EMF Exposure Limits and Compliance Assessment for Wireless Devices Operating at Frequencies above 6 GHz

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Work Package 2

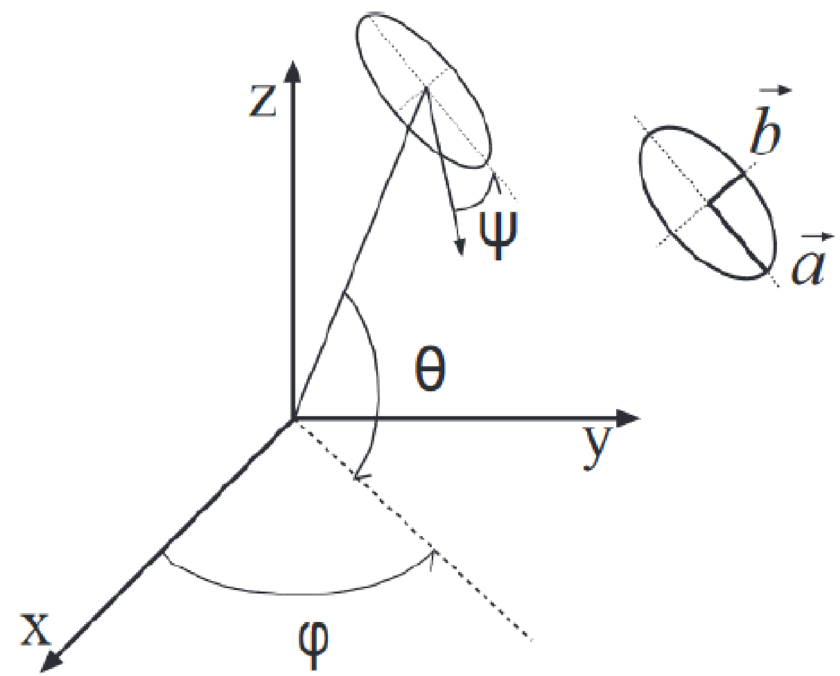
- the design of a novel miniature field probe for assessing the near E-field of antennas in portable devices used in close proximity of the body, operating in the band 10-100 GHz
- addressing:
  - test equipment
  - spatial averaging
  - sampling resolution

Near-Field Probe System

- pseudo-vector probe design
  - designed for optimised isotropy
  - insensitive to mechanical tolerances and field distortion
- probe developed by SPEAG
  - commercial availability: end of Q3 2016
  - open specification for measuring systems
- acquired by IT'IS for this project

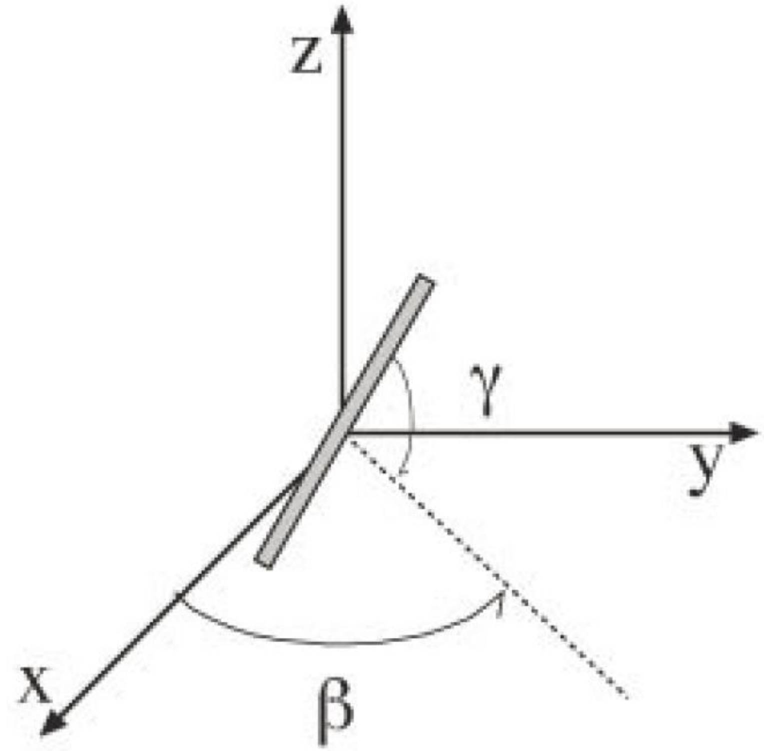
Pseudo Vector Probes

- reconstructs the polarization ellipse by over-sampling the field
- at least 5 measurements are required
- the proposed analysis uses the E-field magnitude and the normal to the polarization ellipse defined in terms of θ and φ.



Pseudo Vector Probes

- vector magnitudes *a* and *b* can be uniquely determined from least-square error for the given set of angles
- overdetermined system of equations to suppress noise and increase the reconstruction accuracy
- solution:
  - probe with two sensors
    - angles: γ_1, $\gamma_2 = \gamma_1 + 90°$
  - perform measurements at three angular rotations: β_1, β_2, β_3
  - ‣ angles optimized for polarization accuracy



Pseudo Vector Probe: Method

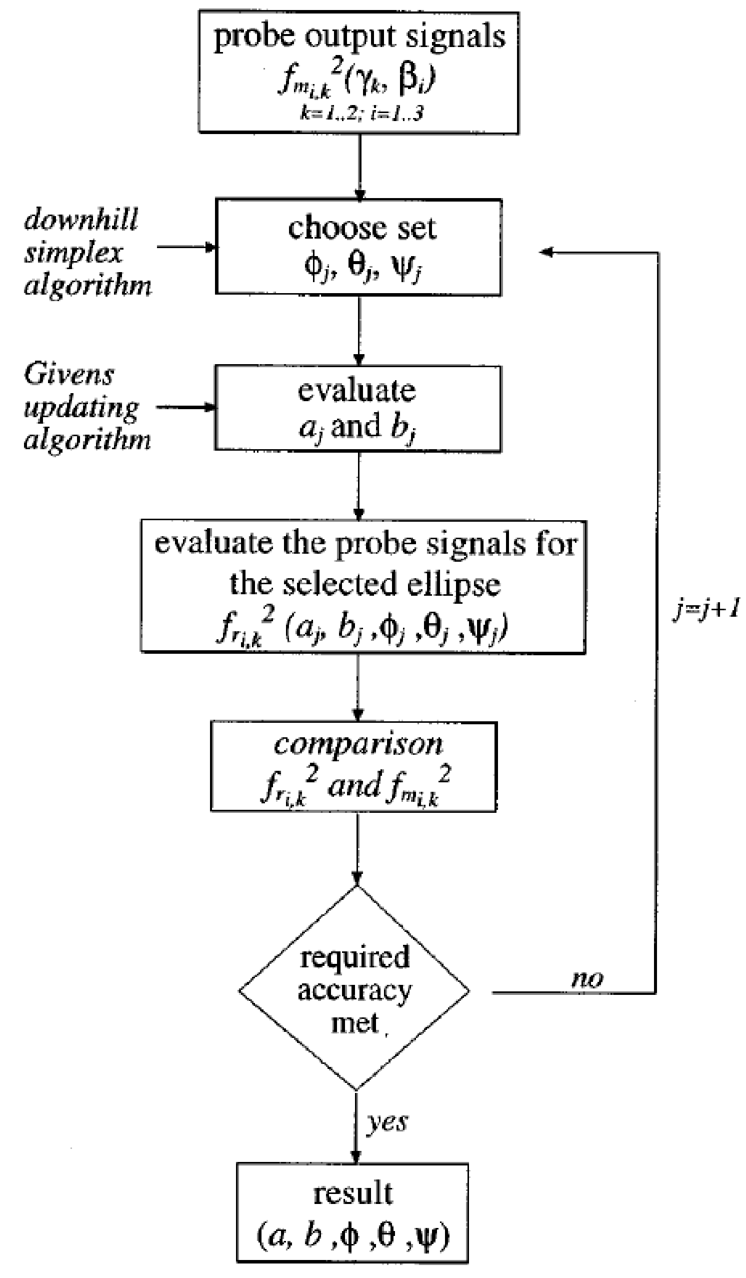
- parameters a, b, ψ, φ, θ are evaluated from

$$f_{ij}^2 = a^2 \cdot [\chi_1 - \chi_2 - \chi_3]^2 + b^2 \cdot [\chi_4 + \chi_5 - \chi_6]^2$$

- where

$$\chi_1 = \cos(\psi) \cdot \cos(\theta) \cdot \sin(\gamma_i)$$
$$\chi_2 = \cos(\gamma_i) \cdot \sin(\psi) \cdot \sin(\beta_j - \phi)$$
$$\chi_3 = \cos(\gamma_i) \cdot \cos(\psi) \cdot \sin(\theta) \cdot \cos(\beta_j - \phi)$$
$$\chi_4 = \sin(\psi) \cdot \cos(\theta) \cdot \cos(\gamma_i)$$
$$\chi_5 = \cos(\gamma_i) \cdot \cos(\psi) \cdot \sin(\beta_j - \phi)$$
$$\chi_6 = \cos(\gamma_i) \cdot \sin(\psi) \cdot \sin(\theta) \cdot \cos(\beta_j - \phi)$$

