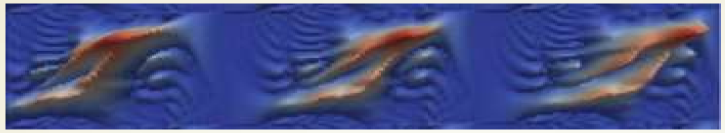


ACCREDIT ACTION IC 1407

IC1407 Advanced Characterisation and Classification of Radiated Emissions in Densely Integrated Technologies (ACCREDIT)

Presentation of STSM: Numerical and experimental study of Noise EM field propagation

STSM grantee: Prof. dr Nebojša Dončov, Faculty of Electronic Engineering, University of Niš, Niš, Serbia

STSM host: Prof. David Thomas, George Green Institute for Electromagnetic Research, The University of Nottingham, Nottingham, UK

COST IC 1407 Action MC meeting in Toulouse, France
ISAE, February 13, 2017

STSM Goals

- The main goal of this STSM was to investigate several EMC-related cases in order to characterise the distribution of deterministic and stochastic EM fields in the near-field and efficiently describe their propagation in the far-field with the combination of numerical TLM method and network oriented correlation matrix approach.
- In addition, a strong laboratory work related by field measurements either in the frequency domain by using vector network analyser (VNA) or in the time-domain by using digital oscilloscope (DO), performed in an anechoic chamber and using a near-field scanner, has accompanied this STSM research.

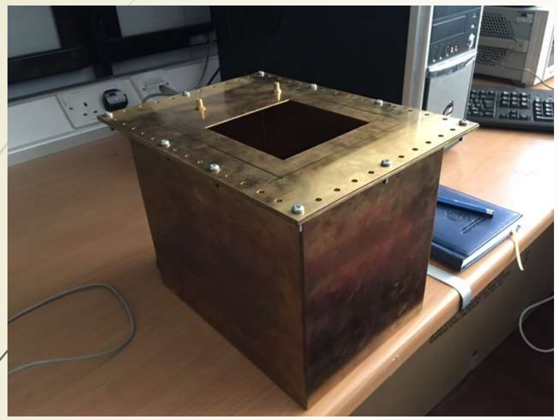
Three activies were carried out during the STSM

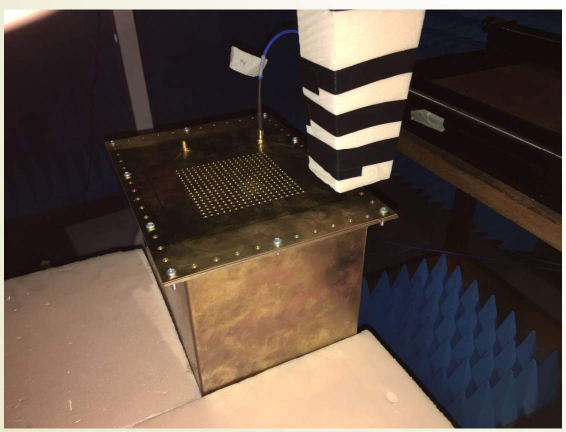
- Numerical modelling of coupling between two monopole antennas inside the metal enclosure with either one big square aperture or an array of circular holes (so-called air-vents) on the removable enclosure lid.
- Experimental and numerical frequency domain characterization of coupling between monopole antennas and RF loop probe positioned slightly above the removable enclosure lid.
- Time-domain sampling of noisy EM field in the near-field above the Intel Galileo board using two near-field probes.

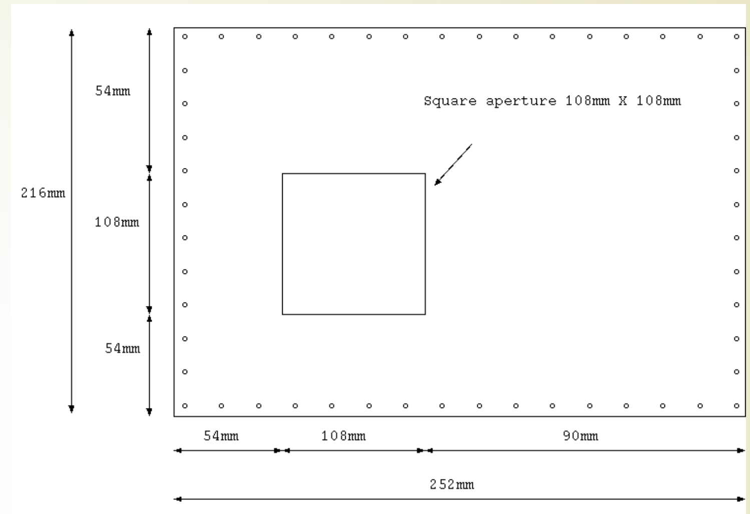
First activity

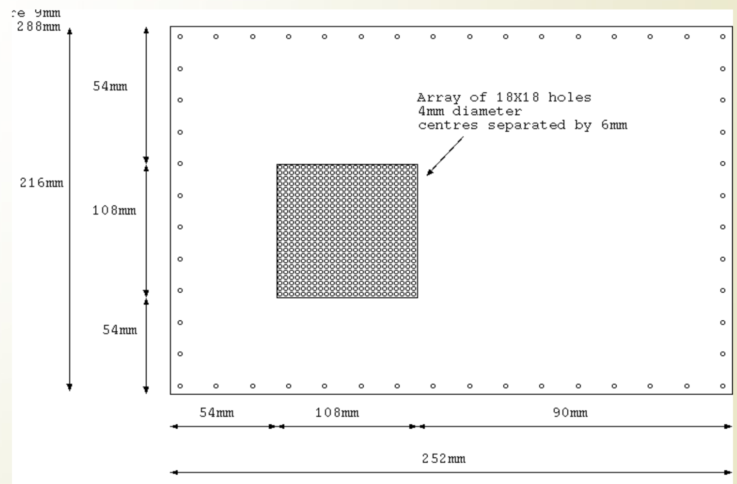
- The internal dimensions of the enclosure are (216x180x252) mm.
- The dimensions of the removable enclosure lid with one square aperture or an array of circular holes are (216x252) mm, extended on both sides in y-direction by 18 mm from the edges of enclosure.
- Thickness of the enclosure walls, made of Brass sheet with 10 Ohm/square, is 1 mm. The area of removable enclosure lid under aperture(s) is (108x108) mm, symmetrically positioned in y-direction (at distance of 54 mm from edges) and asymmetrically positioned in z-direction (at distance of 90 mm from one and at distance of 54 mm from the other edge).

