FULL-VEHICLE ANTENNA AND OVER-THE-AIR TESTING A MUST FOR ENABLING RELIABLE AUTOMOTIVE CONNECTIVITY

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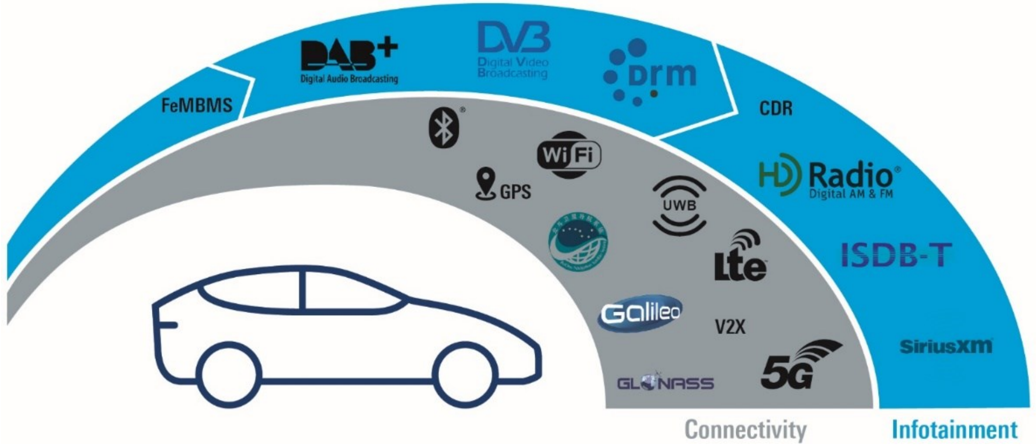
ROHDE&SCHWARZ

Make ideas real

INTRODUCTION

- Modern vehicles feature a multitude of antennas and wireless technologies
  - Satellite navigation
  - Wi-Fi
  - UWB
  - Cellular services



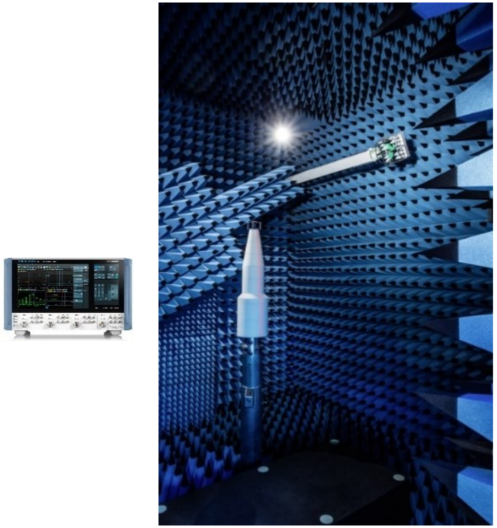
- Antenna performance evaluation requires far-field (FF) measurements in fully anechoic chambers (FAC)

- The car structure, material and antenna placement influence the radiated performance, what justifies a growing demand for full-vehicle antenna test (FVAT) systems

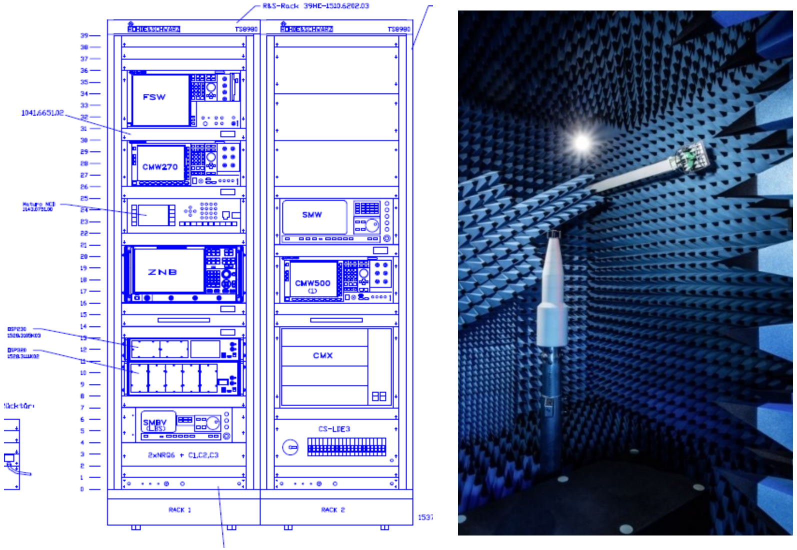
- As the performance of communication systems cannot be straightforwardly assessed anymore without the antenna, FVAT facilities are also required to integrate over-the-air (OTA) measurement capabilities

ANTENNA MEASUREMENT VS. OTA TESTING

- ► Antenna measurement: evaluation of fundamental antenna radiation properties
- ► OTA: assessment of the transceiver performance, including the antenna pattern



Antenna testing system



OTA testing system

2G / 3G / 4G / 5G NR FR1, WLAN and A-GNSS

SPECIFICITIES OF OTA TESTING

- ► No cable access to the DUT
- ► Wideband modulated signals with complex waveforms
- ► DUT Tx / Rx RF chains are different
- ► DUT controlled via signaling / communication tester
- ► Measurement of system parameters (EIRP, TRP, EIS, TIS, ACLR, EVM…)
- ► Dynamic capabilities of the DUT to support maximum link quality
  - – TAS: transmit antenna switch
  - – Beam-steering for 5G NR FR2

EIRP: Equivalent Isotropic Radiated Power

$$EIRP(\theta,\Phi) = G(\theta,\Phi) \cdot P_{Tx}$$

EIS: Equivalent Isotropic Sensitivity

$$EIS(\theta,\Phi) = G(\theta,\Phi) \cdot P_{REFSENS}$$

TRP: Total Radiated Power

$$TRP \cong \frac{\pi}{2NM} \sum_{i=1}^{N-1} \sum_{j=0}^{M-1} \left[EIRP_{\theta}(\theta_i, \phi_j) + EIRP_{\phi}(\theta_i, \phi_j) \right] \sin(\theta_i)$$

TIS: Total Isotropic Sensitivity

$$TIS \cong \frac{2NM}{\pi \sum_{i=1}^{N-1} \sum_{j=0}^{M-1} \left[\frac{1}{EIS_{\theta}(\theta_i, \phi_j)} + \frac{1}{EIS_{\phi}(\theta_i, \phi_j)} \right] \sin(\theta_i)}$$

STANDARDIZATION ACTIVITIES

5GAA

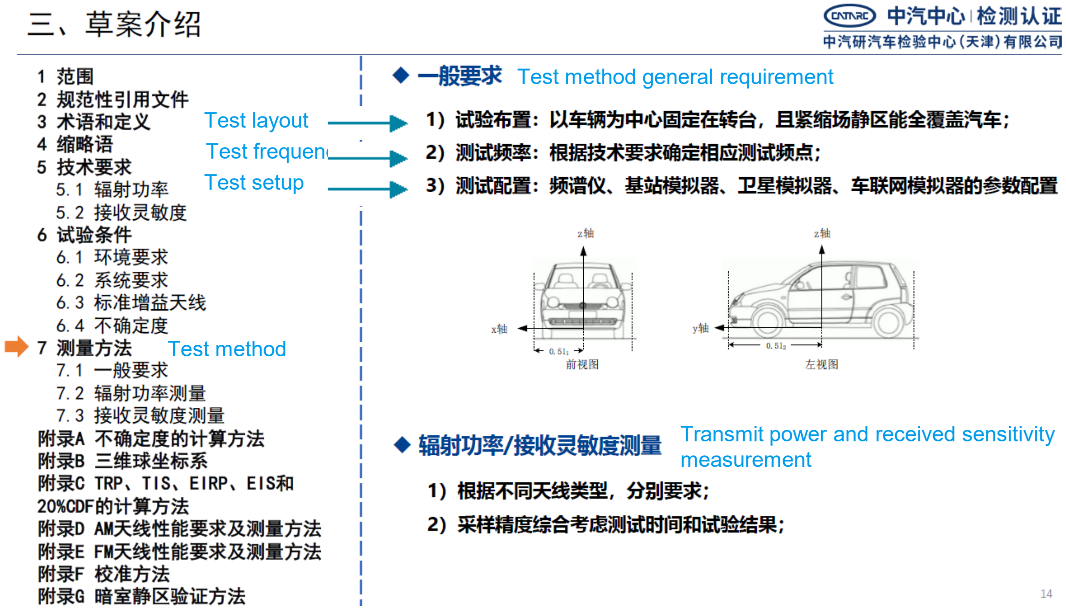
- Vehicular Antenna Test Methodology (VATM) Work Item running since end of 2019, under 5GAA WG3
- Scope:
  - Full Vehicle Testing
  - Only <7GHz technologies: 2G to 5G NR, V2X @ 5.9GHz and GNSS
  - High level guidance for testing and test sites
  - SISO only
- TR was expected to be published by end of January 2021, but has been delayed – target completion date: May 2021

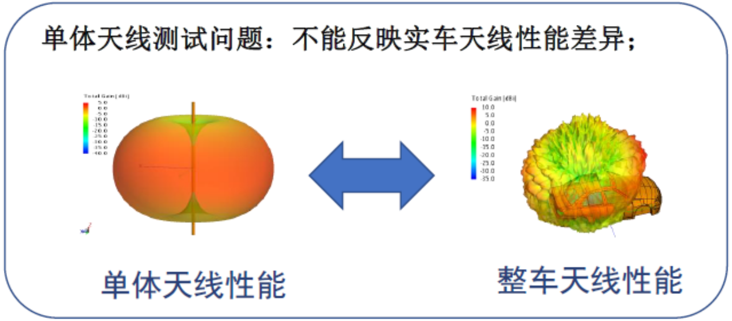
CTIA

- Discussion started in October 2018, focused on the test of automotive "shark fin" antennas
- Scope:
  - TRP/TIS measurements including the TCU (ECU, OCU, OBU…)
  - Standardized ground-plane
  - Re-use existing "CTIA chambers"
- 5GAA and CTIA OTA are in close communication and discussing on how to converge both methods: FVT and standardized ground-plane

