

Numerical Field Simulation for EMC

Dr. Franz Schlagenhauer

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franz-s@watri.org.au

<http://www.watri.org.au>

The University of Western Australia

Western Australian Telecommunications Research Institute (WATRI)

Australian EMC Environment

Very little high-volume manufacturing of electrical and electronic goods

⇒ Little demand for standard compliance testing

Design and manufacturing of products for niche markets

⇒ Test houses are challenged to perform many different kind of tests on different products, but there is high-volume testing

Large infrastructure projects

⇒ Demand for System level EMC should be expected (Mining sector,

National defence industry

⇒ EMC test facilities for military equipment exist; EMC research related to EMC is done, mostly in co-operation with overseas partners (UK, US, Europe)

EMC at the Western Australian Telecommunications Research Institute (WATRI)

WATRI is a joint venture of two Perth Universities (The University of Western Australia, and Curtin University of Technology). The EMC Group at WATRI was and is involved in a number of research projects.

1. Analysis of power/ground planes on Printed circuit boards (PhD project, finished)
2. The field around open via ports on printed circuit boards (PhD project, ongoing)
3. Near Field – Far Field conversion based on Genetic Algorithms (PhD project, ongoing)
4. Radiation from PCB traces dependent on matching techniques (Master project, finished)
5. EMC for lighting installations (Master project, due to start in 2008)
6. Simulation of reverberation chambers and design of hybrid TEM/Reverberation test chambers (investigation in cooperation with University of South Australia)
7. Measurement techniques for large machines (investigation in cooperation with Technical University Dresden, Germany)
8. Investigation of shielding enclosures with slots (WATRI internal project)

Introduction

- Simulation is based on modelling, i.e. the transformation of a *physical model* into a *mathematical equation system* which is then solved by a computer.
- This transformation is based on physical principles, in our case mainly on *Maxwell's equations* or derivations from them.
- Hopefully, the *solution of the equations system*, resulting numbers represent *meaningful physical quantities for the original physical model*.

Introduction

- 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 simulator.*

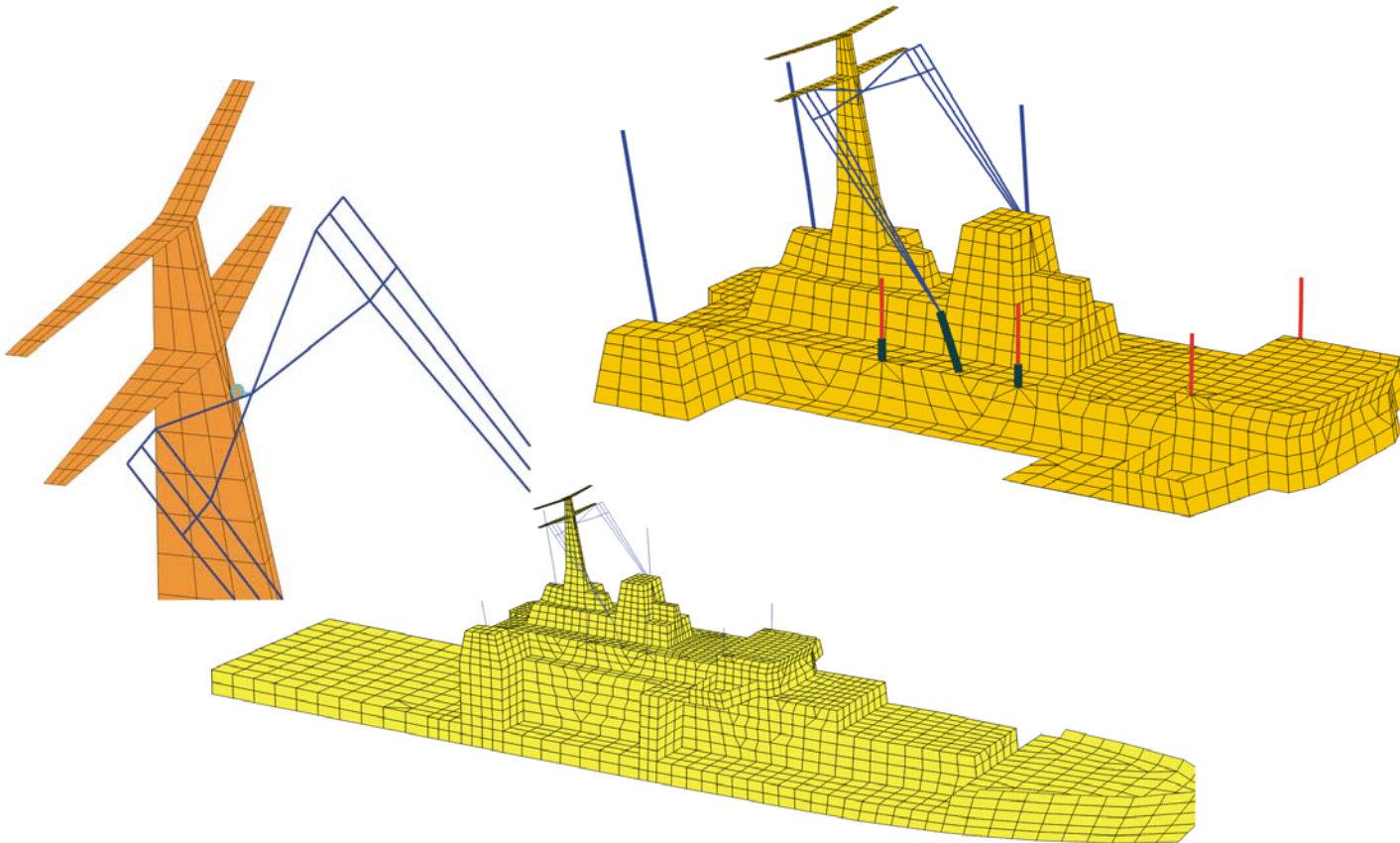
Reasons for a Simulation

- **Prototype not available**
 - Antenna arrangement on ship or aircraft during design phase
- **Controlled variation of parameters not possible**
 - 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**
 - The field between power-ground planes on a PCB; or SAR values in a dielectric body

Prototype not available

Antenna arrangement on ship or aircraft during design phase

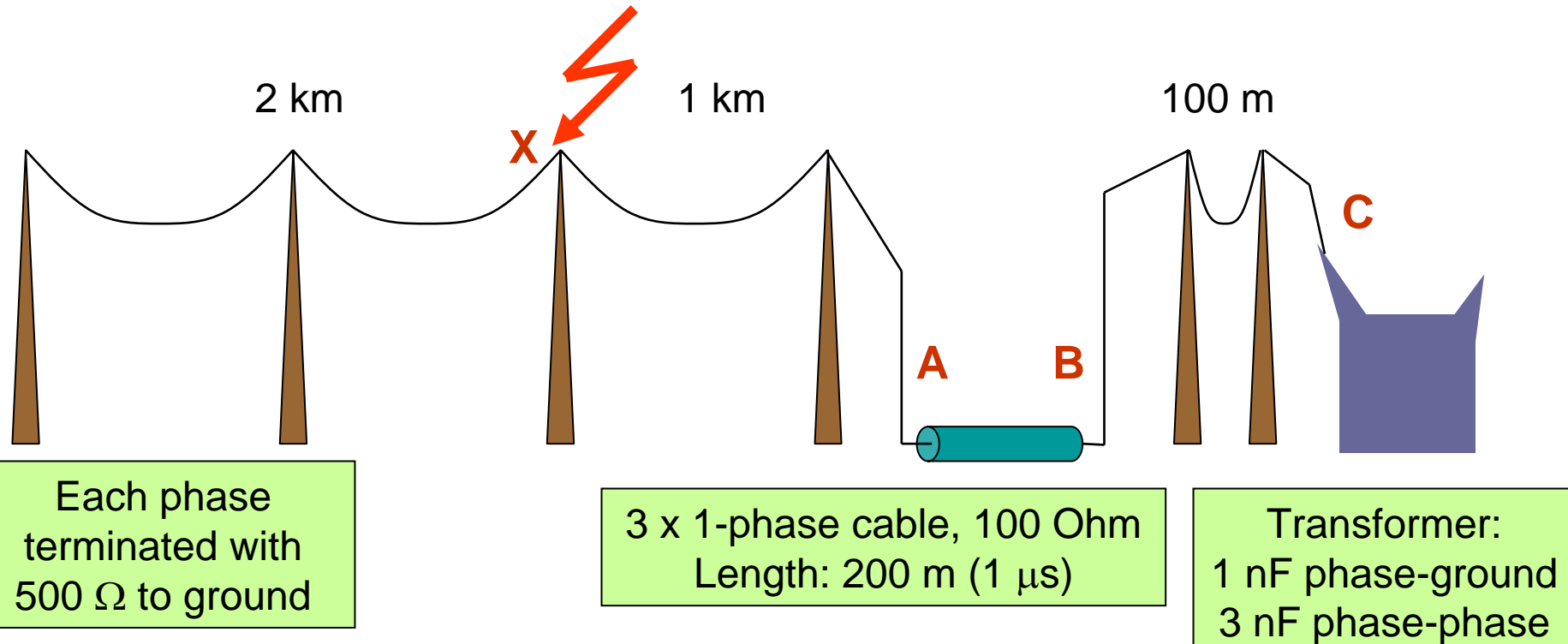
CONCEPT-Data: HF - Model



Controlled variation of parameters not possible

Voltage induced by lightning strokes: comparison of different over-voltage protection devices

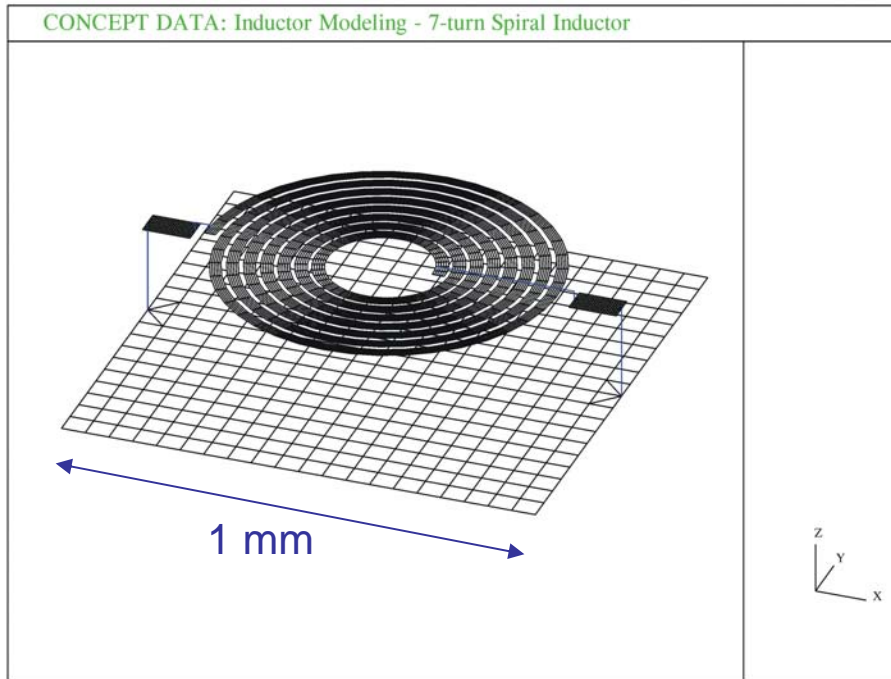
3-phase overhead transmission line



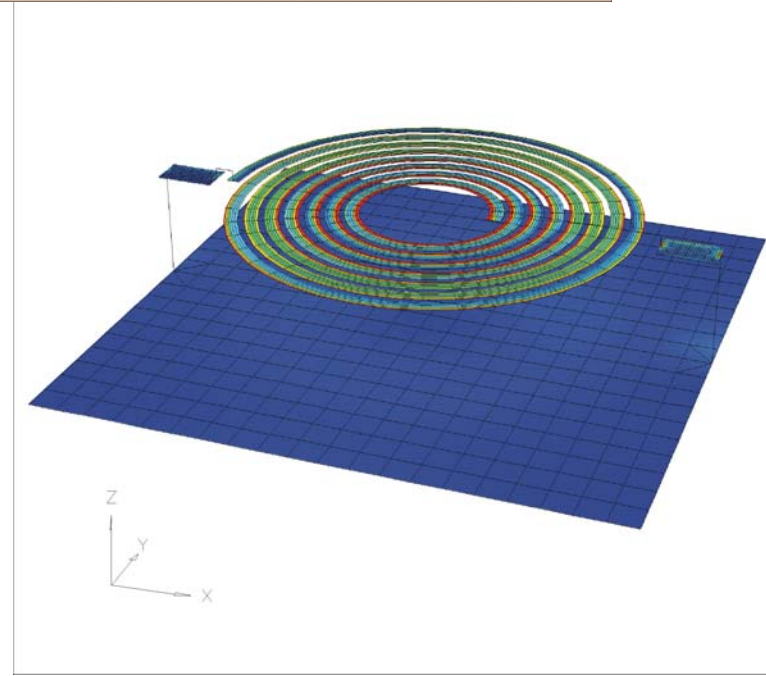
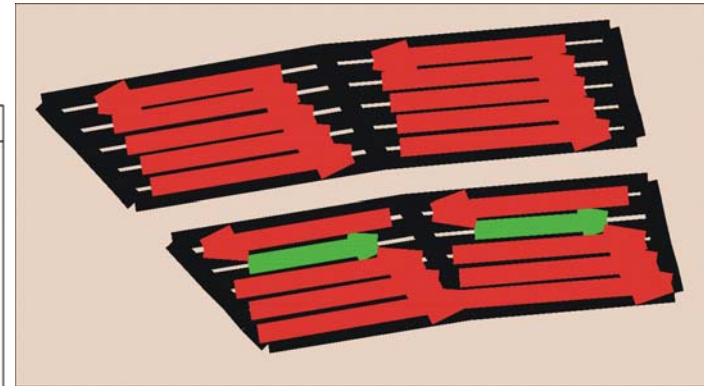
The cables A-B and the Transformer C have to be protected against lightning:
Where to place a surge arrester, at A, B, C, or everywhere?

Physical value of interest not (easily) accessible

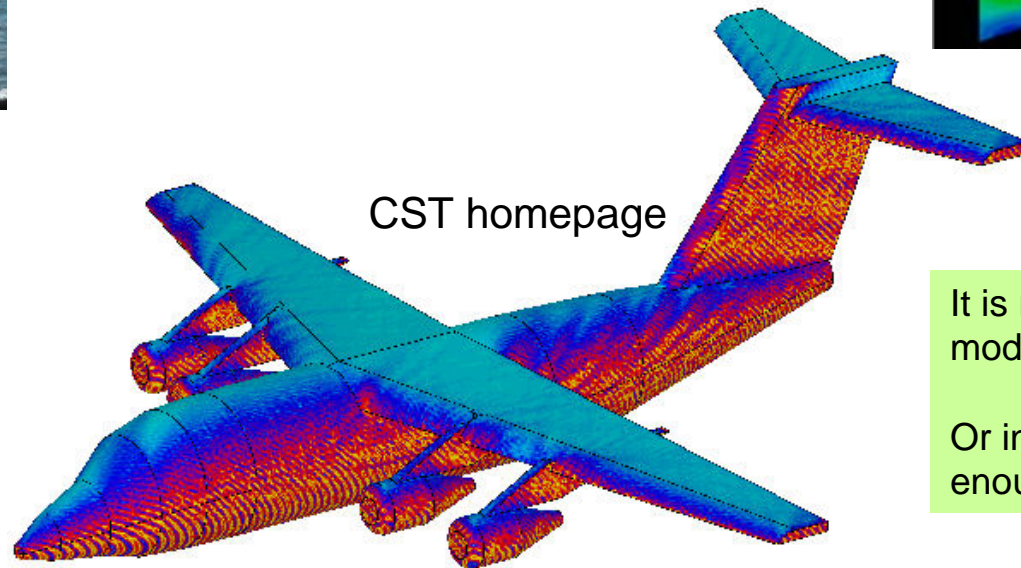
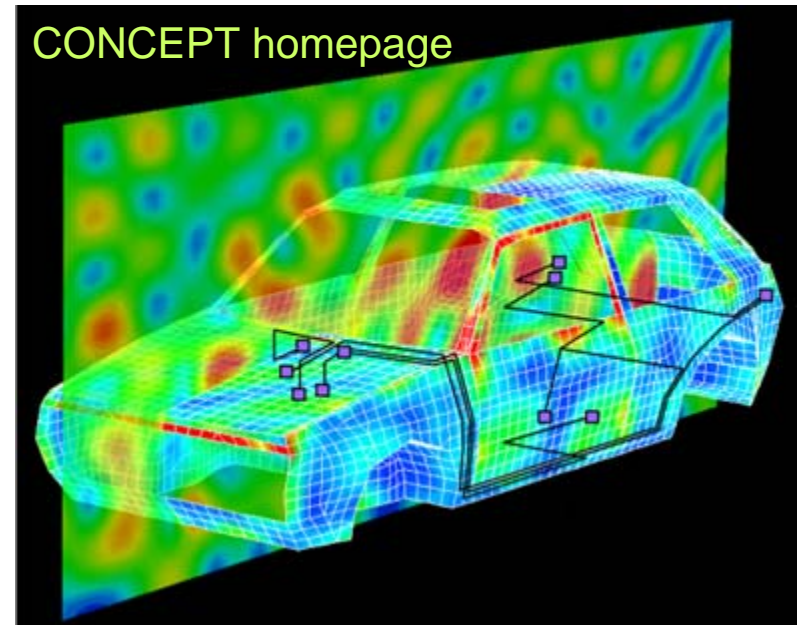
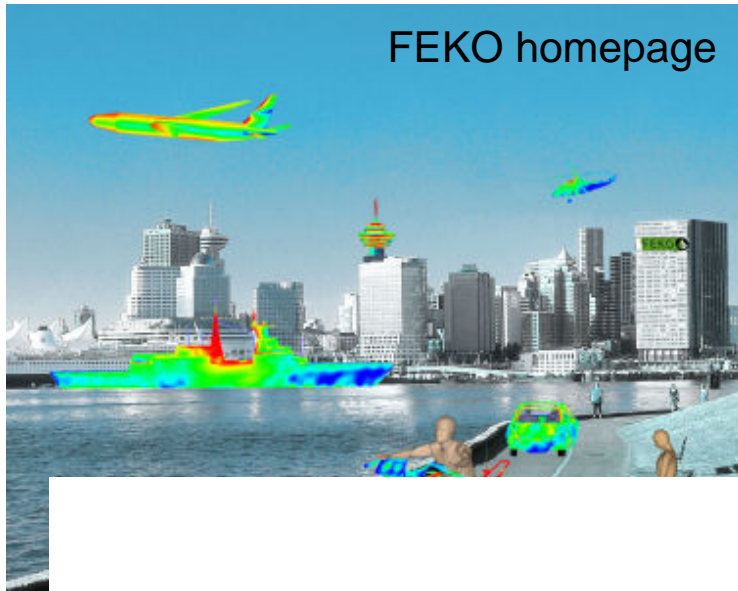
- The field between power-ground planes on a PCB; or SAR values in a dielectric body



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



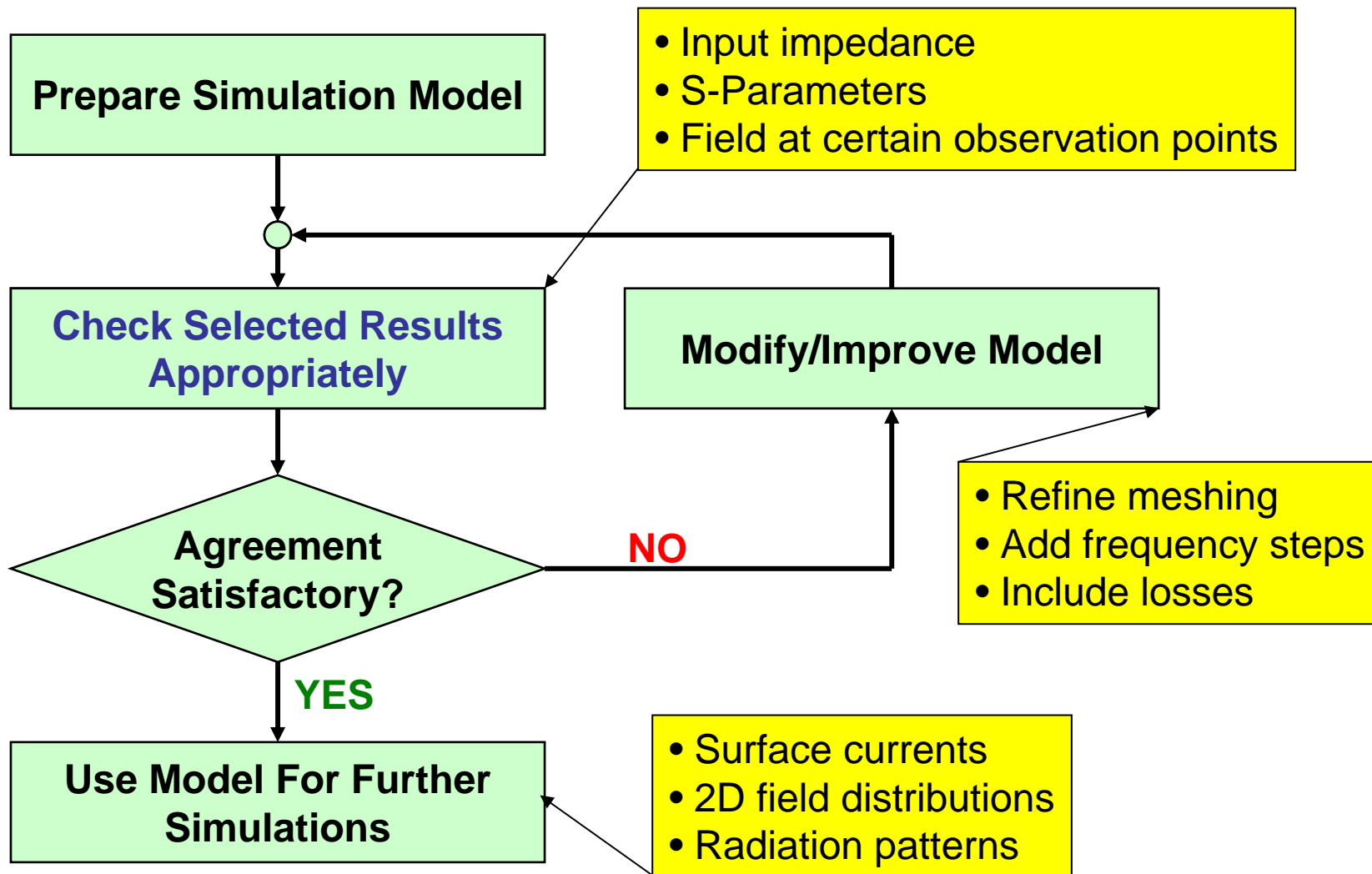
Everything is possible!



It is really sufficient to make a detailed enough model to get good results?

