Konformitätsprüfung gegenüber Grenzwerten für MMW-Strahlung

Sven Kühn, IT'IS Foundation

Content

- 5G - “the reason” for mmWaves
- sub6: 600 MHz – 6 GHz
- mmWave: 6 – 110 GHz
  - safety guidelines: open issues
  - review of mmWave near-field assessment methods
  - test method
  - system validation
  - system verification
  - application in compliance tests
- upcoming solutions in research & development
  - forward transformation evaluation
  - maximum exposure evaluation
  - combining SAR and Power Density
  - assessment of transmitted power density
- Conclusions

5G brings…

- …mmWaves into consumer electronics
- …mmWaves into consumer electronics used on the body
- a previously rare and far-field type exposure becomes ubiquitous and a near-field type exposure

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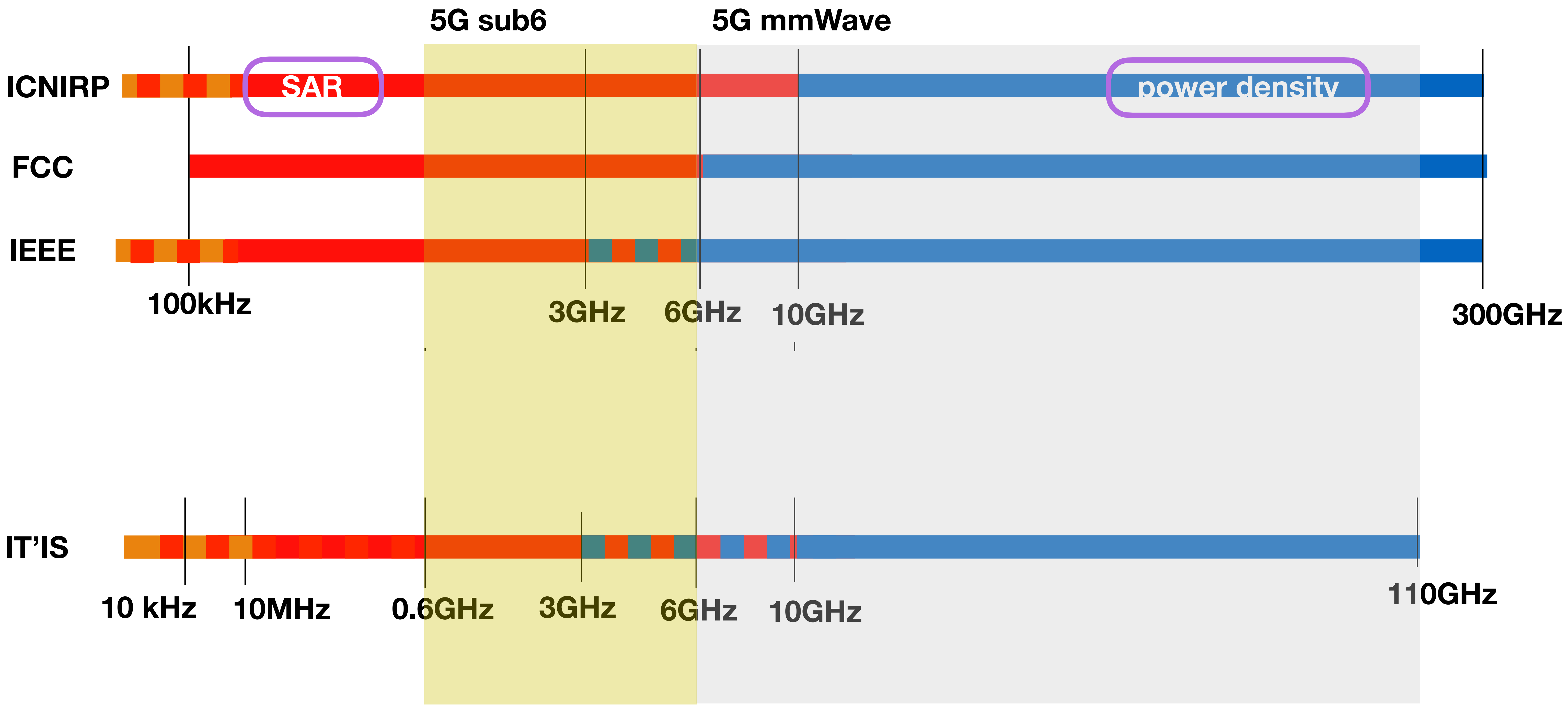
EM Safety Guidelines / Regulations - sub6 & mmWave



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sub6: 600 MHz – 6 GHz

Gold SAR Standard: Robot Based

- IIEC 62209
- FCC KDB 865664 …
- IEEE 1528
- ANSI-C63.19
- IEC 62232
- EN 50385
- EN 50383:2010
- EU Directive RED 2014/53/EU
- AS/NZS 2772-2:2011
- ARIB STD T-56 3.1
- IS16133
- DT-IFT-007-2015
- IEEE/IEC 1528-62209
- etc.

mmWave: 6 (10) – 110 GHz

compliance testing of mobile devices with mmWave transmitters

Safety Guidelines: Open Issues

Regulation: Safety Guidelines Being Currently Revised / Equipment Developed

- incident power density
  - poorly defined in the reactive near-field
  - instead SAR or Str should be used < 20GHz
- transmitted power
  - instrumentation test systems not ready
- correlation w/ temperature
  - averaging area
  - averaging time
  - pulse limitation
  - combination w/ SAR

ICNIRP
INTERNATIONAL COMMISSION ON NON-IONIZING RADIATION PROTECTION

ICNIRP Radiofrequency Guidelines
Public Consultation Version
June 26th, 2018

Basic Restrictions Summary

Table 2. Basic restrictions for electric, magnetic and electromagnetic field exposure (≥ 6-minutes).[a]

Exposure Scenario	Frequency Range	Whole body average SAR (W kg^{-1})	Local head/torso SAR (W kg^{-1})	Local limb SAR (W kg^{-1})	Local S_{tr} (W m^{-2})
Occupational	100 kHz – 6 GHz	0.4	10	20	---
	>6 GHz – 300 GHz	0.4	---	---	100
General Public	100 kHz – 6 GHz	0.08	2	4	---
	>6 GHz – 300 GHz	0.08	---	---	20

[a] Note:
1. Whole body average SAR is to be averaged over 30-minutes.
2. Local SAR and S_{tr} exposures are to be averaged over 6-minutes.
3. Local SAR is to be averaged over a 10-g cubic mass.
4. Local S_{tr} is to be averaged over 4 cm^2 (>6-30 GHz), or 1 cm^2 (>30 GHz).

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The Need

a test system that…

- can assess the safety in terms of incident power density in the closest vicinity of the device under test
- combines the exposure to EMF from multiple simultaneous sources (MIMO, WIFI, Bluetooth, WPT, carrier aggregation, multi-band transmission) in various frequency ranges with different basic restrictions

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Review:
mmWave Reactive Near-field Assessment Methods

Possible mmWave Near-Field Assessment Methods

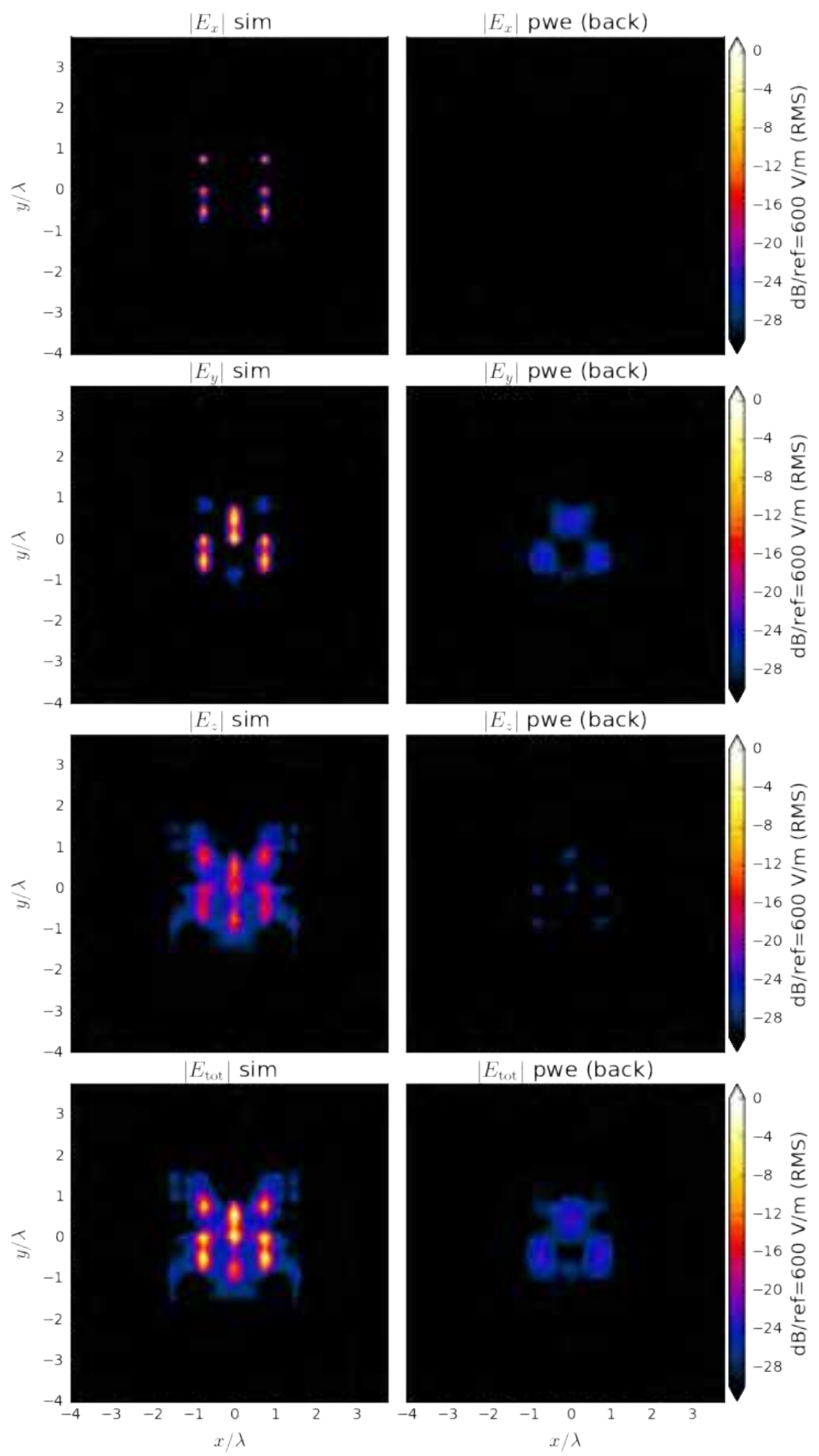
Via Measurement in the Far-Field

- measurement with horn antennas in the far field + backward transformation to the near-field
  - challenges
    - error < a few dBs

By Direct Measurement in the Near-Field

- E-field probes (broadband)
  - challenges
    - field distortions by substrates / probe body
    - receiving pattern
- H-field probes (broadband)
  - challenges
    - field distortion / scattering by probe body
    - parasitic E-field sensitivity
- electro-/magneto-optical probes
  - challenges
    - spatial resolutions
    - sensitivity
- wave-guide
  - challenges
    - large field distortions
    - fixed impedance

Backward Transformation (Towards the Source)



- information about reactive fields and evanescence fields are missing
- backward transformation falls apart very close to the source
- unreliable with uncertainties >>3 dB
- cannot be used for compliance testing

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Near-Field Assessment Methods

Via Measurement in the Far-Field

- measurement with horn antennas in the far field + backward transformation to the near-field
  - challenges
    - error < a few dBs

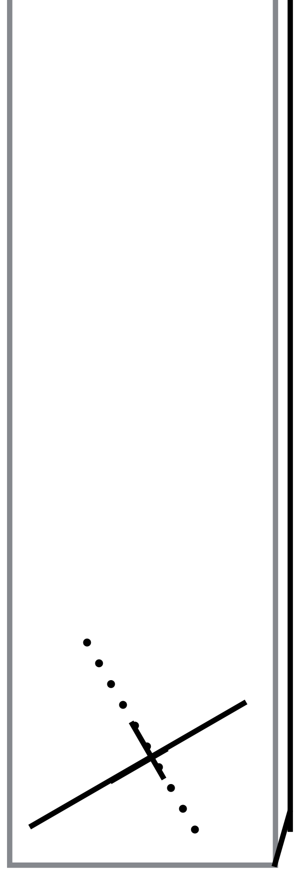
By Direct Measurement in the Near-Field

- E-field probes
  - challenges
    - field distortions by substrates / probe body
    - directionality
- H-field probes
  - challenges
    - field distortion/scattering by probe body
    - E-field sensitivity
- elctro-/magneto-optical probes
  - challenges
    - spatial resolutions
    - sensitivity
- wave-guide
  - challenges
    - large field distortions
    - fixed impedance