CATARC (NTCAS)

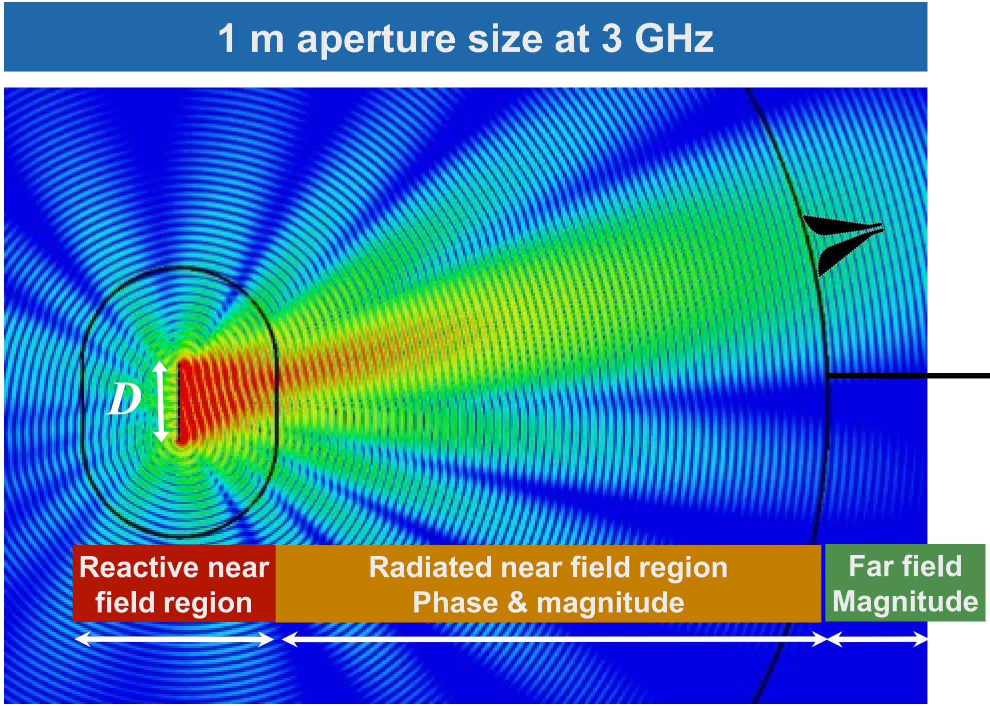
- China has ambitious plans on autonomous driving and usage of C-V2X for road safety
- FVAT and OTA are seen as cornerstones of the commercial C-V2X deployment
- Plan to finalize the standard within 3 years





FAR-FIELD TESTING METHODOLOGIES FOR FULL-VEHICLE

FAR-FIELD AND FRAUNHOFER DISTANCE



Fraunhofer distance

$$\frac{2D^2}{\lambda} = 20\,m$$

FAR-FIELD MEASUREMENT METHODOLOGIES

Reference method.
Full scope OTA.
Broadband.
Less than 2 angles of rotation at DUT possible.
Best adapted for FV.

Direct FF (DFF)

Indirect FF (IFF) - Hardware near-field transformation

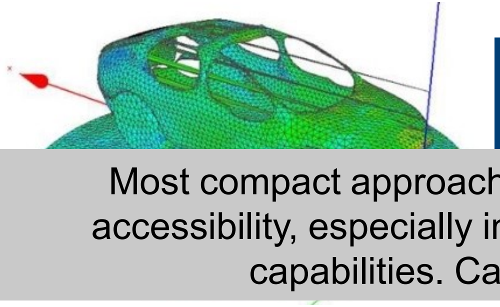
Full scope OTA.
The most compact OTA approach.
Narrow-band (typ. 1.6 to 5 GHz)
2 angles of rotation at DUT.

Plane-Wave Synthesis

Full scope OTA.
More compact than DFF, yet large at low frequencies.
Broadband.
Most expensive.
2 angles of rotation at DUT.

Compact Antenna Test Range

B. Derat et al., **Promises of near-field software and hardware transformations for 5G OTA**, IEEE CAMA, Sep. 2018

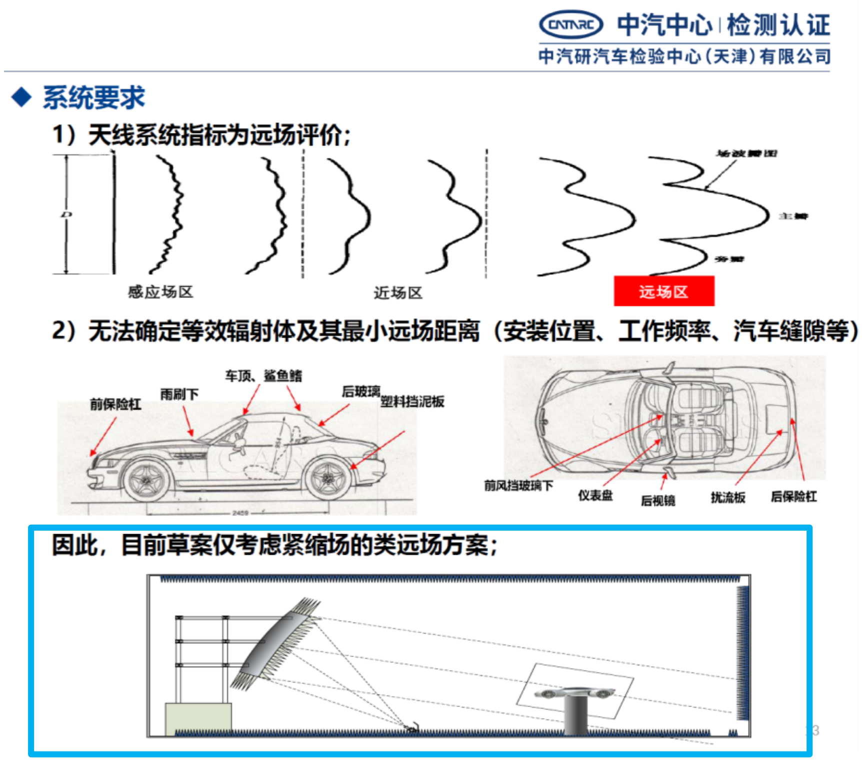


Indirect FF (NFTF)
Software near-field transformation

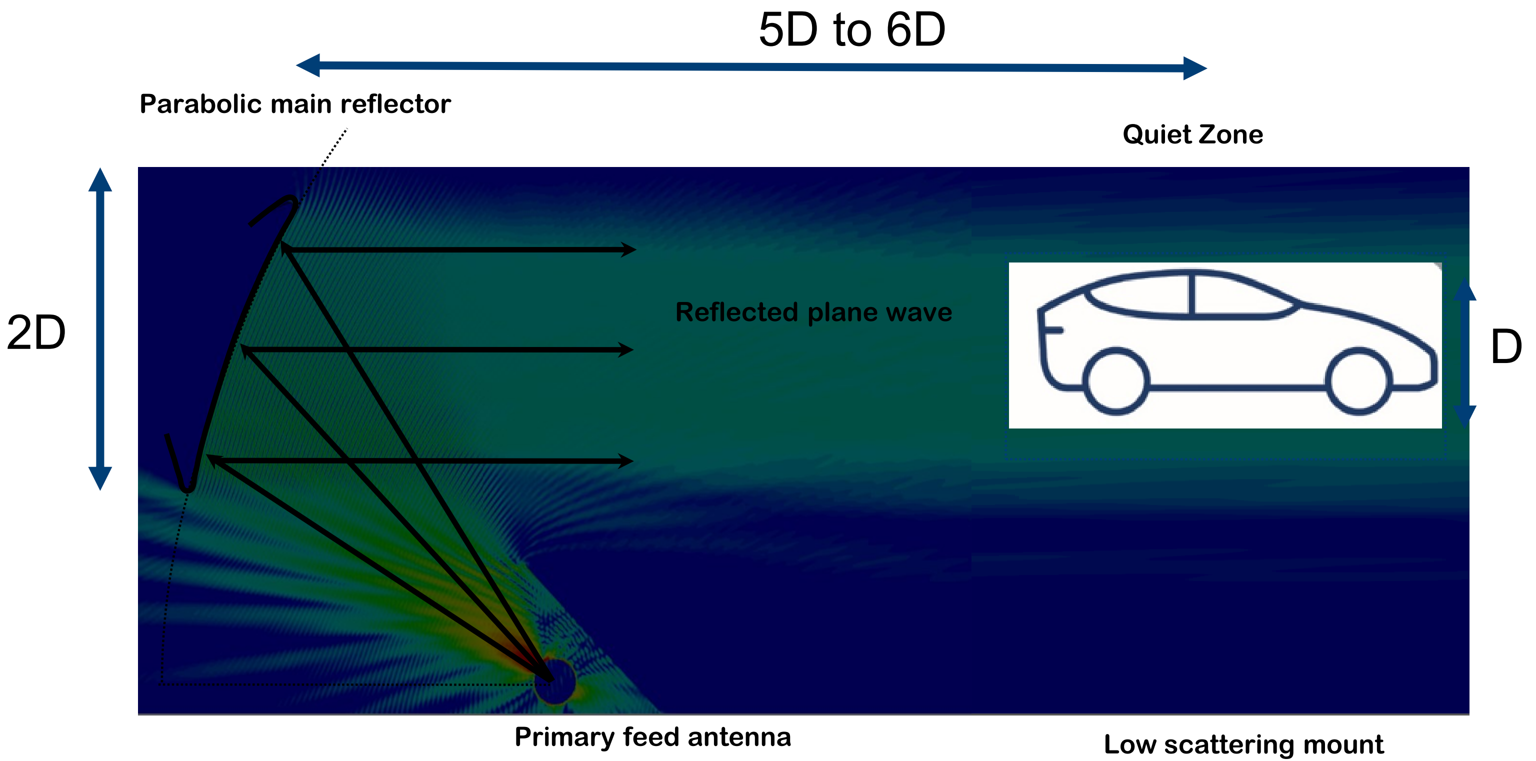
Most compact approach. Limitations in OTA due to phase accessibility, especially in Rx. Advanced scenarii simulation capabilities. Can be combined with DFF.

