THE ANTENNA VIRTUAL TWIN – WHEN MEASUREMENTS AND SIMULATIONS UNITE

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OUTLINE

- Context and problem statement
- Principle of simulation-augmented measurements with the antenna digital twin
- Example applications
- Conclusion

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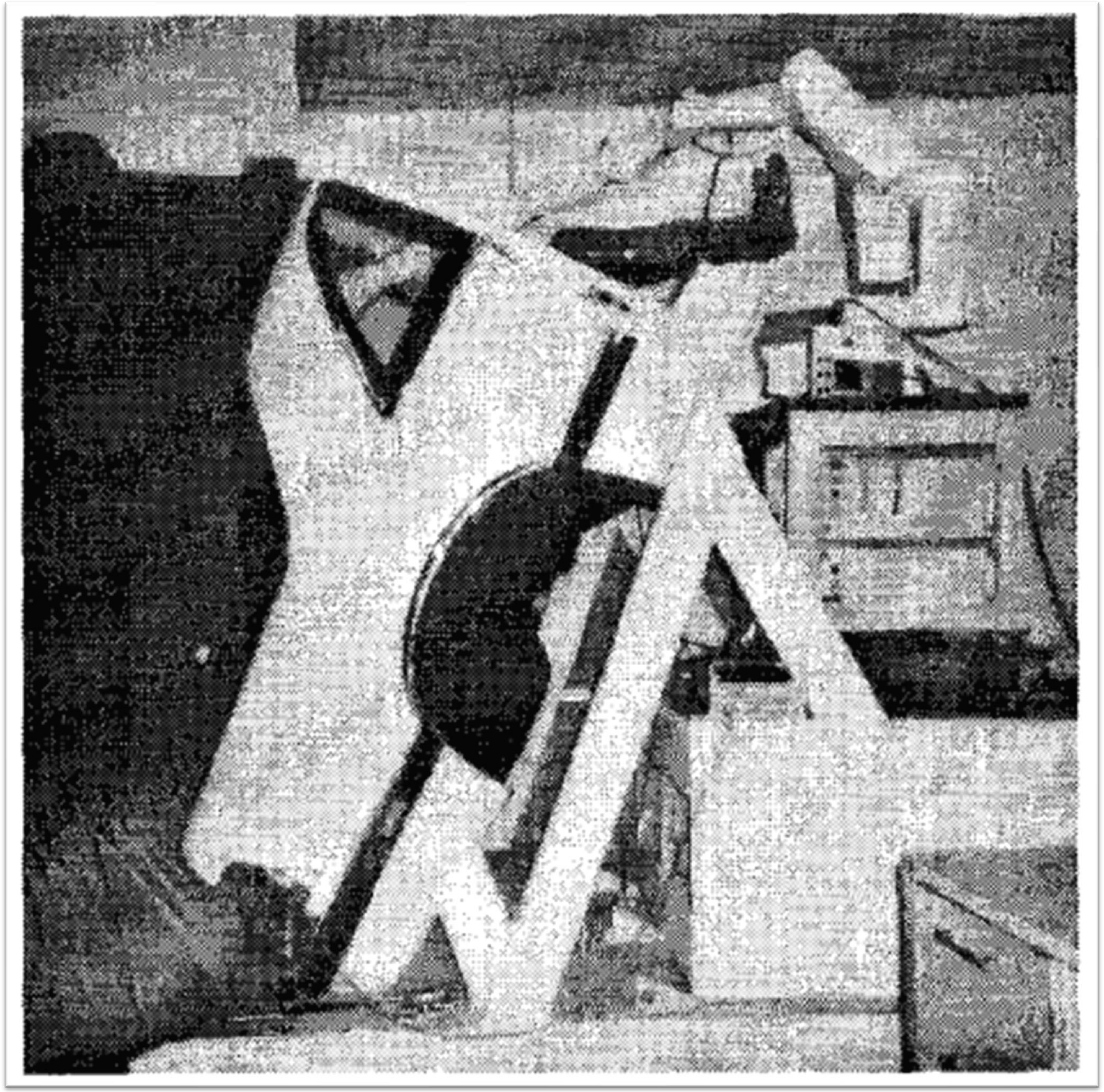
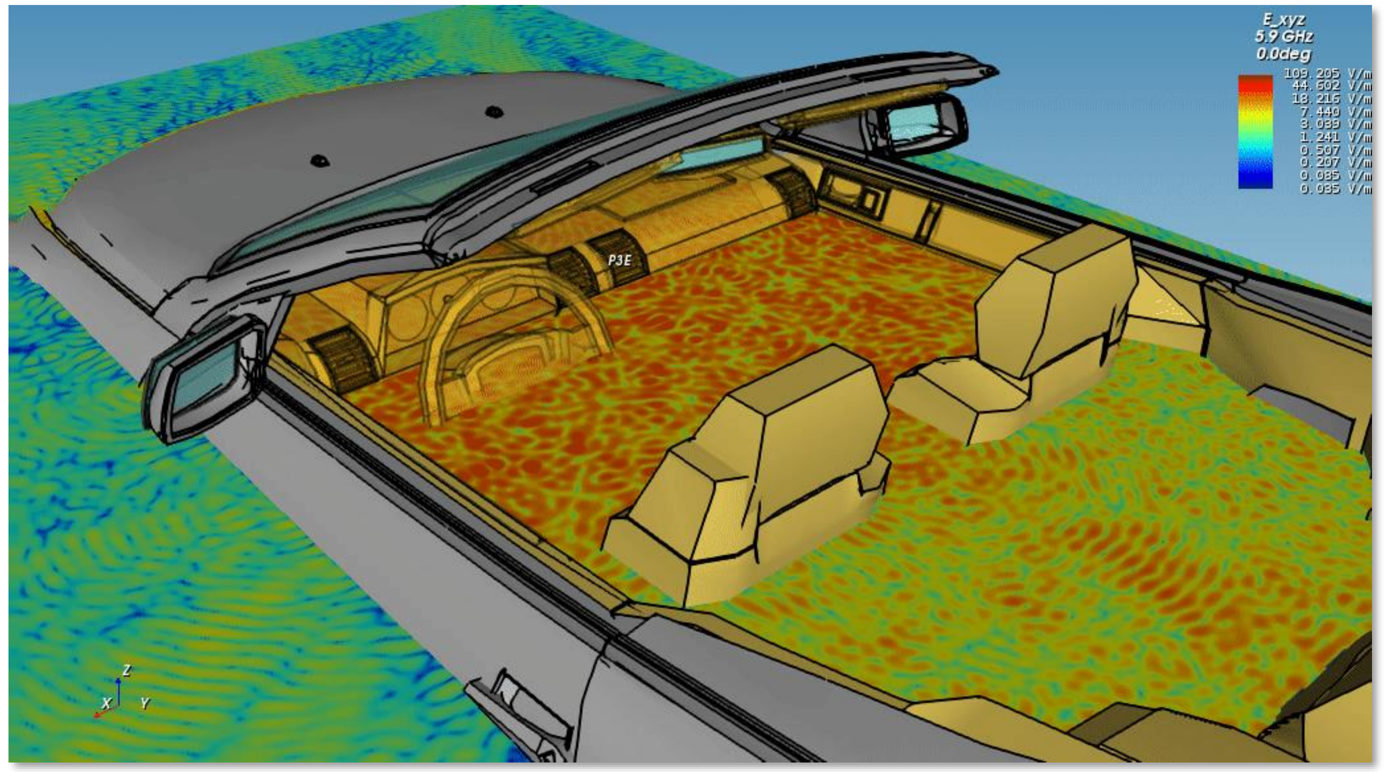
SAR MEASUREMENT SETUP FOR CAR PASSENGERS

► SAR = Specific Absorption Rate

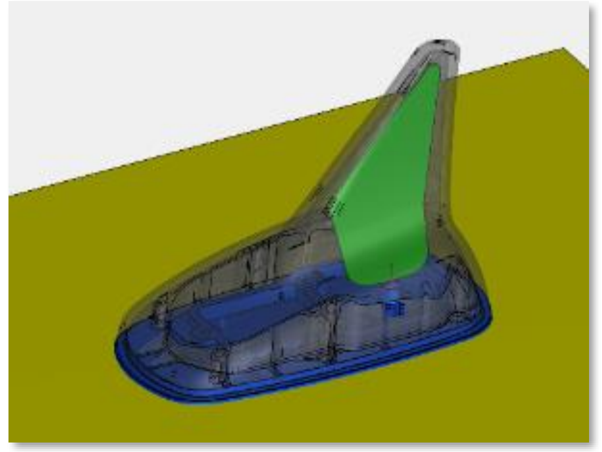


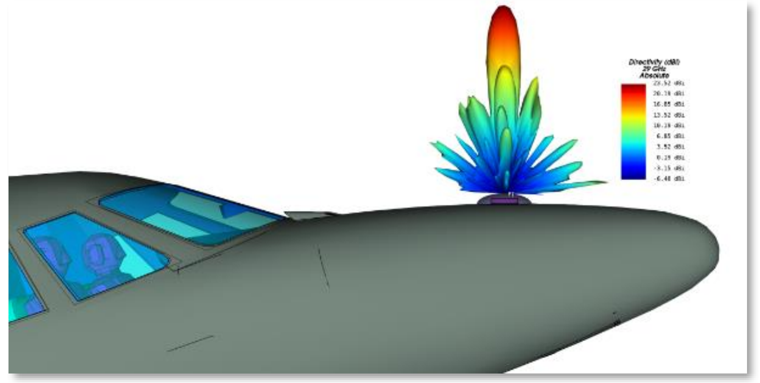
D. O. McCoy, D. Zakharia and Q. Balzano, "Field strengths and specific absorption rates in automotive environments," 1999 IEEE 49th Vehicular Technology Conference

NEED FOR ADVANCED CHARACTERIZATION TECHNIQUES

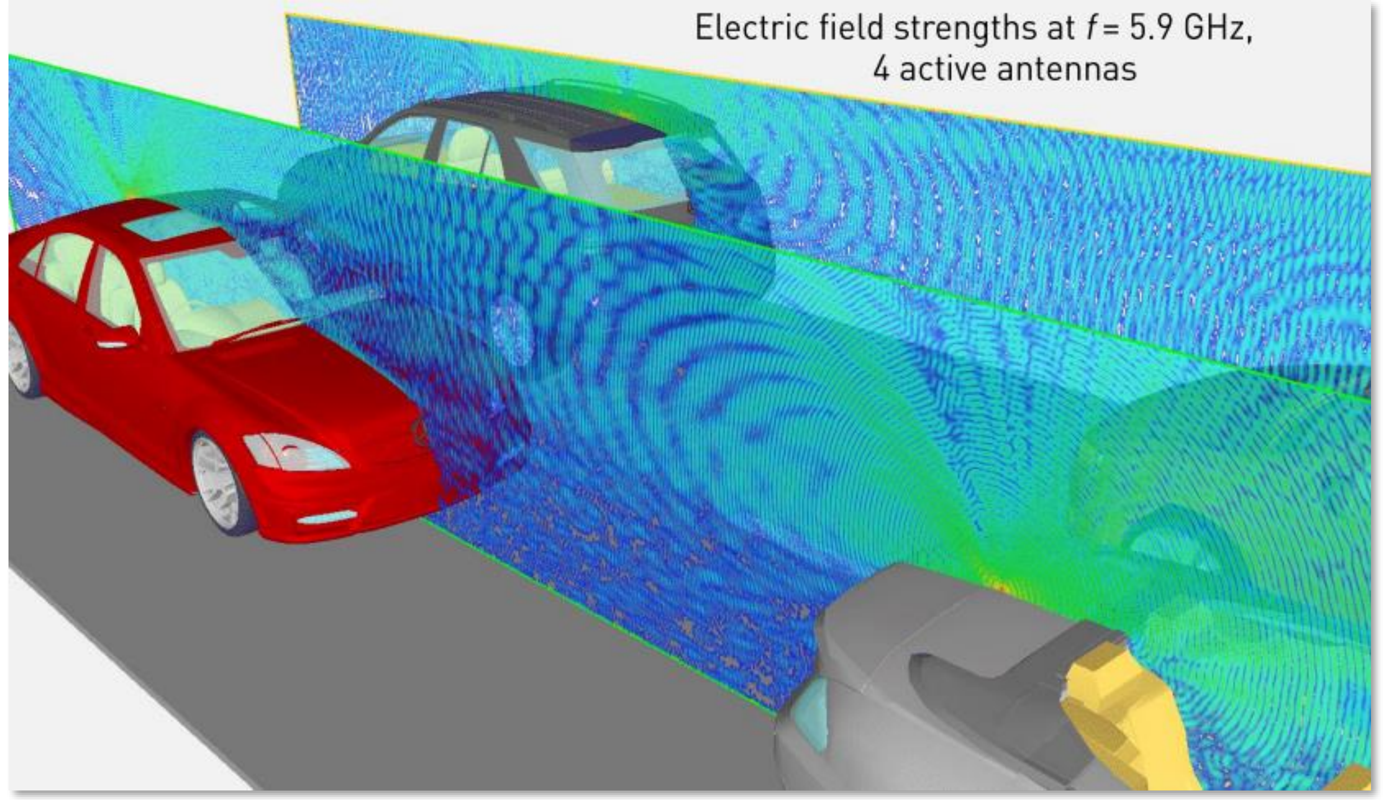


In-vehicle connectivity optimization

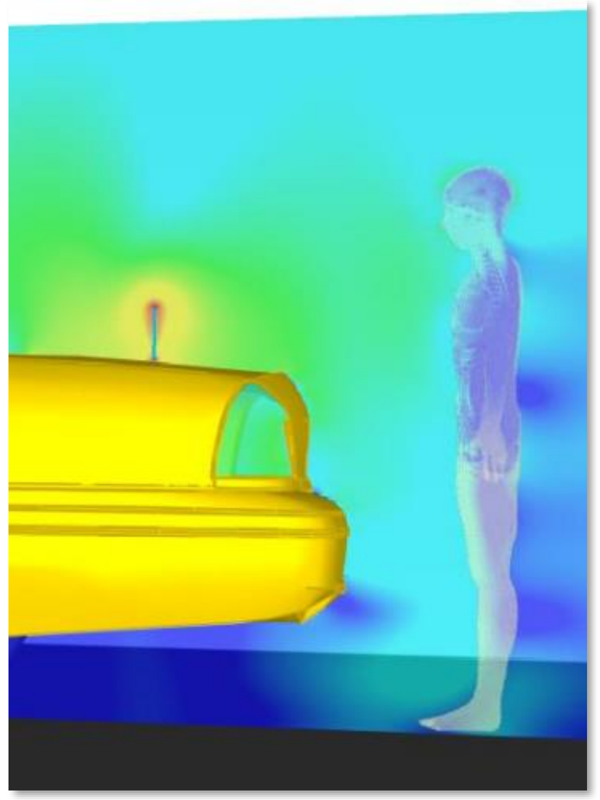




Antenna and placement optimization



Complex scenarii simulations



Human exposure evaluation

MEASUREMENT, SIMULATION AND THEIR COMBINATION

	Antenna / OTA measurement	Full-wave electromagnetic simulation
Pros (measurement) / Cons (simulation)	Blind: no designer knowledge required Full system characterization Includes production and operation tolerances	Requires deep knowledge on DUT No complete system, e.g. active circuits Modelling of tolerances is cumbersome
Cons (measurement) / Pros (simulation)	Limited to canonical test environments Not every field distribution can be measured Time may explode when configurations multiply	Highly complex scenarii can be simulated Every field distribution can be computed Parametric modelling and batching allow simulations round the clock

Simulation-augmented antenna / OTA measurements (**OTAA**)

