<u>WS-Summary with selected view graphs:</u>

Challenges in Special Applications of *Electrically Small*, HF Vehicular Antennas - Simulations and Experimental Validation – (Automotive EMC, Shortwave Antennas and Propagation)

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Typical applications are, aside from Military / Special-Forces users, e.g. NGOs with mission critical emergency communication needs in remote disaster areas. These Organizations use mobile, vehicular shortwave communications for humanitarian, medical and technical support purposes. Voluntary amateur radio services are many times effectively supporting these helpers. Reliable Short and Long Distance radio communications is essential.

Satellite Phone Networks may be congested and expensive. 3G or 4G mobile phones are often no option, because the supporting infrastructure (base stations) is down or destroyed. HF shortwave (1.5/3-30 MHz) communications, on the move, can provide a quickly deployable, reliable and cost effective land mobile radio solution.

For driving vehicles civilian road safety regulations however often limit the permissible mechanical height of mounted vertical whip antennas to max. 4m (ground to tip). This is short in terms of used wavelength (e.g.**160m/1.8MHz** to **20m/14MHz**).

Therefore a major technical challenge occurs: **Low antenna efficiency** with may be only 1% or less at e.g. 2MHz. Car-battery powered HF-Transceivers (RX/TX) with about 100W output will under these conditions only effectively radiate 1W. Even this is optimistic! Efficiency is further reduced by unfavorable vertical radiation pattern (momentarily optimal skip/elevation distance via ionosphere) of short, typically resonated monopole antenna (a distributed series resonance circuit) [Fig. 1]. In this presentation we are mainly dealing with **resonated whip/rod antennas.**

Long distance communications calls for low elevation take off antenna angle. Short distance needs steep take off angles (NVIS) **into the conducting ionosphere**. Low antenna efficiency makes equally the received signals low. This requires the vehicle to have low conducted/radiated EM emissions (automotive EMC). Additionally the external, EM environmental background noise must be low, if a reasonable signal to noise (SNR) is to be achieved. Some partly underestimated EMI Noise data is published in ITU-R-P.372-13 (now to be updated) and lately correctly evaluated in [0].

Antenna fundamentals are treated in well-known text books [1], [2] and [3], but not all aspects are yet very well researched. The limited size of the ground plane, the metallic car chassis, is one challenge. The antenna system interaction with the soil/ground under the vehicle is another one. Therefore it is not surprising that electrically short vehicular HF antennas are still today a current Ph.D. and R&D topic [4] and [5], at least for a specialized, small community.

From earlier R&D work 1949/48 [6], [7] on electrically small antennas we know there are fundamental performance limitations in efficiency. Short whip antennas are capacitive. A coil is needed to compensate/resonate the antenna. A small antenna, with low internal losses, has a very limited bandwidth. Inductance factor Q (unloaded e.g. 100 to 1000) of this resonance circuit determines quality. The radiation resistance is typically very low. Because of the series resonance nature the ground losses contribute mainly, on the low bands, to the loaded Q of the system.

The ratio of radiation resistance to the sum of all losses, including the radiation resistance, defines the best possible efficiency. The radiation pattern, in the far field, can further impact efficiency. Low Antenna (input/feed point) impedance matching networks may additionally add losses to the system.

Depending on the planned radio communication use of the vehicular HF antenna system there is a need for short or long distance communications.

Short wave propagation, via the ionosphere (acting like a conductive, time dependent, ionized layer, at high altitude around the earth) uses different modes for long and short range communications. Propagation is solar cycle, season and day/night time affected. The sun initiates ionization.

The maximum usable frequency (MUF) is high at daytime and drops at dusk. Consequently there are at night only the low bands e.g. 1.8/3.5/ (7 MHz/40m)) left for effective communications. Right here we have low antenna efficiency. The ionized, conducting E, F1 and F2 ionospheric layers (less than 100 to 700km high), as “spherical mirror” around the earth, reflect incoming transmitted HF signal to far (e.g. 100km to > 1000km) or even closer (NVIS: near vertical incidence sky-wave, mostly from vertical mag. loops) receive destinations [8], [9]. The vertical elevation take-off angle of the antenna (radiation pattern [10]) and any impact by e.g. soil/ground under the car or possibly tires [11] can be important. We have shown tires do not affect antenna efficiency in the low bands. However their added capacitance to ground detunes the resonance of an antenna system Fig. 1.

It goes without saying a suitable **far-field test site**, for such HF vehicular antenna systems, **is very big**. Mostly frequency bands above 3MHz are used to communicate. To get into the 80m (3.5MHz) wavelength far-field region, where the antenna pattern is developed, it takes a distance of at least 6 to 10 wavelength**. No EMC anechoic chamber is big enough**. Aircrafts and drones were not available to us. Therefore we needed sky-wave, ionospheric tests and **computer code simulations**.

For the efficiency critical low bands of the shortwave spectrum (around 1.8/3.5/7 MHz) we first measured **Ant.-Efficiency over 2.8 km flat farm land** with **Ground-Wave**. This includes comparing prototypes and commercially available systems. In this test no antenna elevation radiation diagram can be measured. Detailed measurements of the dielectric soil properties could not be done. Moreover the soil may not have constant properties (typically epsilon 13, sigma 0.005 S/m, rich farmland) over all the 2.8 km farmland test distance.

Ground-Wave was followed by **Sky-Wave testing** with efficiency estimates from extended HF ionospheric propagation experiments and statistics in the EU. In all these tests the key factor is a **suitable Reference Antenna** for the, to be tested, frequency range.

Our prototypes of low loss, vertical, resonant **reference antenna-systems 1.8 /3.5/ 7 MHz** allowed detailed, **absolute efficiency simulations**. [Fig. 2] shows a reference antenna for 1.8 MHz (Q, unloaded coil ca.1000) on a saltwater beach in Denmark/ Romo Island. This environment has almost close to ideal “metallic ground” properties.

For further details of experiments/simulations, refer to [Fig. 3] to [Fig. 13] under selected view graphs.