THE QUESTION OF QUIET ZONE SIZE

- Quiet zone (QZ): DUT test region with target uniformity in measurement probe field amplitude and phase
- Antennas couple to the car structure: actual radiation aperture size not known in advance
- Antennas can be anywhere on the car – in a DFF approach, the antenna phase center shall be ideally at the center of coordinates
- Having the whole car encompassed into a large QZ would be a straigthforward approach



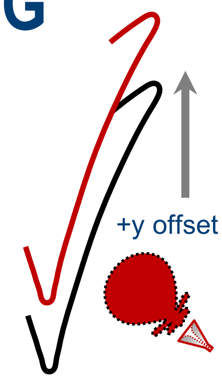
CATR PRINCIPLE

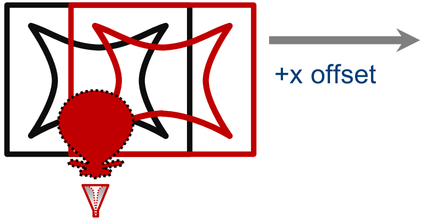


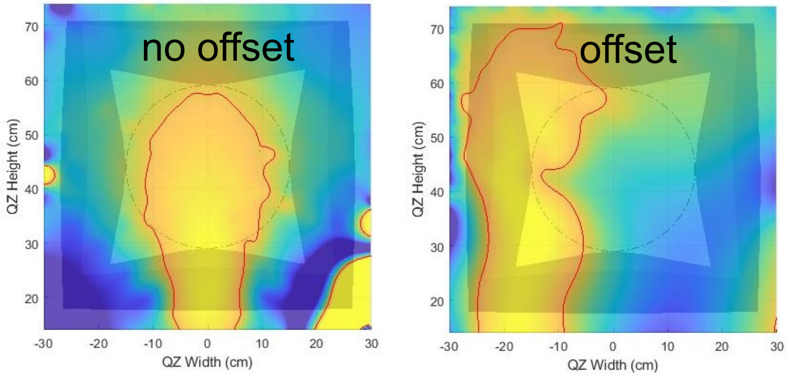
LIMITATIONS OF CATR FOR FV TESTING

- Combined-axis rotation of a car: accurate rotation of such a heavy load requires extremely expensive and large positioning structures

- Offset reflector feeding: allows to change the angle of the plane-wave in the test zone BUT:
  - Significant power budget drop
  - The quiet zone location shifts in space
  - The maximum achievable angle is strongly limited by uniformity constraints – typically ±15°





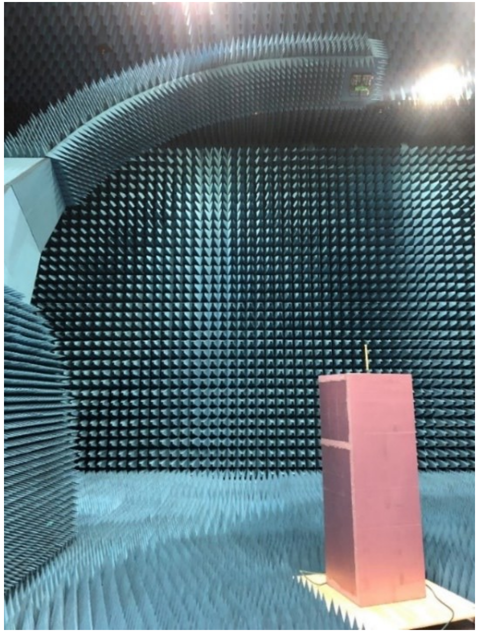


55 cm edge reflector with choke horn feed
28 GHz, 7 cm feed offset in x and y
P2P degradation from 1.7 dB to 3.5 dB, 20 cm QZ shift

THE PREFERRED CHOICE OF DFF GANTRY TEST SYSTEMS

- ► Distributed-axis positioners are cost-effective, accurate and fast
  - – Gantry arm with test probe rotating in elevation
  - – DUT on turn-table rotating in azimuth

- ► The smaller quiet zone in DFF systems is an exagerated problem and encompassing the vehicle in the quiet zone is an overkill
  - – Not large antennas but rather small antennas localized on and coupled to a large structure



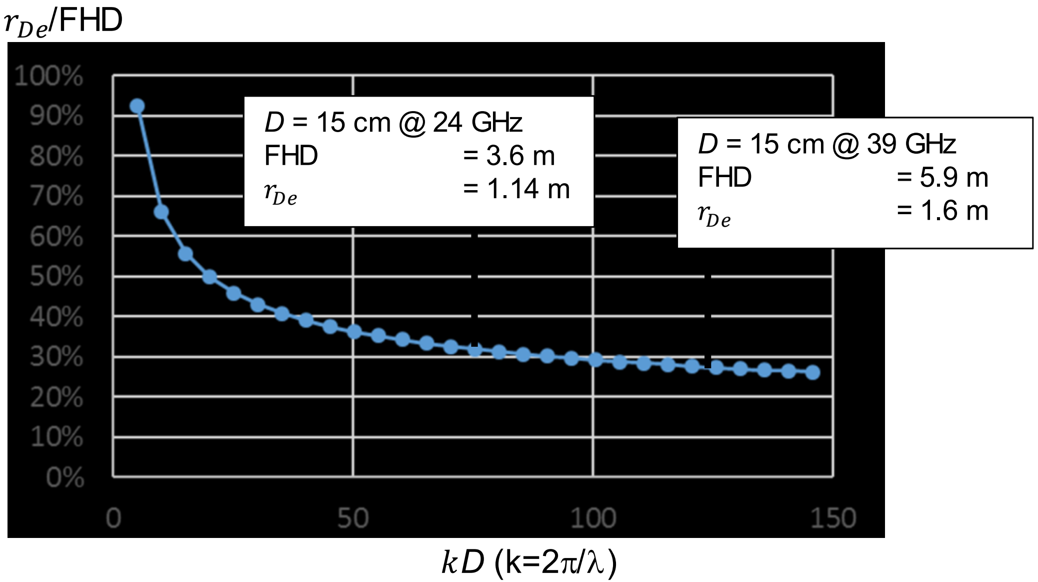
Munich, Germany, and Tianjin, China / 01.10.2020

CATARC (Tianjin) Automotive Engineering Research Institute Co.,Ltd. selects Rohde & Schwarz to supply full vehicle antenna test (FVAT) system

SHORTEST OTA MEASUREMENT RANGE LENGTH

$$r_{De} = \lambda \left(\frac{\pi D}{\lambda}\right)^{0.8633} \left[0.1673 \left(\frac{\pi D}{\lambda}\right)^{0.8633} + 0.1632\right]$$

- ► Recent publications demonstrated that peak EIRP, TRP, EIS and TIS can be accurately measured at distances much lower than Fraunhofer



B. Derat, **5G antenna characterization in the far-field: how close can far-field be?**, Int. Symp. Electrom. Comp. (APEMC), May 2018, pp. 959 – 962.

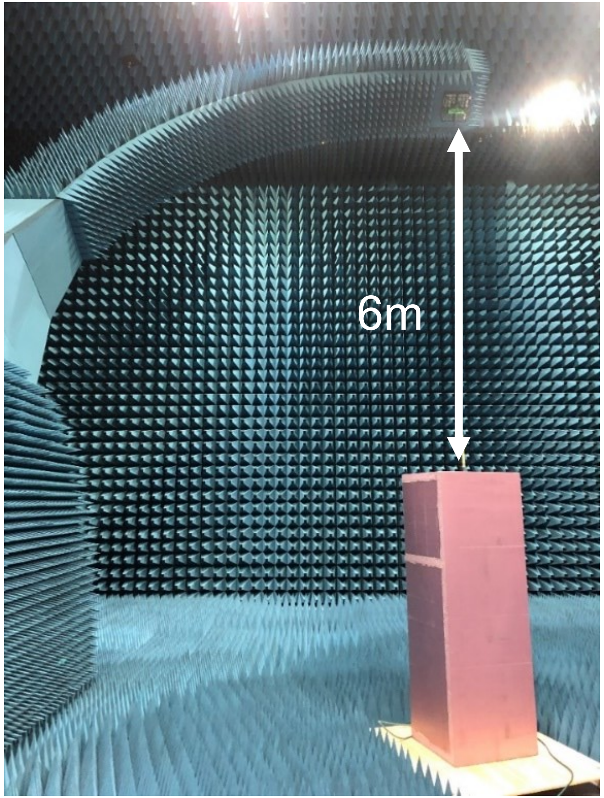
B. Derat, G. F. Hamberger, F. Michaelsen, **Shortest range length to measure the total radiated power**, *IET Microwaves, Antennas & Propagat.*, Special issue, 2019.