OTA = Over-The-Air

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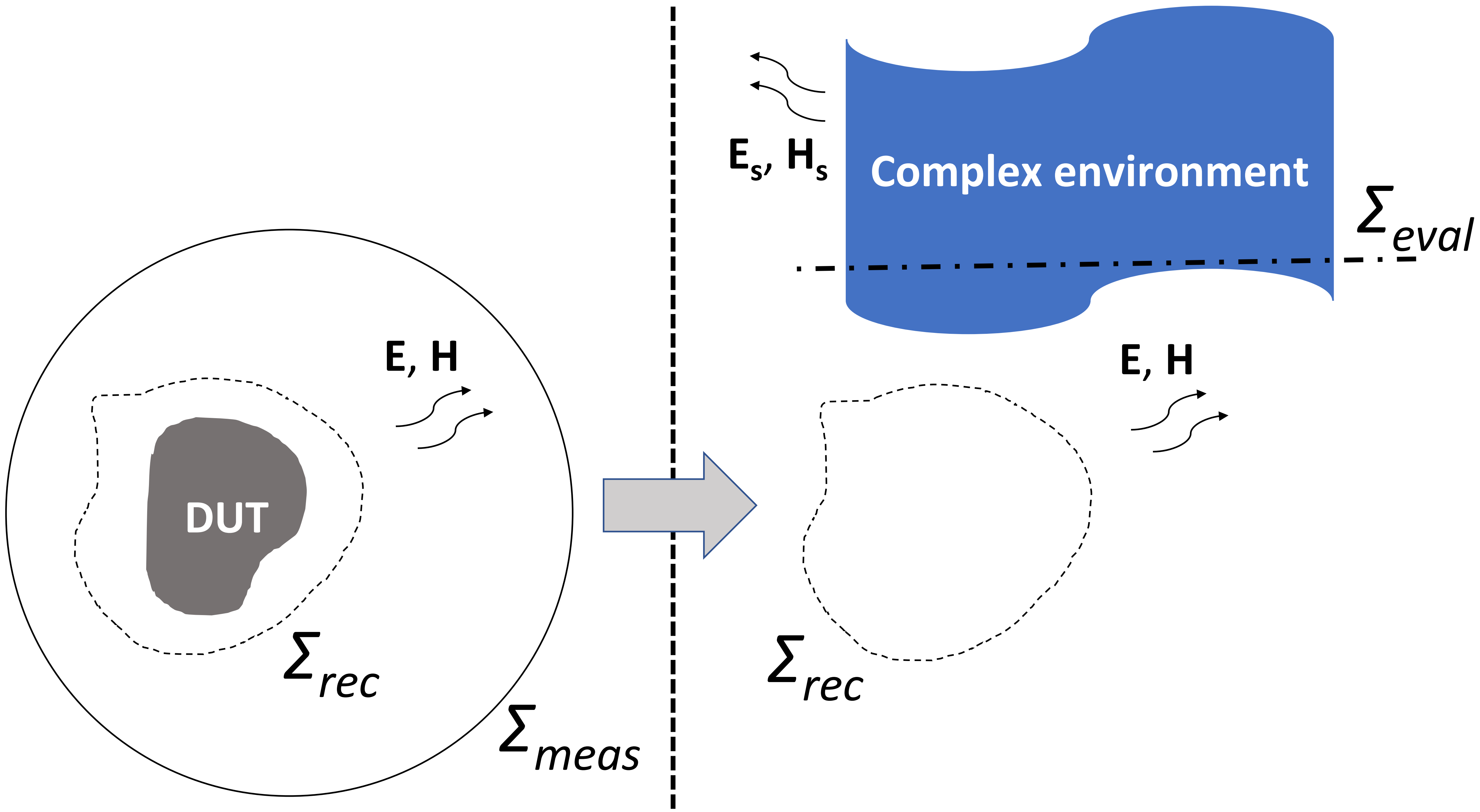
PRINCIPLE OF SIMULATION-AUGMENTED MEASUREMENTS

Step 1 - Field **measurements**

Step 2 - Equivalent currents reconstruction / **Digital twin creation**

Step 3 - Simulation of the complex scenario in a full-wave EM software

Post-processing of relevant metrics based on simulated fields

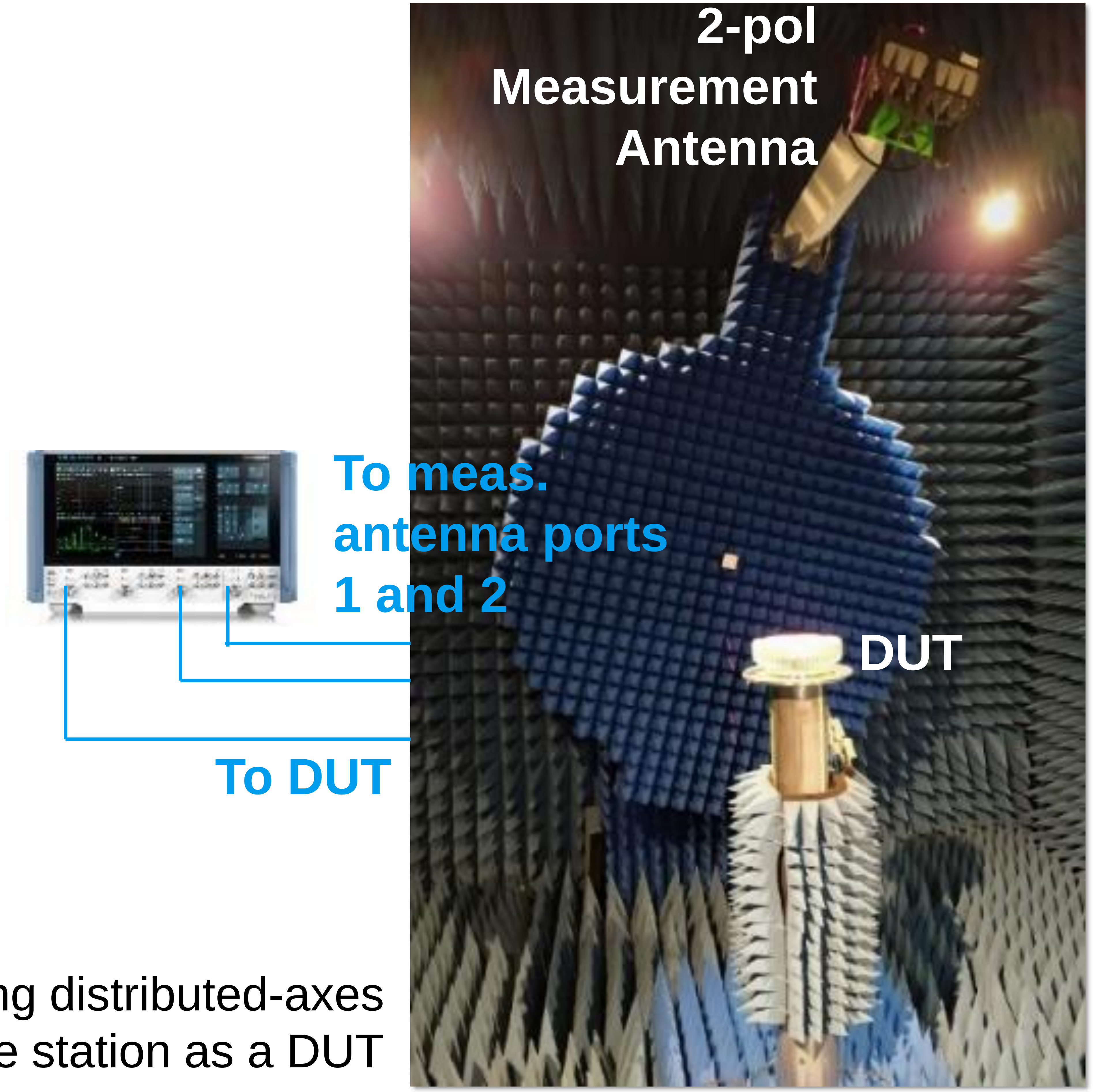


Experimental / physical domain

Simulation / numerical domain

STEP 1 - MEASUREMENTS

- Making use of the Huygens principle
- Measure at least two phasor components among the six of the radiated **E** and **H** fields
- Closed surface encompassing the DUT



Spherical scanning distributed-axes system with radio base station as a DUT

STEP 2 - ANTENNA DIGITAL TWIN CREATION

- Equivalent source reconstruction – inverse problem resolution
- FIAFTA (Fast Irregular Antenna Field Transformation Algorithm) developed at the Chair of HF Engineering of the TU Munich – FIAFTA operator:

$$U(\vec{r}_M) = \iiint_{V_{Probe}} \vec{w}_{Probe}(\vec{r} - \vec{r}_M) \cdot \iint_{\Sigma_{rec}} \left[\overleftrightarrow{G}_J^E(\vec{r}, \vec{r}') \cdot \vec{J}_A(\vec{r}') + \overleftrightarrow{G}_M^E(\vec{r}, \vec{r}') \cdot \vec{M}_A(\vec{r}') \right] da' dv$$

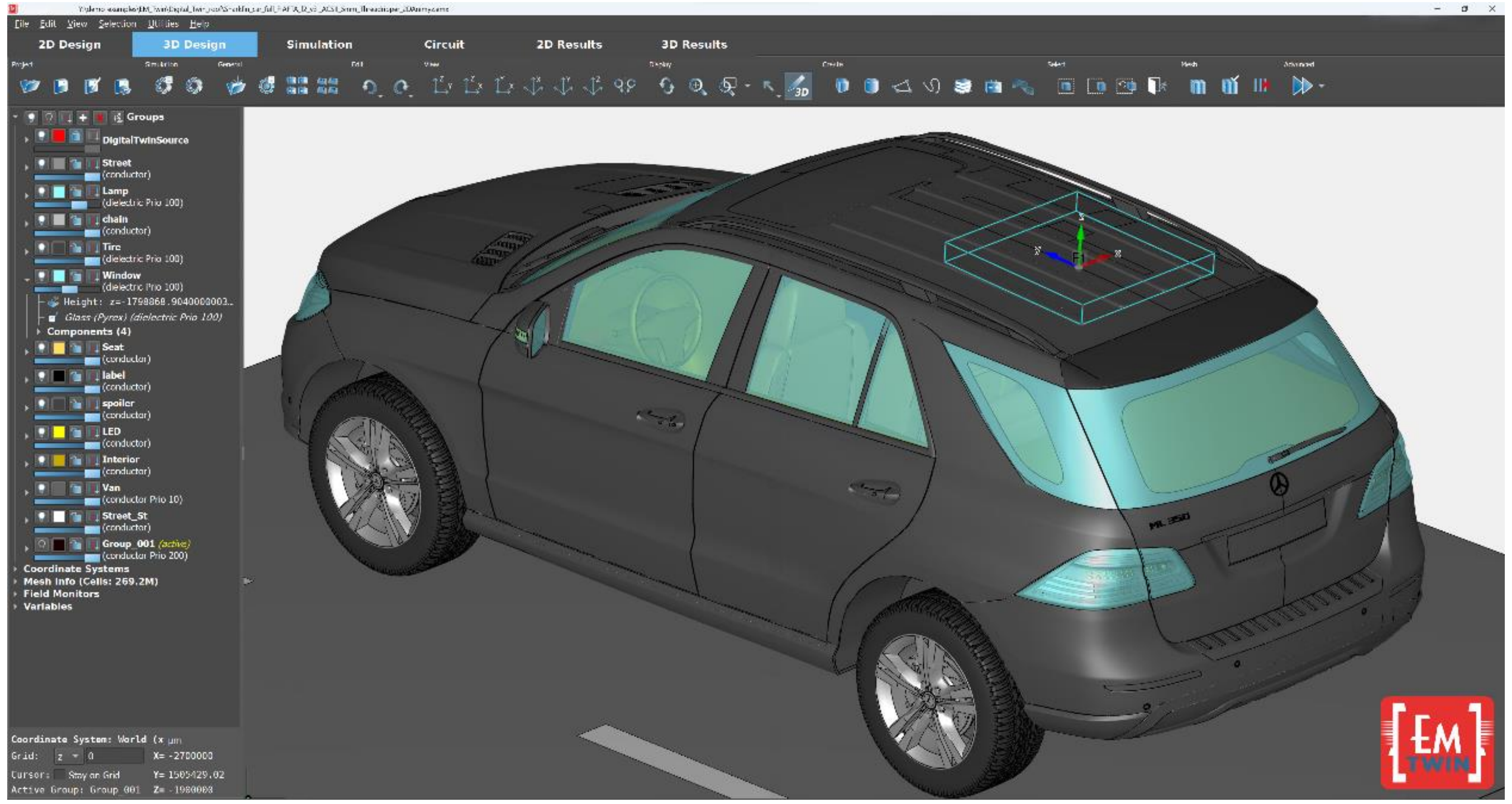
$$\overleftrightarrow{G}_J^E(\vec{r}, \vec{r}') = -jkZ_F \left(\overleftrightarrow{I} + \frac{1}{k^2} \nabla\nabla \right) \frac{e^{-jk|\vec{r} - \vec{r}'|}}{4\pi|\vec{r} - \vec{r}'|}$$

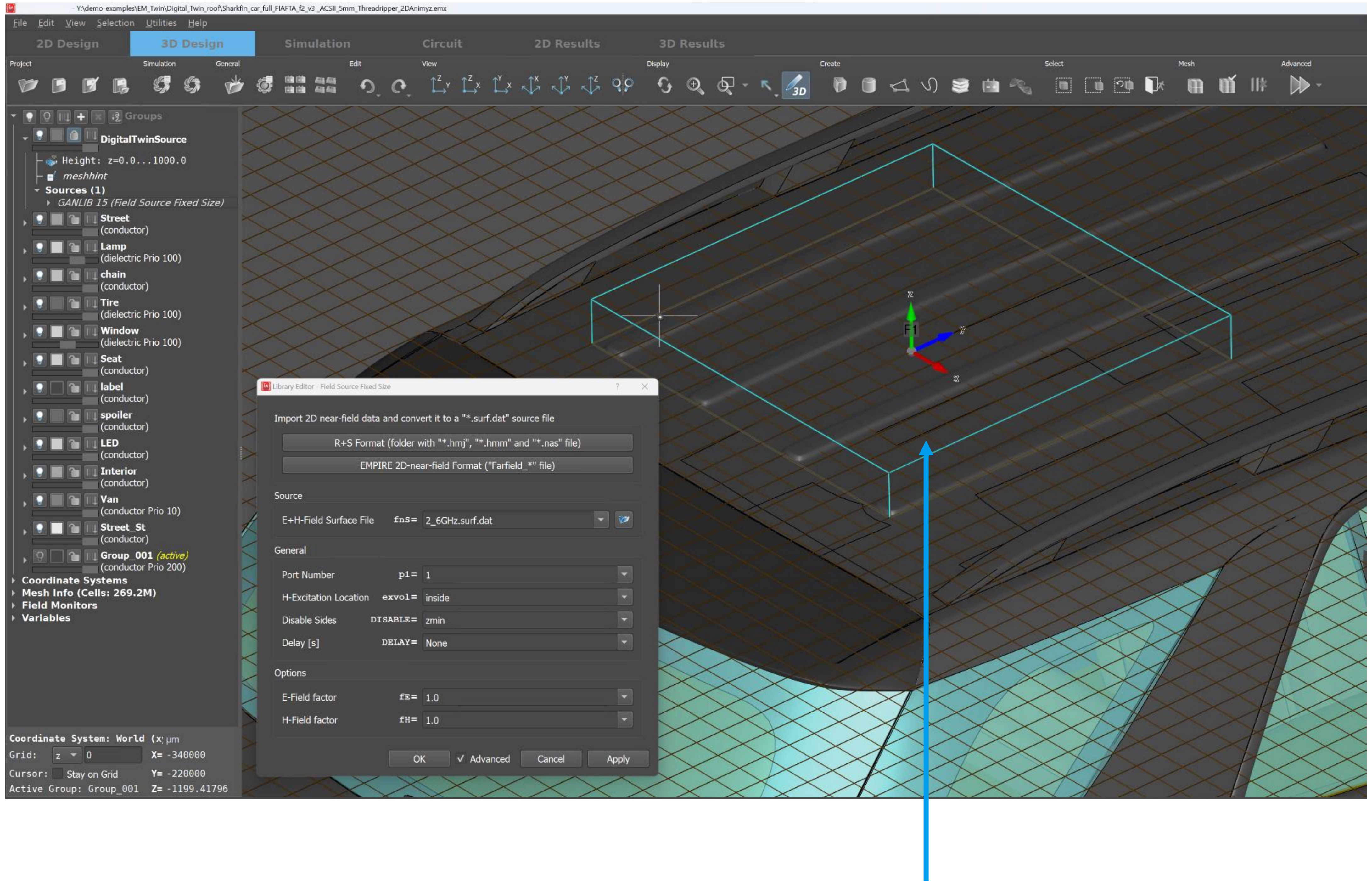
$$\overleftrightarrow{G}_M^E(\vec{r}, \vec{r}') = -\frac{1}{4\pi} \nabla \times \overleftrightarrow{I} \frac{e^{-jk|\vec{r} - \vec{r}'|}}{4\pi|\vec{r} - \vec{r}'|}$$