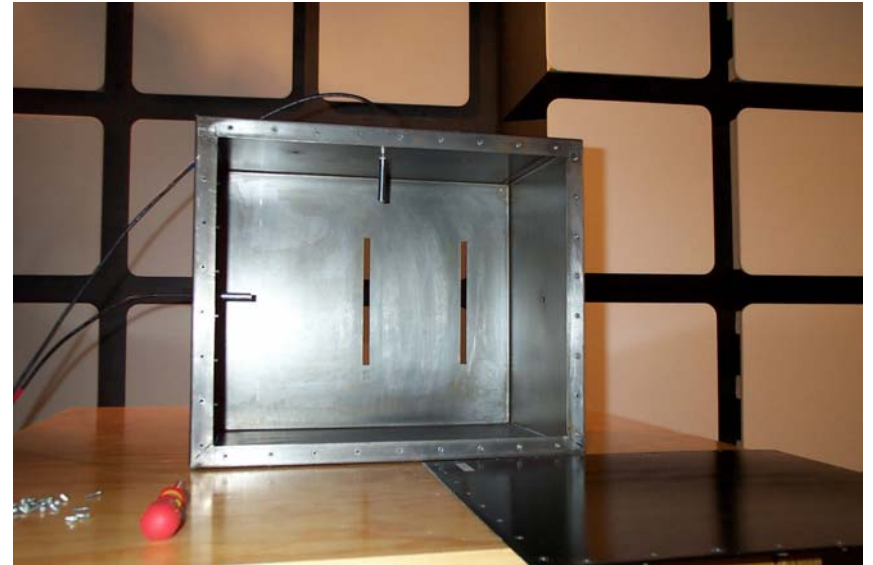
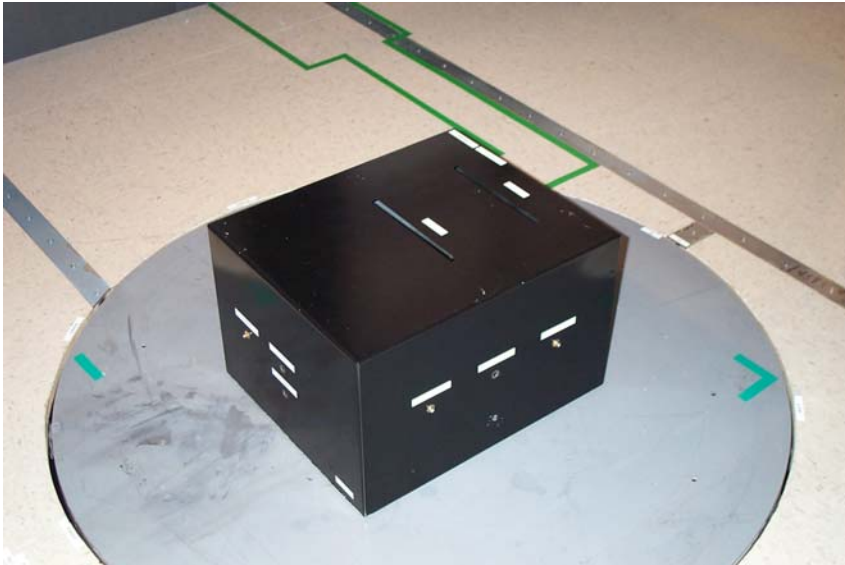
Or in other words: can a model really be made in enough detail to get good results?

Simulation Procedure



Simulation Procedure

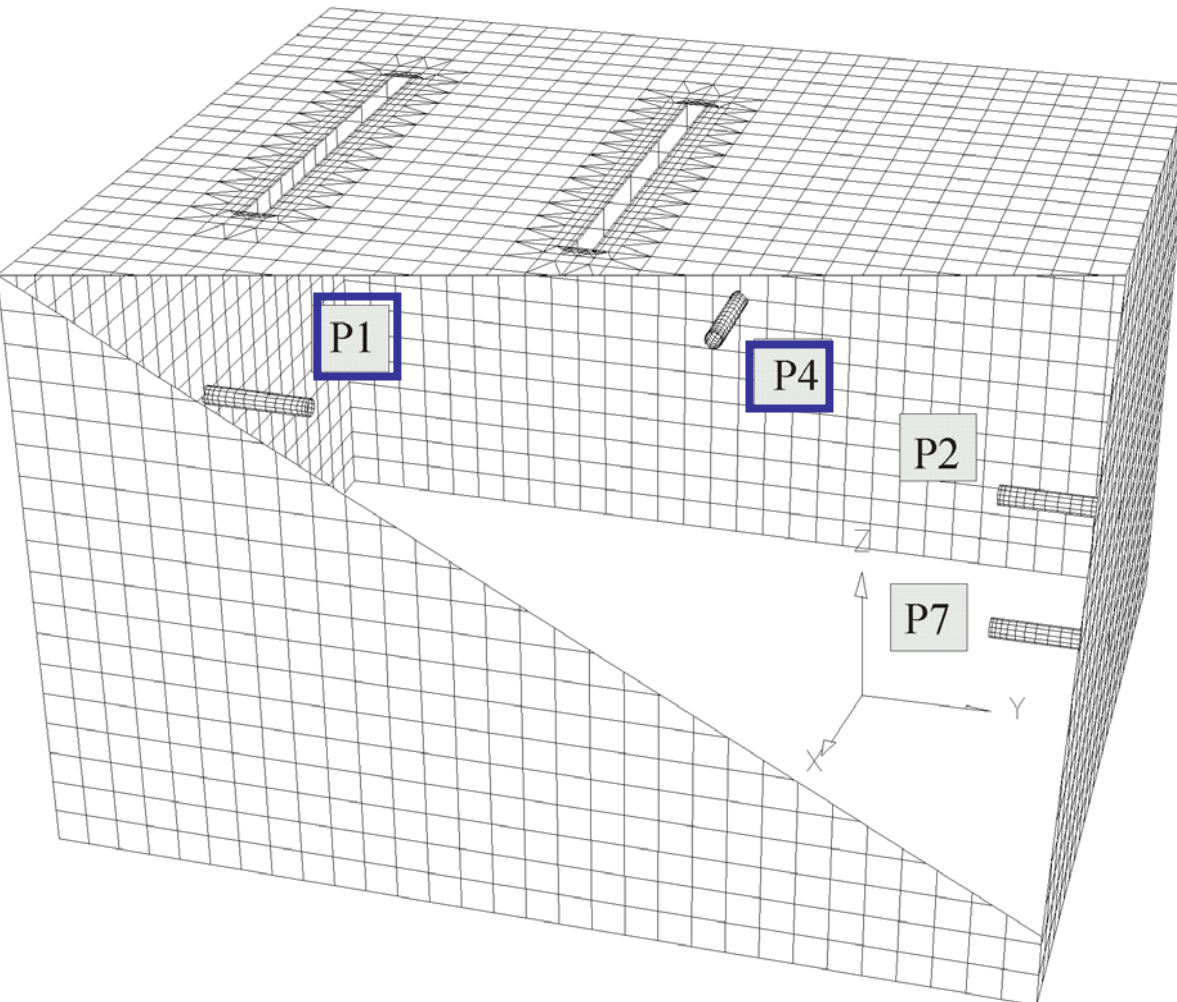
Generic Model – Empty Metal Box With Slots



- 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

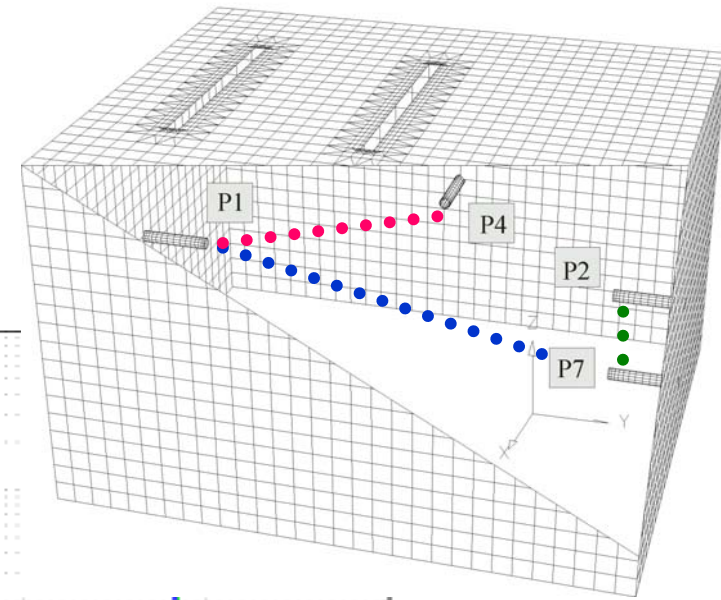
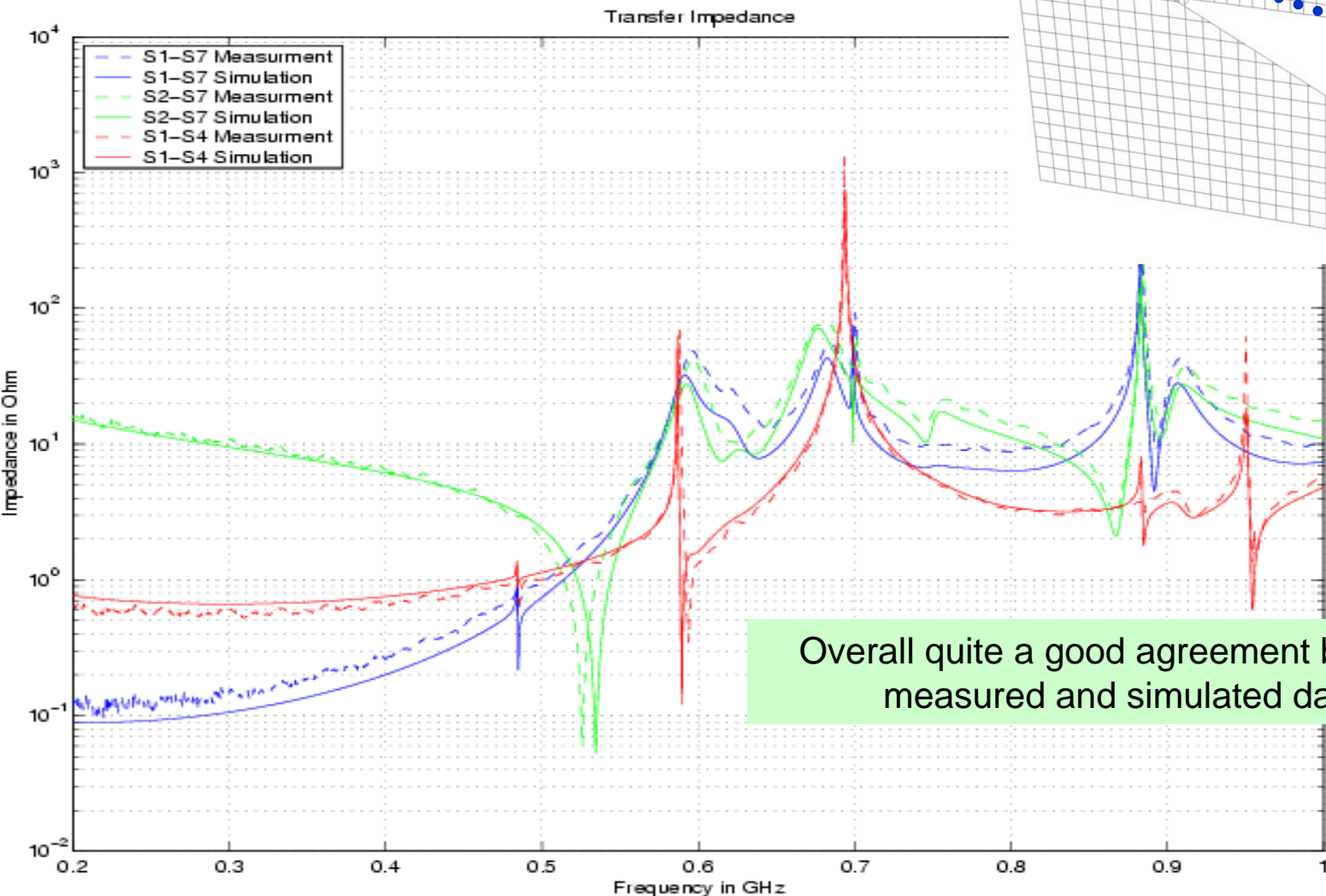
Indicator for relationship between electric and magnetic field and feeding/load current and voltage.

Transfer impedance

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

⋮

Simulation Procedure

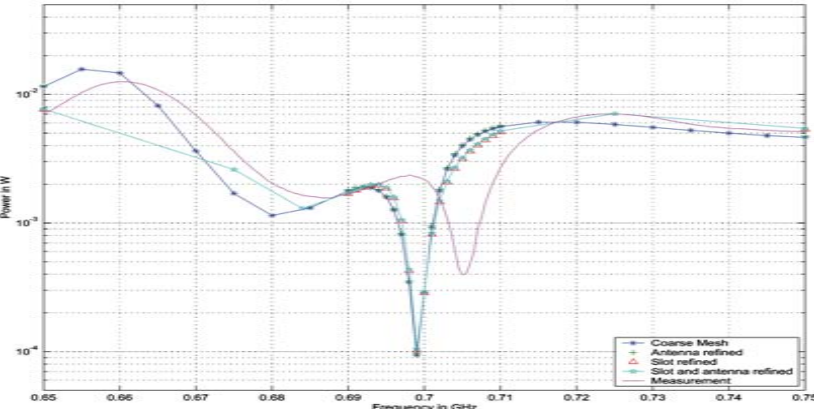
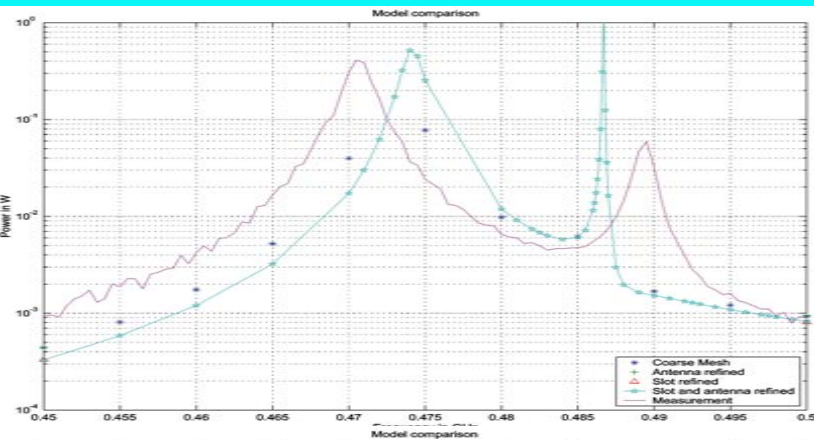


Overall quite a good agreement between measured and simulated data.

Power Budget

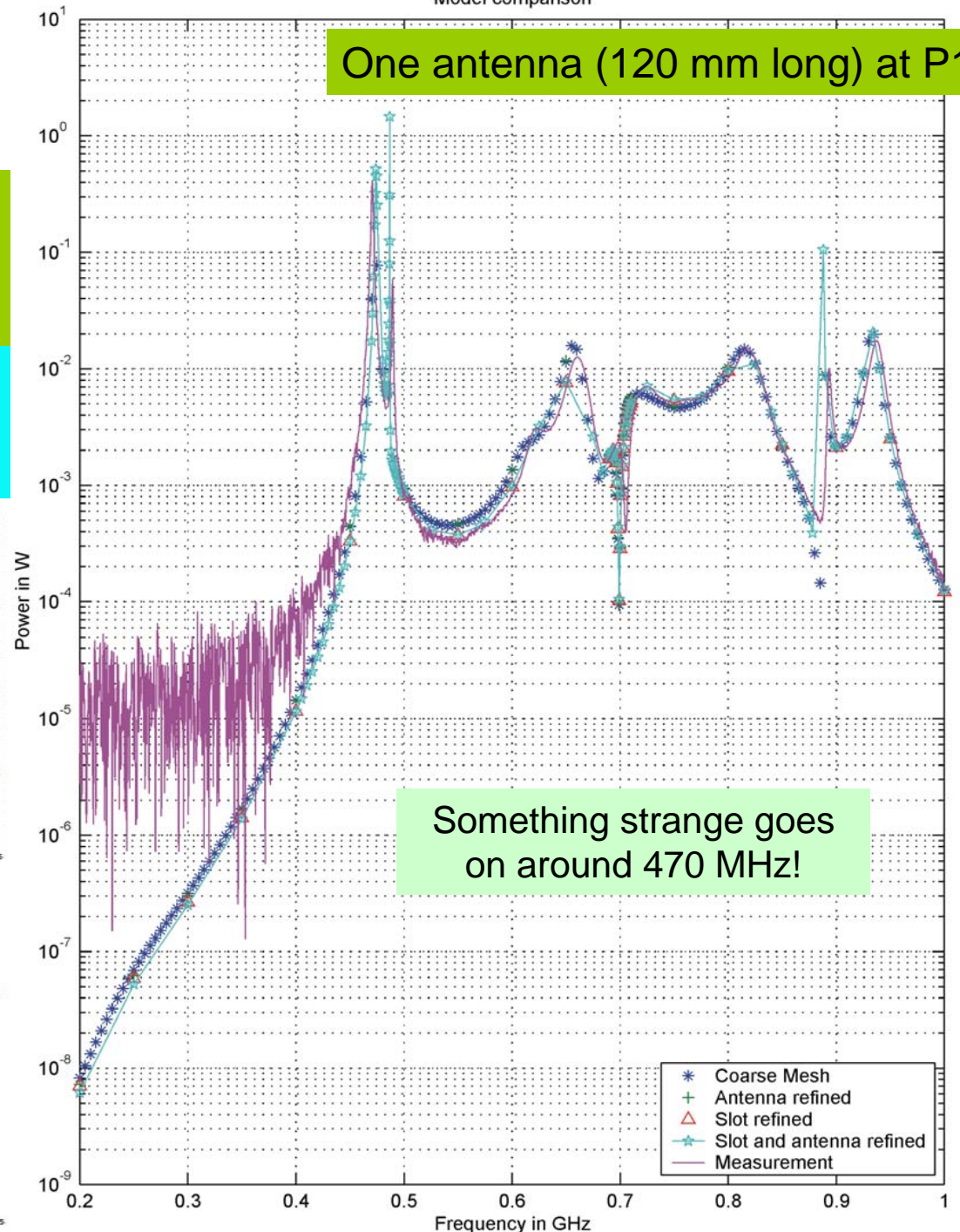
Measured Input Power
Simulated Radiated Power

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



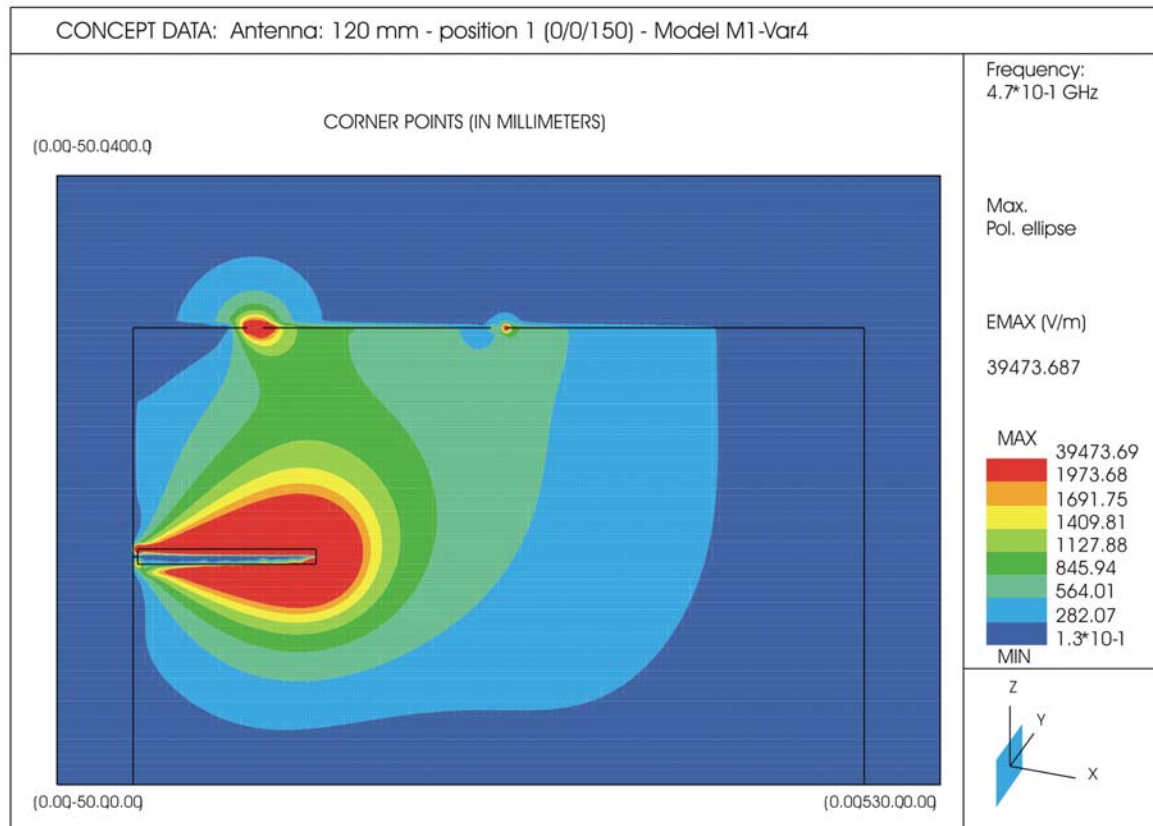
Model comparison

One antenna (120 mm long) at P1



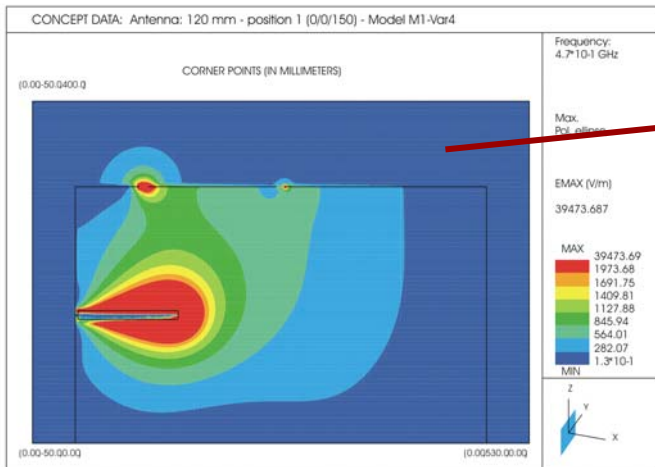
Something strange goes on around 470 MHz!

