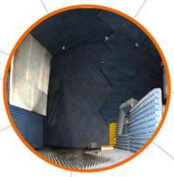
Investigation of Probe (Im)perfection vs Measurement Accuracy in Spherical Near-Field Systems

MVG
Microwave Vision Group

April 22, 2021, On-Line, AMTA Regional Event



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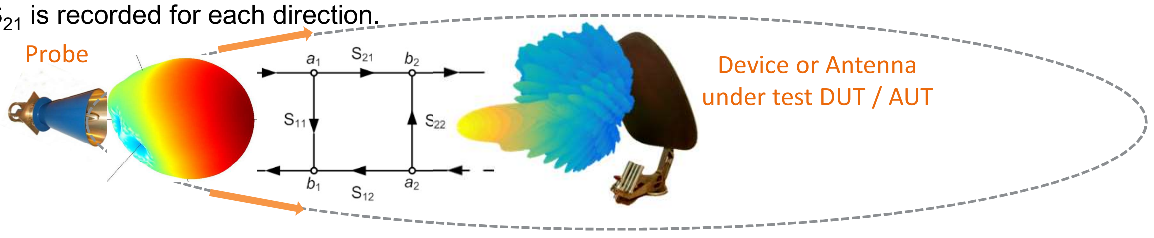
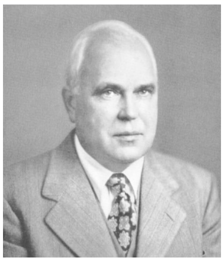
Introduction to Antenna Measurements

- Antenna measurements are an evaluation of the radiation characteristics in the Far Field (FF). This is a paradox since a major part of our daily communication is in the Near Field (NF). However, the FF is a convenient common standard situation for antenna evaluation and comparison.
- In the FF the normally spherical wave front of an antenna becomes a plane wave. Testing in FF conduction is thus equal to exposing the DUT to a plane wave from the probe (and vice-versa).
- The simplest but not necessarily most practical way to evaluate antenna radiation is to measure the coupling, S_{21} between, the Device/Antenna Under Test (DUT/AUT) and a probe antenna, directly at FF distance.
- Either the probe or DUT is fixed – commonly the probe. The other antenna is moved while the coupling S_{21} is recorded for each direction.



Introduction to Antenna Measurements

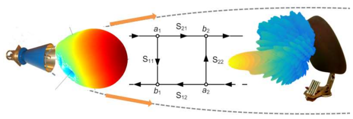


- Harald Trap Friis was a Danish scientist know for his significant contributions to radio propagation, radio astronomy, and radar while working at Bell Laboratories (US).
- His two Friis formulas on noise and transmission remain widely used today.
- *Friss Transmission Formula*:

$$S_{21}^{dB} = Pathloss^{dB} + Gain_{Probe}^{dB} + Gain_{DUT}^{dB}$$

$$S_{21} = \frac{Power_{DUT}}{Power_{Probe}}$$

$$Pathloss^{dB} = FSPL^{dB} + SystemLoss^{dB}$$



Free Space Path Loss

$$FSPL^{dB} = 20log10\left(\frac{\lambda}{4\pi Distance}\right)$$

- The S21 is directly linked to the gain of the DUT, Probe and the distance between them.
  - Note that at a distance of one wavelength from the source the FSPL is ~ -22dB.
  - Each time the distance increases by a factor of 2 the FSPL increases 6dB.
- Knowing the pathloss and the probe gain the gain of the AUT can be determined (however, not always possible and not always accurate)

Introduction to Antenna Measurements

- A widely used technique to determine antenna gain in both FF and NF is the Gain Substitution Technique. It requires a second measurement with a calibrated (known) reference antenna.

1st Measurement (System Calibration):

$$S_{21REF}^{dB} = Pathloss_{REF}^{dB} + Gain_{Probe}^{dB} + Gain_{REF}^{dB}$$

2nd Measurement:

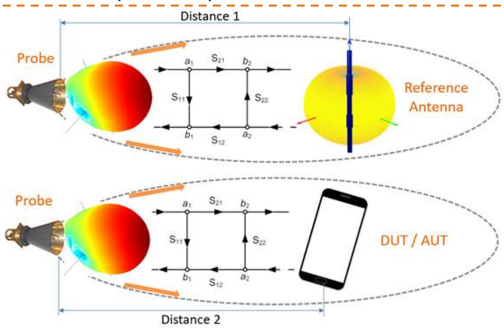
$$S_{21DUT}^{dB} = Pathloss_{DUT}^{dB} + Gain_{Probe}^{dB} + Gain_{DUT}^{dB}$$

Gain Determination:

$$Gain_{DUT}^{dB} = S_{21\,DUT}^{dB} - S_{21\,REF}^{dB} + Gain_{REF}^{dB} - \Delta Pathloss_{DUT-REF}^{dB}$$

Isotropic Power to Probe Power ratio:

$$S_{CAL}^{dB} = S_{21REF}^{dB} - Gain_{REF}^{dB} = Power_{Probe}^{dB} - Power_{DUT\,Isotropic}^{dB}$$



- The first measurement in the gain substitution technique is also a System Calibration. The term S_{CAL}^{dB} is the ratio of isotropic power "in-to" or "out-of" Probe / DUT (for a given measurement distance). The probe becomes a virtual connectorized port of the DUT.

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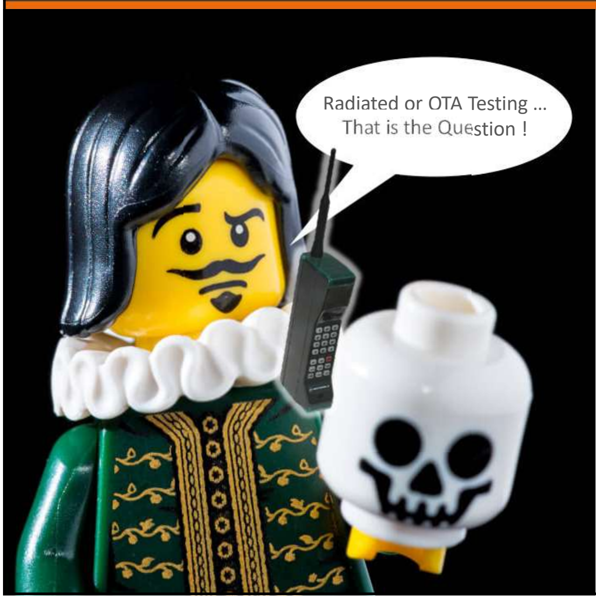
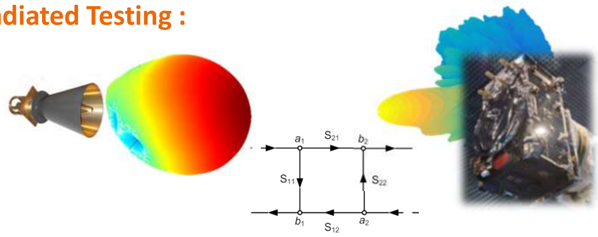
Introduction to Antenna Measurements (OTA)



Radiated Testing :



OTA Testing :

After system calibration, the probe becomes a **virtual connectorized port** of the DUT