First activity



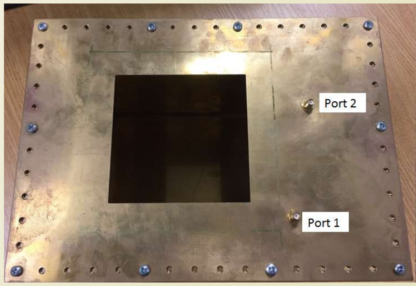






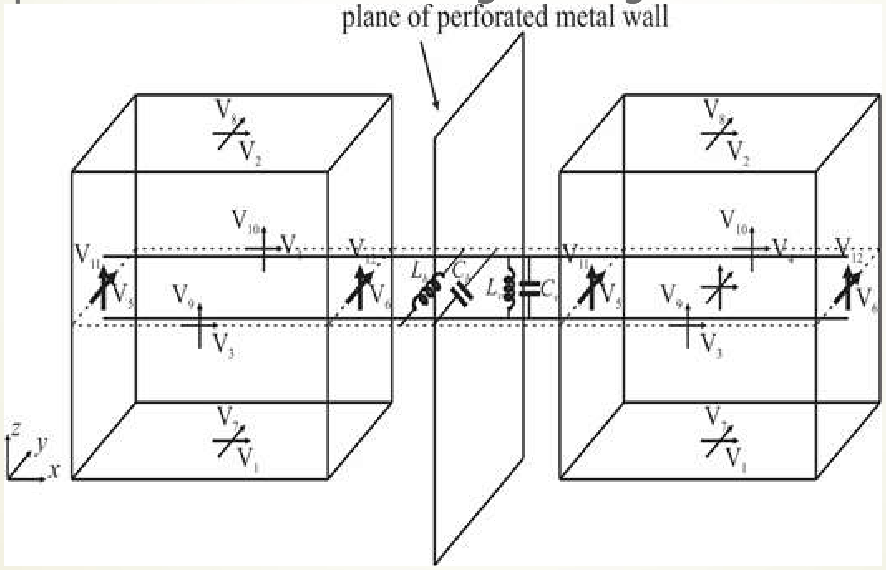
First activity

- One square aperture was of (108x108) mm size, while the air-vent was made of 18x18 circular holes of 4 mm diameter and the distance between centers of two neighboring holes of 6 mm.
- The monopole antennas inside the enclosure were attached to the removable enclosure lid and they were of 27 mm lengths and 0.5 mm radius.
- Position of the monopole closer to the apertures (monopole 1) was offset by 9 mm in y- and 27 mm in z-direction from the lid area under aperture(s) while the second monopole (monopole 2) was offset by 81 mm in y- and 45 mm in z-direction from the lid area under aperture(s).



Brief description of TLM Air-vent model

- The compact TLM air-vent model consists of:
  - two reactive circuits per propagation direction
  - placed between two neighboring TLM cells



- The cells coincide with the position of perforated metal wall.
- $L_h C_h$ circuit for horizontal and $L_v C_v$ circuit for vertical polarization.

Brief description of TLM Air-vent model

- Each circuit interacts with voltage pulses travelling through one of two orthogonally polarized link lines of TLM cell.
- The circuits are in the form of parallel connection of
  - the inductance used to describe current running near the borders of apertures,
  - the capacitance for modeling the EM field distribution inside the apertures.

- The equivalent reactance *X*, can be empirically found by a series of TLM fine mesh simulations conducted for a plane wave illuminating perforated metal wall of various thicknesses and with different aperture spacing.

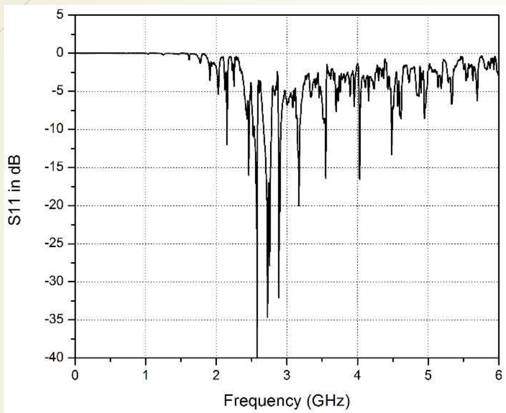
Brief description of TLM Air-vent model

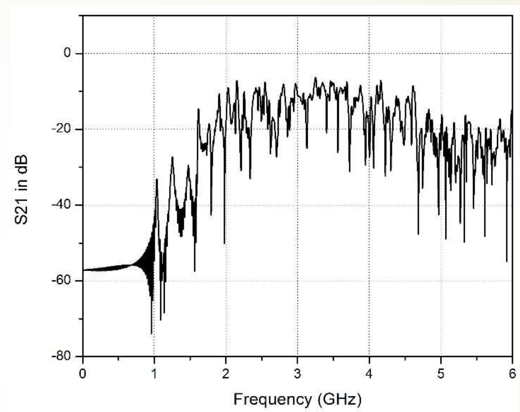
- $X = \omega A_0 \left(\frac{Z_0/2}{2\pi f_c}\right)(A_1 cov + A_2 cov^2 + A_3 cov^3) Exp\left(-A_4 \frac{t}{v/(2\pi f_c)}\right)$,
  - where constants A_i, $i = 0, 1, 2, 3, 4$ are given for each considered aperture shape and appropriate polarization
- Product of angular frequency and four other terms:
  - Aperture cross-section form
  - Cut-off frequency of aperture, f_c,
  - Coverage, *cov* (percentage of wall surface covered by apertures),
  - Wall thickness, t (or perforation depth)
- Transmission coefficient, *T*, is defined by an equivalent circuit consists of a line of characteristic impedance Z_0 loaded with reactance X in the middle point.
- $T = jX/(jX + Z_0/2)$

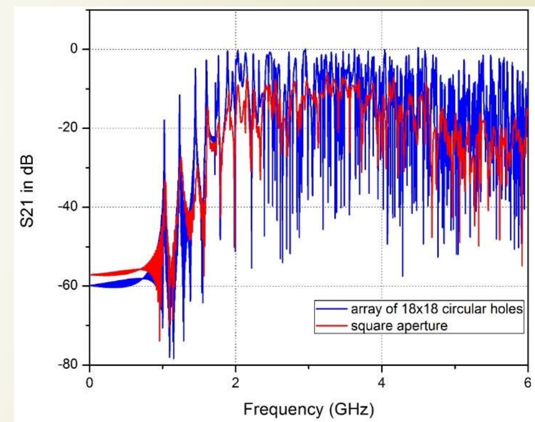
Brief description of TLM Air-vent model

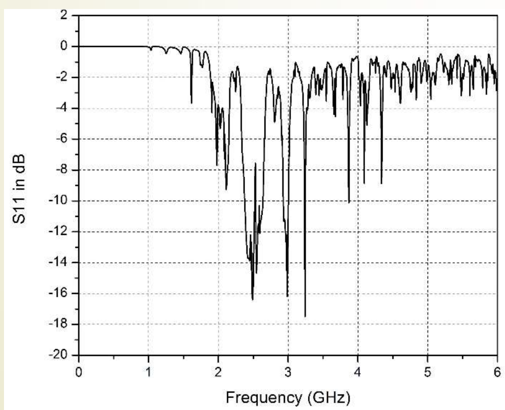
- Some advantages:
  - uses a coarse mesh to describe model with cells potentially bigger in size than individual apertures,
  - more efficient than the TLM fine mesh model,
  - there is no need to model aperture depth.
- A few drawbacks:
  - there are no structures beyond a perforated wall,
  - the model is applicable to the frequencies below the cut-off frequency of the aperture (the aperture on metal wall – an extremely short, highly cut-off waveguide).