- Love-type boundary condition: ***E***=***H***=0 inside the equivalent source surface

STEP 3 - SIMULATION

► We used the Finite Difference Time Domain (FDTD) code

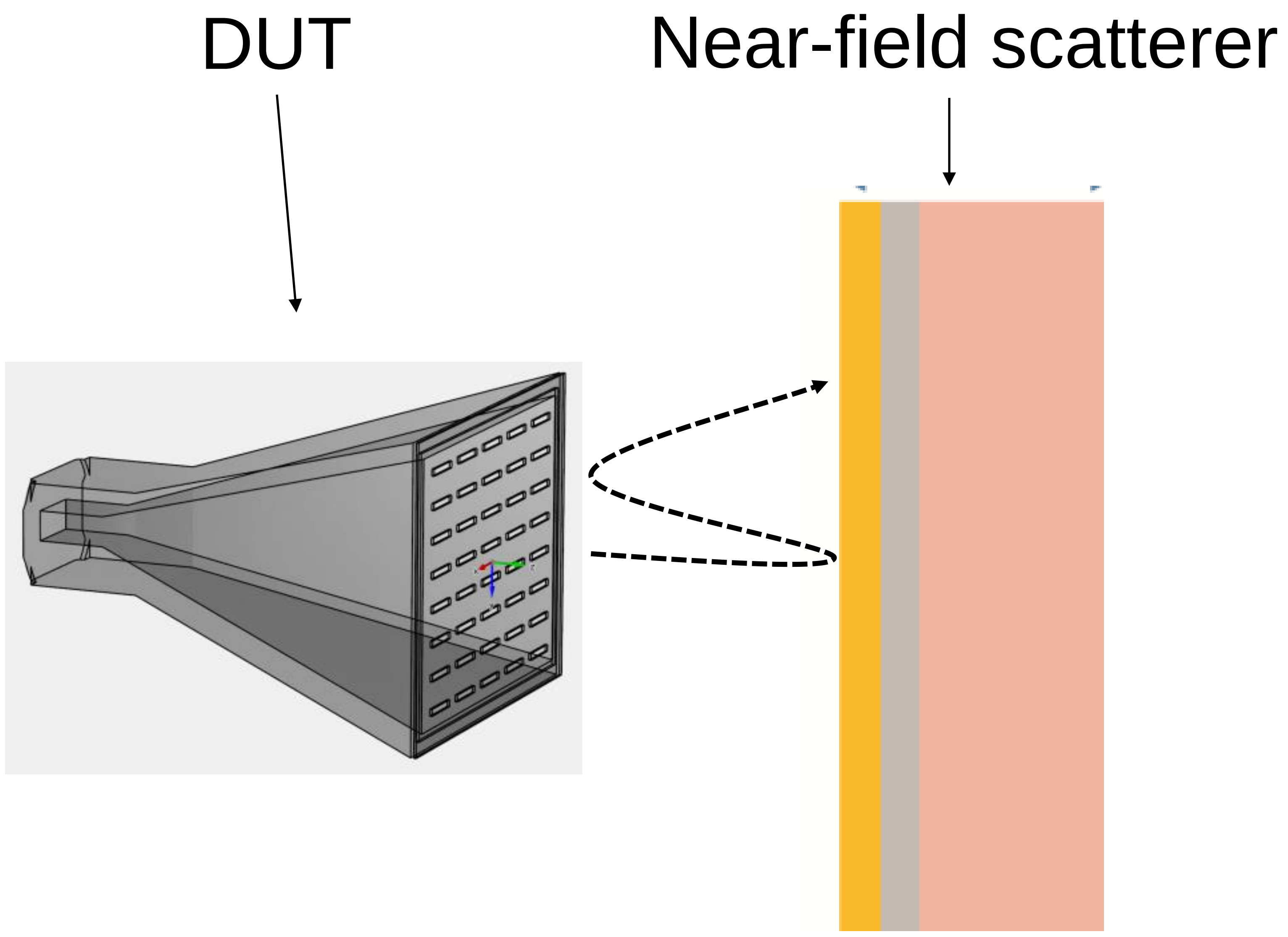




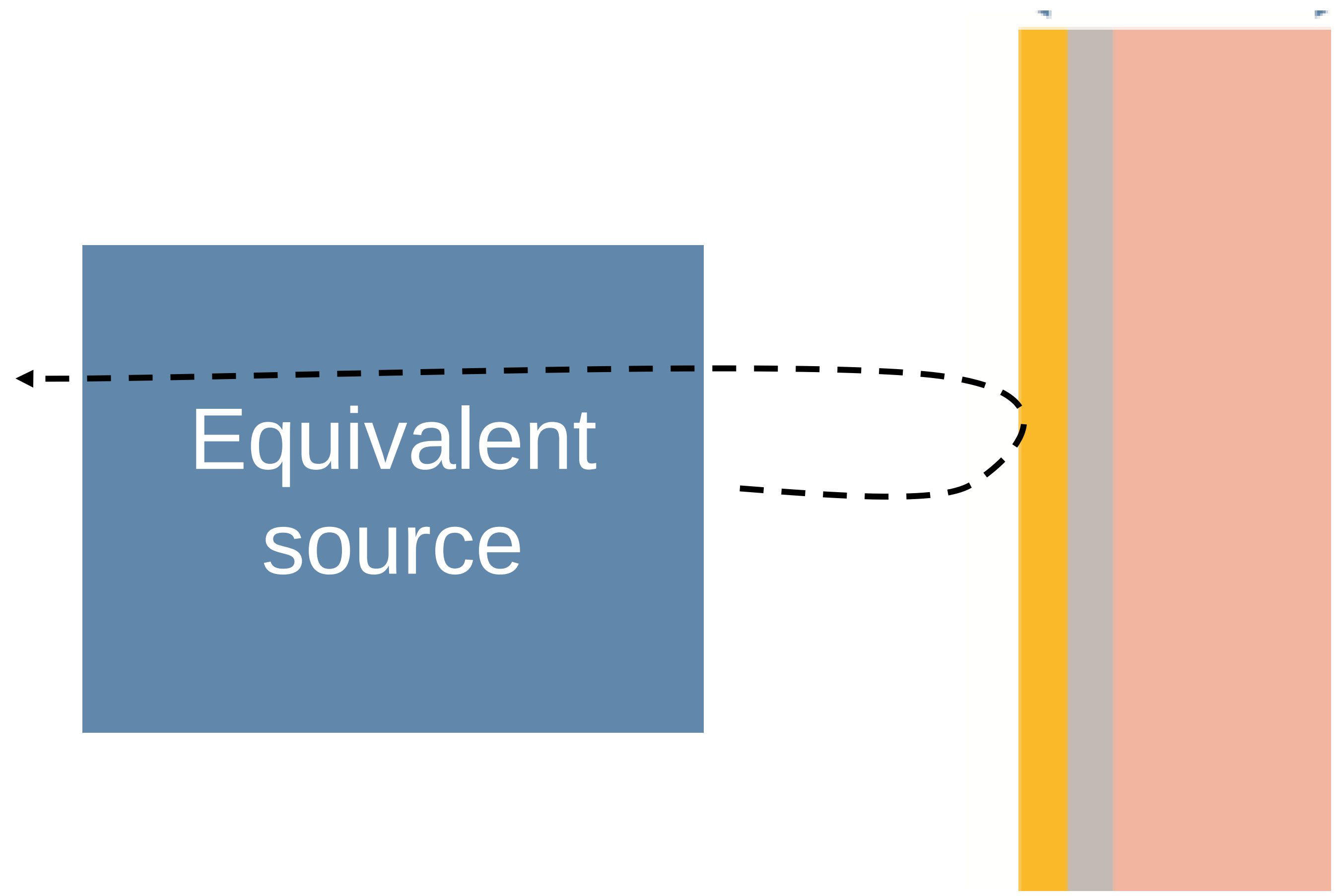
Equivalent source box

AN EQUIVALENT RADIATION SOURCE

- The equivalent source created by FIAFTA is only *equivalent* to the DUT with respect to its **radiation** properties not its **scattering** properties: we call it a **non-reflective digital twin**



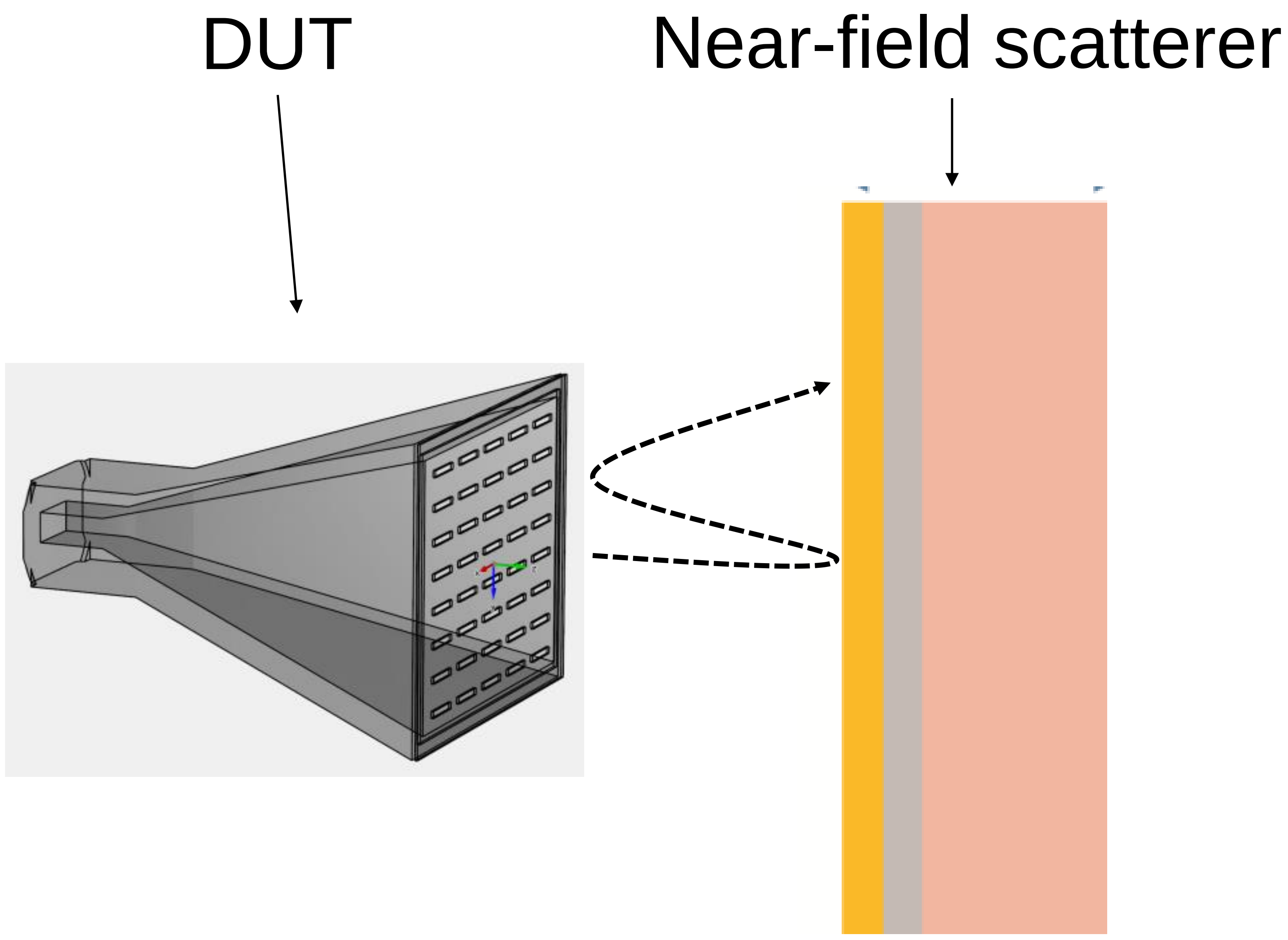
Actual scenario



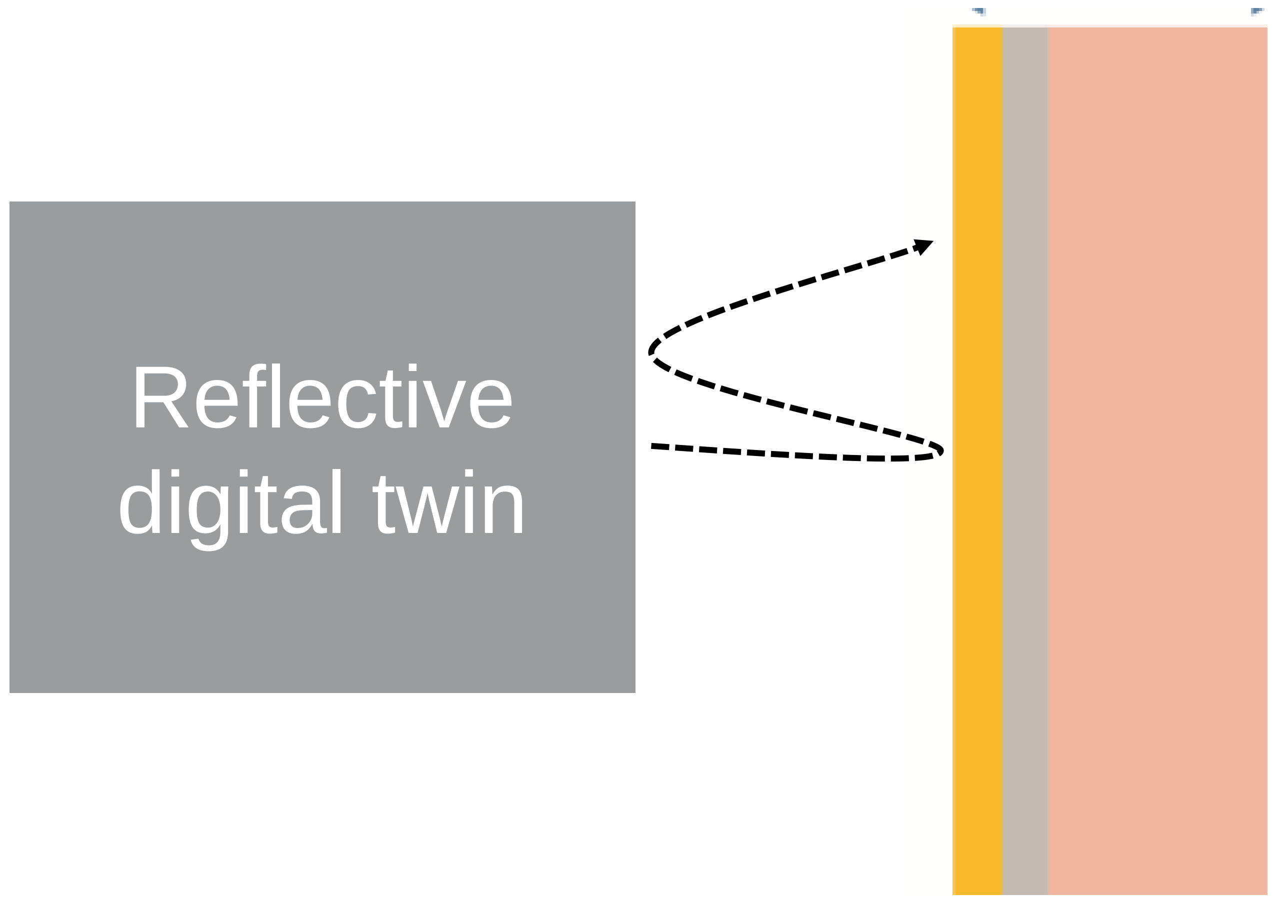
Approximate scenario with source replaced by its radiative non-reflective equivalent

AN EQUIVALENT RADIATION AND SCATTERING MODEL

- The Love condition allows to control scattering properties independently from radiation properties
- Scattering properties can be applied in the FWEM software on a surface encompassed in the FIAFTA reconstruction surface to create a **reflective digital twin**