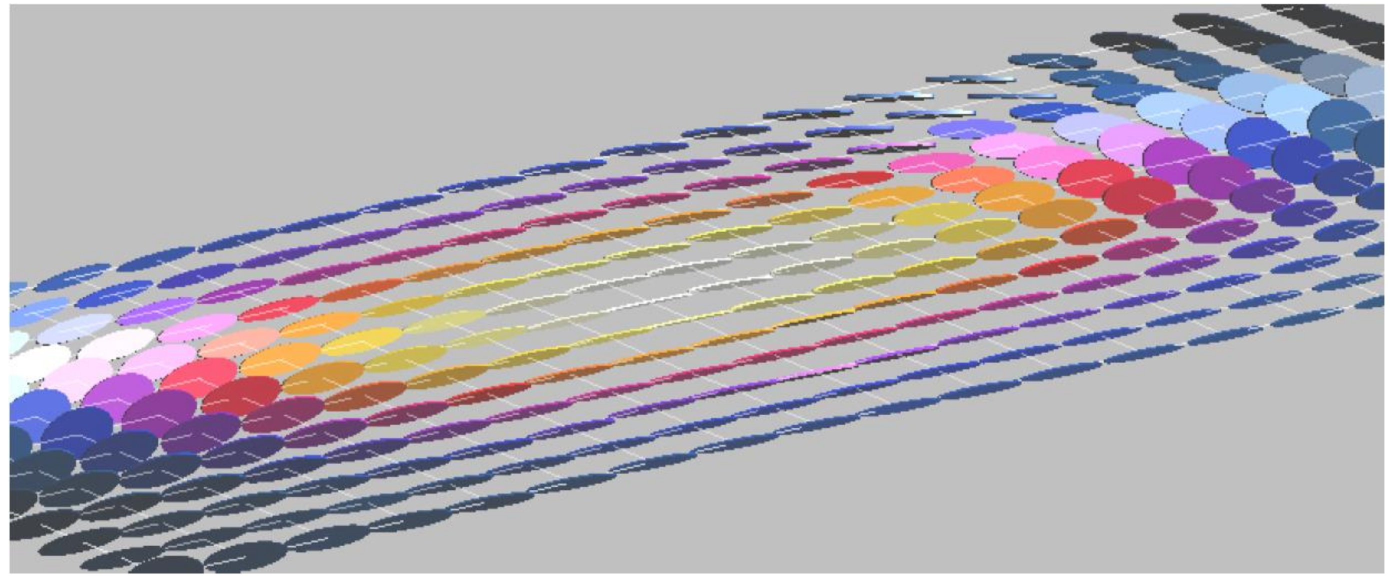
- apply Givens algorithm [1] with downhill simplex optimization

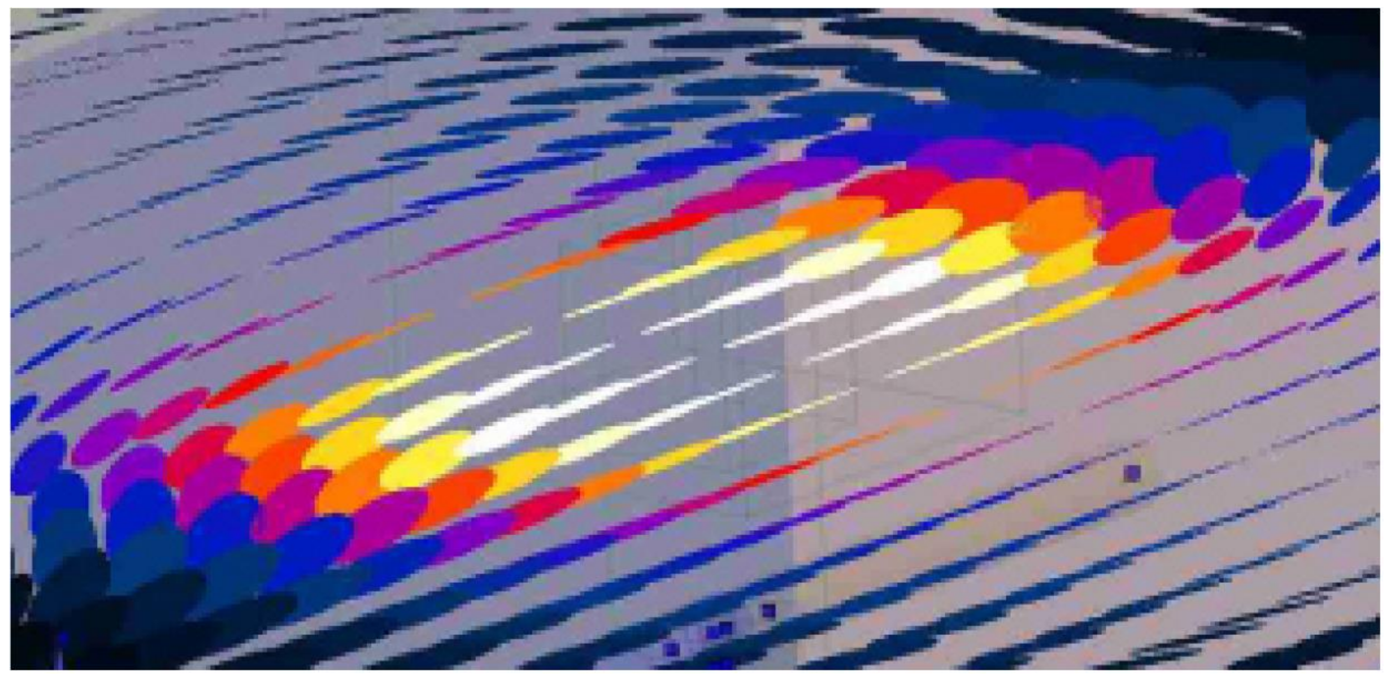


[1] G. H. Golub and C. F. Van Loan, *Matric Computations*. Baltimore, MD: Johns Hopkins Univ. Press, 1990.

Validation of Concept

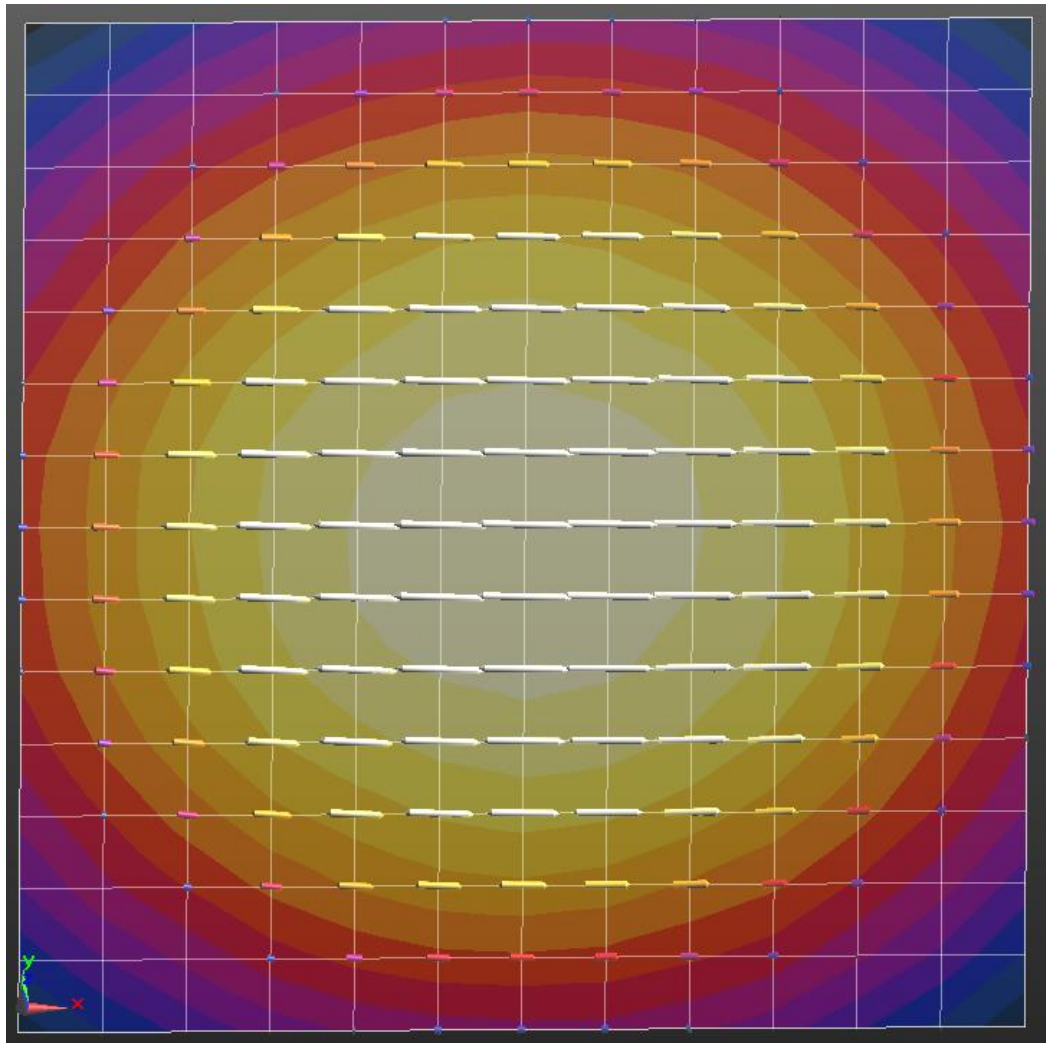
- amplitude and polarization of E field
- measurement (top) vs simulation (bottom)





