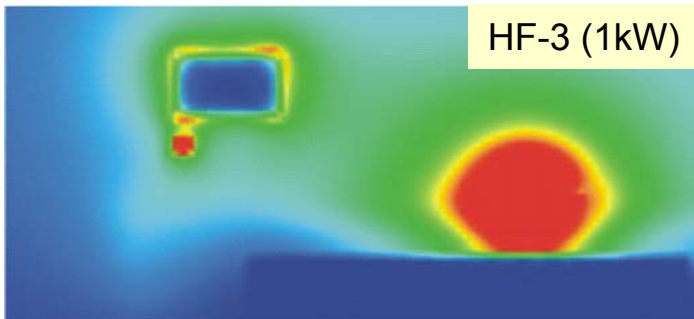
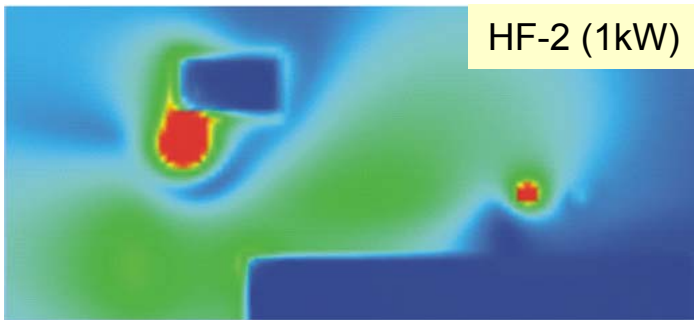
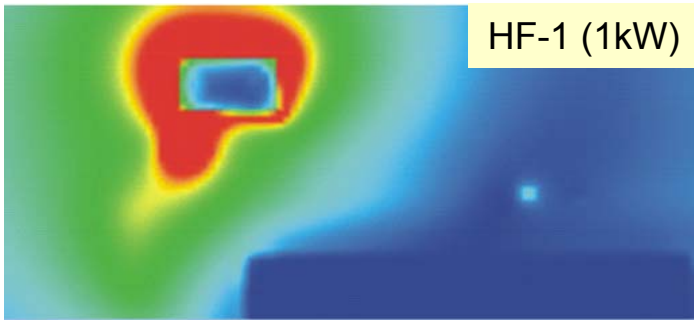
Superposition of Field Strength



- A RADHAZ assessment for the indicated observation plane shall be made.
- For one observation point the field strength due to each HF antenna is determined (considering the maximum transmission; limited either by available power, or maximum feeding voltage).
- A worst case transmission scenario is chosen.



Superposition of Field Strength



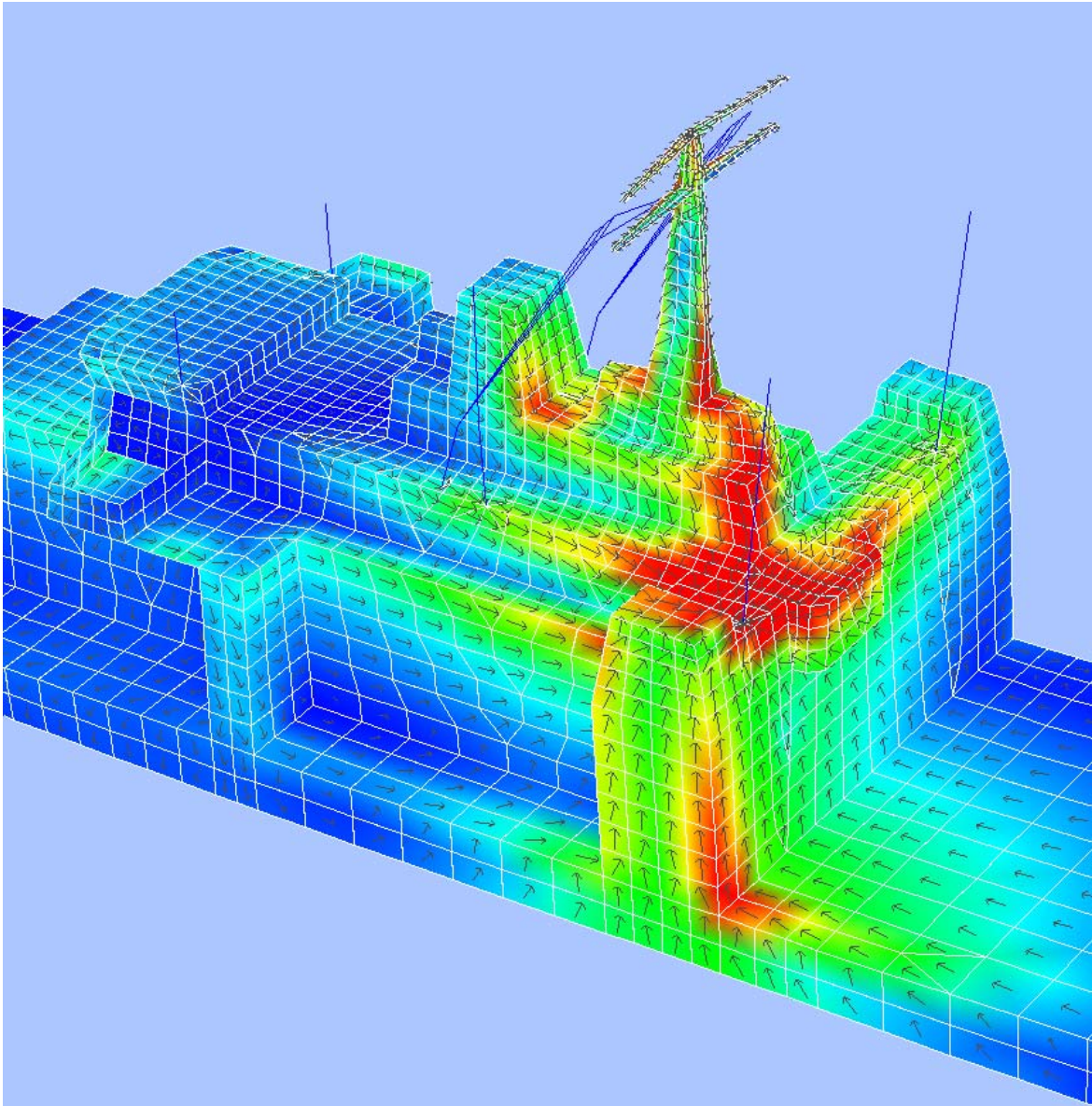
Antenna	Power	Frequency	Limit value
HF-1	1 kW	7 MHz	124 V/m
HF-2	1 kW	14.5 MHz	87 V/m
HF-3	1 kW	5 MHz	174 V/m
HF-17	2 kW	19.5 MHz	87 V/m

Model Validation

Results must be critically validated before used for decision making. Beside some general guidelines, listed below, results must be constantly interpreted and checked for consistency:

- Surface current distribution is looking 'smooth';
- Currents and fields concentrate along edges and at corners;
- Power budget: input power = radiated power + power loss;
- Reciprocity: $Z_{ij}=Z_{ji}$ for passive systems;
- Electric field perpendicular to perfect conductors;
- Results not reacting too sensitive to model variations.
- ...

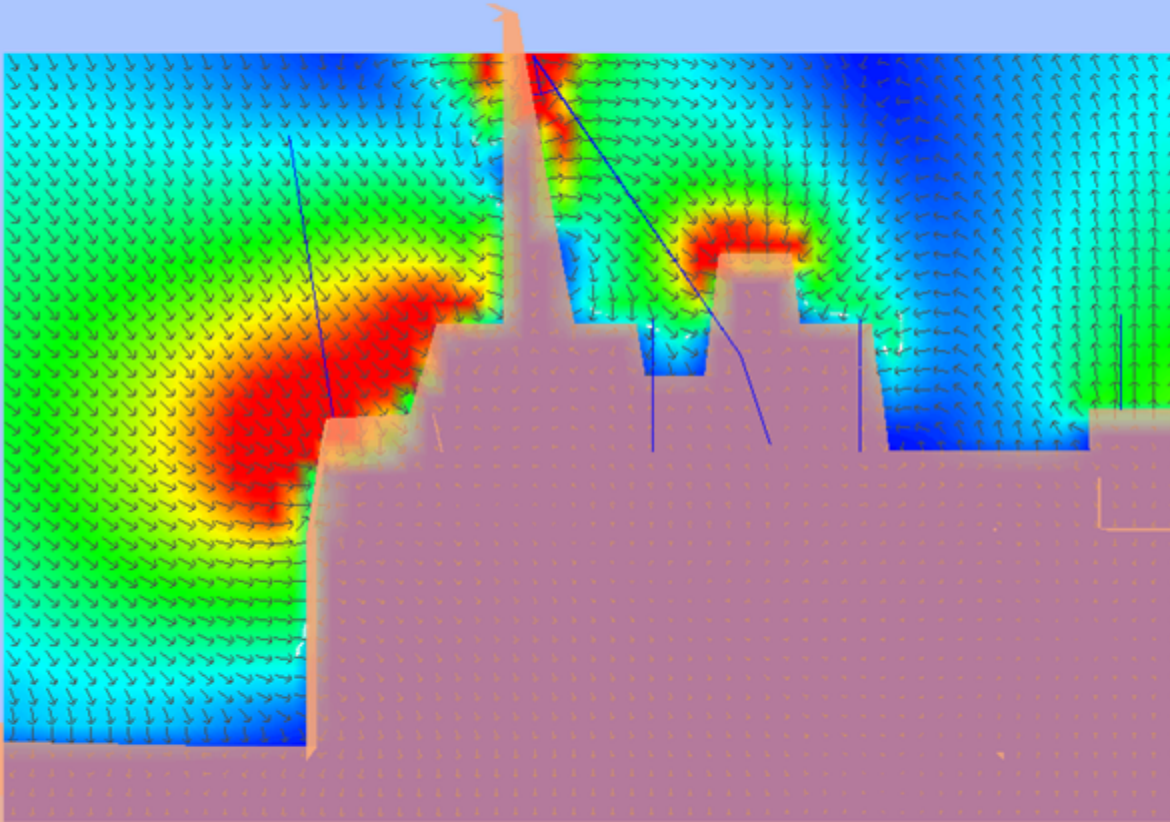
Surface Current Distribution



- Current distribution (maximum values) for HF-1 transmitting at 6 MHz.
- The current density is higher around the antenna feed point and along some edges in the vicinity of the transmitting antenna.
- The current distribution looks 'smooth', i.e. The current direction is uniform and changes only slightly from patch to patch.

Electric Field Strength

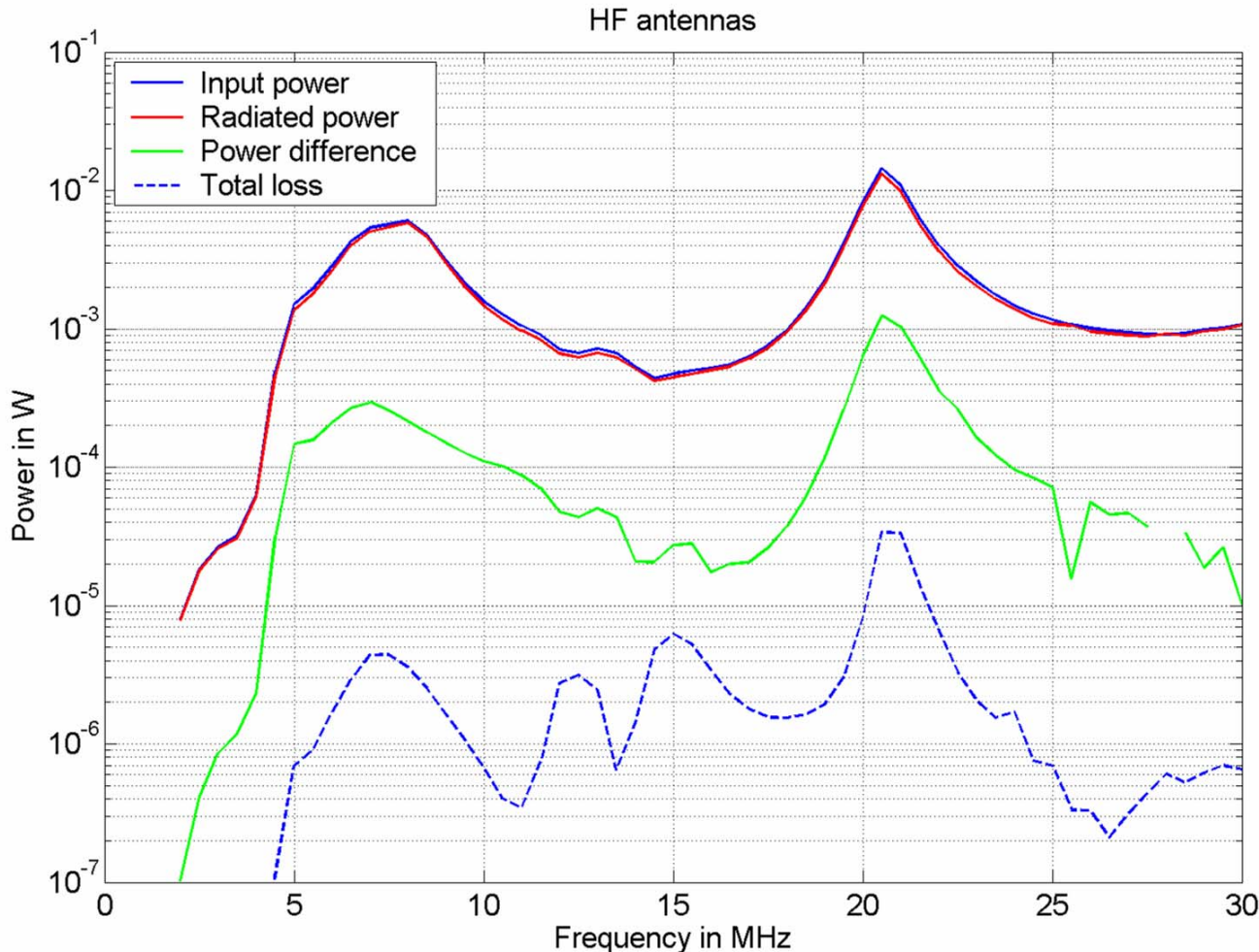
HF-1 transmitting at 6 MHz;
Observation plane through
symmetry plane of the ship.