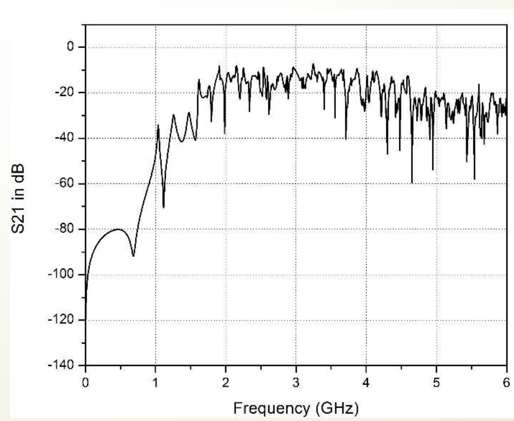
The S11 and S21 results, obtained numerically by the in-house TLM solver and GGIEMR GGI-TLM solver, and representing what would measure with a VNA connected to the two ports on the experimental enclosure lid with an array of circular apertures, are shown below







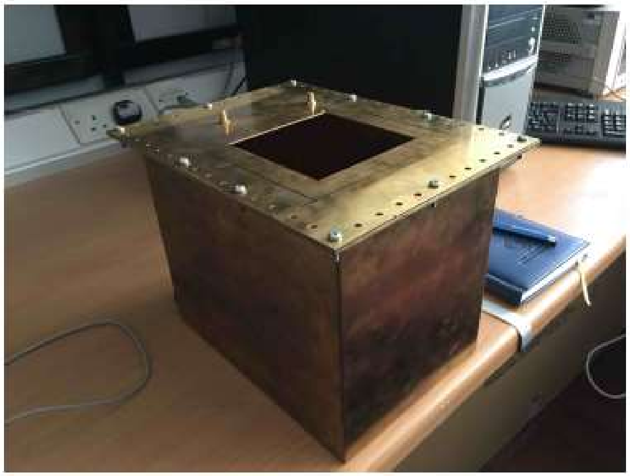




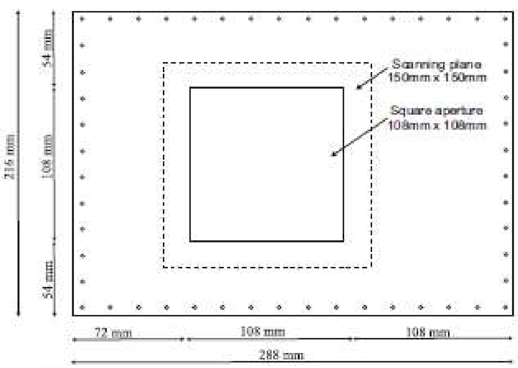
Second activity

- Measurements of coupling between monopole antennas and RF loop probe R 50-1, positioned slightly above the removable enclosure lid were carried out in an anechoic chamber.
- The scanning plane was of (150x150) mm size and it was symmetrically positioned above either one square aperture or an array of circular holes on the removable enclosure lid. It was divided into (31x31) points mutually separated by 5 mm.
- The RF loop probe was accurately placed in each point by using the LabVIEW software. One channel of VNA was used to excite either separately each monopole antenna or both antennas at the same time using the power splitter, while the other channel was connected to RF loop probe.

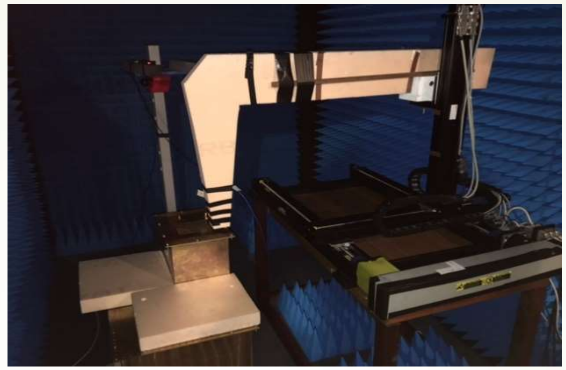
Second activity



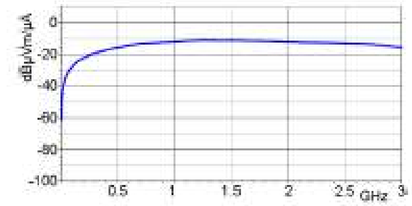
(a) An enclosure with removable lid.



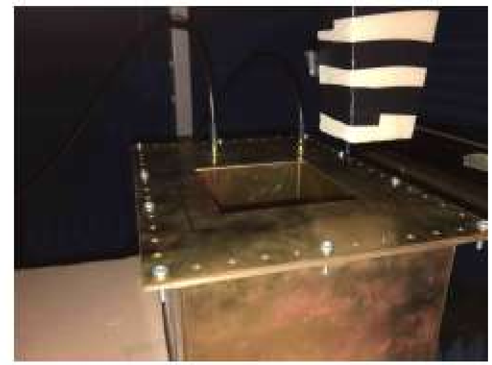
(b) The removable enclosure lid with one square aperture.



(a) RF loop probe.



(b) Frequency characteristic of RF probe used in measurements.



(c) Experimental enclosure with RF loop probe placed above the removable enclosure lid.

Fig. 2. An enclosure with RF loop probe.

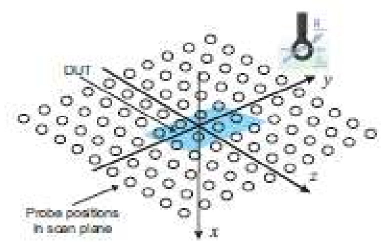


Fig. 3. Near-fied probe positions.

Second activity

- The following cases were considered experimentally within the second activity:
  - Only monopole 1 was excited.
  - Only monopole 2 was excited.
  - Both monopole antennas were excited at the same using the power splitter.
- These cases were considered in order to later study how the possible level of correlation between the sources (fed in practice with currents e.g. in phase or mutually delayed) would affect the EM field distribution inside and outside the enclosure.
- The measurements in the frequency-domain for all three cases were conducted for one square aperture and for an array of 18x18 circular holes on the removable enclosure lid. Also in all cases, the RF loop probe in the scanning plane points was placed at two different heights above the enclosure lid: 10 mm and 50 mm.

S-parameter description

- Linear passive distributed microwave circuits can be described by S-parameters. We consider a cavity with multiple sources exciting EM fields. The sources can be represented by *N* antennas distributed within the cavity.
- The tangential components of the aperture field can be sampled by an array of *M* near-field probes or by a single near-field probe which is sequentially moved to *M* sampling points.
- If the field distribution is known on the aperture, the field outside the cavity can be determined according to uniqueness theorem for deterministic sources.
- The passive structure, including source and near-field probing antennas, can be modeled by a distributed microwave circuit, where each antenna feed represents one port. At each port, an incident power wave **a** and a reflected power wave **b** can be defined. The power waves are related to the port's current I and voltage V by

$$I_n = \frac{1}{\sqrt{Z_0}}(a_n - b_n) \, ,$$
$$V_n = \sqrt{Z_0}(a_n + b_n) \, ,$$

Z_0 is the reference impedance and index *n* refers to the port number

S-parameter description

- Incident and reflected power waves can be summarized in the vectors **a** and **b**.

$$\mathbf{a} = [a_1 \dots a_N \, a_{N+1} \dots a_{N+M}]^T \, ,$$
$$\mathbf{b} = [b_1 \dots b_N \, b_{N+1} \dots b_{N+M}]^T \, ,$$

- where ^{T} denotes the transpose vector. Both, incident and reflected power waves are related to each other via the scattering matrix **S**.

$$\mathbf{b} = \mathbf{S}\,\mathbf{a} \, .$$

- With *N* antennas that will be connected to excitation sources and *M* near-field probing antennas, we can introduce submatrices as follows

$$S = \begin{bmatrix} \mathrm{S_{NN}} & \mathrm{S_{NM}} \\ \mathrm{S_{MN}} & \mathrm{S_{MM}} \end{bmatrix} .$$

S-parameter description

- Correlations between the power waves can be defined for the incident waves in the matrix $\mathbf{C_a}$ and for the reflected waves in the matrix $\mathbf{C_b}$.

$$\mathrm{C_a} = \langle \mathrm{a}\mathrm{a}^{\dagger} \rangle \ ,$$
$$\mathrm{C_b} = \langle \mathrm{b}\mathrm{b}^{\dagger} \rangle \ .$$

- Here, <…> denotes the ensemble average and + the Hermitian conjugate. From the last two equations we obtain

$$\mathrm{C_b} = \mathbf{S}\, \mathrm{C_a}\, \mathbf{S}^{\dagger} \ .$$

- Assuming that the near-field probes scanning the field can be considered non-invasive there will be no incident power waves from these port, i.e. $a_n = 0$ for n = $N + 1, \ldots, N + M$.