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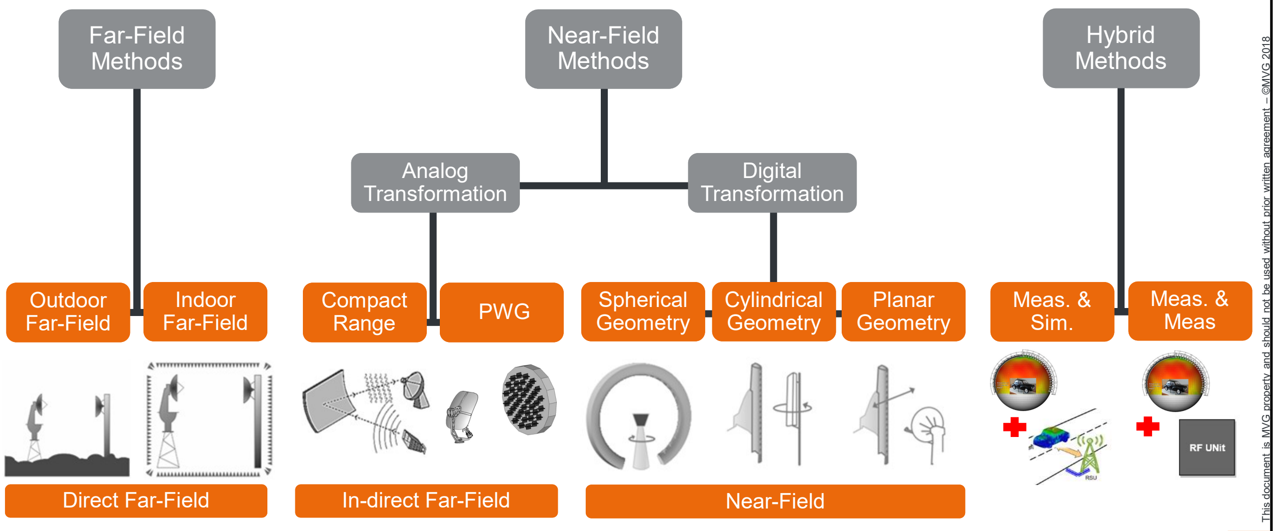
Modern Measurement Solutions



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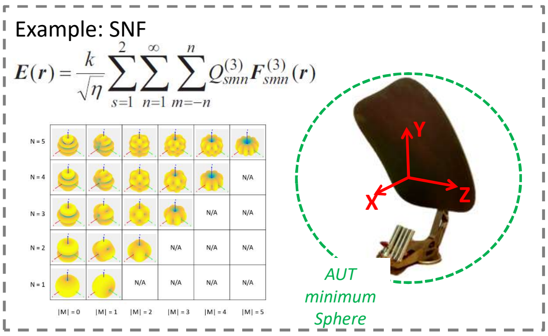
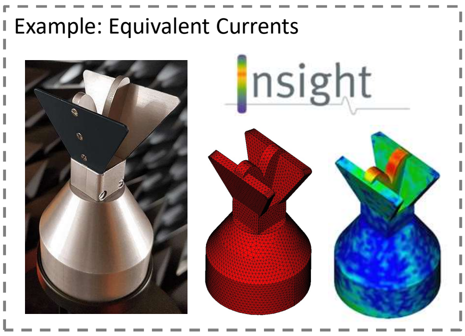
Measurement emulation "toolbox"

- Examples of NFFF expansion functions are :
  - PNF: Plane waves
  - SNF: Spherical wave functions
  - CNF: Cylindrical wave functions
  - Any near field geometry: Equivalent Electric and Magnetic Currents (important for diagnostics).





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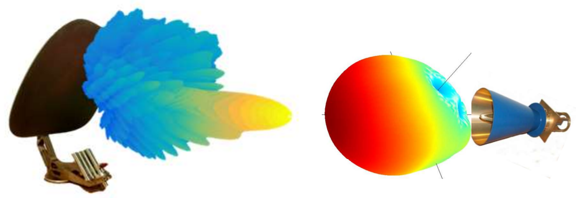
Measurement emulation "toolbox"

- The classical spherical wave transmission formula determines the coupling between the probe and AUT given their respective spherical modal spectrum.



Measured Signal

$$w(A,\chi,\theta,\phi) = \frac{1}{2}\sum_{\substack{smn\\ \sigma\mu\nu}} Q^{(3)}_{smn} e^{jm\phi} d^{n}_{\mu m}(\theta) e^{j\mu\chi} C^{sn(3)}_{\sigma\mu\nu}(kA) R^{p}_{\sigma\mu\nu}$$

DUT coefficients

Rotation & Translation Functions

Probe coefficients

- Limitations:
- Minimum sphere of AUT and probe cannot overlap. A minimum distance is needed.
- Only forward coupling between AUT and probe (no multiple reflections) but takes into account all NF effects of both antennas.

J. E. Hansen (ed.), "Spherical Near-Field Antenna Measurements", Peter Peregrinus Ltd., on behalf of IEE, London, United Kingdom, 1988

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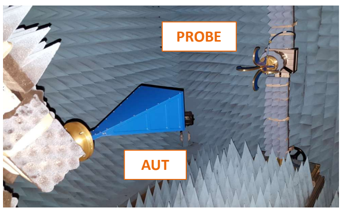
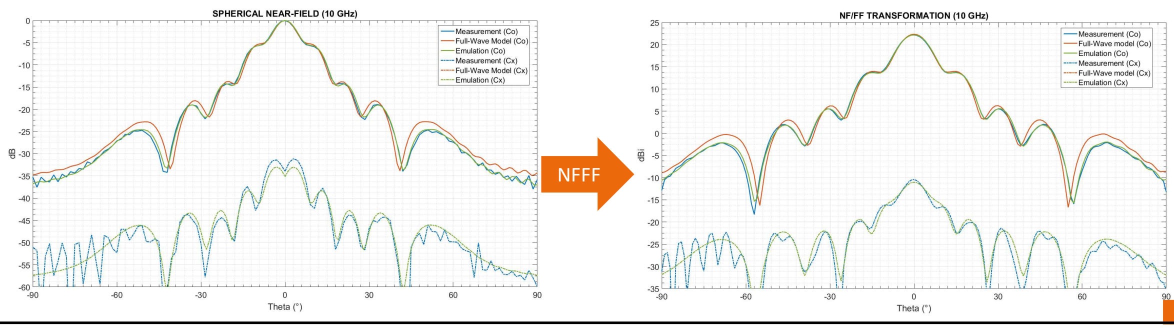
Measurement emulation "toolbox"

- "Accuracy" of the TX-formula:
  - Measurement of an SGH @ 10GHz with a "dirty" probe (QH800)
  - Full-wave model of the SGH used in the TX-formula (AUT)
  - Full-wave model of the QH800 used in the TX-formula (PROBE)
  - Excellent agreement between measurement and emulation (both in NF and after NF/FF transformation & in co-polar and cx-polar)





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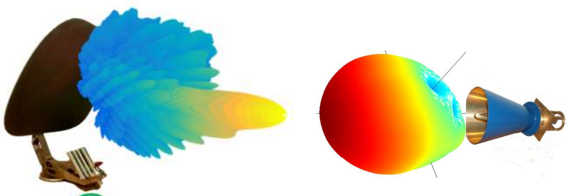
Measurement emulation “toolbox”

