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Antenna Measurement Challenges and Opportunities

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Abstract
This Roadmap overviews present challenges and opportunities for the development of antenna measurement techniques and technologies to support the all-pervasive and ever-increasing demand for radio-frequency wireless systems in modern society. The Roadmap comprises 19 inspiring contributions by 34 leading experts in antenna measurements.

Key terms
Antenna Measurements; Wireless Systems; Challenges; Future Techniques and Technologies

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Modern society relies increasingly on well-functioning wireless systems - for communication, for sensing, or for energy transfer - and wireless systems rely significantly on well-functioning antennas. Though computational tools improve continuously, the increasing complexity of modern antennas in terms of their functionalities, materials, and structures, as well as always stricter performance requirements, mean that experimental measurements remain of utmost importance for development, validation, and calibration of antennas.

Antenna measurement techniques and technologies face numerous near-future challenges. Wireless systems from submarine communication to deep-space satellite radiometers now span frequencies from less than 1 kHz to above 1 THz. Between Internet-of-Things sensors to high-speed interconnects, bandwidth requirements range from tenths to tens of a percentage. Radiation patterns assume almost any shape between 0 dBi isotropic WiFi nodes and 100 dBi pencil-beam radio telescopes; and adaptive or reconfigurable antenna patterns may assume a multitude of different shapes for the same antenna. In addition, antennas are increasingly integrated with front-end circuitry or entire receiver/transmitter systems as well as embedded with the wireless device; or they are otherwise heavily dependent on the surrounding environment as for automotive applications and medical implants. From hearing aids to communication satellites, the size and weight of the antennas vary by several orders of magnitude. Environmental conditions affecting the antenna performance may span wide ranges of pressure and temperature; e.g., from almost zero to many hundreds of Kelvins. Also, antenna testing faces demands of increasing accuracy, decreasing cost and time, need for characterization in production lines or in-situ operational conditions outside controlled measurement ranges. Finally, new wireless technologies call for determination of non-traditional antenna performance metrics – which often require substantial post-processing of the raw measurement data.

This Roadmap addresses state-of-the-art antenna measurement techniques and technologies and surveys solutions to the many challenges. These solutions may well depend on the particular sector of wireless systems, but they all rely on progress in technical-scientific research and engineering across many disciplines; not least computational science where Artificial Intelligence is currently of enormous interest. To this end, the Roadmap includes 19 contributions by 34 leading experts addressing a multitude of developments in antenna measurement theory, in measurement techniques and procedures, in measurement instrumentation and technology, in error mitigation and uncertainty estimation, in post-processing of measurement data, and in measurement standards. In combination, these inspiring contributions document that antenna measurements constitute a vibrant and fast developing technical-scientific field that holds numerous opportunities for the individual antenna measurement researcher or engineer.

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Novel Near-Field to Far-Field Transformations

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Introduction. Electromagnetic near-field (NF) far-field (FF) transformations (NFFFTs) compute the FF radiation pattern of a device under test (DUT) from a sufficiently large number of NF observations, with the DUT being measured either in transmit or in receive mode due to reciprocity. In particular, when the influence of a non-trivial measurement probe, i.e., not an infinitesimal dipole, shall be corrected, NFFFTs need to be set up in the form of a linear inverse problem, where the underlying forward operator gives a relation between a set of degrees of freedom (DOFs) representing the radiated fields of the DUT, and the measurement signals as observed at the output of the measurement probes, see also Fig. 1 for an illustration. Remarkably, the early NFFFTs were implemented numerically as extremely efficient, fast Fourier transform (FFT) based accelerated direct inversion methods utilizing the orthogonality of modal field expansions in cylindrical, spherical, or Cartesian (planar) coordinate systems [1, 2, 3]. Such methods are moreover very robust, they can achieve excellent numerical accuracy, and they allow for accurate measurement probe correction, providing the orthogonality of the modal expansion is not destroyed by the probe or the measurement arrangement. As such, these NFFFTs require regularly-spaced sample locations and uniformly oriented probes, where the probes must also have certain symmetries as in the spherical case. In view of the availability of such extremely powerful NFFFTs, this perhaps in combination with sophisticated interpolatory schemes [4], was arguably the state of the art until comparatively recently with most NF antenna measurement facilities being designed in order to comply with the requirements of the NFFFTs. The fact that modal expansions of a certain order are able to accurately represent the radiation fields of a canonical volume of a certain size containing the DUT (a cylinder with a given radius and height, the intersection of a sphere and a cylinder with given radii, or a box with given side lengths, corresponding to cylindrical, spherical, or planar measurements, respectively) underpinned the reliability and tremendous success of the approach.