- The correlation matrix obtained for the voltages at the observation ports is than obtained only from the reflected power waves at those ports as

S-parameter description

- The correlation matrix obtained for the voltages at the observation ports is than obtained only from the reflected power waves at those ports as

$$\mathbf{C}_{\mathbf{V_M}} = \left\langle \mathbf{V_M} \mathbf{V_M}^{\dagger} \right\rangle = Z_0 \mathbf{C}_{\mathbf{b_M}} ,$$

where $\mathbf{V_M} = [V_{N+1} \dots V_{N+M}]^T$ and $\mathbf{C}_{\mathbf{b_M}} = \left\langle \mathbf{b_M} \mathbf{b_M}^{\dagger} \right\rangle$ with $\mathbf{b_M} = [b_{N+1} \dots b_{N+M}]^T$. Correlations of the source

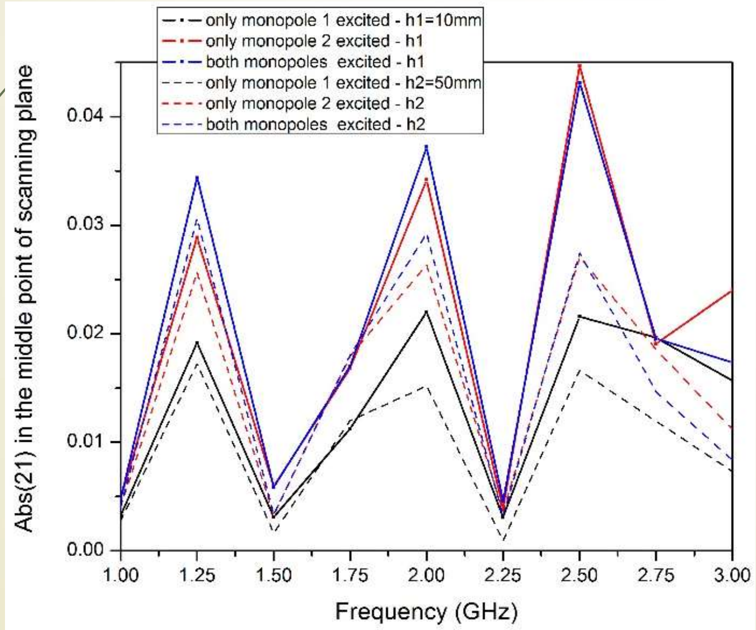
- Correlations of the source currents $\mathbf{I}_N = [I_1 : : : I_N]^T$ and their relation to the incident power waves at the source ports is given as

$$\mathbf{C}_{\mathbf{I_N}} = \left\langle \mathbf{I_N} \mathbf{I_N}^{\dagger} \right\rangle = \frac{1}{Z_0} \Big(\mathbf{C}_{\mathbf{a_N}} + \mathbf{S_{NN}} \mathbf{C}_{\mathbf{a_N}} \mathbf{S_{NN}}^{\dagger} - \mathbf{S_{NN}} \mathbf{C}_{\mathbf{a_N}} - \mathbf{C}_{\mathbf{a_N}} \mathbf{S_{NN}}^{\dagger} \Big) ,$$

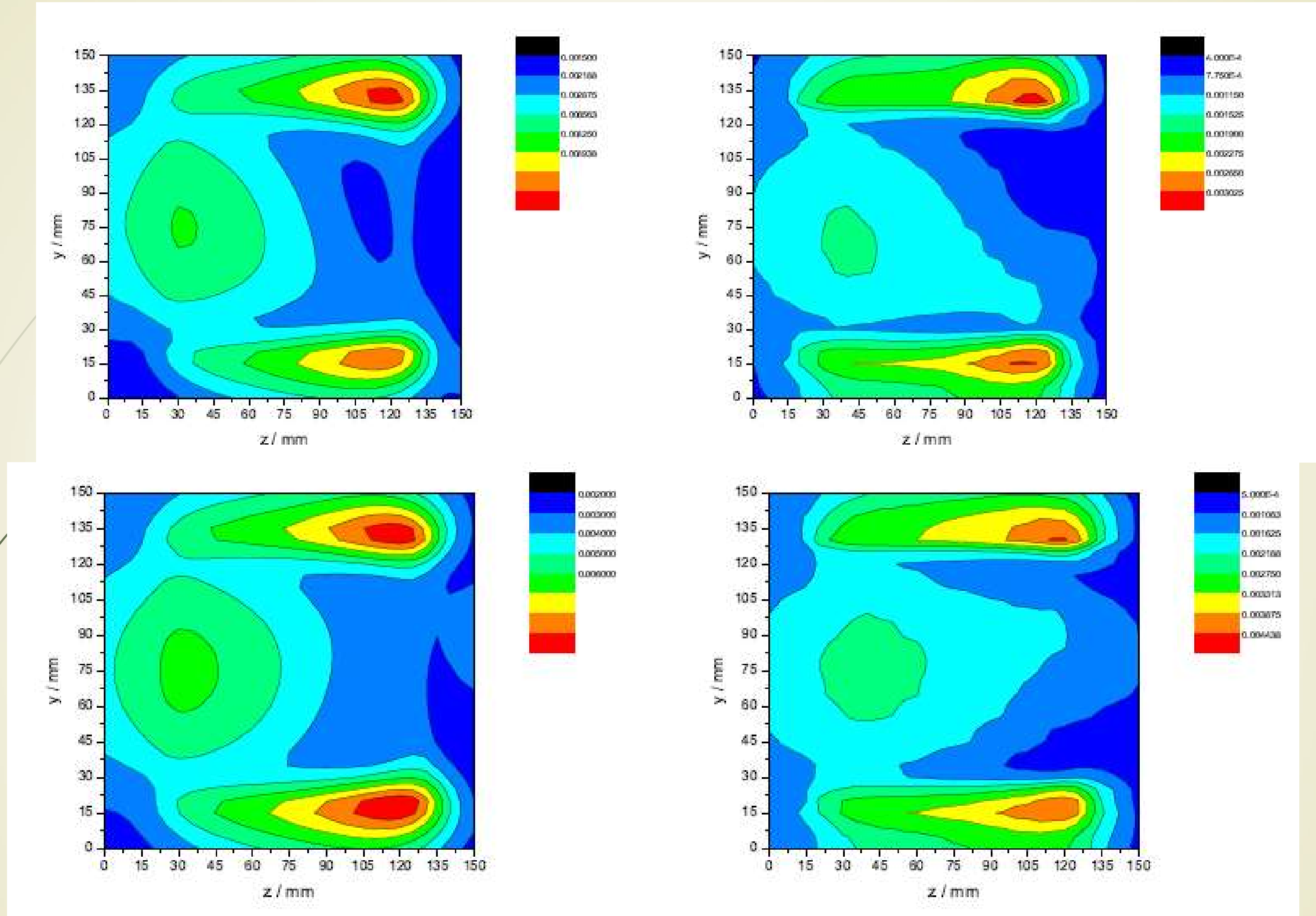
with $\mathbf{C}_{\mathbf{a_N}} = \langle \mathbf{a_N} \mathbf{a_N}^{\dagger} \rangle$ where $\mathbf{a_N} = [a_1 \dots a_N]^T$.