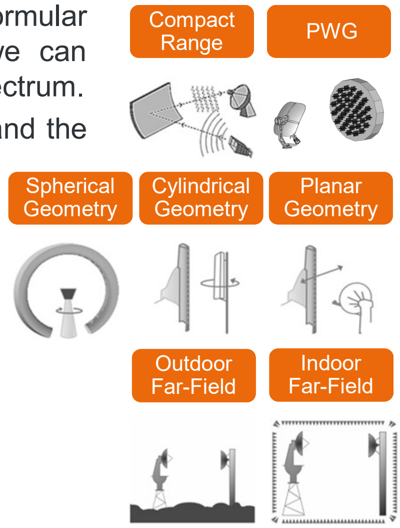
- The “probe” in the classical spherical wave transmission formular can be almost any antenna measurement system that we can measure or model and thus determine the spherical mode spectrum.
- The “probe” or AUT can be interchanged when one is fixed and the other moving.



Measured Signal

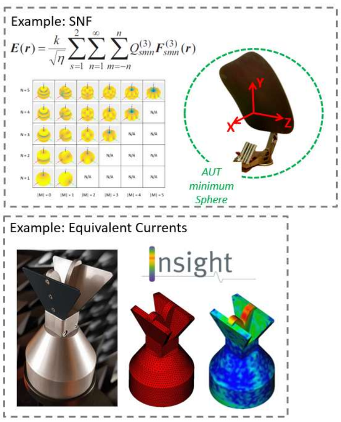
$$w(A,\chi,\theta,\phi) = \frac{1}{2}\sum_{\substack{smn\\ \sigma\mu\nu}} Q^{(3)}_{smn} e^{jm\phi} d^{n}_{\mu m}(\theta) e^{j\mu\chi} C^{sn(3)}_{\sigma\mu\nu}(kA) R^{p}_{\sigma\mu\nu}$$

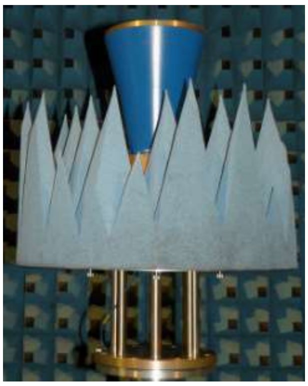
DUT coefficients — *Rotation & Translation Functions* — *Probe coefficients*



SP1100 “First Order” Probe Higher Order Mode Errors.

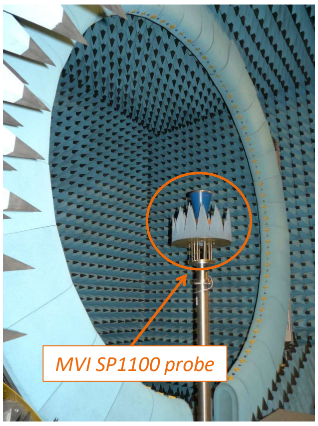
- Investigation of higher order spherical modes in dual polarized probe SP1100 (1.1-2GHz) @ 1.25GHz from measurements.
- We use spherical mode and equivalent current expansion of measured data.

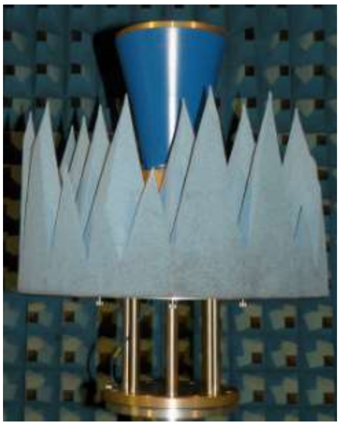


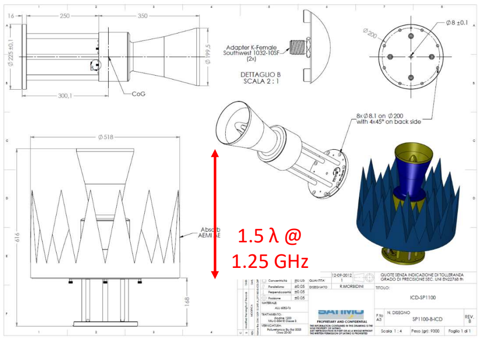


SP1100 “First Order” Probe Higher Order Mode Errors.

- SP1100 (1.1-2GHz) during measurement in SG64 spherical multi-probe system in Paris.
- Investigated frequency is 1.25GHz.







L. J. Foged, A. Giacomini, F. Saccardi and L. Scialacqua, "Analysis of measurement probe spherical higher order modes based on equivalent currents," 2016 IEEE International Symposium on Antennas and Propagation (APSURSI), Fajardo, 2016, pp. 1329-1330.

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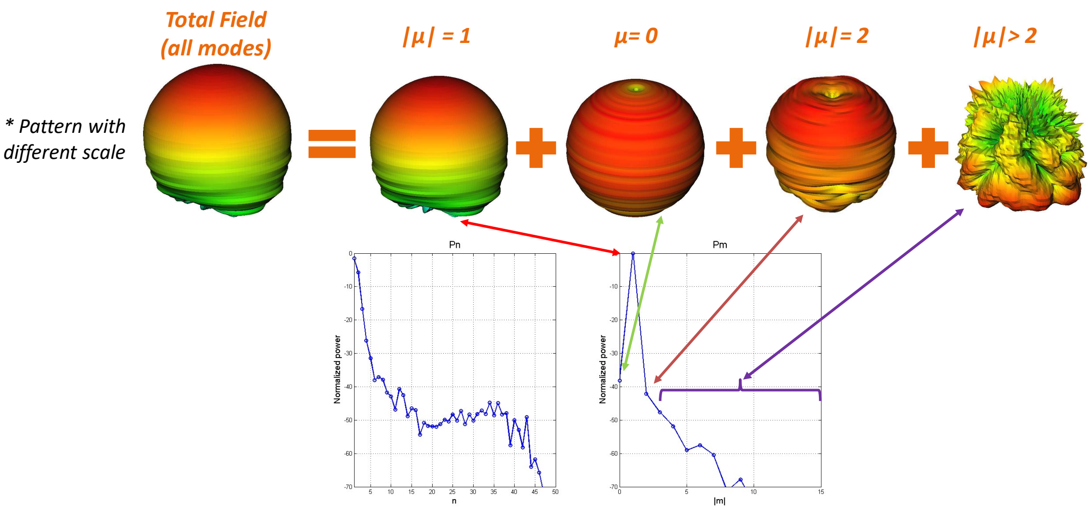
SP1100 “First Order” Probe Higher Order Mode Errors.