Simulation Procedure



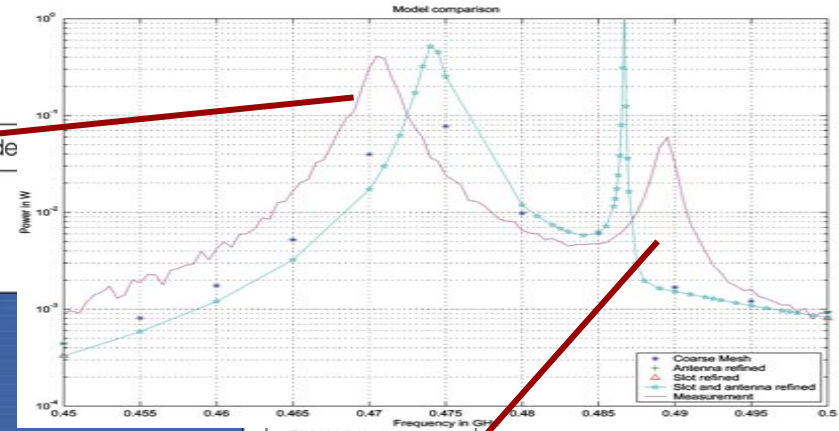
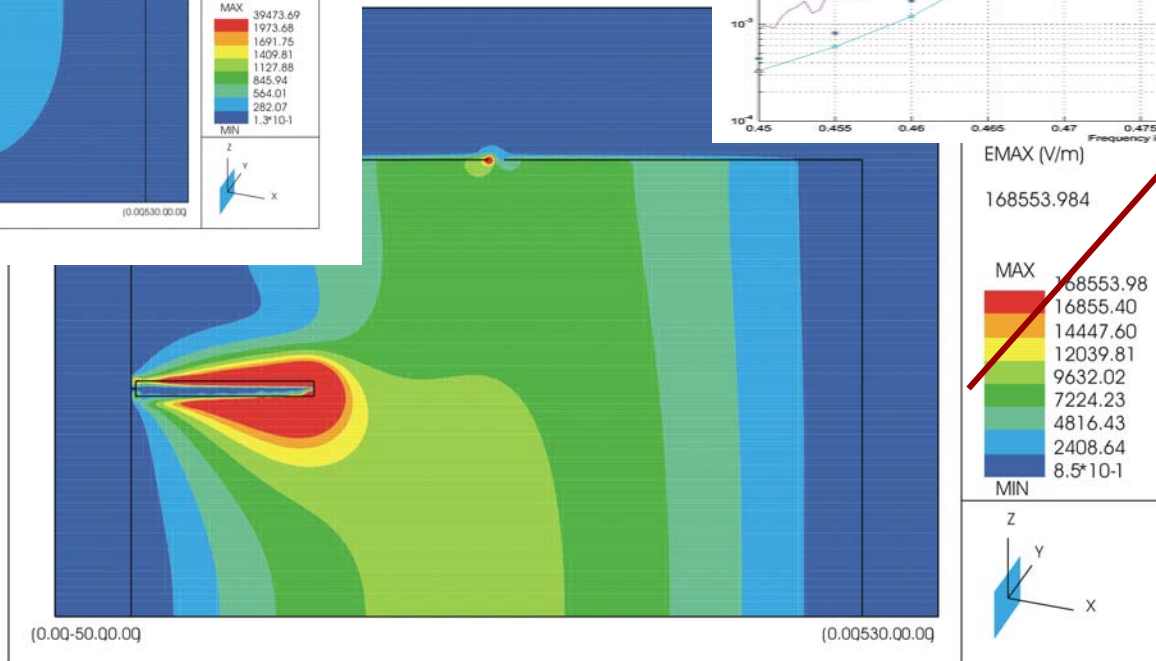
470 MHz: High field strength around slots leads to significant radiation – this is the dominant loss mechanism and modeling the box as perfect conductor is perfectly fine.

Simulation Procedure



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

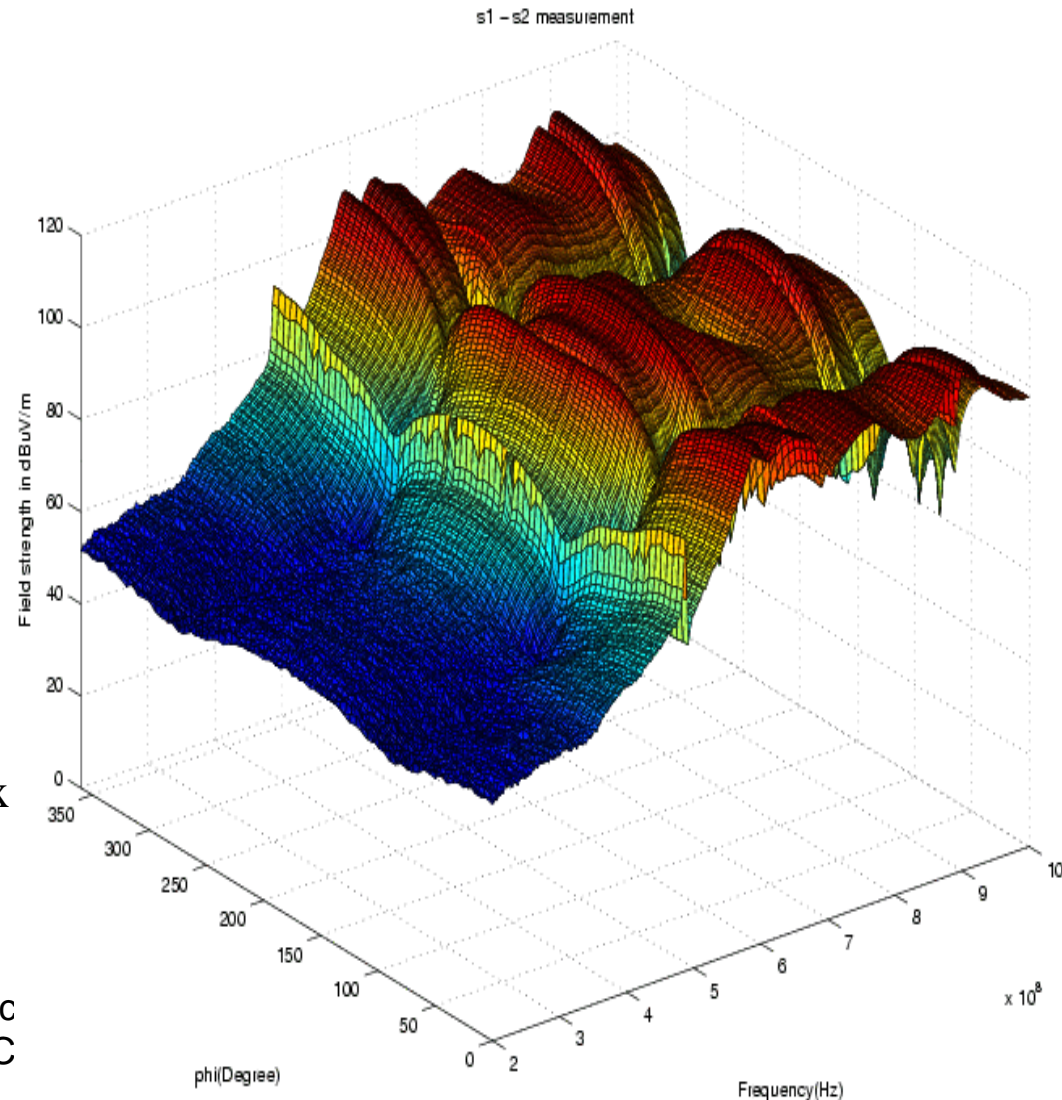
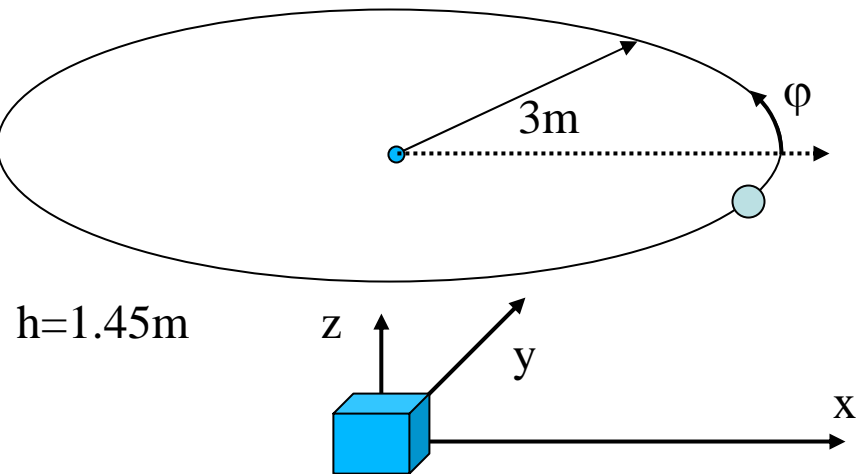
NER POINTS (IN MILLIMETERS)



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!)

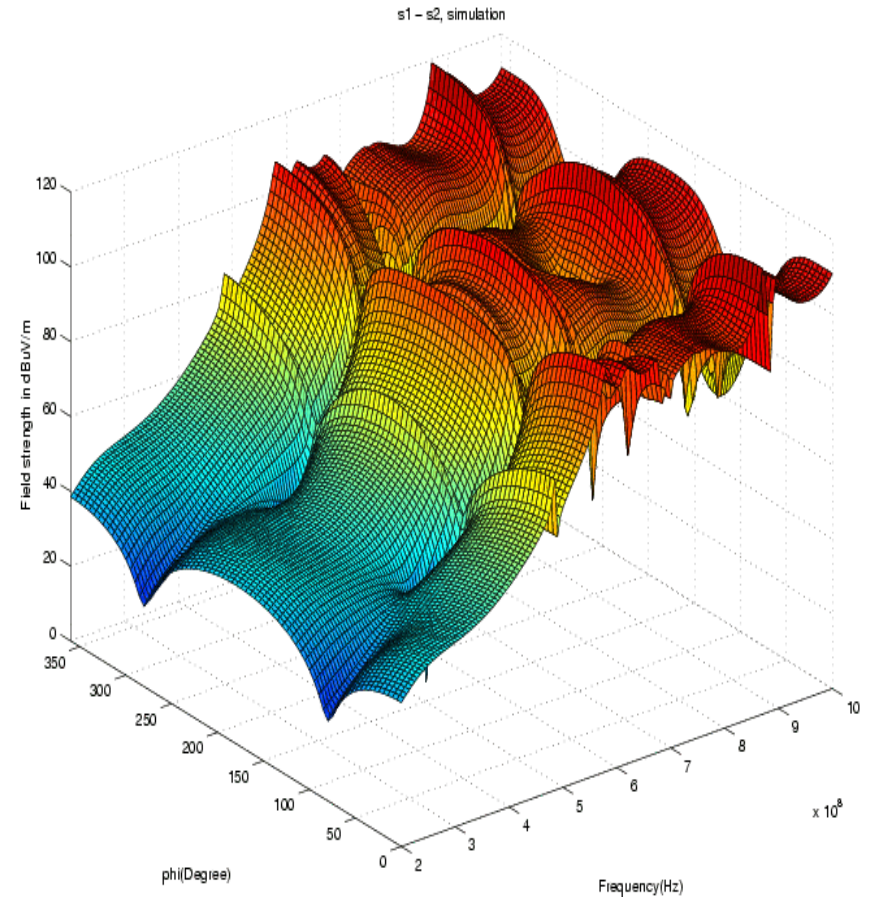
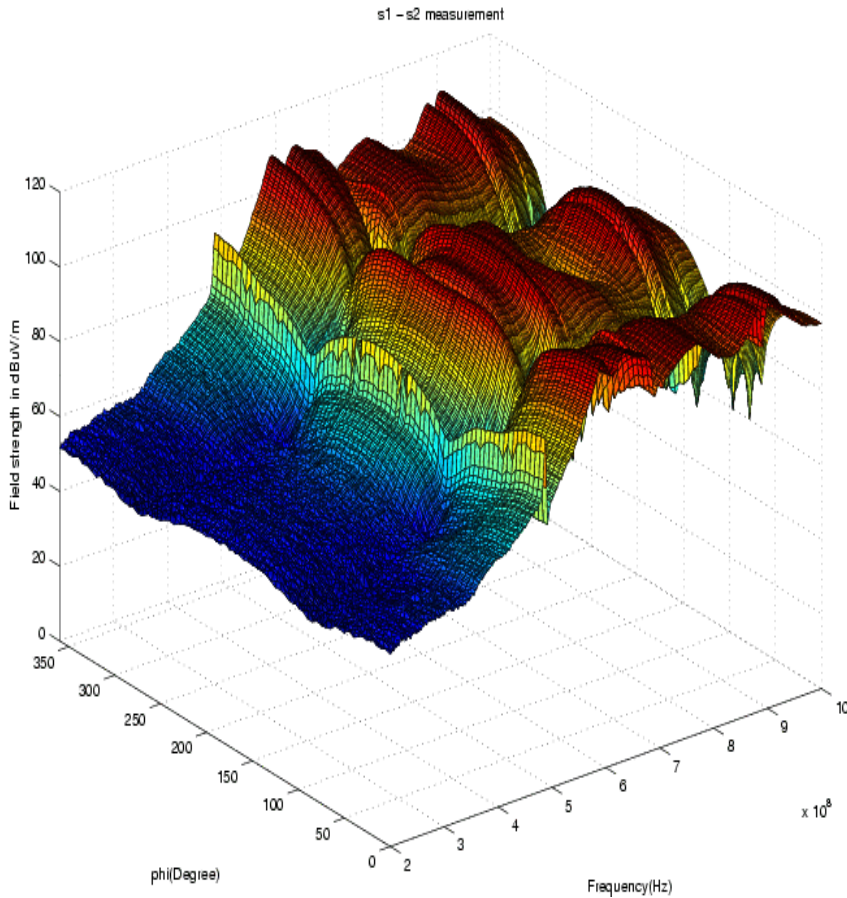
Simulation Procedure

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



Franz Sc
EMC

Simulation Procedure



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

Simulation Procedure

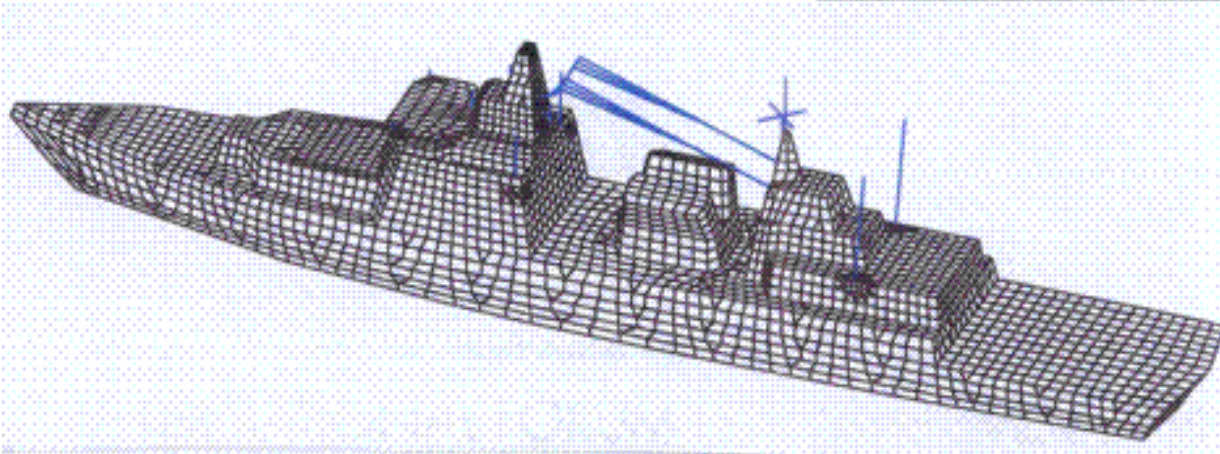
- Modelling and pre-processing
- Meshing
- Calculation
- Validation of results
- Post-processing

Simulation Procedure

- Modelling and pre-processing
 - Transforming the physical model in a mathematical one
 - Is the used method suitable for the problem?
 - Is the computer big enough?
 - Are all assumptions reasonable (linearity, time invariance, homogeneity, cross section dimensions ...)?
- Meshing
- Calculation
- Validation of results
- Post-processing

Detailed Simulation Model

(Still many details missing!)



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?



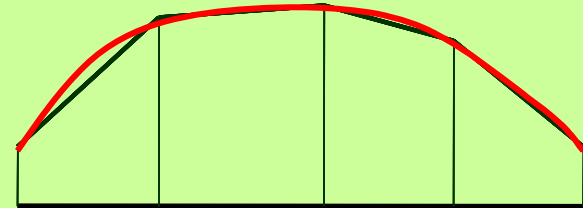
Simulation Procedure

- Modelling and pre-processing
- Meshing
 - Discretize the model and generate the input data
 - Patch/segment size based on wavelength, geometry or location of observation points
 - Check the input data
 - What is the actual size of the problem in terms of hardware requirements (number of unknowns, estimated computation time, RAM and disk space requirements, numerical stability ...)?
- Calculation
- Validation of results
- Post-processing

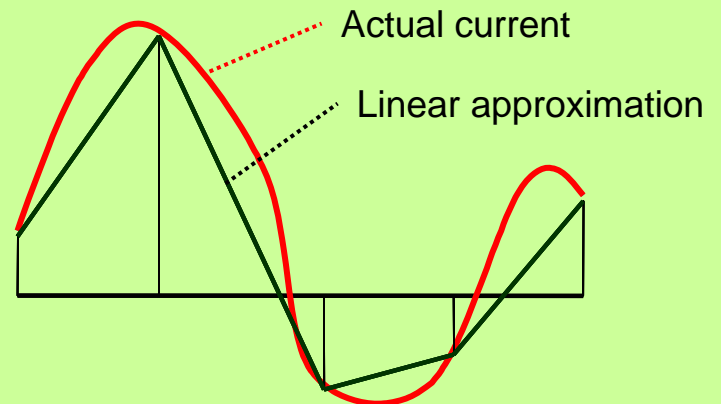
Meshing Requirements

- 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.



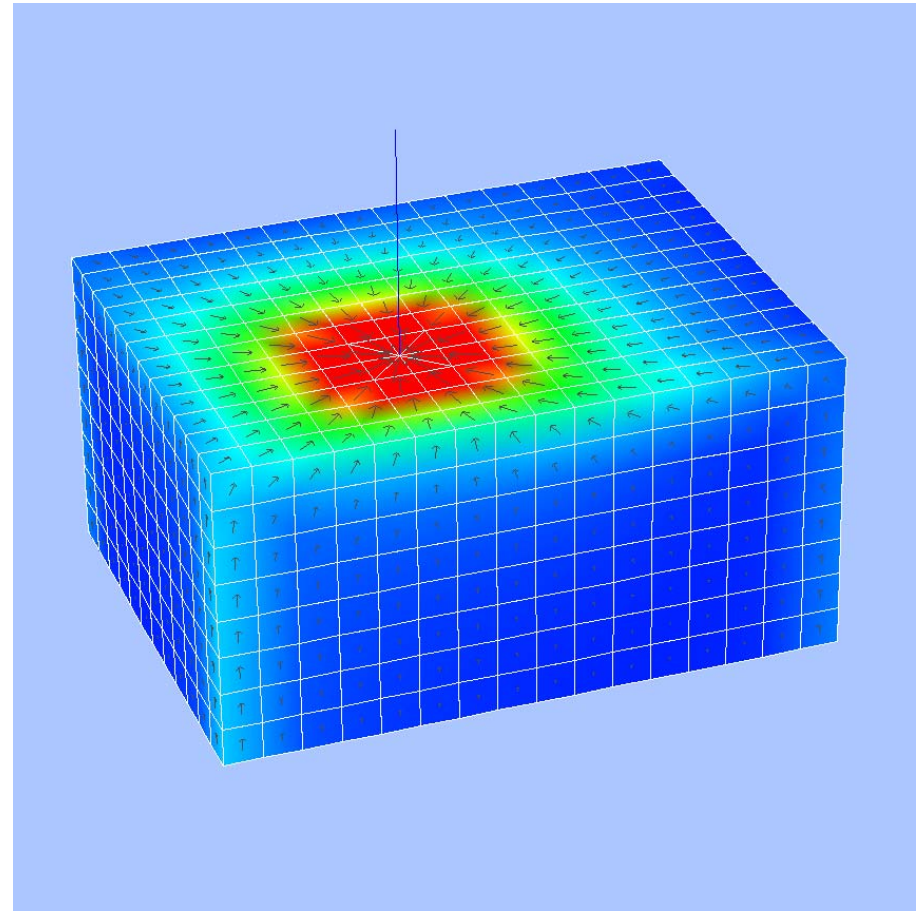
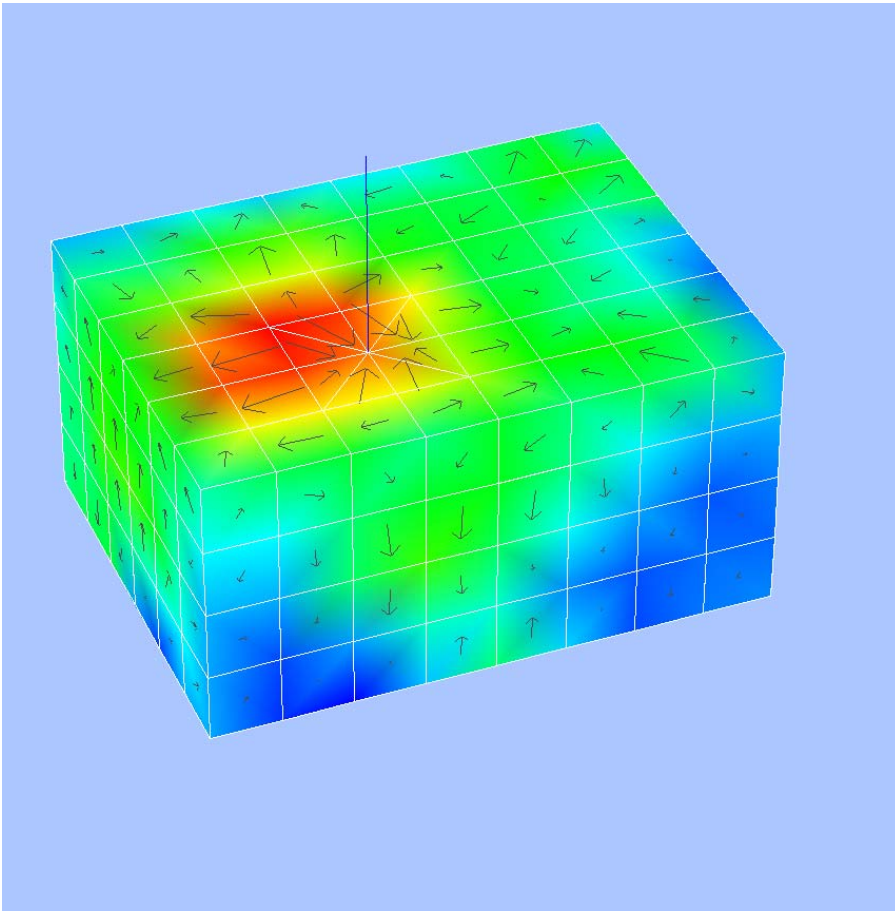
Simulation Procedure

- Modelling and pre-processing
- Meshing
- Calculation
 - Choose time or frequency steps appropriately
 - Time steps based on rise/fall times, resolution of propagation times and propagation time differences
 - Frequency steps based on Q-factors for resolution of resonances
 - Frequency/time intervals suitable for FFT or IFFT
 - Solution method (e.g. Gauss L/U decomposition or iterative solutions)
- Validation of results
- Post-processing

Simulation Procedure

- Modelling and pre-processing
- Meshing
- Calculation
- **Validation of results**
 - Current and charge distributions should be smooth and physically sound
 - Power budget: $\text{Input power} = \text{Radiated power} + \text{Loss}$
 - Comparison with measurements or analytical solutions (eventually from similar models)
 - Sensitivity check: variation of results when modifying the input data
- Post-processing