- The electric field strength is checked for an observation plane cutting through the superstructure.
- Field concentrations are noted around the transmitting antenna, around both masts, and to some degree above the elevated part of the bridge.
- The field strength is perpendicular to the structure.
- The field inside the superstructure is very small.

Power Budget (HF Antennas)

- Input power and radiated power are almost identical. Differences (Input power – Radiated power) are generally less than 10% of the input power.
- For a small frequency range (27-28 MHz) the radiated power is slightly bigger than the input power and is not shown in the logarithmic scale.



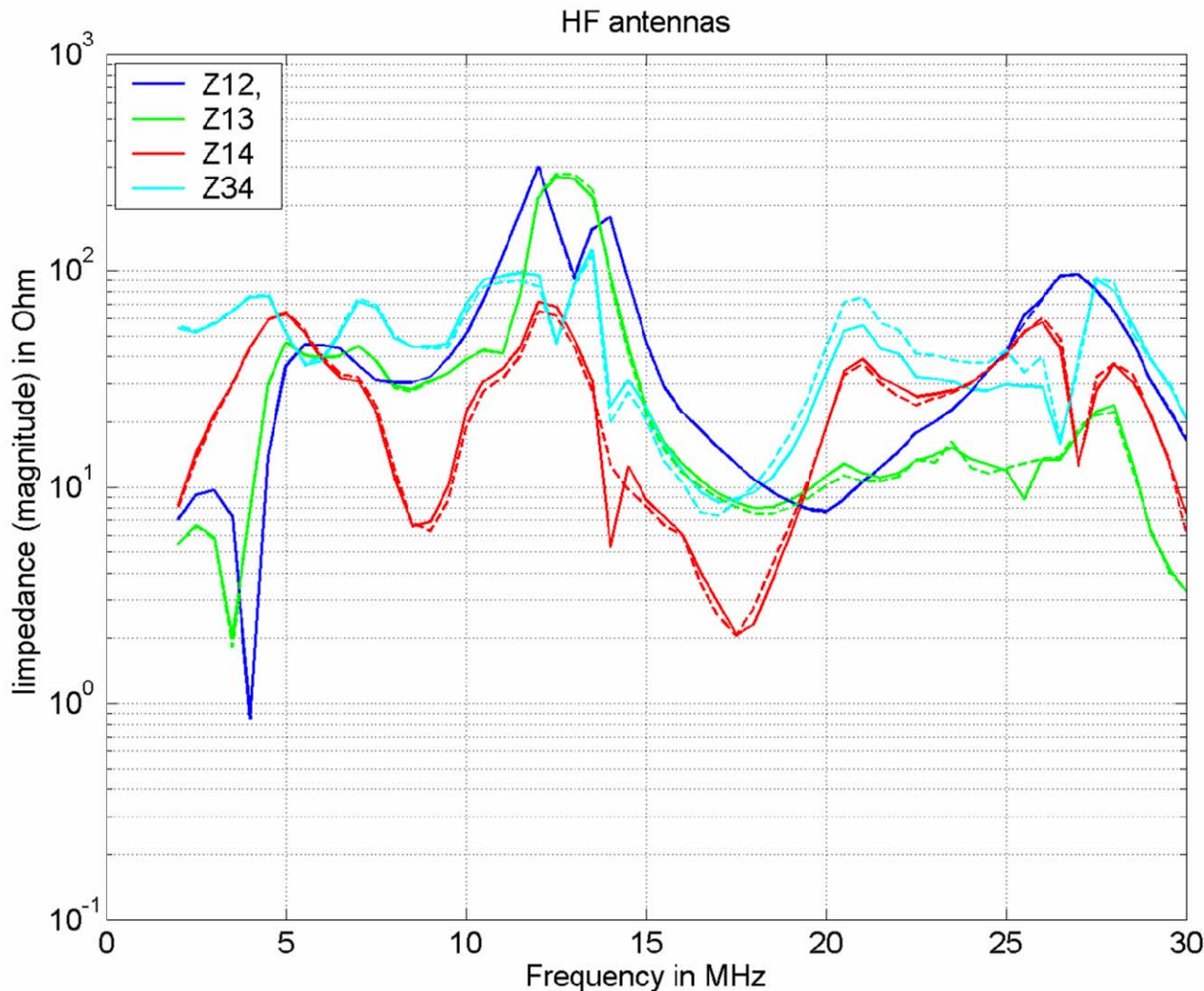
- Power loss also occurs in the termination resistors: 50Ω for the VHF antennas, $1 \text{ m}\Omega$ for the transmitting HF antenna and $1 \text{ M}\Omega$ for all other HF antennas.
- These losses are however much smaller and are negligible in this case.

Reciprocity

Transfer impedance between two antennas is the voltage at open terminal of one antenna (V_i) divided by the feeding current of the other antenna: (I_j).

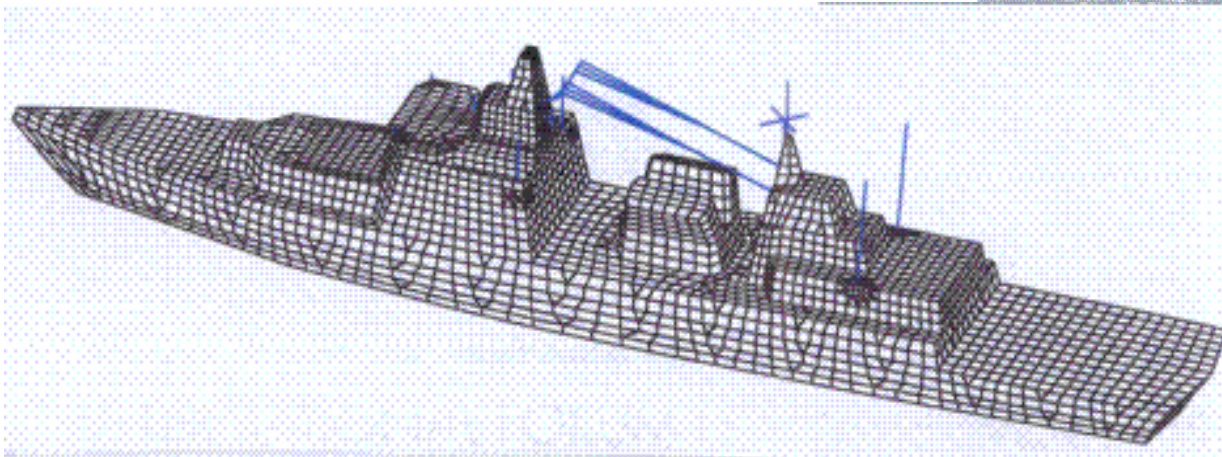
For passive systems it must be: $Z_{ij}=Z_{ji}$.

$$Z_{ij} = \frac{V_i}{I_j} \stackrel{?}{=} \frac{V_j}{I_i} = Z_{ji}$$



- Reciprocity theorem is fulfilled satisfactorily.
- Symmetry for the coupling between HF-1 and HF-2 is very good.
- For the coupling between HF-1 and HF-3 and between HF-1 and HF-4 some differences can be noted for a few frequencies.
- The coupling between HF-3 and HF-4 shows small differences for the frequency range 21-26 MHz.

Detailed Simulation Model

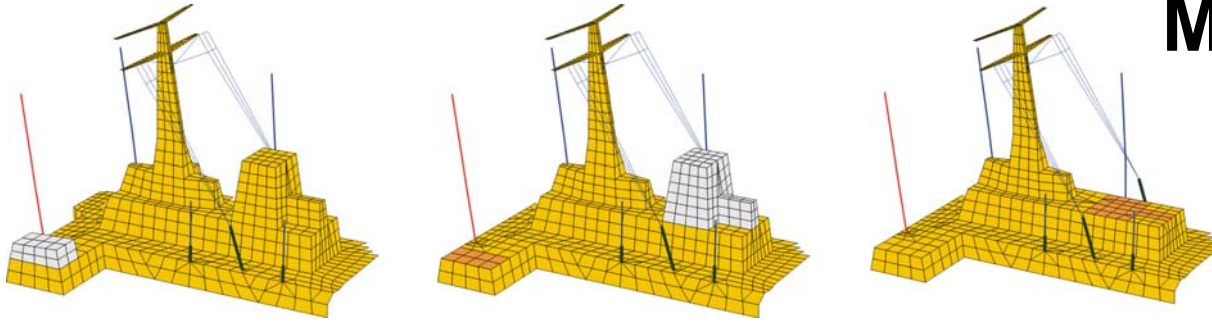


Computer model and real world structure of German frigate:

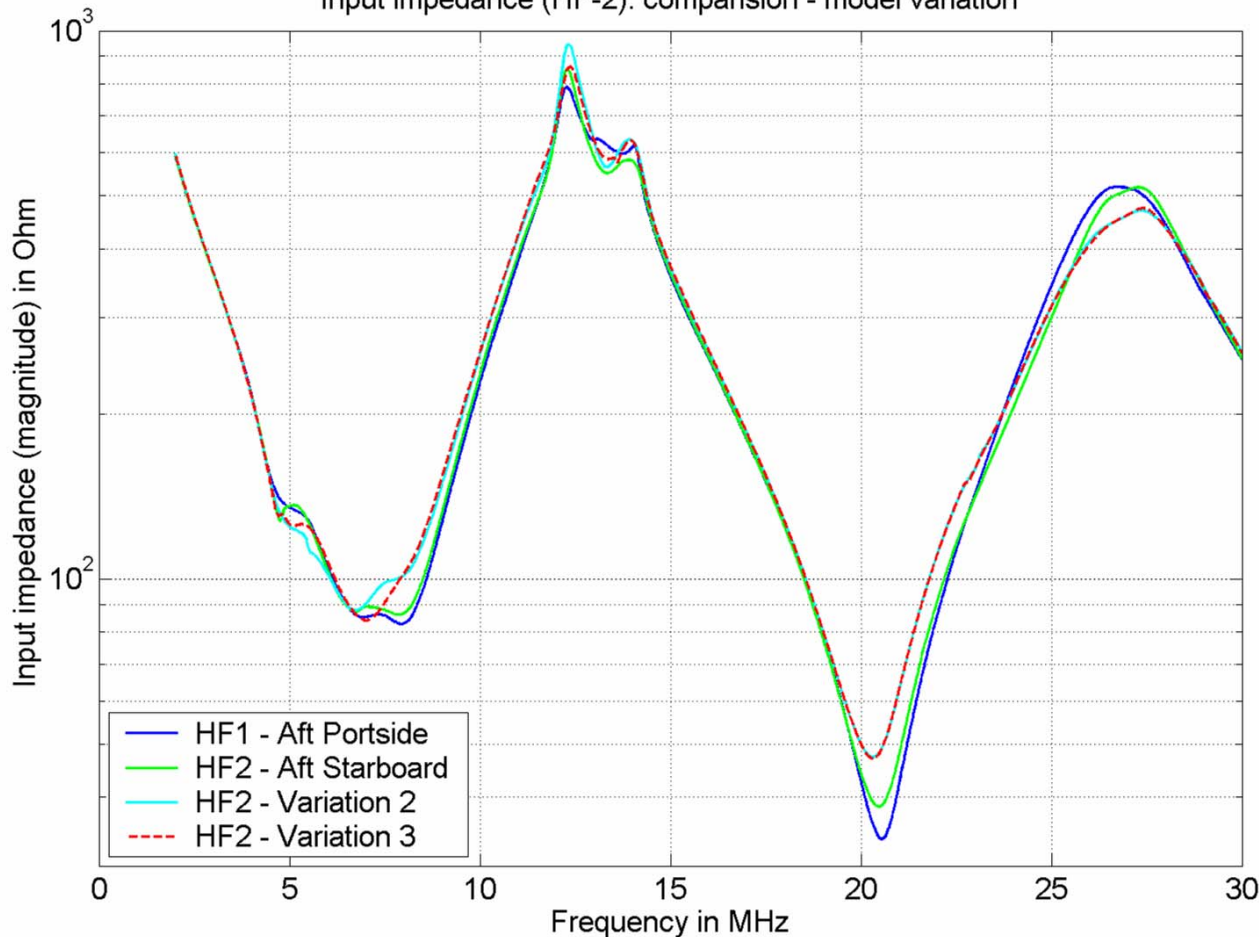
Are computer simulation results reliable, even when many details of the real world structure are neglected?