- Different |μ|-modes have been isolated to investigate their origin. (F=1.25GHz)



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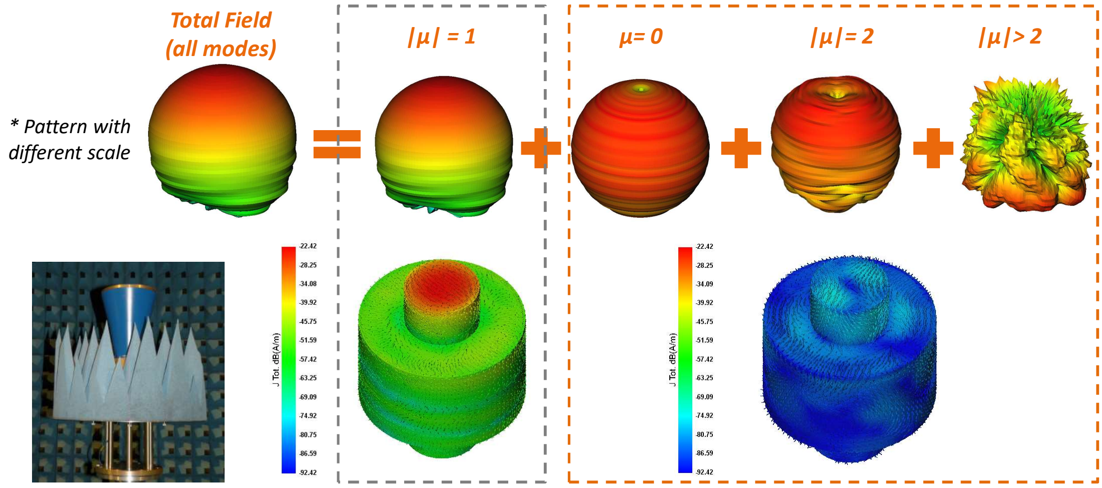
SP1100 "First Order" Probe Higher Order Mode Errors.

- |μ| = 1 modes have been isolated to investigate their origin.



- Contributes from higher order modes are very low - |μ| = 1 modes are from aperture.

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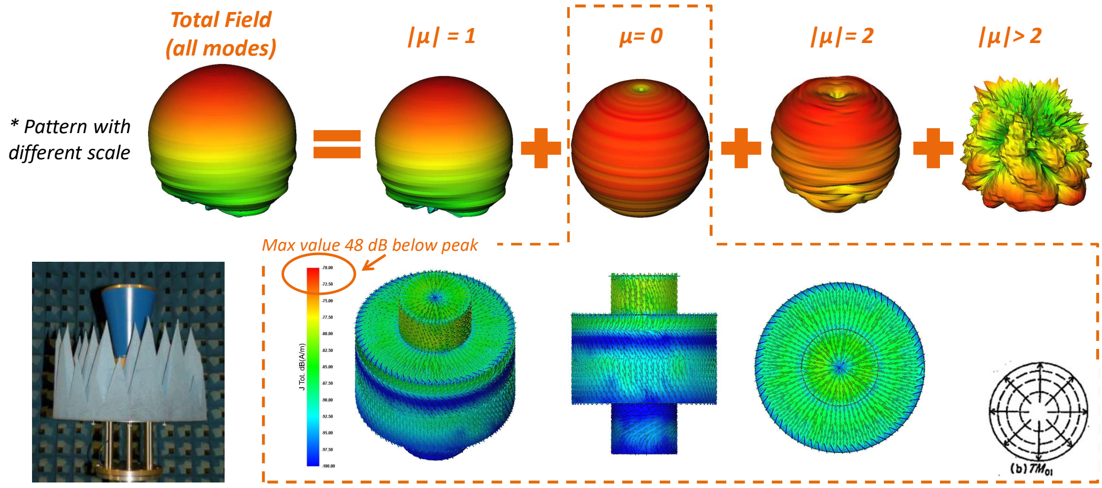
SP1100 "First Order" Probe Higher Order Mode Errors.

- |μ| = 0 mode have been isolated to investigate the origin. (F=1.25GHz)



- **μ = 0** is (mainly) associated to the radiation of the TM_{01} mode in a circular waveguide.