Results

- Transfer function describing the coupling between monopole antennas attached to enclosure lid and RF loop probe, positioned in each of (31x31) points of scanning plane of (150x150) mm size, symmetrically positioned above either one square aperture or an array of circular holes at height 10 mm or 50 mm, was obtained by measurements in the frequency range from 1 GHz to 3 GHz.



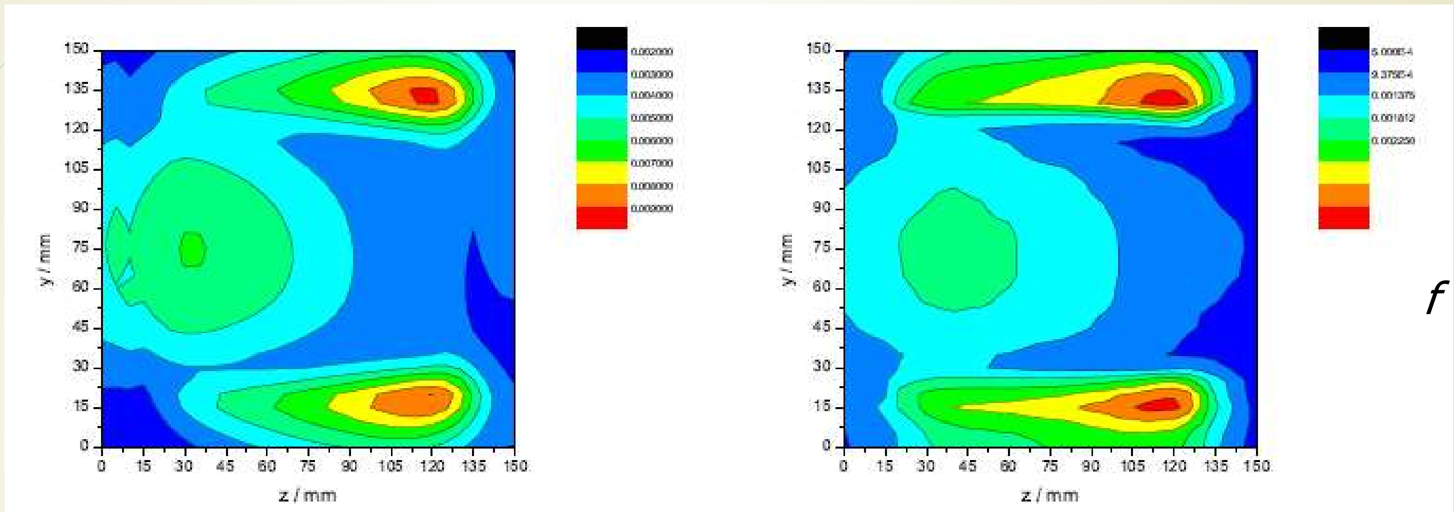
Transfer function describing the coupling between monopoles and RF loop probe placed at the point in the middle of scanning plane above the enclosure lid with one square aperture



f = 1 GHz

Measured coupling
between monopoles and probe

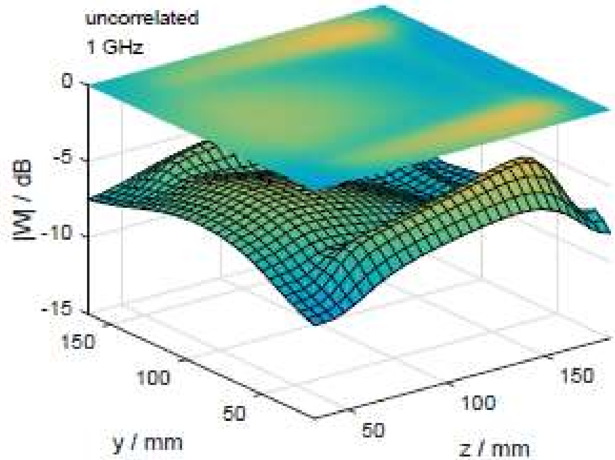
|Hy| from simulation



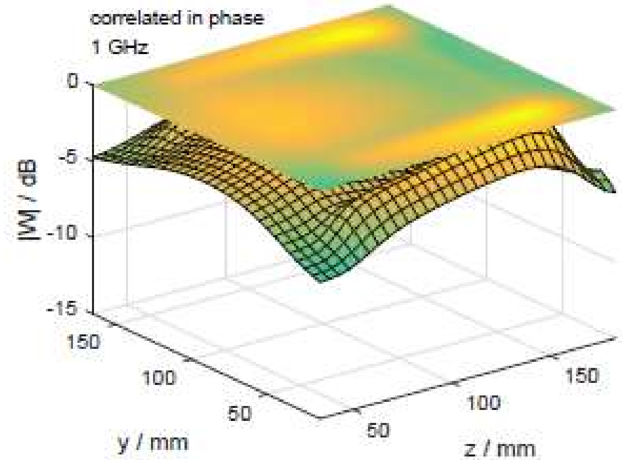
Measured coupling
between monopoles and probe

|Hy| from simulation

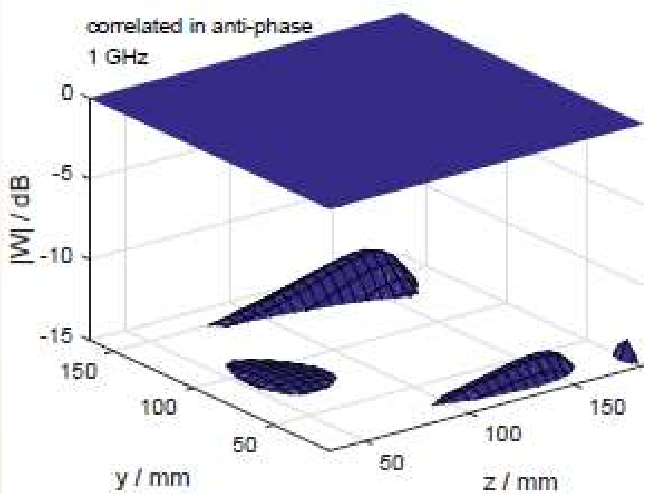
f = 1 GHz



(a) SED due to excitation by two uncorrelated sources.



(b) SED due to excitation by two correlated sources in phase.