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

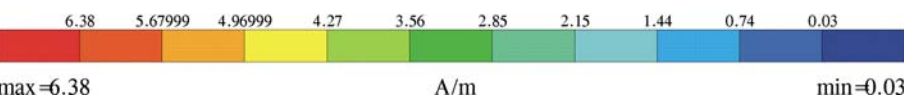
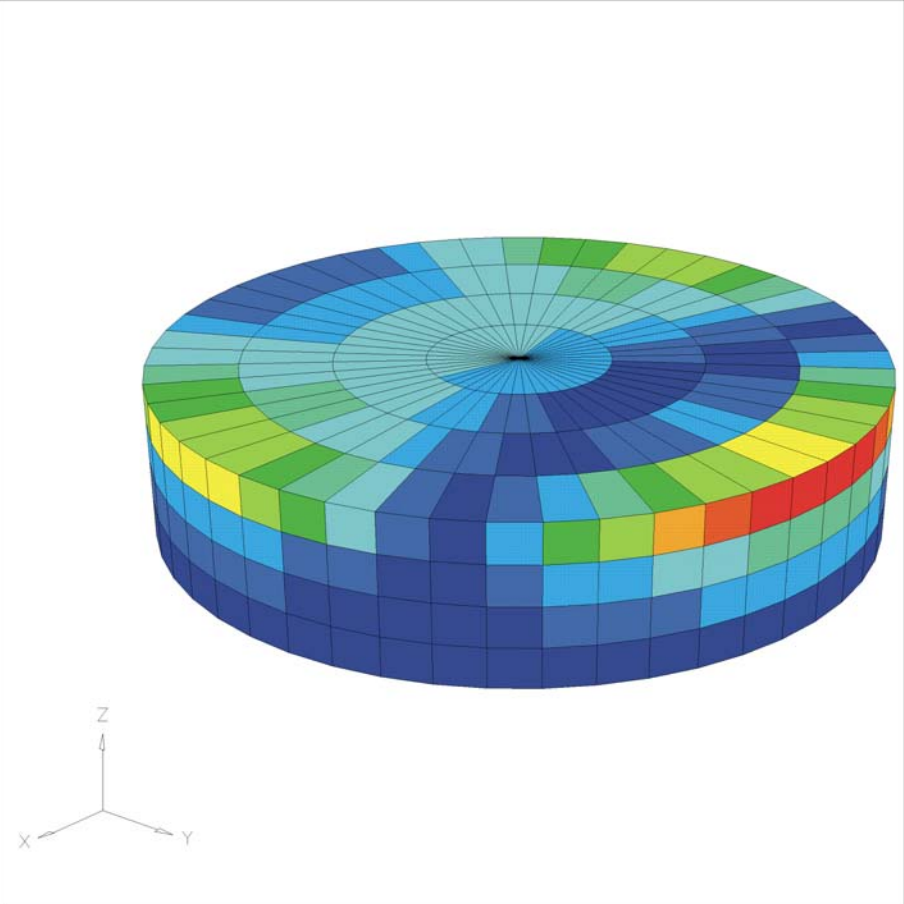


Simulation Procedure

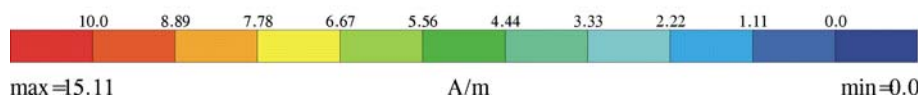
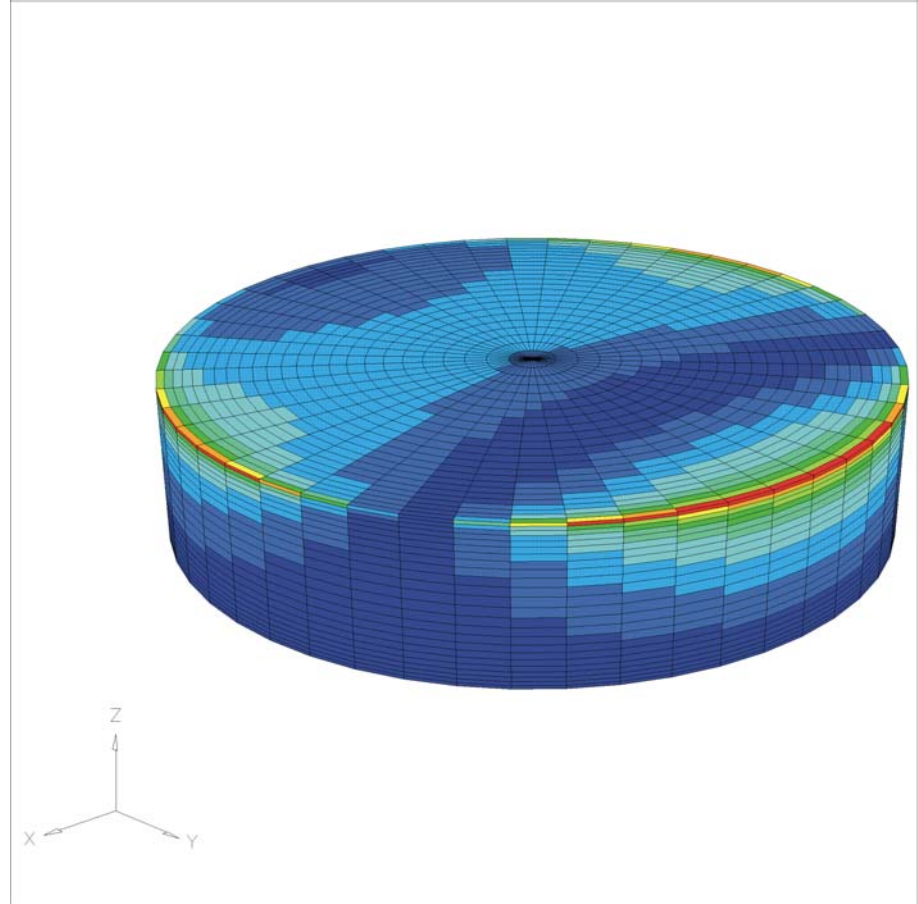
- Modelling and pro-processing
- Meshing
- Calculation
- Validation of results
- **Post-processing**
 - Present/process current, voltage and field strength at observation points
 - Present current and electric charge distribution on surfaces
 - Draw 2D and 3D radiation patterns
 - Compute SAR values and Poynting Vectors
 - From currents and voltages compute S-parameters
 - Apply interpolation and smoothing algorithms
 - Apply FFT of IFFT
 - Create animated pictures

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

CONCEPT-Data: Electrical Charge Distribution - 500 MHz

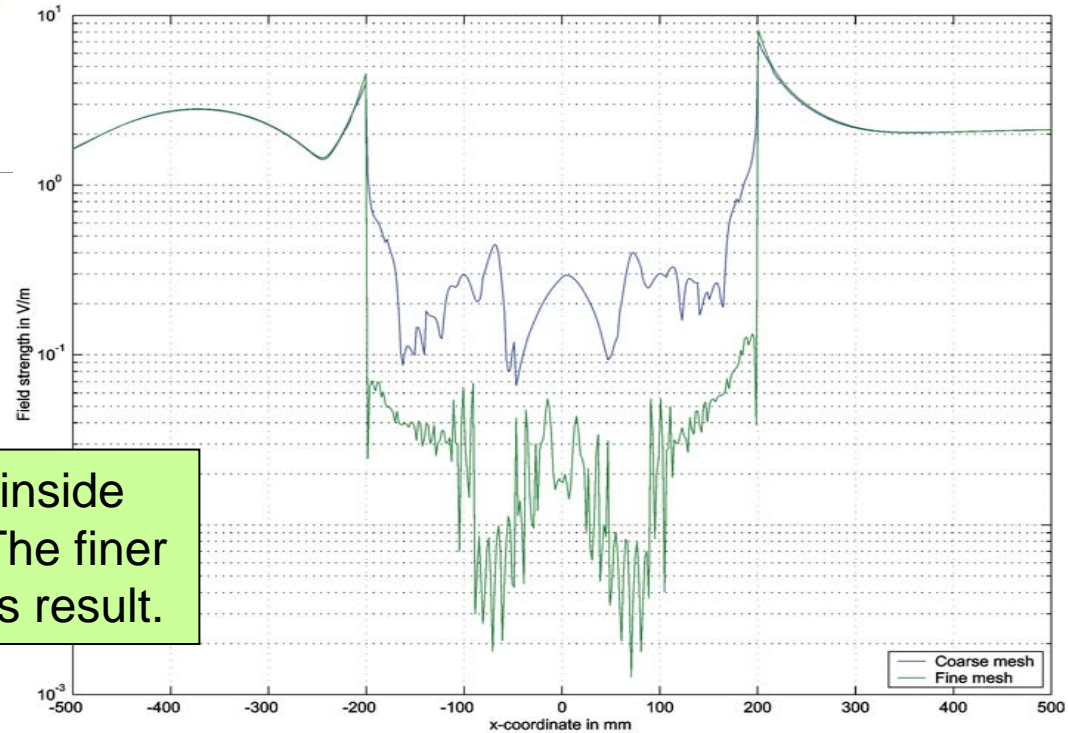
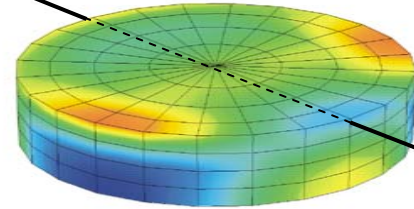
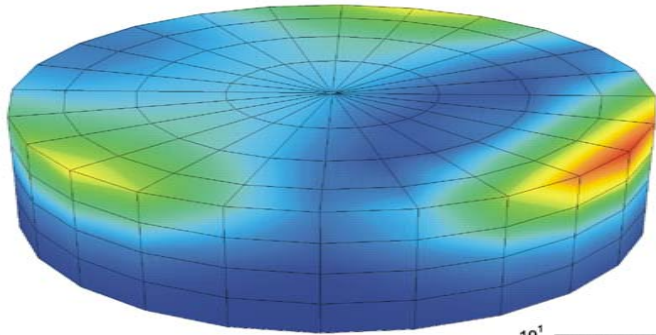


CONCEPT-Data: Electrical Charge Distribution - 500 MHz



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

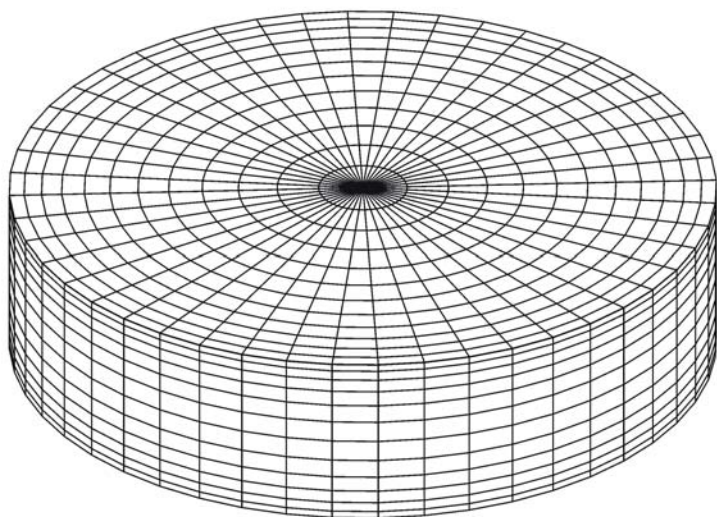
Field observation line just underneath the lid



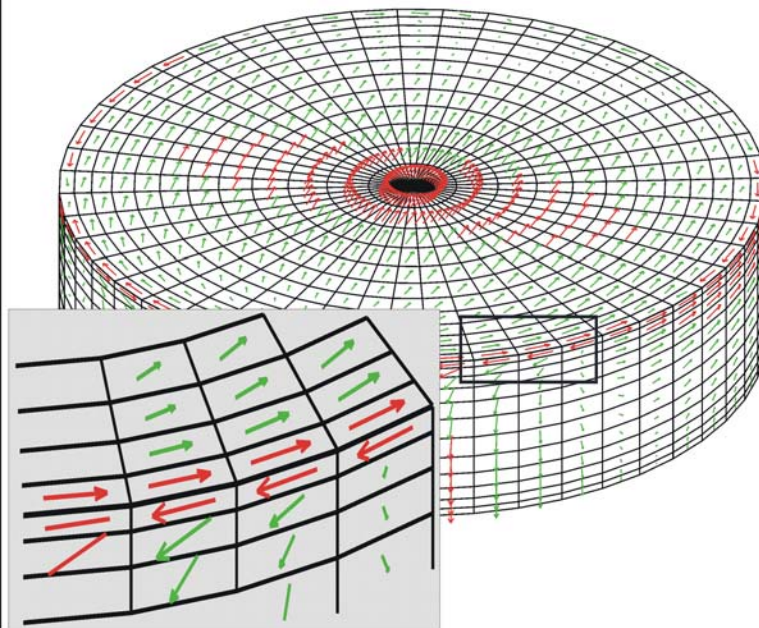
Ideally, the field strength inside the box should be zero. The finer mesh comes closer to this result.

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

CONCEPT DATA: What's Wrong



CONCEPT DATA: What's Wrong

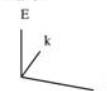


Frequency:
 $500.0 \cdot 10E-3$ GHz

$58.888 \cdot 10E-3$ A/m

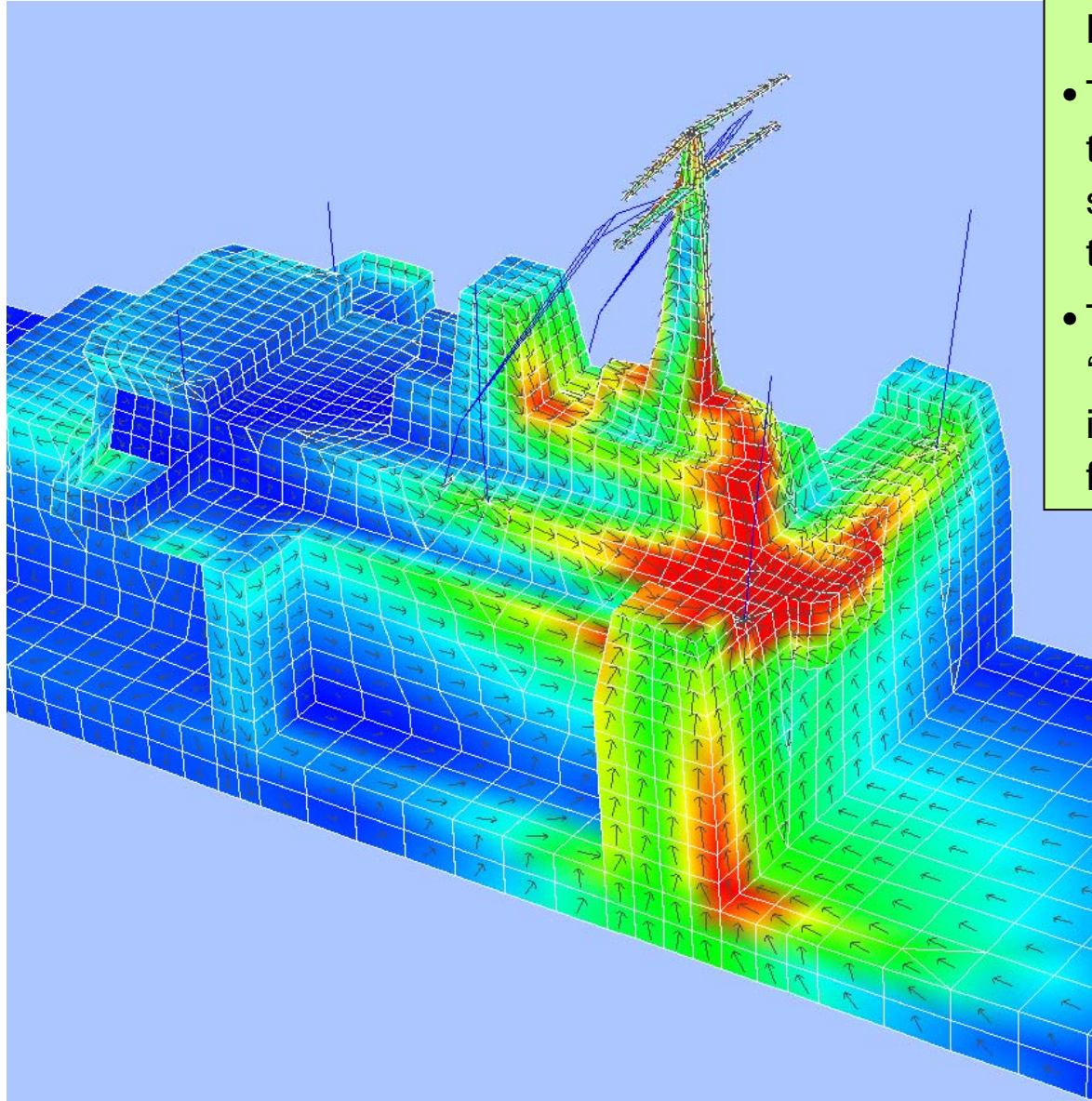
$5.889 \cdot 10E-3$ A/m

Plane wave:



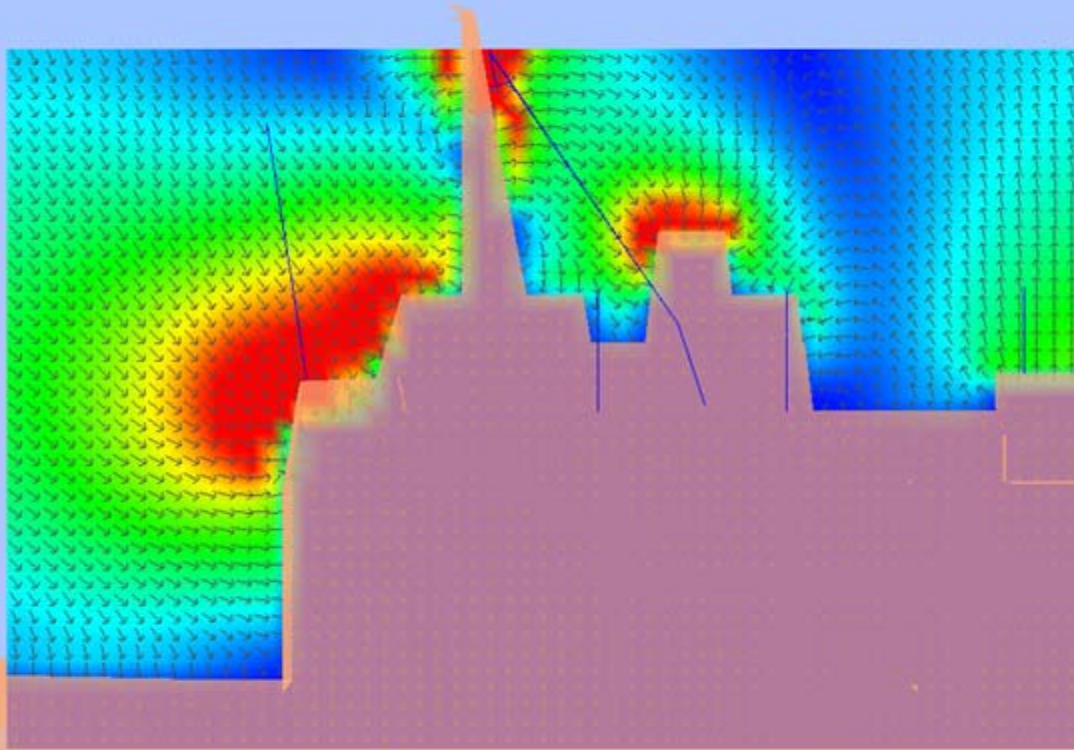
A simulation code might provide the option to test for nodes that are only a tiny bit apart, and suggest that they should actually be identical: but maybe these nodes are really different? How could the program guess what the user wanted to simulate?

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.

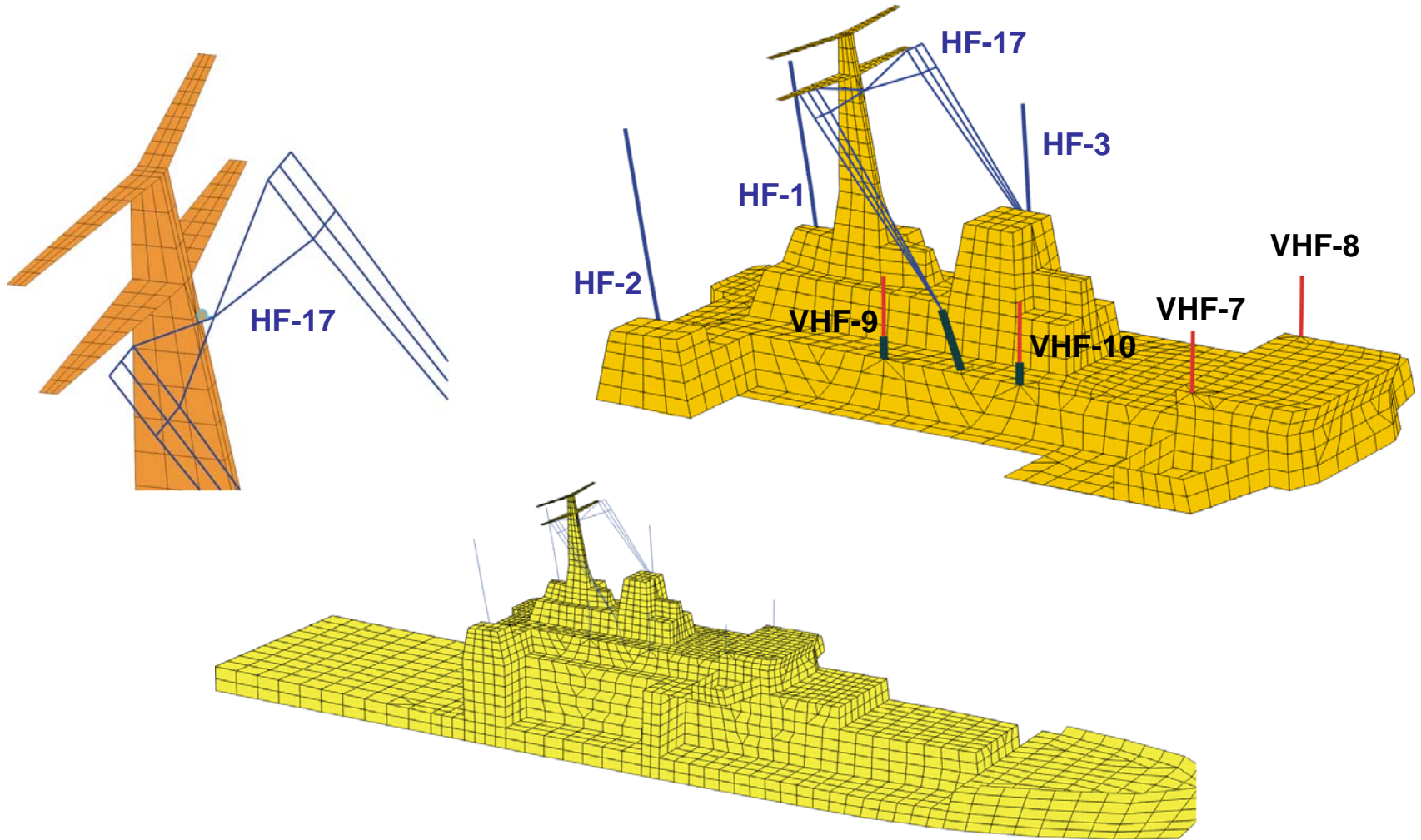
Electric Field Strength



- 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.