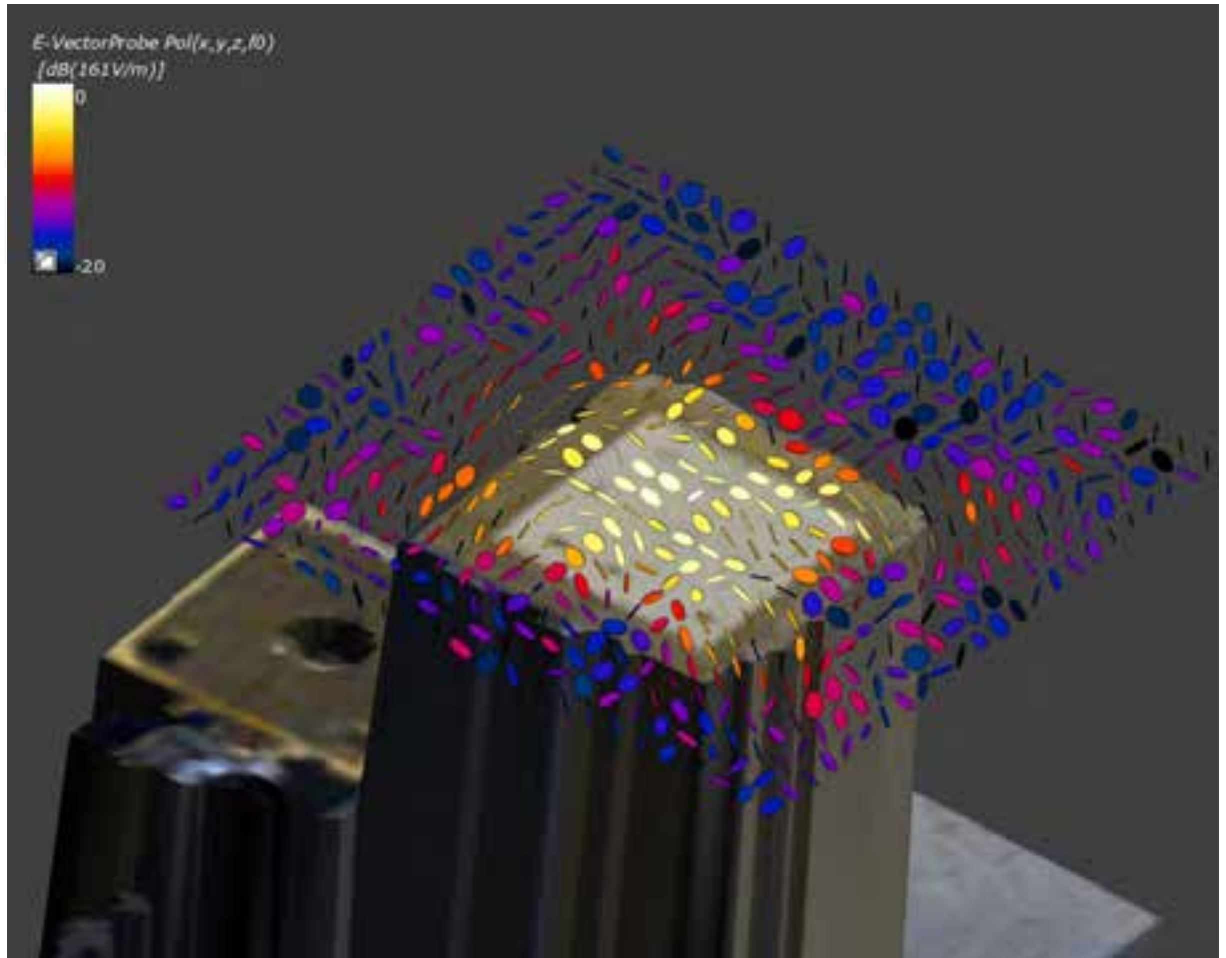
Implemented mmWave Test Method

Reactive Near-Field E-Field Probe <10 to >100 GHz

EUmmWV2 Probe: Pseudo-Vector Design



- probe
  - 2 dipoles (one each side of the quartz substrate)
  - ≈0.9 mm long and diode loaded
  - typical distance between physical tip and sensor center: 1.5 mm
- quartz substrate
  - 0.9 mm wide
  - 20 mm long
  - 0.18 mm thick
  - dipole sensors present
  - ε_r = 3.8 (quartz) homogeneous
- measurement: three rotations around axis, (i.e., six E-field measurements in total)
- reconstruction of polarization and elimination of mechanical tolerances



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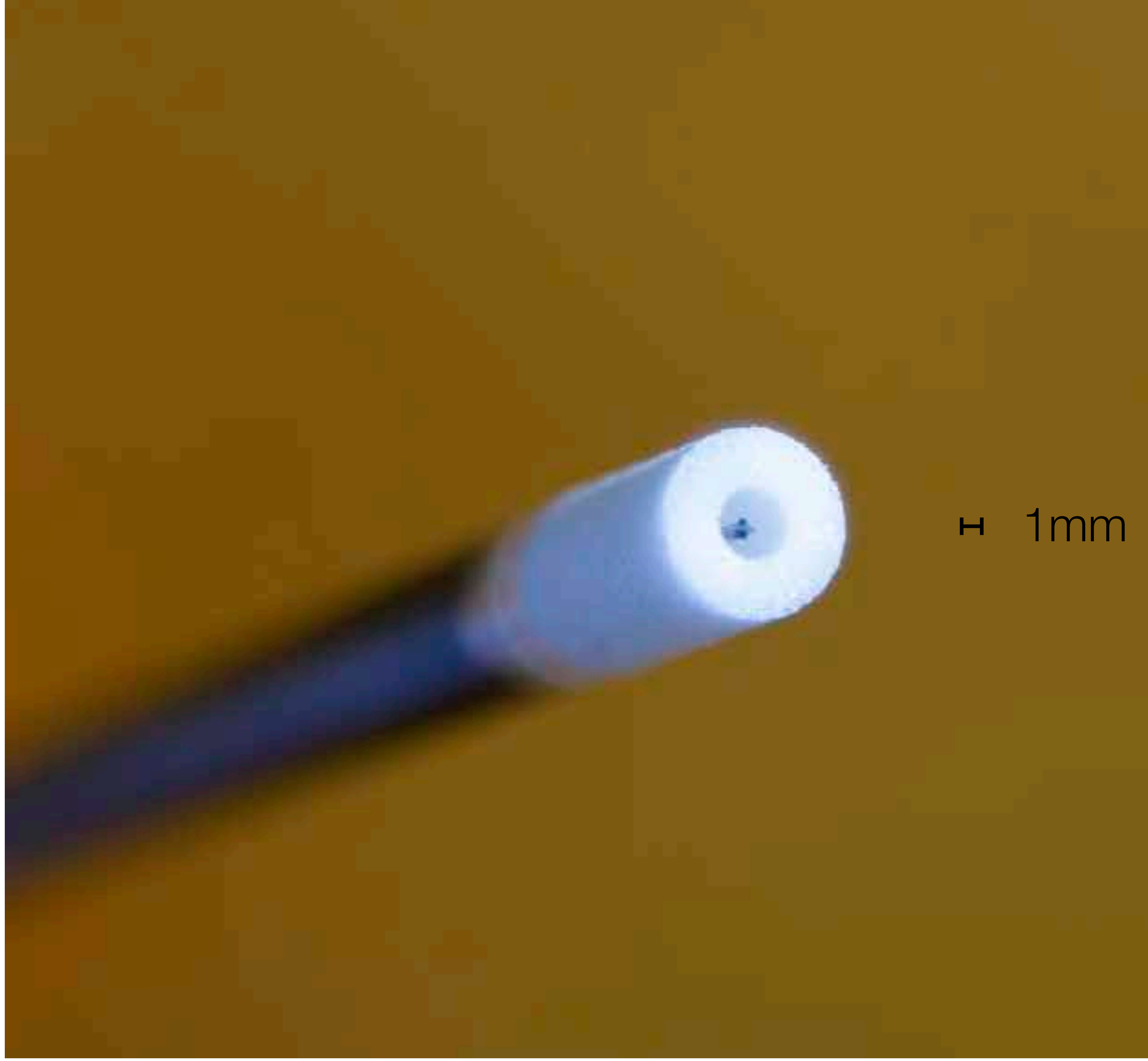
EUmmWV2 Probe Performance

- frequency range: 750 MHz – 110 GHz
- dynamic range: <20 – 10,000 V/m with PRE-10 (minimum <50 – 3000 V/m)
- deviation from hemispherical isotropy: <0.5 dB at 60 GHz
- linearity: <0.2 dB



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EUmmW Probe: System Integration in Automated Test Systems

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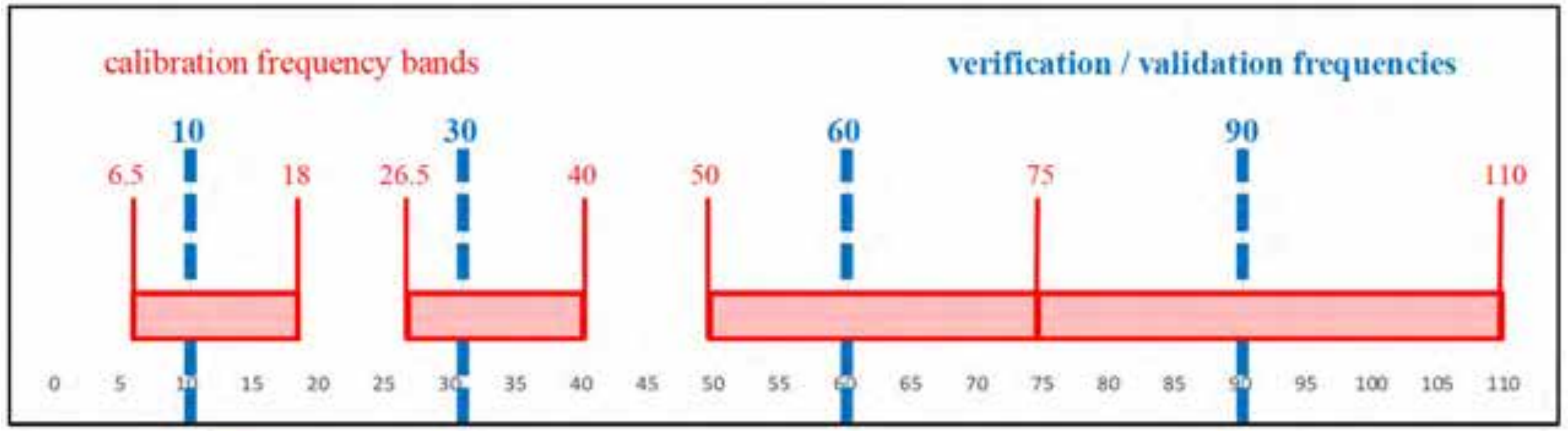
Calibration Method & Procedure

- sensor model (f): 6 parameters
- known calibration field: 3-antenna method
- calibration points: 25 + 8 frequencies and different inclination
- determination of the sensor model parameters with a least square fit
- assessing deviation at 33 frequencies
- determination of isotropy at x frequencies