Greater flexibility in terms of DUT representation and acquisition type is provided by inverse equivalent source methods, which work with a spatial source representation, e.g., in the form of a discrete set of surface current densities defined on a meshed surface surrounding (or sometimes just in front of) the DUT. Such methods discretize the forward operator from a discrete set of sources to the field observations into a linear system of equations, and then solve the discrete problem in the form of an appropriate mean square norm minimizing normal equation, or alternatively as some kind of pseudo inverse solution [3]. Initially, these methods attempted to harness the power of FFT acceleration [5], with the associated restriction of regular discretizations. Subsequently, however, fully three-dimensional, i.e., non-canonical, approaches with arbitrary (triangular) discretizations and full probe correction capabilities have emerged and become established tools [6, 7, 8]. Here, computational efficiency is in particular obtained by utilizing the concepts of the multilevel fast multipole method (MLFMM) [3, 7]. Such methods do not only allow the visualization of the obtained sources, thereby providing a bridge to non-invasive diagnostic methods and subsequent radiation studies within various radiation environments, but they also enable the suppression of spurious parasitic radiation within the measurement environment.

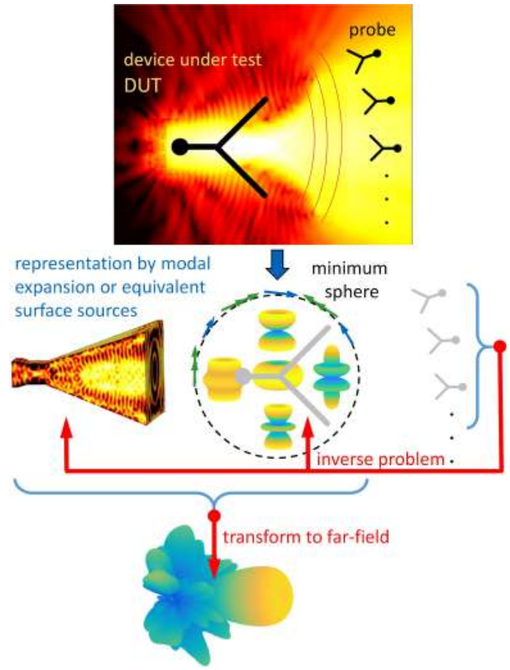

Figure 1: Principle of NFFFTs.

Future Challenges and Developments. Standard NF measurement approaches, and the corresponding canonical NFFFTs will continue to provide excellent measurement results in the future, but we will also see a large variety of measurement setups, not all of which are specifically designed for high-quality antenna measurements. Of particular note are industrial multi-axis robots, which have recently been used for measurements within arbitrary environments. Future NFFFTs must be able to perform well with the measurement data of all these measurement approaches. As such, we need NFFFTS which work well in echoic or anechoic environments, possibly also in the extreme NF, and which are able to extract as much information as possible about the DUT from as little measured data as possible. We need NFFFTs, which can work with the standard operational signals of radiating devices. However, we also need NFFFTs which can work without providing a reference for the phase or the magnitude or for both, that work with complex waveforms and ideally; we would like to have NFFFTs which do not need any information about the probing antenna, i.e., which determine the DUT and the probe properties simultaneously. Moreover, we would like to have NFFFTs, which can incorporate as much information as possible about the DUT for the benefit of working well with a reduced number of observation samples, whilst still being sufficiently sensitive to be able to reliably detect deficiencies within the DUT itself. If we think about such developments, we must, however, always keep in mind that the measurement community is spoiled by the tremendous computational power of the existing canonical NFFFTs. Therefore, attractive computational efficiency and sensitivity is also a key requirement for any new NFFFT.

(a) NFFFTs and Computational Electromagnetics. Enormous potential for the development of future NFFFTs will evolve from their unification with computational electromagnetics (CE). Many of the currently available NFFFTs have already been inspired by CE methods, e.g., by fast integral methods such as the MLFMM. In future, we will see sophisticated models of the DUT or the measurement environment integrated into NFFFTs, as, e.g., seen in [9], or we will model the measurement setup in the form of a digital twin in order to better understand and analyze the error behaviour of the measurement and field transformation process [3].