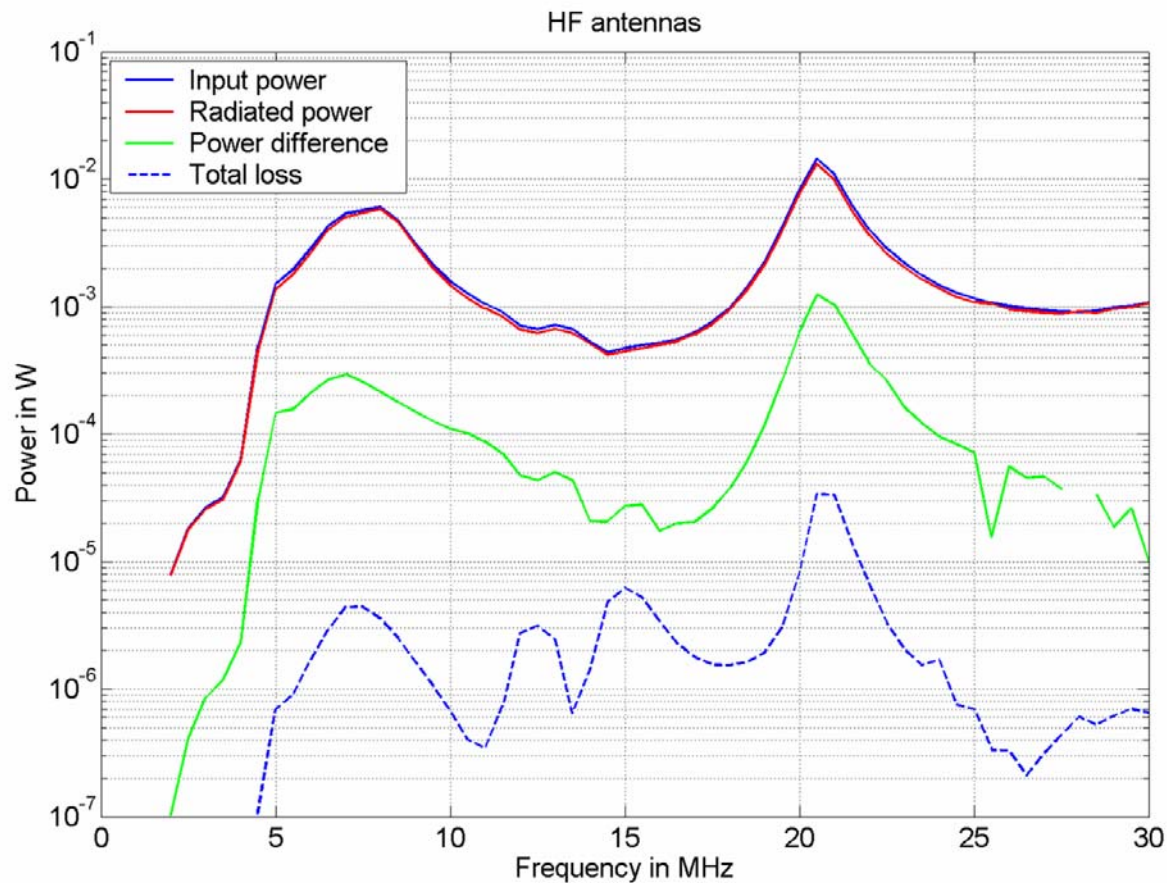
HF/VHF Antenna system on naval platform

CONCEPT-Data: HF - Model



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.

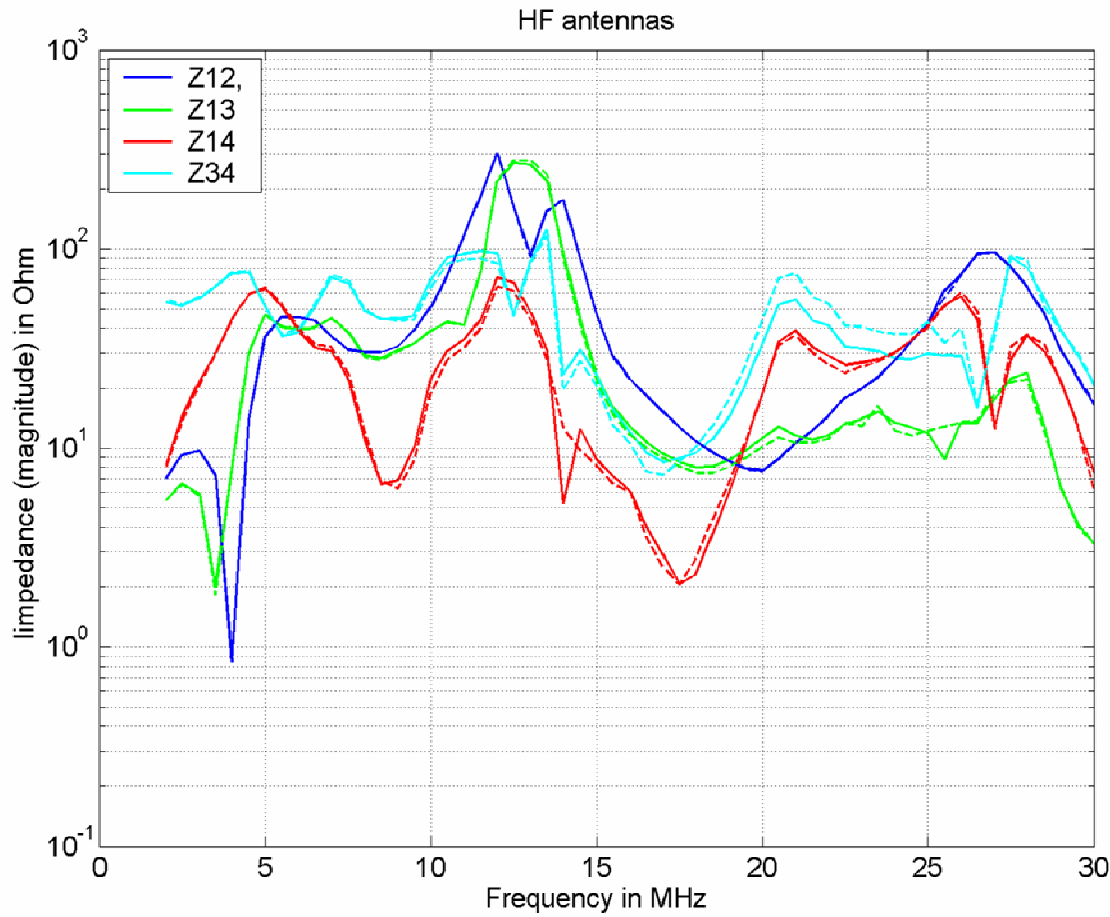


- Power loss also occurs in the termination resistors: 50Ω for the VHF antennas, $1 \text{ m}\Omega$ for the transmitting HF antenna and $1 \text{ M}\Omega$ for all other HF antennas.
- These losses are however much smaller and are negligible in this case.

Reciprocity

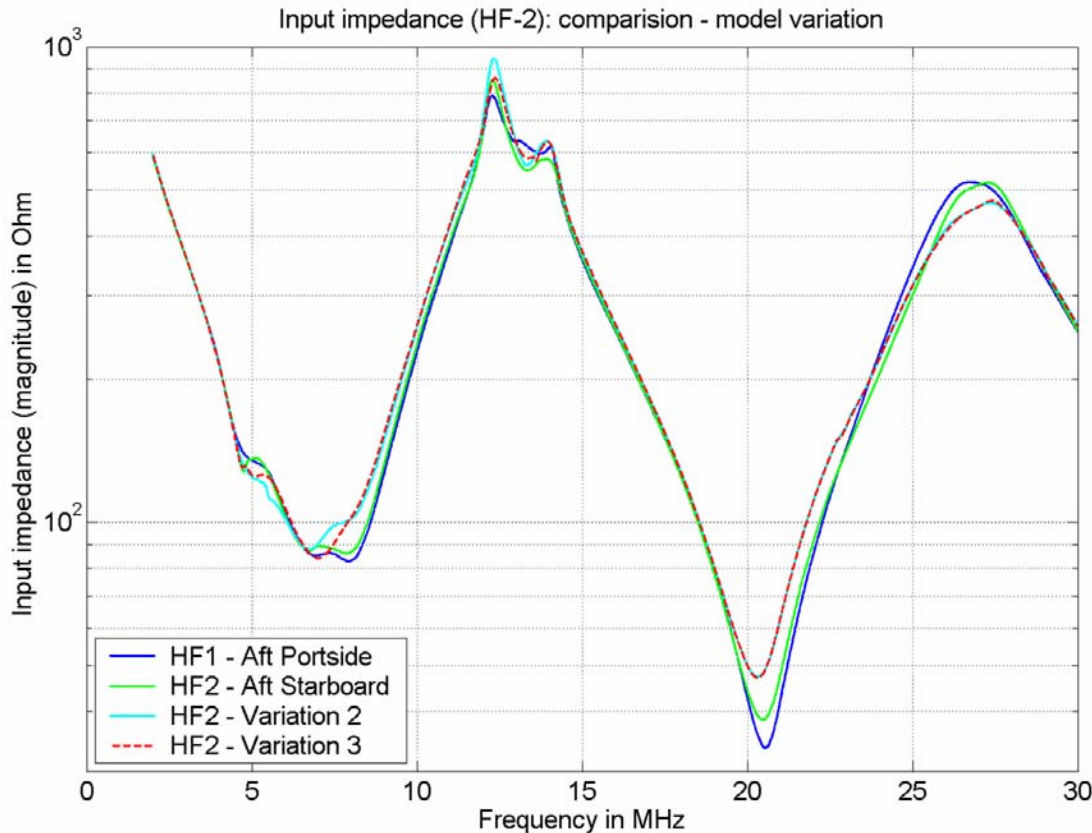
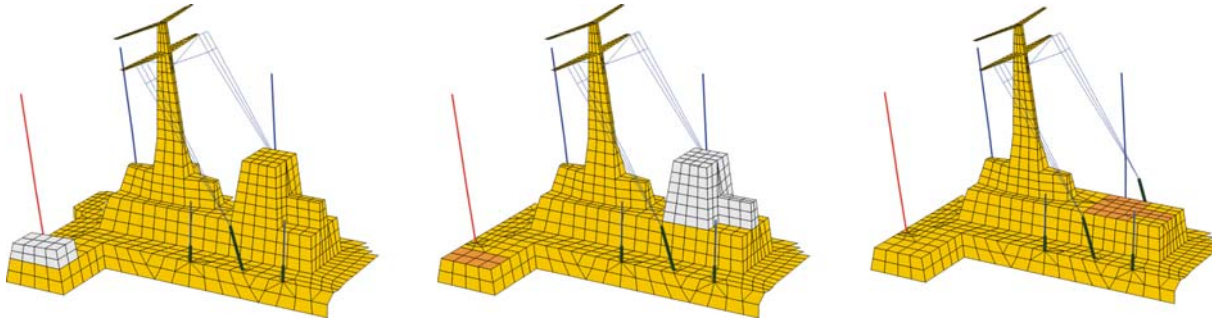
Transfer impedance between two antennas is the voltage at open terminal of one antenna (V_i) divided by the feeding current of the other antenna: (I_j). **For passive systems it must be: $Z_{ij}=Z_{ji}$:**

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



- 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.

Model Comparison



- 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.

Scaling Results

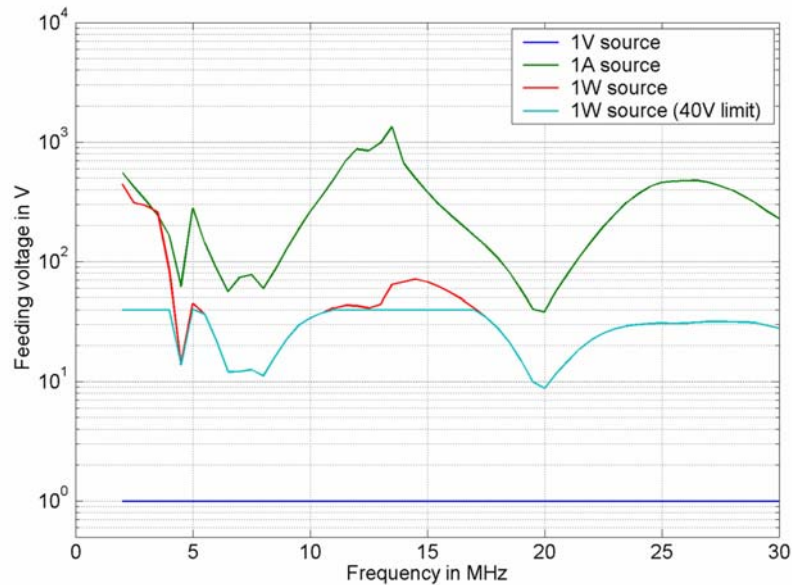
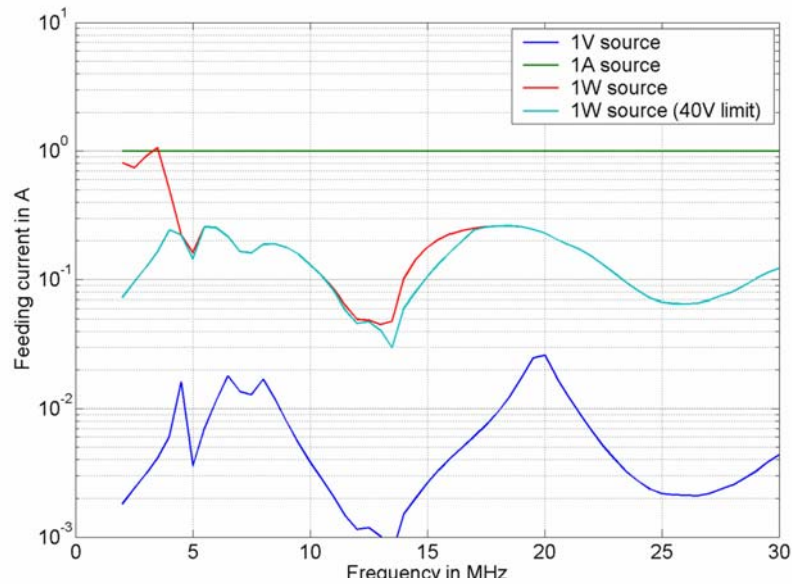
- Considering the correct excitation scenario is sometimes difficult, as the exact voltage or power fed into the antenna may not be known when the simulation is started.
- Scaling the results, e.g. currents and voltages, or electric and magnetic field strength, is possible, as the systems is considered to be linear.
- Currents, voltages, and electric/magnetic field strength are proportional to the feeding current
- Radiated power and power consumed in lumped elements are proportional to the square of the magnitude of the feeding current.

Feeding current from initial field simulation: $V_{in} = 1\text{V}$: $I_{in} = \frac{V_{in}}{Z_{in}}$

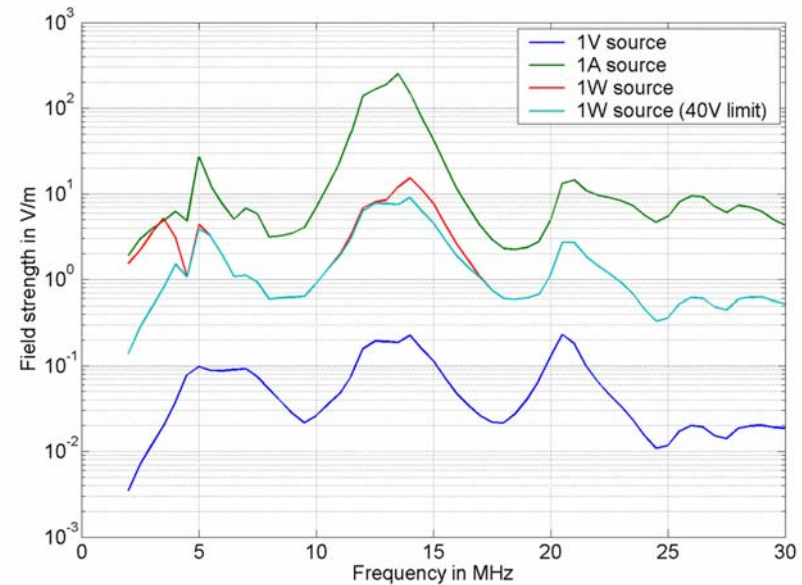
Feeding current for power source: $I_{Feed} = \sqrt{\frac{2P_{Feed}}{\text{Re}\{Z_{in}\}}}$

Feeding voltage, when feeding with power source: $|V_{Feed}| = \sqrt{\frac{2P_{Feed}}{\text{Re}\{Z_{in}\}}} \cdot |Z_{in}|$

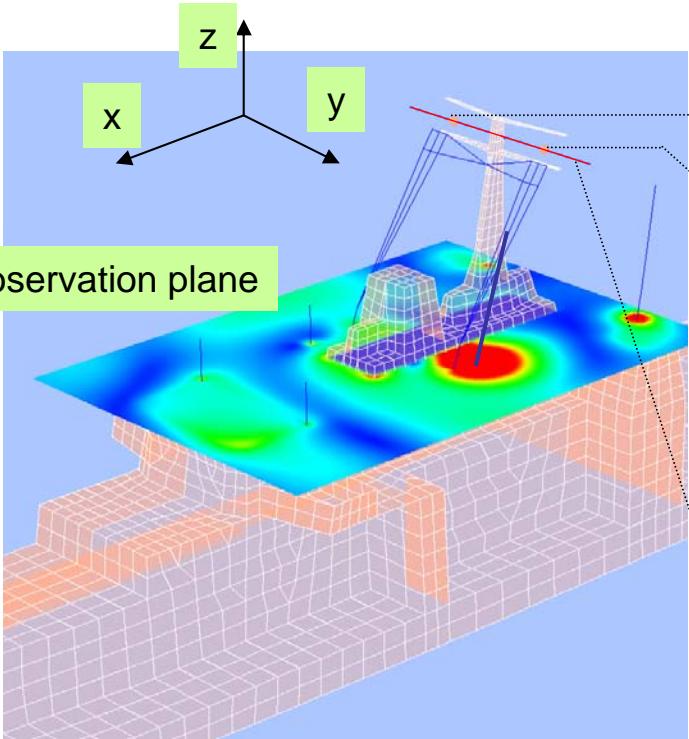
Scaling Results



- HF antennas have often a small real part of the input impedance at low frequencies while the imaginary part might be quite large.
- In such a case, the maximum voltage delivered by the source rather than the maximum available power limits the power fed into the antenna.
- Field strength (or voltage, currents etc.) can be scaled according to:
$$E = E_{in} \frac{I_{Feed}}{I_{in}}$$
- I_{Feed} is the actual feeding current, I_{in} is the feeding current from the initial field simulation, and E_{in} is the field strength (or other quantity) obtained from the initial field simulation.

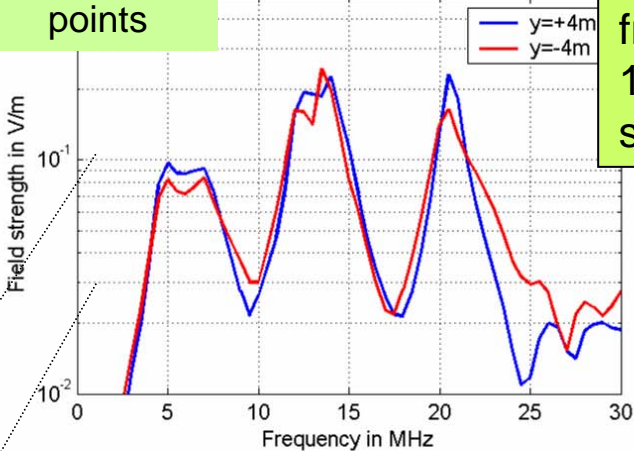


Field Strength Values

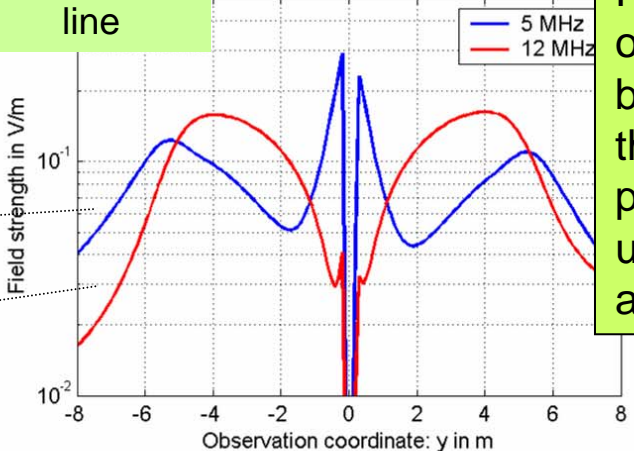


Field strength values at observation points may be used to determine frequencies for which 1-D or 2-D plots should be generated.

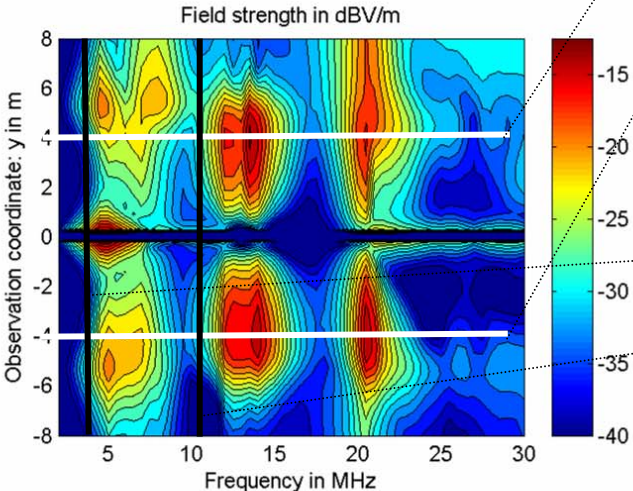
Observation points



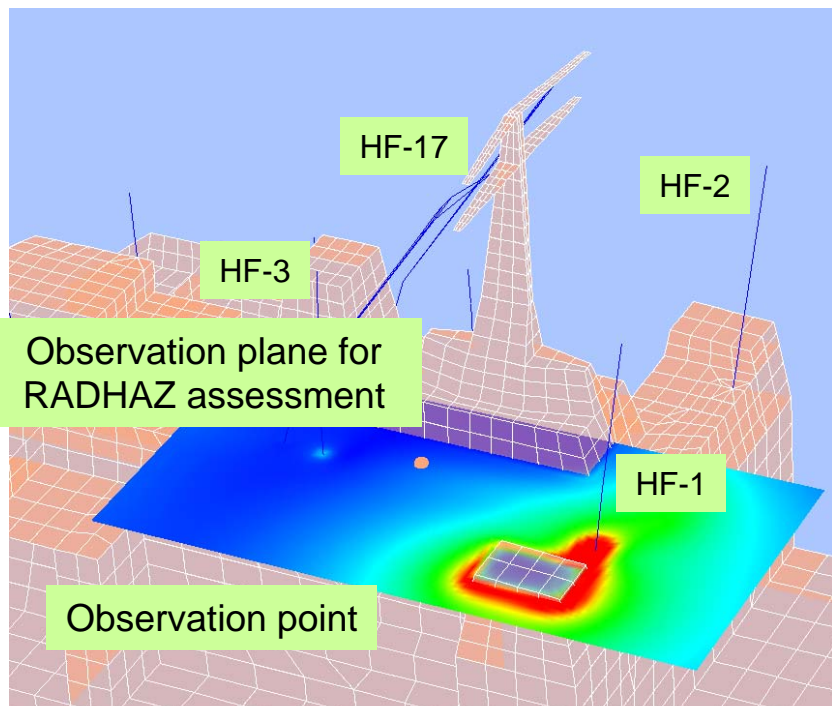
Observation line



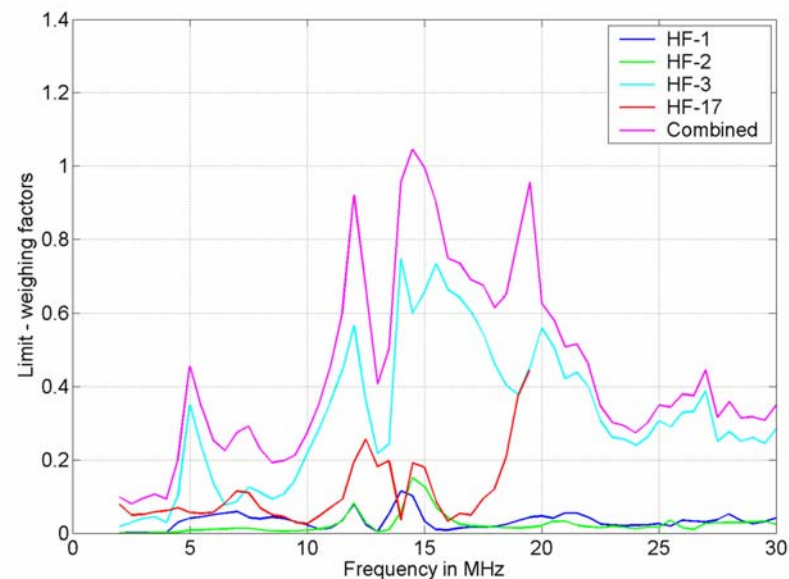
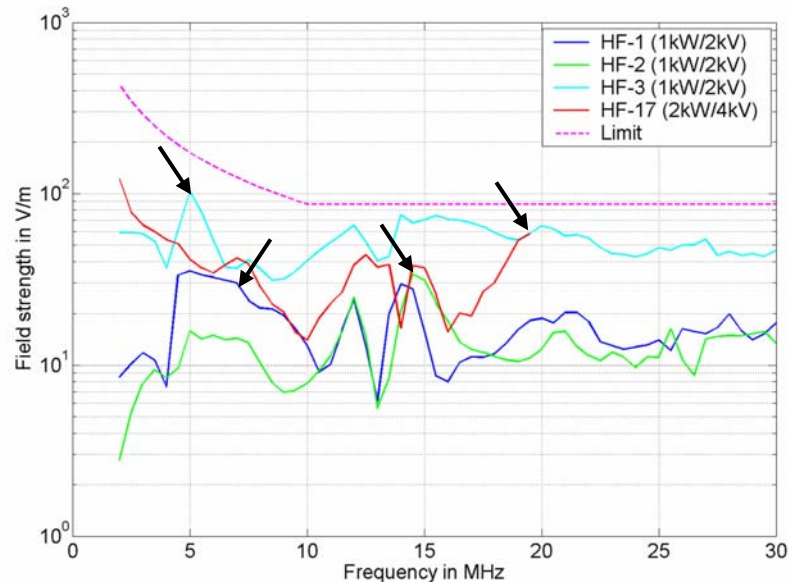
Field strength values on 2-D planes may be used to determine the values for which points should be used for further analysis.