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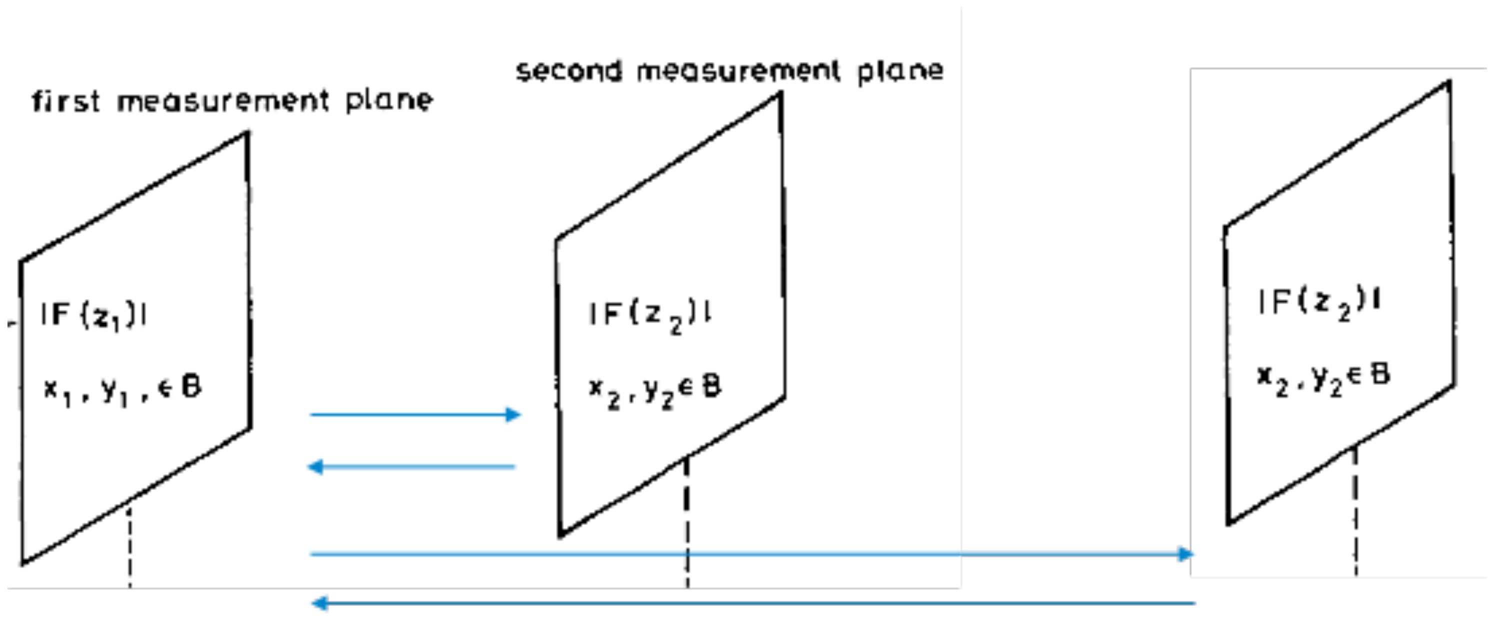
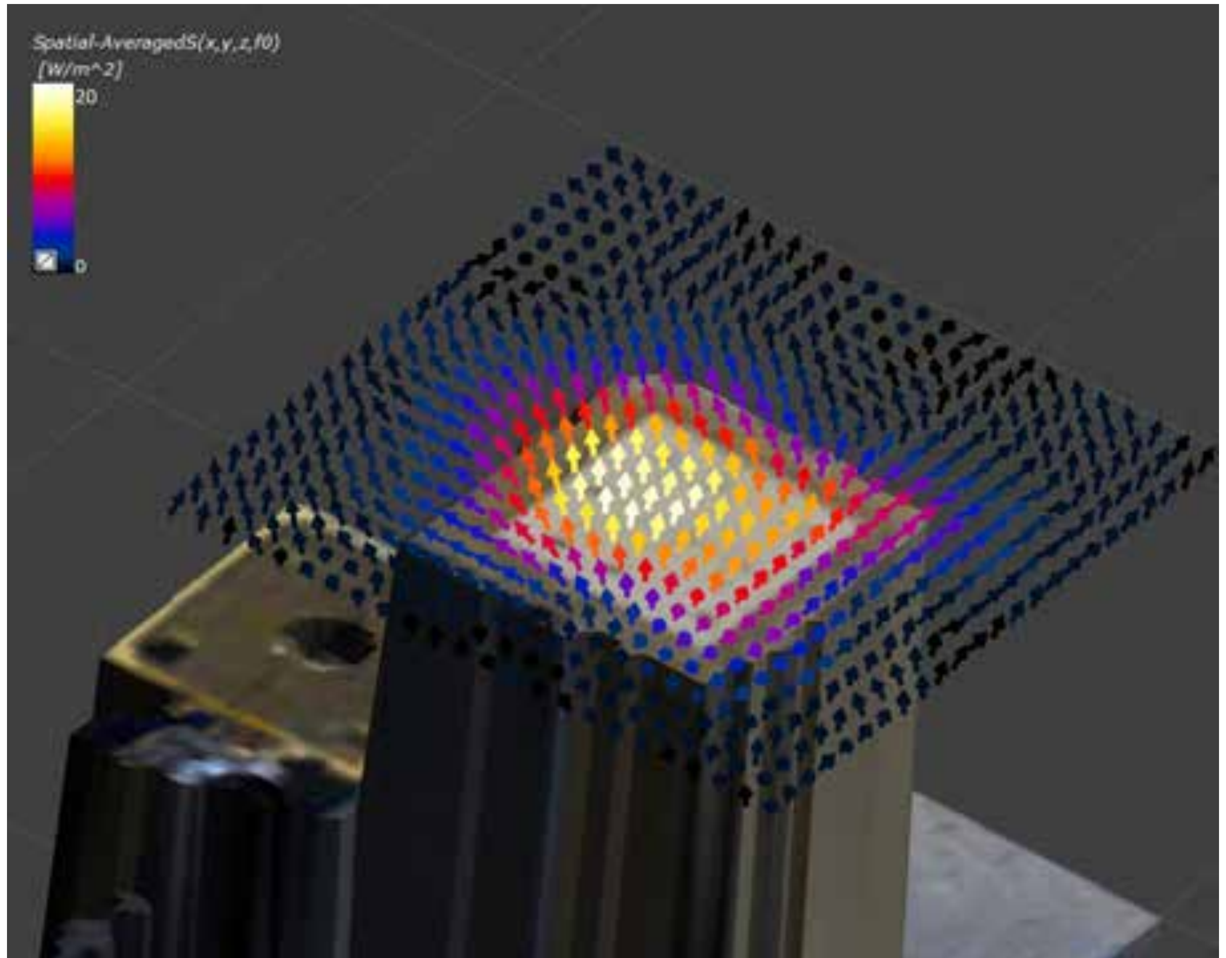
Scanning, Field Reconstruction and Power Density Calculation

Reconstruction





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- determination of Poynting Vector
- knowledge of E-polarization field on two planes allows reconstruction of phase and H-field
- our solution for reconstruction
  - novel and improved algorithm based on Gerchberg–Saxton (GS) (R. W. Gerchberg and W. O. Saxton, “A practical algorithm for the determination of the phase from image and diffraction plane pictures,” Optik 35, 237 (1972))
- measurement requirement:
  - 2 planes (grid-step λ/4)
  - λ/(2π) minimum distance (<2mm @ 28 GHz)

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

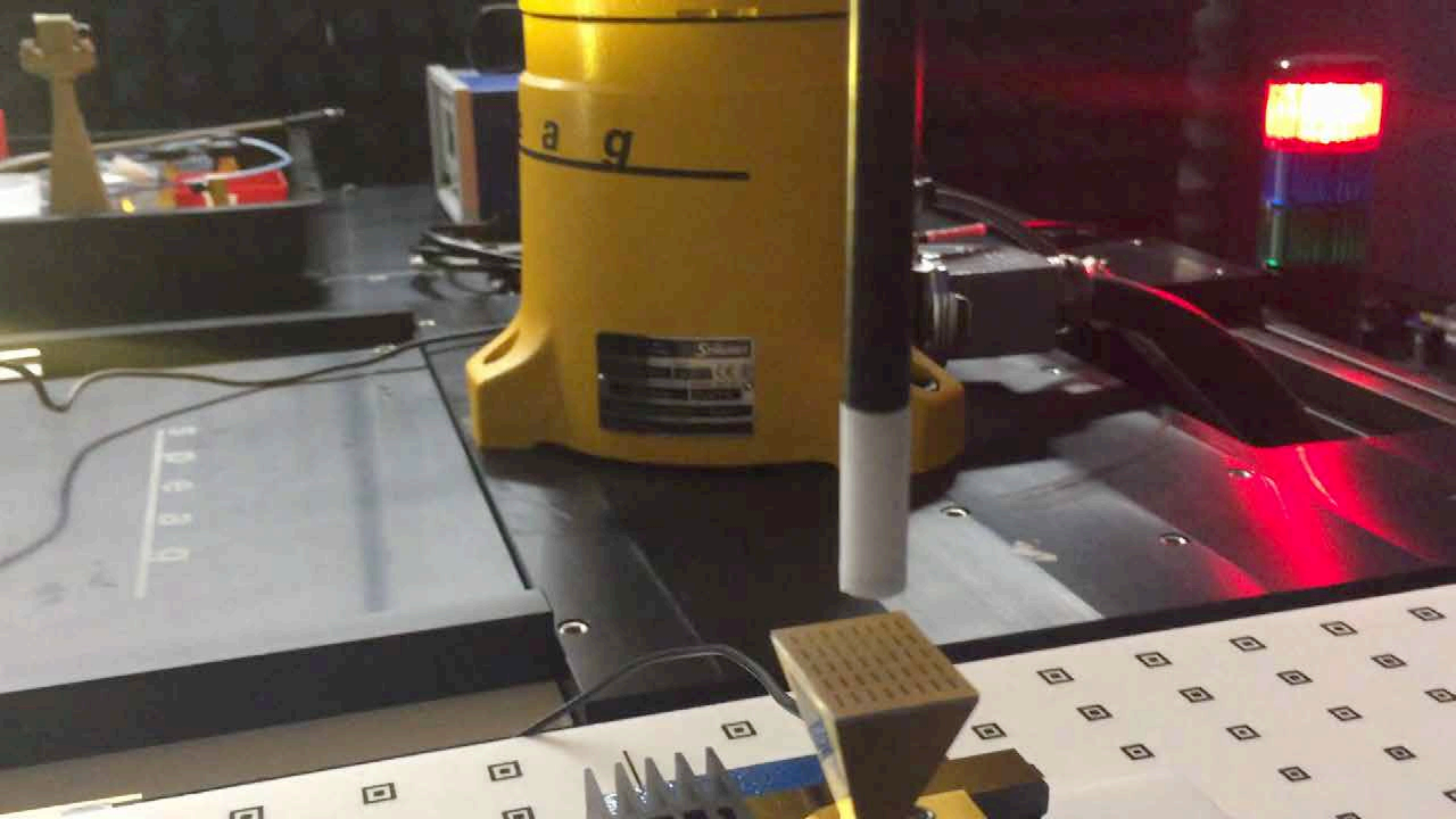
Total Field Reconstruction in the Near Field Using Pseudo-Vector *E*-Field Measurements

Serge Pfeifer, Eduardo Carrasco, *Senior Member, IEEE*, Pedro Crespo-Valero, Esra Neufeld, Sven Kühn, Theodoros Samaras, Andreas Christ, Myles H. Capstick, and Niels Kuster, *Fellow, IEEE*

***Abstract*—Exposure assessments in the frequency range above 10 GHz typically require knowledge of the power density very close to the radiator (at 2-mm distance), which can be obtained through the total electric and magnetic fields. However, phase measurements are often not feasible in this frequency range, in particular in the reactive near field. We developed a novel phase reconstruction approach based on plane-to-plane reconstruction algorithms. It uses *E*-field polarization ellipse information, which can be obtained extremely close to the source with probes based on the pseudo-vector sensor design. The algorithm's robustness and accuracy were analyzed and optimized for distances of a fraction of the wavelength λ, and a comprehensive set of realistic exposure conditions was simulated to evaluate the algorithm. For distances greater than λ/5, the error of the spatially averaged peak incident**

Human exposure to millimeter-wave sources has so far mainly been considered as a far-field problem, but it becomes a near-field problem with integration into mobile devices. This presents potential problems regarding the introduction of 5G technology, as current safety guidelines [1] may not be appropriate for localized sources. Furthermore, there is a lack of measurement equipment available to test compliance very close to 5G millimeter wave devices with regard to current safety guidelines, i.e., the averaged power density **S** incident to human skin.

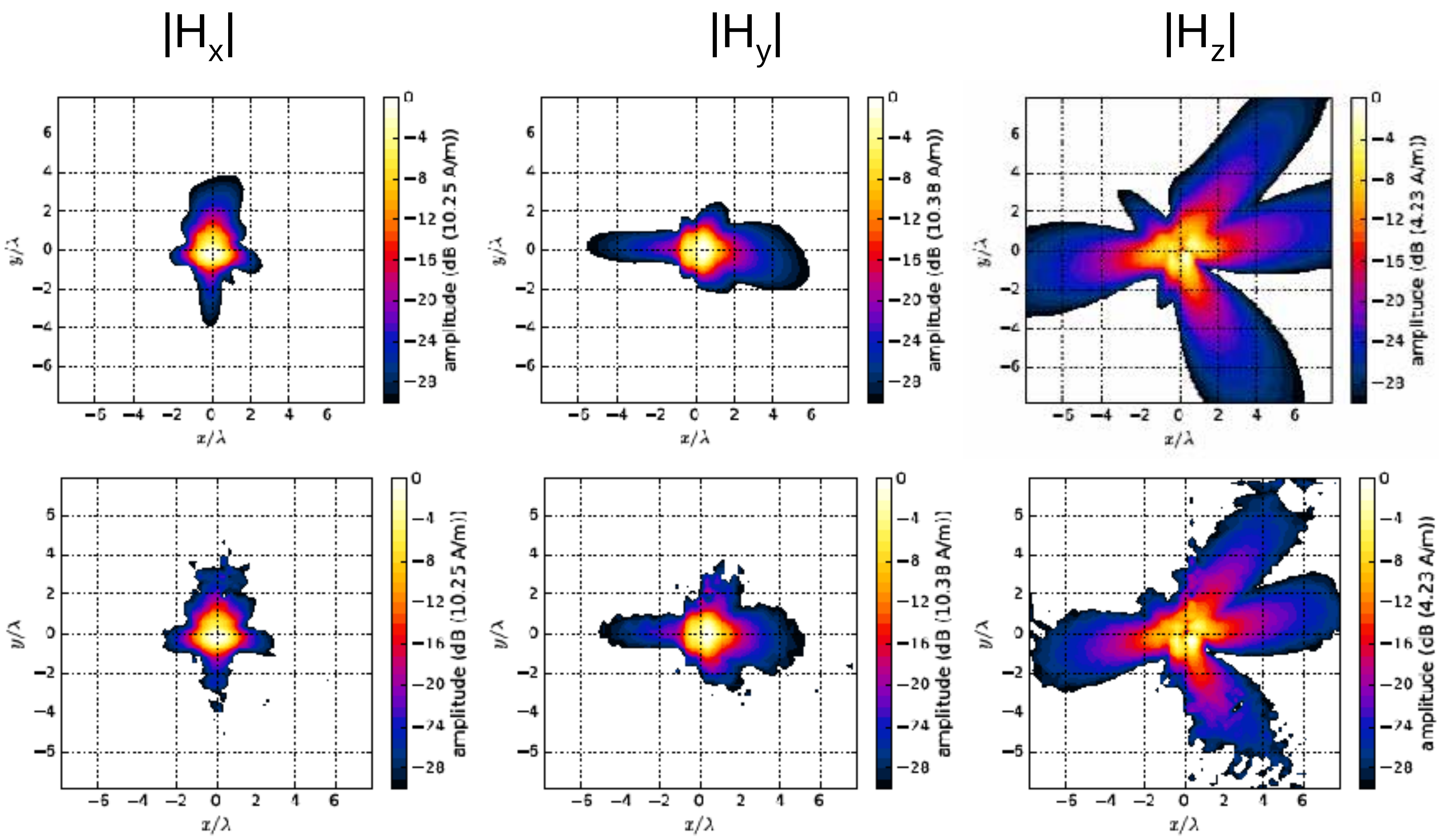
Computation of **S**, in general, requires knowledge of the complex *E*- and *H*-field vectors in the plane of incidence. Further-