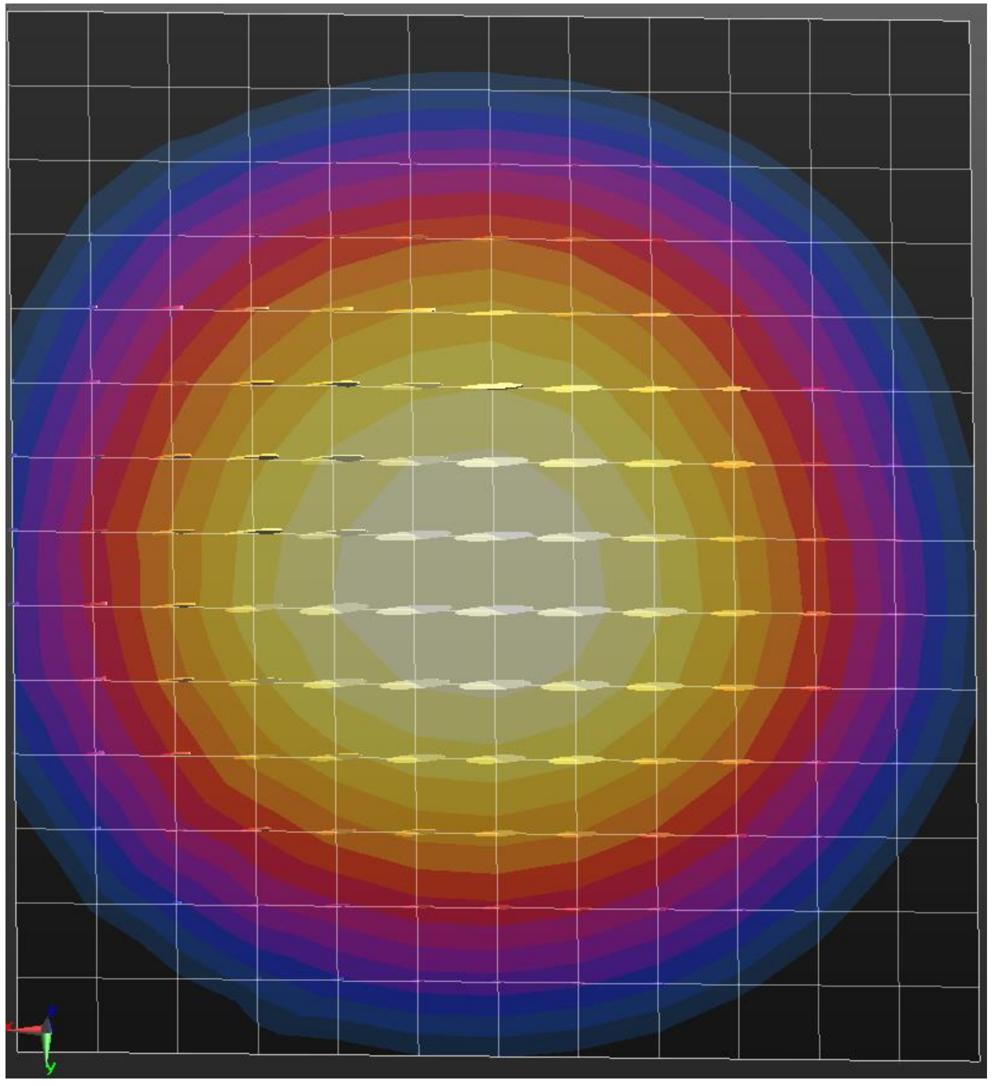
Pseudo-Vector Field Scans (6.5 – 18 GHz)

- field scan 10 cm above 10 GHz horn
- scan 60 x 70 mm step 5 mm
- field distribution verified



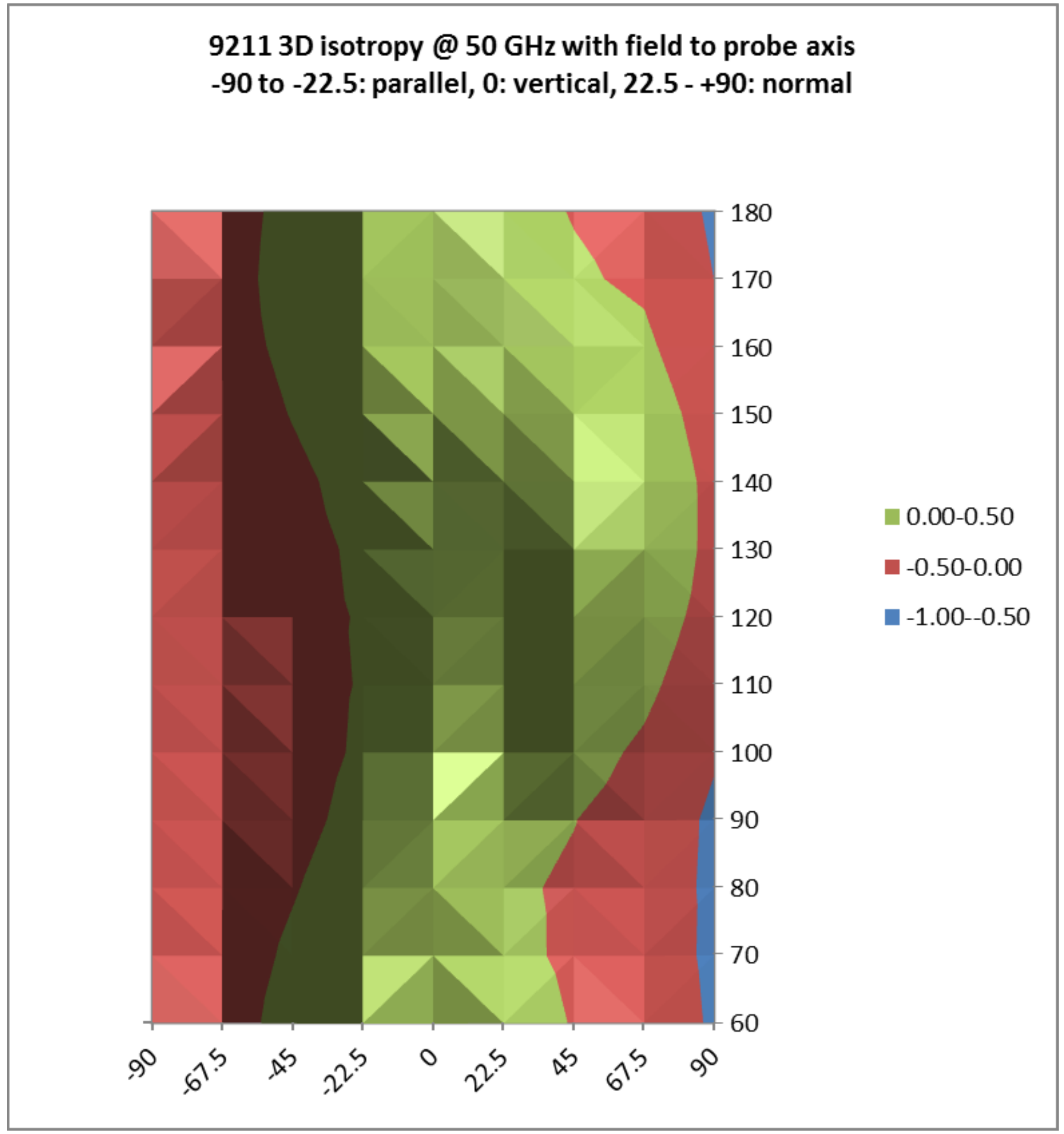
Pseudo-Vector Field Scans 50 - 75 GHz

- field scan 15 cm above 50 GHz horn
- scan 60 x 70 mm step 5 mm
- field distribution verified