MAXIMUM APERTURE SIZE MEASURABLE IN FF CONDITIONS

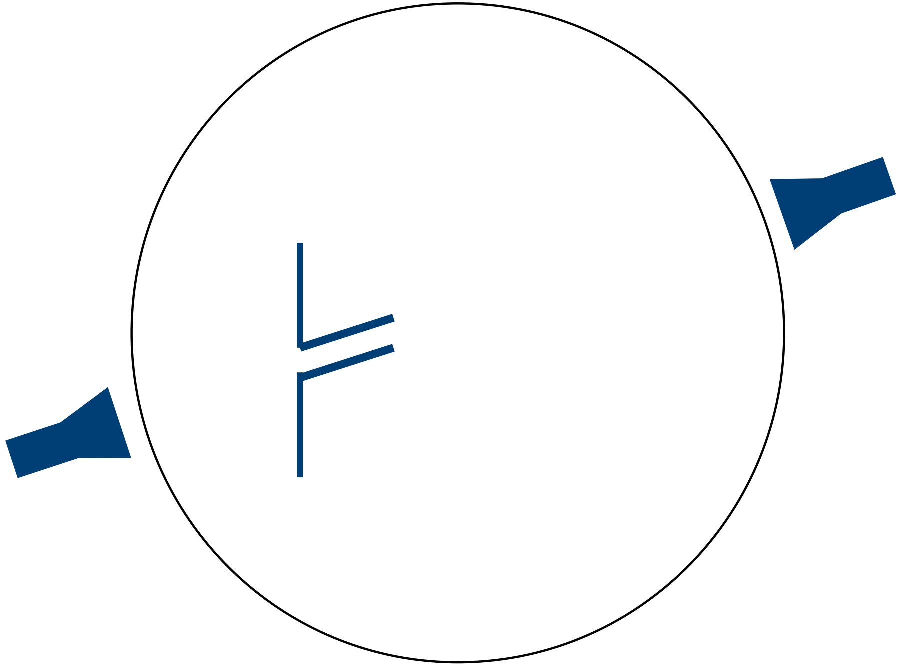
- 6 m gantry radius

- Maximum radiating aperture which can be measured in FF conditions, **based on the Fraunhofer distance**:
  - 1 m @ 900 MHz
  - 39 cm @ 6 GHz

- Maximum radiating aperture which can be measured in FF conditions, **based on the novel mid-range definition**:
  - 1.51 m @ 900 MHz
  - 71 cm @ 6 GHz



INFLUENCE OF OFFSET FROM CENTER OF COORDINATES



- Two major errors affect measured radiation pattern when the antenna is off from the center of coordinates
  - Variations in path length across the scanned sphere
  - Variations of DUT phase center in a local coordinate attached to the probe / effective probe gain
- These errors get larger at smaller range lengths

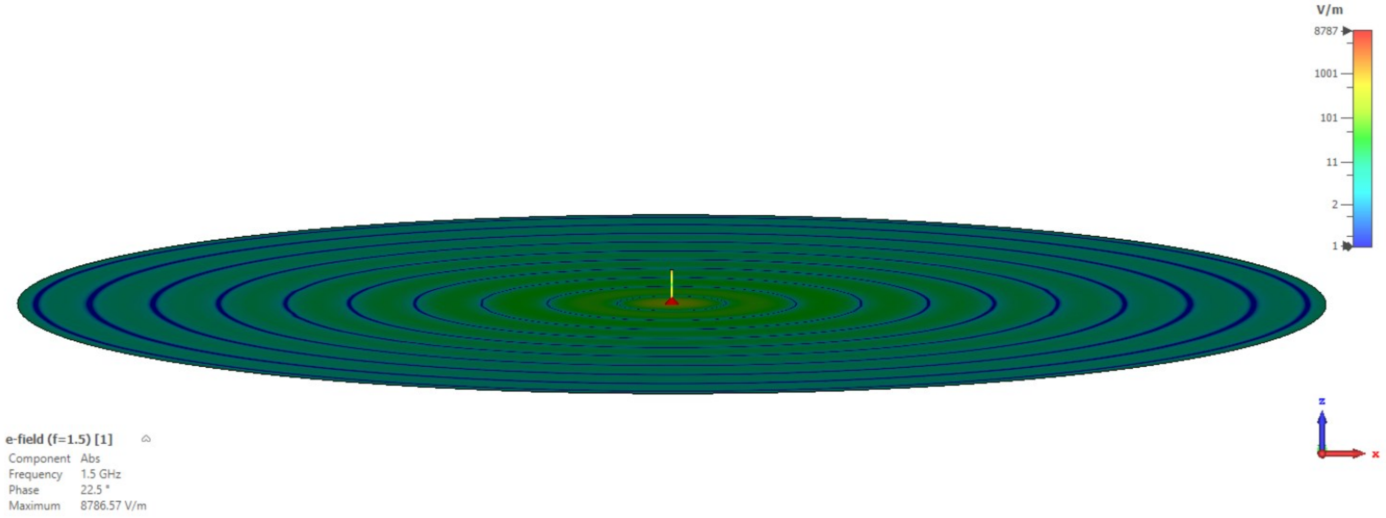
OFFSET CORRECTION TECHNIQUE APPLICABLE TO OTA

- Published technique applicable to OTA measurements
  - Requires magnitude E-field measurements only (no phase)
  - Applies as post-processing in Tx case, and pre-processing in Rx case (adjustment of power levels as a function of sampled solid angle)
- Inputs to the algorithm
  - Probe directivity pattern for each polarization
  - (x,y,z) offset from antenna under test to the center of coordinates
- Baseline hypothesis: offset DUT radiating aperture and measurement probe are in the FF

G. F. Hamberger, J.-A. Antón, S. Lachner, B. Derat, **Correction of over-the-air transmit and receive wireless device performance errors due to displaced antenna positions in the measurement coordinate system**, *IEEE Trans. Antennas & Propagat.,* Vol. 68, Issue 11, Nov. 2020.

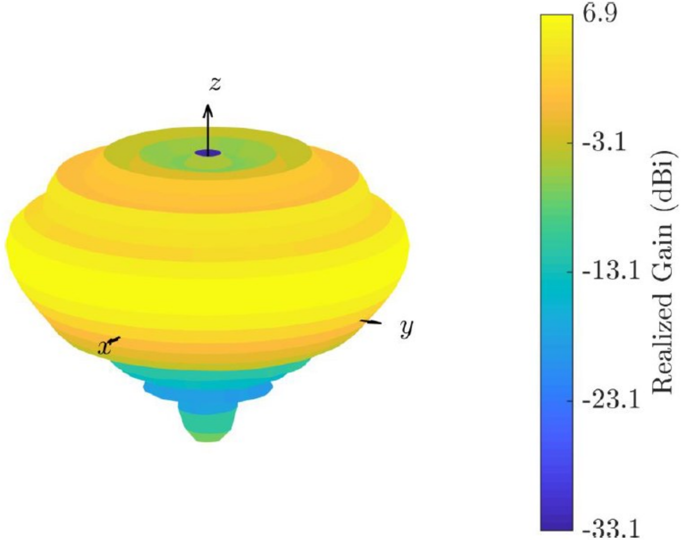
OFFSET MONOPOLE SIMULATION CASE

- Monopole at 1.5 GHz over 1m radius groundplane disc
- Center position: $x = y = 0$, $z = 1$ m; offset position: $x = y = 2$ m, $z = 1$ m (2.8 m radial offset);
- Simulated range length: 4.5 m

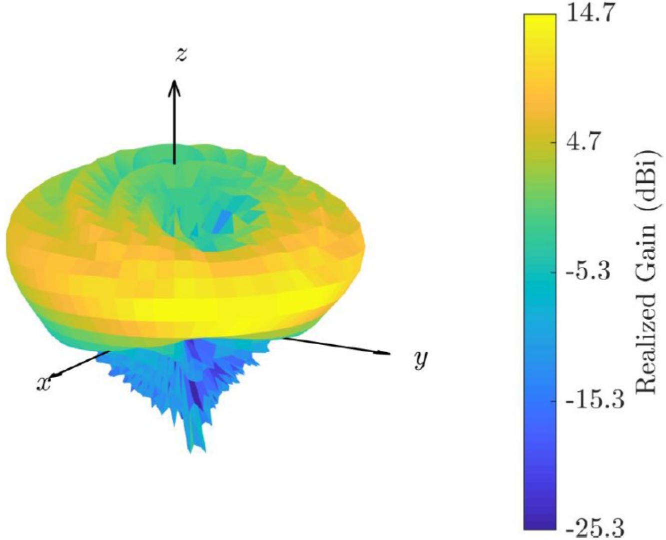


REFERENCE (CENTERED) AND OFFSET 3-D GAIN PATTERNS

- 2.8 m offset from center of coordinate: 2m in *x*, 2m in *y*
- 5° measurement sampling rate



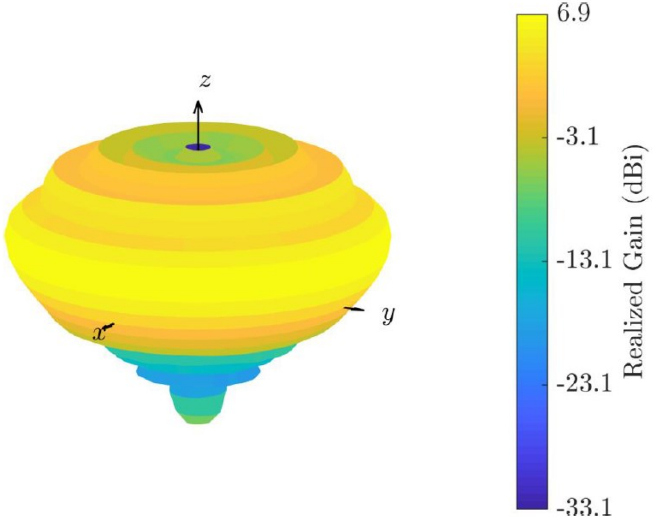
Reference pattern



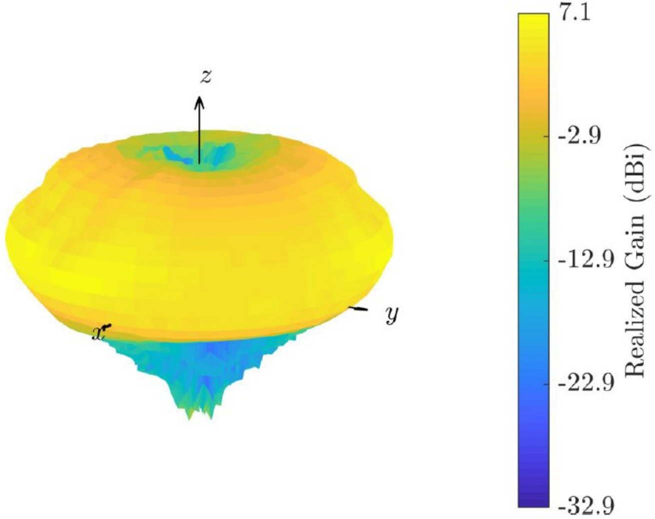
Offset pattern

REFERENCE (CENTERED) AND OFFSET-CORRECTED 3-D GAIN PATTERNS

- 2.8 m offset from center of coordinate: 2m in *x*, 2m in *y*
- 5° measurement sampling rate