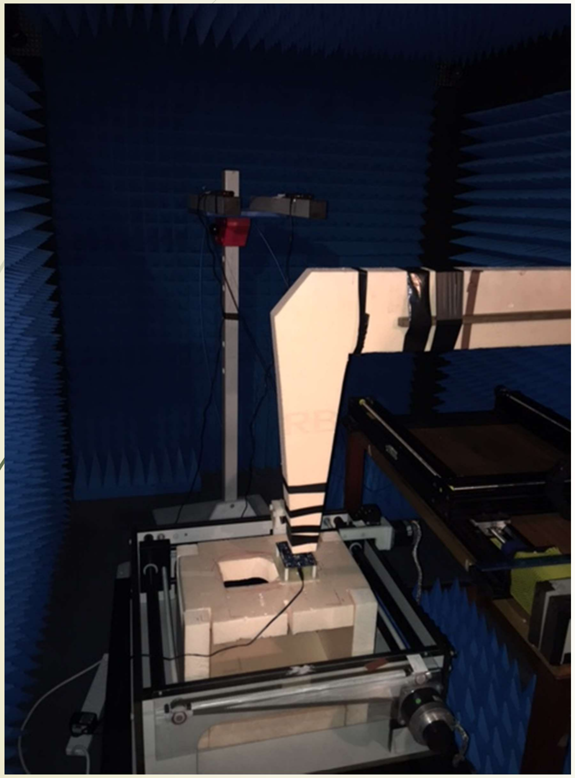


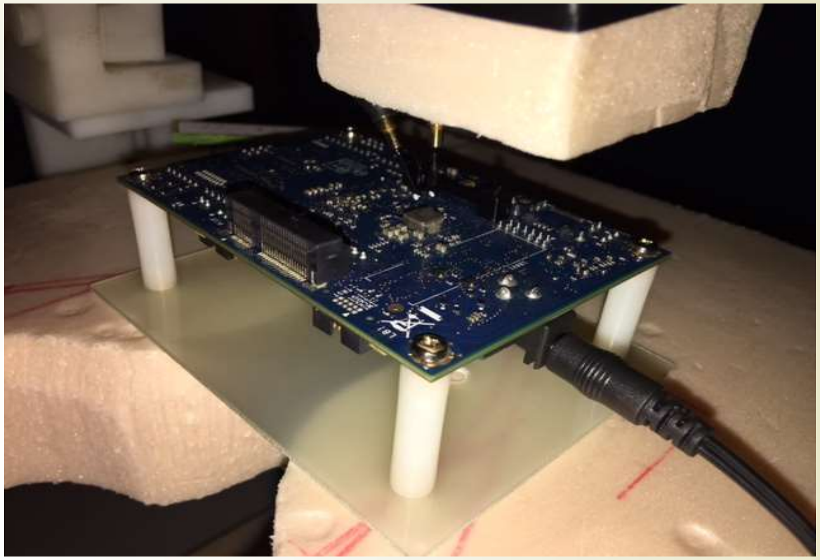
(c) SED due to excitation by two correlated sources in anti-phase.

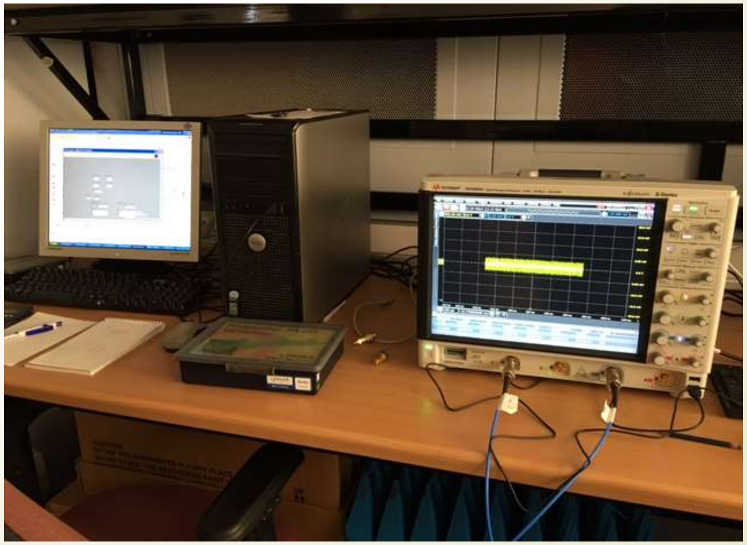
Third activity

- The sampling of noisy EM field in the near-field above the Intel Galileo board is conducted in an anechoic chamber.
- The approach presented in [J.A. Russer, P. Russer, "Modeling of Noisy EM Field Propagation Using Correlation Information", IEEE Transactions on Microwave Theory and Techniques, Volume 63, Issue 1, pp.76-89, 2015] was used to sample the EM field and later, after processing the measured data, to calculate the correlation matrix in the near-field and to perform principal component analysis (PCA).
- Two near-field probes with preamplifier PA 203, positioned slightly above the back side of the Intel Galileo board, were used to sample the EM field.
- The scanning plane was either of (30x30) mm or (50x50) mm size and it was positioned in such way to mostly include the noisy field distribution above the memory part of the board and partially above the board processor.
- It was divided into either (7x7) or (11x11) points mutually separated by 5 mm. The RF probes were accurately placed in the scanning plane points by using the LabVIEW software while the measurements in the time-domain were conducted by using DO with 2 GSA/s whose two channels were connected to the near-field RF probes.

Third activity

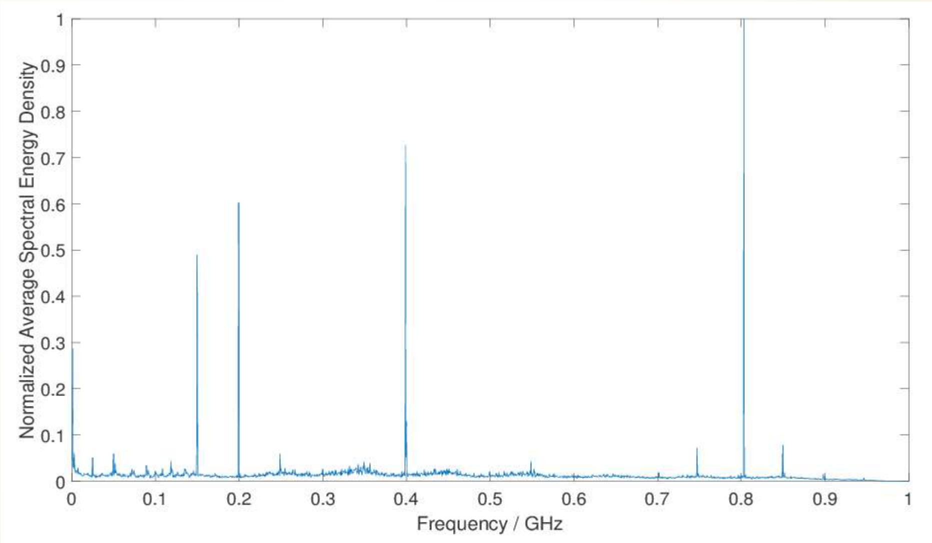






Results

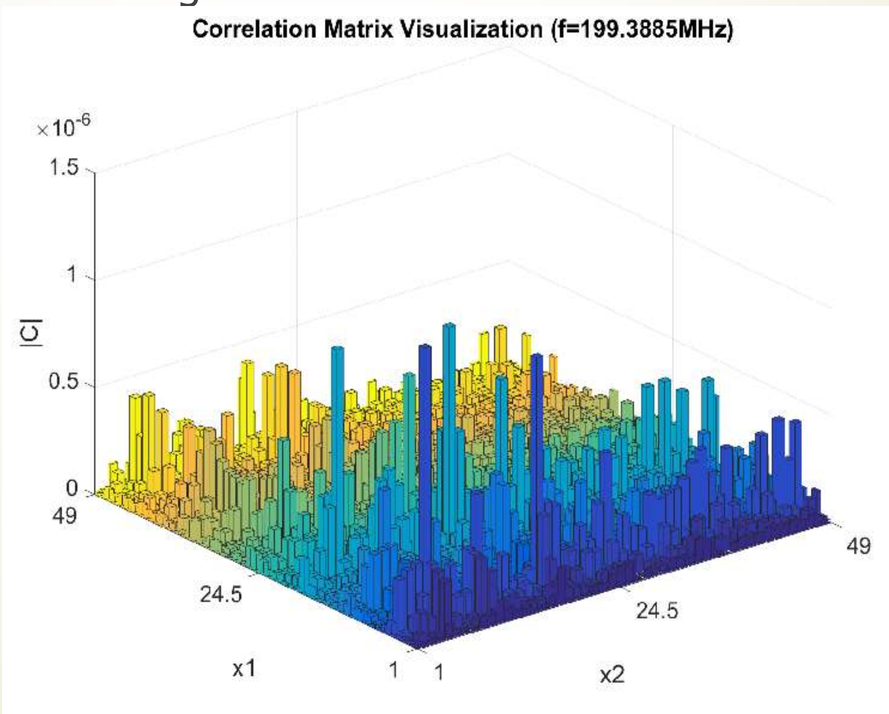
- From the measured field data, sampled by two near-field probes at 3 mm height from the Intel Galileo board (sampling frequency was 2 GHz), and following the approach given in [J.A. Russer, P. Russer, "Modeling of Noisy EM Field Propagation Using Correlation Information", IEEE Transactions on Microwave Theory and Techniques, Volume 63, Issue 1, pp.76-89, 2015], the spectral energy density is calculated allowing to identify emission frequencies at which a noisy EM field is radiated from the board.