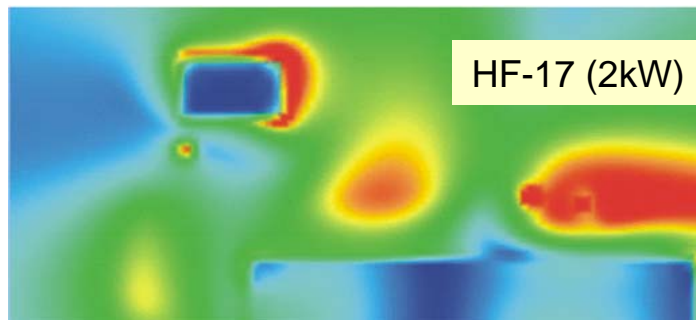
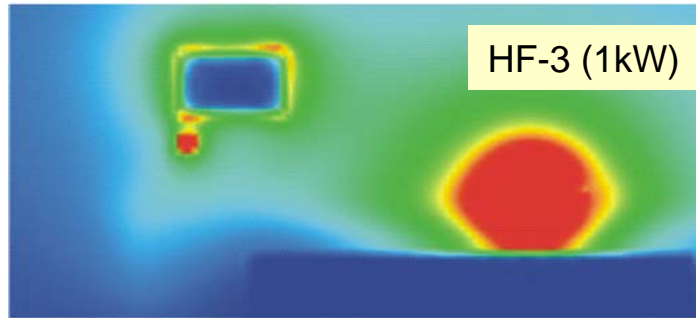
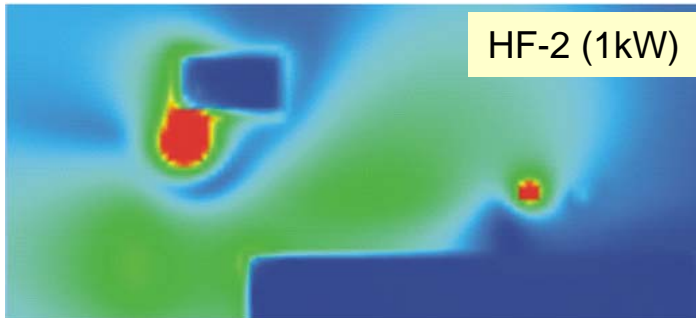
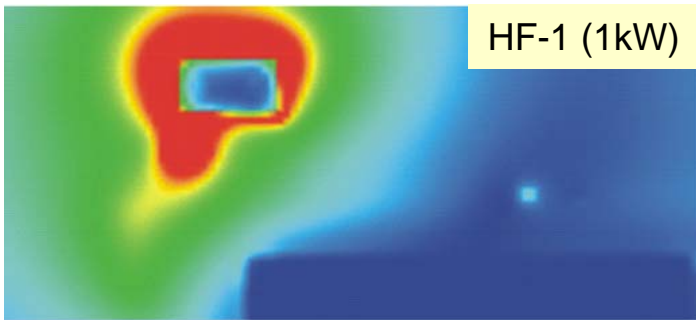
Superposition of Field Strength



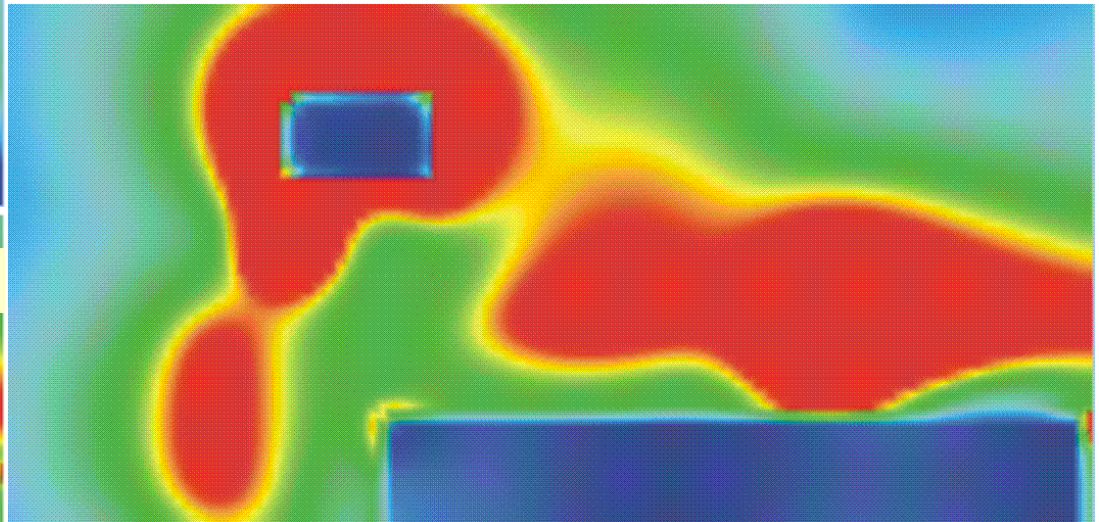
- A RADHAZ assessment for the indicated observation plane shall be made.
- For one observation point the field strength due to each HF antenna is determined (considering the maximum transmission; limited either by available power, or maximum feeding voltage).
- A worst case transmission scenario is chosen.



Superposition of Field Strength

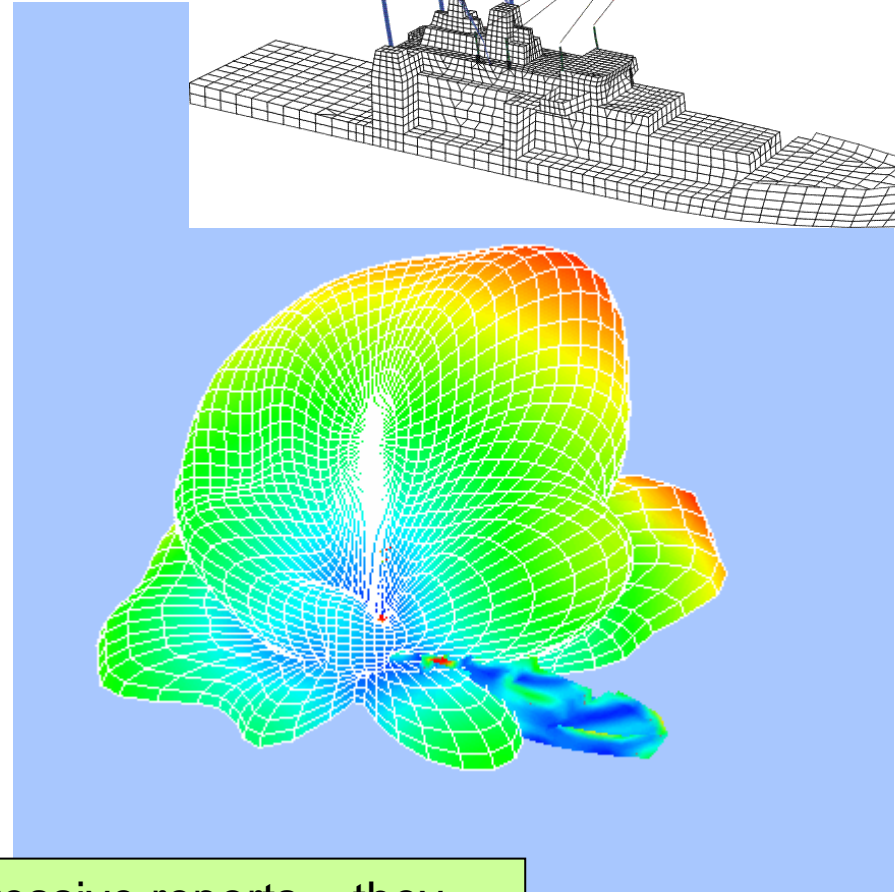
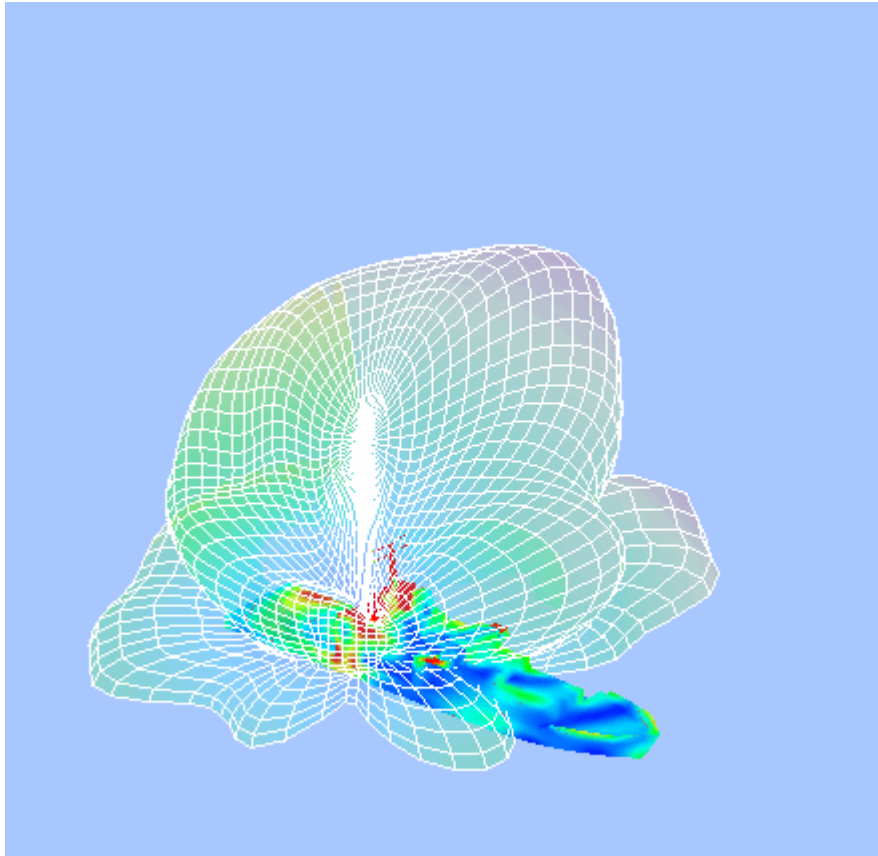


Antenna	Power	Frequency	Limit value
HF-1	1 kW	7 MHz	124 V/m
HF-2	1 kW	14.5 MHz	87 V/m
HF-3	1 kW	5 MHz	174 V/m
HF-17	2 kW	19.5 MHz	87 V/m

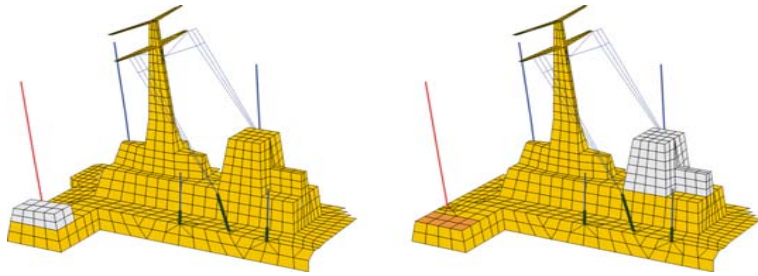


HF Antenna System Simulation

3D Radiation pattern and ship structure

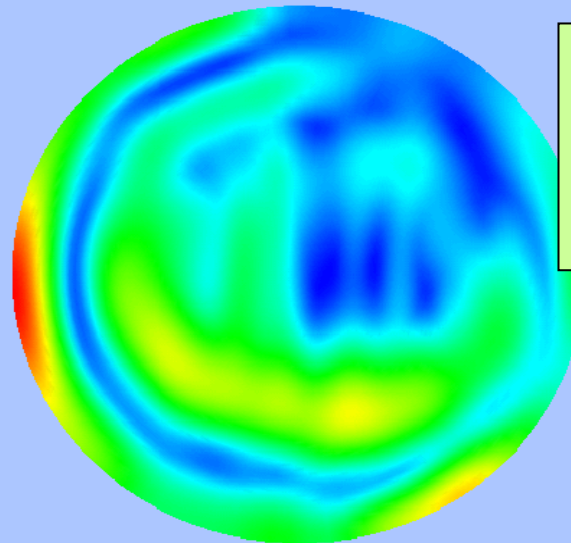
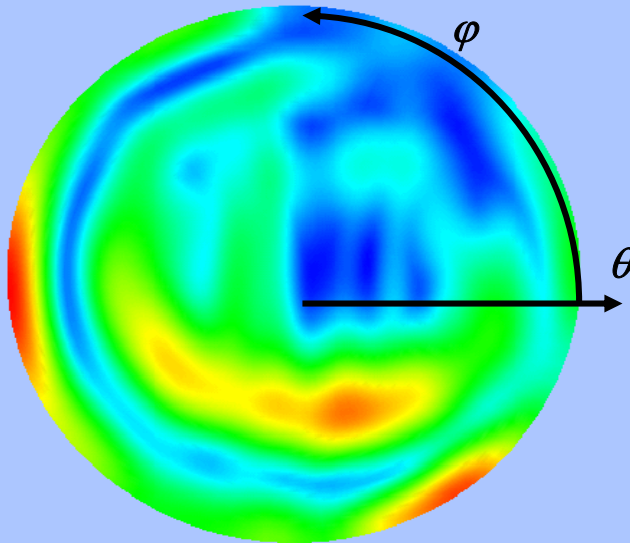
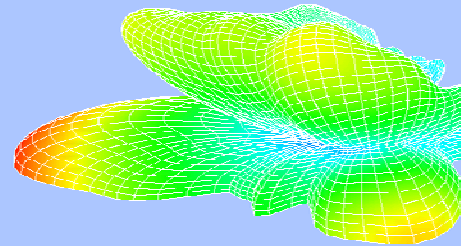
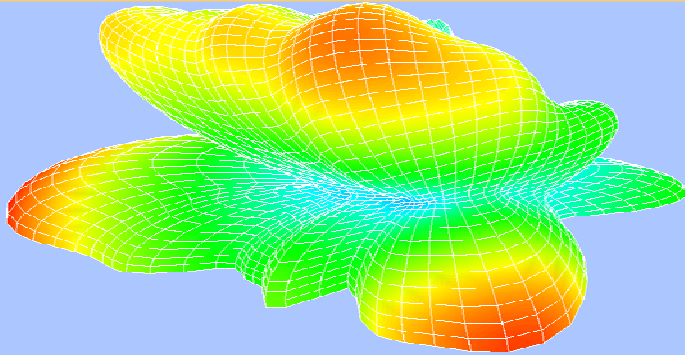


This is the type of pictures that make impressive reports – they are often pretty useless from an engineering point of view.



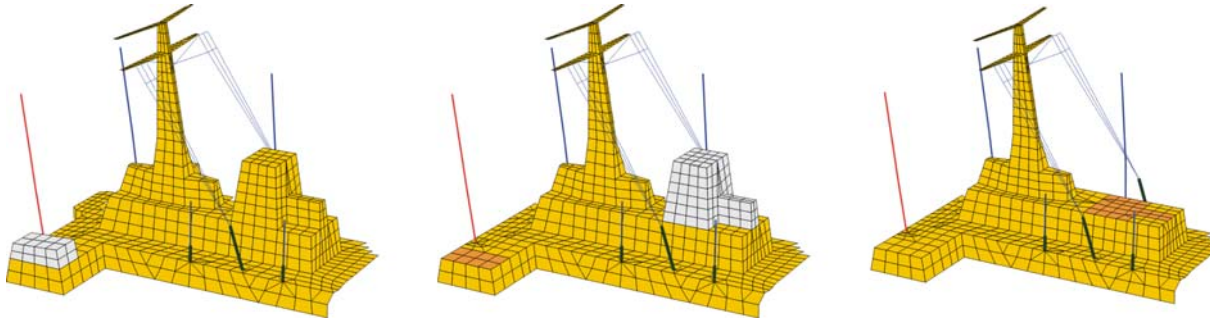
Radiation Pattern

3D patterns give a good impression of the radiation behaviour, in particular when the orientation of the graphic can be changed interactively

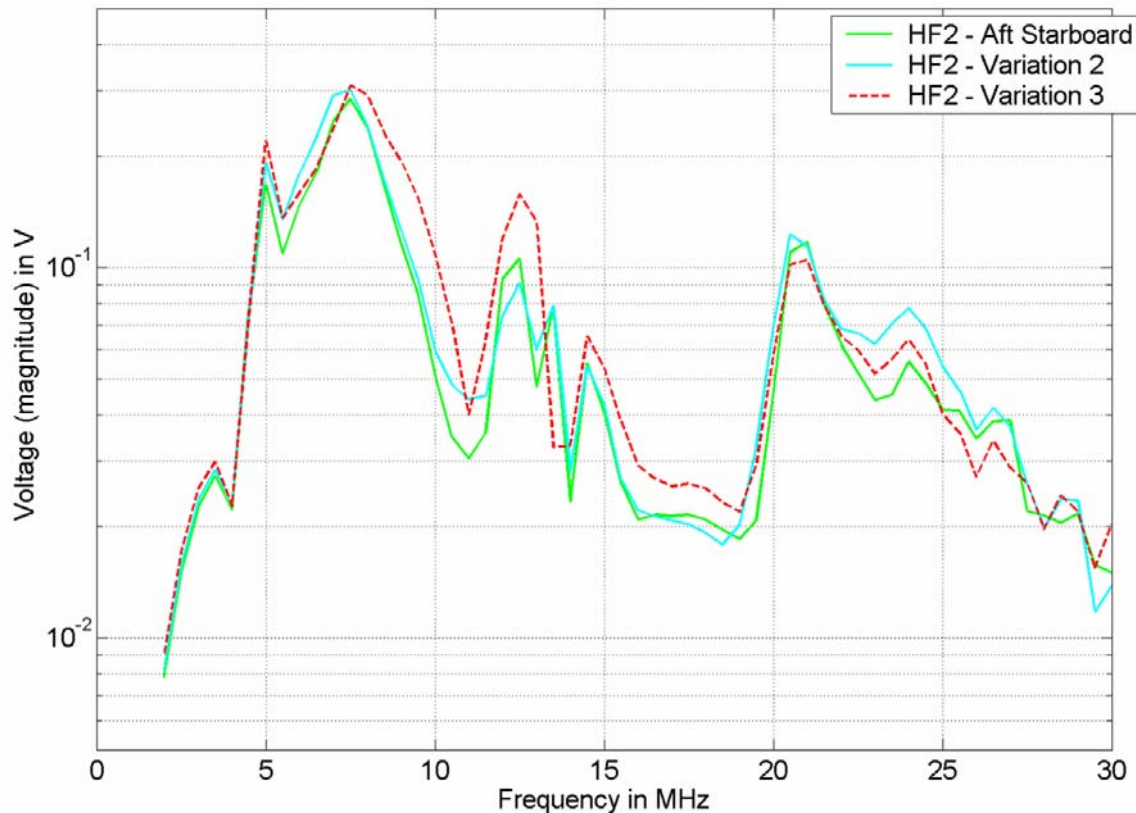


2D presentations need a little practice to read, but are better suited for comparisons.