Demonstration: H-Field Reconstruction from E-Field Magnitudes

reference (simulation)

reconstruction



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Measurement Uncertainty

Preliminary Module mmWave Uncertainty Budget
Evaluation Distances to the Antennas > λ/2π
Based on the 62209 Standard Family

Error Description	**Uncertainty Value (±dB)**	**Probability Distribution**	**Div.**	**(ci)**	**Std. Unc. (±dB)**	**(vi) veff**
Measurement System						
Probe Calibration	0.49	N	1.00	1	0.49	∞
Hemispherical Isotropy	0.5	R	1.73	1	0.29	∞
Linearity	0.2	R	1.73	0	0.00	∞
System Detection Limits	0.04	R	1.73	1	0.02	∞
Modulation Response	0.4	R	1.73	1	0.23	∞
Resource Block Offset	0.1	R	1.73	1	0.06	∞
Readout Electronics	0.03	N	1.00	1	0.03	∞
Response Time	0	R	1.73	1	0.00	∞
Integration Time	0	R	1.73	1	0.00	∞
RF Ambient Noise	0.04	R	1.73	1	0.02	∞
RF Ambient Reflections	0.21	R	1.73	1	0.12	∞
Probe Positioner	0.04	R	1.73	1	0.02	∞
Probe Positioning	0.3	R	1.73	1	0.17	∞
Savg Reconstruction	0.6	R	1.73	1	0.35	∞
Test Sample Related						
Power Drift	0.1	R	1.73	1	0.06	∞
Input Power	0.27	N	1.00	0	0.00	∞
Combined Std. Uncertainty				0.74	∞	
Expanded Std. Uncertainty				**1.48**		

- <1.5 dB (95th percentile coverage) for arbitrary mmWave sources

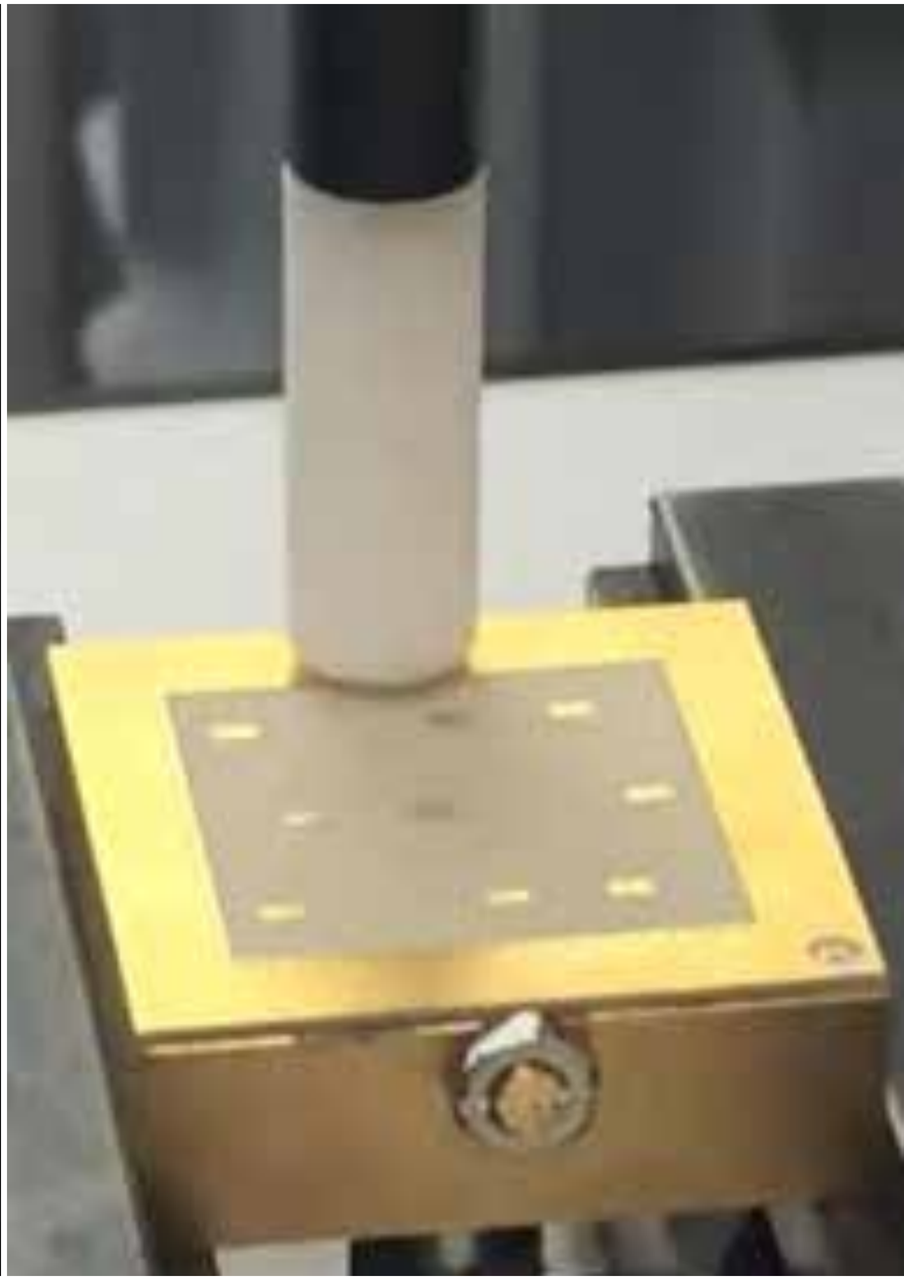
System Validation

by test system manufacturers according to IEC/IEEE 63195

Validation Sources (Compliant with IEC/IEEE 63195)

- two fundamental EM sources
  - electric dipoles
  - magnetic dipoles (slots)
- simulated & measured
- test for E, H, S reconstruction within test uncertainty

- sources
  - Cavity Backed Array of Dipoles
  - Pyramidal Horn with Slot Array
- frequencies: 10, 30, 60 90 GHz
- validated at IT'IS
- ongoing round-robin (12 labs)



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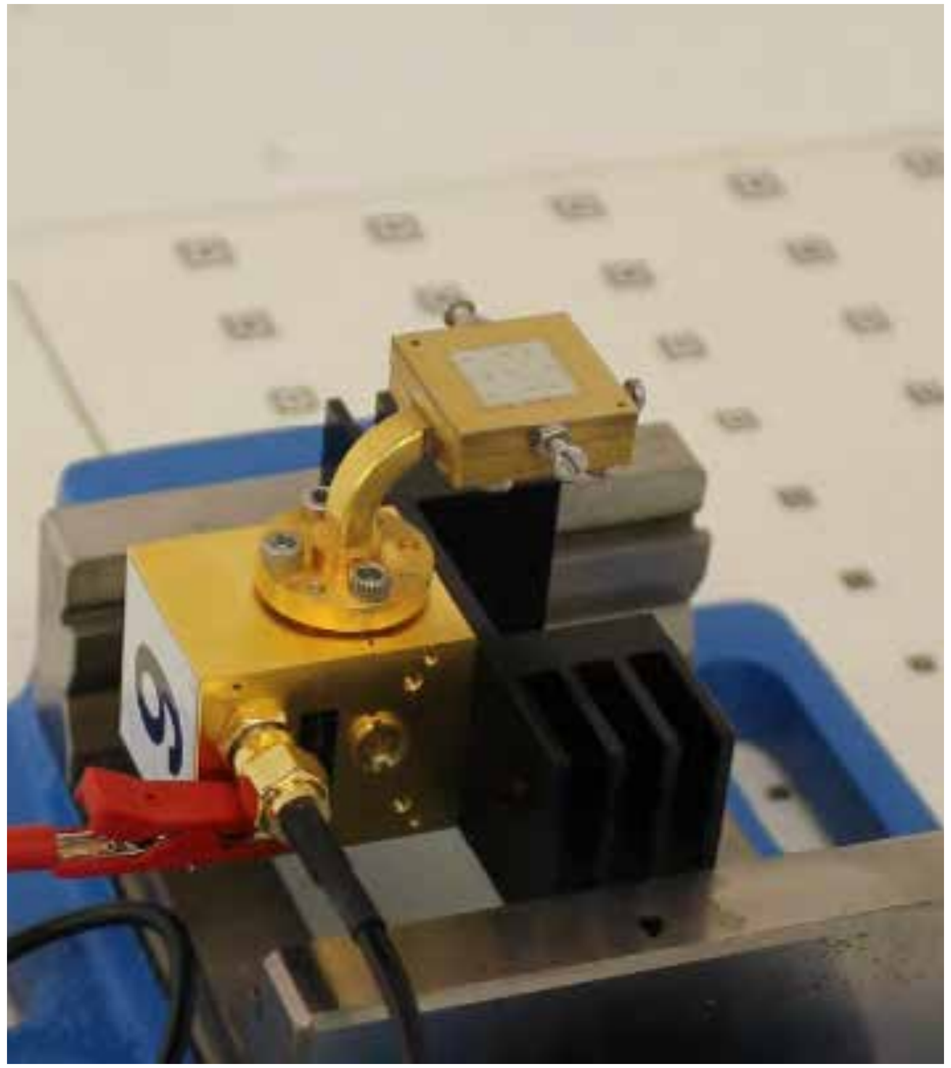
60 GHz Cavity Backed Array of Dipoles (cont.)

- normalized to 0-dBm radiated power

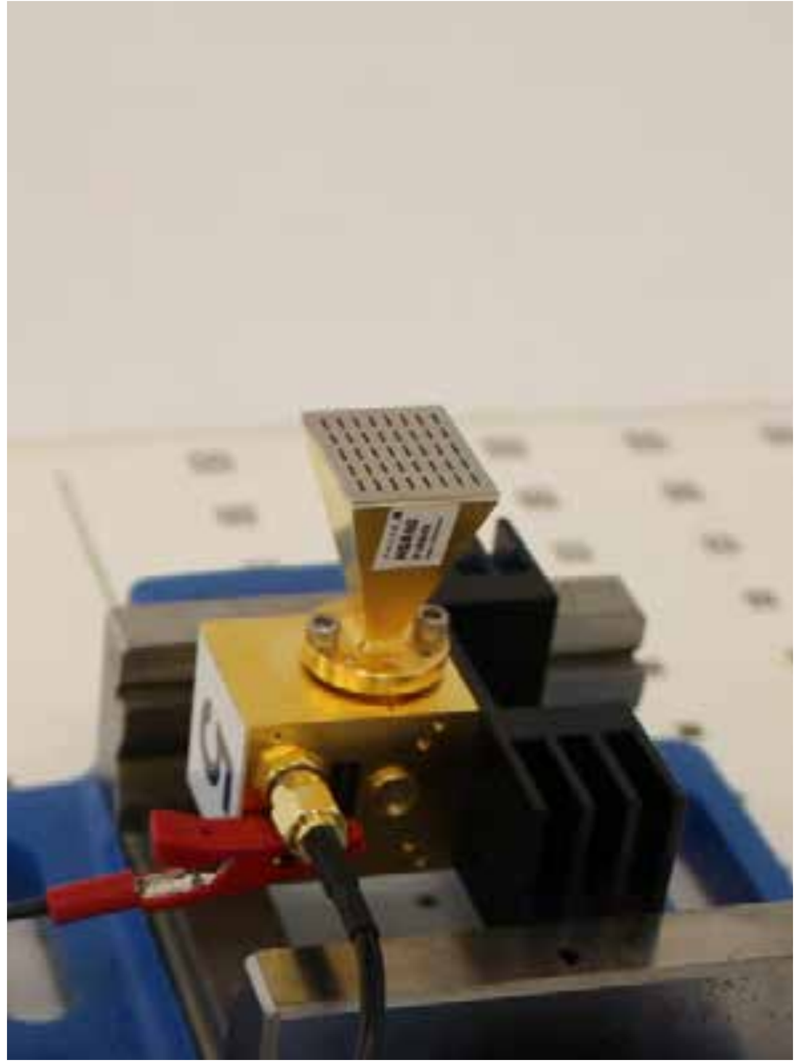
distance (mm)	simulated		measured		deviation	
	E_{total} (V/m)	S_{avg1cm^2} (W/m^2)	E_{total} (V/m)	S_{avg1cm^2} (W/m^2)	E_{total} (dB)	S_{avg1cm^2} (dB)
2	89.2	7.53	98.2	6.99	0.8	-0.3
5	93.2	5.20	94.4	5.31	0.1	0.1
10	72.9	4.40	75.6	4.46	0.3	0.1
20	44.0	3.28	45.8	3.13	0.4	-0.2
50	18.6	0.873	19.5	0.873	0.4	0.0



60 GHz Pyramidal Horn with Slot Array (cont.)

- normalized to 0-dBm radiated power

distance (mm)	simulated		measured		deviation	
	E_{total} (V/m)	S_{avg1cm^2} (W/m²)	E_{total} (V/m)	S_{avg1cm^2} (W/m²)	E_{total} (dB)	S_{avg1cm^2} (dB)
2	65.1	4.51	75.0	4.96	1.2	0.4
5	63.0	3.87	64.5	4.12	0.2	0.3
10	46.9	3.37	49.3	3.51	0.4	0.2
20	33.4	2.36	37.6	2.54	1.0	0.3
50	24.7	1.48	26.2	1.48	0.5	0.0