Model Comparison

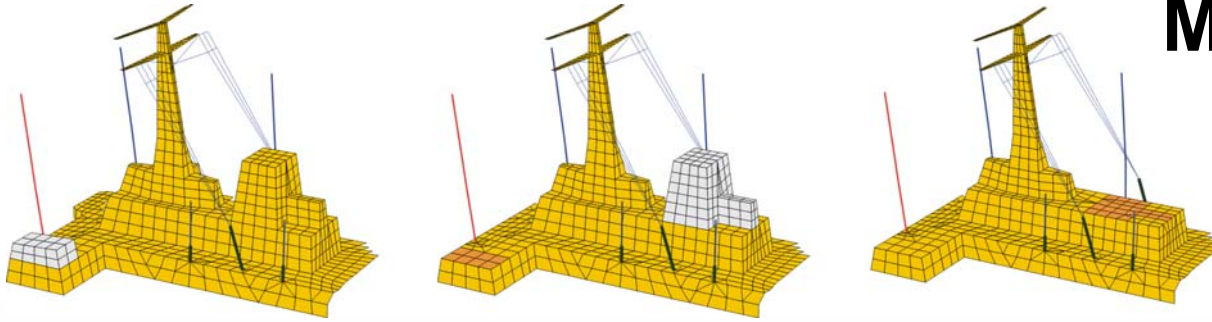


Input impedance (HF-2): comparison - model variation

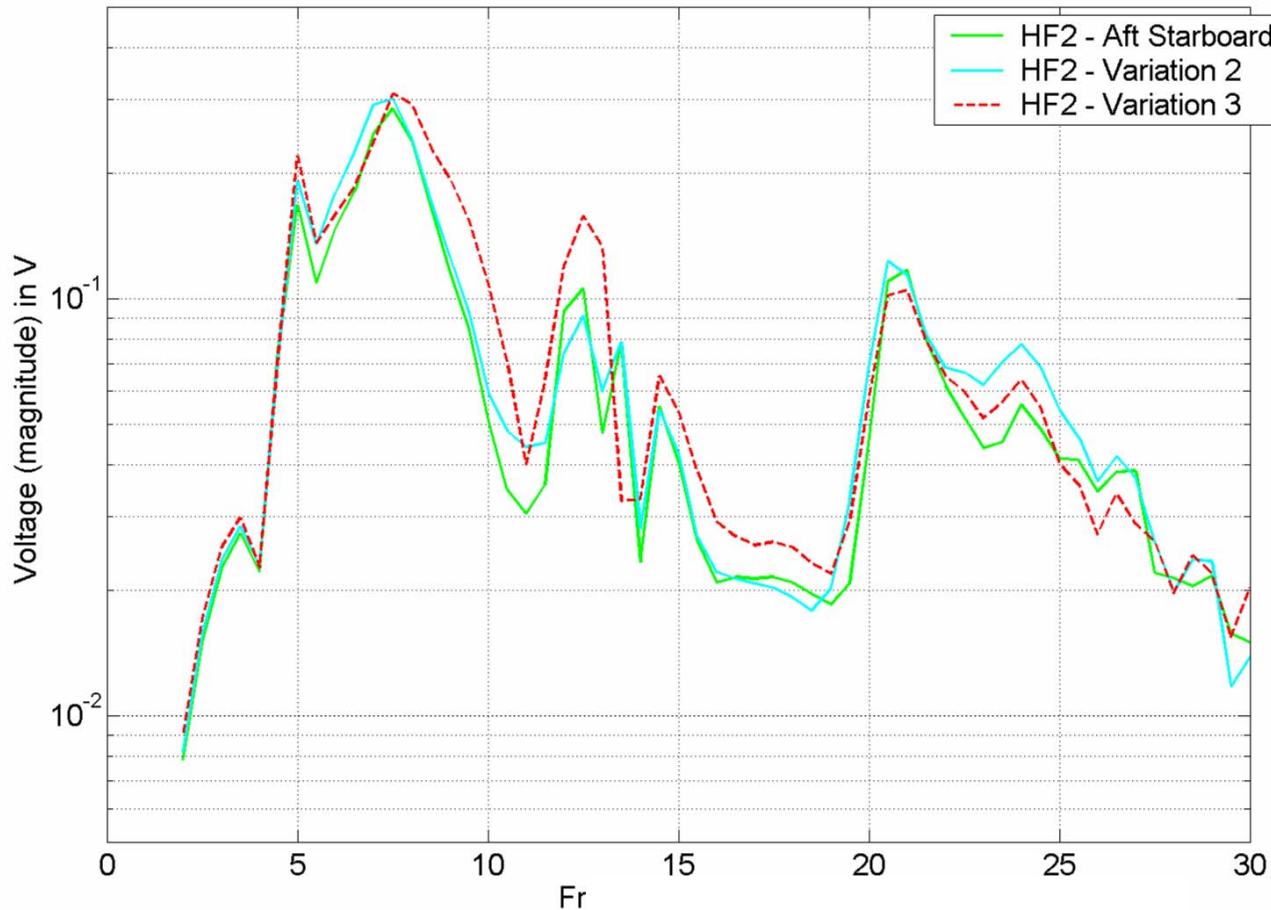


- Small changes to the simulation model should have only a small impact on the result.
- The model has a slightly un-symmetric shape, and the input impedance of HF-1 and HF-2 differ slightly.
- While removing the upper section of the aft exhaust structure the input impedance of HF-2 is calculated, and small changes are noted.
- Modifying the model again, this time by removing the forward mast structure, has only a very marginal impact.

Model Comparison

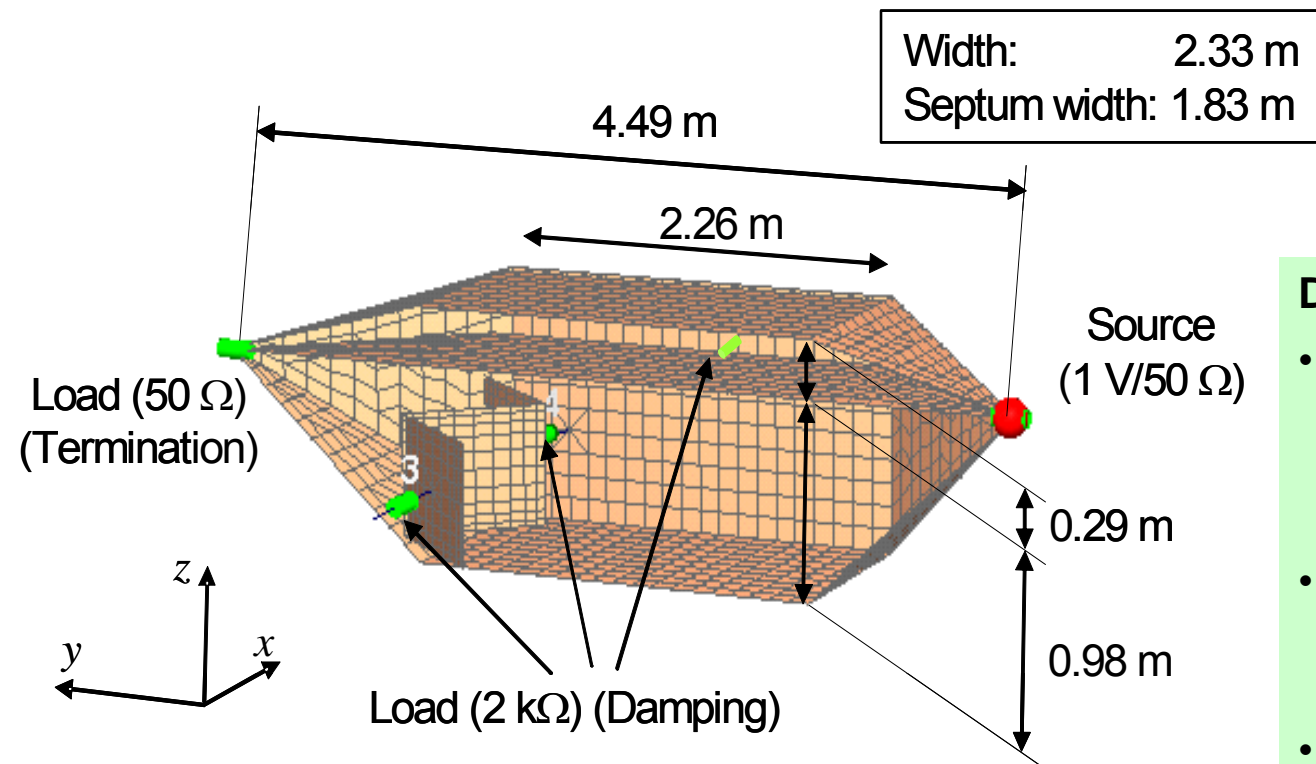


Voltage in HF-3 (HF-2 transmitting): comparison - model variation



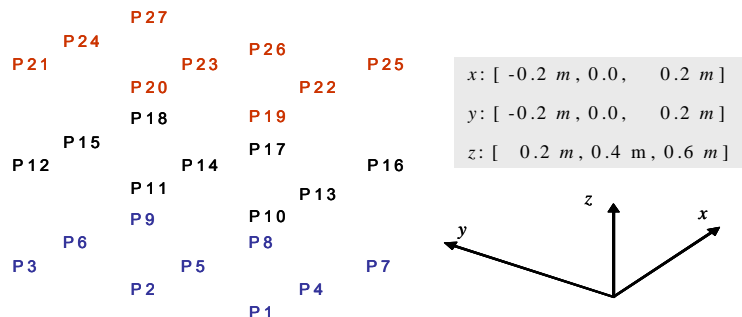
- While transmitting with HF-2 the voltage coupled in the open terminal of HF-3 is calculated.
- Both modifications have only a very marginal impact on the result at low frequencies.
- Removing the forward mast produces a different voltage compared to the basic model and the case where only the aft exhaust are modified.
- Use meaningful values for checking the sensitivity – the input impedance is not the only and often not the most important one.

Example II – Hybrid TEM/Reverberation Chamber



Design objectives:

- Extend frequency range for TEM operation by dampening the first few resonance frequencies;
- Don't disturb field uniformity with introduction of stirrer;
- Optimize stirrer shape and location for reverberation operation.



Requirements

TEM cell

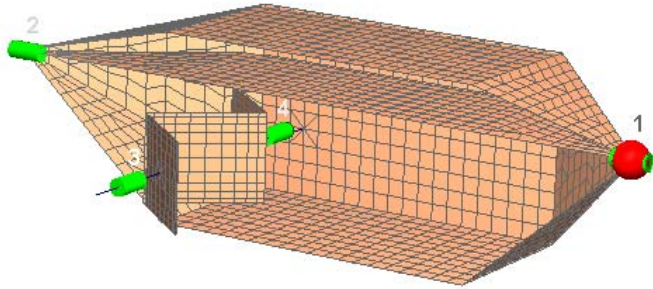
- Field strength varies not too much from one frequency to the next;
- E_z dominates over E_x and E_y ;
- Field uniformity $< 6\text{dB}$.

Reverberation chamber

- Field uniformity over one complete stirrer turn;
- Cross polarisation: all field components of similar magnitude over one complete stirrer turn;
- Typically this is achieved beyond the first 60 cavity modes.

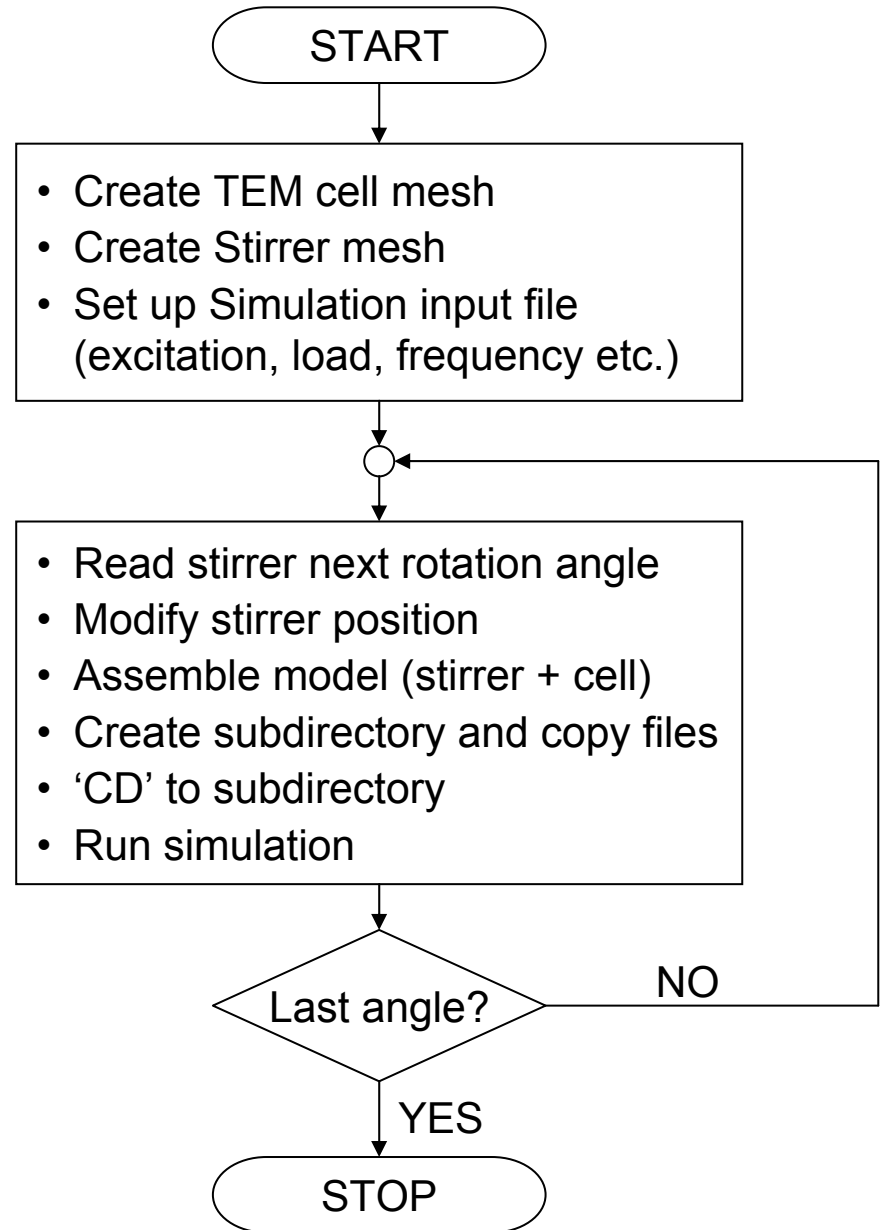
Simulations take preferable:

- Just a few seconds (interactive)
- Up to an hour (during lunch break)
- Several hours (over night)

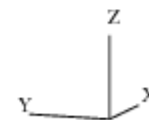
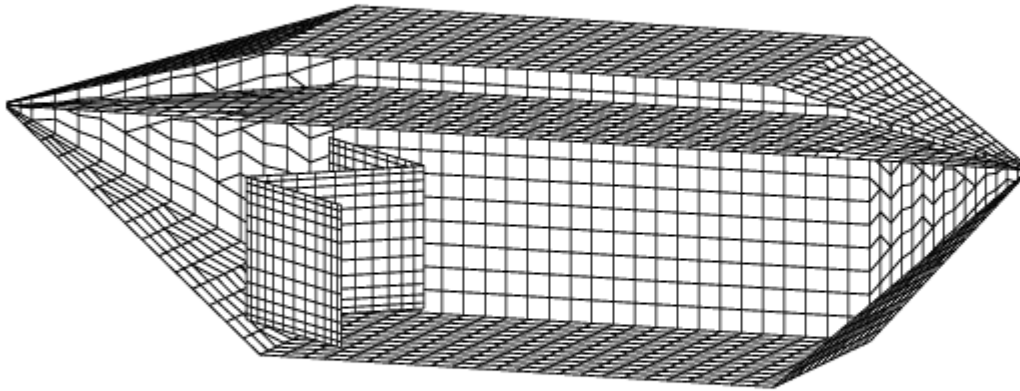


The simulation of this TEM/Reverb hybrid cell takes a few hours, but requires numerous, slightly different models.