In the **ionospheric tests** we used a widely, globally distributed, digital SDR receiver/ antenna beacon network. This network reports, via internet, received/decoded identification/call-signs of a HF transmitting mobile or sometimes also a HF fixed reference station. The relative result, in the spectrum band of interest, is a signal noise ratio (SNR) in dB values between the two antennas. A histogram in numbers of reported beacons vs. SNR is given. Since there are many simultaneously receiving beacons in the EU, this leads to a mean / standard deviation comparison of two antennas, e.g. **averaged over hours**. This procedure minimizes variations by unavoidable fading and propagation changes. The worldwide **WSPR (Weak Signal Propagation Reporter)** beacon system network was first developed (2008), for Amateur Radio use, by **Prof. Dr. Joe H. Taylor**. He has the US-FCC Amateur Radio Call sign K1JT and received, in his professional career, the Nobel Prize in Physics-Astronomy, 1993.

Our research shows clearly such complex experiments must be supplemented by experimentally validated simulations (e.g. for reference antennas) to be sure the trend and the in-situ antenna efficiency on the HF low bands are right. The changing ionosphere status and the corresponding radio propagation, with strong fading effects (up to over 20dB), need to be analyzed very carefully.

Estimating the accuracy of our simulation was done e.g. **comparing to Near Field (H) measurement data around the Audi A6** on a wide spaced, object free parking lot. Fig. 14 shows the very good agreement for H fields. The exact dielectric soil characteristic could not be measured. Furthermore considering our simple H field sensor system, with about +/-1.5 dB measurement uncertainty, this is excellent agreement between test and simulation data.

E-field testing is far more sensitive [12], [13] to externally impacting factors. These may be reflections from the ground (soil) /car surface and the presents of a human body (dielectric) testing personnel holding the sensor.

Measured/simulated E and H Field (3.5 MHz) data from the inside of the passenger compartment will also be shown / briefly discussed.

Keep in mind: Experiment and EM-Simulation need to go hand in hand! This is many times a challenge on both sides.

Joint Workshop: General Content (all approximated Timing for Topics):

09:00 to 10:40

1. Project **Motivation, Background**, **Goals**

2. Open Literature, interested **Antenna Users**, some **State of the Art Ant. Products**

3. Basic **Technical Challenges**: Emergency Communication needs in remote disaster areas, Automotive EMC, inefficient electrically short HF Antennas, critical communications SNR on short wave (HF) low bands, general review of radio wave propagation on shortwave (low bands 1.8/3.5/7 MHz)

4. **El. Small Ant. Basics/Theory** and Discussion of Assumptions/Limits in the Experiments and Simulations.

5. **Basic Antenna Problem Analysis** by equivalent circuit

6. **Test Cars** : Mainly Audi A6 Avant , similar in most results to the BMW 316i Touring, Ford Ranger 32

7. **R&D Reference-Antenna Design** and choice of tested frequency bands was based on an existing government transmission license as HAM radio operator. This allowed in principle using of HF spectrum bands from 1.8 to 29.7 MHz, focus low bands

   (10:40 Break 1)

11:20 to 12:40

8. **Experimental Ant. efficiency-tests: Ground-Wave** over 2.8 km flat farmland, **Sky-Wave** efficiency estimates by statistics from extended EU Ionospheric Propagation experiments. Experimental dB (or %) efficiency => ranking of various types of el. short HF mobile antennas. Both R&D as well as typical commercially available HF land mobile antennas tested.

9. Lessons learned from **experimentally** comparing HF mobile to a known **fixed reference dipole type antenna** with NEC simulated sky-wave radiation pattern (WSPR tests)

10. **Simulation Model** (interaction short Monopole with car chassis , tires , soil/ground under the vehicle)

11. **Efficiency impacting Parameter Simulation-Studies** (partly measured/simulated): Tire capacitance impact, Antenna Input Impedance, VSWR (S11), e.g. on 80m (ca. 3.5MHz, R&D Test Antenna, capacitive head, 1.88m long, vertical radiator, large XL resonance coil-Hi Q-)

    (12:40 Break 2)

14:00 to 15:20

12. **Reference Ant. Simulation**: Far Field Ant. Radiation Pattern (azimuth, elevation, 1.8, 3.5, 7 MHz) impact of different soil/ground characteristic under the automobile, incl. simulated **absolute antenna efficiency**

    (15:20 Break 3)

16:00 to 17:00

13. **What makes a better radiator?** Some Experiments / **Simulation**
    Comparison of two 80m (3.5MHz) Reference Antennas over PEC ground (efficiency, elevation angle). Ant 1: short HF monopole, Ant 2: vertical, resonated wire mesh as alternative antenna. Result: radiator-length seems dominant for efficiency

14. **Outlook:** Now we start understanding the underlying physics. **Discussion** of ideas to possibly **improve antenna principles** (E or H near field dominant etc.) **by innovative** approaches and **design**.

15. **Conclusions**

16. Literature

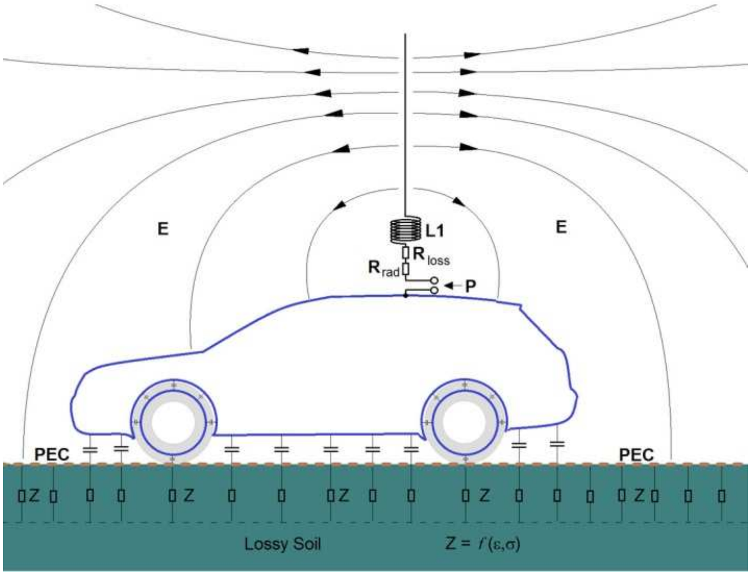
    (17:00 WS End)