Model Comparison



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

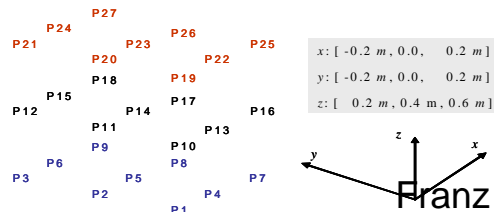
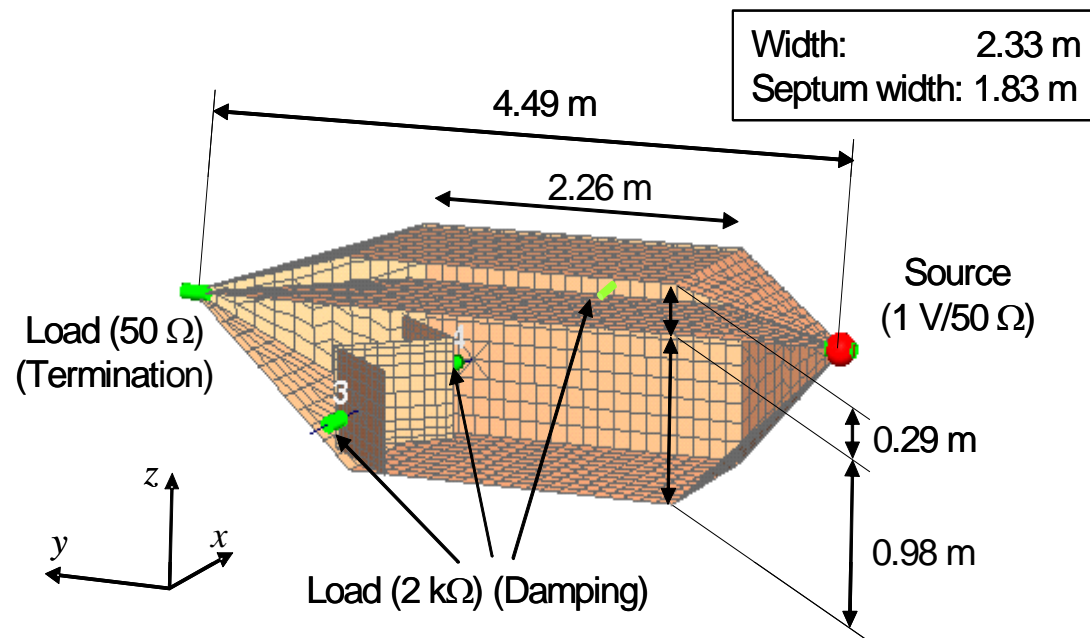


- While transmitting with HF-2 the voltage coupled in the open terminal of HF-3 is calculated.
- Both modifications have only a very marginal impact on the result at low frequencies.
- Removing the forward mast produces a different voltage compared to the basic model and the case where only the aft exhaust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

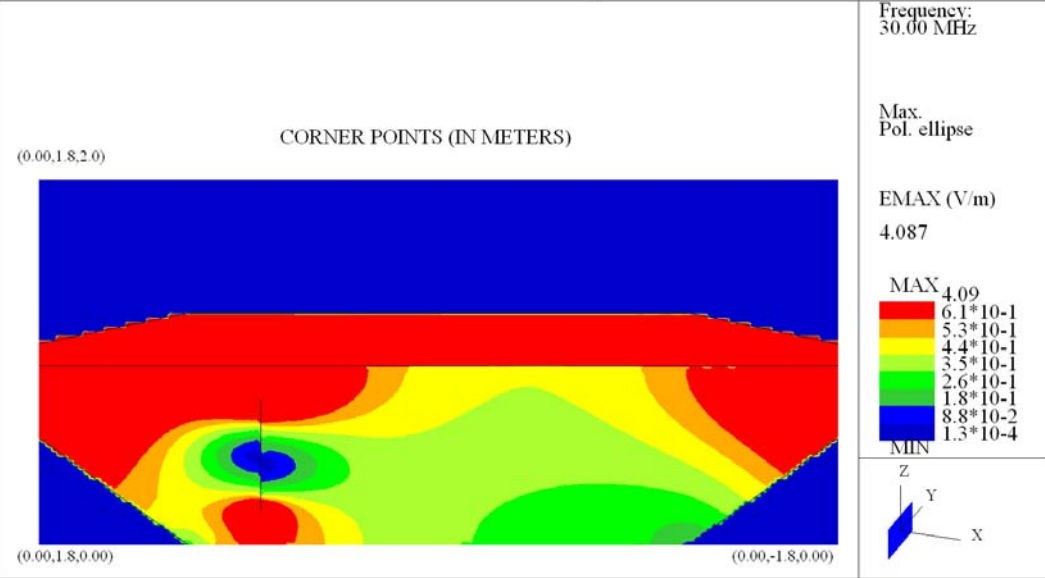
1. Introduction and Motivation

Design objectives:

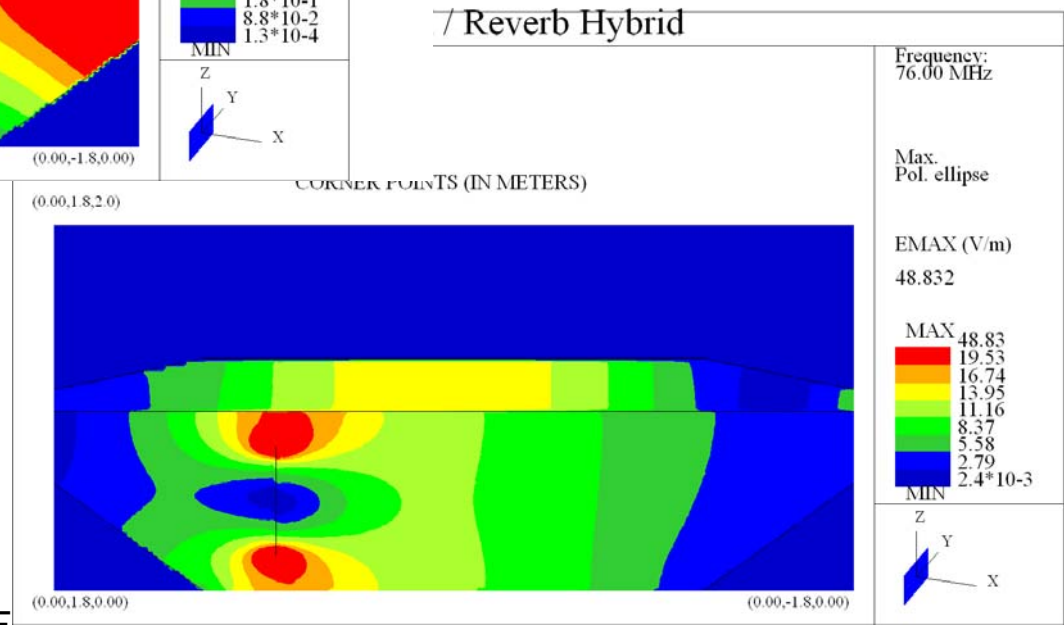
- Extend frequency range for TEM operation by dampening the first few resonance frequencies;
- Don't disturb field uniformity with introduction of stirrer;
- Optimize stirrer shape and location for reverberation operation.

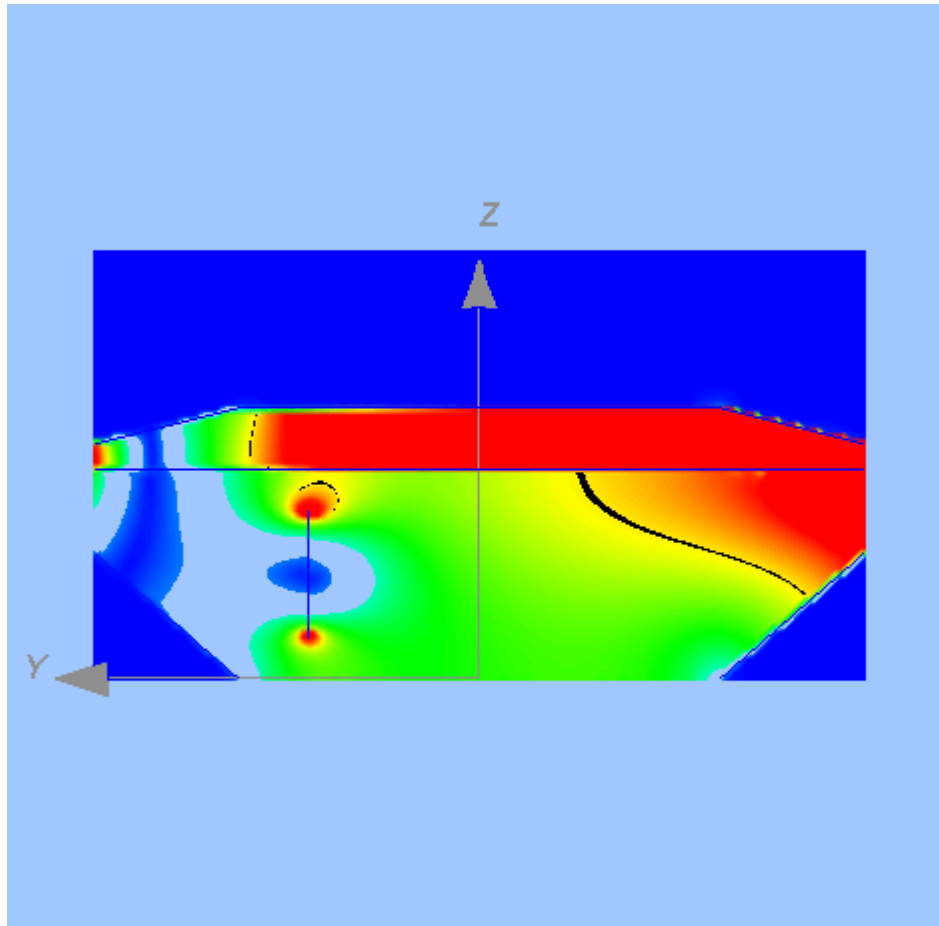


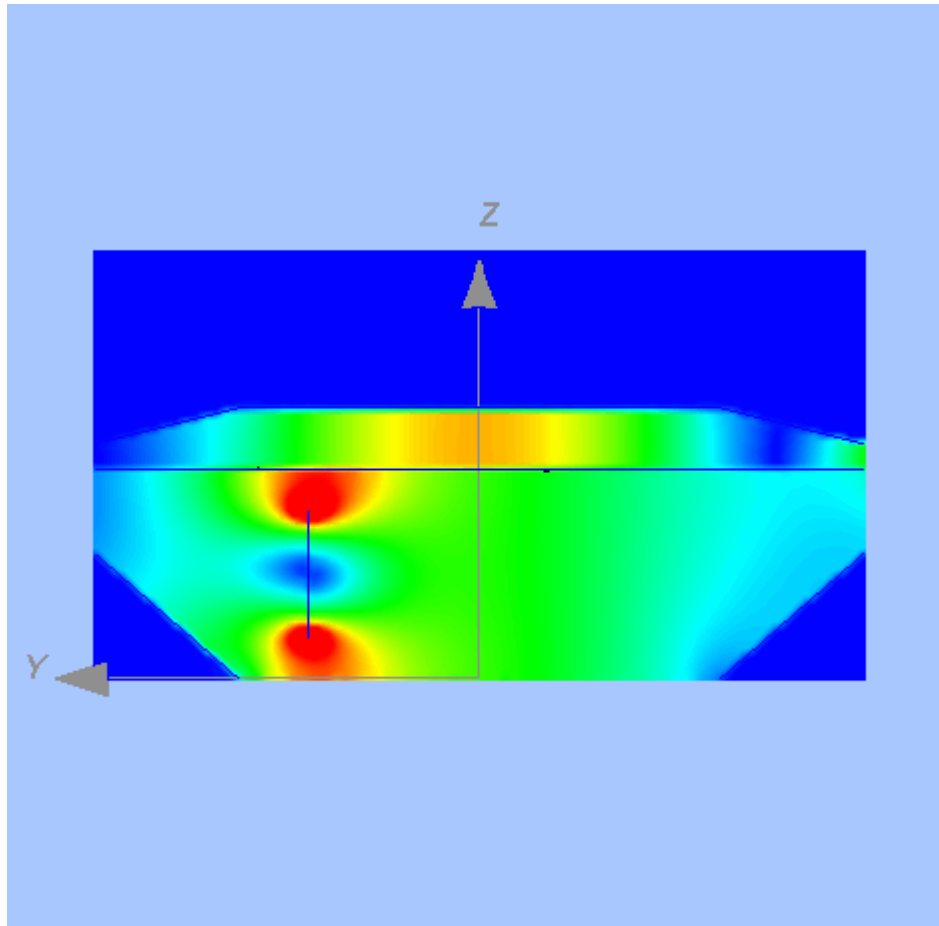
CONCEPT DATA: TEM / Reverb Hybrid



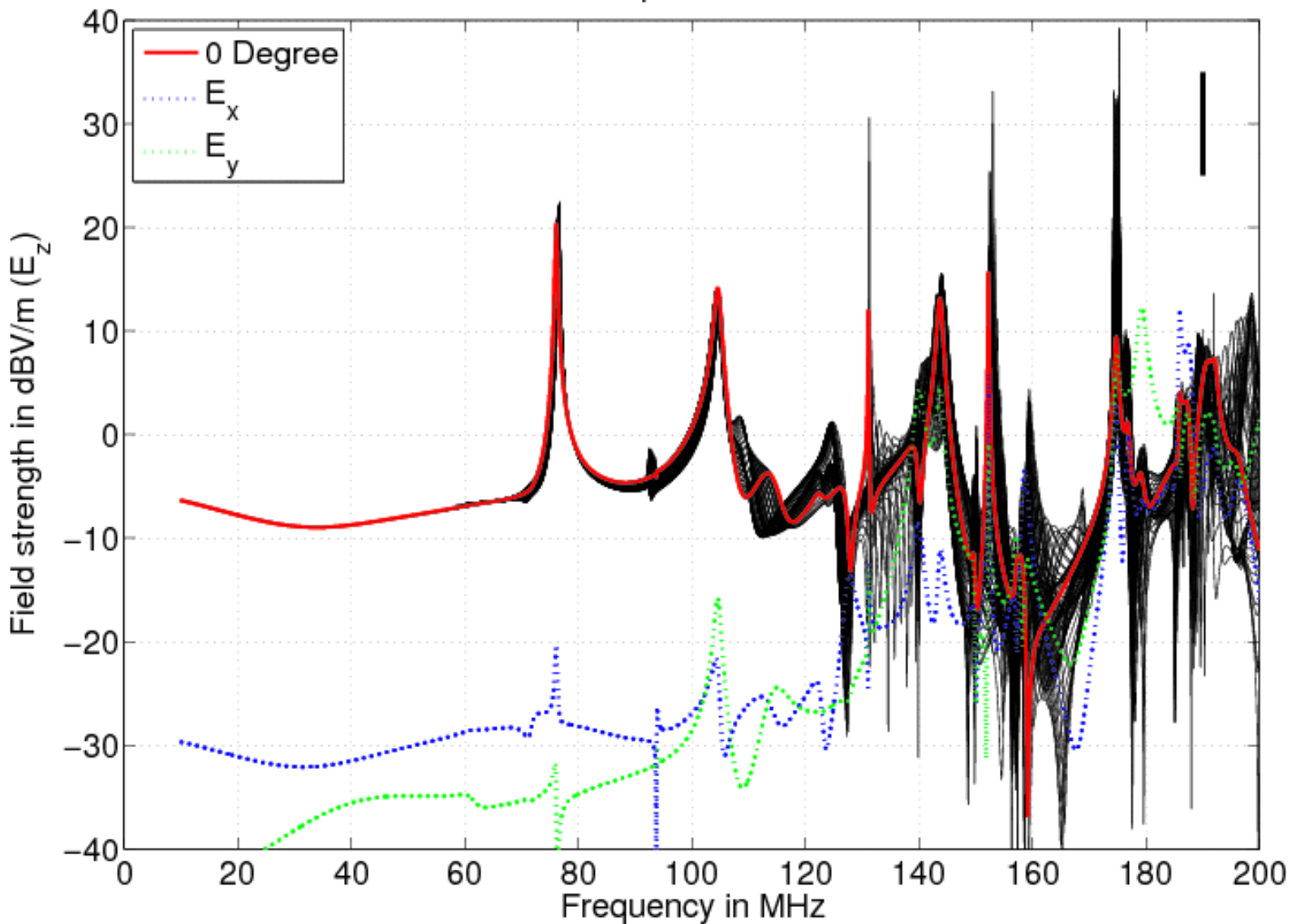
/ Reverb Hybrid







Field observation point: -0.2m/-0.2m/0.6m

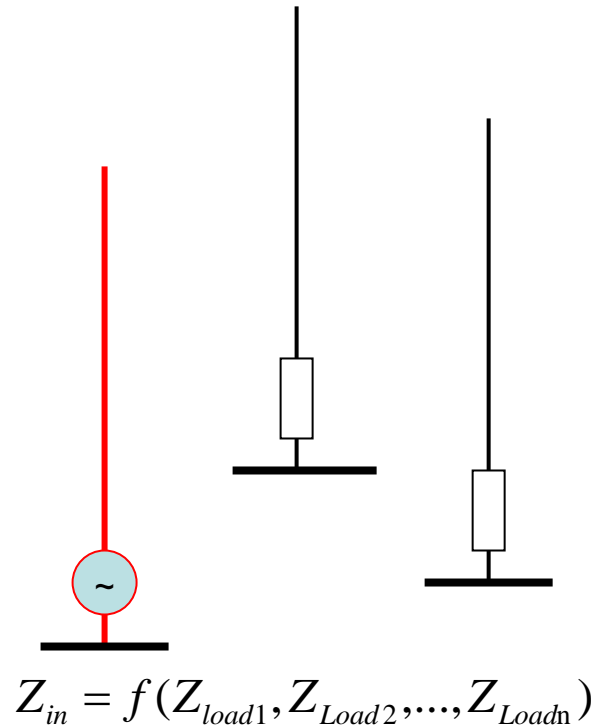


Variation of HF Antenna Terminations

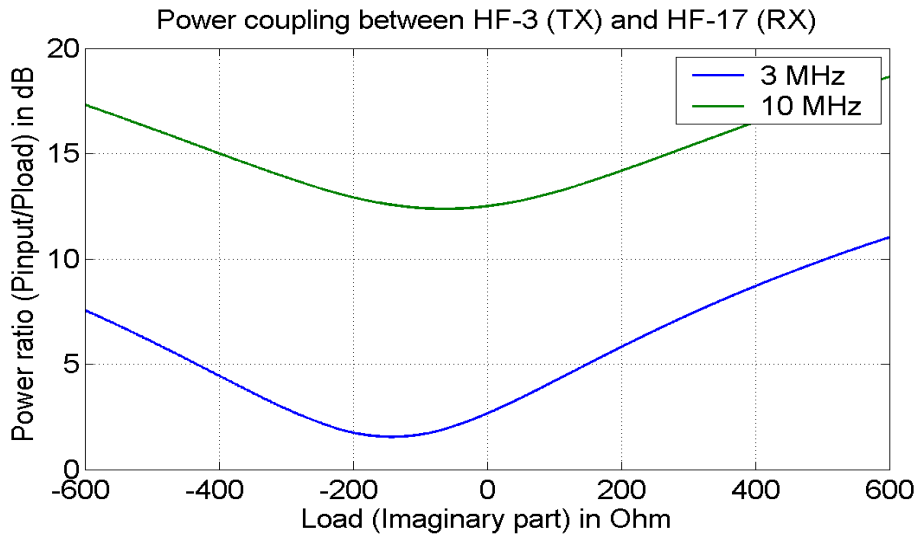
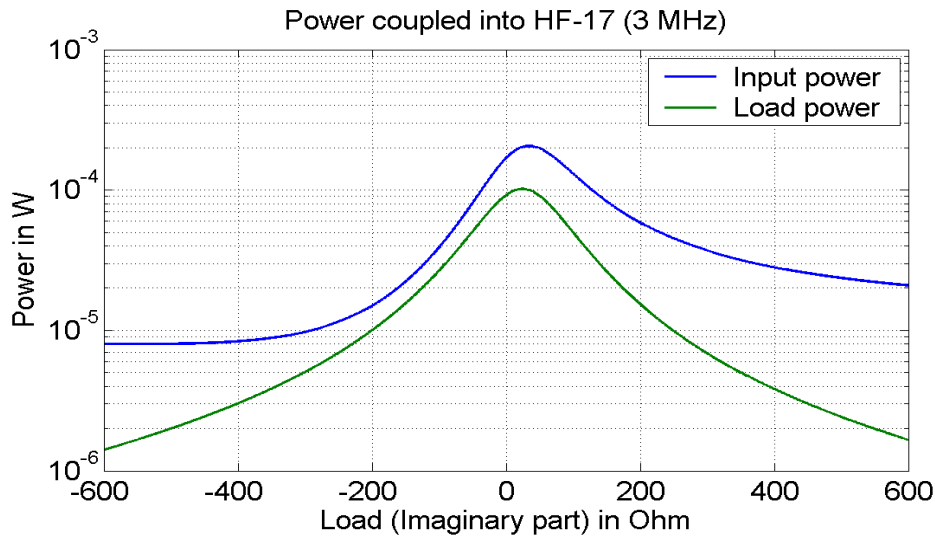
- A platform with several HF antennas can be considered as an n -port network, with each of the antenna terminals an accessible port where load impedances and sources can be changed.
- Sources are put at transmitting antennas, and load impedances are connected to the antenna terminals in the form of 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.



Maximum HF-HF Coupling



$$P_{in} = |I_{in}|^2 \operatorname{Re}\{Z_{in}\}$$

$$I_{in} = \frac{V_{source}}{Z_{in} + Z_{source}}$$

$$Z_{in} = Z_{11} - \frac{Z_{12}Z_{21}}{Z_{22} + Z_{Load}}$$

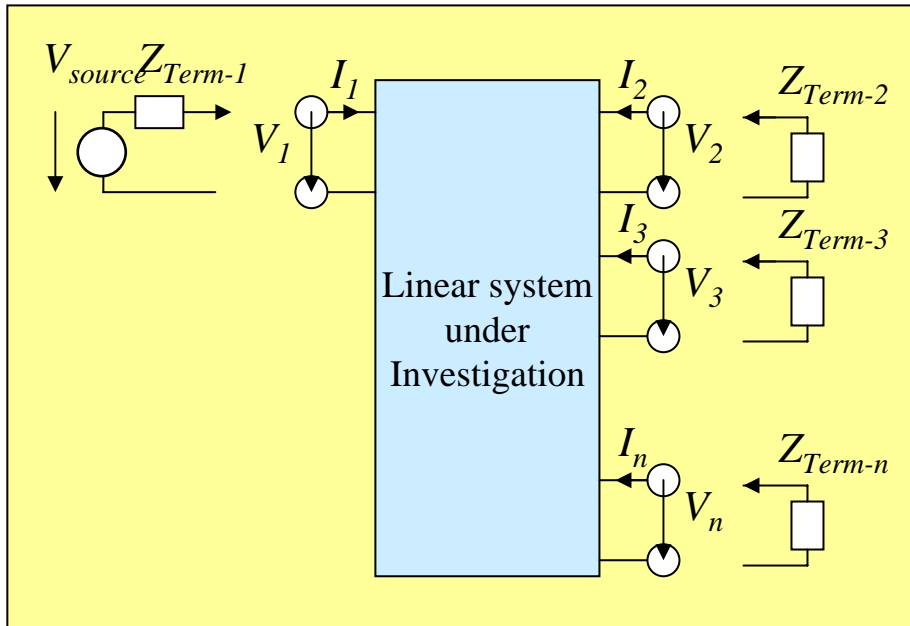
$$P_{Load} = |I_{Load}|^2 \operatorname{Re}\{Z_{Load}\}$$

$$I_{Load} = \frac{Z_{12}V_{source}}{ZZ - Z_{12}Z_{21}}$$

$$ZZ = (Z_{11} + Z_{source})(Z_{in} + Z_{source})$$

$$a = 10 \cdot \log(P_{in} / P_{Load})$$

N-Port Theory



Linear Network

$$[V] = [Z] \cdot [I]$$

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

Voltage on port i when feeding port j with current I_j . All other ports are open.

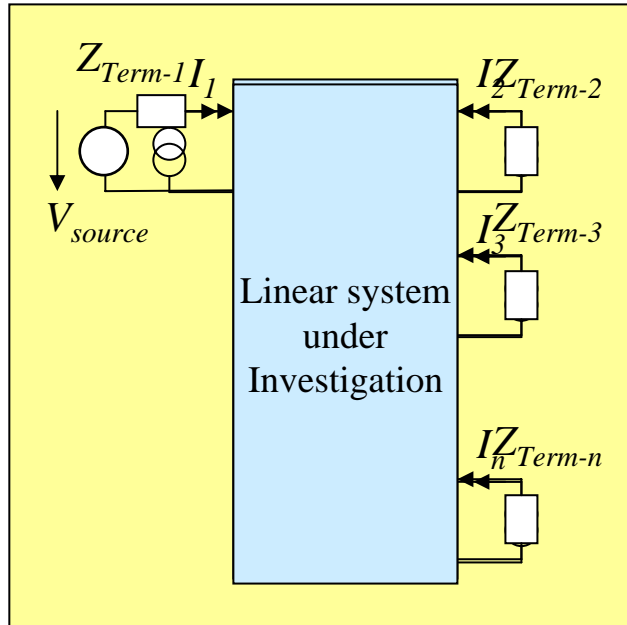
Termination

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

N-Port with arbitrary Termination

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

Radiating linear N-Port



Radiated fields caused by internal currents.

$$\vec{F}_{obs} = \sum_{j=1}^m (\underbrace{\vec{f}_j}_{\text{Geometry based vector relationship}} I_j) \quad I_j : \text{Current amplitude on patch } j$$

$$\vec{F}_{obs} = \sum_{j=1}^m \left(\underbrace{\vec{f}_j}_{\text{Geometry based vector relationship}} \sum_{i=1}^n (p_{ij} I_i) \right) = \sum_{j=1}^m \sum_{i=1}^n (\vec{f}_j p_{ij} I_i)$$

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

The electric/magnetic field at any observation point is a linear combination of contributions due to each port current.