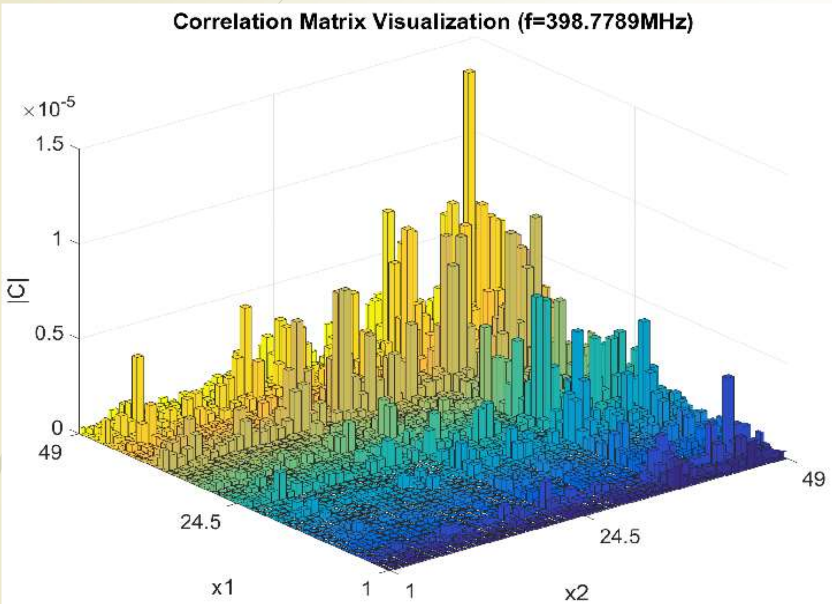
The normalized average spectral energy density at 3 mm height from the *Intel Galileo board*

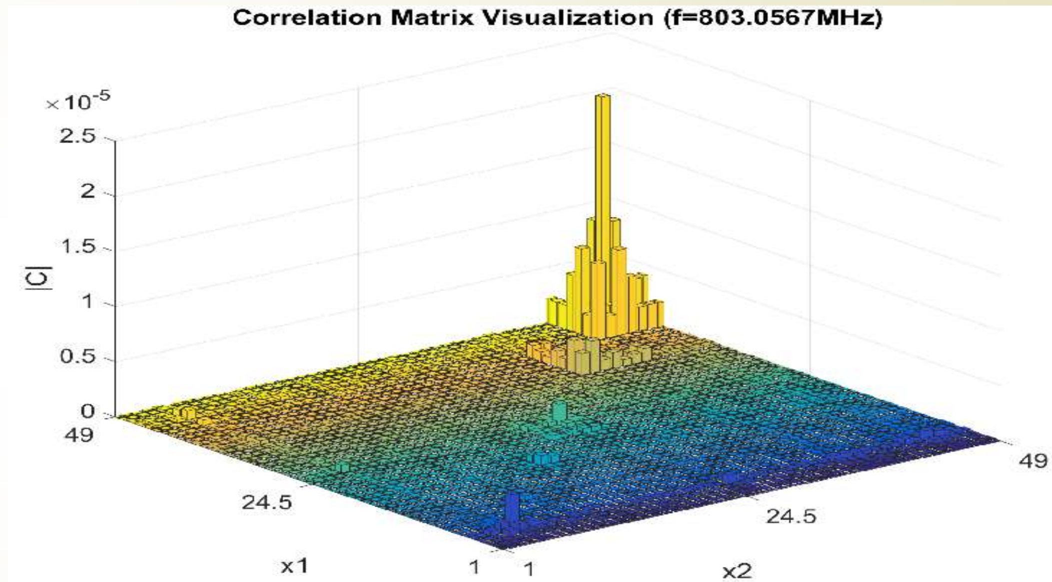
Results

- By calculating the auto- and cross-correlation functions of the time-windowed (~1 milliseconds) field amplitudes at any pair of (7x7) points, in which near-field probes were placed, the correlation matrix of size (49x49) in the near-field is calculated in the time-domain and then by using FFT transferred to the frequency domain at some of the emission peaks identified in previous figure.



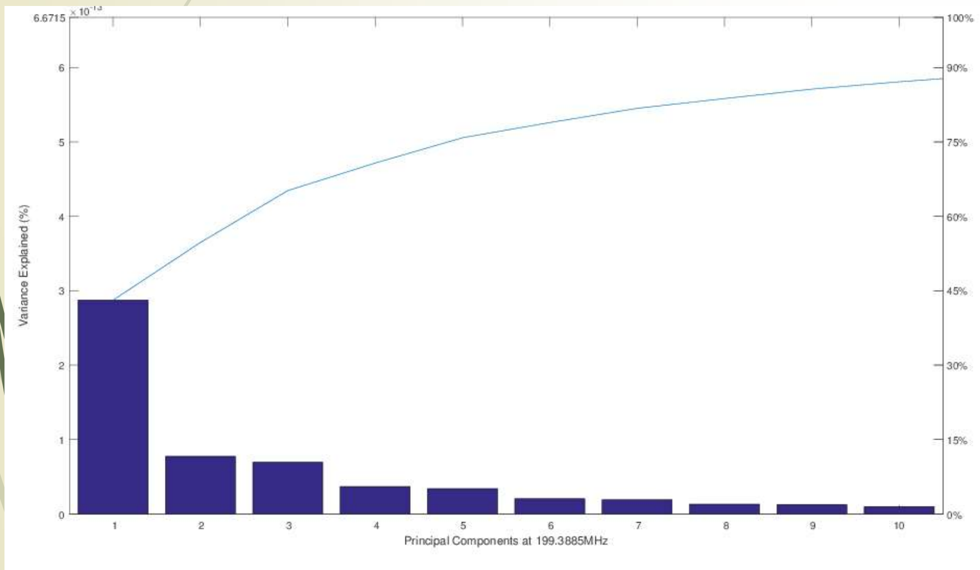
Results

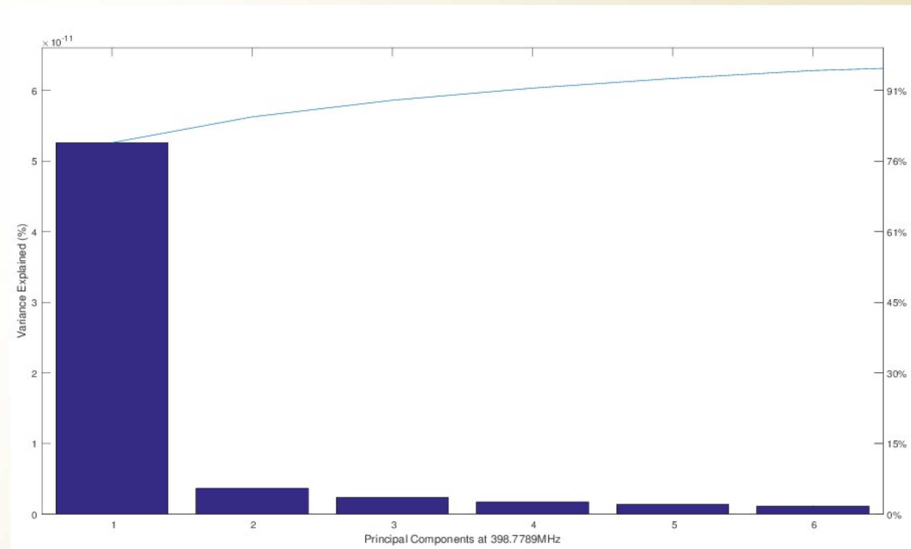

Correlation Matrix Visualization (f=398.7789MHz)
×10^-5
1.5
1
0.5
0
|C|
49
24.5
x1
1
1
24.5
49
x2