(b) Echo Resilient Methods. A key capability for modern NF measurements situated within arbitrary environments is the availability of methods for the suppression of parasitic echoes [3]. Time gating and other measurement hardware supported methods will continue to play an important role. However, we also need improved methods which are integrated into the NFFFT itself, as already started in [10]. We need accurate spatial localization, combined with spectral localization, and also combined with temporal localization. Furthermore, the concepts of virtual probe arrays and of highly-oversampled measurements will of course further extend these aims.

(c) Reduced Sampling Methods. Reduced sampling methods have been attracting notable attention for several years now with sparse compressed sensing methods in particular yielding many new ideas [11, 12]. Equivalent source based NFFFTs can easily process the sparse observation data, however, improved concepts concerning the placement of the sources and methods for appropriately including the available information about the DUT into the NFFFT will further enhance these methods to achieve new levels of performance [13]. Here, not only statistical approaches such as those based on sparsity assumptions may be of use, but also methods, which utilize the peculiarities of the underlying radiation operator itself, may prove beneficial [14].

(d) Phase-less Methods. Interest in phase-less near-field measurements dates back many decades and stems from noting that the availability of phase-less NFFFTs would be very attractive for the simplification of many measurement approaches. The rapid increase in the interest of using un-tethered, uninhabited air vehicles (UAVs), i.e., drones, higher frequency applications employing industrial multi-axis robots, and 5G/6G communication system testing utilizing complex waveforms have only served to further increase the need for phase-recovery. However, really reliable, truly general purpose approaches which work completely in the absence of phase information are probably hard to achieve for microwave frequencies and below. In particular, it is often forgotten that the accuracy requirements for magnitude only measurements are commonly considerably harder than for the case with phase and magnitude information. In principle, magnitude-only NFFFTs are available in the form of optimization methods, where the major problem is not the NFFFT, but rather the question of how to collect enough information for the unique solution of the optimization problem [15]. Therefore, these problems are perhaps more closely connected with the measurement approaches than the NFFFTs, with non-linear optimization based RF measurement techniques also proving fruitful [16].

(e) Probe Correction and Error Correction Methods. Probe correction is a most important pre-requisite for accurate NFFFTs. In general, the FF results can only be as good as the probe correction, where the influence of the probe is certainly different for different measurement configurations and, e.g., is also dependent on the measurement distance. An attractive NFFFT would be an NFFFT, which does not need any a-priori probe information at all, i.e., one which is able to retrieve the necessary probe information from the observation data itself [17]. Such methods may be seen in a similar light as phase-less methods. Here, the necessary information for solving the NFFFT problem is not automatically available within a standard measurement, and we have to bring more information into the NFFFT process. Once sufficient information for the solution of the problem is available, similar algorithms as in the case of the phase-less methods can probably retrieve the desired information from the measured data. Such thoughts can also be carried over to methods for the intrinsic correction of errors, e.g., probe positioning or orientation errors. With a sufficiently large amount of observation data available, via high-speed acquisition systems, this now appears more plausible than ever before.

(f) Artificial Intelligence and Machine Learning. Artificial Intelligence (AI) and Machine Learning (ML) methods will have great potential for further improving NFFFTs. They can help us in the identification and subsequent extraction of unknown echoes, in the appropriate placement of measurement samples in reduced sampling methods, and of course also in the placement of the equivalent sources, as well as for the purpose of efficient and accurate phase recovery. In principle, AI can learn AUT types, probe representations, and echo signal representations during the course of many measurements, and it will inevitably help us in the interpretation of both measurement, and transformation results.

(g) Improved Computational Efficiency & Sensitivity. Excellent numerical efficiencies are a pre-requisite for the acceptance and adoption of any new NFFFTs. Therefore, a significant amount of effort and ingenuity will need to be invested in the continuous improvement of computation speeds of NFFFTs. Improved equivalent source representations can, e.g., lead to improved efficiencies [18], or we may see novel preconditioning techniques [19], where even multiple frequency solutions may benefit from each other. The aforementioned reduced sampling methods may lead to further speed-ups, or we may pre-compute parts of a particularly complicated solution algorithm in a smart way. Finally, although many existing transformation algorithms are implemented utilizing parallel processing techniques, there is still great scope for further enhancement with these algorithms being ported to highly-parallel computation platforms such as graphics processing units (GPUs), etc.