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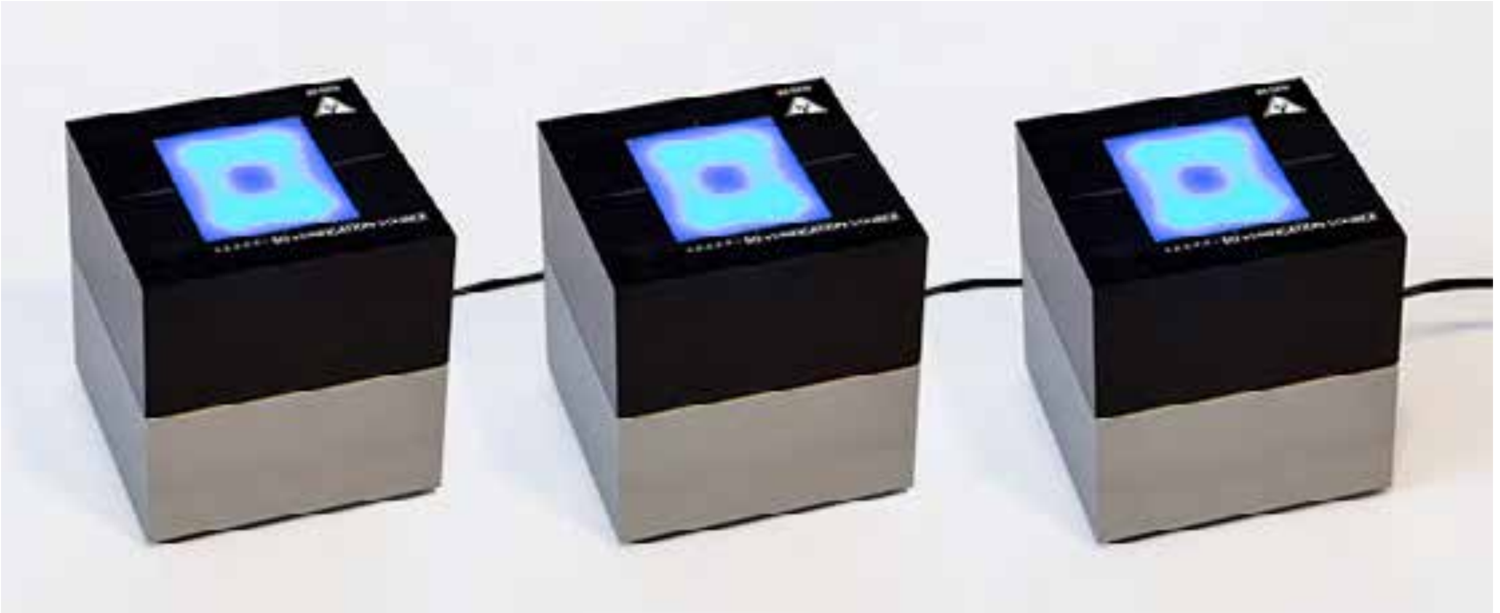
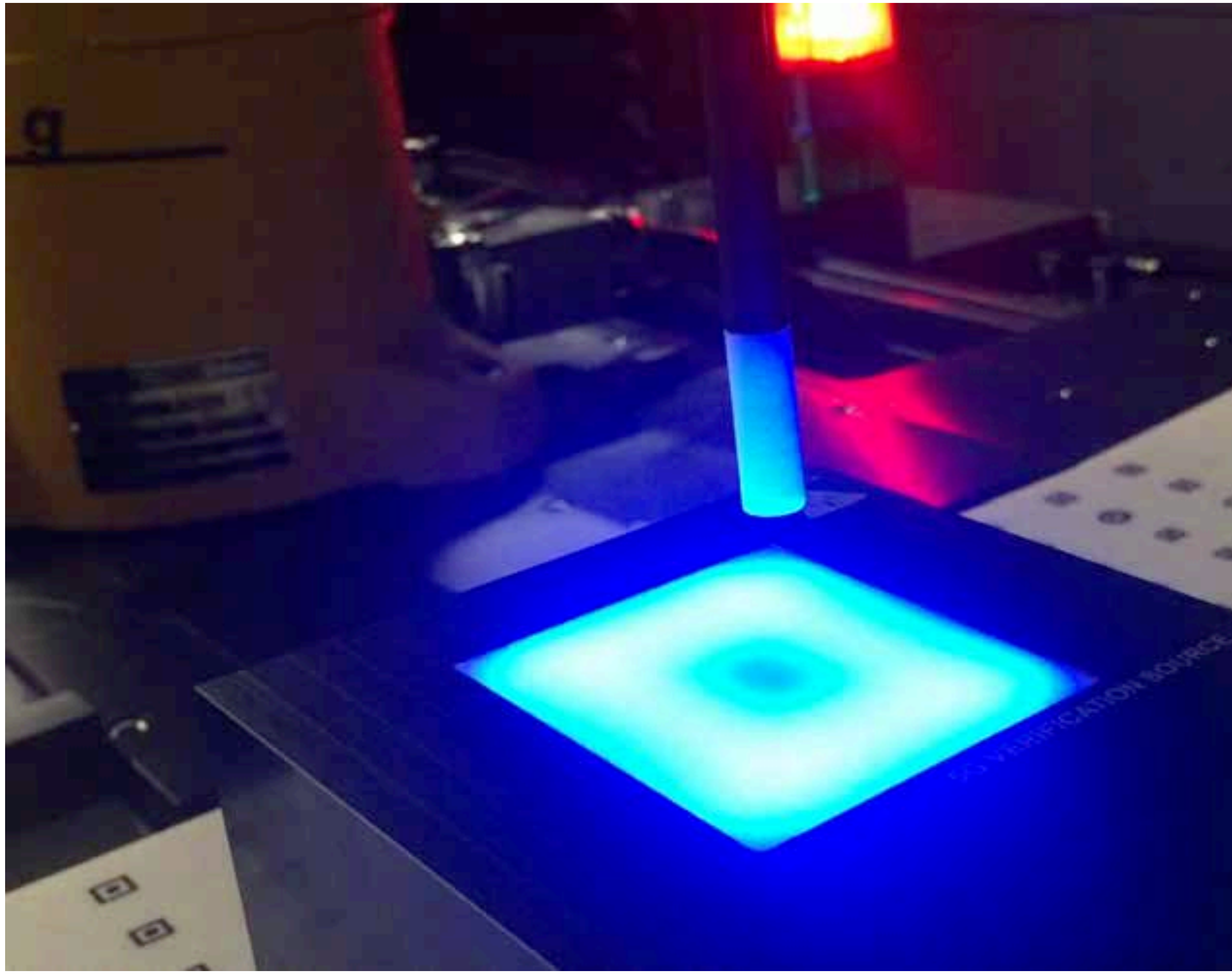
System Verification

5G System Verification Packages: 10, 30, 45, 60, and 90 GHz

- system check before a compliance test at a test lab
- 10, 30, 60, and 90 GHz: stand-alone fixed-frequency sources with integrated with horns
- compliant with IEC/IEEE 63195
- verification uncertainty <0.66dB (k=2)





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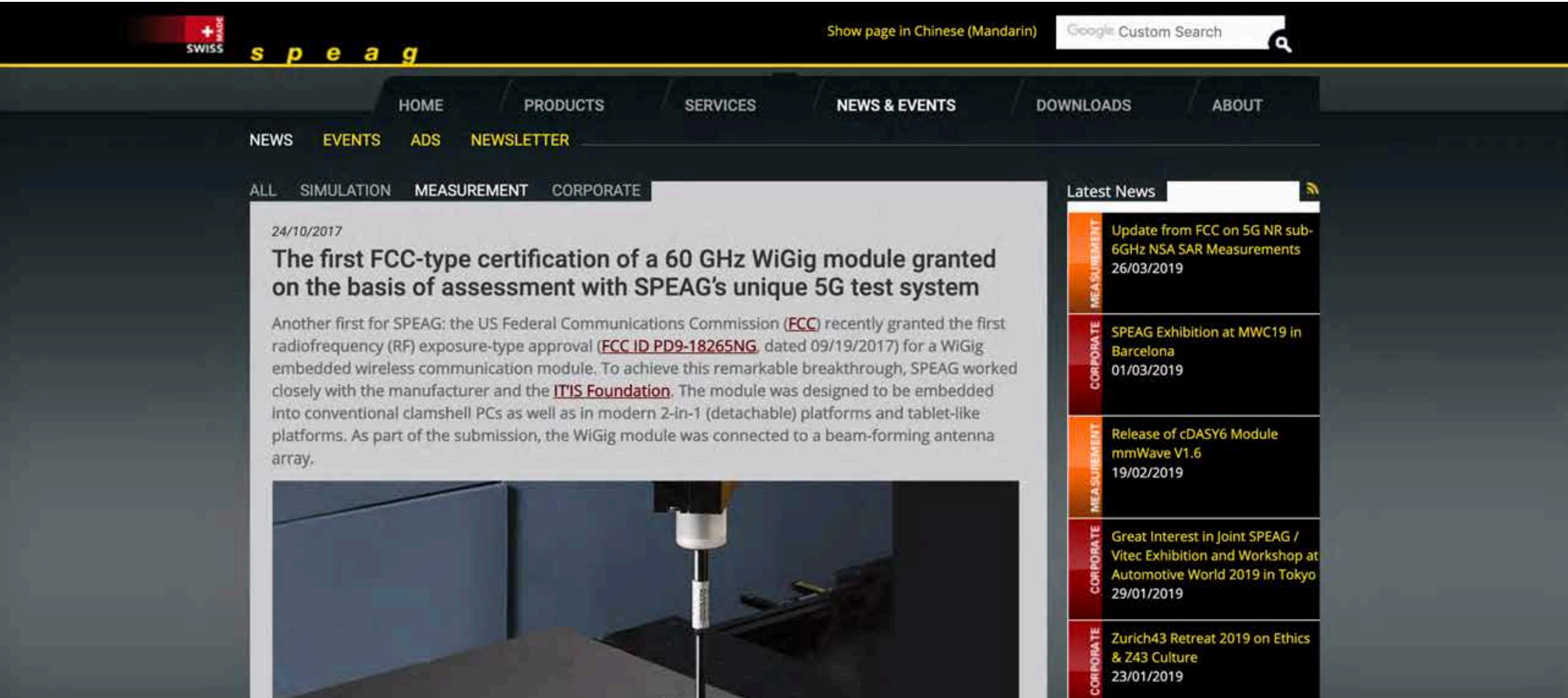
Application in Compliance Tests

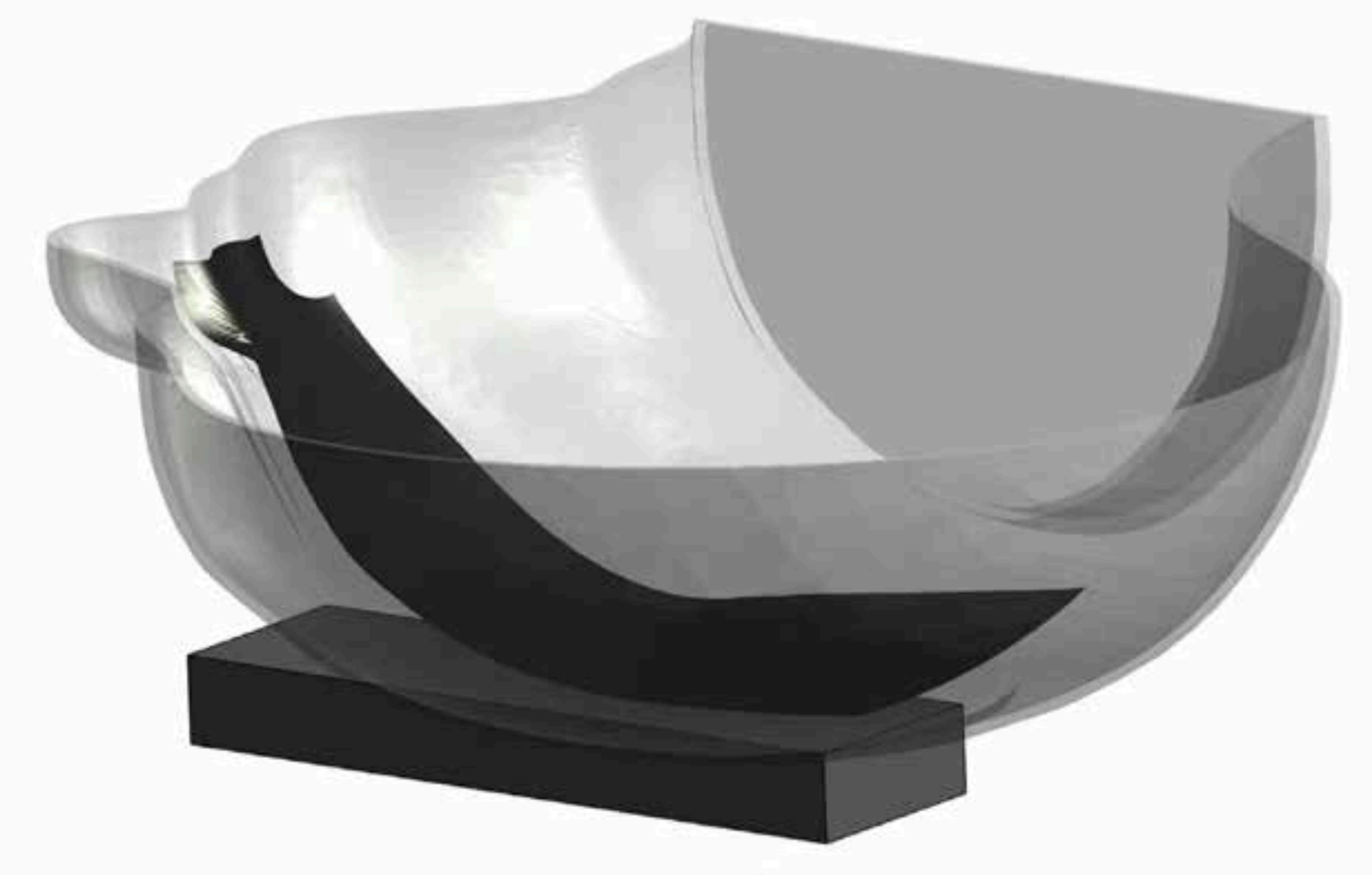
Applied Since 2017 for Compliance Testing