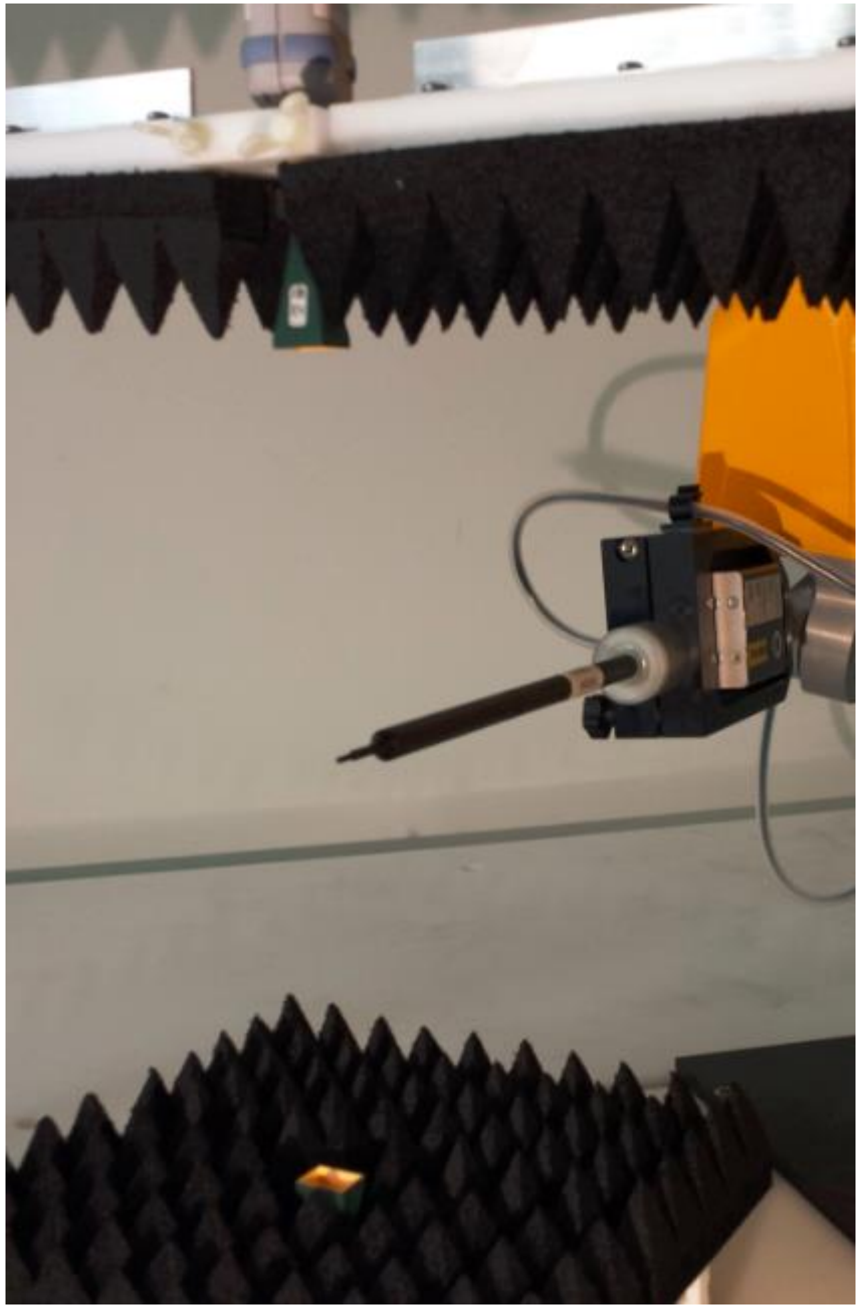
EUmmW Parameters

- example for 3D isotropy
  - probe at 50 GHz
  - all orientations above horn
  - plot for total field
- spherical isotropy deviation < 0.5 dB
  - < 0.2 dB below 30 GHz
- dynamic range
  - 30 V/m to > 1000 V/m



Calibration Process

- three antenna method
  - 2 horn antennas for transmitter and receiver
  - probe as third antenna
  - advantages over TEM cell or waveguide methods
- two-step process
- step 1:
  - align transmit & receive horns
  - characterize electric field at fixed point
  - measure at 3 different heights
  - determine phase center vs frequency
- step 2:
  - remove receive horn
  - insert probe at calibration point
  - probe is outside reactive near field

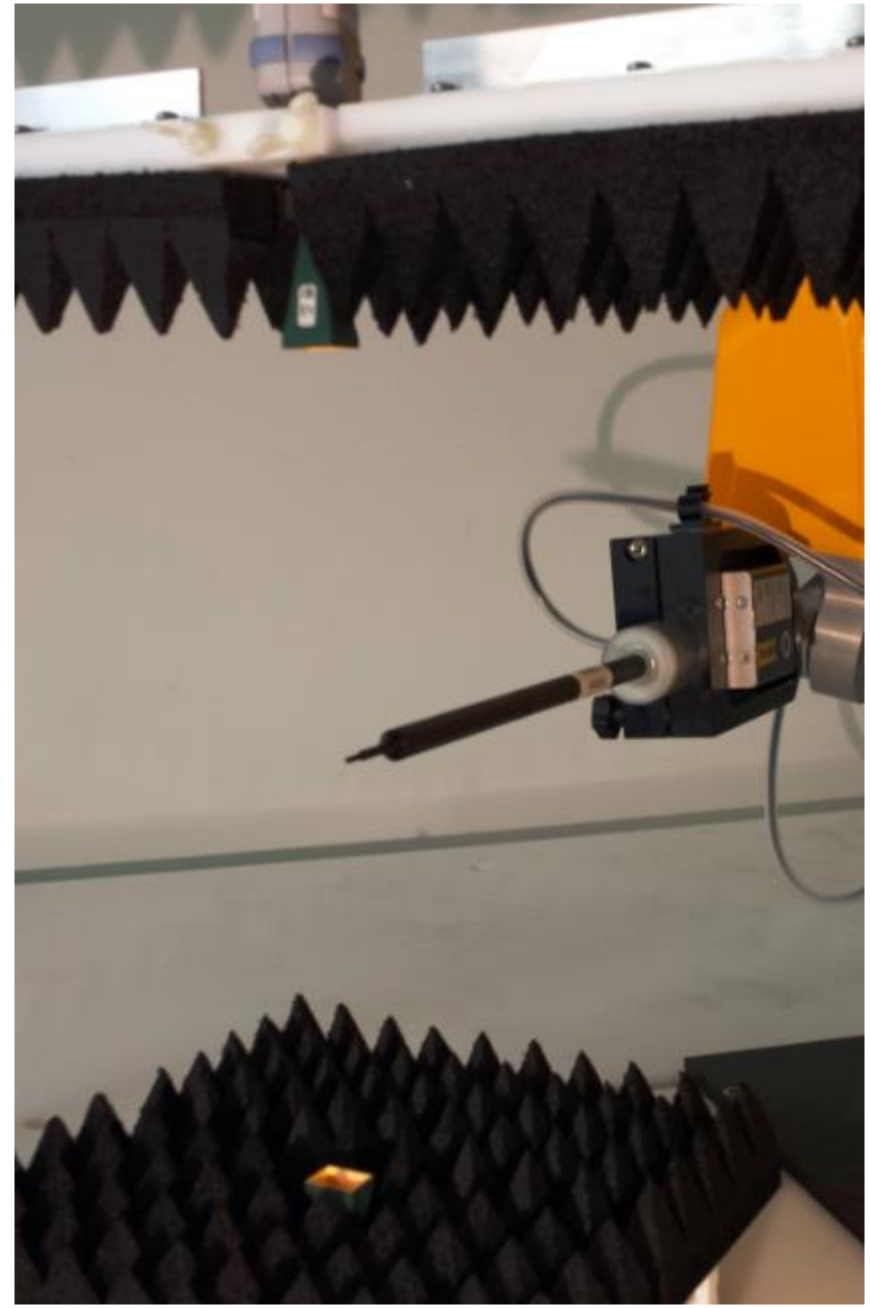


Calibration Method: 6.5 – 18 GHz

- 2 identical horns
  - specified gain
- 3 fixed horn distances
  - field calibration
- calibrated input power
  - field verification
- monitoring antenna
  - removable
  - reduces reflections
- full 3D probe movement

Calibration Method: 50 – 75 GHz

- identical concept as lower band



Conclusion – Calibration System

- calibration method developed
- calibration uncertainty: < ± 1.0 dB
- frequency range: 6 – 75 GHz
- ISO/IEC 17025 accreditation
  - accredited for frequencies below 6 GHz
  - accreditation in process for frequencies above 6 GHz