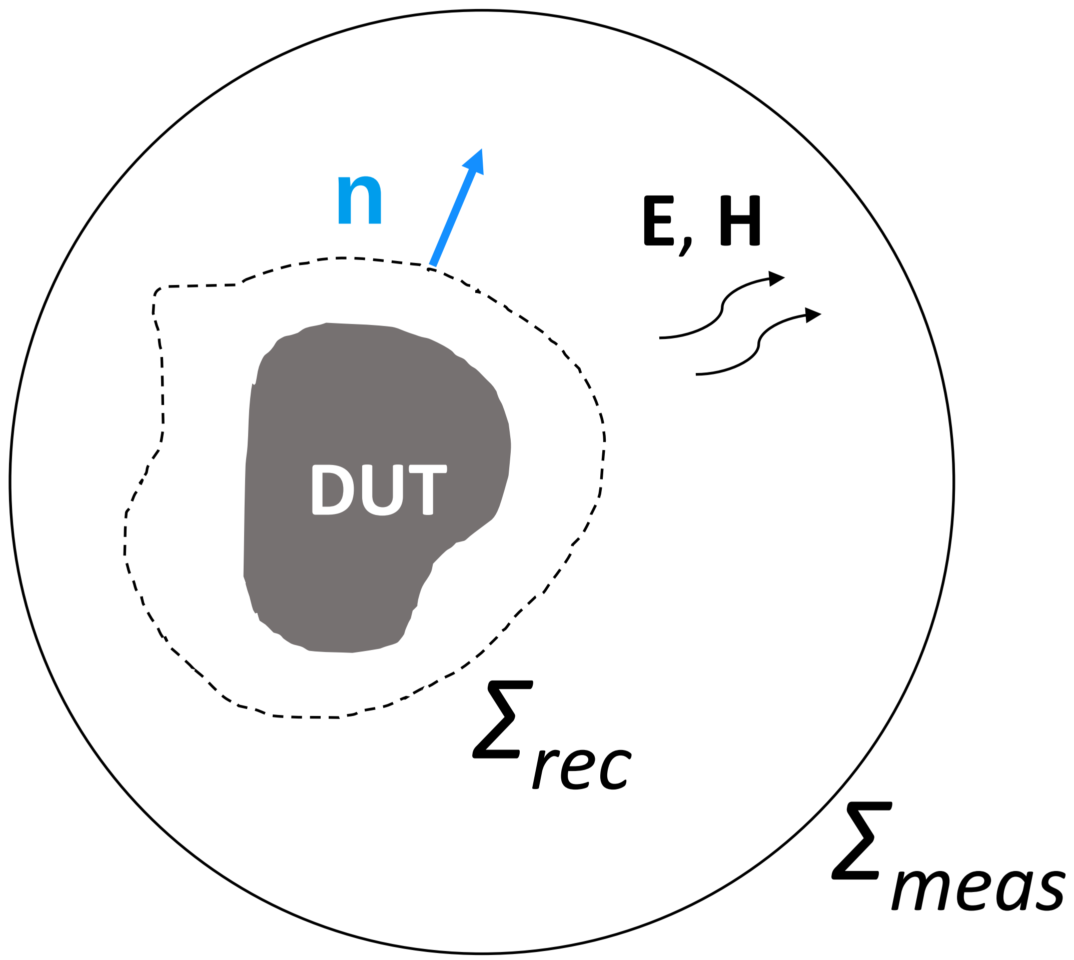
Actual scenario



Approximate scenario with source replaced by its reflective digital twin

POWER NORMALIZATION IN A SIMULATION-AUGMENTED MEASUREMENT

- In measurements and simulations, evaluating the power applied and accepted by the antenna is straightforward
- What to do in combination of measurement and simulation?



- Time-average active power flow calculated from the Poynting vector

$$S_n = \frac{1}{2}\mathrm{Re}\left\{\mathbf{E} \times \mathbf{H}^* \cdot \mathbf{n}\right\}$$

- The total power crossing the equivalent surface is normalized to the measured total radiated power (TRP)

$$P_{tot} = \iint_{\Sigma_{rec}} S_n \, d\Sigma = \iint_{\Sigma_{meas}} S_n \, d\Sigma$$

D. Schaefer et al. , "Power Normalization for Over the Air Augmented Exposure Assessment," 2024 GeMiC.

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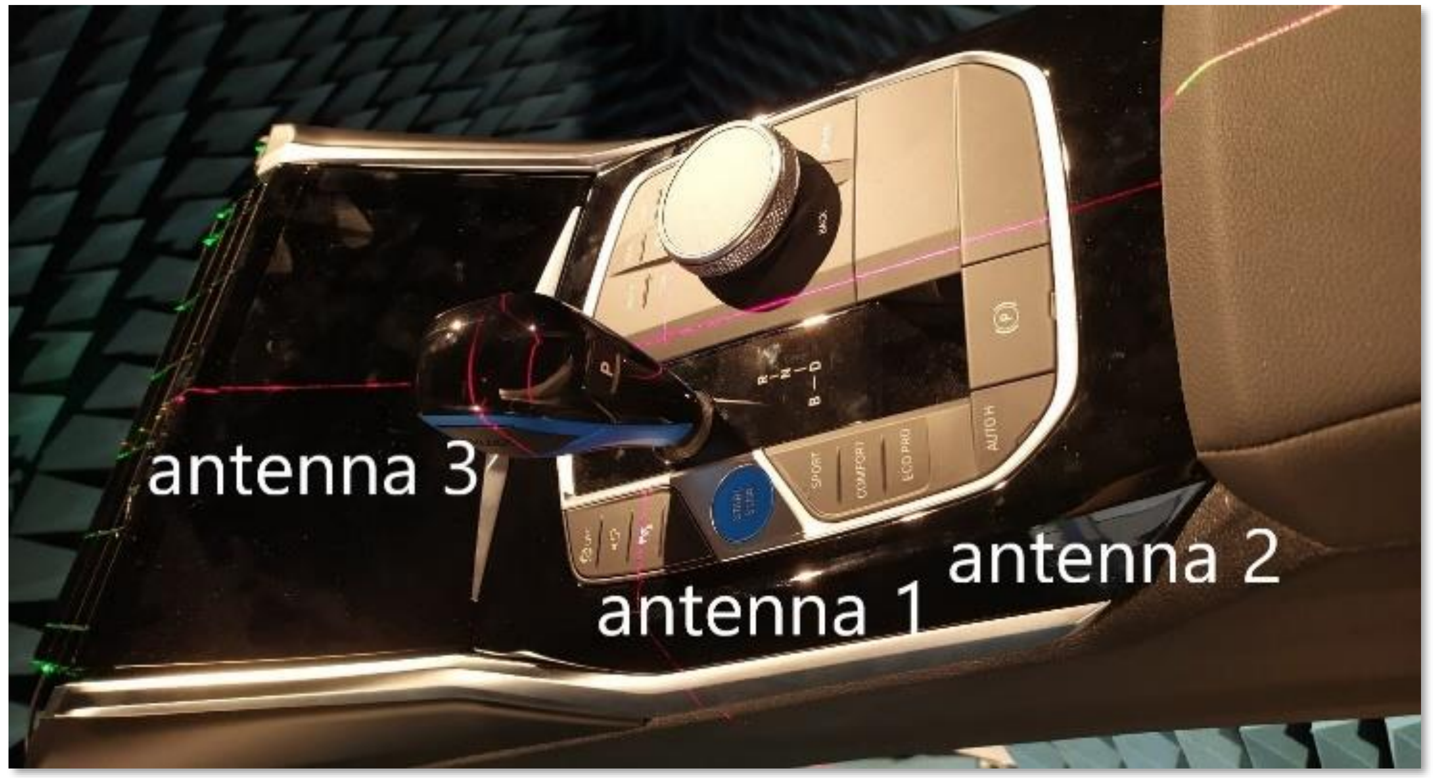
APPLICATION 1: AUTOMOTIVE WIFI / BT ANTENNAS INTEGRATION



- **Objective:** determine the best antenna positions and operating frequencies for achieving an optimal in-car connectivity performance

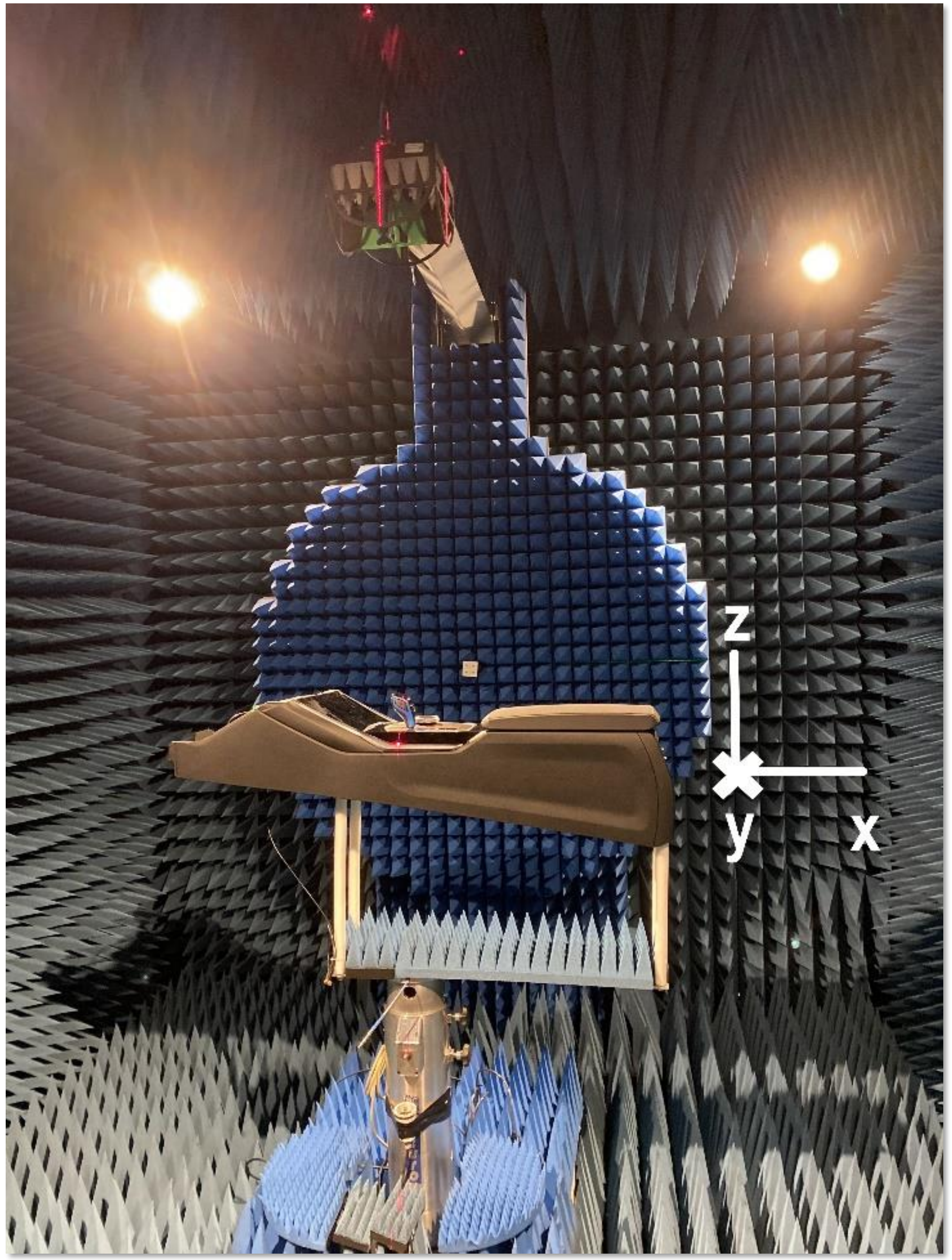
- **Challenges:**
  - Impossible to measure such effects by probing inside the car in various possible interior and loading configurations
  - Numerical modeling works but is limited by the knowledge of the objects to simulate

ROHDE&SCHWARZ IMST BMW GROUP MINI ROLLS-ROYCE MOTOR CARS LTD

B. Derat et al., "Optimization of In-Vehicle Connectivity through Simulation-Augmented Antenna Measurements," 2022 Antenna Measurement Techniques Association Symposium (AMTA)

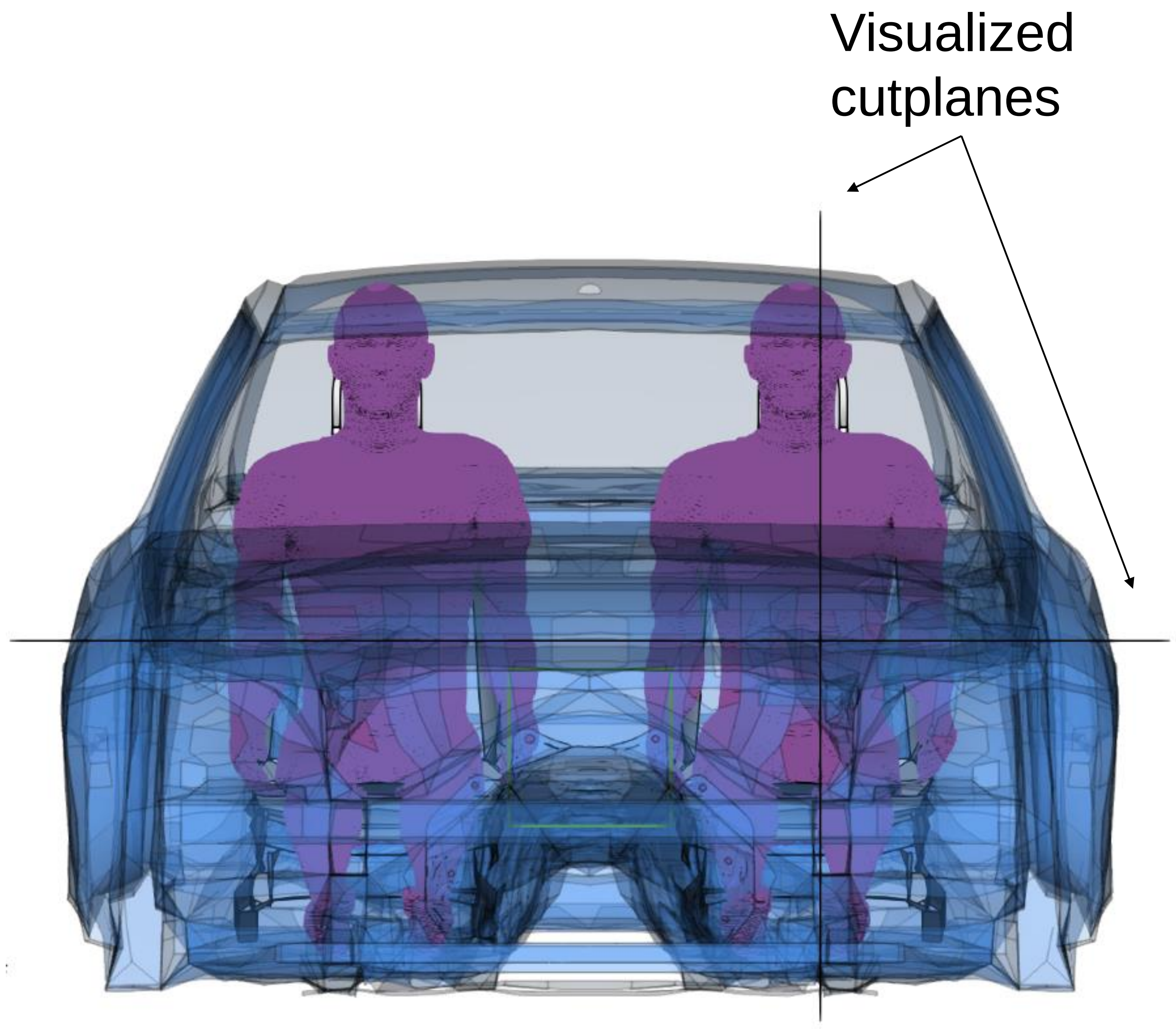
MIDDLE CONSOLE MEASUREMENTS

- Full console as DUT with 3 integrated antennas
- Measured with spherical scanning system and VNA (2 deg sampling rate)
- Benefits of considering the full console as DUT
  - Accounting more precisely for very near-field interactions
  - RF cables are routed in the same way as in the vehicle