Therefore the simulation task is set up as a Batch Job using the flow chart shown on the right hand side.



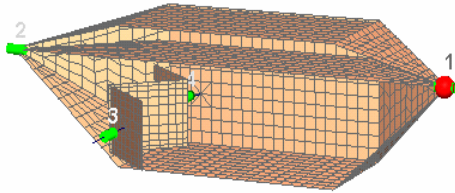
CONCEPT DATA



Computation Time

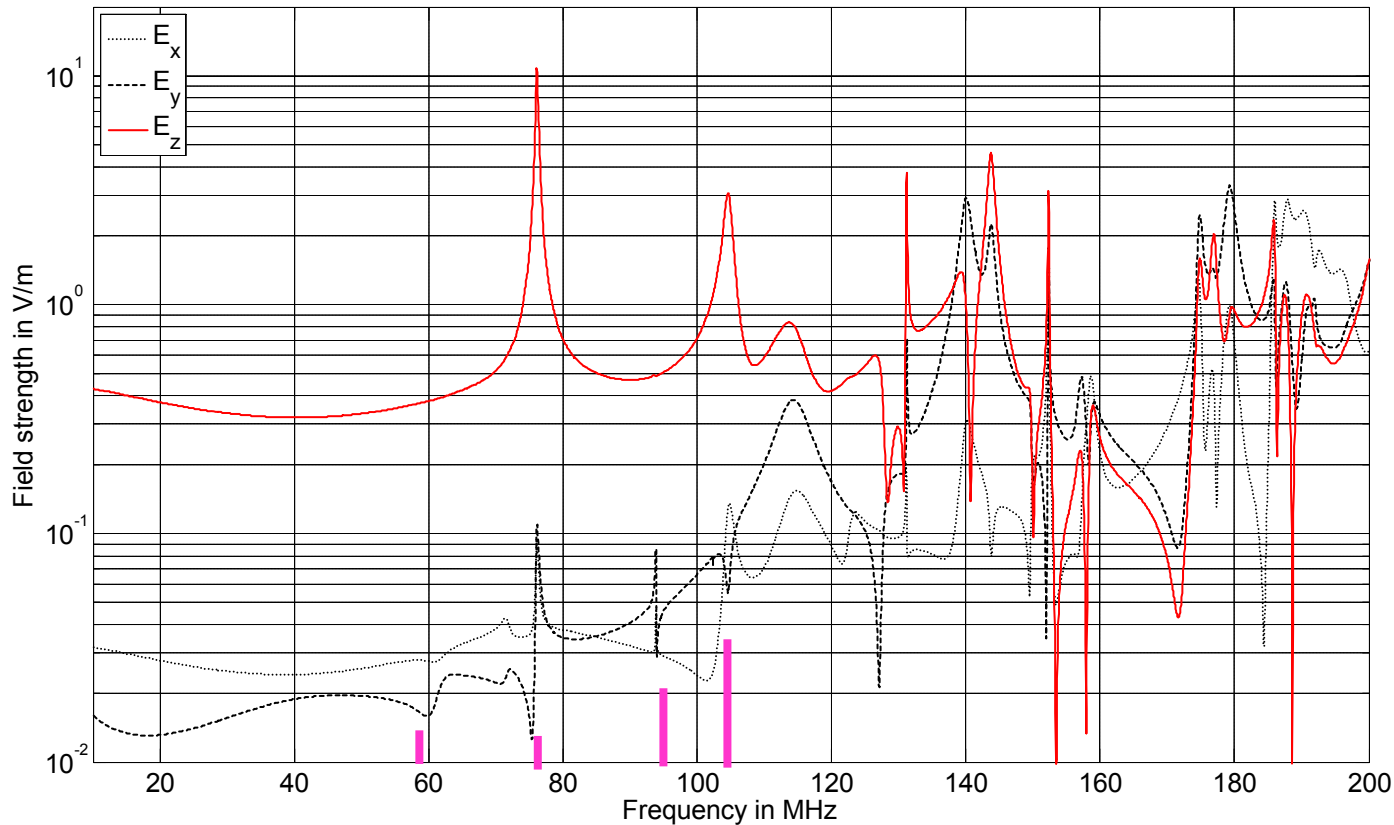
- 3 GHz CPU → ~3 min per frequency;
- Transition frequency range: ~ 10 resonances (~200 frequencies);
- 5-10 degree steps: 36-72 stirrer positions;
- CPU time: ~720 hrs;
- Price for measurement equipment (signal generator, spectrum analyser): ~100k\$;
- Price for 50 state-of-the-art PCs: ~100k\$ (8 hrs on 100 CPUs)

Example Results



Stirrer in 0 degree position, observation point: 0.2m/0.0/0.4m

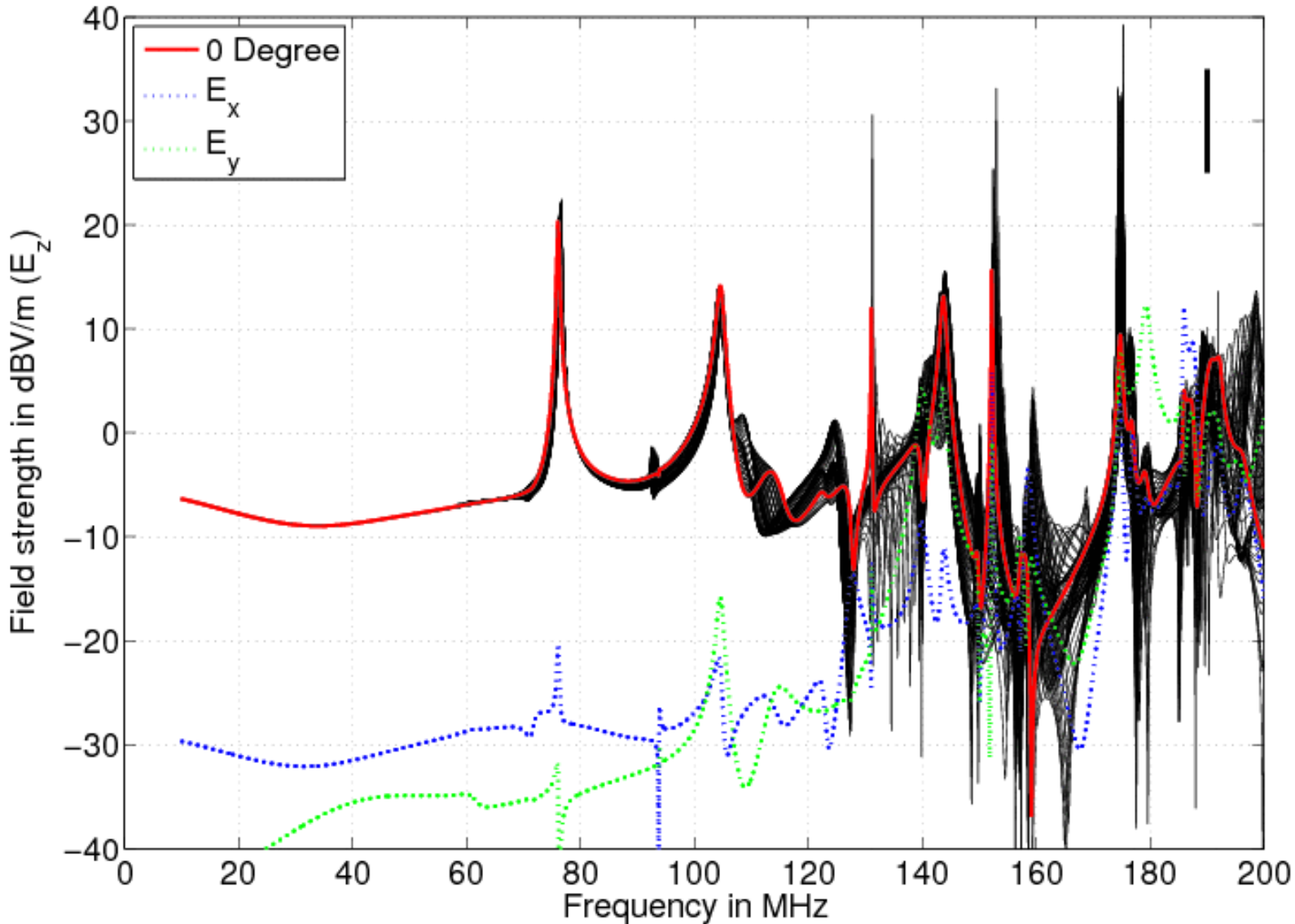
Field strength at **one** point
and for **one** stirrer angle.



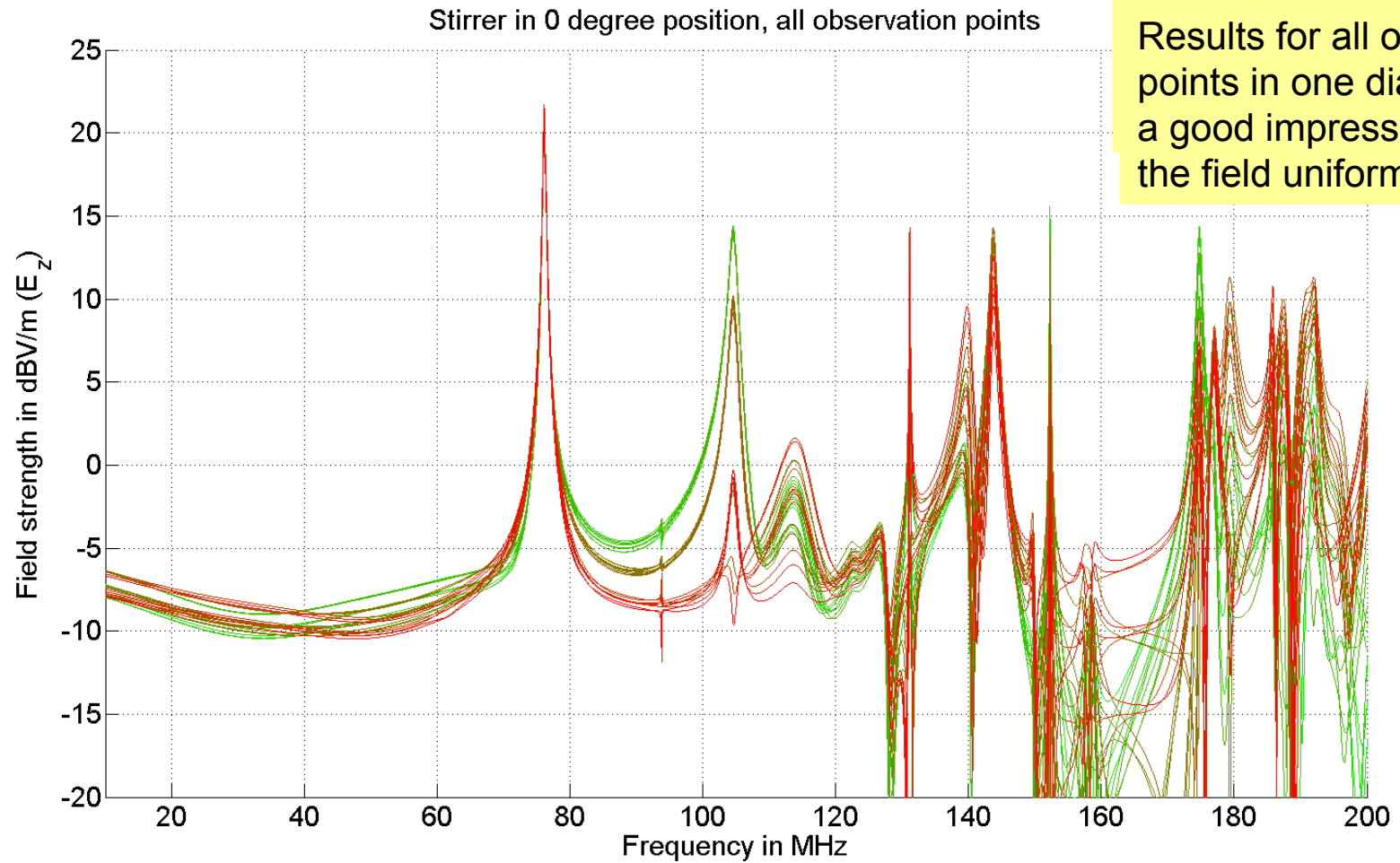
Useful to determine
frequencies where a
closer look is required.