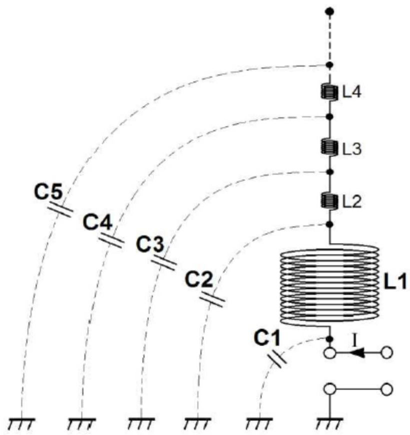
<u>Selected View-Graphs and Fig. Descriptions</u>

With a validated, trusted model (background realistic equivalent circuit see Fig.1, whip antennas are presently mostly in use in this field for civilian applications) one can fairly quickly and cost effectively run simulated parameter studies. At P the input TX power to the antenna is applied vs. the metallic car chassis. L1 is the resonating inductance, compensating the stray capacitance of the vertical radiator rod. A capacitive top loading may be added to reduce losses (less inductance, higher radiation resistance). Conjugate impedance matching at the feed point is important to get the maximum accepted power into the antenna.

Fig.1 Equivalent Circuit Model for an el. short, transmitting, vertical Monopole Antenna (no top loading, E-Field simplified, PEC: perfectly conducting ground, stray capacitances visualized)

Stray capacitance at the start of antenna is less effective for radiation and should therefore be minimized e.g. by moving the coil higher. That also increases radiation resistance/efficiency. The inductance (L_n) compensates the rod capacitance (C_n). We get resonance. This monopole antenna is excited against the metallic car body. The TX is inside the car. Ideally a low loss 50 Ohm impedance matching circuit is installed on the roof. By properly bonding the feeding coaxial cable, when leaving the passenger compartment, a good “inside” shielding effectiveness is maintained.





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The losses occur predominately in the real ground/soil. PEC means Zero loss over a perfectly conducting, large metal plate, similar to saltwater. There is additionally coil loss resistance (CU-losses + skin effect + inter-winding proximity effect). Electrically small antennas (low band) exhibit a very small radiation resistance of may be less than 1 ohm. For better efficiency we like to make this value as high as possible. Procedures will be discussed.

One ground/soil position example is given in Fig.2. Audi A6 Avant test car with 160m Monopole on a saltwater beach.

The coupling to the ground is primarily important on the low bands. This affects capacitance between car body/chassis and ground. In case of a real ground/soil a frequency dependent dielectric epsilon and conductivity sigma comes into play.

Fig.2 Audi A6 test car with 1.8 MHz / 160m (3.5m long radiator, large Hi-Q coil, 1m diameter top load) Monopole on a saltwater beach. This is only a stationary, experimental reference antenna.

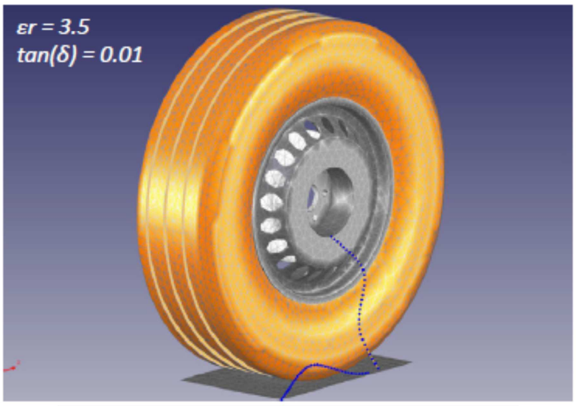
Fig. 3 shows the individually measured and simulated capacitance of a BMW tire (similar to Audi). Measurements were taken with a Vector Network Analyzer and a 1 kHz low frequency capacitance bridge (not shown). Losses up to 7/10 MHz are minor.

Fig.3 Validation of Wheel/Tire Model

Part I: Validation of Wheel Model

BMW 316i Individual Tire/ Rim Capacitance Tests (Model 1)

Measurement Setup



Simulation Model in EMCoS Studio

Model BMW 316i Wheel (Metal Sheet 35 cm x 25 cm)	Capacitance
Measurements	53 pF
Simulations (without test leads)	57.7 pF
Simulations (with test leads)	58.5 pF

Measurements were provided by EES Dr. Hansen Consulting

Fig. 4 demonstrates the car body + tire capacitance (basically lossless up to 10MHz). This capacitance is an important element in the near field coupling current return path of the antenna through soil / ground. These values are to our knowledge not publishes elsewhere, doing a systematic investigation. Audi A6 Avant over metal plane (PEC) with/out tires: tires about 400pF, car body about 600pF

Fig.4 Measurement and simulation results car body with/out tires

Part II: Audi A6 Avant Capacitance Tests

Comparison of Simulation and Measurement Results

Audi A6 Avant (Ground Plane 3.5 m x 7 m)	Capacitance
Measurements (car body/ rim/ break disk/ tire)	900 pF – 1000 pF
Simulations (car body/ rim/ break disk)	613 pF
Simulations (car body/ rim/ break disk/ tire)	1023 pF

- *Intel Xeon CPU L5640 @ 2.27 GHz (12 cores)*
- *Calculation time ~20 min*

Measurements were provided by EES Dr. Hansen Consulting

Note:

Characteristics, geometric parameters and internal structure of the tires play important role in the capacitance simulation. Slight changes will have an impact.

Fig.5 shows the charge density concentation in the static model at the low part of the tires.