Reference pattern

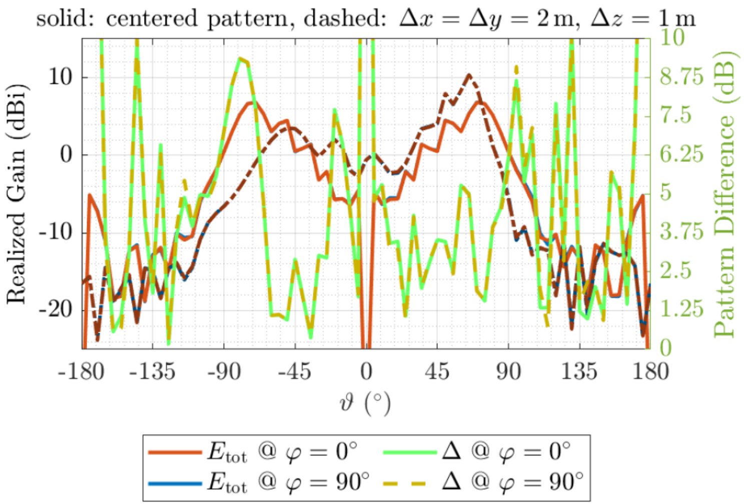


Corrected offset pattern

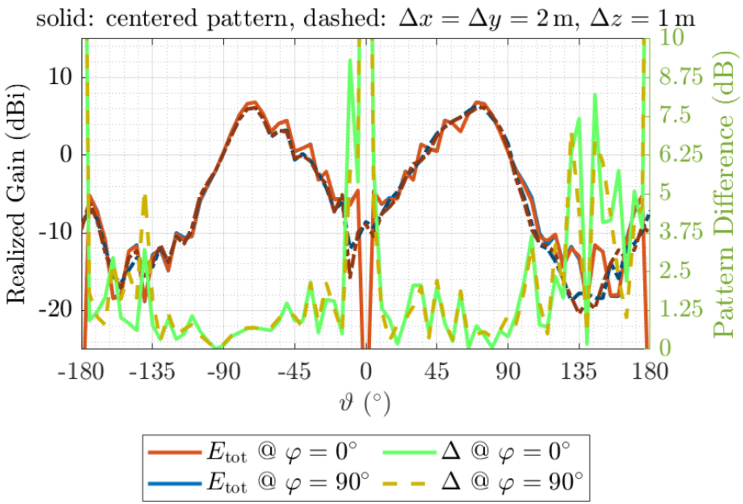
ACCURACY OF THE OFFSET CORRECTION ALGORITHM

- Realized gain values reconstructed within ±0.3 dB
- Main-beam peak positions are recovered correctly
- Applied with coarse 5° sampling – at least 1.7° step-size would be necessary to perform an accurate NF-FF transform

Uncorrected



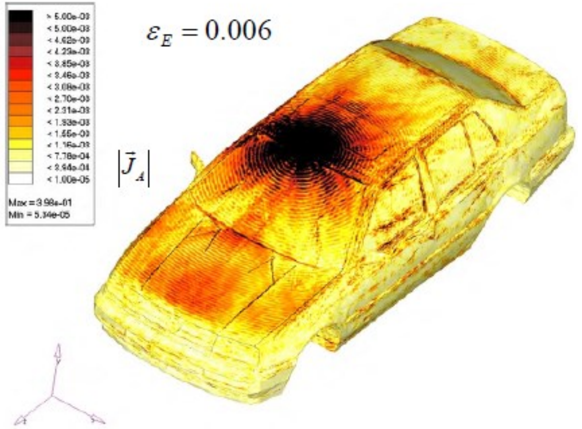
Corrected



RADIATING APERTURE AND PHASE CENTER IDENTIFICATION

- ► Use of near-field measurement approach (magnitude and phase)
- ► Equivalent reconstruction algorithms enable identification of the radiating region
- ► Phase center determination algorithms can be applied
- ► The radiating area and phase center can then be physically placed at the center of coordinates for OTA testing, or offset correction may be used

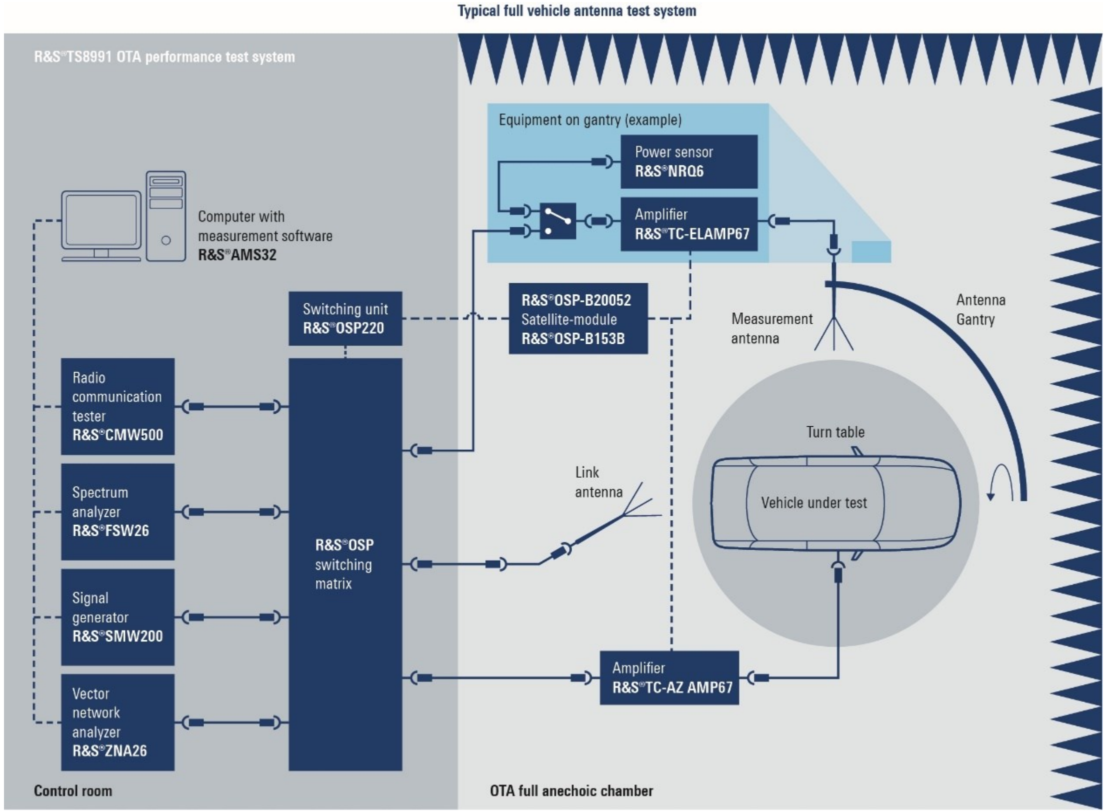
Electric surface current density from inverse current solution (FIAFTA)



Thomas F. Eibert, Carsten H. Schmidt, **Multilevel Fast Multipole Accelerated Inverse Equivalent Current Method Employing Rao-Wilton-Glisson Discretization of Electric and Magnetic Surface Currents**, *IEEE Transactions on Antennas and Propagation, Vol. 57,* No. 4, pp. 1178–1185, April 2009.