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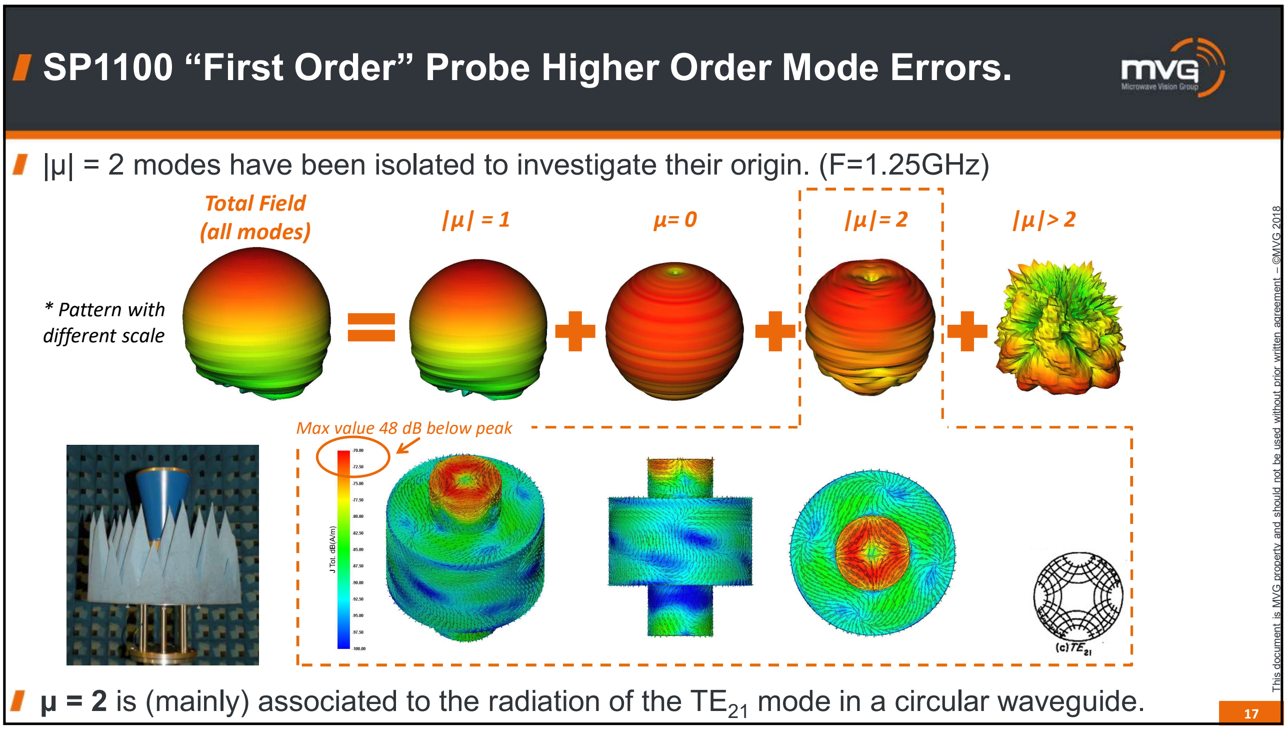
SP1100 “First Order” Probe Higher Order Mode Errors.
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|μ| = 2 modes have been isolated to investigate their origin. (F=1.25GHz)
Total Field (all modes)
|μ| = 1
μ= 0
|μ|= 2
|μ|> 2
* Pattern with different scale
Max value 48 dB below peak
(c) TE_{21}
μ = 2 is (mainly) associated to the radiation of the TE_{21} mode in a circular waveguide.
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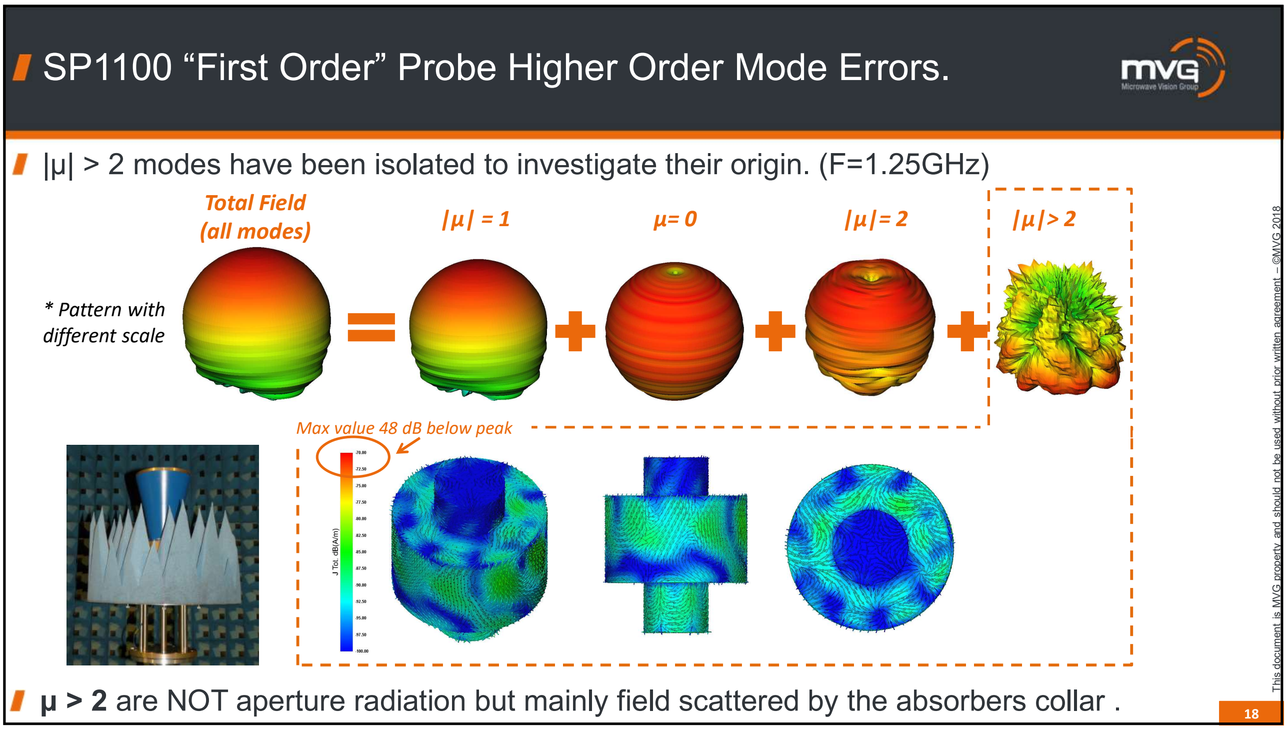
SP1100 “First Order” Probe Higher Order Mode Errors.
mvg Microwave Vision Group
|μ| > 2 modes have been isolated to investigate their origin. (F=1.25GHz)
Total Field (all modes)
|μ| = 1
μ= 0
|μ|= 2
|μ|> 2
* Pattern with different scale
Max value 48 dB below peak
μ > 2 are NOT aperture radiation but mainly field scattered by the absorbers collar .
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SP1100 “First Order” Probe Higher Order Mode Errors.

- A “first order” (μ = +/- 1) probe has been measured and analyzed for sources of higher order mode content using expansions in spherical wave and equivalent currents
- Classical probe corrected Spherical NF measurement require a probe with first order spherical modes. This requirements is needed in classical probe compensated NFFF transformation.
- The measured SP1100 has very little higher order spherical mode content. The cause of these modes has been analyzed in detail using INSIGHT.
- Spherical higher order modes (μ = 0 and |μ| = 2) are mainly radiated by the aperture and thus due to undesired waveguide modes (TM_{01} and TE_{21}), caused by BFN errors.
- |μ| > 2 modes are due to the field re-radiated by the absorber collar.

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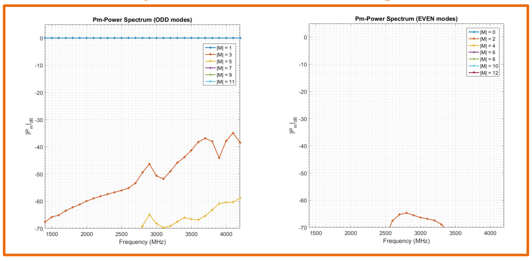
Influence of Probe Imperfections in SNF

- TX-formula is an excellent tool to study the influence of the probe imperfections on the measurement accuracy
- EXAMPLE → Quasi-first-order wideband probes (SP1400):
  - Bandwidth → 1:3 (1400 – 4200 MHz)
  - Directivity → 7 – 16 dBi
  - Dual linear polarization
  - Quasi-first-order probe → Higher order modes expected at higher frequency (mainly due to feeding errors)

Spectrum → Ideal Feeding



Spectrum → 0.5dB equivalent feeding error

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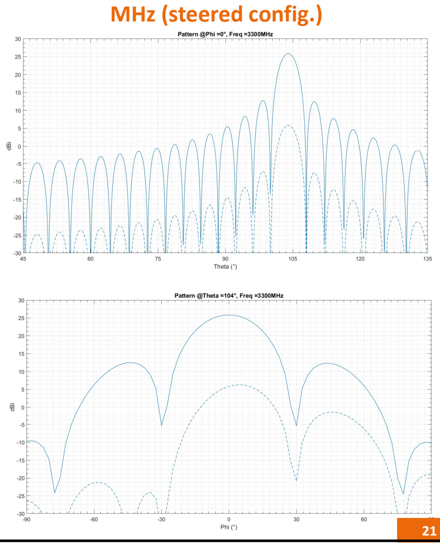
Influence of Probe Imperfections in SNF

Study applied to the measurement of base-station antenna

	Antenna for B1 1400 – 2700 MHz	Antenna for B2 2700 – 3300 MHz	Antenna for B3 3300 – 4200 MHz
Height	2.7 m	1.6 m	1.3 m
Columns	1	4	4
Offset (Z)	0 m	0.55 m	0.7 m
Min. Sphere (R_{min})	1.35	1.35	1.35
Directivity	19-22 dBi	26-27 dBi	26-28 dBi
Polarization	Slant 45°	Slant 45°	Slant 45°
Steering (Elev)	0° & -14°	0° & -14°	0° & -14°
HPBW (Elev)	3.9-2.0°	3.5-2.8°	3.4-2.6°
HPBW (Azim)	106°	24-20°	24-19°
1° SLL (Elev)	13.2 dB (6.3-3.3°)	13.2 dB (5.7-4.7°)	13.2 dB (5.5-4.3°)
1° Null (Elev)	35-60 dB (4.4-2.3°)	35-60 dB (4.0-3.2°)	38-55 dB (3.9-3.0°)
On-axis XPD	20 dB	20 dB	20 dB

Example of AUT pattern at 3300 MHz (steered config.)