- next step: publication of method and calibration

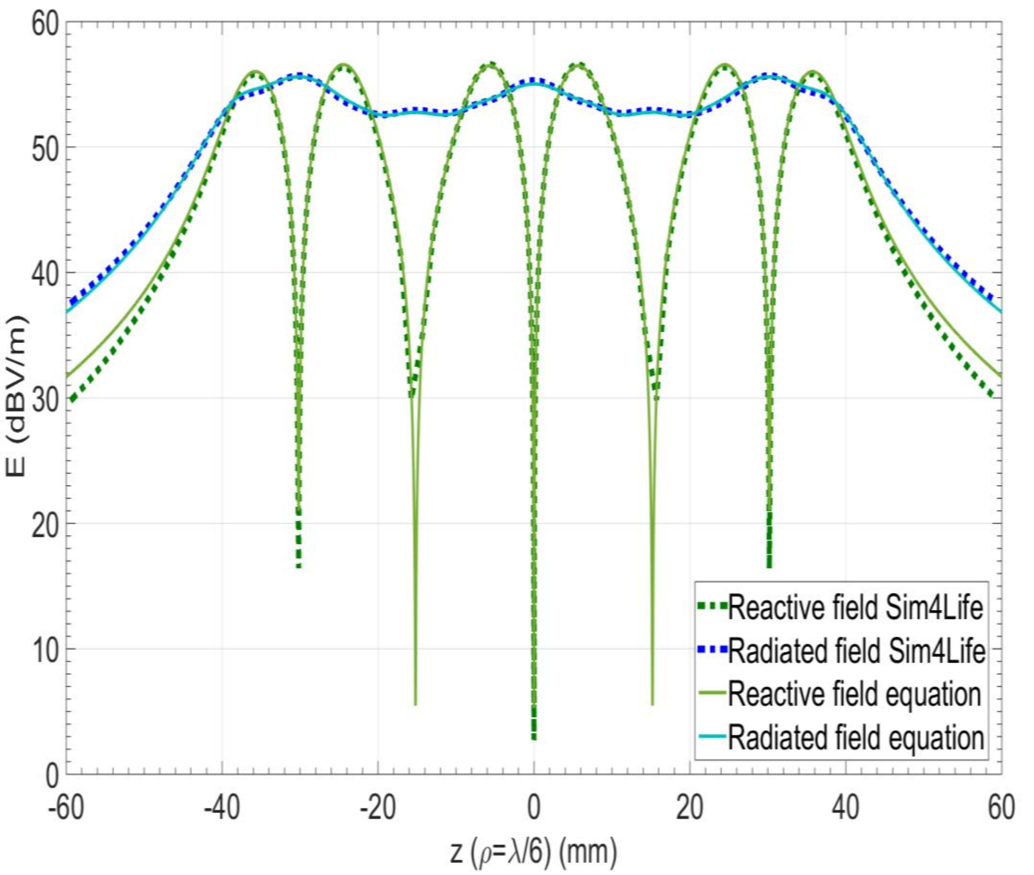
Near Field of Arrays: Unexplored Topic

- new theory of electromagnetic fields near dipole arrays developed and tested by extensive numerical computations.
  - also applicable to slot arrays
- reactive near fields (RNF) extend only as far as RNF of individual array elements. Distance (≈$\lambda/2\pi$) much smaller than previously predicted. In RNF zone, non-propagating reactive e-fields are predominant.
- at $\lambda/2$ distance, radiated E-fields are predominant. Radiative near fields extend out to antenna-sized dependent Fraunhofer zone (far field).
- near E-fields' nature dictates type of power density measurements near arrays.

Dosimetry Needed in Reactive Near Field

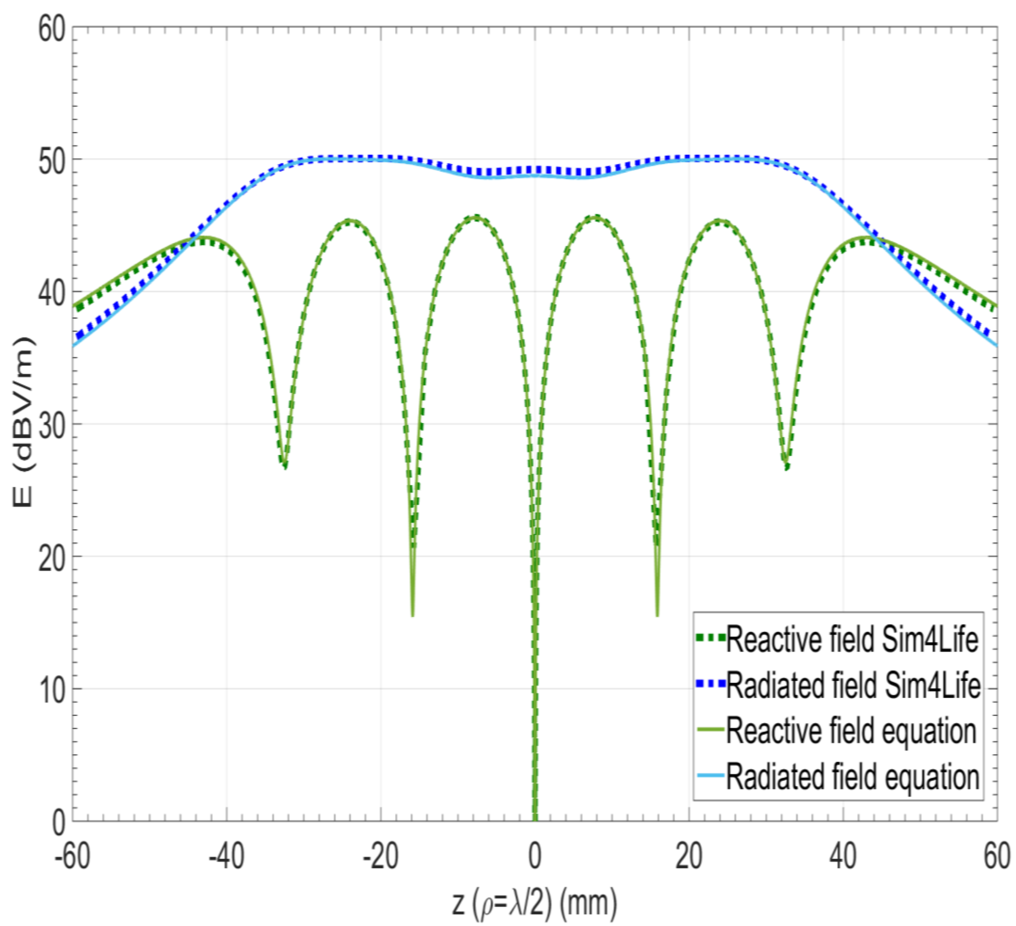
- regions defined by ratio: E_z / E_ρ
- formulas derived for electric dipoles
- reactive near field: d < λ/6
  - $E_z << E_\rho$
  - power density measurements not indicated
  - reactive coupling between exposed body and antenna alters free field distribution of current and charges on radiating elements
  - ‣ dosimetric measurement needed as at lower frequency bands

‣ distance much lower than estimated by Balanis (based on phase change)



Power Density in Radiative Near Field & Far Field

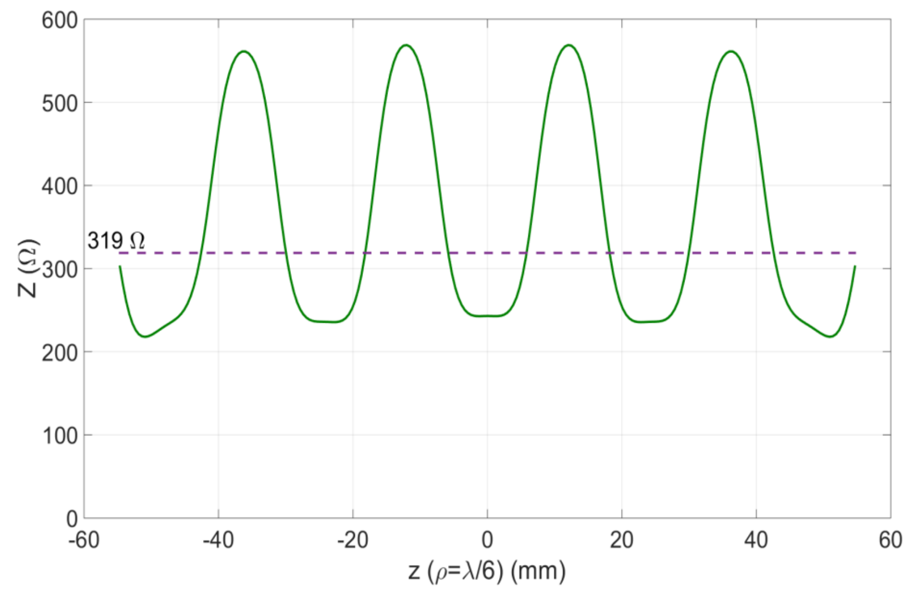
- transition zone: λ/6 < d < λ/2
  - field polarization needed
  - pseudo-vector electric field probes can be used
- radiative near field: d > λ/2
  - $E_z >> E_\rho$
  - power density measurements
  - scalar electric field probes or waveguides may be used

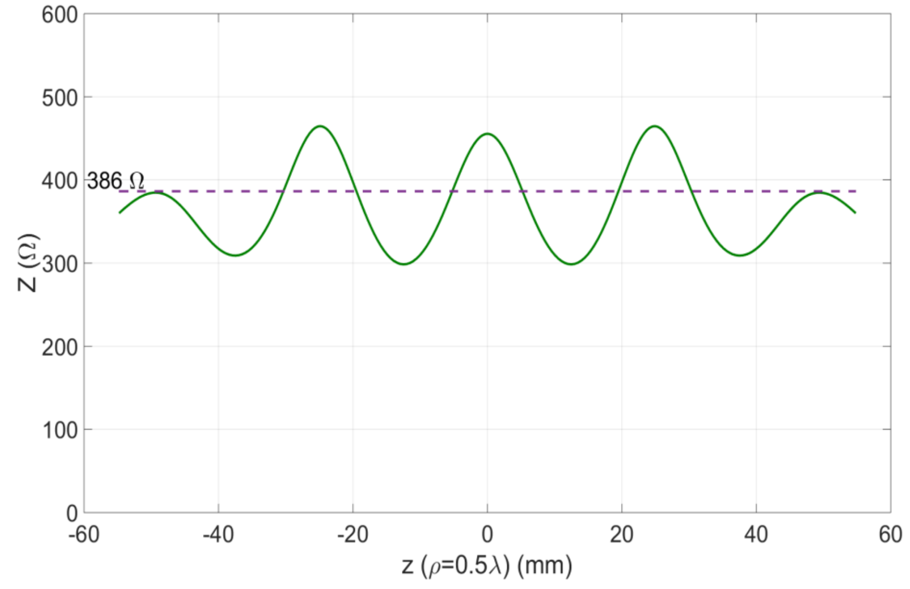


‣ resolve field polarization to determine upper bound on exposure metric

Impedance in Radiative Near Field & Far Field

- impedance calculated
  - E_z / H_y
- 5-element collinear dipole array
  - 10 GHz
  - 0.8 λ separation
- two distances
  - d = λ/6: Z variation > 3 dB
  - d = λ/2: Z variation < 2 dB
- λ/2 seems to be minimum distance for measurements with scalar E-field probes or waveguides
  - e.g., 15 mm @ 10 GHz, 2.5 mm @ 60 GHz