Example Results

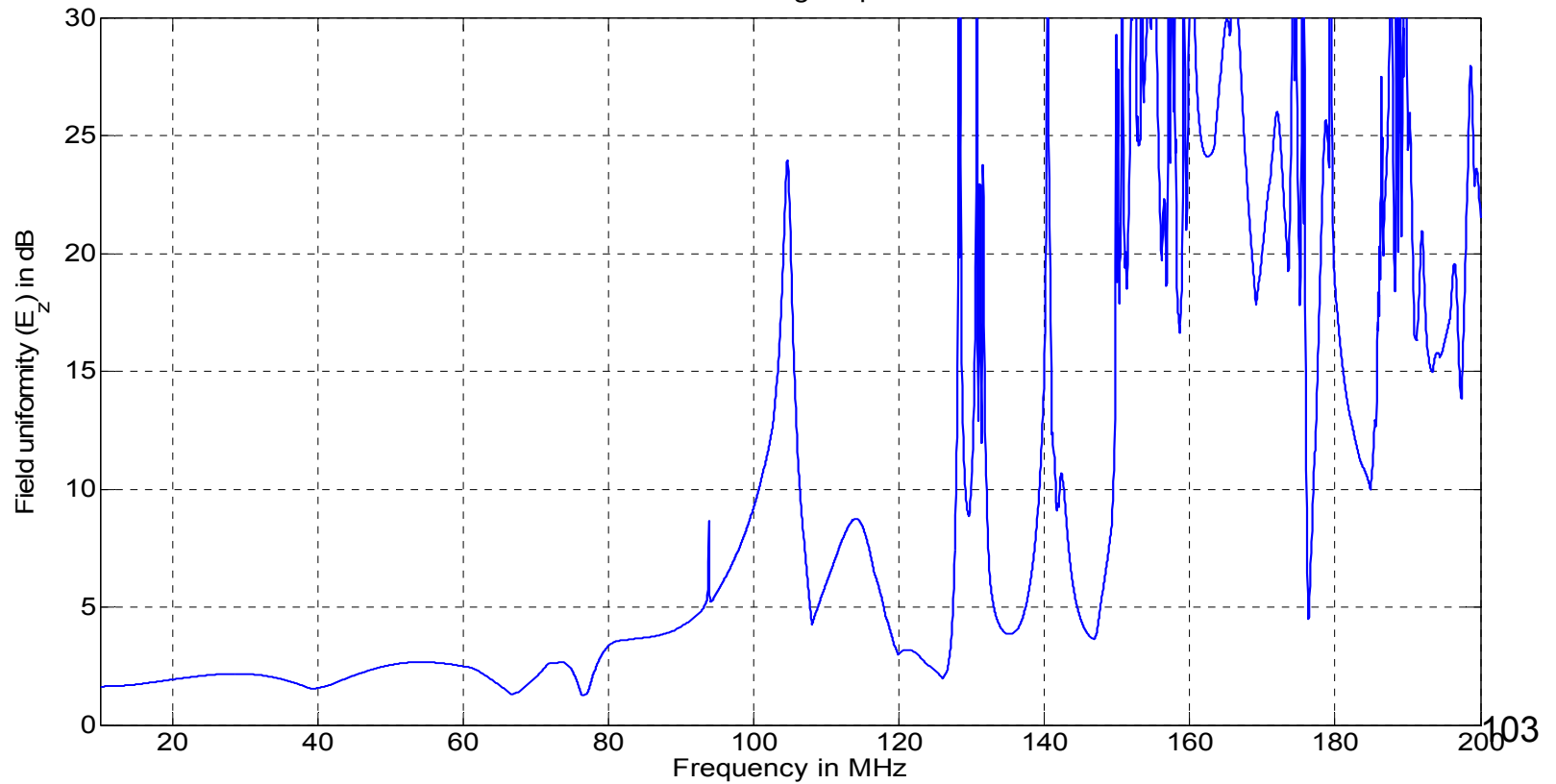
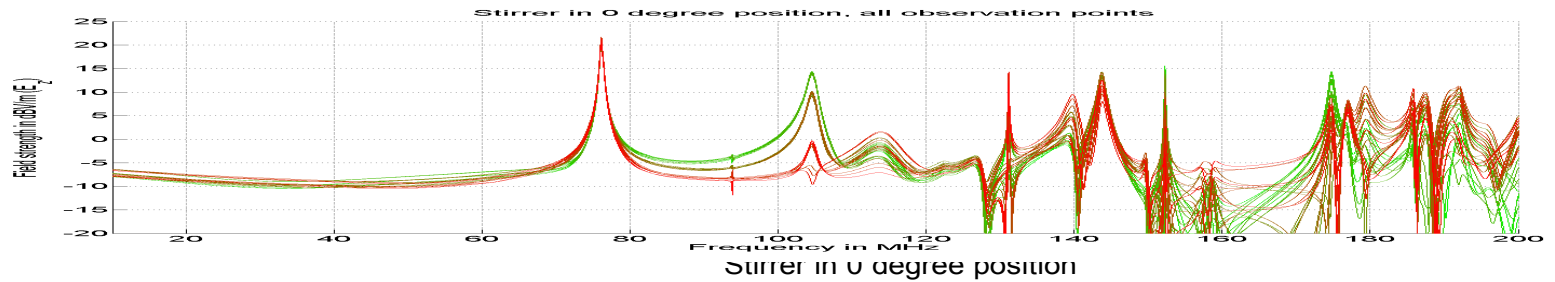
Field observation point: $-0.2\text{m}/-0.2\text{m}/0.6\text{m}$



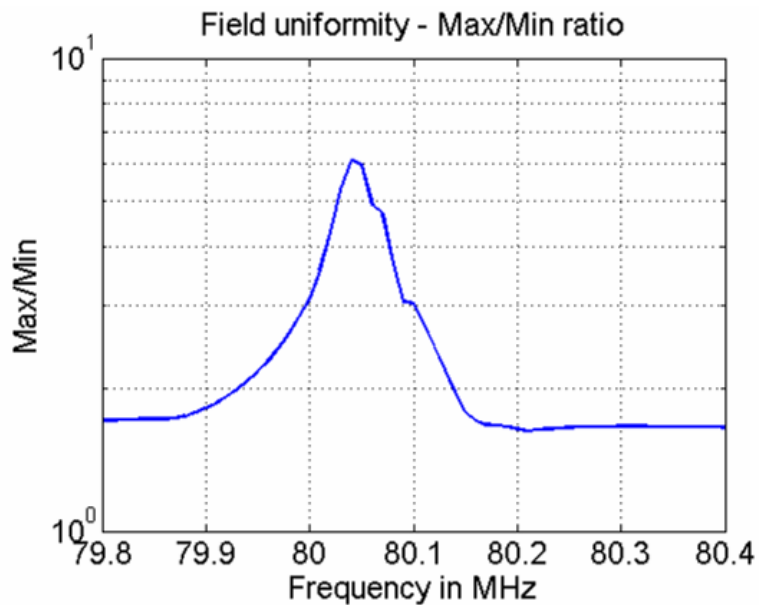
Example Results



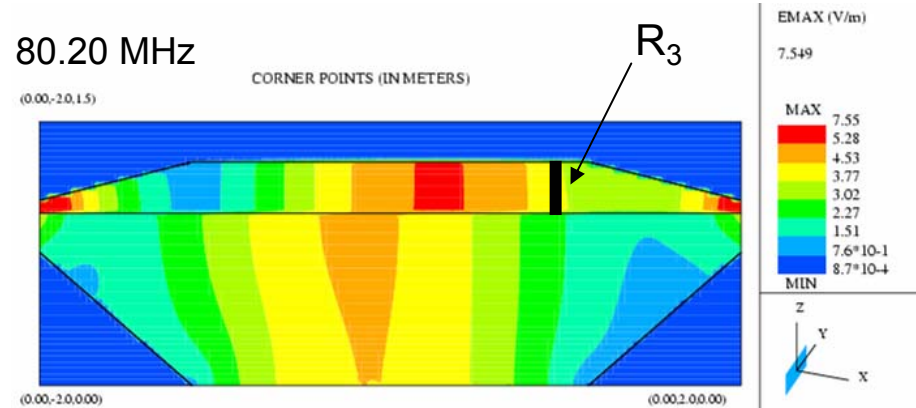
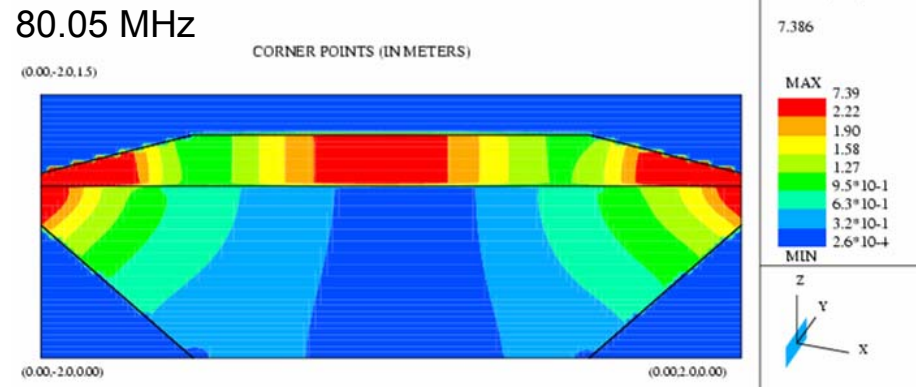
Example Results



Resonance dampening – improve field uniformity

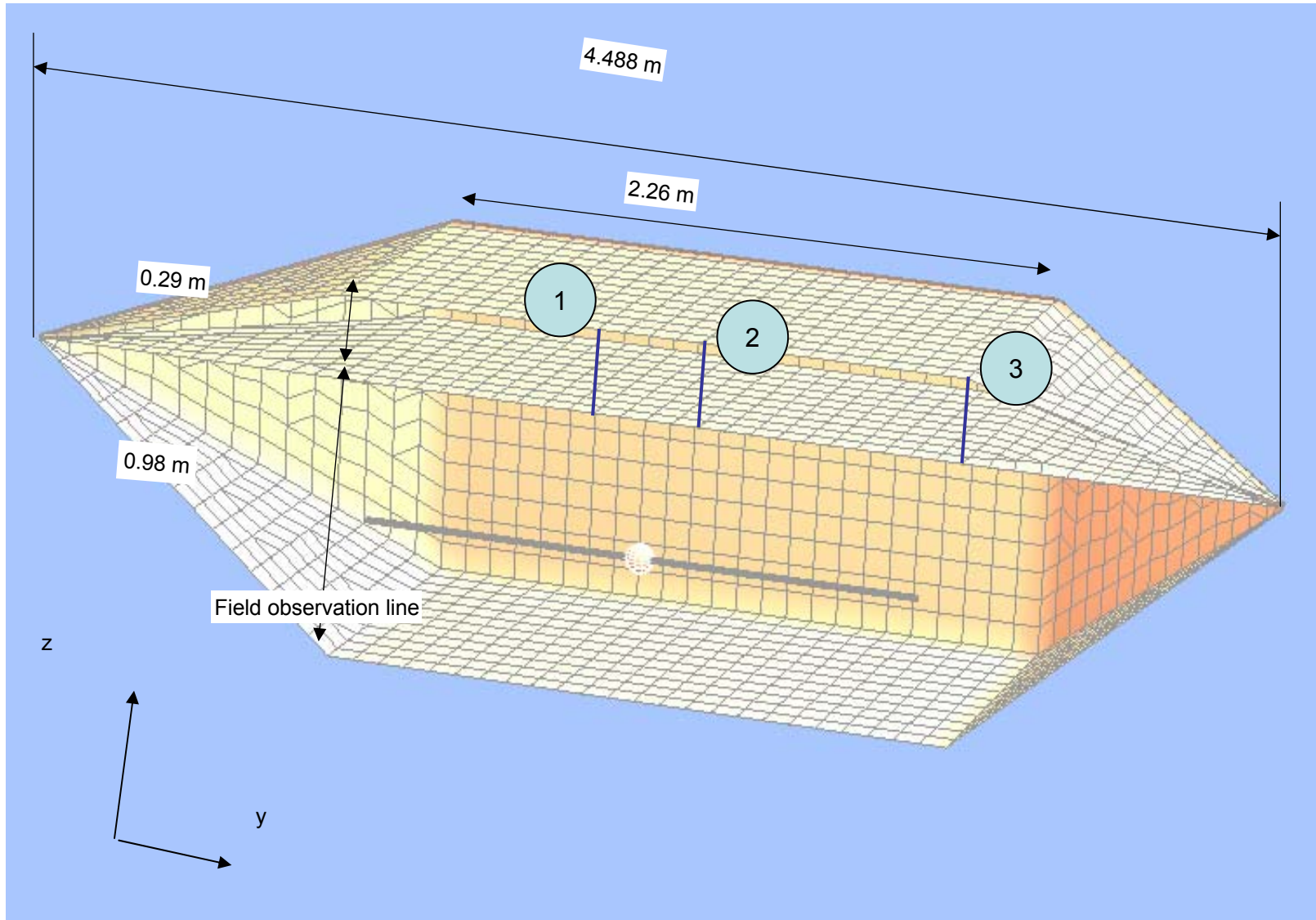


The ratio between maximum and minimum value at the first resonance is found to be a factor of 6 (~15 dB).

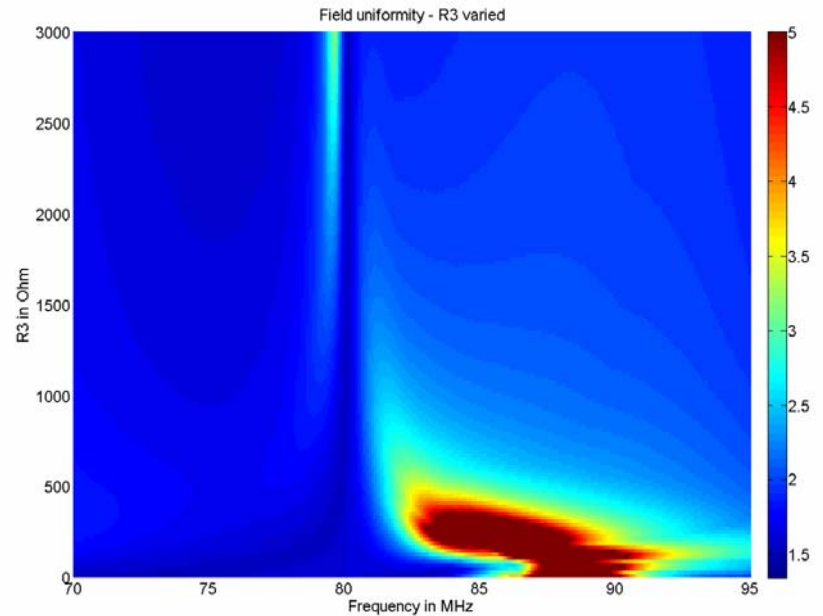
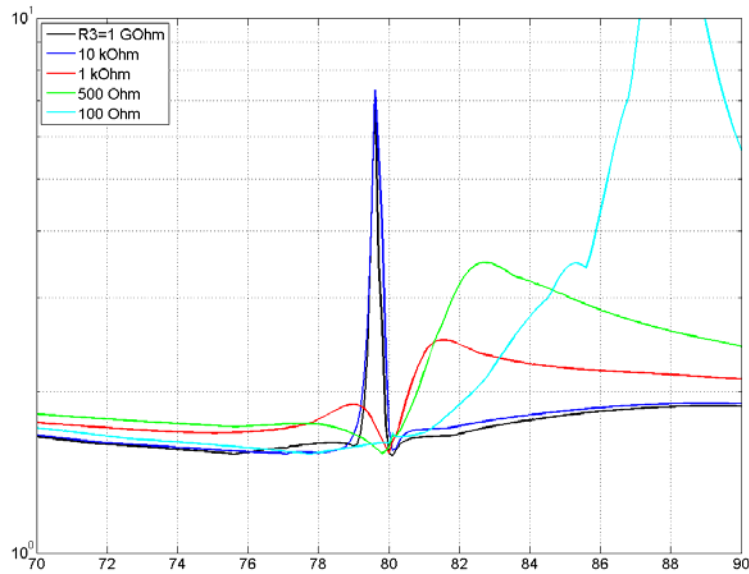


The electric field has a maximum on the upper part of the TEM cell (between septum and top) at this resonance. The field in the lower section (working volume) has a minimum in the centre of the cell just below the resonance, and maximum just above the resonance. Putting a resistive load between septum and top should dampen this resonance.