Solutions Currently Under Development

Forward Transformation Evaluation (FTE)

- the need: projection of S on arbitrary volumes / surfaces for combination with SAR
- measurements on two or three planes for each side of the phone
- conservative averaged PD evaluator based on either:
  - validated simulations
  - measurements of each antenna group separately (can be controlled individually with a code book)
- evaluation of the exposures in 3D based on forward propagation techniques
- evaluation of PD distribution on any virtual surface (e.g., SAM head, ELI phantoms, face-down)



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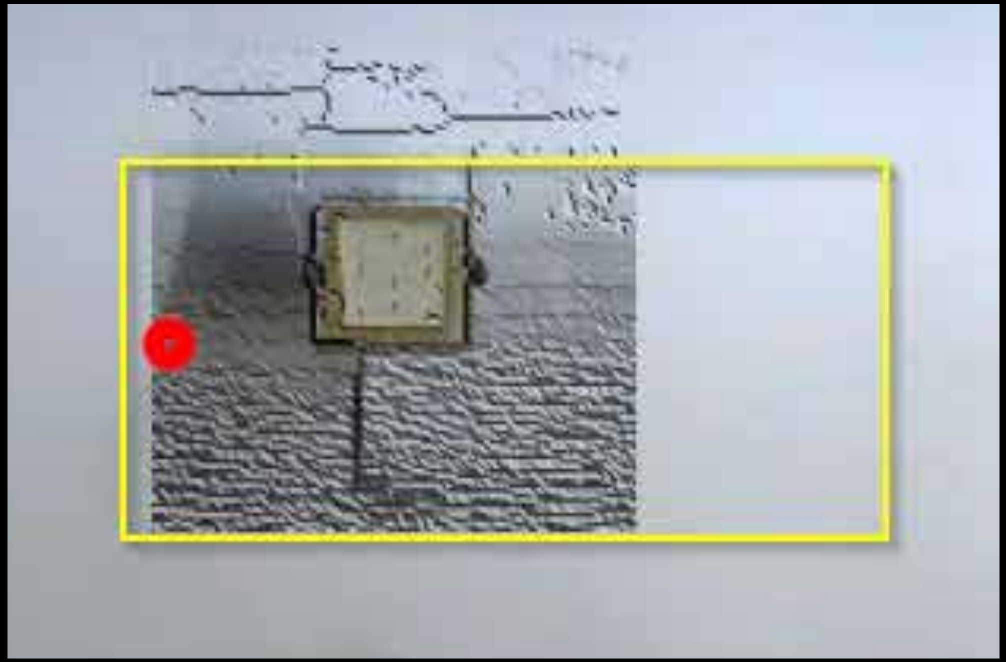
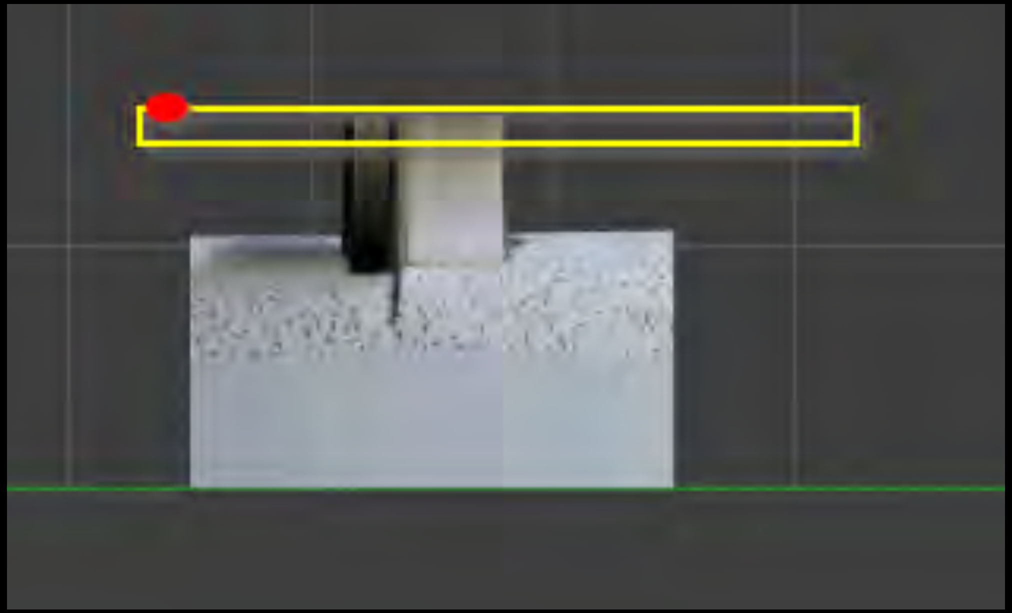
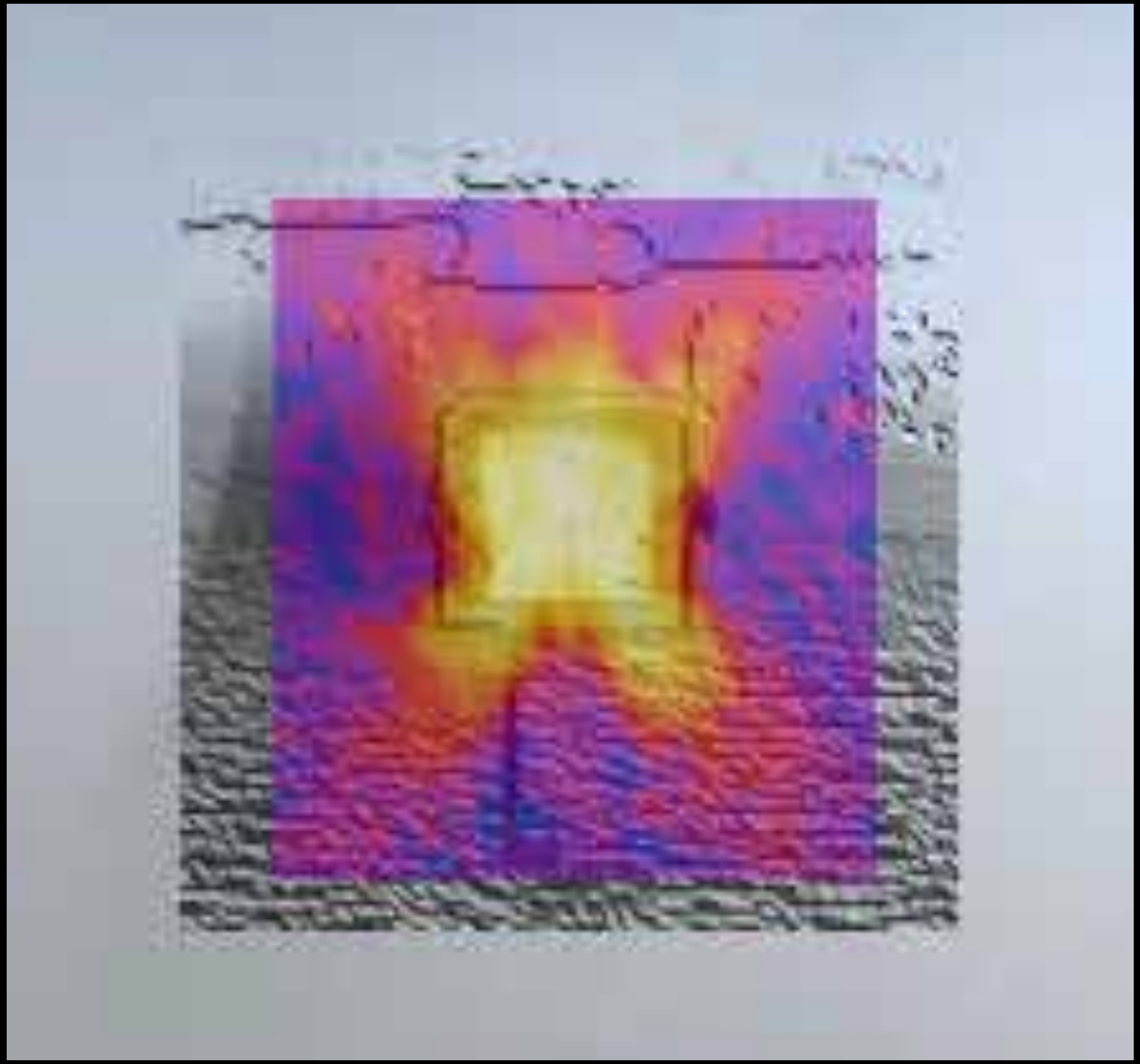
First Results