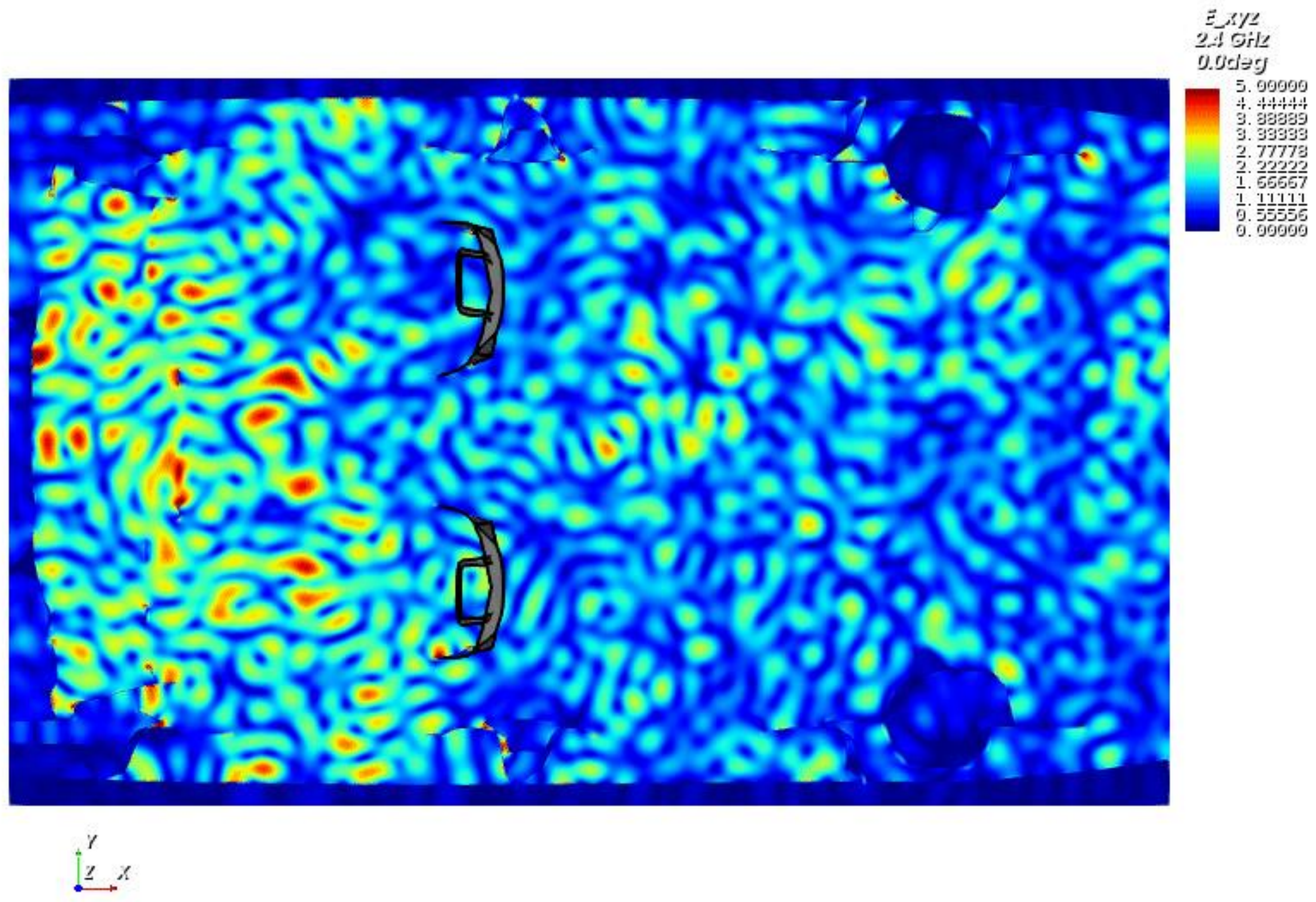
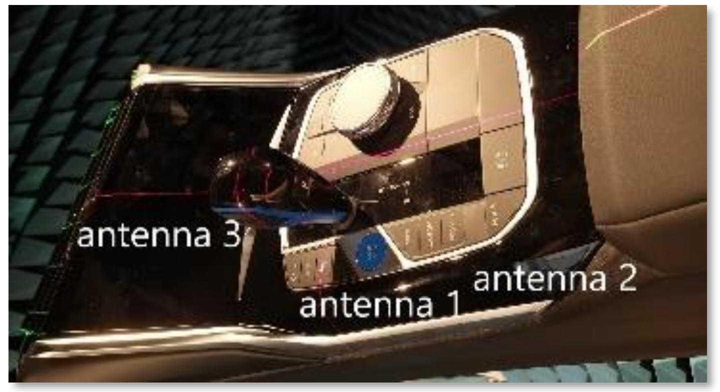
COMPUTATIONAL MODEL

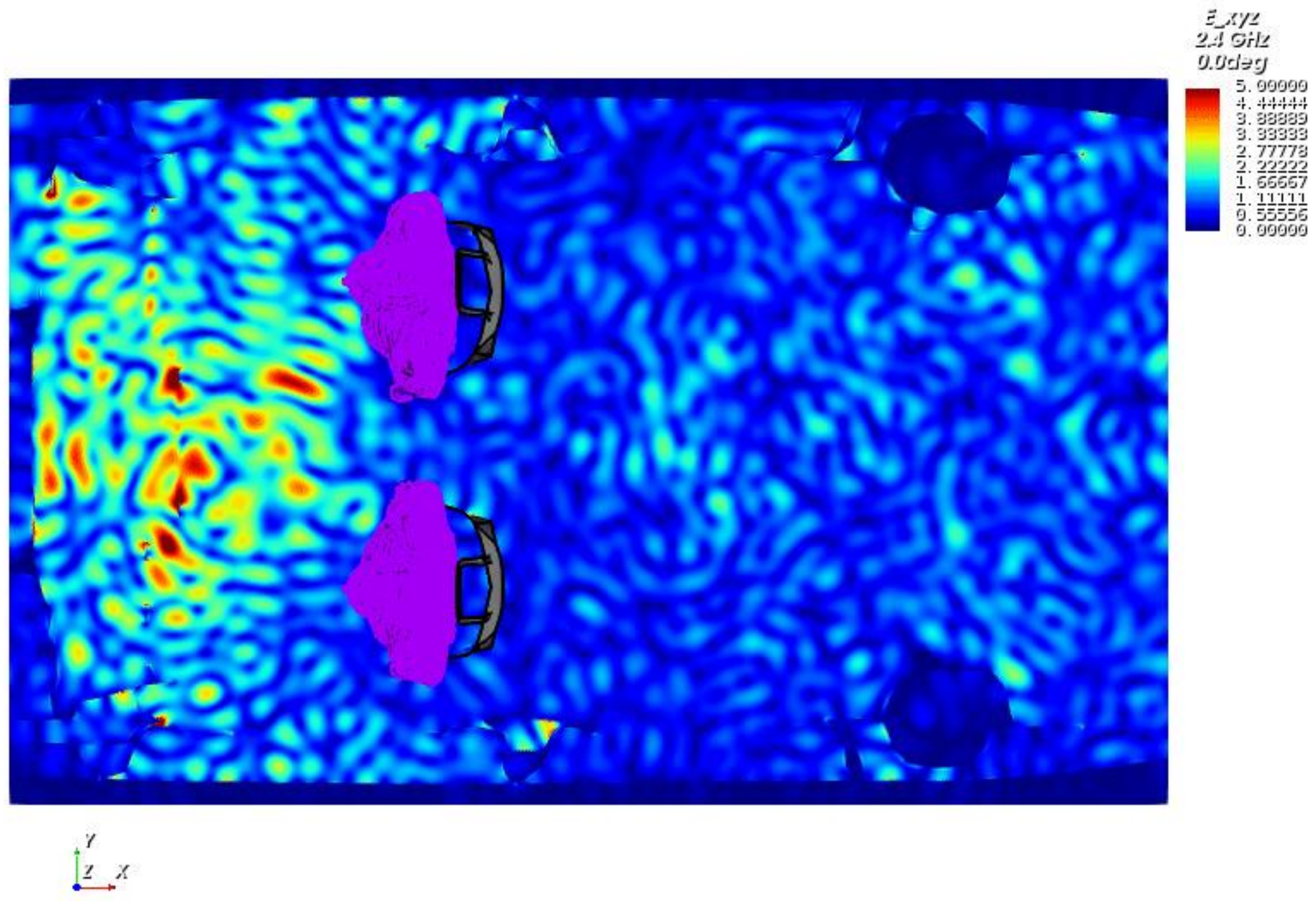
- Middle-console replaced by equivalent source box
- Two conditions: empty car, or with driver and front passenger
- Posed anatomical human models (ca. 50 body tissues)
- 350 MCells (2.5 to 3.5 mm size) computed in less than 30 min with less than 30 GB memory usage: **equivalent source approach can reduce by a factor 10+ the size and time of the computation**



IN-VEHICLE FIELD DISTRIBUTION ANTENNA 1 / 2.4 GHZ

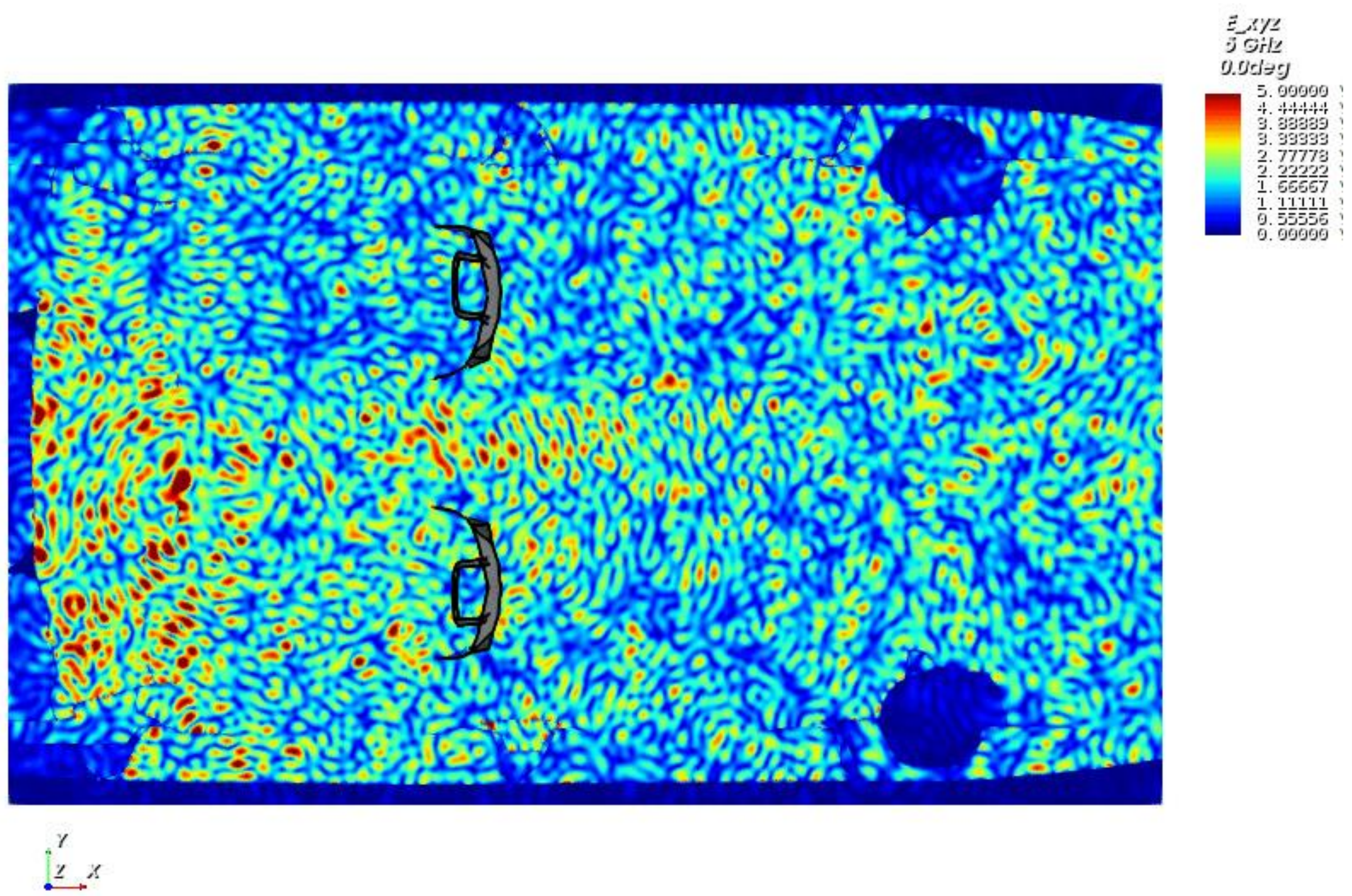
- Magnitude E-field distributions: linear scales 0 to 5 V/m
- Unloaded field distribution shows higher amplitudes at the front, with larger amount of energy towards the driver
- Due to antenna location and main directions of radiation: significant power decay towards the second row