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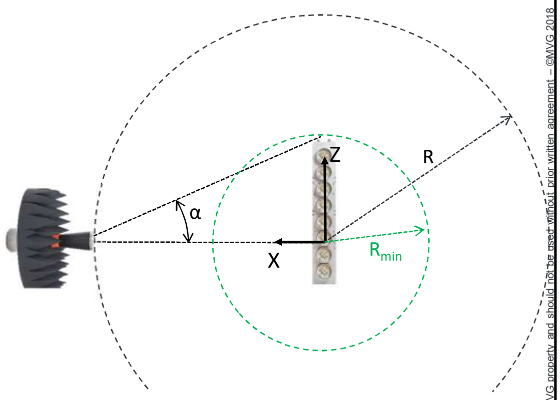
Influence of Probe Imperfections in SNF

Emulated measurement scenario

	Antenna for B1 1400 – 2700 MHz	Antenna for B2 2700 – 3300 MHz	Antenna for B3 3300 – 4200 MHz
Probe	SP1400	SP1400	SP1400
Measurement Radius (R)	2.09 m	2.09 m	2.09 m
AUT minimum sphere (R_{min})	1.35 m	1.35 m	1.35 m
Sampling (Δϑ)	1.5°	1.5°	1.0°
Sampling (Δφ)	5°	5°	5°
Max AUT-Probe View Angle (α)	32°	32°	32°



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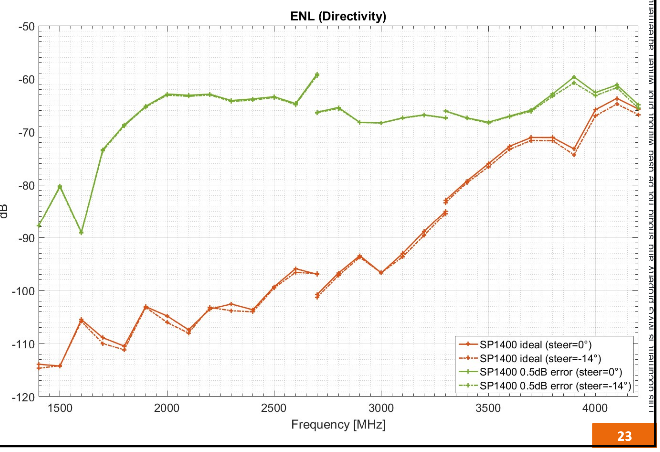
Study of influence of probe imperfections: EXAMPLE

- NF/FF transformation with 1st order probe correction is applied to the emulated measurements
- Equivalent Noise Level (ENL) on whole 3D pattern at different frequencies

$$ENL = 20\log_{10}\left(RMSE\left|\frac{E(\theta,\varphi) - \tilde{E}(\theta,\varphi)}{E(\theta,\varphi)_{MAX}}\right|\right)$$

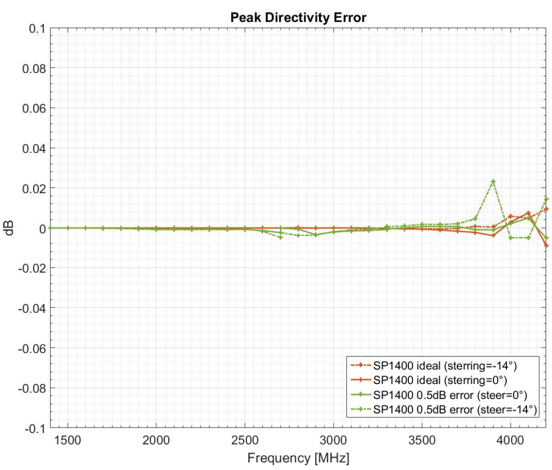
Examples of ENL and corresponding P2P errors at different Antenna Pattern Levels (APL)

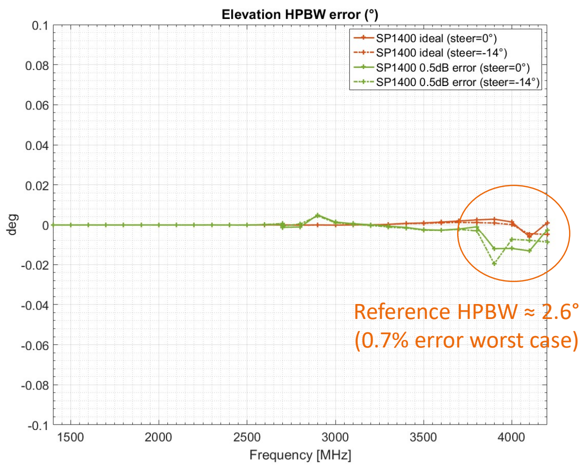
ENL	0 dB APL	-10 dB APL	-20 dB APL	-30 dB APL	-40 dB APL
-40 dB	0.17	0.54	1.66	4.77	12.04
-60 dB	0.02	0.05	0.17	0.54	1.66
-80 dB	0.00	0.01	0.02	0.05	0.17



Influence of Probe Imperfections in SNF

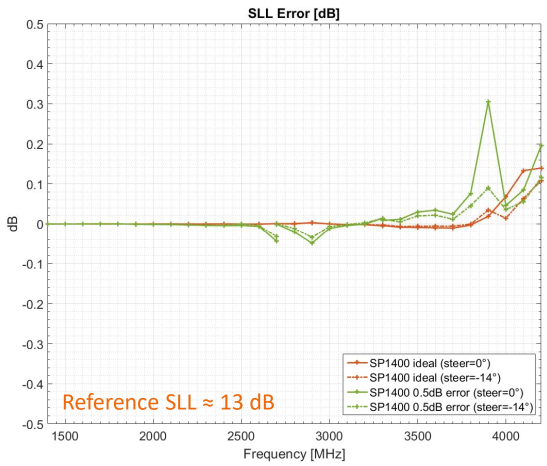
- Peak directivity & HPBW error

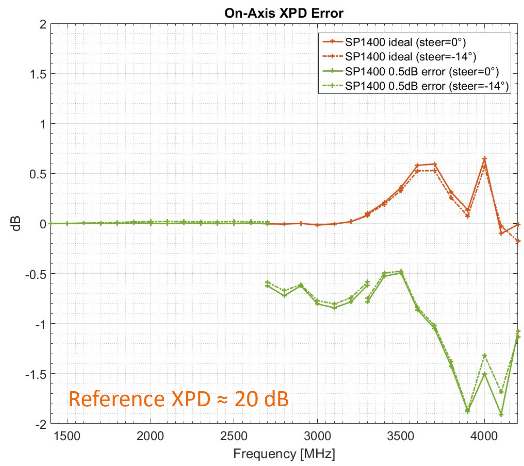




Influence of Probe Imperfections in SNF

- First SLL and on-axis XPD error





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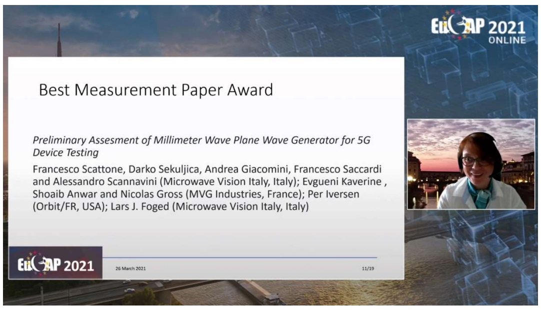
StarWave – Analysis and Design of moving PWG system

- Live-person & 5G enabled device testing at millimeter-wave frequencies (24-42GHz).
- Dual linear polarized, QZ of 350mm @ 1200mm distance.