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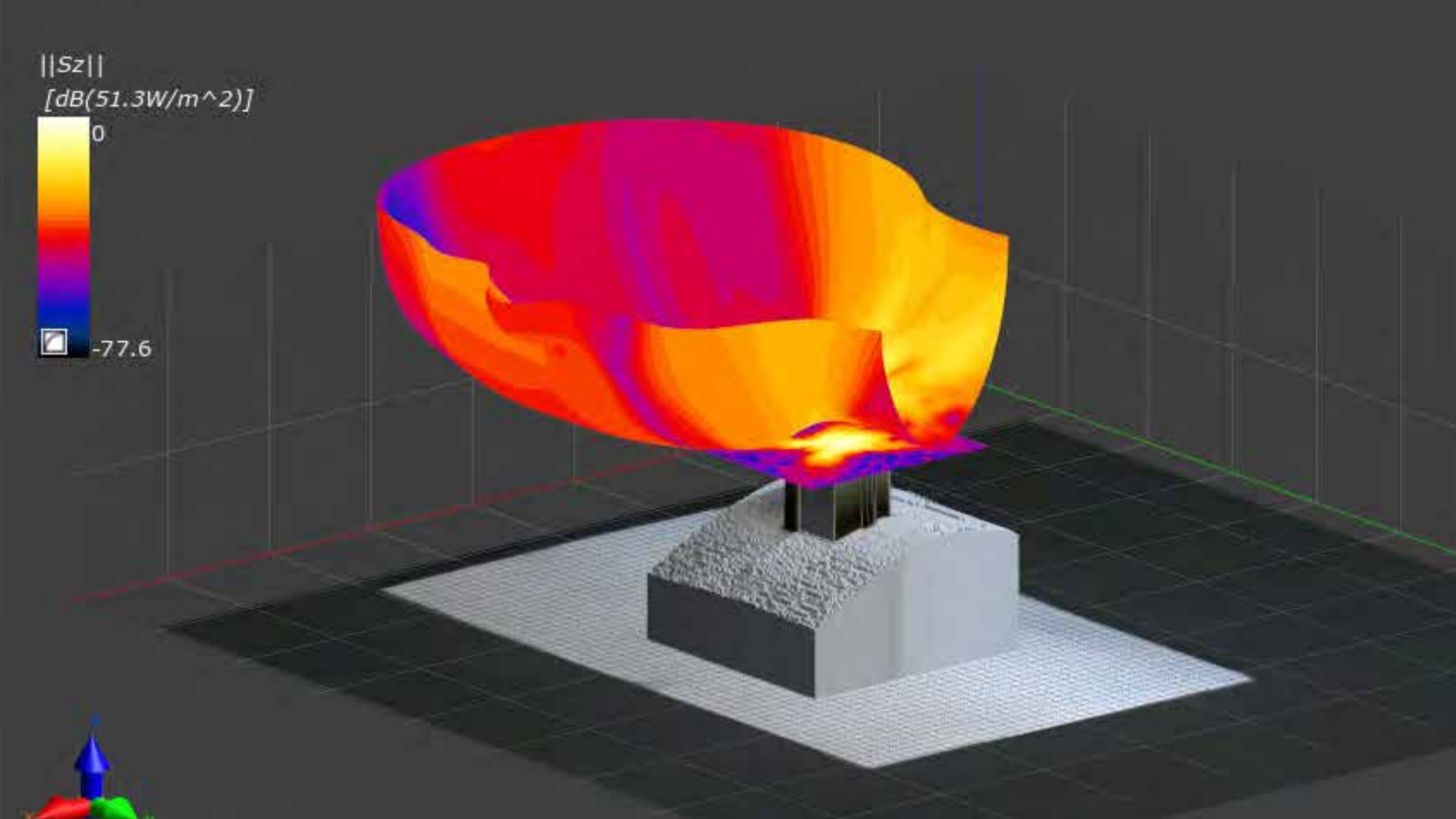
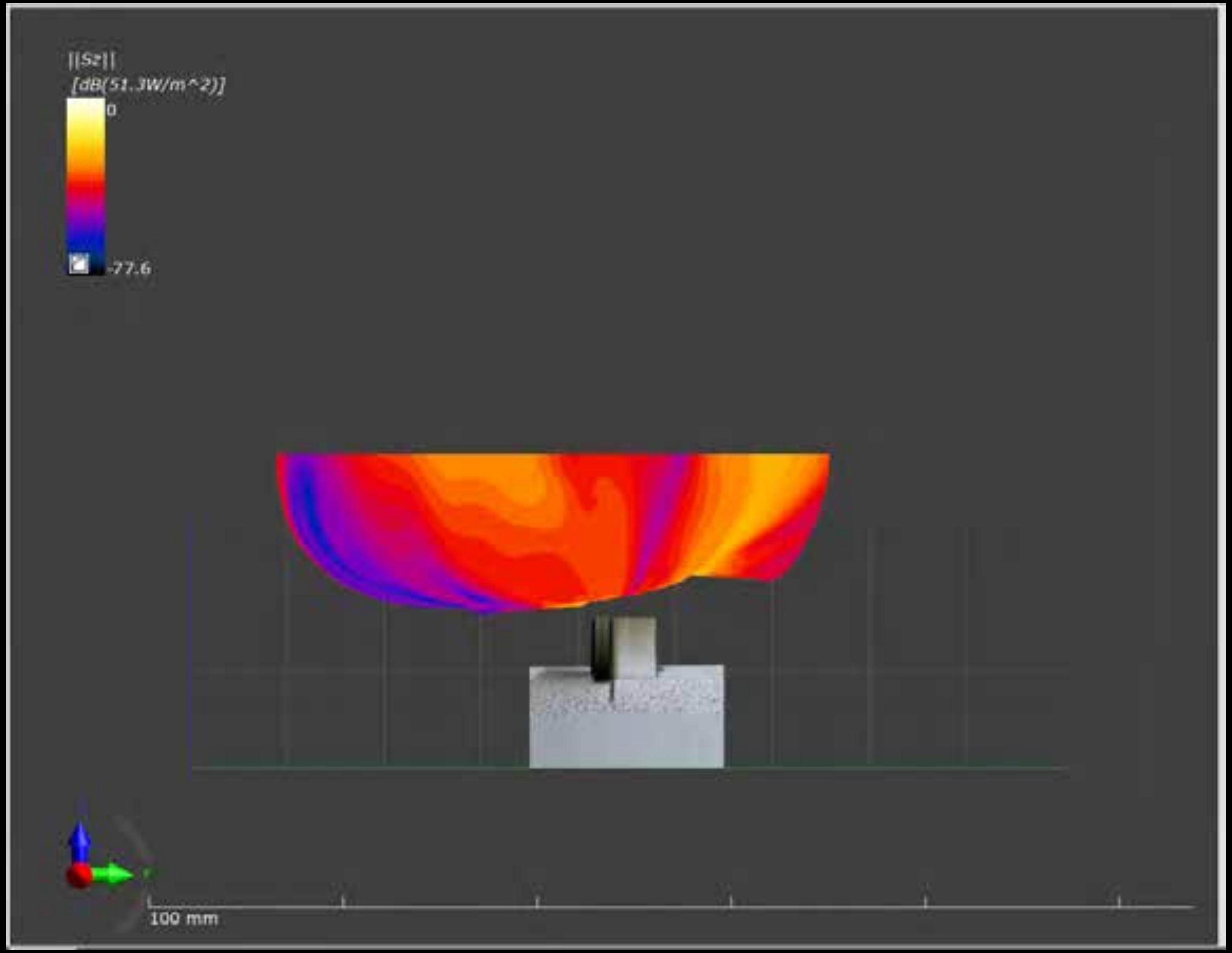
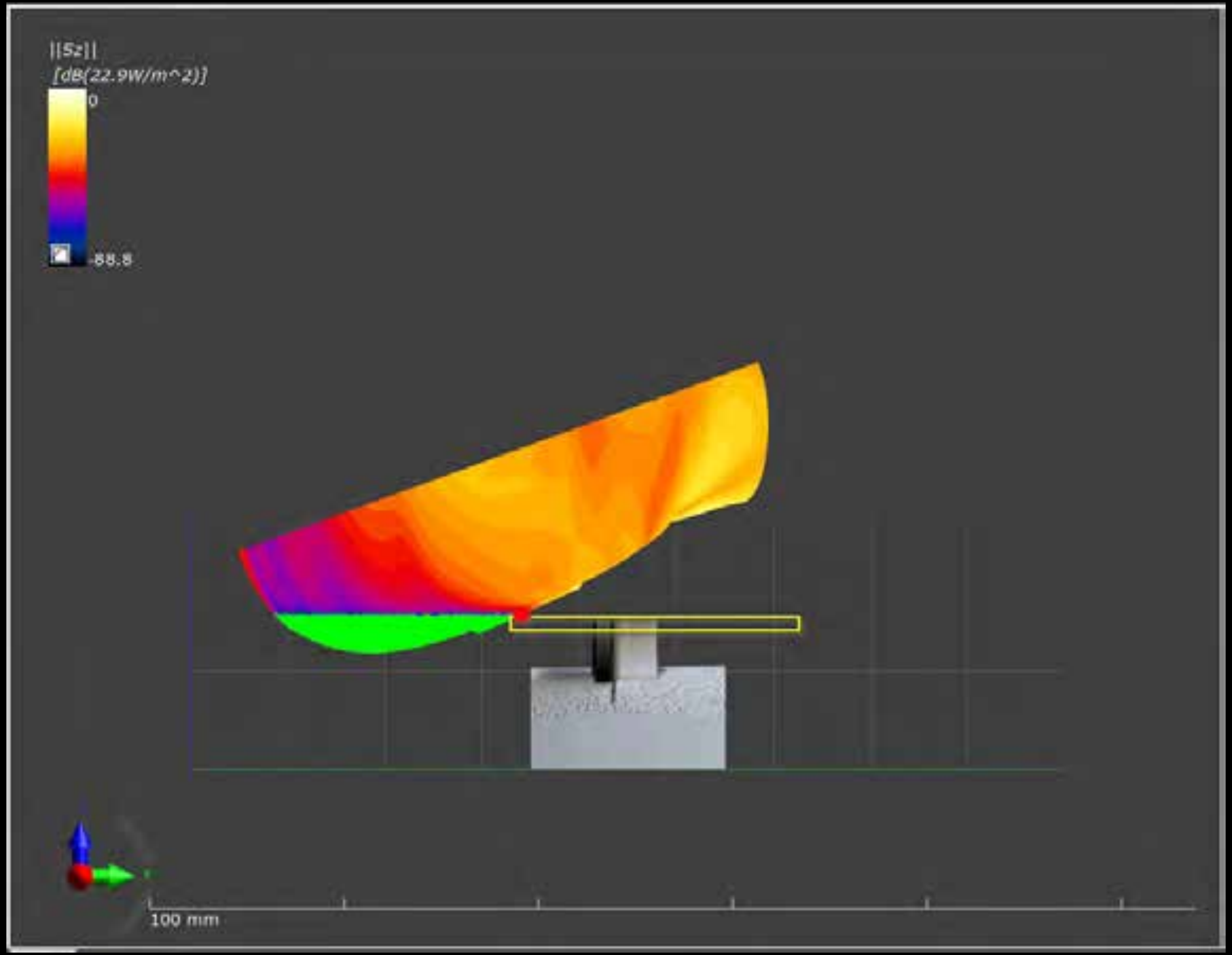

||Sz||
[dB(51.3W/m^2)]
0
-77.6

Right Head: Cheek & Tilt





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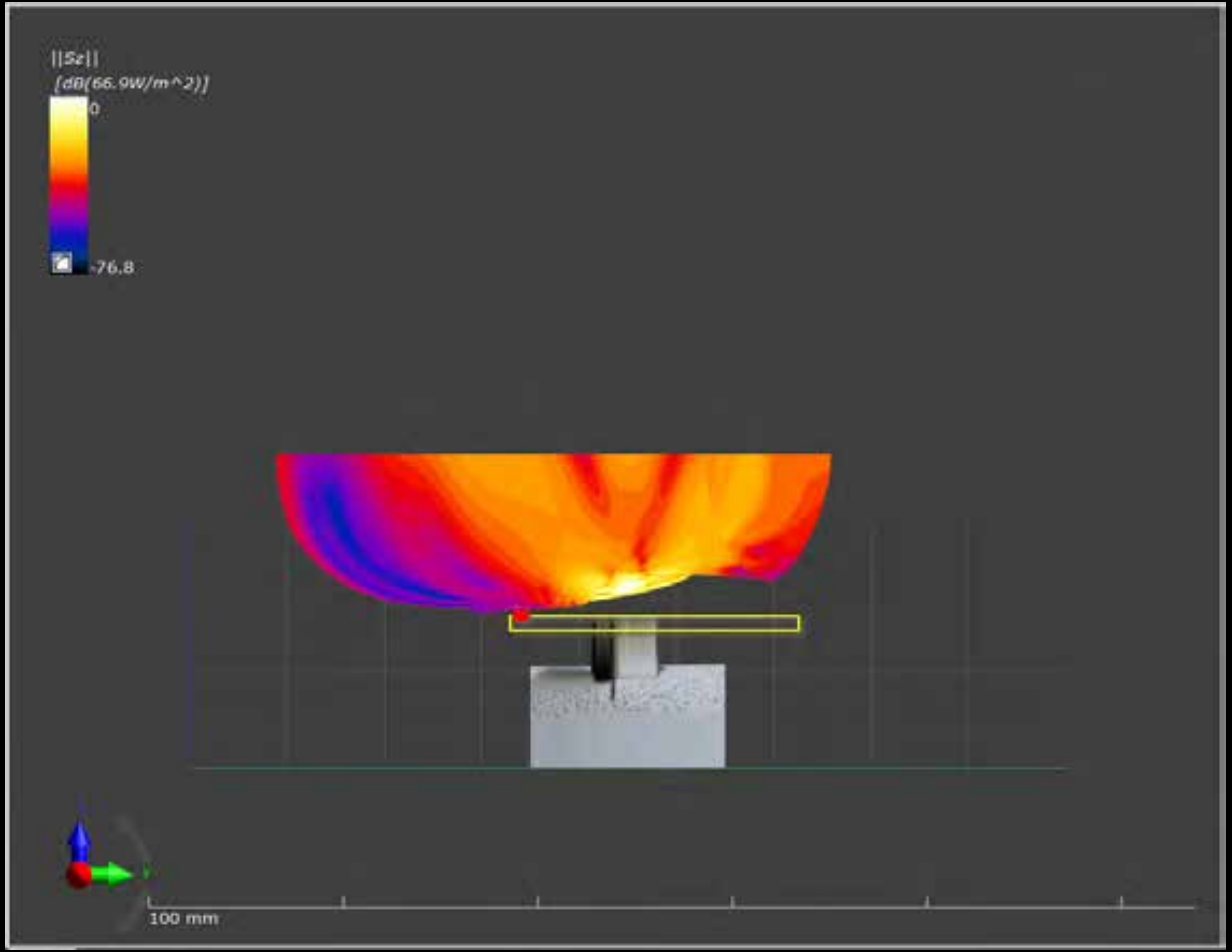
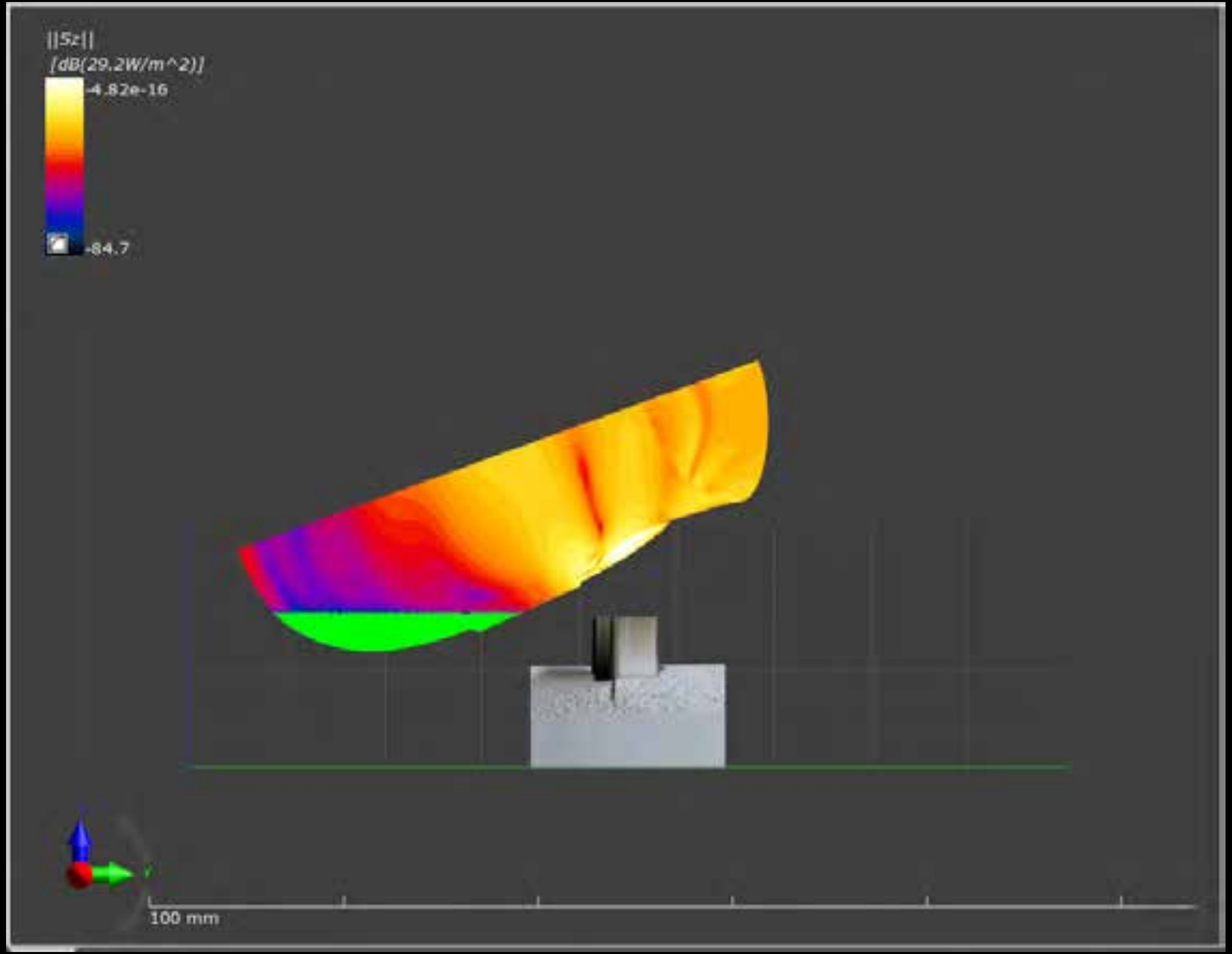
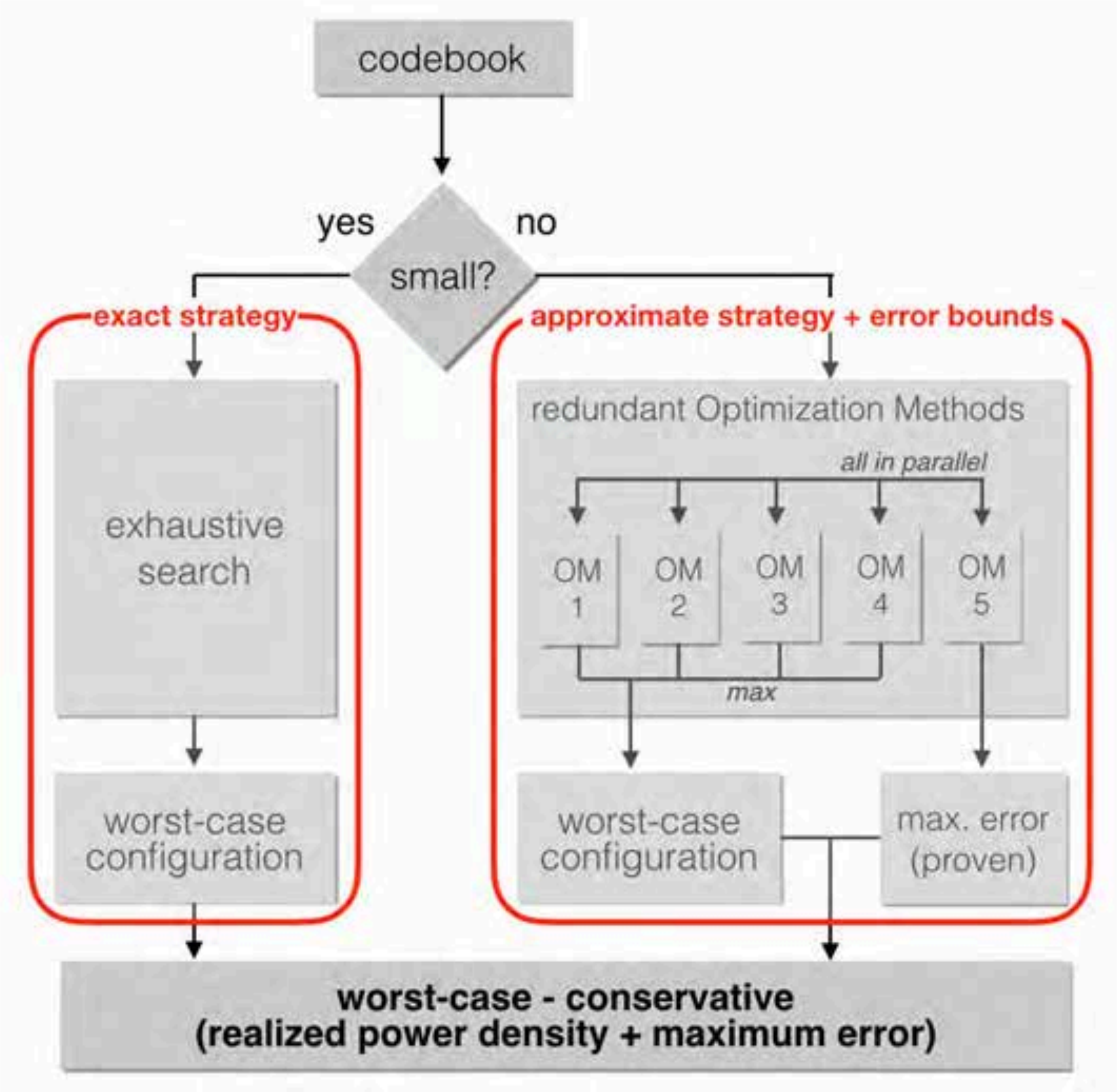
Left Head: Cheek & Tilt