Correlation Matrix Visualization (f=803.0567MHz)
×10^-5
2.5
2
1.5
1
0.5
0
|C|
49
24.5
x1
1
1
24.5
49
x2

Results

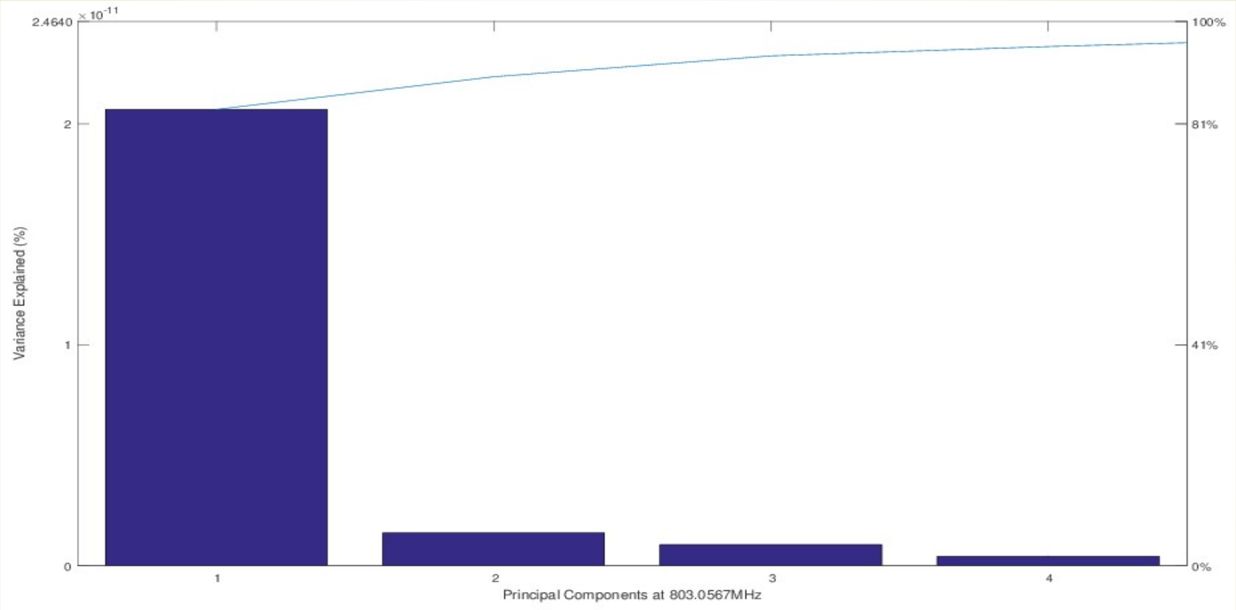
- Eigenvalue decomposition performed by using the PCA approach [T. Asenov, J.A. Russer, and P. Russer, "Efficient Characterization of Stochastic Electromagnetic Fields using Eigenvalue Decomposition and Principal Component Analysis Methods,", Proceedings of URSI 2014 GASS, Beijing, August 16-23,2014] at the first few maxima in the emission spectrum shows that there is mostly one dominant principal component.





Principal Components at 198.3885 MHz and 398.7789 MHz

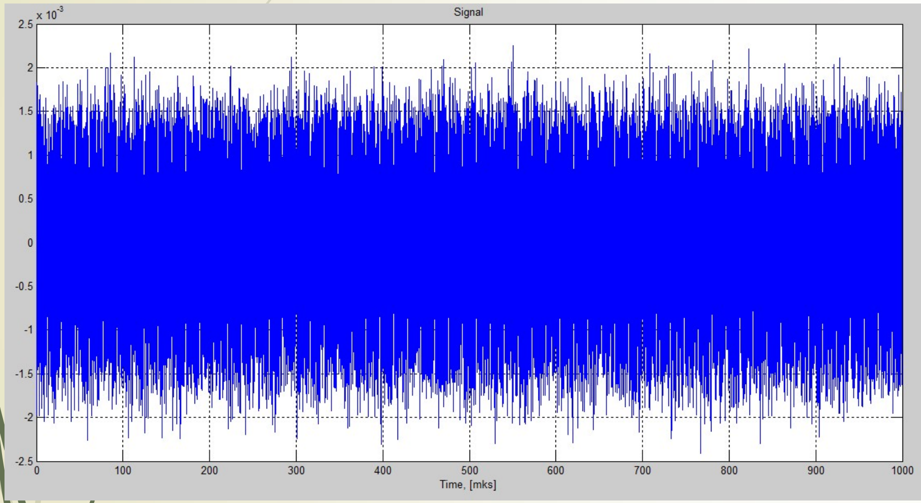
Results

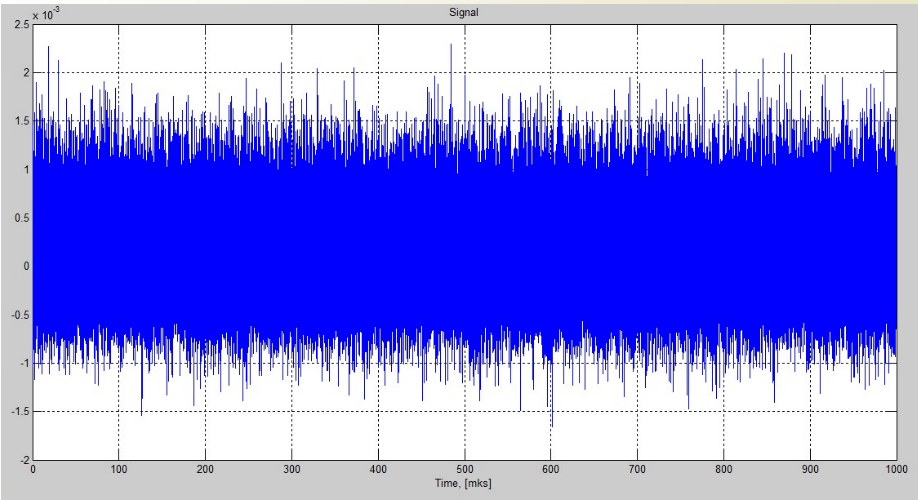


Principal Components at 803.0567 MHz

Problems

- Data collected by the second probe showed some bias!





Acknowledgment

I would like to thank Prof. David Thomas, Dr. Chris Smart and PhD student Mohd Hafiz Baharuddin from the GGIEMR for their strong support and help during the STSM. Also, I would like to thank Dr. Johannes Russer and PhD student Michael Haider from Technical University of Munich for their suggestions and help to efficiently post-process the measured data.

Thank you!

Any questions?