Resonance dampening – improve field uniformity

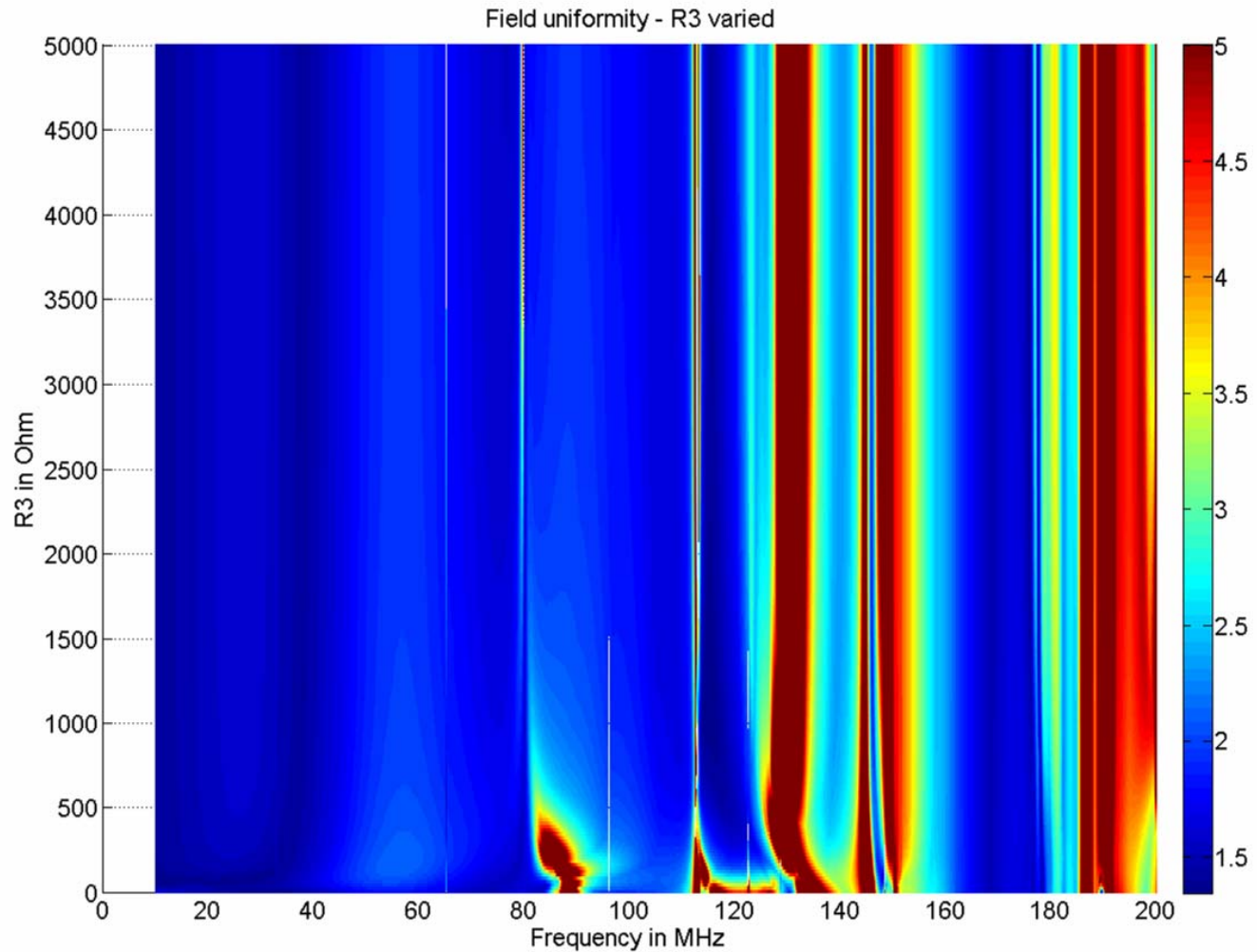


Resonance dampening – improve field uniformity



The resistor reduces the field non-uniformity, as expected. A value of $10 \text{ k}\Omega$ has no significant effect, a $1 \text{ k}\Omega$ resistor gives a better reduction; further reducing the resistor value increases the field uniformity again. The optimum value is around $1.5 \text{ k}\Omega$.

Resonance dampening – improve field uniformity



Post Processing

In many cases, the raw results are not the ultimate goal of the simulation but must be post processed further.

Field simulations are almost always time consuming, and predicting the effect of variations without repeating the calculation is desirable:

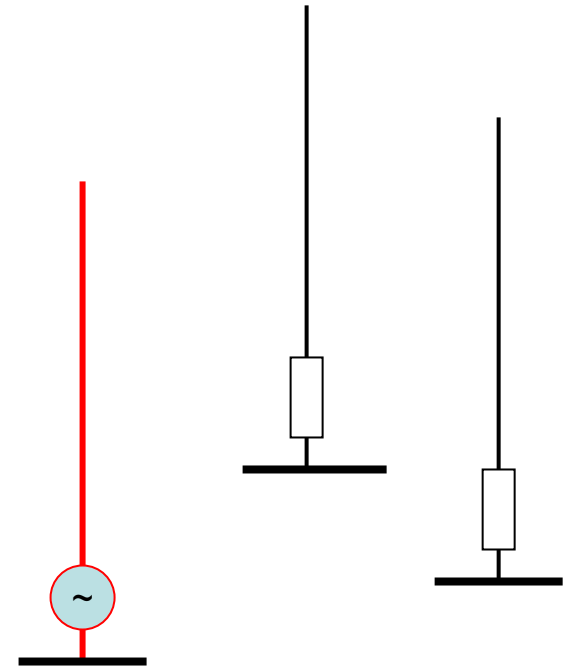
- Variation of HF antenna terminations;
- Maximum coupling between HF antennas;
- HF-to-VHF antenna coupling;
- Scaling results;
- Superposition of field strengths.

Variation of HF Antenna Terminations

- A platform with several HF antennas can be considered as an n -port network, with each of the antenna terminals an accessible port where load impedances and sources can be changed.
- Sources are put at transmitting antennas, and load impedances are connected to the antenna terminals in the form of matching and tuning networks.
- Each HF antenna is excited individually during n field simulations while all non-transmitting antennas are open circuit.
- The field simulation provides values for input and transfer impedances. Transfer impedances are calculated as ratio of open-circuit voltage and feeding current.
- With the knowledge of the complete impedance matrix for the n -port network, port currents can be calculated for a new load/source scenario by inverting an n -by- n matrix.

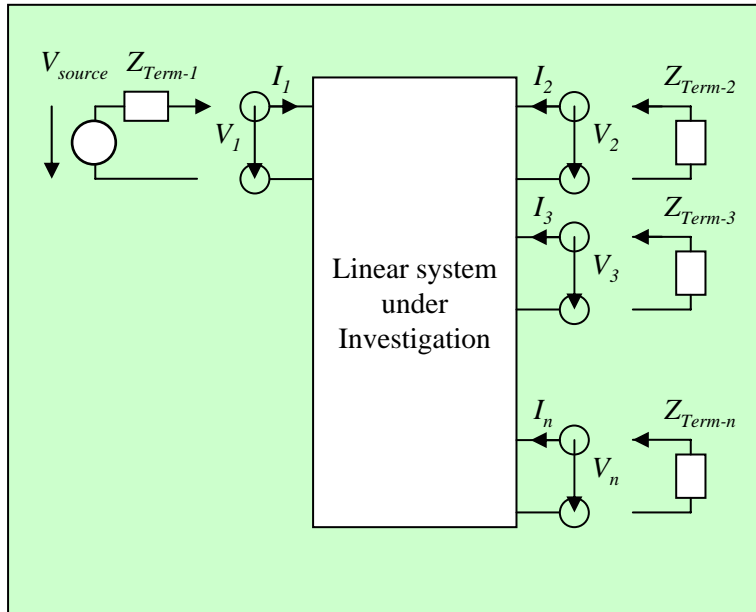
$$[I] = [Z + Z_{Term}]^{-1} \cdot [V_{source}]$$

- Based on port currents it is possible to compute input impedances and coupling factors.



$$Z_{in} = f(Z_{load1}, Z_{load2}, \dots, Z_{loadn})$$

Port Voltages and Currents



Linear N-Port:

$$[V] = [Z] \cdot [I] \quad Z_{ij} = \frac{V_{i-j}}{I_j}$$

Port terminations – Source and load:

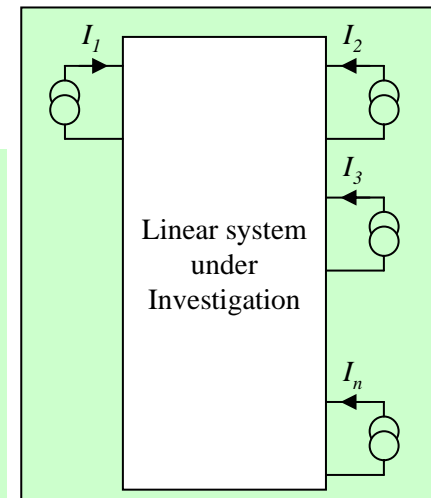
$$[V] = [V_{source}] - [Z_{Term}] \cdot [I]$$

Terminated N-Port:

$$[I] = [Z + Z_{Term}]^{-1} \cdot [V_{source}]$$

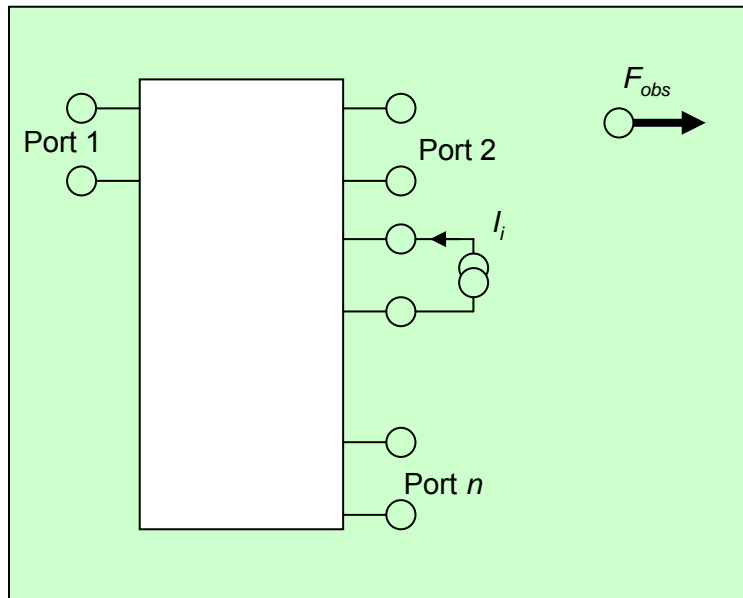
The radiation behavior of the system does not change when the port terminations are replaced by equivalent current sources.

This implies that radiation is only due to currents and charges on the system – Source and load elements do not contribute to radiated fields.



Port Currents and Field Strength

Full wave field simulations



Exciting port i while leaving all other ports open gives:

Feeding current I_i and voltage V_i

Voltages for other open ports V_{i-j}

$$\Rightarrow Z_{ij} = \frac{V_{i-j}}{I_i}$$

Electric or magnetic field strength at arbitrary observation point

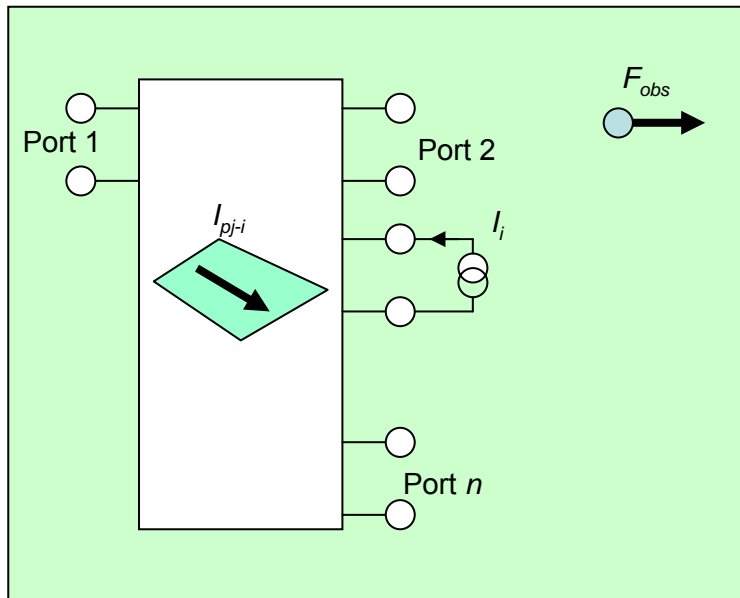
F_{obs-i}

n simulations give a complete description for a network with n accessible ports **including relationship between port current and field strength:**

$$a_i = \frac{F_{obs-i}}{I_i}$$

Port Currents and Field Strength

Principle of superposition



Field due to current on segment/patch j when feeding port i with I_i :

$$F_{obs-i-j} = f_j \cdot I_{pj-i} = f_j \cdot (p_{ji} \cdot I_i)$$

Total field when feeding port i with I_i :

$$F_{obs-i} = \sum_{j=1}^{n_{patch}} (f_j \cdot p_{ji}) \cdot I_i = a_i \cdot I_i$$