Part II: Audi A6 Avant Capacitance Tests

Simulation Results (Car Body with Tires)

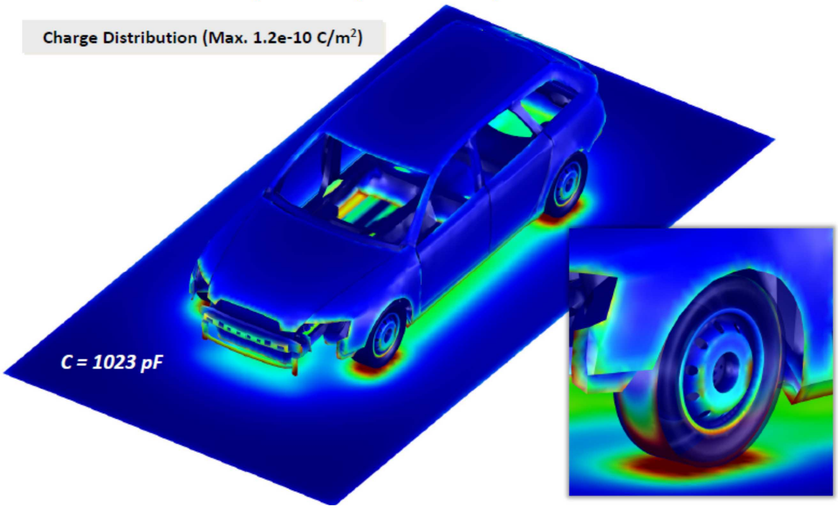


Fig.6 displays test and simulation result for real ground (15/003) of the Reference R&D 80m XL antenna

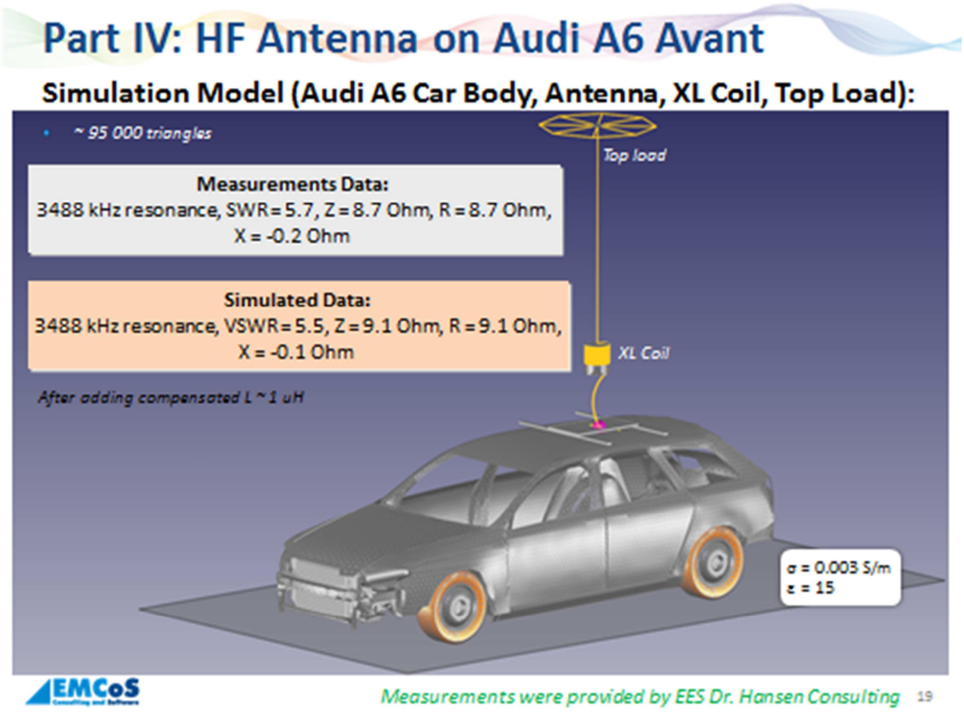


Fig.7 Audi A6 over real ground (poor 0.001S/m, Epsilon 5), FYI: avg. 0.05/13, very good 0.03/20, sea water5/80. Aside from **XL**, other Reference Antenna Simulations **XXL** (160m, 1.8MHz) and **L** (49m, 7 MHz) will be shown.