F. Scattone, D. Sekuljica, A. Giacomini, F. Saccardi, A. Scannavini, S. Anwar, N. Gross, E. Kaverine, P. O Iversen, L. J. Foged, "Preliminary Assessment of Millimeter Wave Plane Wave Generator for 5G Device Testing", 15th European Conference on Antennas and Propagation, EuCAP 2021, Germany

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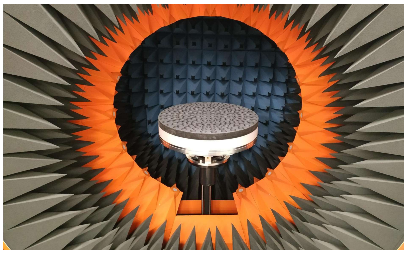
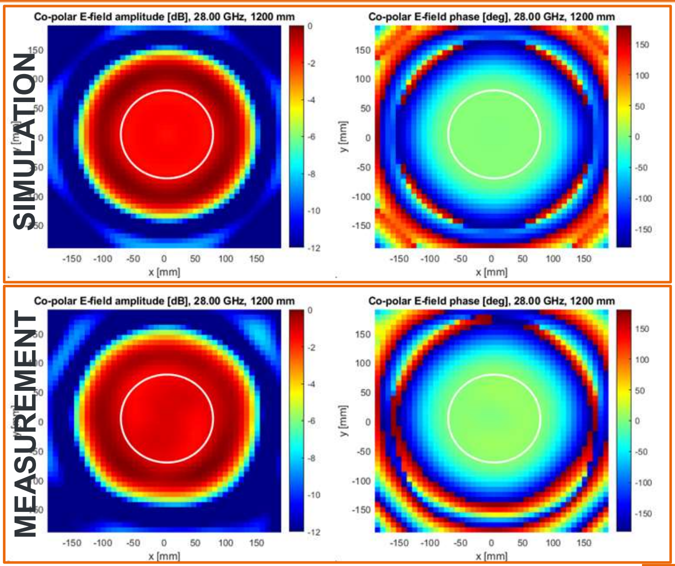
StarWave – Analysis and Design of moving PWG system

- Ex: The StarLab 50GHz measurements of ring-shaped sub-arrays were used to synthesize 150mm diameter QZ.

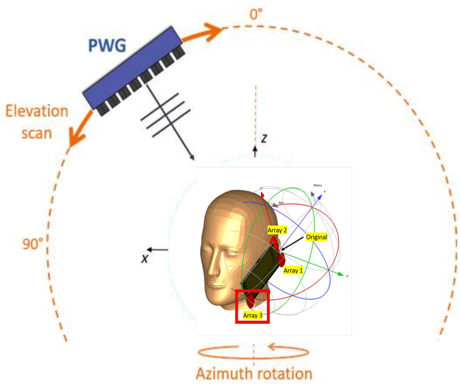


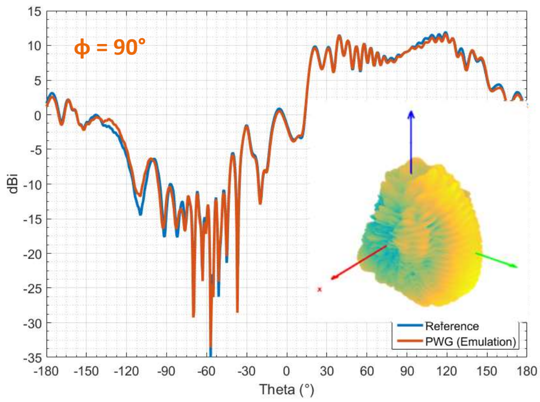
- The synthesized QZ shows the following characteristics (worst case within the entire spherical volume):
  - Δ Amplitude +/- 0.3 dB
  - Δ Phase +/- 5 deg



StarWave – Analysis and Design of moving PWG system

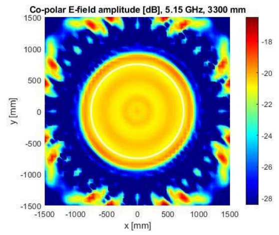
- Emulation of PWG measurement.
  - Simulated model of user equipment (UE)+ phantom @ 28 GHz (~30λ)
  - Three 4x1 phased arrays in different positions on the phone (array #3 is considered)

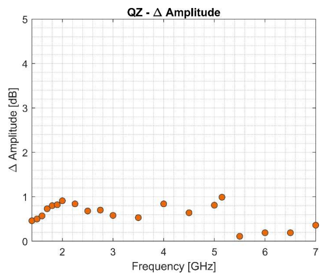


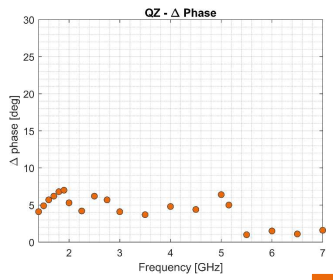


Plane Wave Generator (sub6GHz PWG)

- Application of array based PWG. Sub6GHz base-station testing at 600MHz*-7.1GHz.
- Room dimension: 6m x 3m x3m (for 2-7.1GHz system).
- Dual linear polarized, QZ of 150cm @ 330cm distance.







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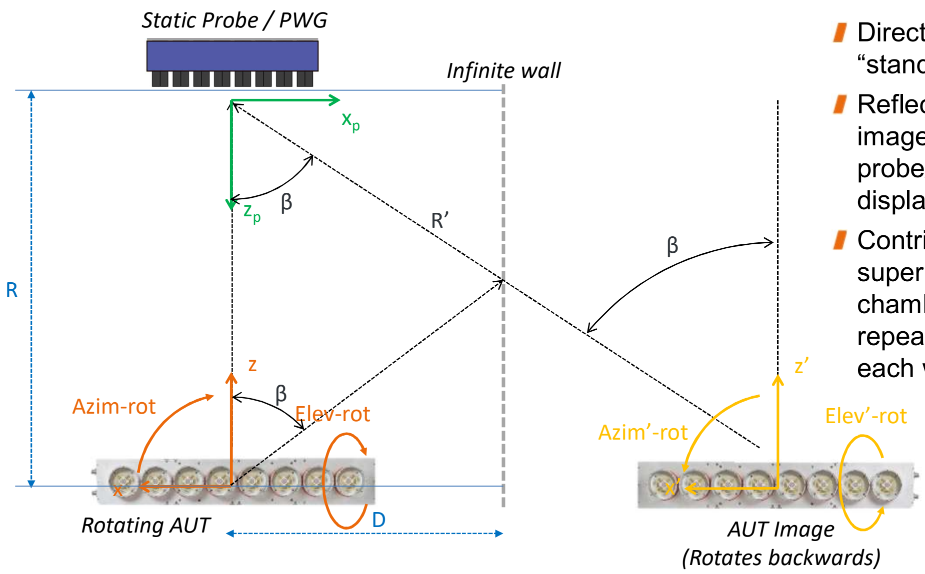
Emulating 1◦ order reflection / chamber effect with TX-Formula