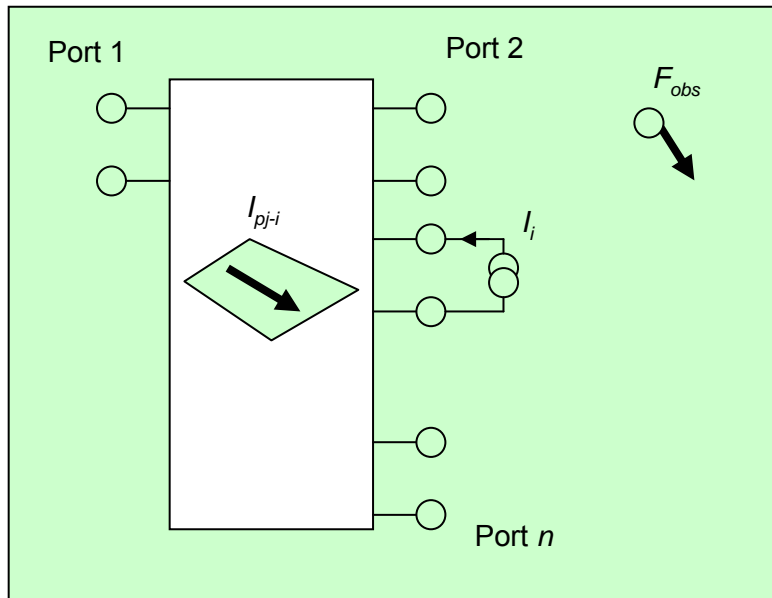
The current on each segment/patch can be expressed as superposition of contributions from all ports currents:

$$I_{pj} = \sum_{i=1}^{n_{port}} p_{ji} \cdot I_i$$

$$\text{Total field: } F_{obs} = \sum_{j=1}^{n_{patch}} (f_j \cdot I_{pj}) = \sum_{j=1}^{n_{patch}} \left(f_j \cdot \sum_{i=1}^{n_{port}} p_{ji} \cdot I_i \right) = \sum_{i=1}^{n_{port}} \left(\sum_{j=1}^{n_{patch}} f_j \cdot p_{ji} \right) \cdot I_i = \sum_{i=1}^{n_{port}} a_i \cdot I_i$$

Port Currents and Field Strength

Principle of superposition



Total field:
$$F_{obs} = \sum_{i=1}^{n_{port}} a_i \cdot I_i$$

$$a_i = \frac{F_{obs-i}}{I_i}$$

Known from initial field simulations.

New port currents I_i can be computed for varying source/load scenarios from:

$$[I] = [Z + Z_{Term}]^{-1} \cdot [V_{source}]$$

No need for repeating field simulation when changing port terminations!

Procedure

Excite each port individually, leaving the other ports open.

N-Port Z-matrix

$$Z_{ij} = \frac{V_{i-j}}{I_j}$$

'field factors' \vec{a}_j

$$\begin{bmatrix} a_{j-x} \\ a_{j-y} \\ a_{j-z} \end{bmatrix} = \frac{1}{I_j} \begin{bmatrix} F_{obs-x} \\ F_{obs-y} \\ F_{obs-z} \end{bmatrix}$$

Calculate new port currents.

$$[I] = [Z + Z_{Term}]^{-1} \cdot [V_{source}]$$

Obtain new field strength values

$$\vec{F}_{obs} = \sum_{i=1}^n \vec{a}_i I_i$$

Example

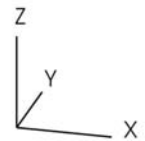
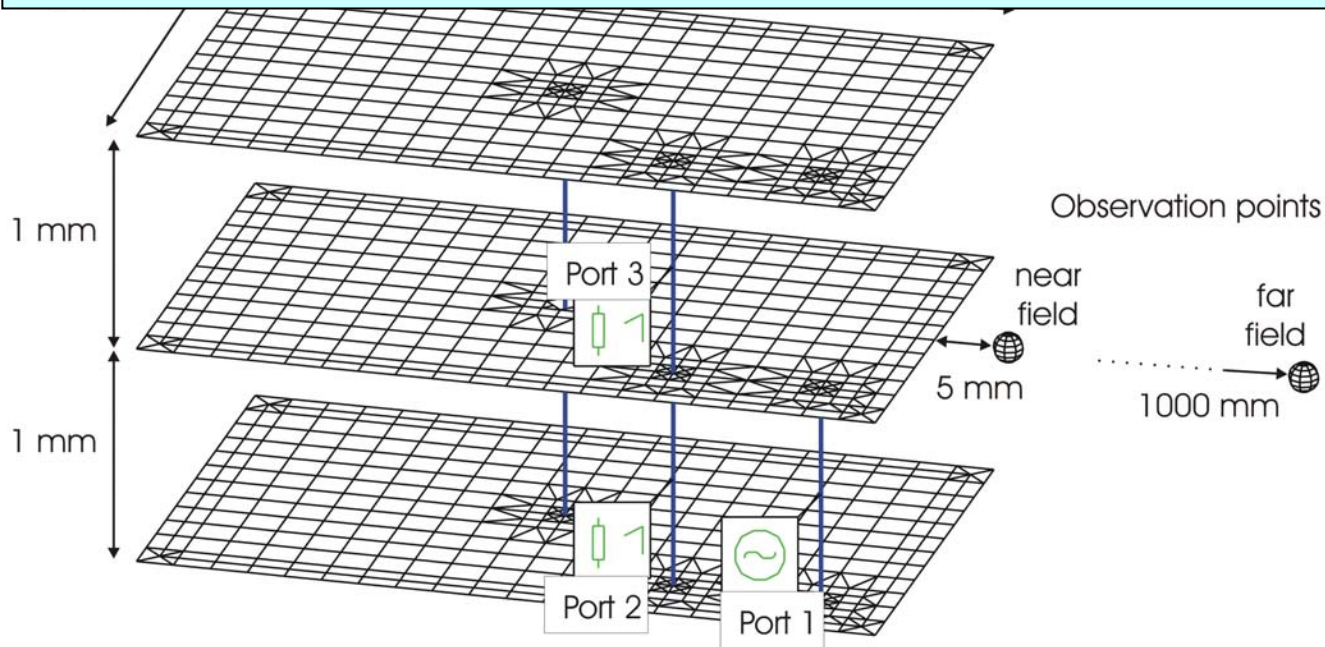
Excite each port individually, leaving the other ports open.

N-Port Z-matrix

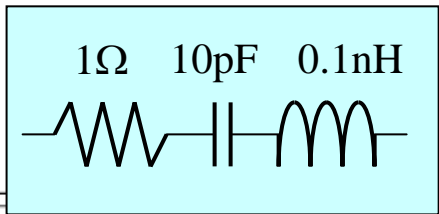
'field factors' \vec{a}_j

$$Z_{ij} = \frac{V_{i-j}}{I_j}$$

$$\begin{bmatrix} a_{j-x} \\ a_{j-y} \\ a_{j-z} \end{bmatrix} = \frac{1}{I_j} \begin{bmatrix} F_{obs-x} \\ F_{obs-y} \\ F_{obs-z} \end{bmatrix}$$



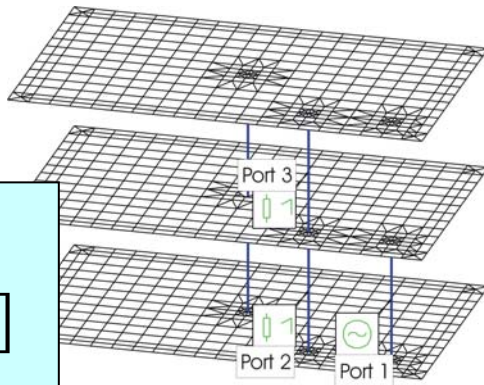
Example



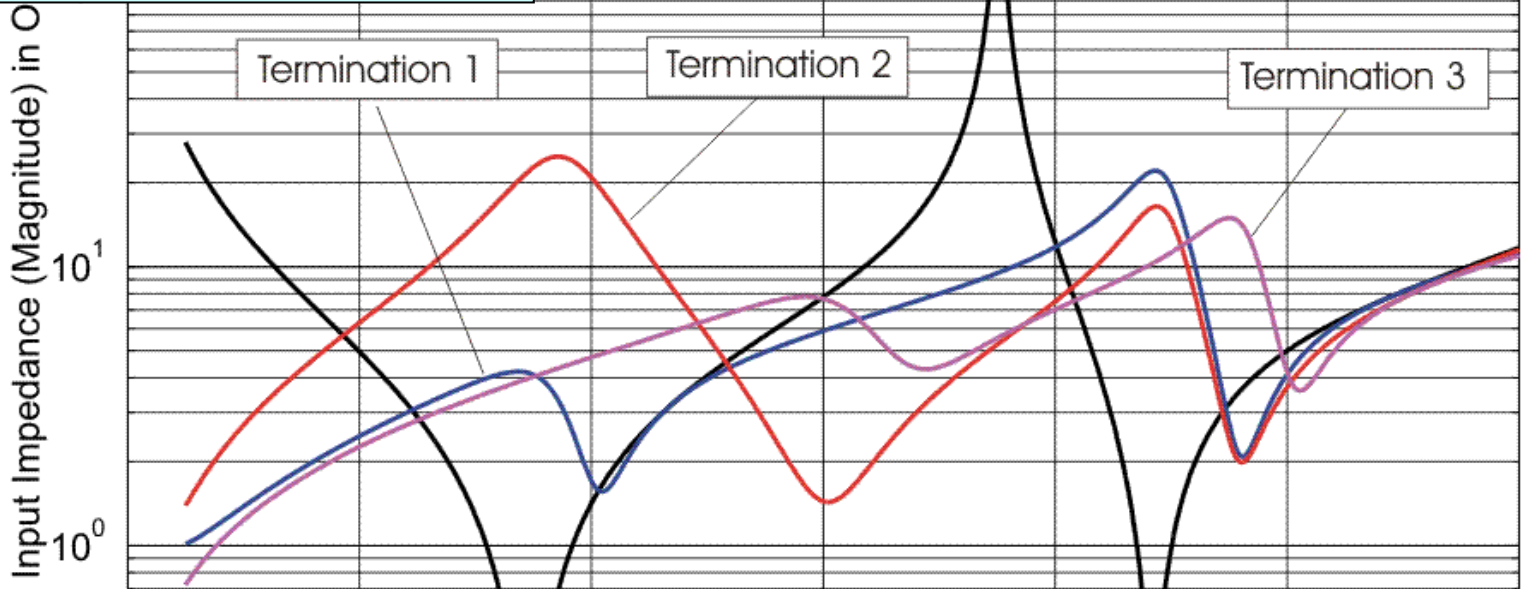
Input Impedance

$$[I] = [Z + Z_{Term}]^{-1} \cdot [V_{source}]$$

$$[V] = [V_{source}] - [Z_{Term}] \cdot [I]$$



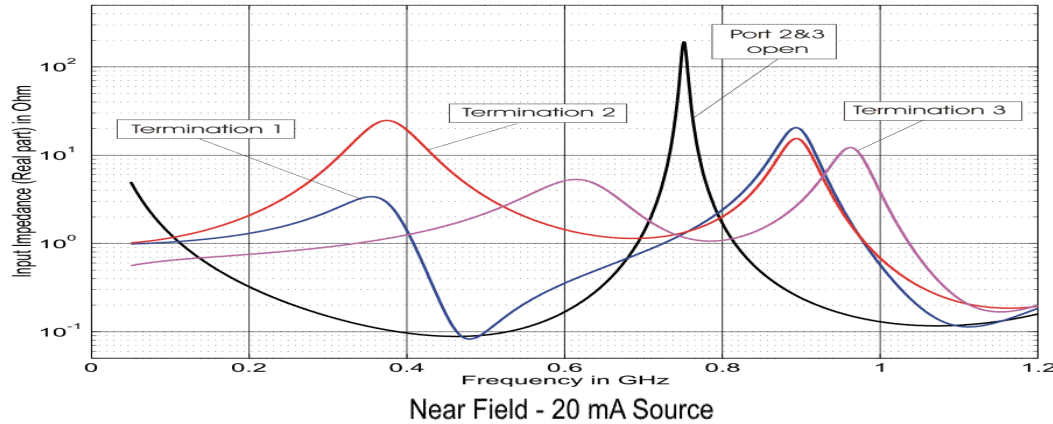
Port 2&3 open



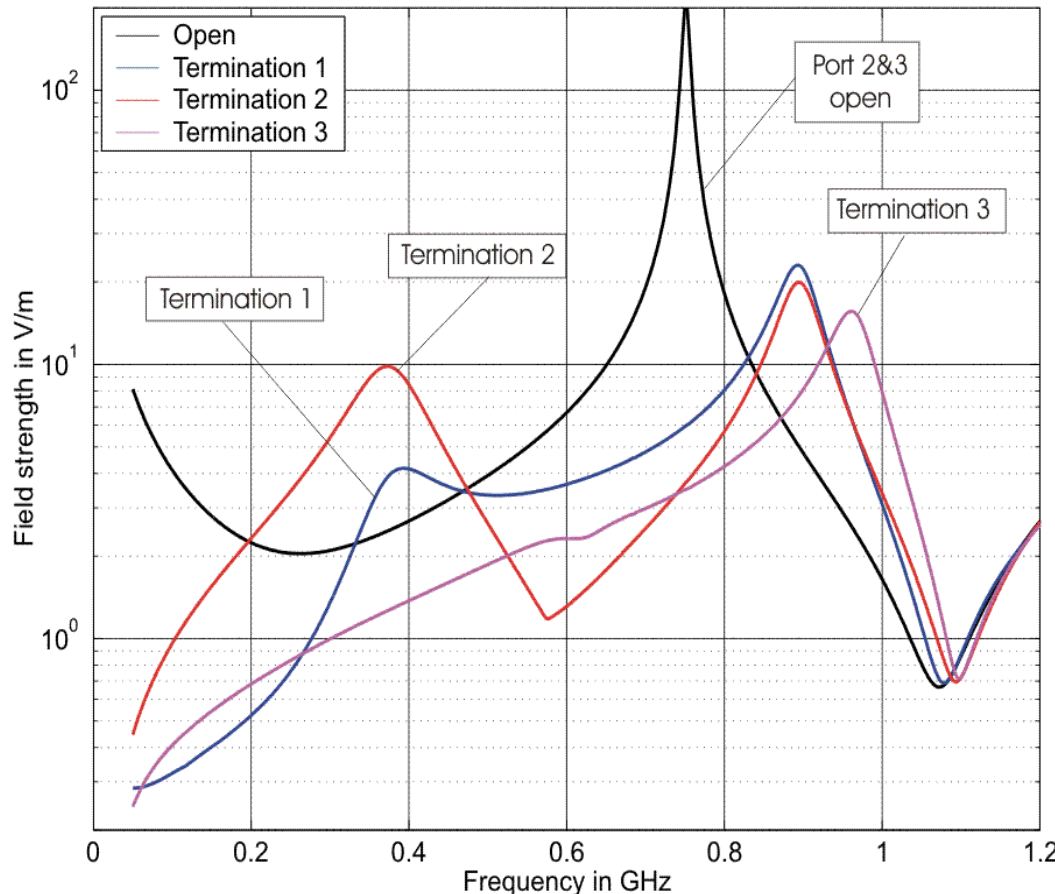
Calculate new port currents.