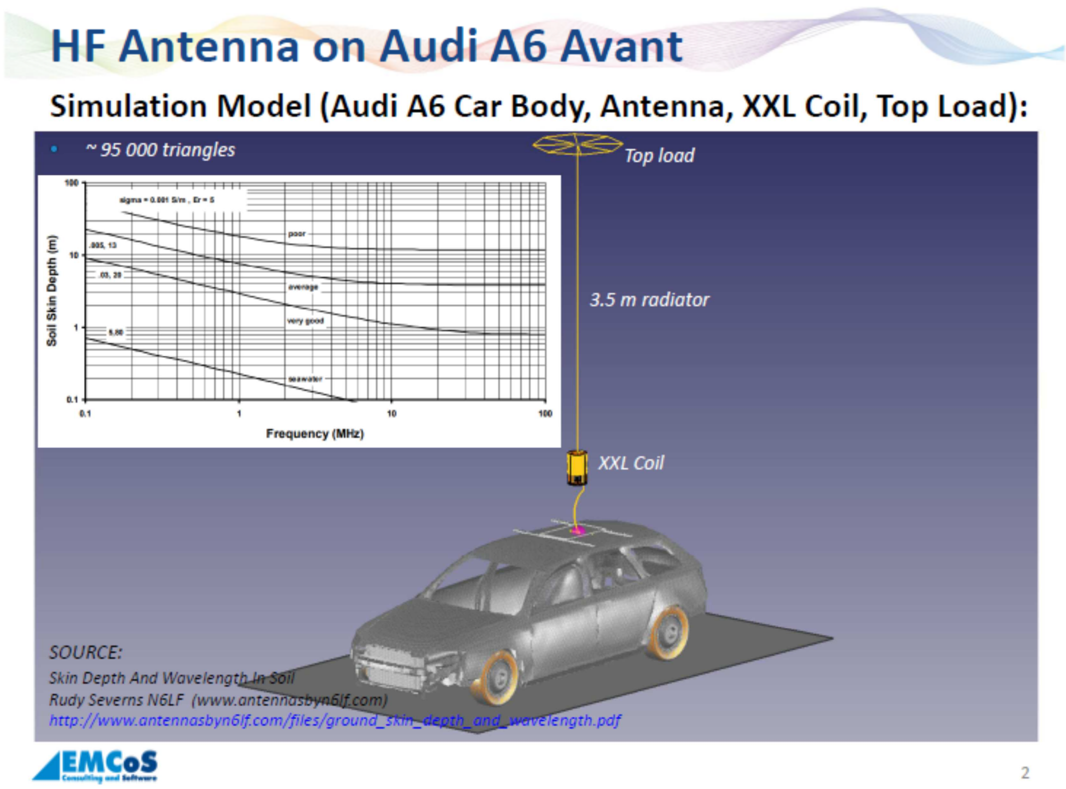


Fig.8 shows simulated Reference Antenna XL Data, 80m ant.-efficiency in [dB] for various grounds and Elevation-Angles. Max. performance difference is approximately 14dB, a major variation/loss contribution.

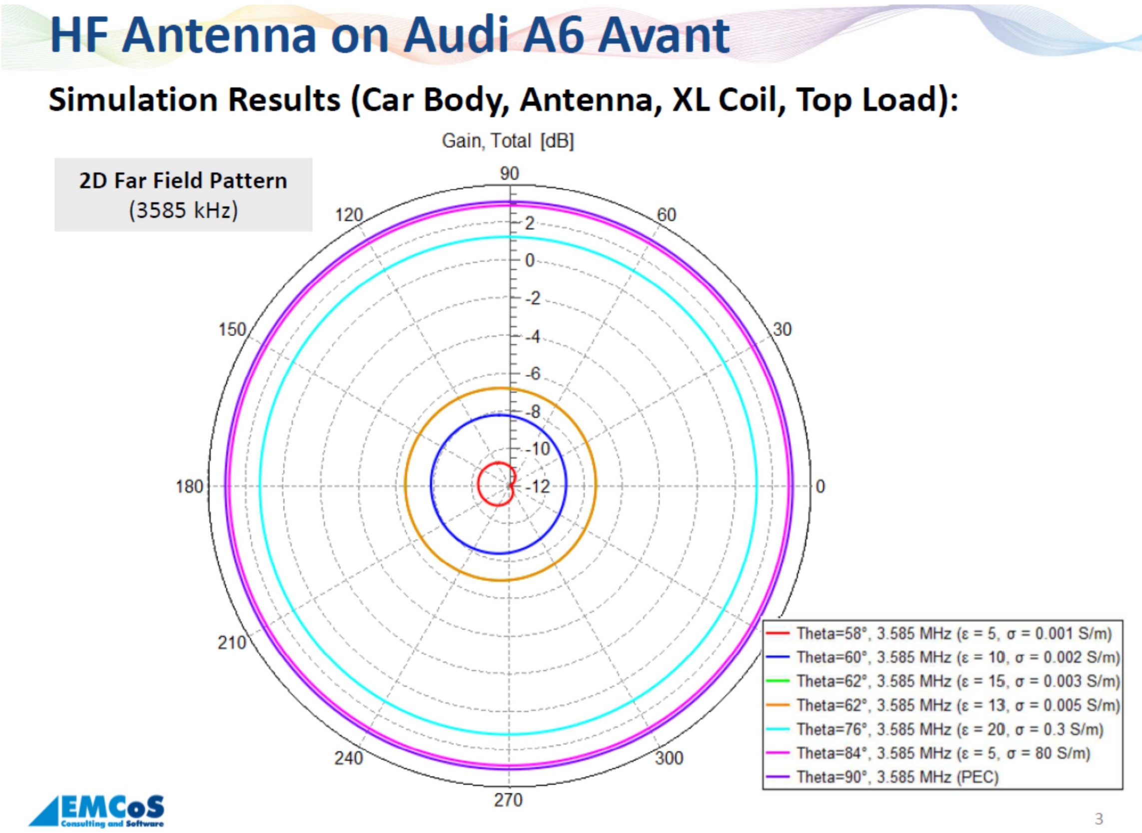


Fig.9 shows simulated 80m XL ant.-efficiency in [dB] for **PEC Ground** and max., flat 0deg. Elevation. Tires do not really contribute to efficiency, but change system resonance.

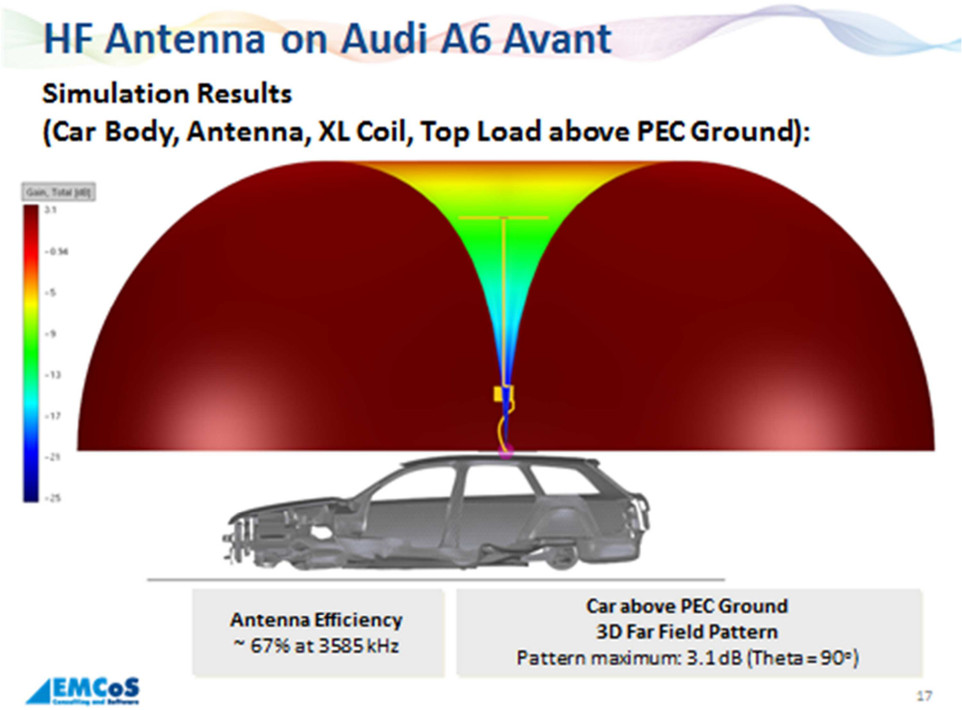


Fig.10 presents 6.5% (80m) efficiency for (90-62=>38 deg. Elevation), rich Farm Land ground. **Sky-Wave tests** indicate approx., in 900 km distance, *6%* (-12.2 dB mean, std. dev.3.8dB), **Ground-Wave tests** show *2 to3 %*.