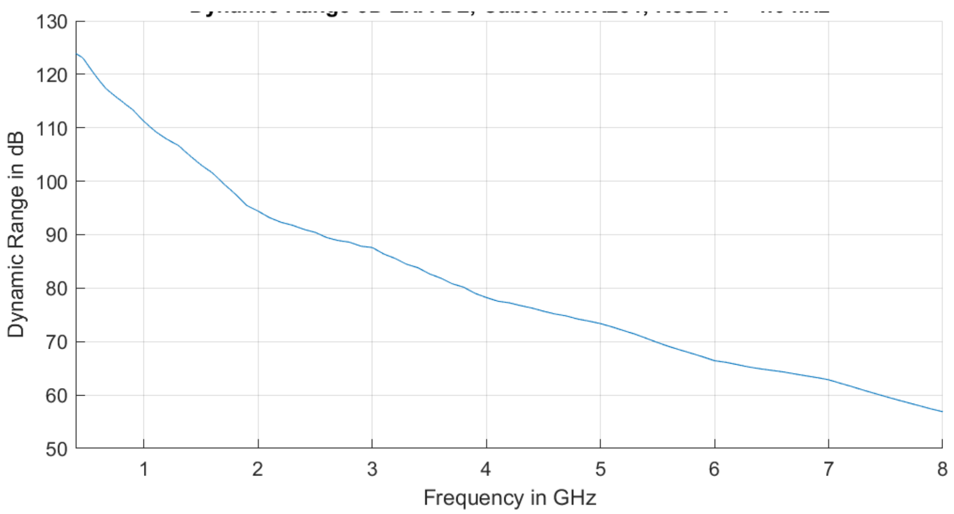
PRACTICAL FVT OTA SYSTEM IMPLEMENTATION

STANDARD 5GAA COMPATIBLE FVT OTA SYSTEM



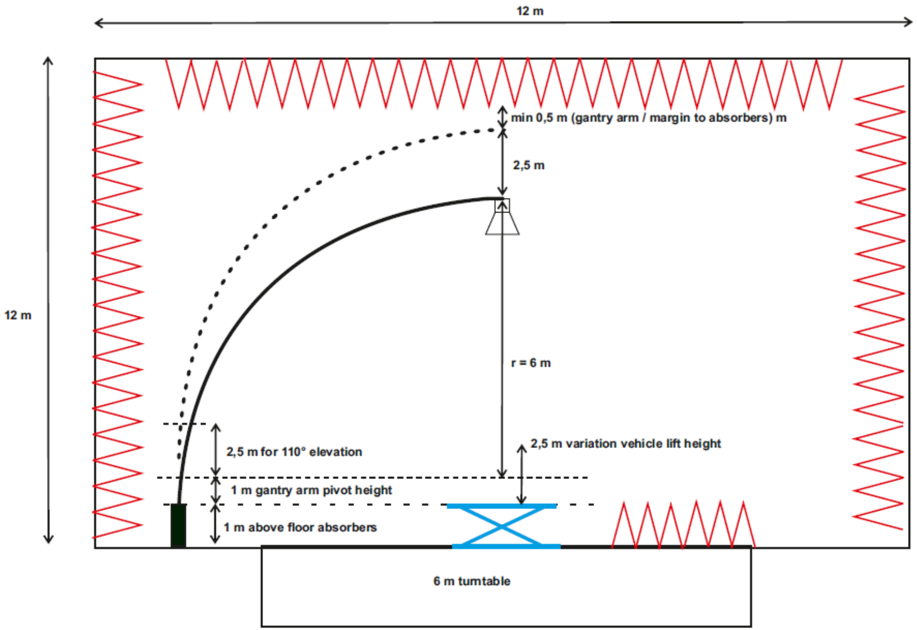
DYNAMIC RANGE MAXIMIZATION – A SYSTEM DESIGN KEY

- Measuring wide variations in the patterns: nulls, side lobes, etc…
- Enabling OTA test cases including low uplink and high downlink scenarii
- Example dynamic of a realized system (figure)
  - 5m Gantry
  - Total cable length: 34 m
  - DUT with 0 dBi gain, RBW = 1 kHz

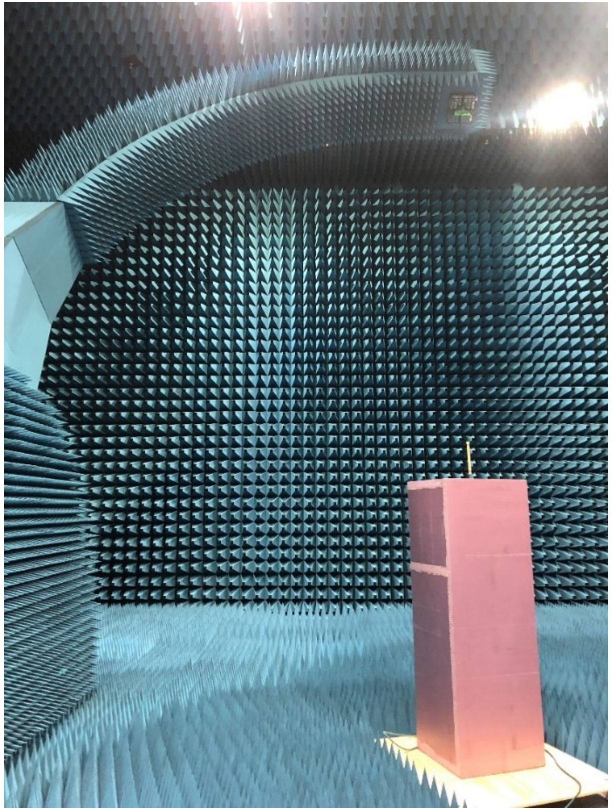


FREE-SPACE MEASUREMENTS AND ANGULAR SCANNING

- Measurements in FAC to increase reliability and reproducibility
- Interaction between the DUT, probe and environment is minimized
  - Car typically lifted up e.g. 1 m above the floor, covered with absorbers
  - Gantry pivotal point at e.g. 2 m height to ensure DUT at the center of coordinates
- Extended elevation range down to 110°
  - Gantry and DUT support with further height adjustment capabilities, e.g. up to 4.5 m

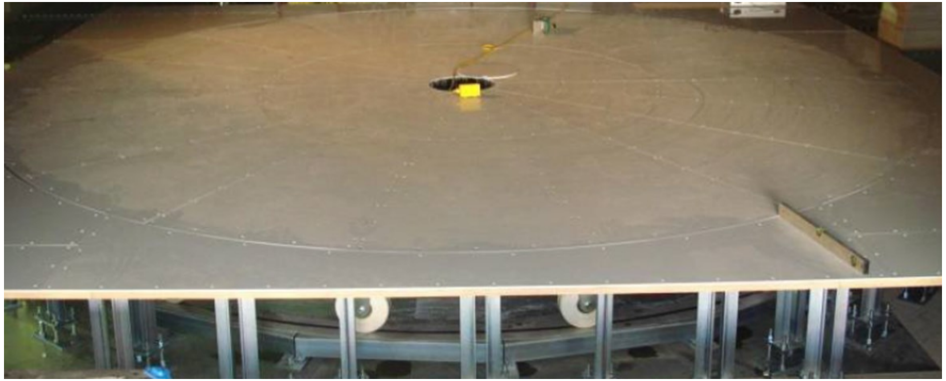


EXAMPLE POSITIONING SYSTEM



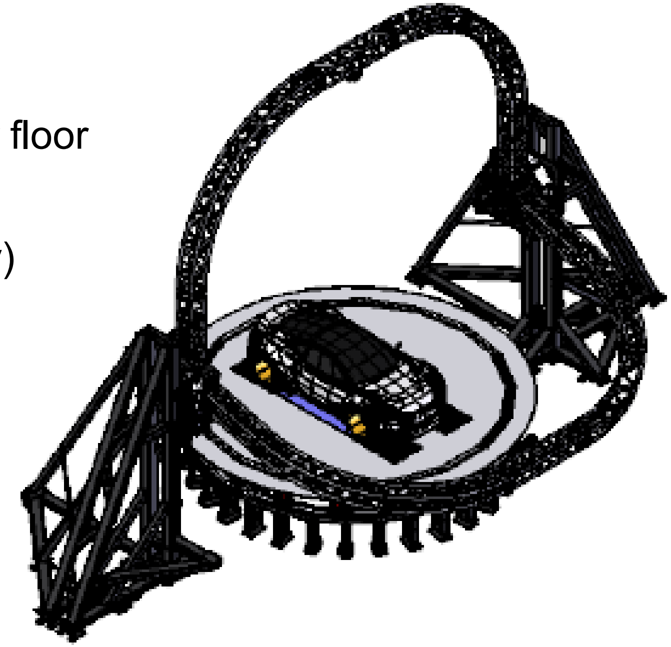
EXAMPLE TURNTABLE SPECIFICATIONS

► Diameter:	7.0 m
► Permissible load:	10.000 kg
► Rotating angle:	360° bi-directional
► Rotating speed:	up to 1 rpm (adjustable)
► Positioning accuracy:	+/- 0.05°



TYPICAL GANTRY CAPABILITIES AND MEASUREMENT TIME

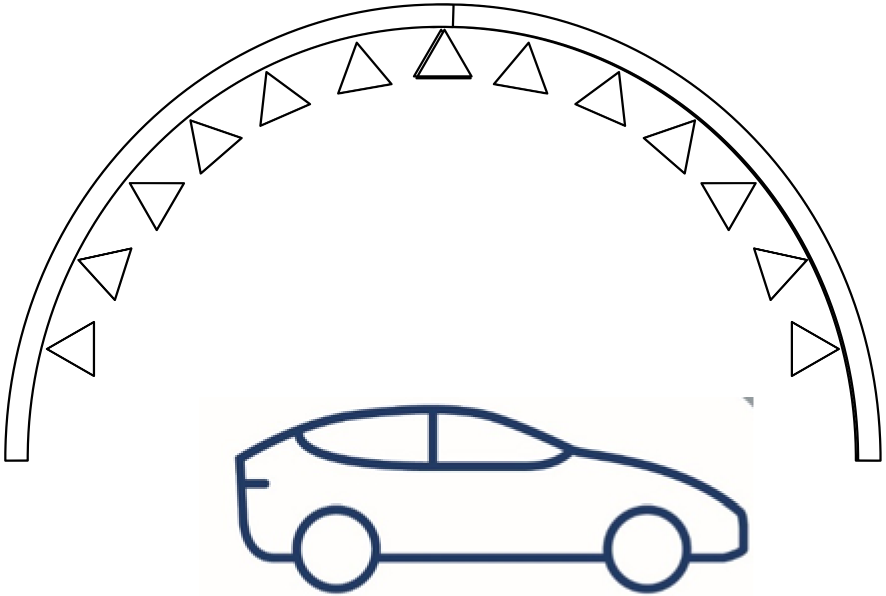
► Max. antenna weight:	10 kg
► Radius:	6 m
► Gantry pivot height:	1.5 m to 2.5 m above chamber floor
► Elevation angle range:	0° to 105°
► Positioning accuracy:	± 0.01° (at pivot point of gantry)
► Positioning speed:	up to 1.2°/sec



Full triggered 3-D scan over 76 frequencies with 3.6 degree sampling rate (suitable for tests at 6 GHz): 18 min

MULTI-PROBE SYSTEMS – BACKGROUND & MAIN QUESTION

- Multi-probe spherical antenna test systems have been commercialized since about 25 years ago
- Original idea: faster to sweep electronically through tens of probes, rather than to move a single probe mechanically at tens of positions
- **MAIN QUESTION:** If the accuracy was the same and if time advantage was that large, then why do we still see, 25 years later, a large majority of single probe antenna test sites?
- There are good reasons why single probe is the golden standard for FV testing



THE LIMITED TIME ADVANTAGE OF MULTI-PROBE SYSTEMS

- With an antenna measurement setup (VNA based) or in OTA Tx, the turn-table speed is the limiting test time factor

- Single probe system measurement process
  - Continuous sweep of turn-table used at full speed
  - Stepped elevation with the Gantry

- Multi-probe system measurement process
  - Stepped azimuth: the turn-table is not used at full speed (typ. 3 times slower than in continuous movement) due to elevation sweep time
  - Electronic sweep of elevation

- For OTA Rx, the limiting time factor is the Bit Error Rate search algorithm
  - As a consequence both single probe and multi-probe systems have the same testing speed.