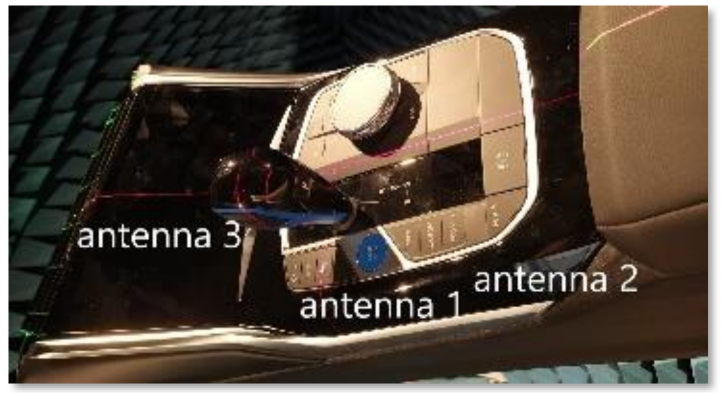



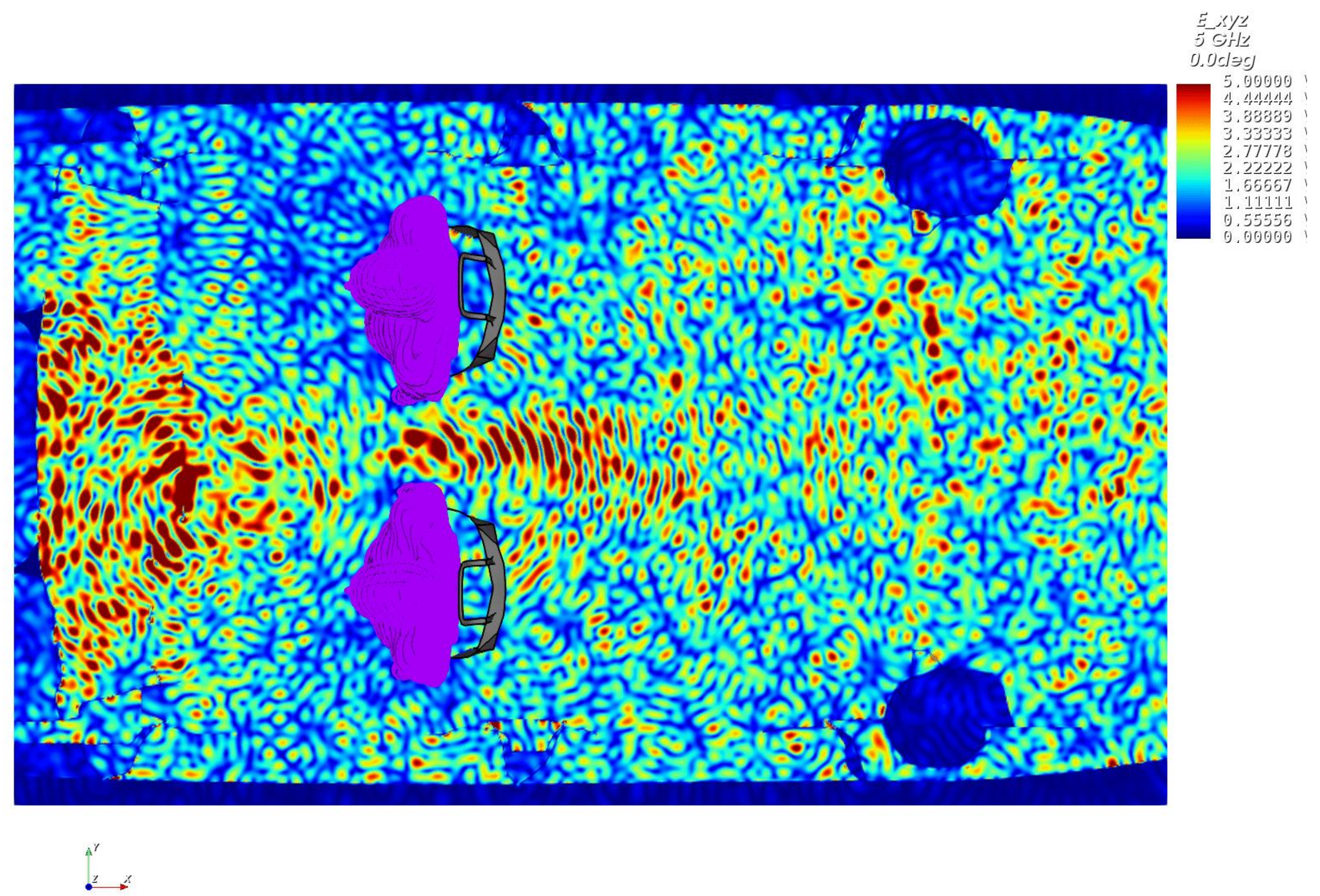


IN-VEHICLE FIELD DISTRIBUTION
ANTENNA 2 / 5 GHZ

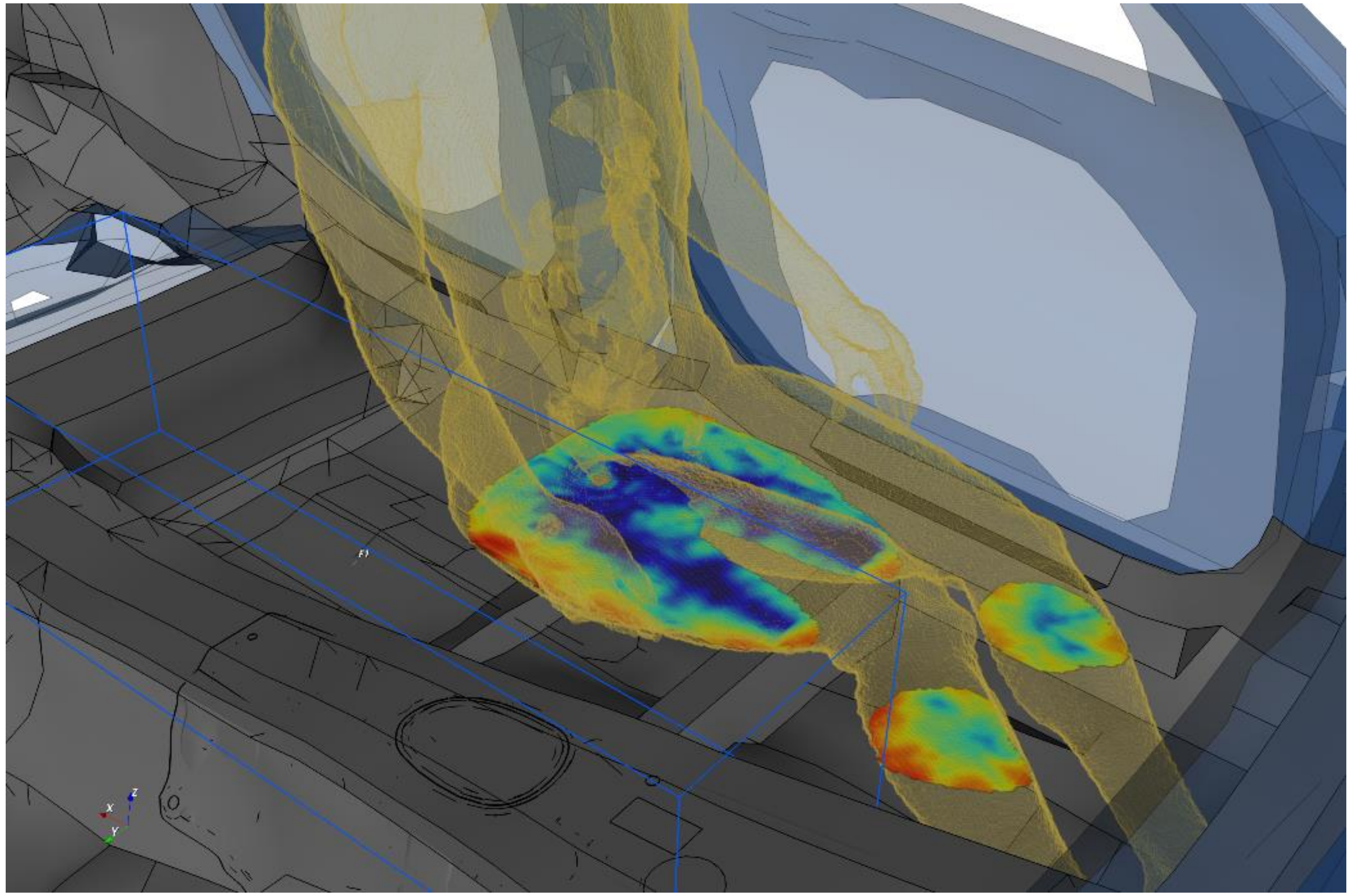
- Magnitude E-field distributions: linear scales 0 to 5 V/m
- Antenna 2 being more central in the middle console, and having a radiation towards the back at 5 GHz (in-between the front seats): influence of front row is reduced

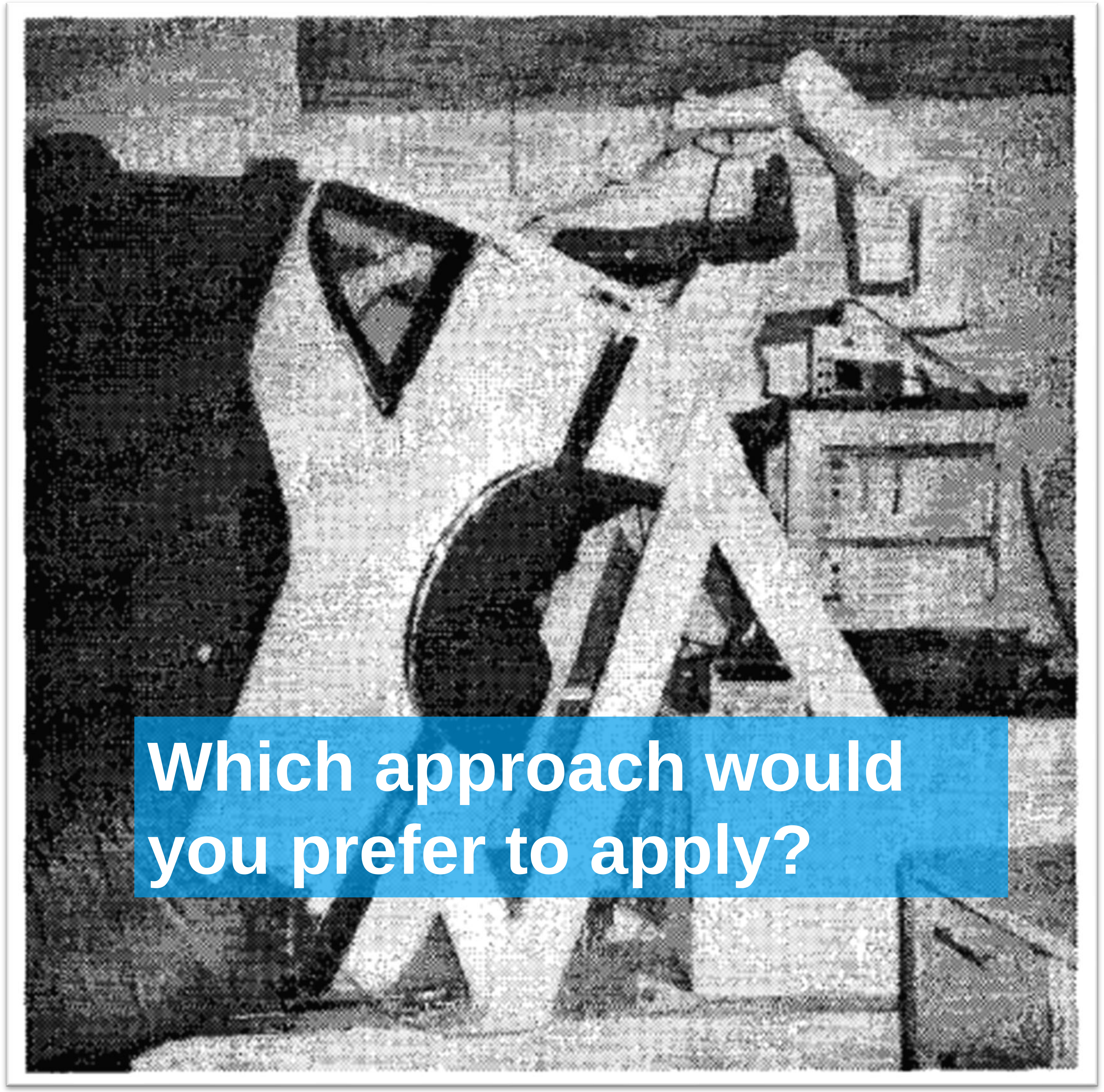






SAR EVALUATION ASPECTS

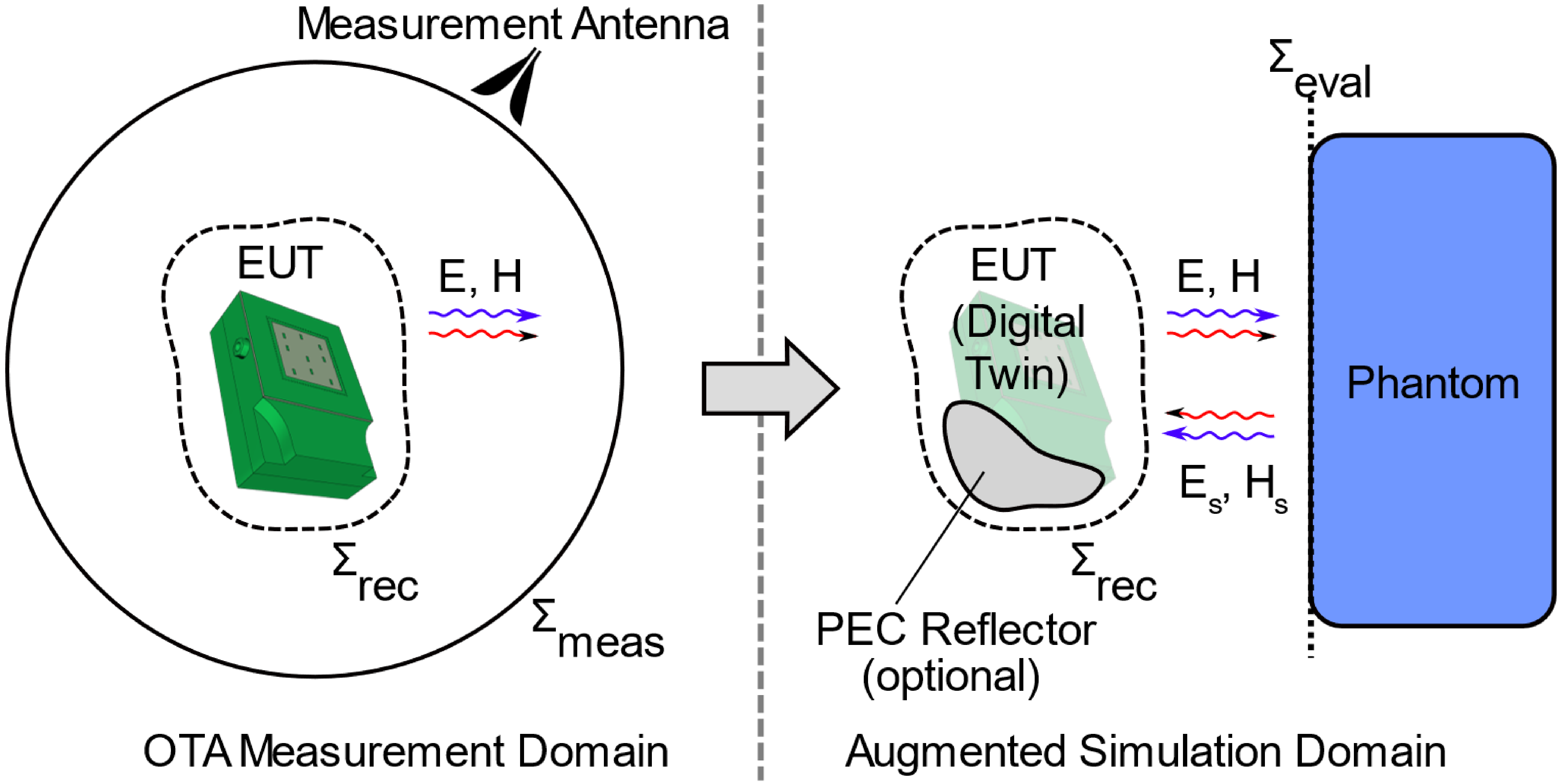




APPLICATION 2: EMF – ABSORBED POWER DENSITY EVALUATIONS FOR MOBILE PHONES AND BASE STATIONS

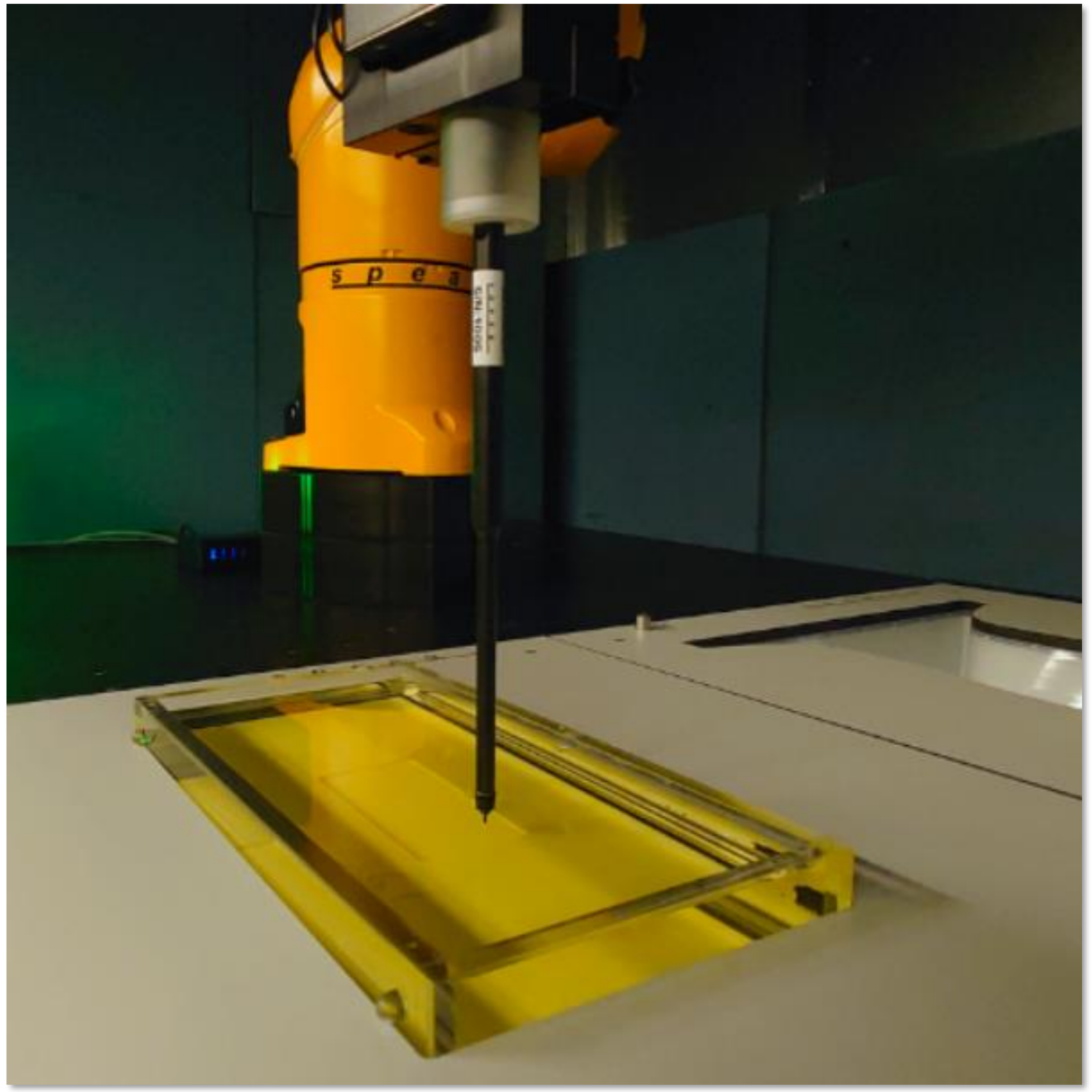
- Wireless manufacturers must ensure that their products comply with applicable regulatory human exposure limits (**EMF compliance**)
- Above 10 GHz, EMF compliance of user equipment (UE) and radio base stations (RBS) is determined from near-field free-space **incident power density measurements (IPD)**
- In 2020, the ICNIRP issued a revision of its guideline changing the basic restrictions from free-space IPD to **absorbed power density (APD)** in epithelial tissues
- APD evaluations at such frequencies raise major challenges, e.g. test time and dynamic range (20 dB attenuation after 2 mm of propagation in the skin at 30 GHz)

SIMULATION-AUGMENTED OTA APPROACH TO IPD AND APD



B. Derat, T. Liebig, D. Schaefer, M. Celik and W. Simon, "Absorbed Power Density Assessment Using Simulation-Augmented Over-the-Air Measurement," in IEEE Access, vol. 12, pp. 28122-28140, 2024.