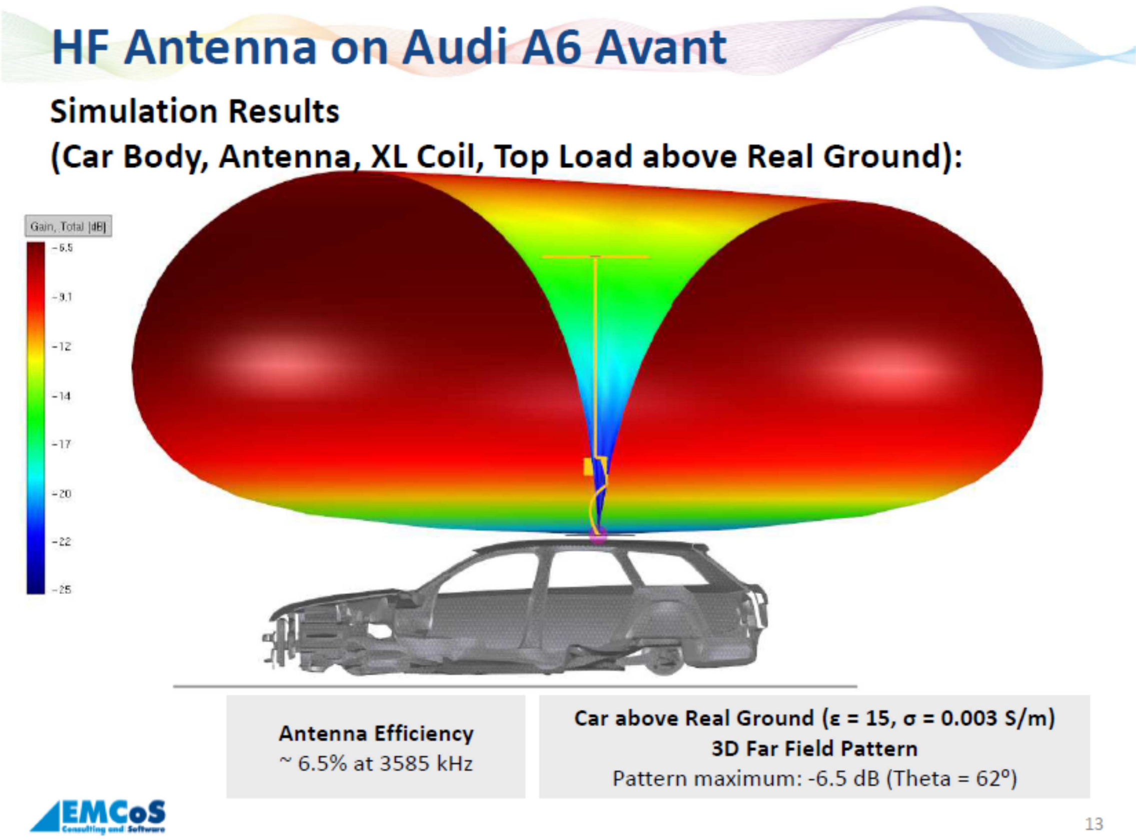


Fig.11 shows 2.4 % (80m, simulated) efficiency for (90-58=>32 deg. elevation), over more lossy Road Soil (5/0.001)

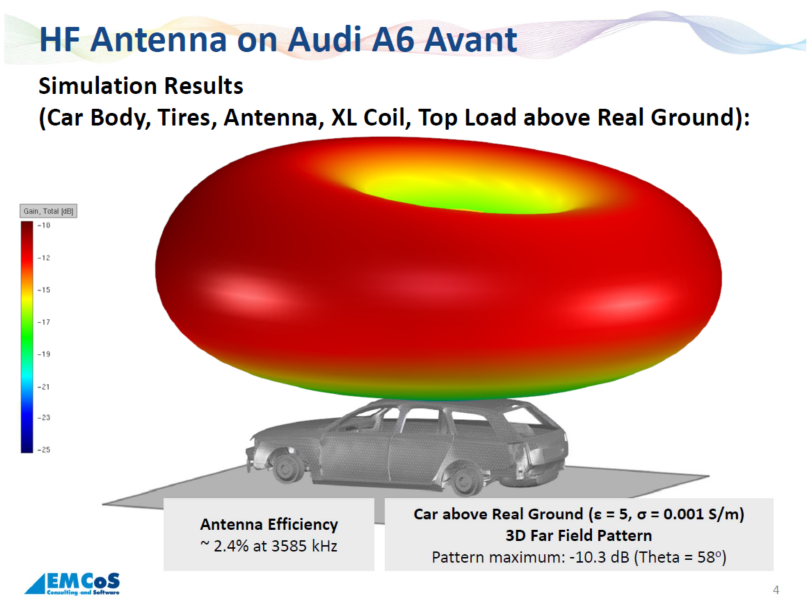


Fig.12 Antenna with “lower antenna height/profile”, resonated around 3.5 MHz; we are now looking for different antenna principles (Near Field is E dominant).