Proposed Procedure

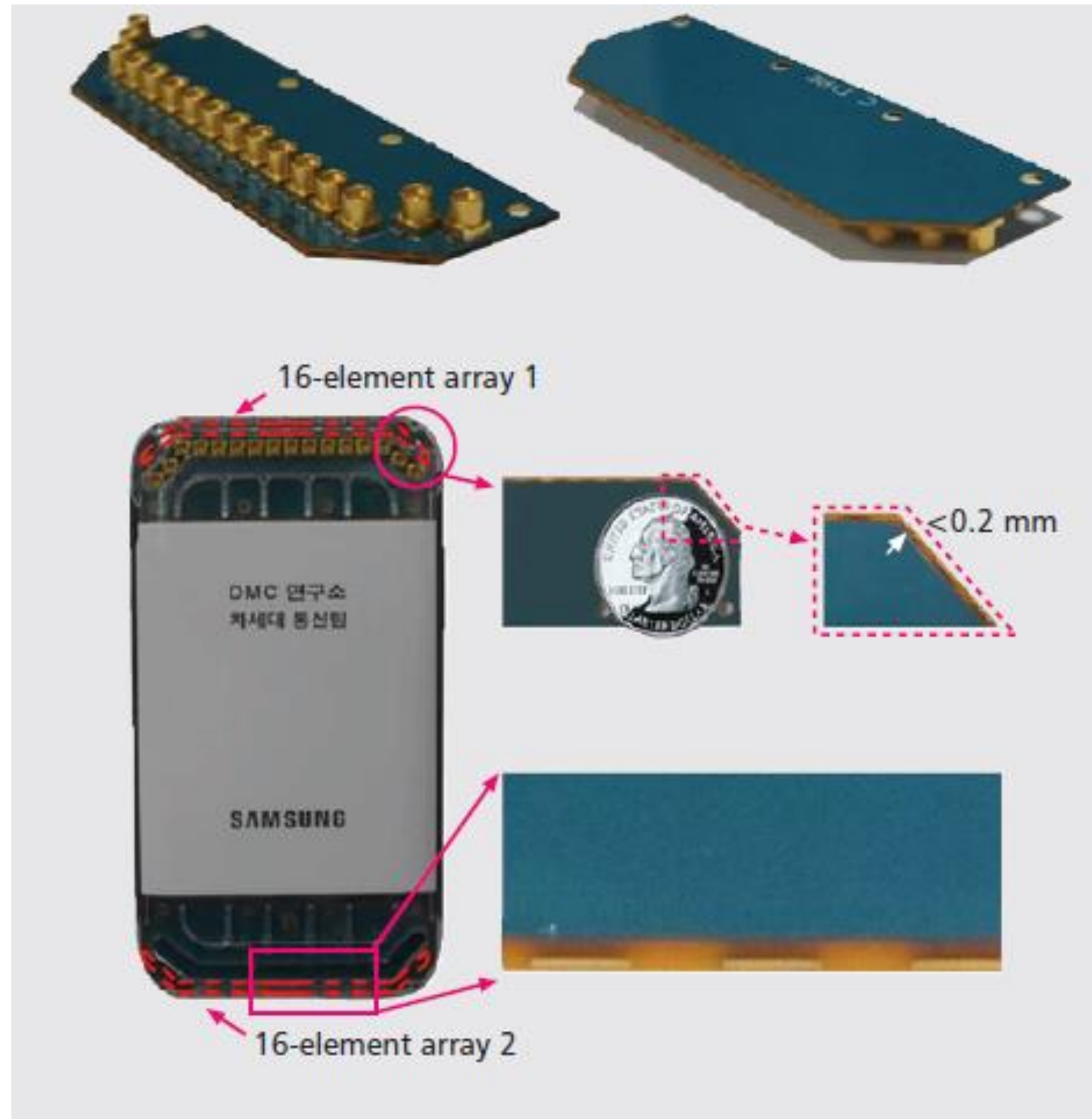
- measurement of the field at the closest distance from the device
  - pseudo-vector near field with EUmmW probe
  - system integration: cDASY6 or DASY52 as test bed
  - adaptive scanning resolution from λ / 10 (depending on distribution)
- determination of the radiative & reactive components
- evaluation of the field with respect to human exposure and regulatory requirements
  - transformation matrix to plane-wave equivalence
  - includes appropriate spatial averaging
- determination compliance and generation of report

Comprehensive Validation

- comprehensive set of sources with respect to
  - frequency
  - field distribution

Implementations of Millimeter Wave Antennas

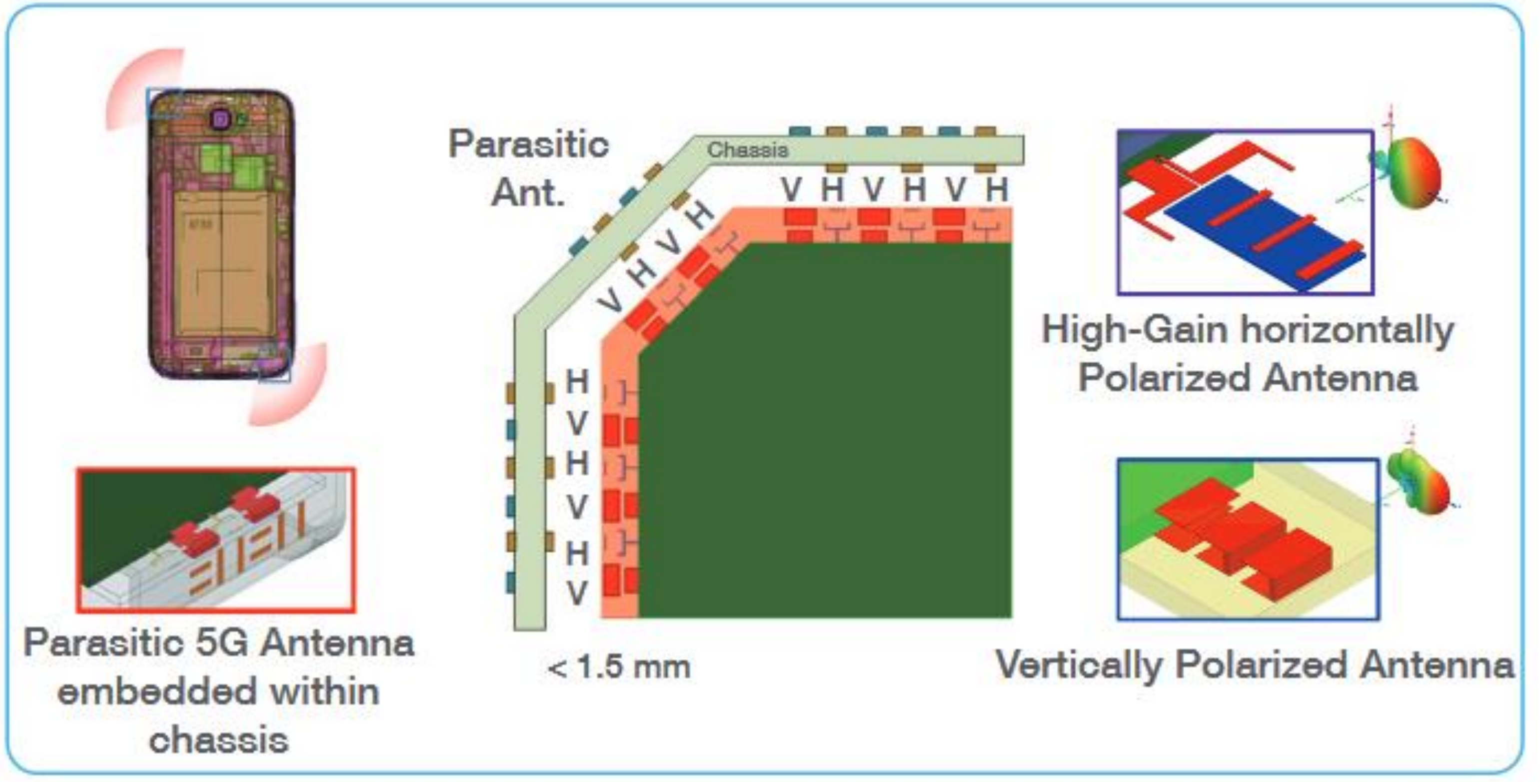
- array of rectangular patches at 60 GHz
- 16 elements
- patch width: 5 mm (λ / 2)
- placed on top or bottom of device



T. S. Rappaport, W. Roh, K. Cheun, “Mobile’s millimeter-wave makeover,” IEEE Spectrum, Vol. 51, nol. 9, pp. 34-58, Sept. 2014.