APD MEASUREMENT APPROACHES

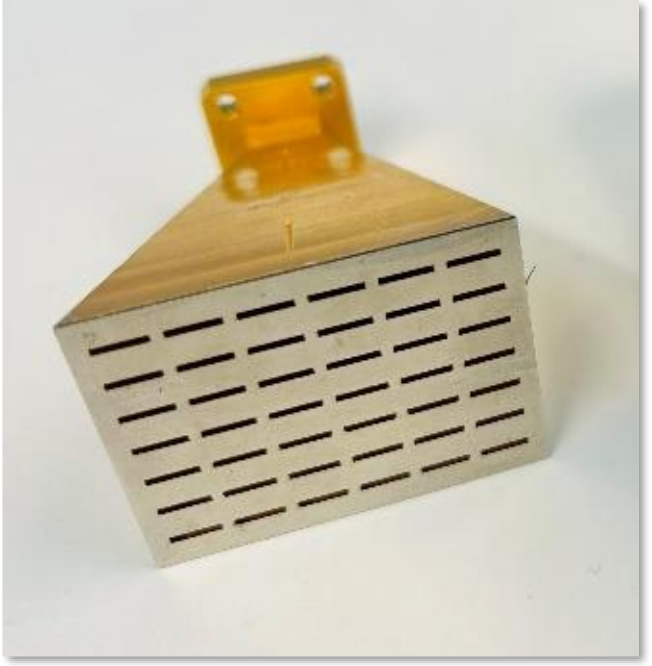


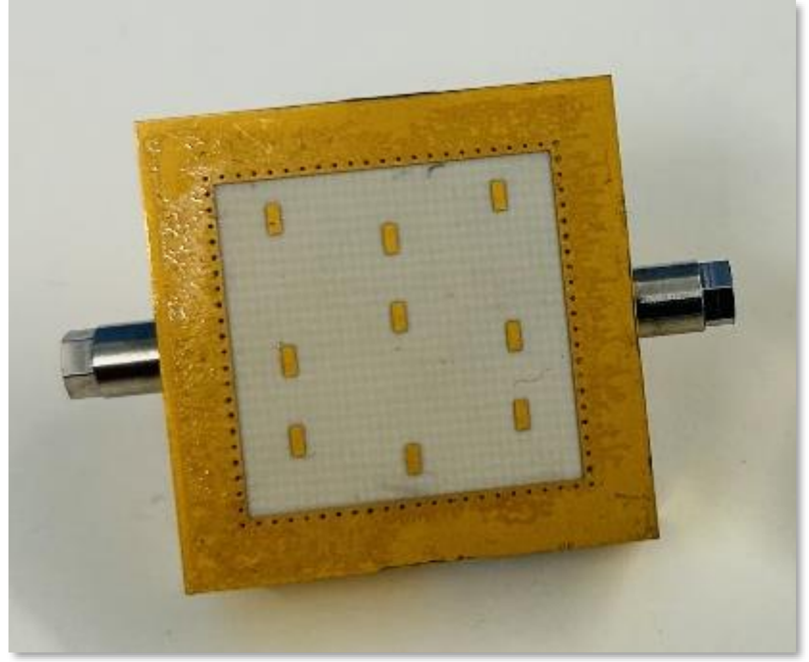
State-of-the-art

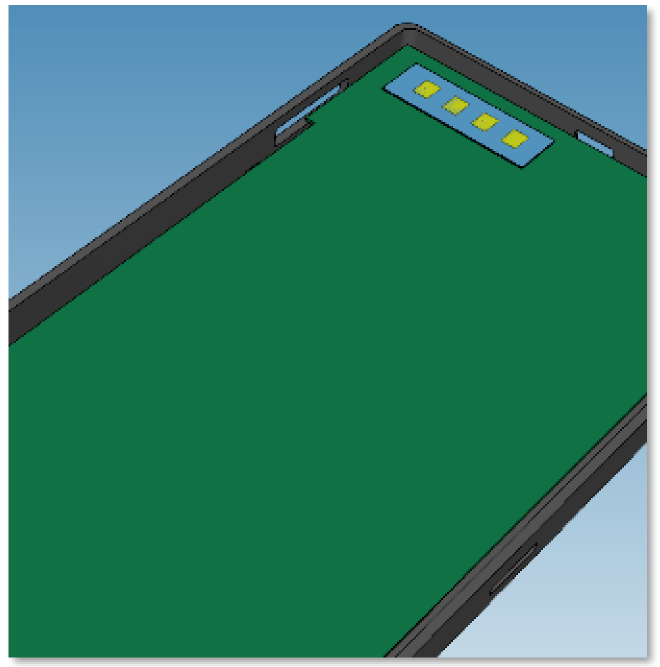
Simulation-augmented measurements

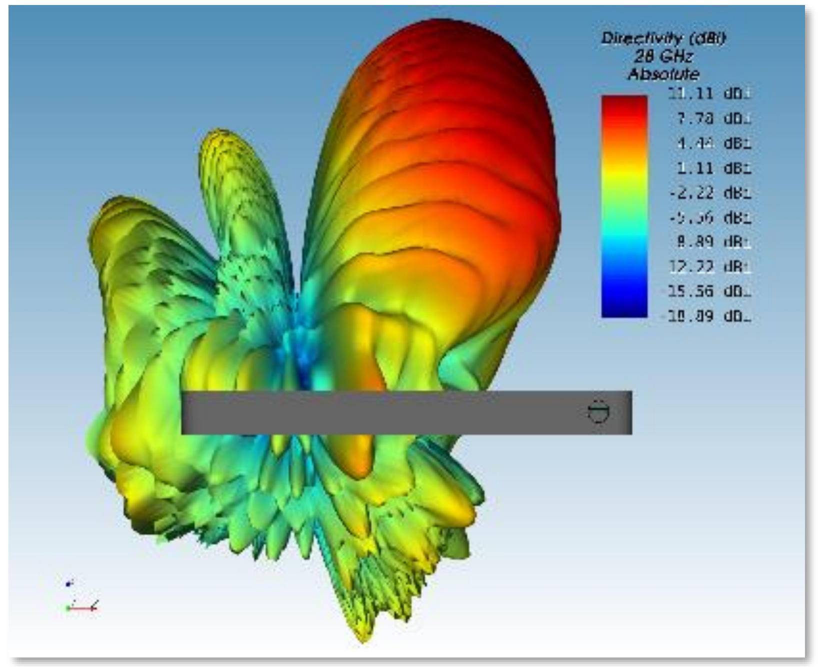
REFERENCE SOURCES USED FOR VALIDATING THE TECHNIQUE

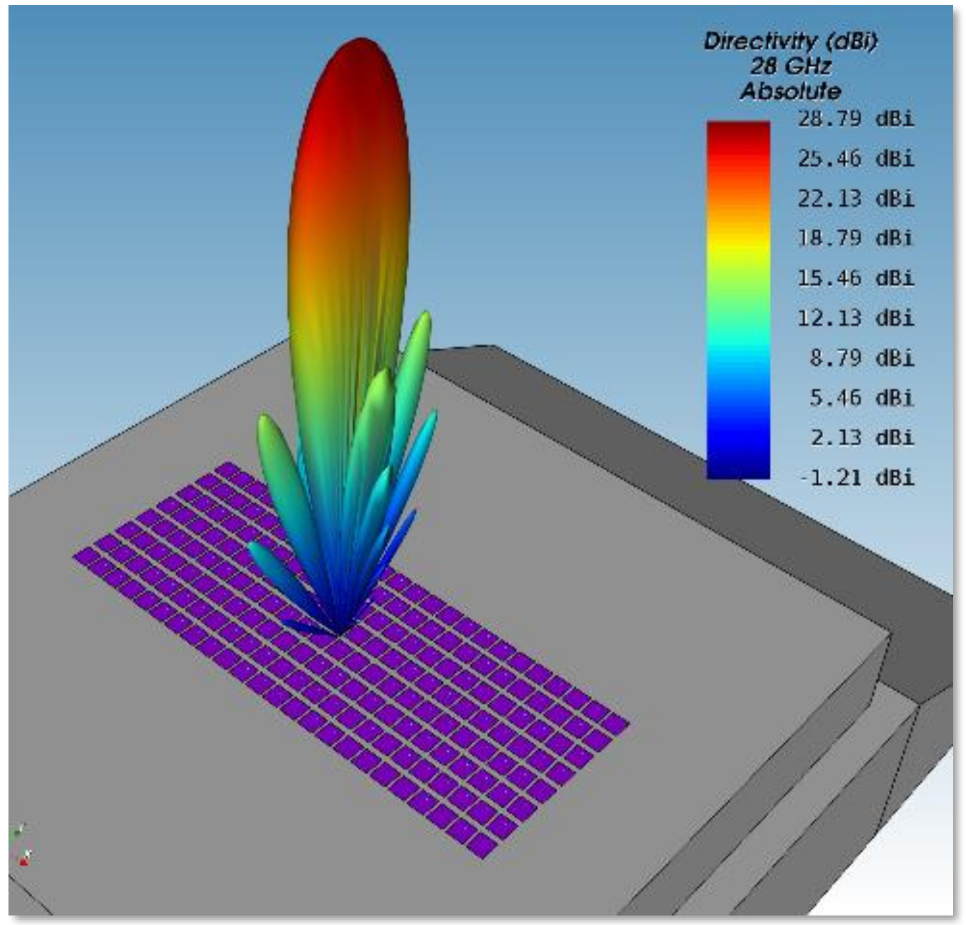
- ► IEC / IEEE 63195 validation antennas at 30 and 60 GHz (simulated and measured)
- ► Mobile device model at 28 GHz with 4x1 patch array and two beam settings
- ► RBS model at 28 GHz with 24x8 patch array and two beam settings



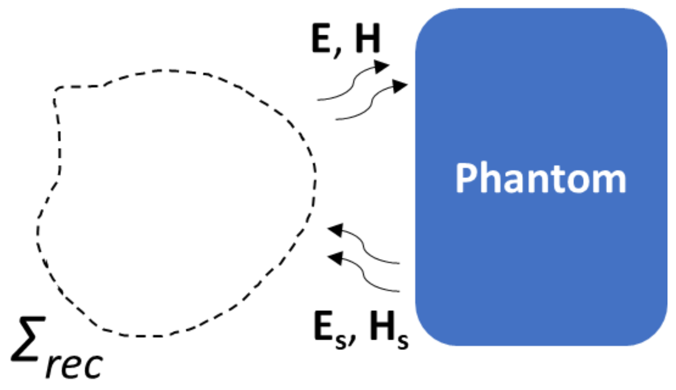






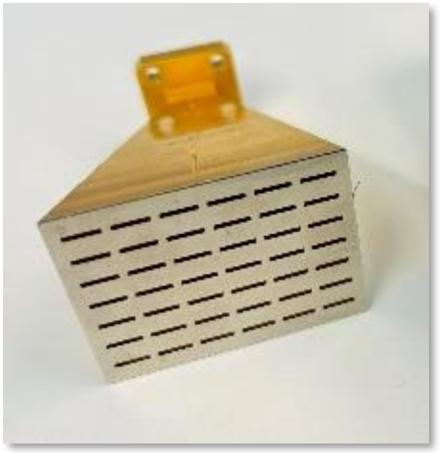


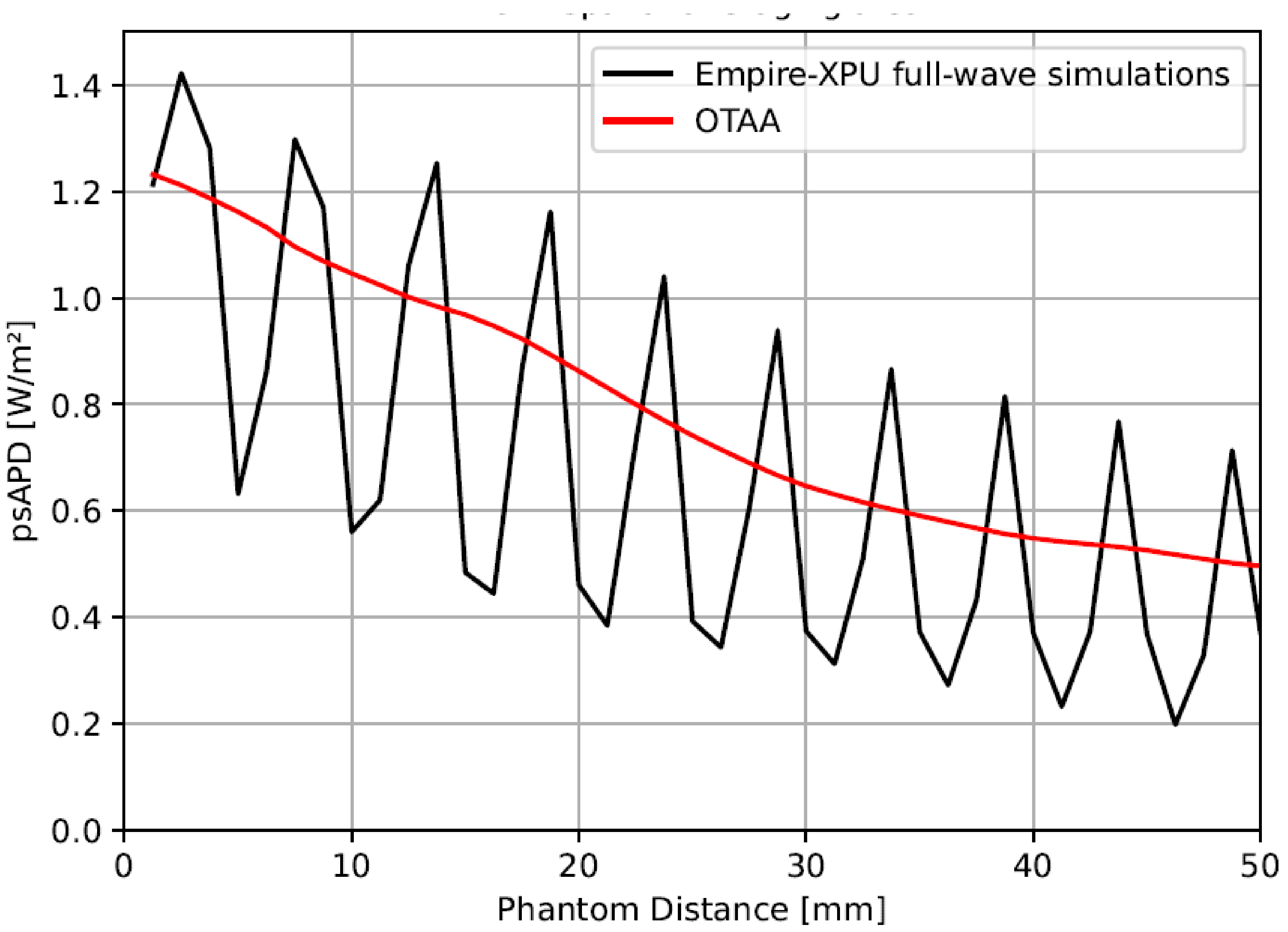
APD RESULTS COMPARISON NON-REFLECTIVE DIGITAL TWIN



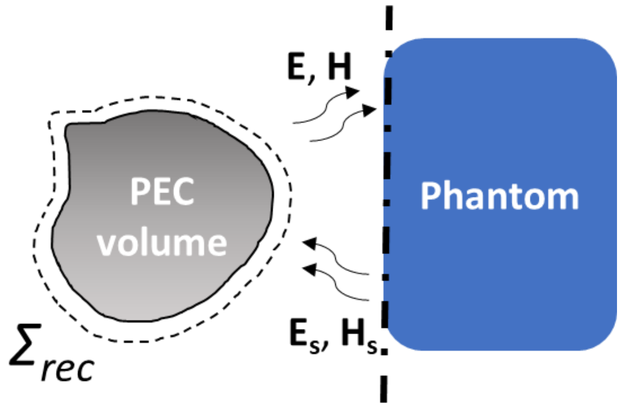
► The OTAA approach gives the trend, yet standing-wave effects are not identified as the equivalent source is a radiation model and does not scatter