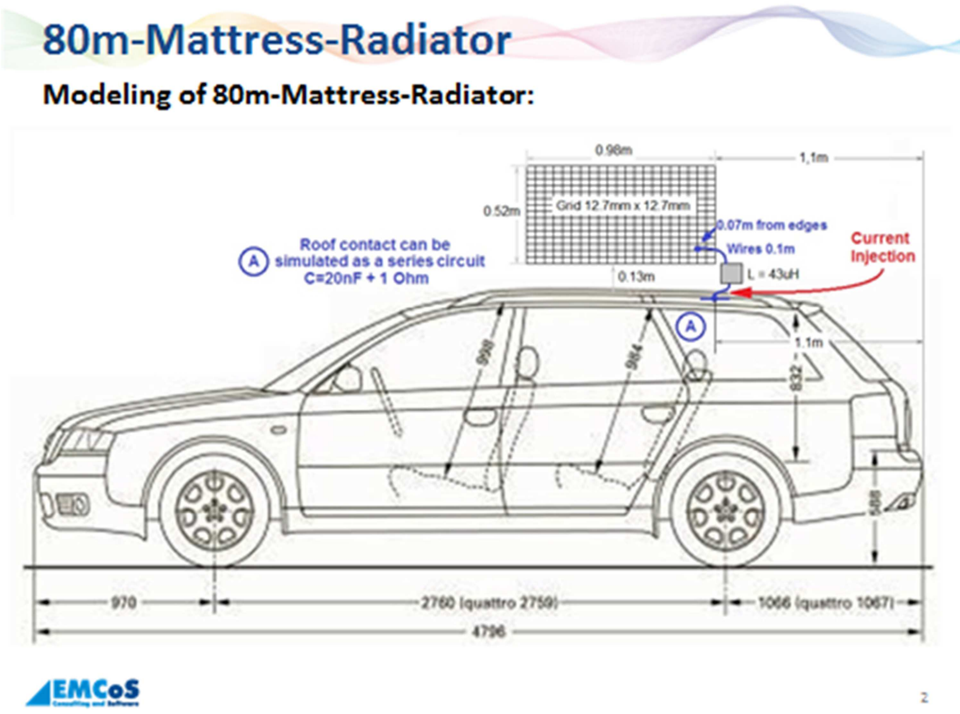
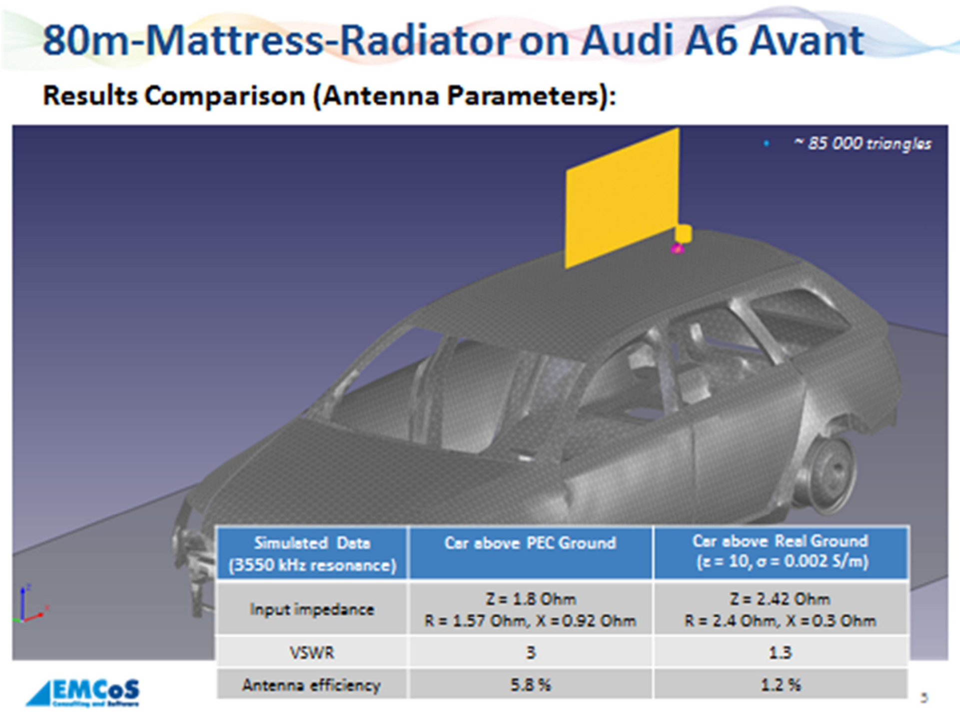
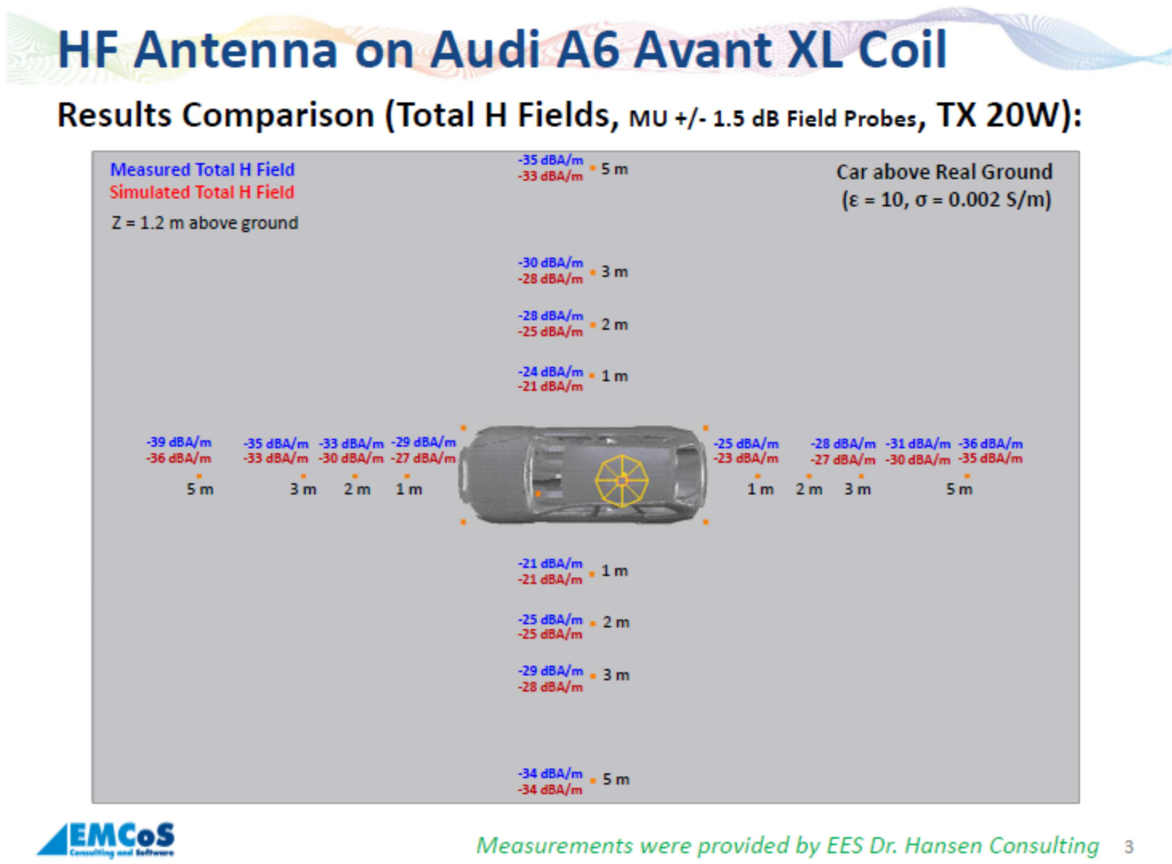