$$[I] = [Z + Z_{Term}]^{-1} \cdot [V_{source}]$$

Example



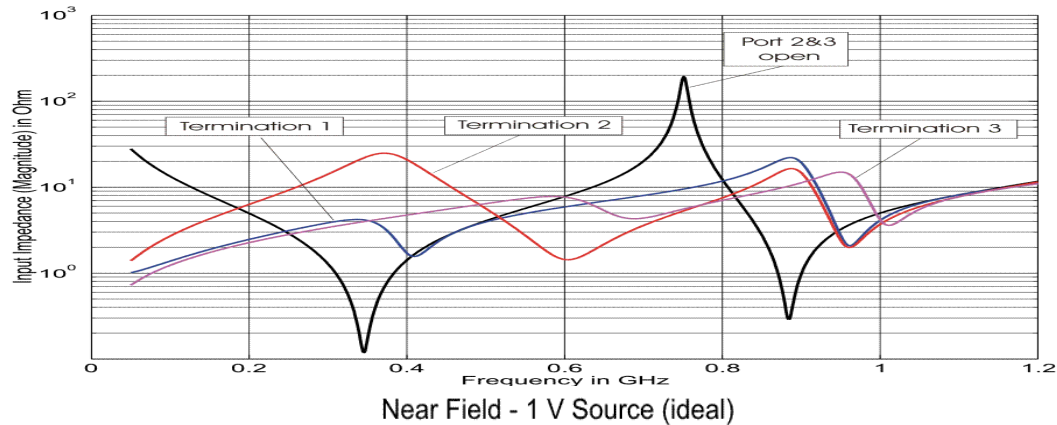
Input impedance
(Real part)



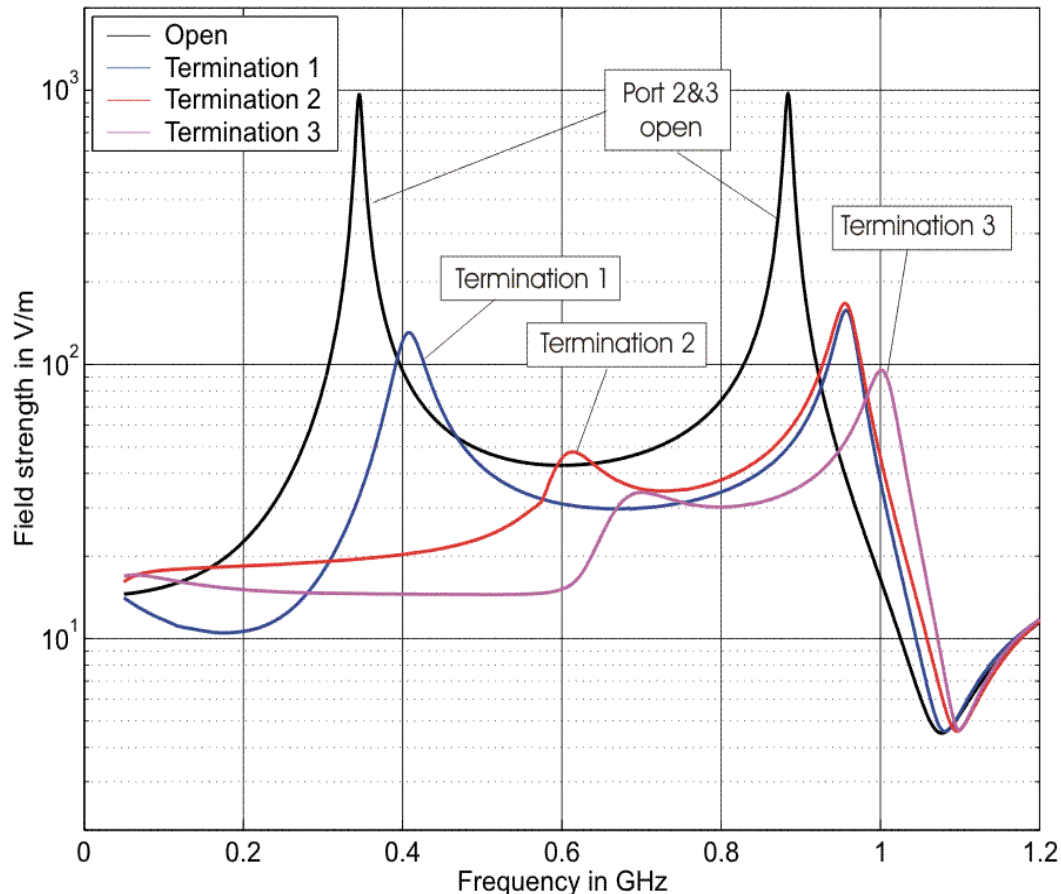
Electric near field
(Source: 20 mA)

Field follows real
part of input
impedance in
general, especially
around peaks.

Example



Input impedance
(Magnitude)

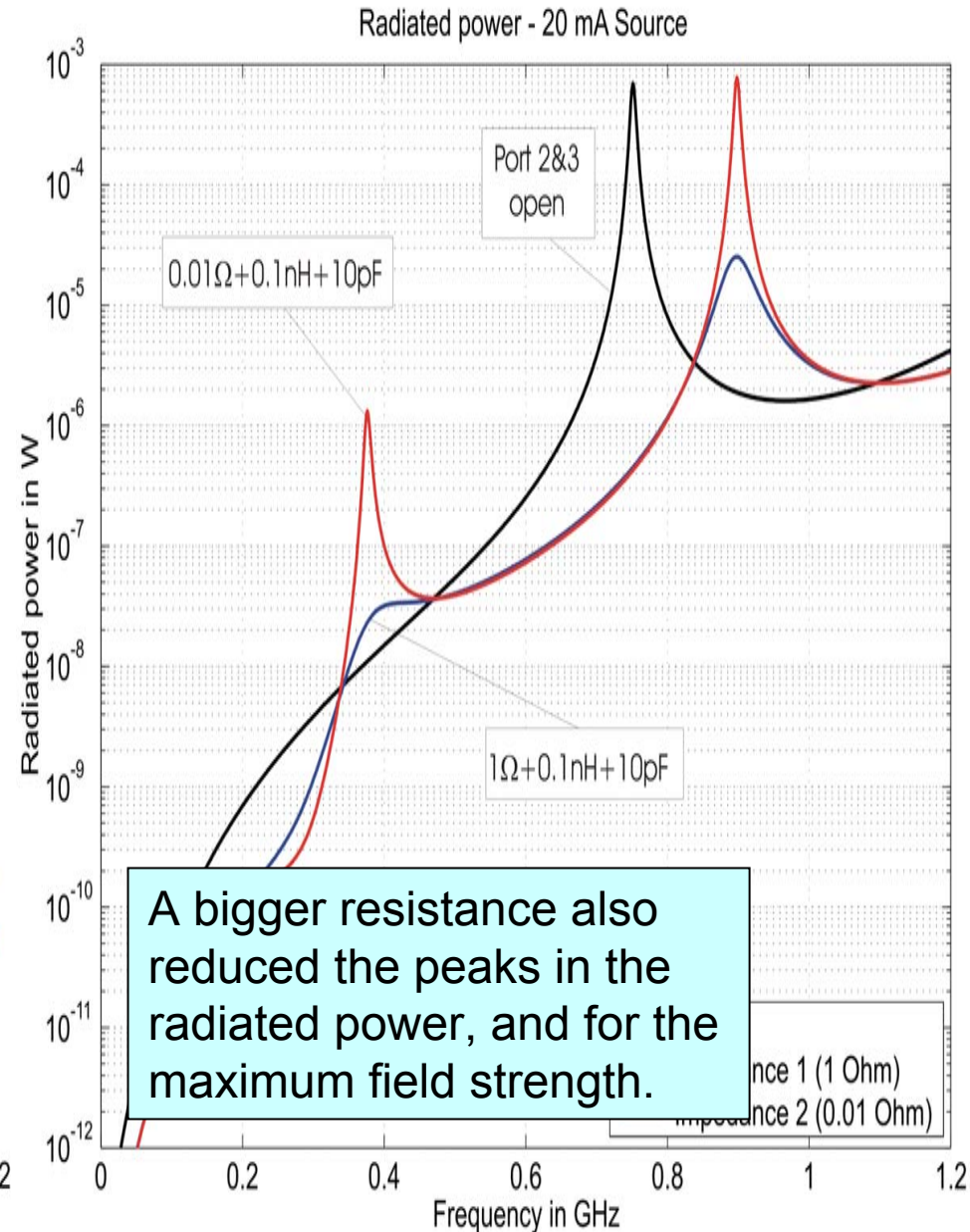
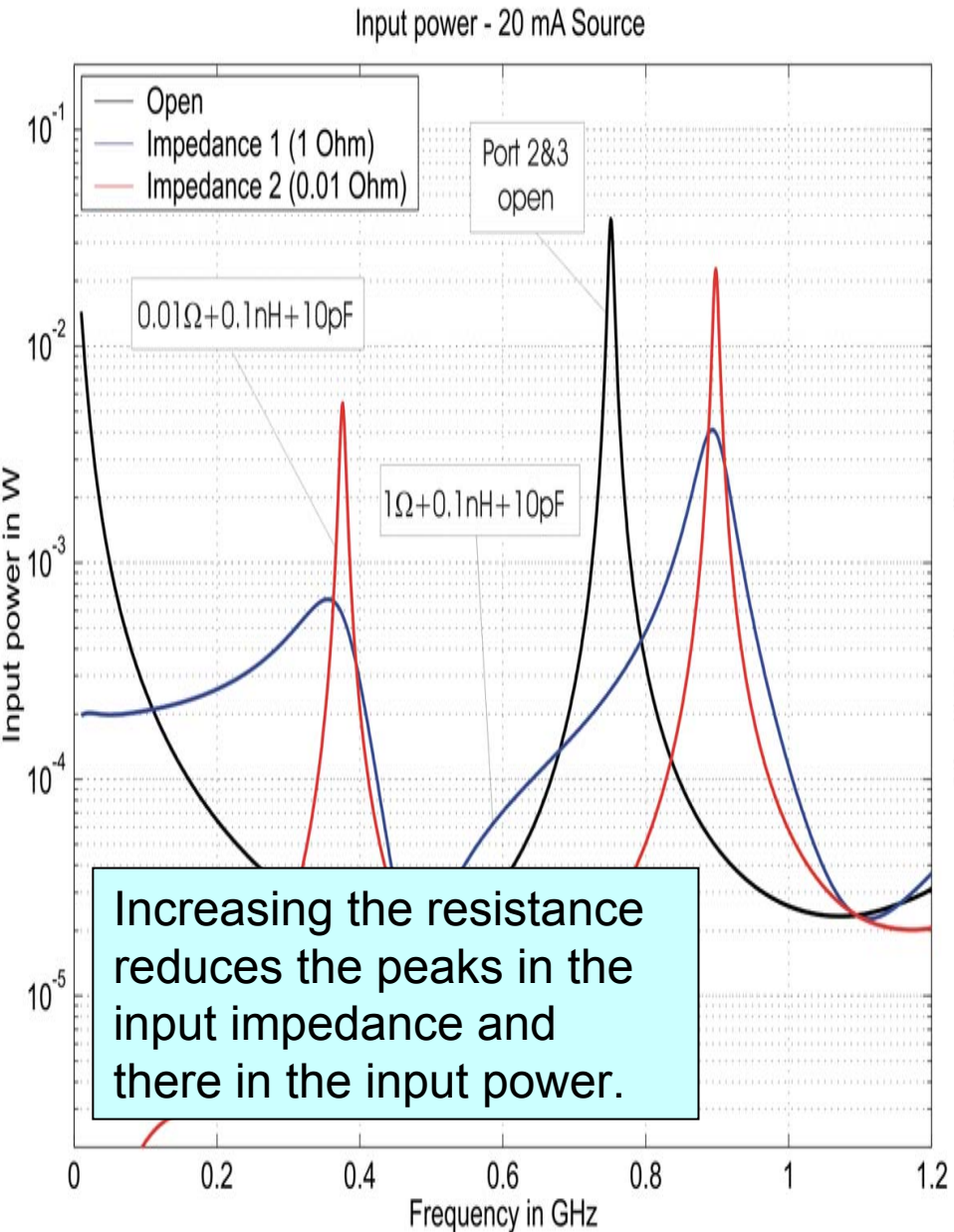


Electric near field
(Source: 1V)

Field follows input admittance in general, especially around minima.

Example

Input power and radiated power



Example

Table 1: Computation times

Process	Time	Repetition
Field simulation (25 frequencies)	200 Min	For each port
Field strength at 762 observation points for each frequency	4 Min	For each port
Interpolation (25 \Rightarrow 1200 frequencies)	5 Min	For each port
Reading all interpolated field data ($\sim 8.3 \cdot 10^6$ complex numbers)	10 Min	Once
New port currents and new field strength values (762 points)	6 Sec	For each new excitation and termination scenario