4 cm^2-square averaging



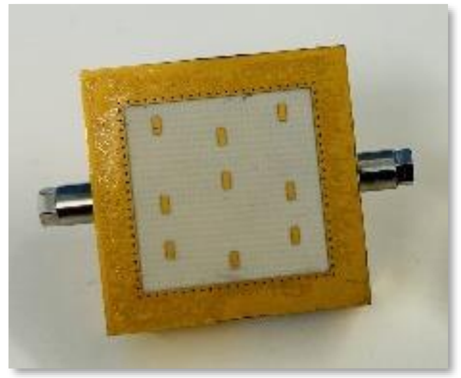


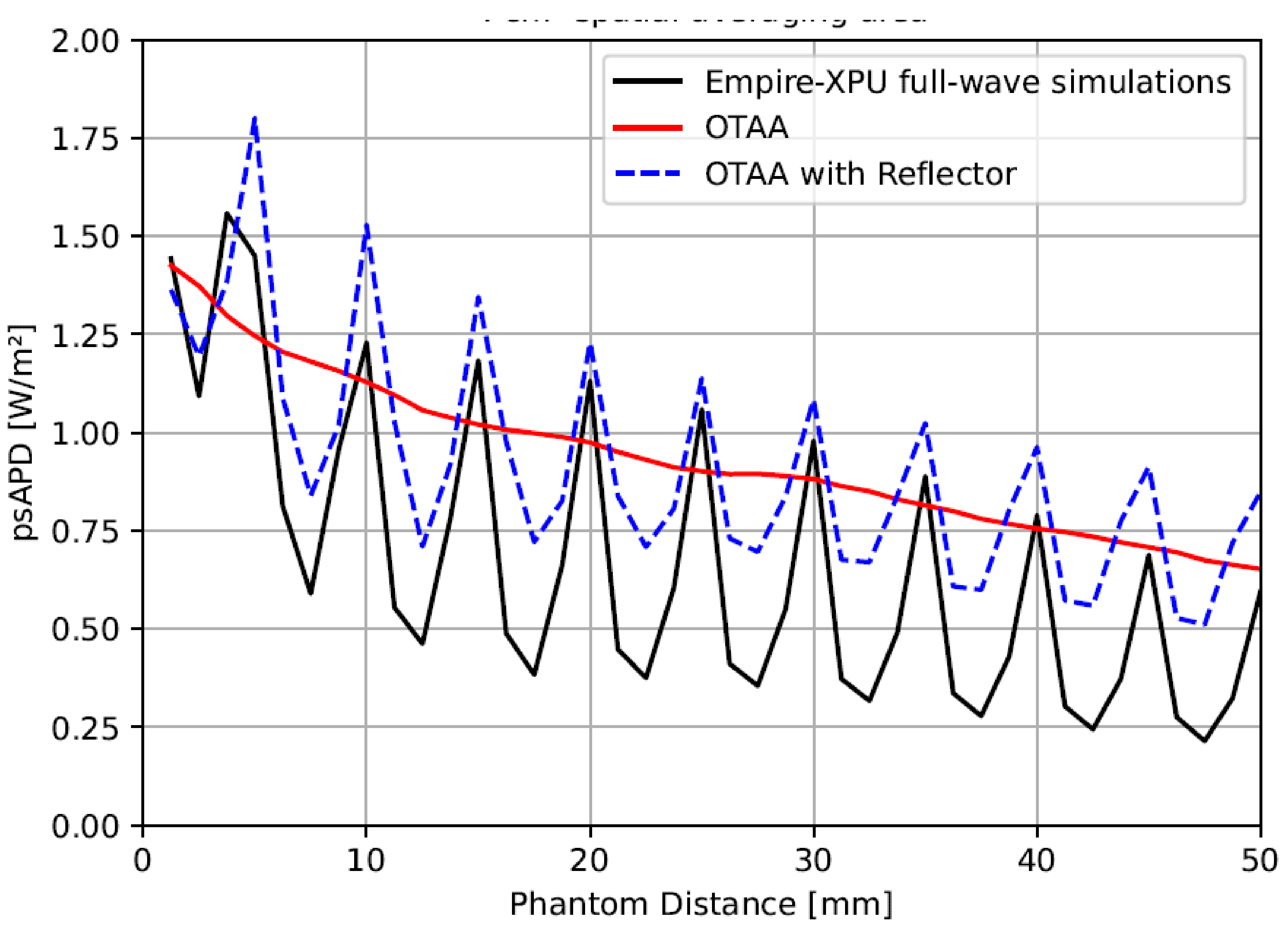
APD RESULTS COMPARISON REFLECTIVE DIGITAL TWIN



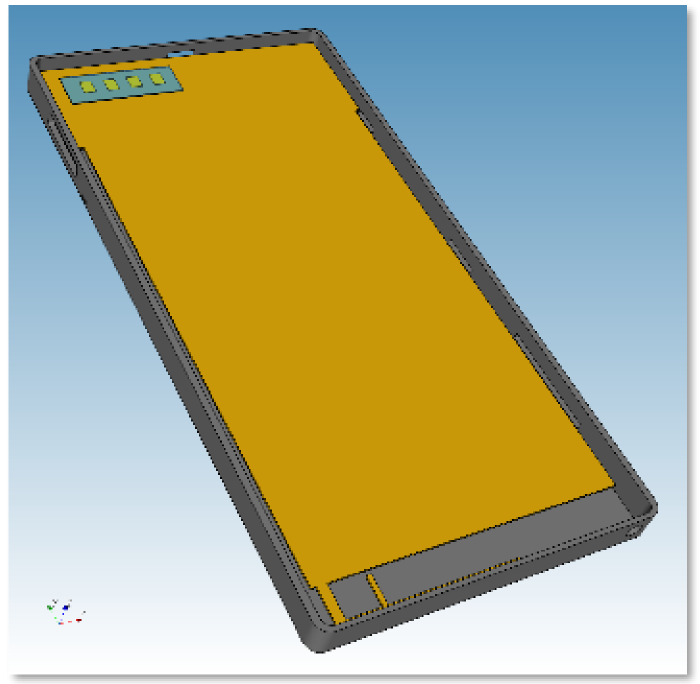
► Standing-wave effects are recovered in a rather conservative fashion

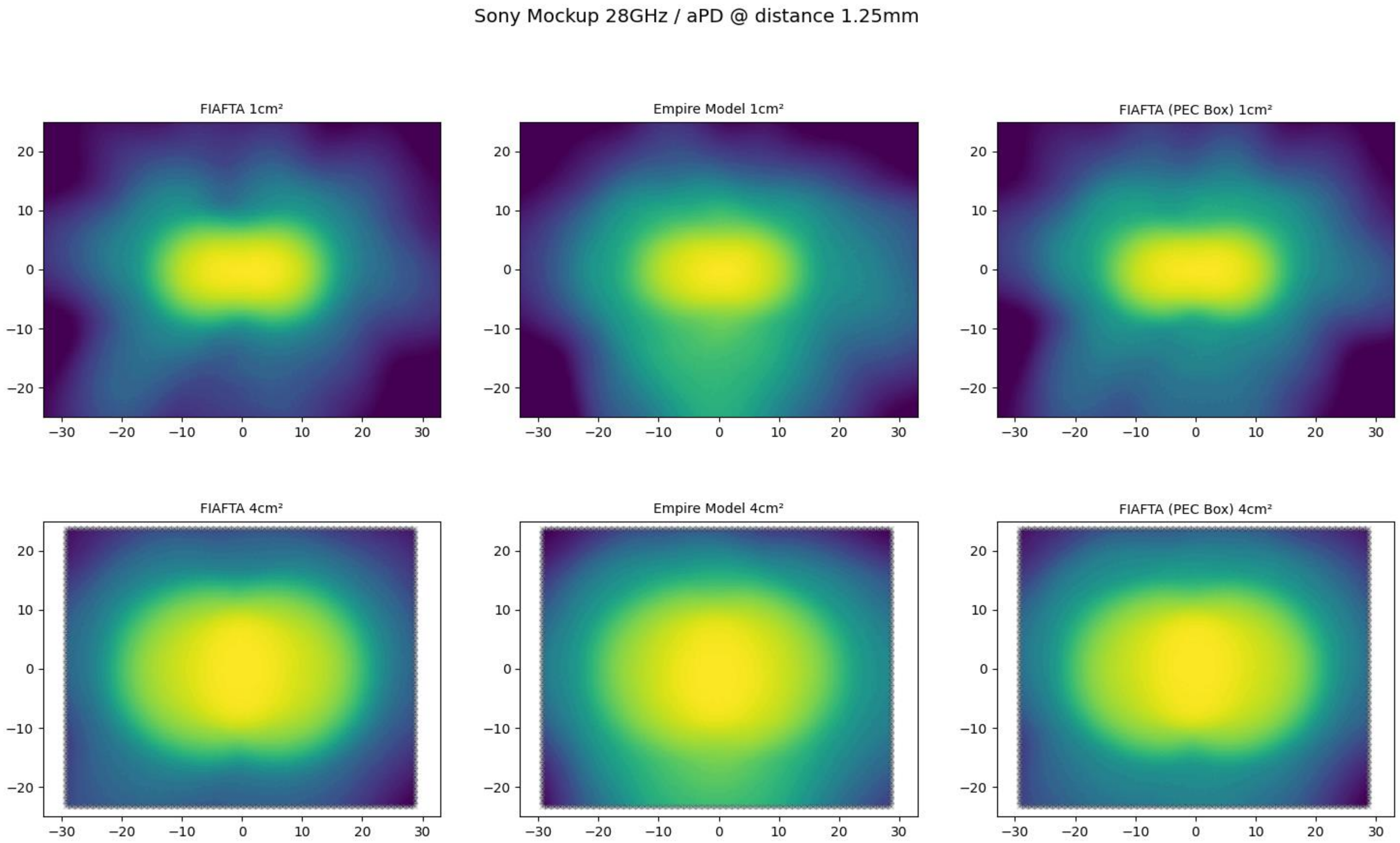
4 cm²-square averaging





EXAMPLE APD DISTRIBUTION COMPARISON





1 cm^2 averaging

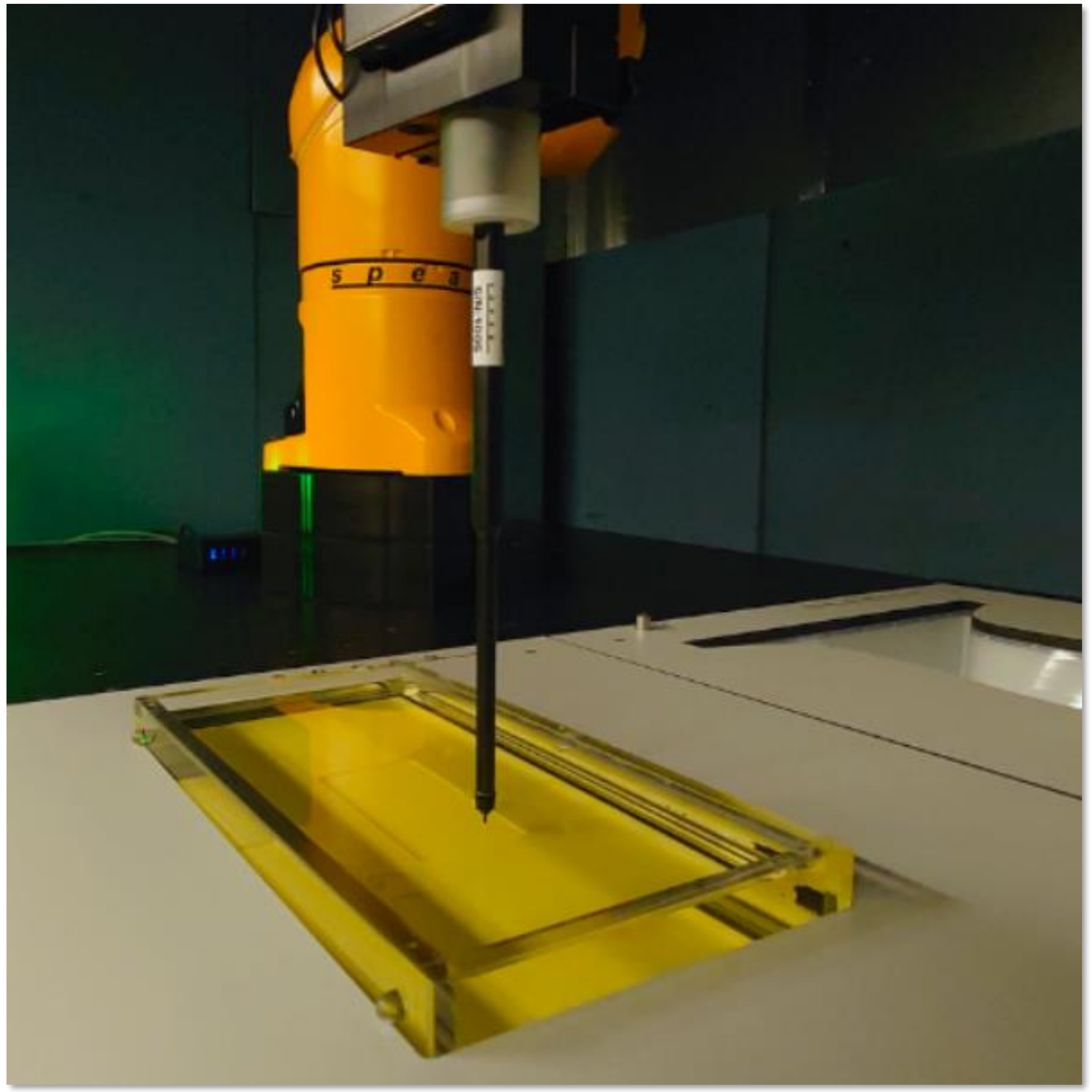
4 cm^2 averaging

OTAA non-reflective

Full-wave reference

OTAA reflective

SAVING MEASUREMENT TIME



8 cm x 8 cm scan grid, with $\lambda/4$ step size **– 2.5 hours test time, 1 DUT facet**

54 mm antenna at 30 GHz – evaluation plane 2 mm

OTAA: 6 deg AZ and EL sampling down to 162 deg in EL **– 4 min test time, 5 DUT facets**

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CONCLUSION

- Antennas couple and interfere with their nearby environment, and *in situ* assessments (e.g. antenna as integrated) are necessary to take the right decisions
- Electromagnetic field and antenna characterizations in real world scenarii can be a challenge
- Simulation is an alternative in such case, but is limited by the knowledge of the DUT
- The antenna digital twin / simulation-augmented antenna measurement approach provides another powerful tool combining the strengths of both the experimental and numerical domains
- The application of this technique demonstrated to provide relevant and even accurate results, along with positive outlook on associated measurement and computational times
- No characterization technique is perfect and whether the digital twin approach is the best for a given application shall be decided based on thorough measurement uncertainty analysis

Virtual Worlds
for Real Life

THANK YOU FOR YOUR INTEREST