The coefficients \vec{a}_j are obtained from field simulations **feeding one port** and **leaving the other ports open**.

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

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

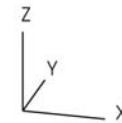
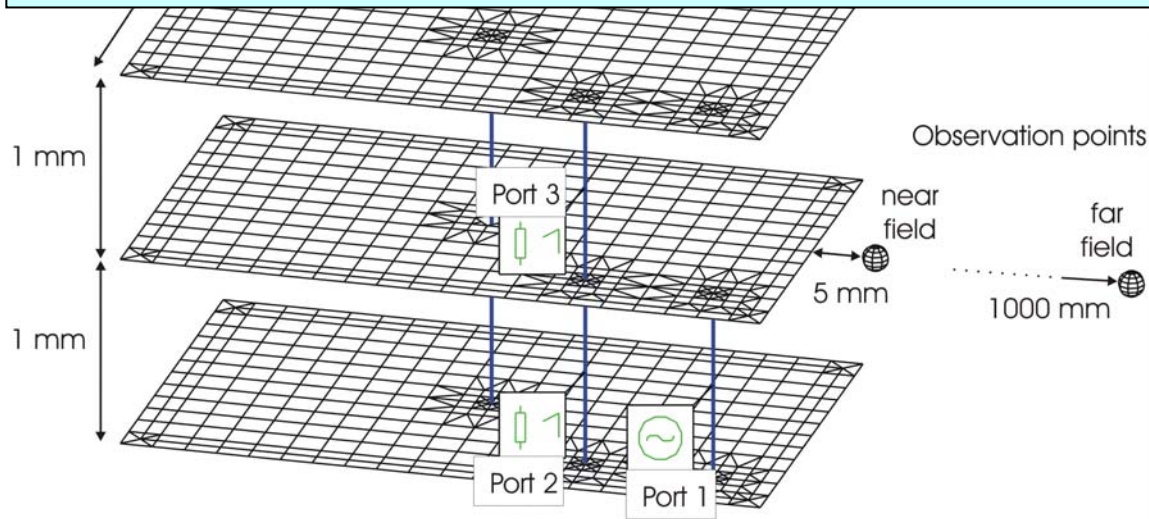
Excite each port individually, leaving the other ports open.

N-Port Z-matrix

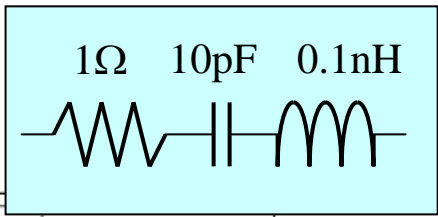
'field factors' \vec{a}_j

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

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



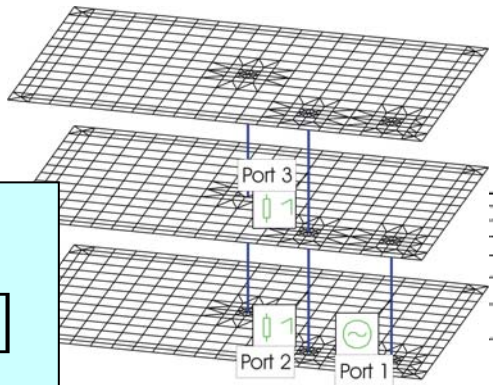
Example



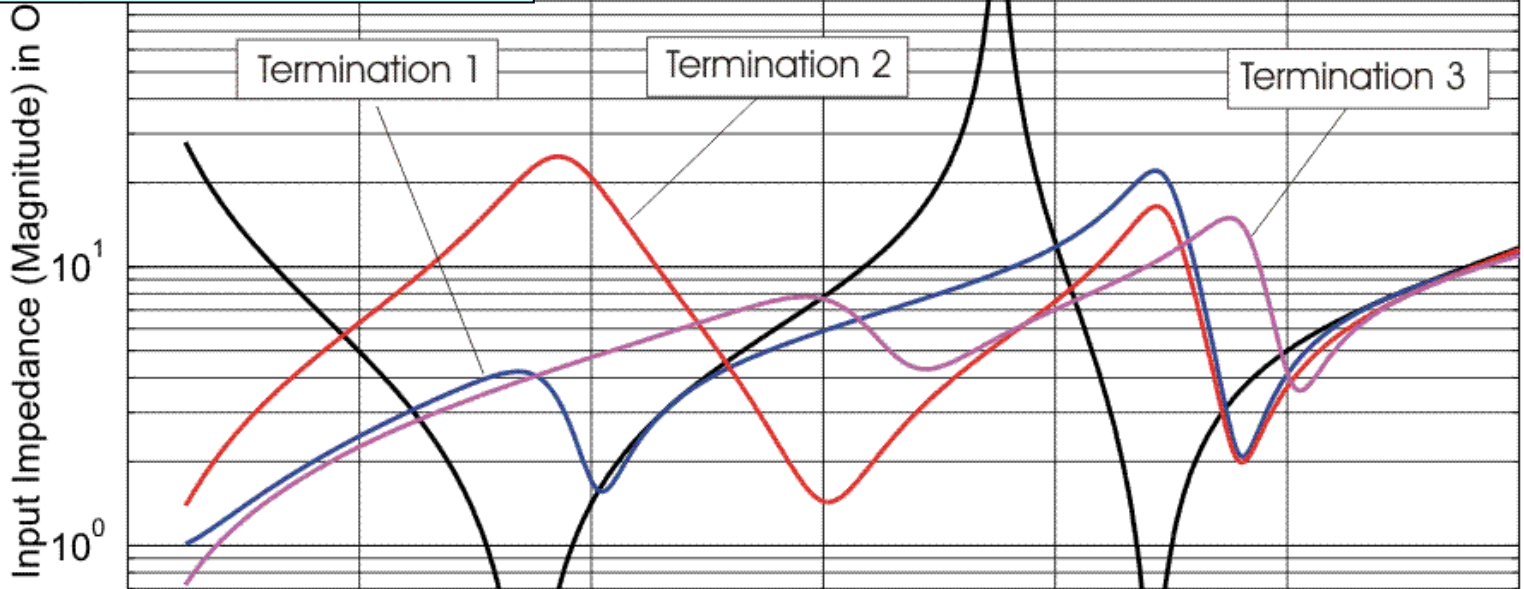
Input Impedance

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

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



Port 2&3 open



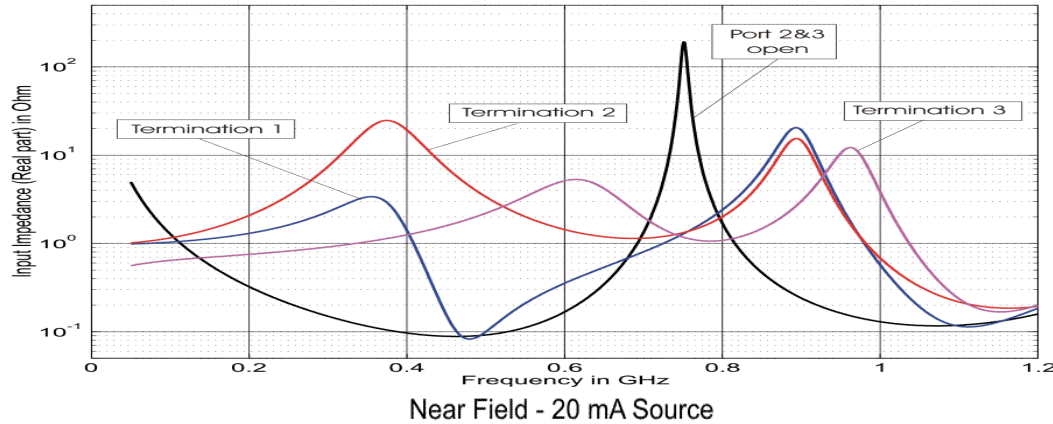
Calculate new port currents.

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

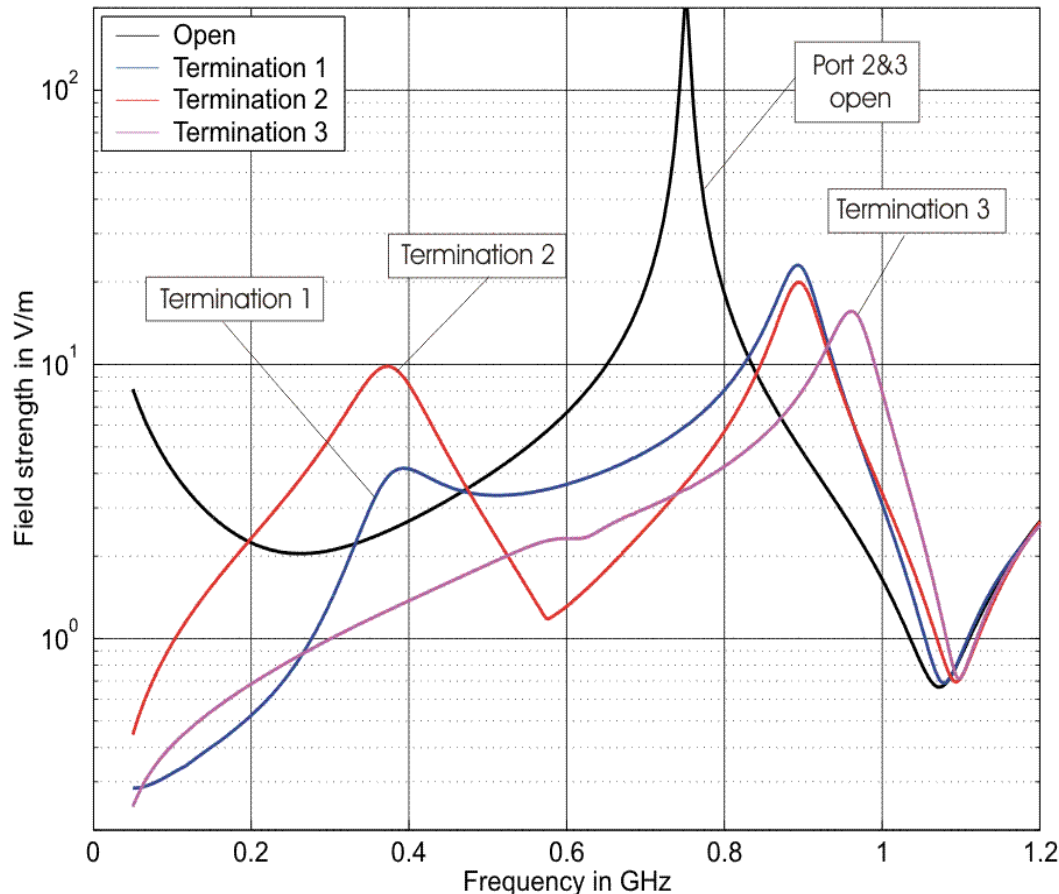
0 0.2 0.4 0.6 0.8 1 1.2

Frequency in GHz

Example



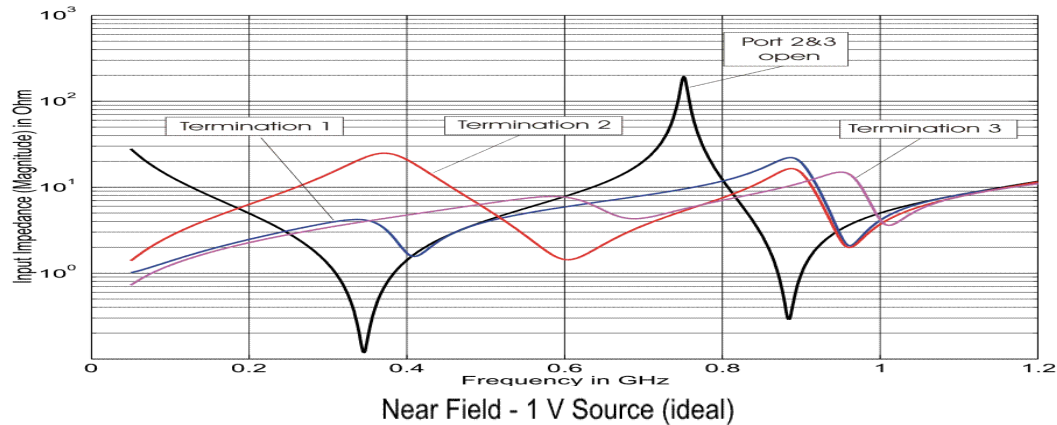
Input impedance
(Real part)



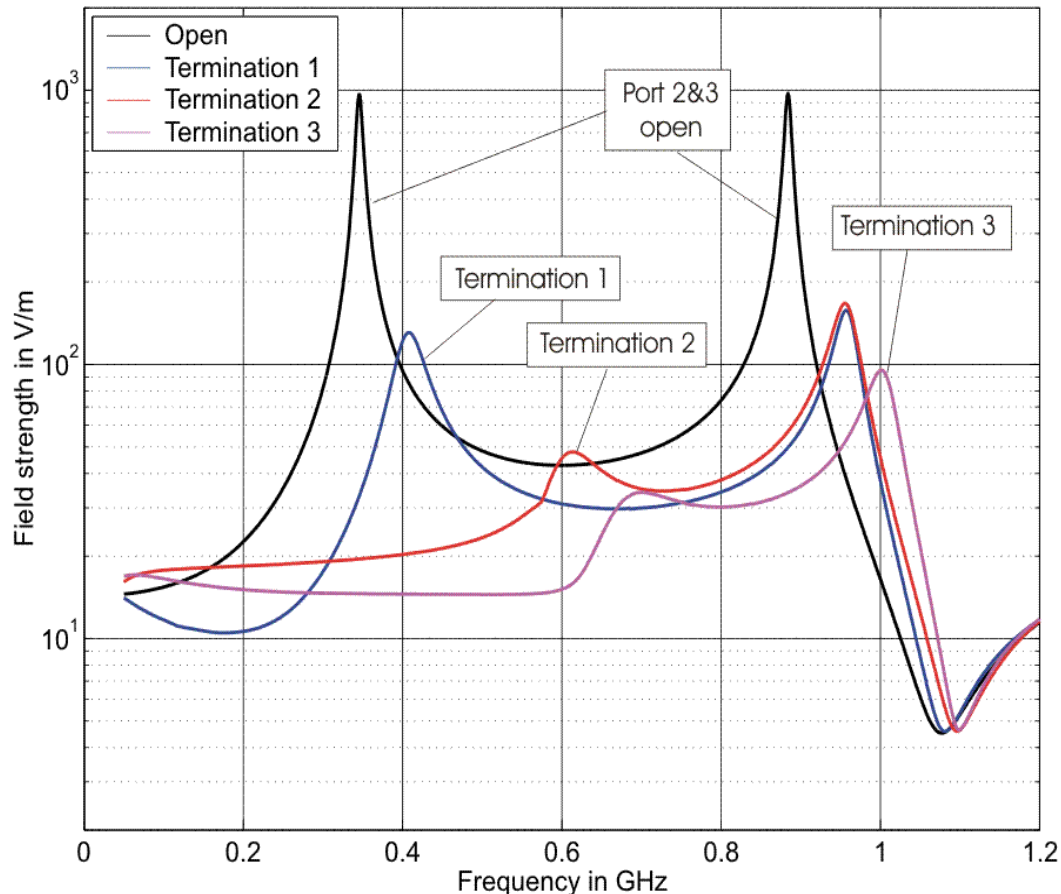
Electric near field
(Source: 20 mA)

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

Example



Input impedance
(Magnitude)

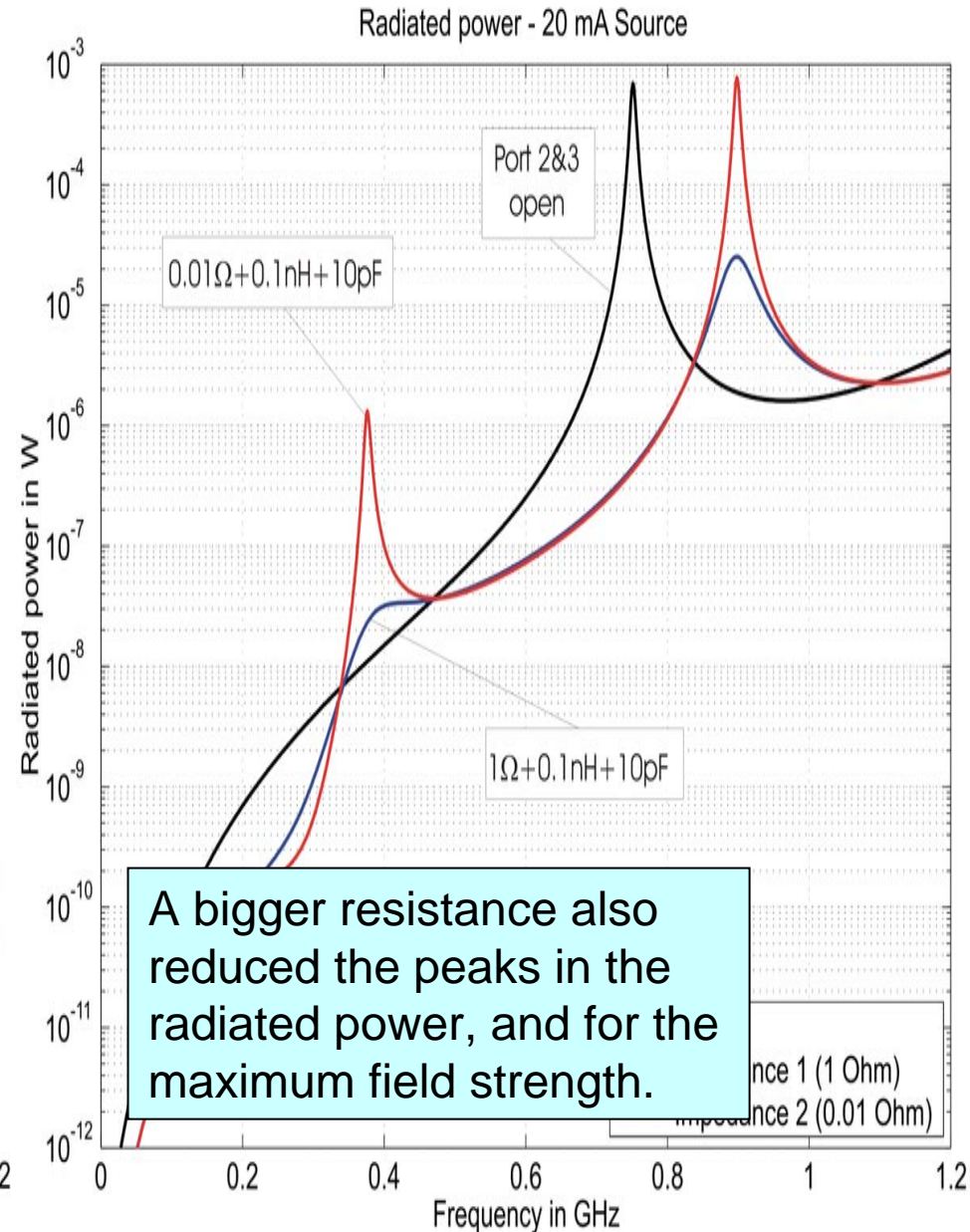
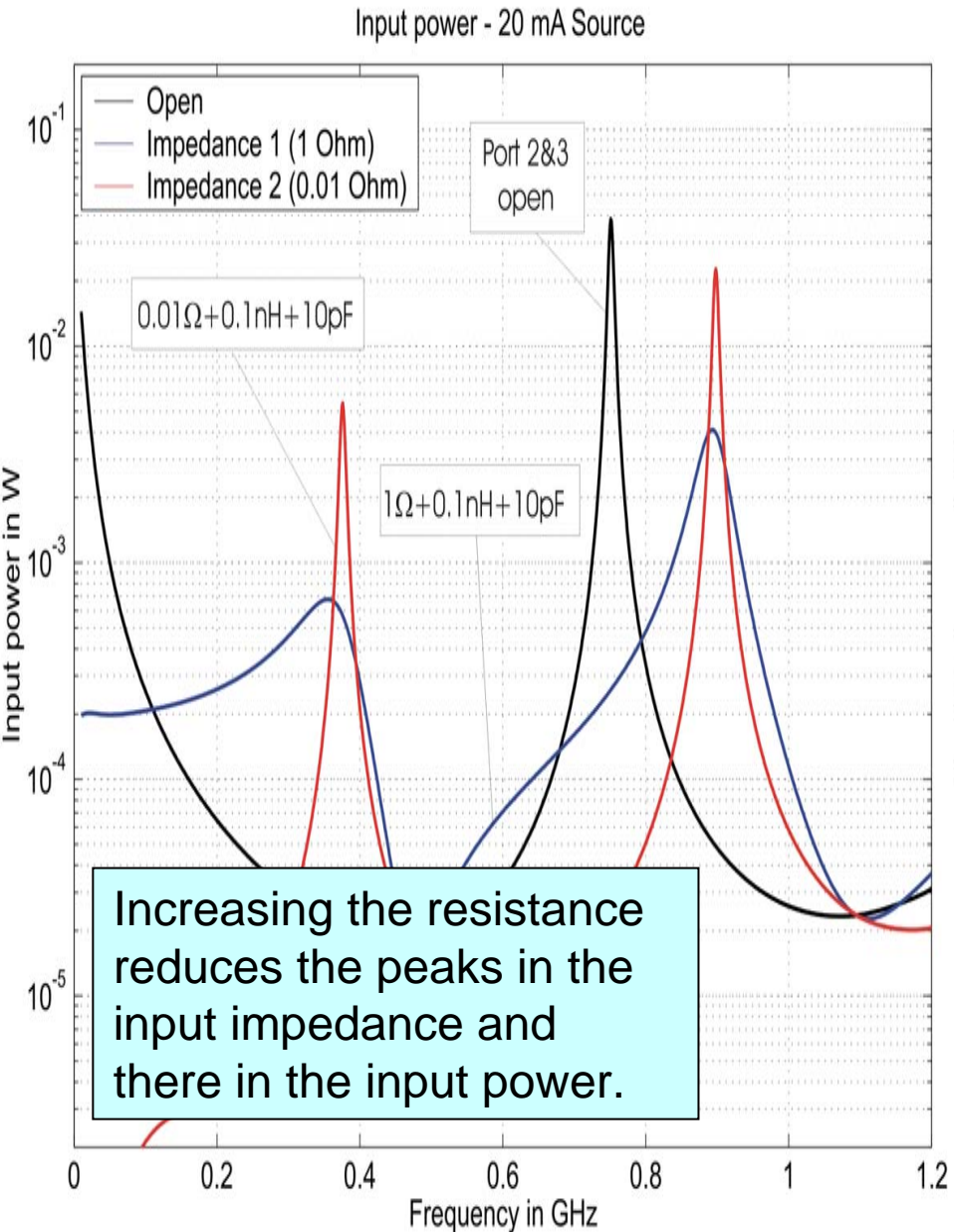


Electric near field
(Source: 1V)

Field follows input admittance
(1/Impedance) 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