MEASUREMENT UNCERTAINTY CONSIDERATIONS

- Single probe-system has the lowest uncertainty
  - Uses a unique probe to measure the field at all the points
  - Most error terms relating to the probe can be treated as biases (systematic errors) and hence calibrated out
- Multi-probe system
  - Each probe has its own error budget
  - The error shows hence angular / pattern dependence
  - Many error terms must be treated as random thereby increasing the measurement uncertainty

Table 4—Sources of Uncertainty in Antenna Measurements

Source of Uncertainty	Value	Type	Distribution	Divisor	Standard Uncertainty
Range Antenna / Reference Antenna Properties					
Alignment / Positioning					
Receiver System Non-linearity					
Noise					
Drift					
Impedance Mismatch					
Leakage and Crosstalk					
Flexing Cables					
Multipath					
Normalization					
Non-uniform Illumination					
Aliasing					
Measurement Area Truncation					
Antenna to Antenna Multiple Reflections					
Random Errors					
Combined Standard Uncertainty					
Coverage Factor					
Expanded Uncertainty					

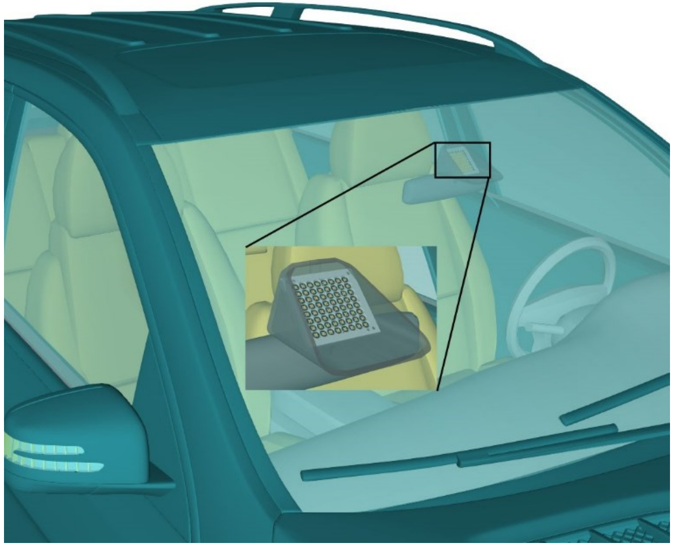
IEEE draft recommended practice for antenna measurements – P149/D8, Apr. 2020

TOWARDS AUGMENTED OTA

NEED FOR ADVANCED ELECTROMAGNETIC FIELD PROCESSING

- A fully anechoic chamber is not a realistic road environment
- Some complex antenna integration scenarii might not be straightforwardly or efficiently evaluated in a FV OTA environment
- Full-wave electromagnetic simulation is an alternative, yet limited by DUT knowledge
- Combining near-field measurements and advanced numerical processing allows to overcome limitations of both pure experimental and numerical approaches

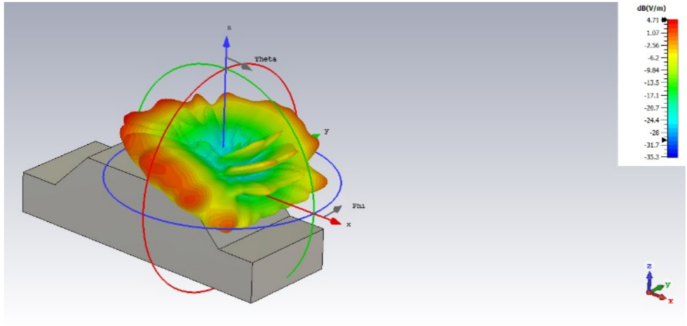
B. Derat et al., **Toward Augmented OTA Testing: Bringing Full-Wave Numerical Modeling and Antenna Measurements Together**, *Microwave Journal,* Vol. 64, Ed. 1, Jan. 2021.



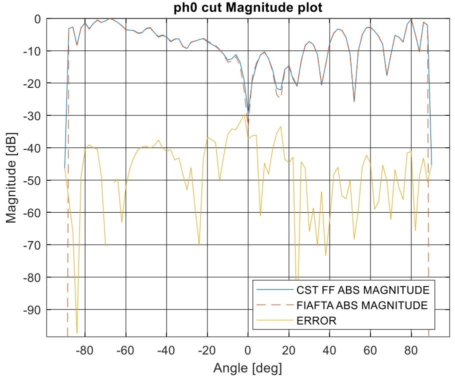
5G mmW antenna array integrated behind windshield

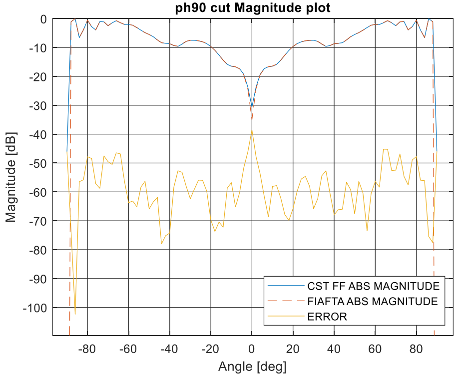
ARBITRARY GROUND SIMULATIONS

- 1 GHz monopole on basic car-like PEC structure
- CST MWS simulations
  - Freespace data used as inputs to FIAFTA-based ground simulation
  - Data with ground used as reference
- NF data probed on a 6m radius truncated sphere with 2° sampling

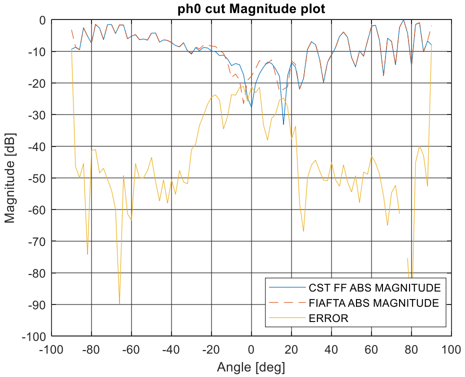


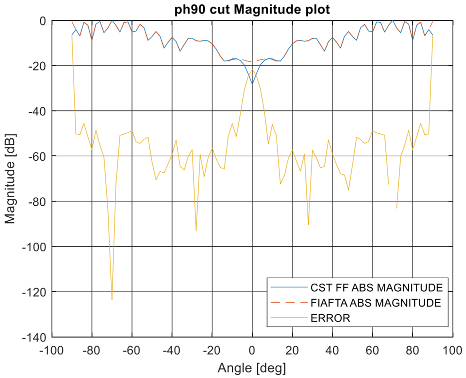
PEC ground



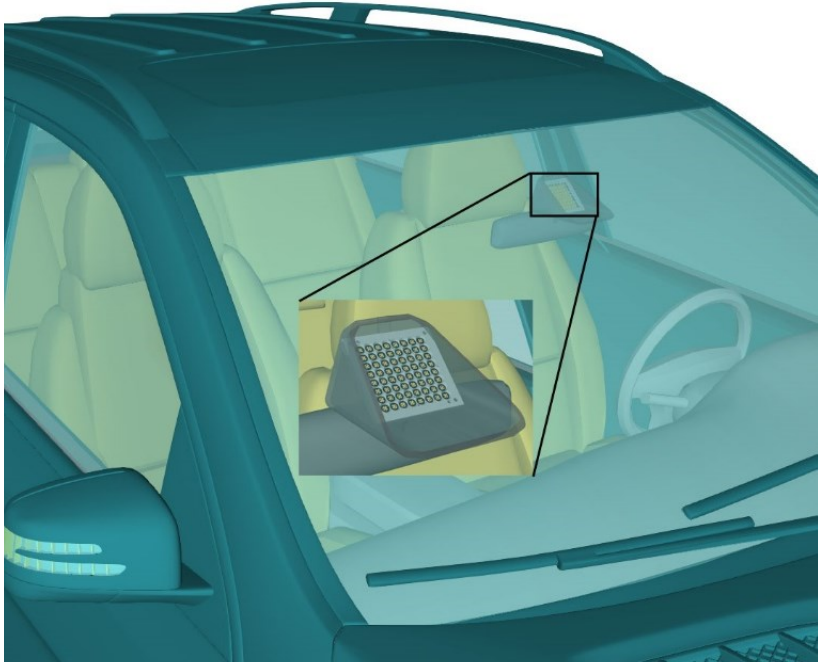


Dielectric ground





INTERFACING MEASUREMENTS AND SIMULATIONS



1 - Experimental step

Measure two orthogonal electromagnetic phasor components around a radiating module