Maximum Exposure Evaluation

- the need: MIMO may require to test millions of configurations to find the worst-case excitation
- measurements on two or three planes for each side of the phone
- conservative averaged PD worst-case optimizer based on either:
  - validated simulations
  - measurements of each antenna group separately (can be controlled individually with a code book)
- evaluation of the exposures in 3D based using advanced forward propagation techniques
- evaluation of PD distribution on any virtual surface (e.g., SAM head, ELI phantoms, face-down)



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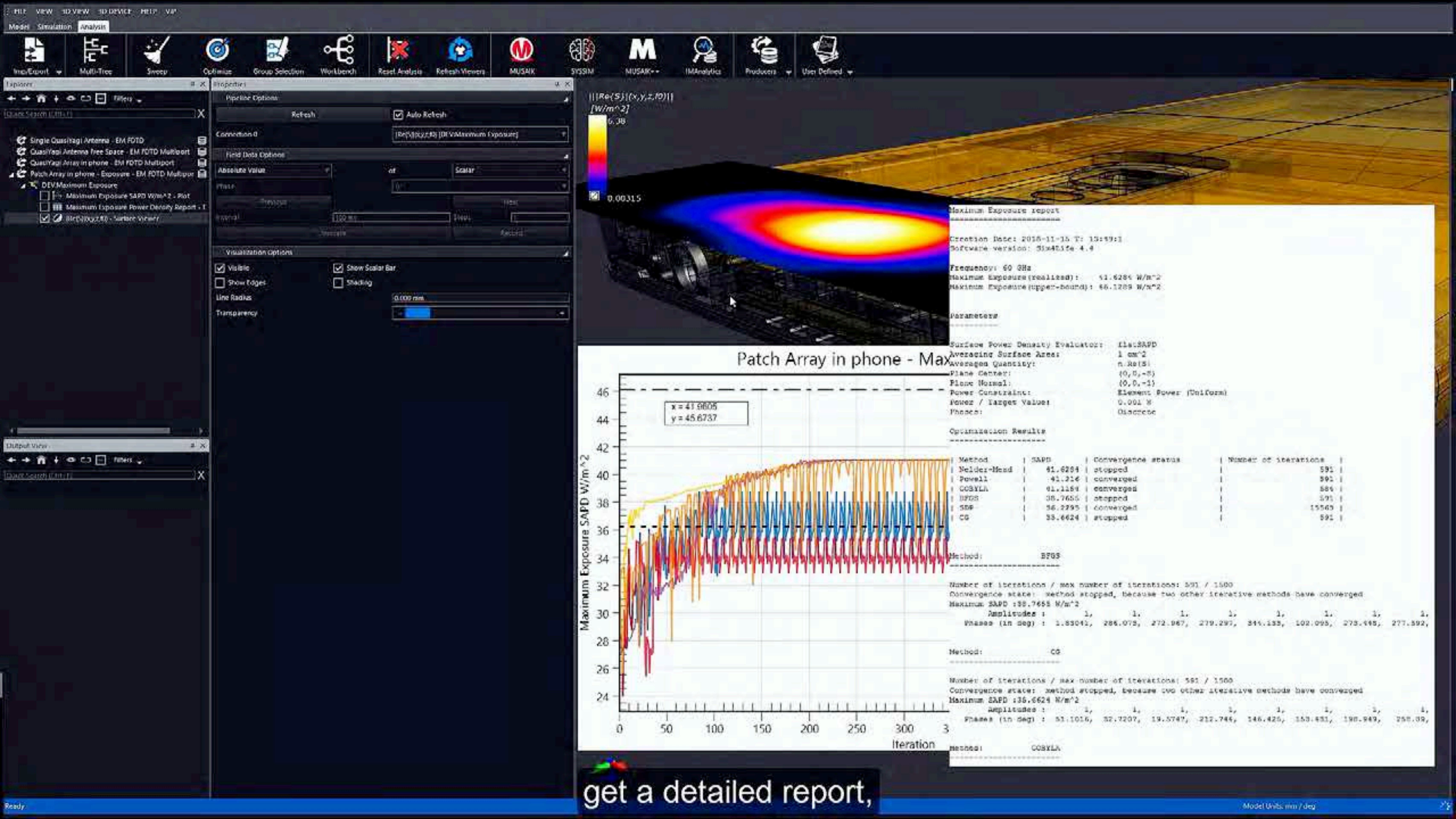

Model
Simulation
Analysis
Imp/Export
Multi-Tree
Sweep
Optimize
Group Selection
Workbench
Reset Analysis
Refresh Viewers
MUSAIK
SYSSIM
IMAnalytics
Producers
User Defined
Explorer
Single QuasiYagi Antenna - EM FDTD
QuasiYagi Antenna free Space - EM FDTD Multiport
QuasiYagi Array in phone - EM FDTD Multiport
DEV:Maximum Exposure
Maximum Exposure SAPD W/m^2 - Plot
Maximum Exposure Power Density Report
Properties
Pipeline Options
Refresh
Auto Refresh
Connection 0
Field Data Options
Absolute Value
Scalar
Visualization Options
Visible
Show Scalar Bar
Show Edges
Shading
Line Radius
Transparency
Output View
[W/m^2]
0.00315
Patch Array in phone - Max
x = 41.9605
y = 45.6737
Maximum Exposure SAPD W/m^2
Iteration
Maximum Exposure report
Frequency: 60 GHz
Parameters
Optimization Results
Method
SAPD
Convergence status
Number of iterations
Nelder-Mead
Powell
COBYLA
BFGS
CG
Method: BFGS
Method: CG
Method: COBYLA
get a detailed report,
Ready

Combination of SAR and Power Density

- the need: combine S with other sub6 sources (SAR distributions)
- based on FTE and worst-case optimizer

$$\frac{\text{Total Exposure}}{\text{Limit}} = \sum_{n=1}^{n} \frac{SAR_n}{SAR_{n,limit}} + \sum_{m=1}^{m} \frac{S_{inc_m}}{S_{inc_m,limit}}$$

Assessment of Transmitted Power (S_{tr})

- evaluation of transmitted PD S_{tr} for frequencies below 24 GHz
- cDASY7 module for measuring transmitted power S_{tr} in phantoms (in development)
- no overestimation in the reactive near-field of transmitters (<λ/2π)

$$\frac{\text{New Total Exposure}}{\text{Limit}} = \sum_{n=1}^{n} \frac{SAR_n}{SAR_{n,limit}} + \sum_{m=1}^{m} \frac{S_{inc_m}}{S_{inc_m,limit}} + \sum_{j=1}^{j} \frac{S_{tr_j}}{S_{tr_j,limit}}$$

11 July 2018

Draft

ICNIRP Guidelines

GUIDELINES FOR LIMITING EXPOSURE TO TIME-VARYING ELECTRIC, MAGNETIC AND ELECTROMAGNETIC FIELDS (100 kHz TO 300 GHz)

International Commission on Non-Ionizing Radiation Protection

1. INTRODUCTION

The guidelines described here are for the protection of humans exposed to radiofrequency electromagnetic fields (EMFs) in the range 100 kHz to 300 GHz (hereafter 'radiofrequency'). This publication replaces the radiofrequency part of the 1998 guidelines (ICNIRP 1998); ICNIRP has already published updated guidelines for the low-frequency part (ICNIRP 2010). Although these guidelines are based on the best science currently available, it is recognized that there may be limitations to this knowledge which could impact on the exposure restrictions. Accordingly, the guidelines will be periodically revised and updated as advances are made in the relevant scientific knowledge.

2. PURPOSE AND SCOPE

The main objective of this publication is to establish guidelines for limiting exposure to EMFs

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Conclusions: 5G Radio Exposure Measurement

Conclusion: 5G mmWave (>6 GHz)

- with 5G mmWave compliance testing became a near-field problem
- incident power density has no meaning below 10/20 GHz
  - SAR or S_{tr} should be used
- new test equipment
  - EUmmW probe with traceable calibration
  - novel validated reconstruction algorithm ($d>\lambda/2\pi$ = 2mm @28GHz)
  - test uncertainty: ~0.7 dB (k=1)
- test solutions currently under development
  - forward transformation - project PD on arbitrary surfaces and combine with other sources
  - optimiser - find worst case exposure configuration for MIMO
  - combiner SAR and Power Density
  - transmitted power density measurement system
- more research required on dosimetric quantities and biological mechanisms