Implementations of Millimeter Wave Antennas

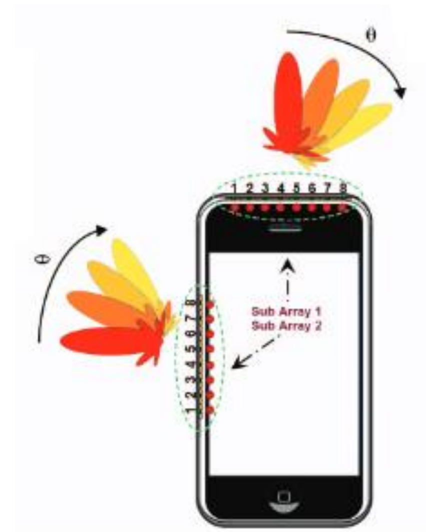
- similar design as previous case
- parasitic elements integrated into the phone chassis

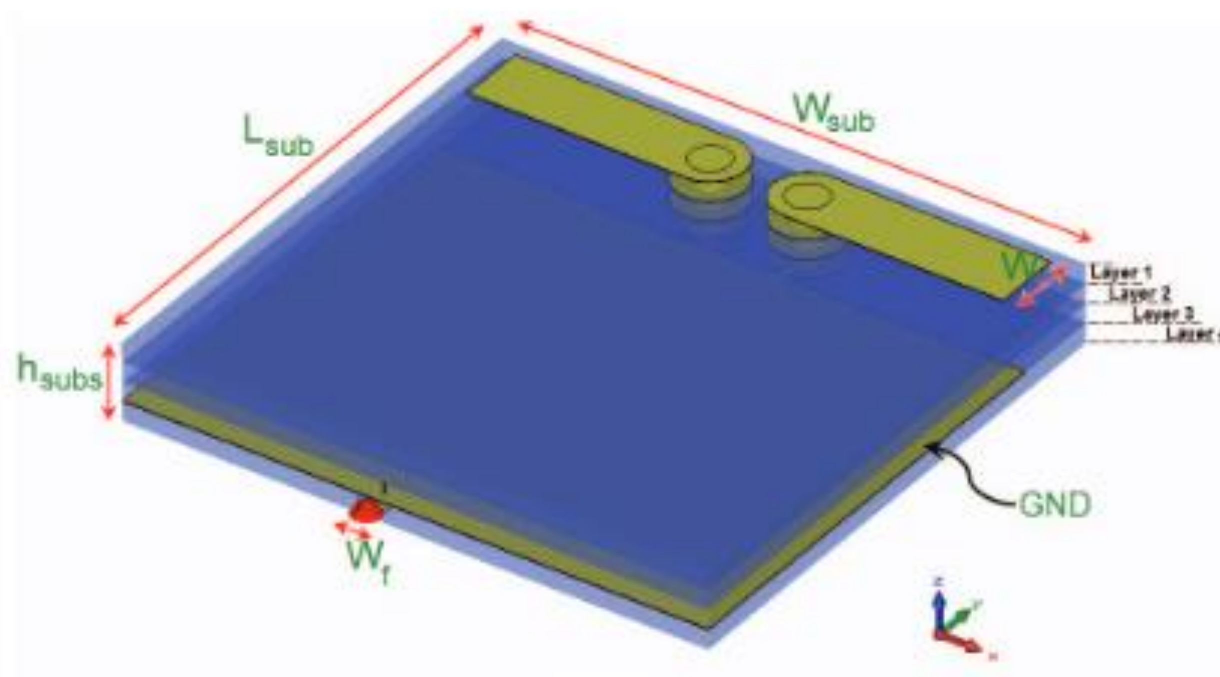


SAMSUNG 5G Vision White Paper, Feb. 2015.

Implementations of Millimeter Wave Antennas

- multi-layered phased array
- off-center dipole antenna elements for MIMO 5G
- frequency: 27 – 29 GHz.

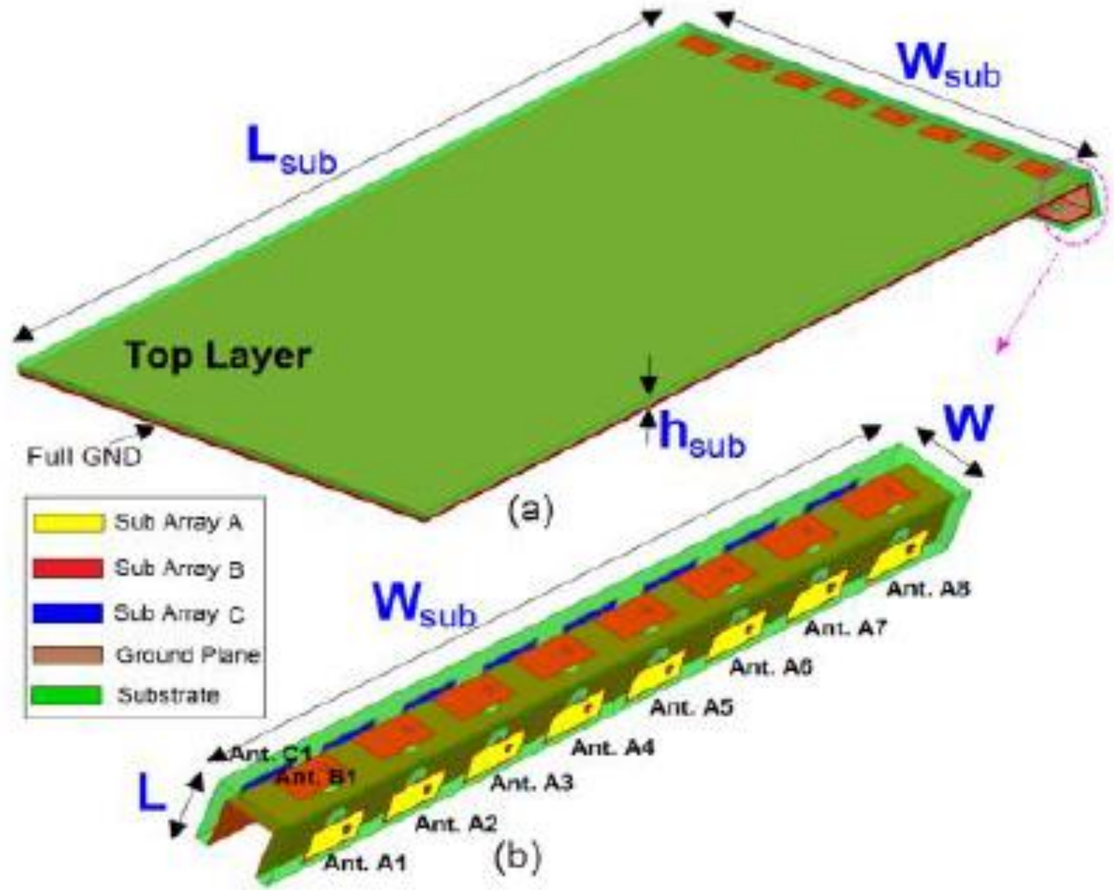




N. Ojaroudiparchin, M. Shen, G. F. Pedersen, "Multi-Layer 5G Mobile Phone Antenna for Multi-User MIMO Communications," Proc. 23rd Telecommunications Forum (TELFOR), Nov. 2015.

Implementations of Millimeter Wave Antennas

- 3D-coverage phase array for 5G
- frequency: 21.5 GHz
- uses 3 sub arrays of microstrip patches (8 patches for each sub array)
- half wavelength spacing
- faces at 0°, 90° and 180°



N. Ojaroudiparchin, M. Shen, S. Zhang, G. F. Pedersen, “A Switchable 3D-Coverage Phased Array Antenna Package for 5G Mobile Terminals,” IEEE Antennas and Wireless Propag. Lett., 2016.

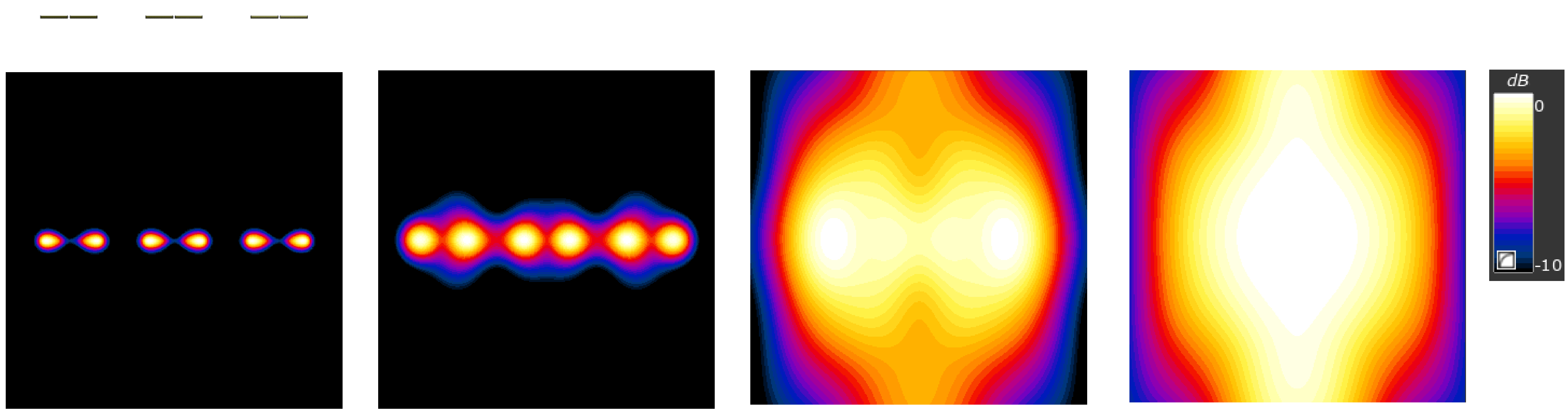
Millimeter Wave Sources Investigated

- Linear array of collinear half-wavelength dipoles (3 elements)
- Linear broadside array of half-wavelength dipoles (3 elements)
- Linear array of collinear half-wavelength slots (3 elements)
- Linear array of half-wavelength square patches (3 elements)
- Planar array of half wavelength patches (9 elements)