Fig.13 **Simulation** of Ant. Efficiency with lower eff. antenna height (over PEC, real ground) – **Ground-Wave tests** revealed about 0.2 % efficiency, over good ground (10/0.002).



Simulated Data (3550 kHz resonance)	Car above PEC Ground	Car above Real Ground (ε = 10, σ = 0.002 S/m)
Input impedance	Z = 1.8 Ohm R = 1.57 Ohm, X = 0.92 Ohm	Z = 2.42 Ohm R = 2.4 Ohm, X = 0.3 Ohm
VSWR	3	1.3
Antenna efficiency	5.8 %	1.2 %

Fig. 14 **Near-Field (mag. H-Field) around the Audi** A6, on an asphalted parking lot, at **3585 kHz** / Refereence Ant (XL 80m) shows **very good agreement between measurement and simulation**. The measurement uncertainty of the sensor instrument is about +/-1.5 dB. This indicates valid simulation results. This proves the suitability of the computer code used.



Literature:

[0] Measurement Methodology and Results of Measurements of Man-Made Noise Floor on HF in The Netherlands, T.W.H. Fockens, A.P.M. Zwamborn, F. Leverink, IEEE Transactions on EMC, Vol 61, No. 2, April 2019

[1] Antennas for all Applications, 3. Ed., John D. Kraus et. al, McGraw-Hill ISDN 0-07-112240-0, 2002

[2] Antenna Theory, Analysis and Design, 4.Ed, Constantine A. Balanis, WILEY, ISBN 978-1-118-642060-1, 2016

[3] SMALL ANTENNA HANDBOOK APPENDIX A, A WORLD HISTORY OF ELECTRICALLYSMALL ANTENNAS,
Robert C. Hansen and Robert E. Collin, 2011 John Wiley & Sons, Inc. Publisher, 2011

[4] Design and optimization of electrically small antennas for HF applications, James M. Baker, Ph.D. Dissertation, Dec. 2014, University of Hawaii (at Manoa)

[5] Optimizing the Receiving Properties of Electrically Small HF Antennas, Steven R. Best, MITRE Corporation, Bedford, MA 01730 USA, in The Radio Science Bulletin No 359 (December 2016), pp.13-28

[6] L. J. Chu , PHYSICAL LIMTATIONS OF OMNIDIRECTIONAL ANTENNAS, MIT Research Lab of Electronics , Ma, USA, TR No.64 , May 1, 1948

[7] H. A. Wheeler, "Fundamental limitations of small antennas," Proceedings of the IRE, vol. 35, pp. 1479-1484, 1947

[8] Near Vertical Incidence Skywave, Interaction of Antenna and Propagation Mechanism, Ph. D. Thesis Ben A. Witvliet, Faculty of Electrical Engineering, Mathematics and Computer Science, University of Twente, P. O. Box 217, 7500 AE Enschede, the Netherlands, 2015, ISBN: 978-90-365-3938-

[9] Near Vertical Incidence Sky-Wave Propagation: Elevation Angles and Optimum Antenna Height for Horizontal Dipole Antennas, Ben A. Witvliet, Erik van Maanen, George J. Petersen, Albert J. Westenberg, Mark J. Bentum2, Cornelis H. Slump, Roel Schiphorst, Univ. of Twente and Radio Agency Netherlands, IEEE Antennas and Propagation Magazine, Vol. 57, No. 1, Feb. 2015, pp.1 -18

[10] Short Coil-Loaded HF Mobile Antennas: An Update and Calculated Radiation Patterns, Dr. John. S. Belrose, Ottawa, Canada, in “The ARRL Antenna Compendium Vol.4, 1996”, ISBN 0-87259-491-2, pp. 83-91

[11] Automotive Electromagnetic Compatibility Prediction and Analysis of Parasitic Components in
Conductor Layouts, Sabine Alexandersson, Doctoral Thesis 2008, Lund University, Sweden, p24 ff
(“Impedance of tires up to 1 MHz”), ISBN 978-91-88934-48-2

[12] CISPR TR 16-3 ED4 Draft (6/2019, e.g. in-situ testing over real ground in CISPR 11)

[13] Issues Concerning Radio Noise Floor Measurements using a Portable Measurement Set-up, Koos (T. W. H.) Fockens, Frank Leferink, Proc. of the 2018 International Symposium on Electromagnetic Compatibility (EMC Europe 2018), Amsterdam

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