2 - Processing bridge

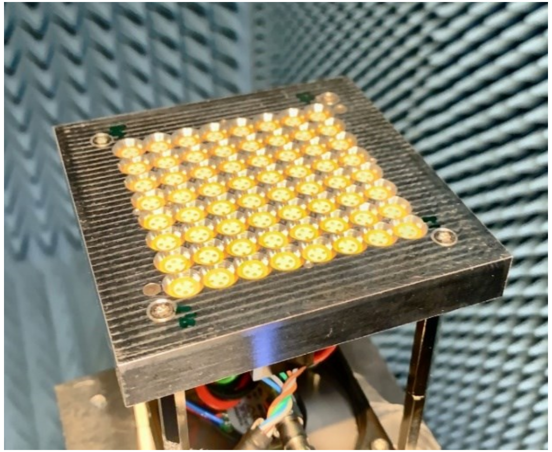
Calculate equivalent source

3 - Simulation of virtual scenario

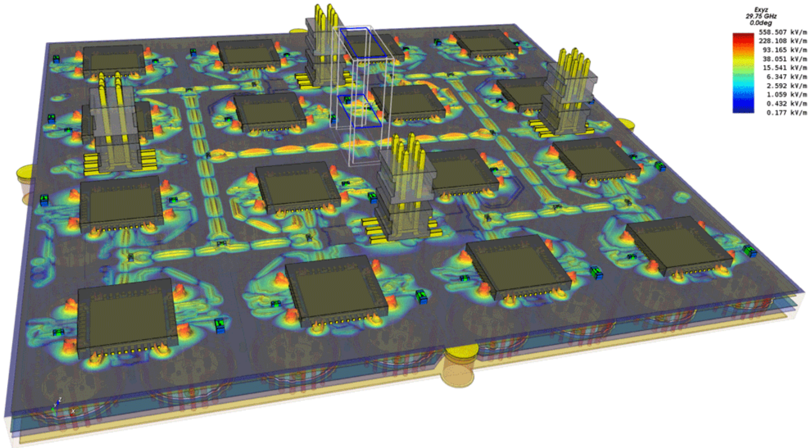
Import equivalent source in full-wave software and compute electromagnetic quantities in modelled scenario

5G MMW BEAM-FORMING ARRAY CASE

► Multi-layer 8x8 5G antenna array operating in Ka-band by IMST GmbH
► 1:8 divider and 16 beamforming chips with individual amplitude and phase control, each one feeding 4 antennas



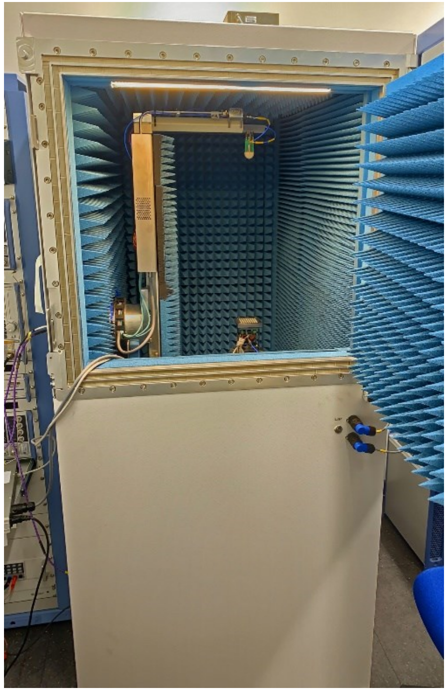
Phyical DUT – front side

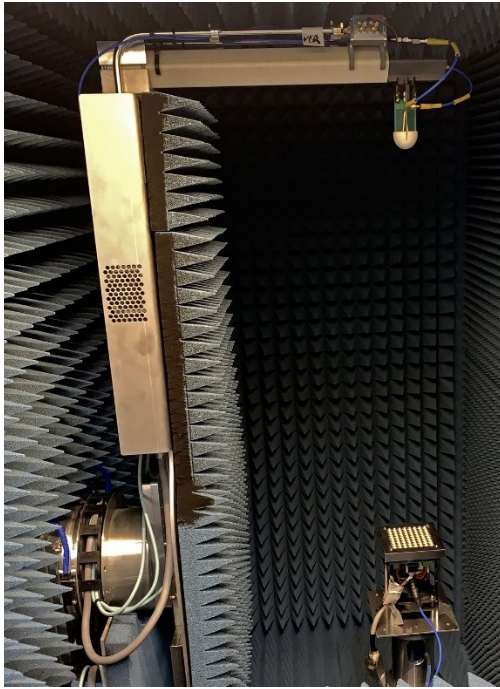


Numerical model of the DUT – back side
Simulated with IMST EMPIRE XPU

MEASUREMENT SETUP

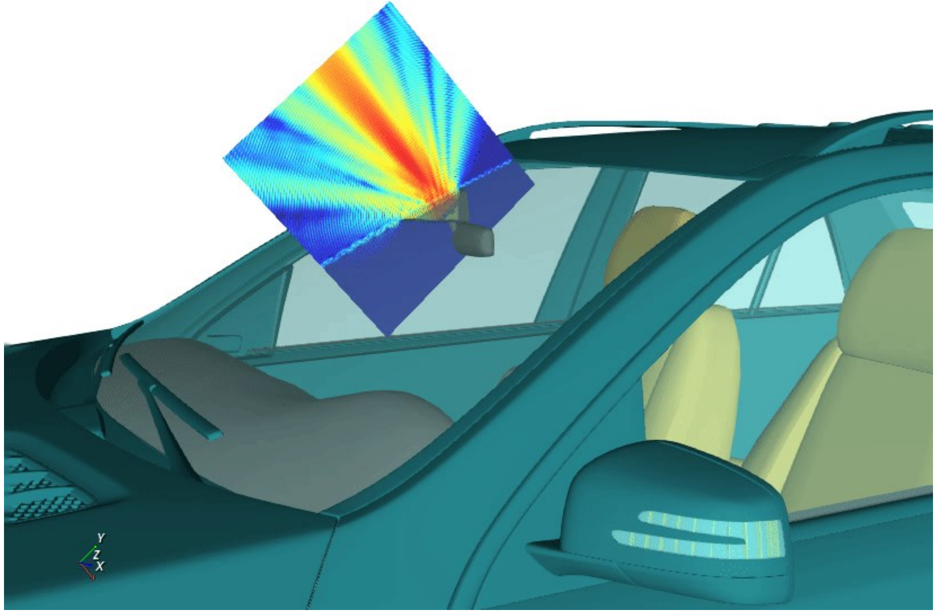
- ► R&S ATS1000 spherical scanning chamber with distributed-axis system
  - – 0.03° angular sampling accuracy
  - – 0.64 x 1.25 x 0.93 m absorber tip-to-tip
  - – 50 cm range length
- ► R&S ZNA43 vector network analyzer
- ► Measurements carried out at 29GHz, 2° angular sampling rate





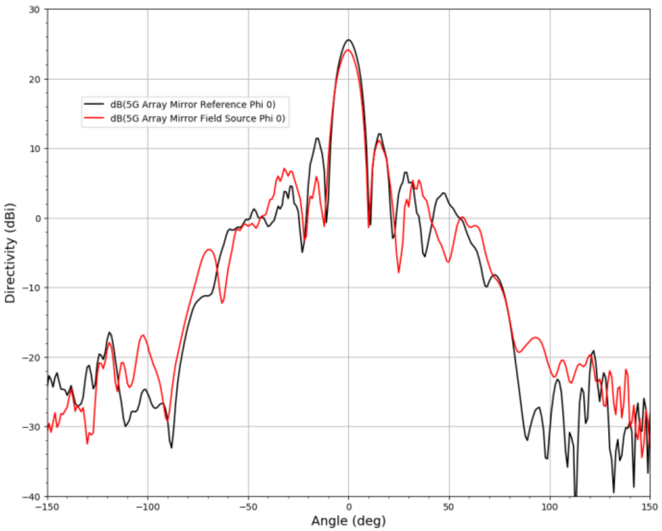
NEAR-FIELD RESULTS

- ► Topside view of E-field magnitude at 29 GHz in a cut-plane going through the array module
- ► Very comparable distributions – more differences in close vicinity from the antenna
- ► Computational performance:
  - Reference simulation:
    3.6 Gcells, 108 GB, 180 min
  - Simulation based on equivalent source:
    0.32 Gcells, 10 GB, 15 min

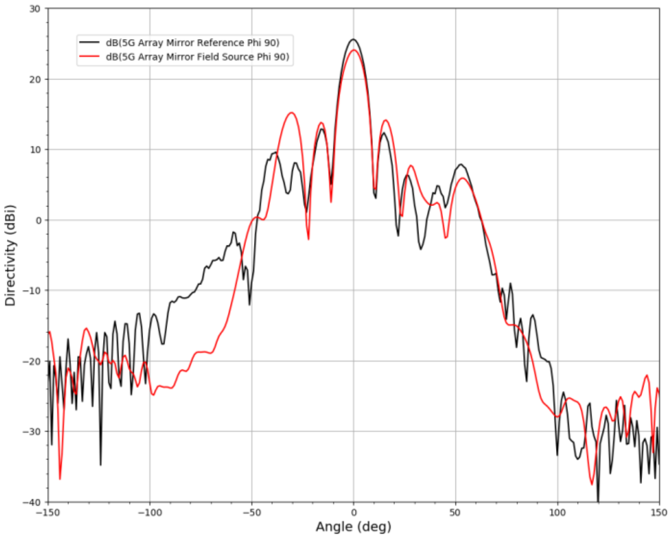


FAR-FIELD RESULTS

- ► Directivity patterns in two orthogonal cutplanes
- ► Reasonable agreement, considering DUT production tolerances, tolerances on active electronic operation points, modeling uncertainty



$\varphi = 0°$



$\varphi = 90°$

Reference simulations

Reconstructed with combination technique taking measurement data inputs

CONCLUSION

- As antennas are influenced by vehicle-integration, reliable OTA performance assessment requires full-vehicle testing in the far-field
- For cost-effectiveness, DUT positioning and test cases coverage reasons, the single probe DFF spherical scanning approach, possibly combined with near-field measurements, is the best suited measurement methodology for full-vehicle testing
- Applying the recent mid-range distance theory, the quiet zone in typically-sized DFF sites appears sufficient to cover all known needs
- The issue of offset from center of coordinates from the radiating aperture in DFF systems can be efficiently mitigated through DUT re-positioning or software compensation

CONCLUSION

- Even though multi-probe systems might seem attractive, the reduction in test time they offer is not so. Multi-probe systems suffer increased measurement uncertainties compared to single probe

- The need for simulation of advanced test scenarii or evaluation of performance in complex integration cases calls for augmented OTA techniques, combining near-field techniques and simulation tools

… Paving the way to the future to bring more capabilities in antenna test facilities


Automotive
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