- frequencies: 10, 24, 60, 90 GHz

Sources Used for Validation of Method

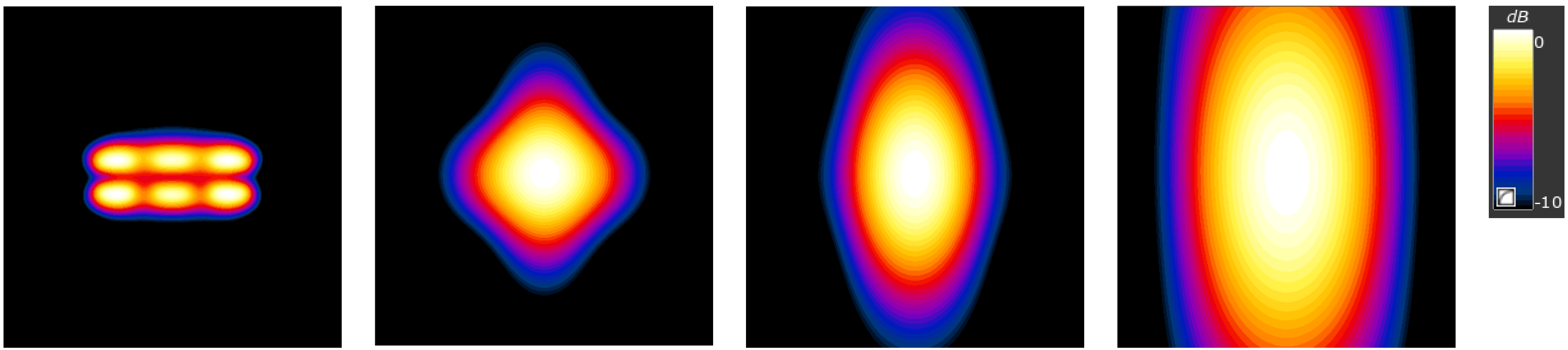
- 3-element array of collinear λ/2 dipoles spaced 0.8λ
- E_{RMS} field – 10 GHz



Plane z=-0.03λ (-1.0 mm) Plane z=-0.1λ (3.0 mm) Plane z=-0.5λ (-15 mm) Plane z=-1.0λ (-30 mm)

Sources Used for Validation of Method

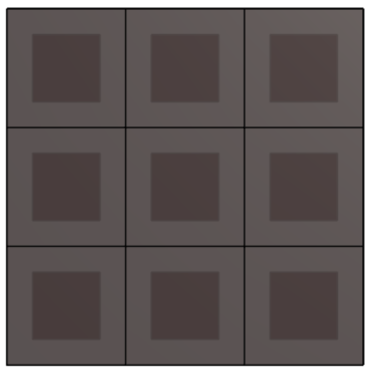
- 3-element array of half-wavelength patches,
- E_{RMS} field – 60 GHz

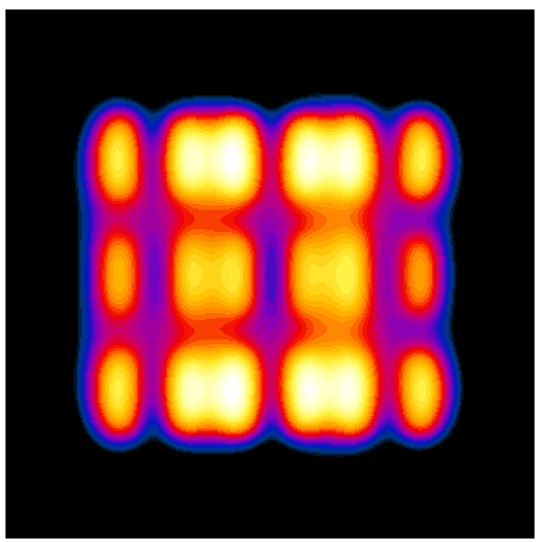


Plane z=-0.1λ (-0.5 mm) Plane z=-0.5λ (-2.5 mm) Plane z=-1.0λ (-5.0 mm) Plane z=-2.0λ (-10 mm)

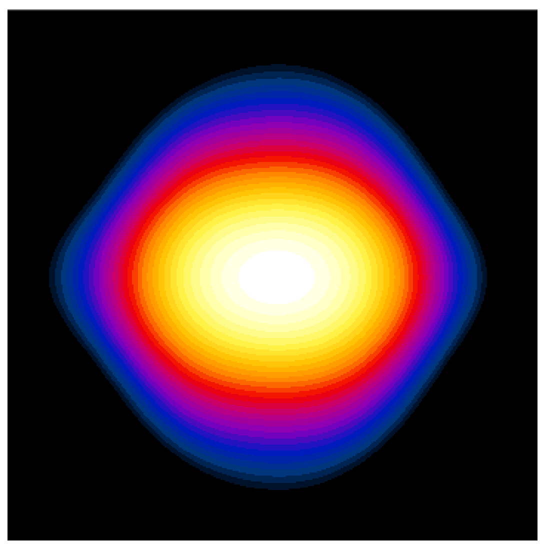
Sources Used for Validation of Method

- 9-element array of half-wavelength patches
- ERMS field – 60 GHz

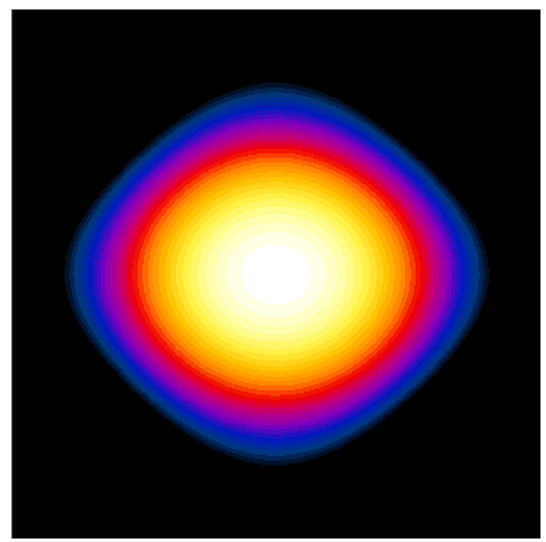




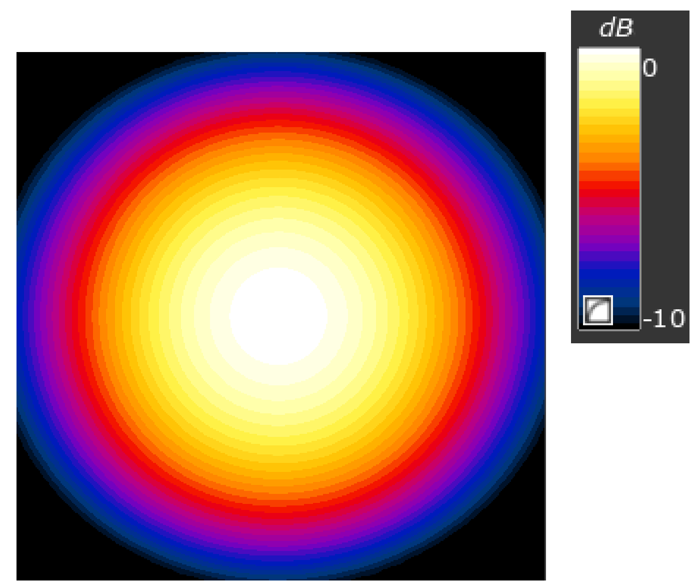
Plane z=-0.1λ (-0.5 mm)



Plane z=-0.5λ (-2.5 mm)



Plane z=-1.0λ (-5.0 mm)



Plane z=-2.0λ (-10 mm)

Publications (Current and Planned) - WP2

- Q. Balzano, K. Foster, M. Ziskin, D. Colombi, E. Carrasco, M. Capstick, “Dosimetry Considerations for Wireless Devices Above 6 GHz,” in progress, planned for IEEE Trans. Vehicular Technology, Q3 2016.
- S. Kühn, M. Douglas, N. Kuster, “Compliance in the Near Field at Millimeter Wave Frequencies using Pseudo-Vector Probes,” in progress, Q3 2016.

Conclusions: WP2

- evaluation of measurement hardware
  - pseudo-vector probe developed from 100 MHz to 75 GHz
  - preliminary integration into DASY52 as test bed
- calibration system
  - 3-antenna system (6 – 75 GHz) developed
  - preliminary uncertainty budget completed
  - ISO/IEC 17025 accreditation extension submitted
- near field to power density transformation
  - new theory developed for determination of near / far field regions
  - development of plane-wave equivalent transformation matrix in progress
- next steps
  - complete transformation matrix (plane-wave equivalence)
  - measurement protocol with compliance criteria implemented in DASY52 and cDASY6
  - publication