- Direct field emulated in the "standard way"
- Reflections emulated with the image source and probe/PWG oriented and displaced accordingly
- Contributions are then superimposed (rectangular chambers can be emulated repeating this process for each wall)

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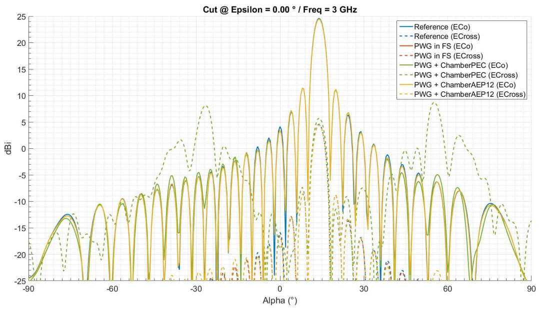
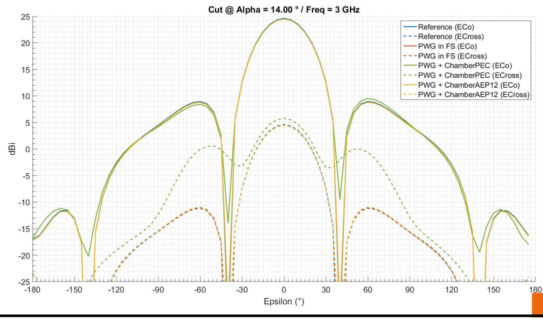
Emulation of base-station antenna measurement with PWG (+ 5 wall Chamber effect)

- 1.4-meter BTS @ 3 GHz
- 14◦ steered beam (25dBi)
- Elevation-Over-Azimuth scanning
- 1st order chamber effect (image theory)
  - PEC walls
  - Absorber walls (-40 dB)

	ENL Azim [dB]	ENL Elev [dB]	GAIN ERROR [dB]
PWG in Free-Space	-51.4	-47.4	-0.1
PWG + ChamberPEC	-29.6	-37.4	-0.1
PWG + ChamberAEP12	-51.3	-47.4	-0.1





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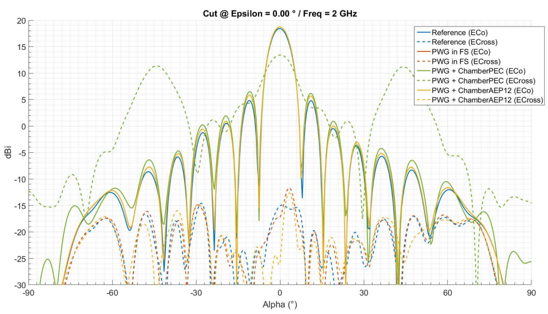
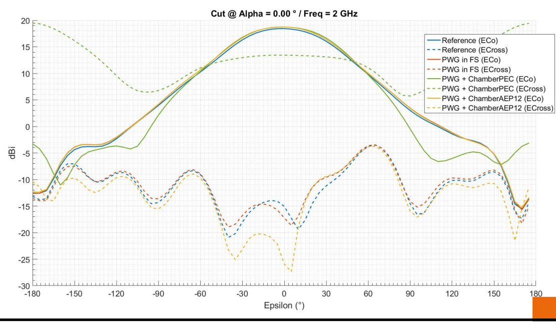
Emulation of base-station antenna measurement with PWG (+ 5 wall Chamber effect)

- BTS1940 @ 2 GHz (19 dBi)
- Emulation real measured data
- Elevation-Over-Azimuth scanning
- 1st order chamber effect (image theory)
  - PEC walls
  - Absorber walls (-35 dB)

	ENL Azim [dB]	ENL Elev [dB]	GAIN ERROR [dB]
PWG in Free-Space	-40.1	-34.7	0.3
PWG + ChamberPEC	-14.9	-5.8	1.4
PWG + ChamberAEP12	-39.8	-34.3	0.3





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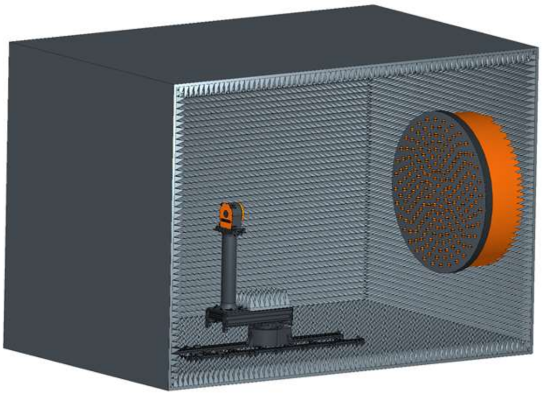
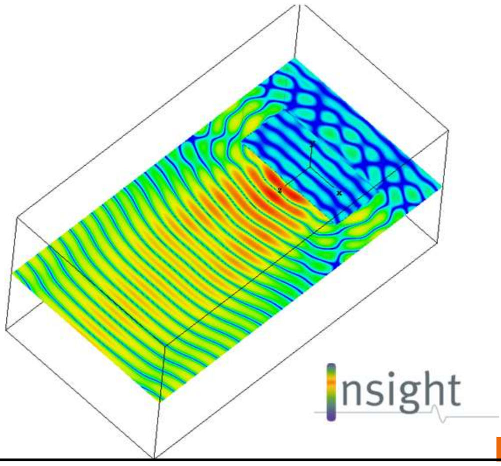
Plane Wave Generator (sub6GHz PWG)

- Application of array based PWG. Sub6GHz base-station testing at 600MHz*-7.1GHz.
- Full wave simulation of PWG and chamber using NFS box (INSIGHT).





Comments / Conclusions

- Different tools enable error evaluation of antenna measurement systems and chambers.
- The full antenna measurement system can be either a measured or simulated “probe”.
- The spherical wave transmission formular enable to appreciate the coupling between a “probe” and AUT. Almost all standard measurement configurations can be modelled.
  - Measurement accuracy vs “Probe quality” (modal content or approximation to plane wave).
  - Alignment and finite precision in probe/AUT relative movement.
  - Approximation of errors due to chamber stray signals.
- The equivalent current expansion of a measured or simulated “probe” enable:
  - Diagnostics on origin of modal errors in probes (SNF).
  - Full wave simulation of chambers and measurement system by the associated NFS.
- The use of both measured and simulated sources in antenna system modelling could be facilitated by standard data exchange tools*.

** M. Sabbadini, P.E. Frandsen, F. Mioc, F. Silvestri and G. A. E. Vandenbosch, "The Electromagnetic Data Exchange Language For Antenna Modelling And Measurement Data", Proceedings for the 30th ESA Antenna Workshop on Antennas for Earth Observation Science Telecommunication and Navigation Space Missions ESTEC, May, 2008*

THANK YOU !

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