Reduction of Near-Field Antenna Measurement Time through Non-Regular Scanning

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Introduction. Antenna measurements from near-field data acquisitions represent, nowadays, an established methodology to collect the field information about an Antenna Under Test (AUT) to characterize its radiative behaviour as well as to diagnose its working conditions. Typically, the Near-Field samples are collected on a surface with a conventional geometry (planar, cylindrical, or spherical), limiting the acquisitions to a portion thereof in the first two cases, as well as in the case of spherical systems, when allowed by the radiative features of the AUT. Standard guidelines have been formulated, leading to conventional sampling strategies over canonically defined acquisition regions. However, a sub-optimal extent of the sampling region and the un-necessarily large number of sampling locations can make the acquisition time uselessly dramatically high. The guiding light towards a reduction of the measurement time is the use of non-regular sampling strategies, aiming at gathering just the indispensable amount of information to the targeted purpose. Up to now, the following key points returning significant results have been faced:

1. Definition of appropriate representations of the source accommodating all the available a priori information.

2. Determination of the number of samples in the measurement region, and their spatial distribution which allows gathering the information needed by the antenna characterization/diagnostics.

Concerning the above points, which are strictly inter-related, to reduce the scanning time for the characterization/diagnostics by properly defining the measurement locations, it becomes crucial to accommodate all the available a priori information on the radiator. In particular, in characterization problems, the exploited information should rely on mild assumptions typically given on the geometry of the source. For diagnostics purposes, the a priori assumptions should not involve only the information of real interest enabling the identification of the faults. Much work has appeared on the definition of the sampling number and locations leading to non-regular sampling strategies with diverse performance. Different solutions have been proposed with different rationales. A non-redundant sampling exploiting the concept of local bandwidth of the field has been developed for several different geometrical models of the source and for the three canonical scanning geometries [20, 21]. An approach relying on the optimization of the singular value behavior of the discretized radiation operator (Singular Value Optimization - SVO) has been introduced, applied to the case of aperture antennas and to the three canonical scanning geometries again [22, 23]. A thinned equiangular or igloo sampling scheme has been also introduced in [24, 25]. Compressed Sensing (CS) has also found application for spherical near-field measurements to reduce the number of sampling points thanks to a sparse representation of the measured field [11, 12, 26]. For cases when the phase is missing, the sampling problem is even more critical since the lack of phase information must be compensated making, as a result, the number of acquisitions larger than that needed for the complex case, significantly affecting the scanning time [27].

Emerging challenges. Notwithstanding the significant advancements and results achieved in the lastest decades on methods to reduce the measurement time which allowed to introduce non-regular sampling techniques that can be now assumed essentially established, different challenges remain to be tackled:

3. Further improving previous points #1 and #2.

4. Definition of unique sampling grids for carrying out the characterization/diagnostics at multiple frequencies.

5. Definition of the minimum region (size and shape) to be sampled.

6. Use of strategies and hardware for the movement (multi-axis/robots) and control of the probe in connection to the definition of optimal scanning paths/motion laws accounting for the features of the available equipment.

7. Development of measurement strategies in the very near-field of the radiator.

8. Development of techniques with reduced resolution or multiple resolution.

9. Development of techniques for partial characterizations.

Future developments to satisfy these challenges. The research activity of the community in very recent years is attempting to give answers to the issues raised above. Developments are expected in the next future to delineate even more effective solutions. In particular, concerning point #3, further refinements on the source representation are being introduced to improve the performance of the sampling techniques, possibly exploiting a unique "optimal" sampling lattice for all the frequencies (see point #4) involved by the characterization/diagnostics. This becomes critical for phaseless acquisitions. Regarding point #5, the possibility of defining the optimal region to be scanned without impairing the results according to a prefixed tolerance (truncation error) is even more crucial, particularly when referring to scanning surfaces with unconventional shapes. Furthermore, the use of unconventional shapes, made possible today by the use of multi-axis robot arms moving the probe, opens new avenues in near-field sampling. Indeed (see point #6), probes installed on one or more robot arms enabling more convenient scanning areas thanks to the offered degrees of freedom in positioning and orientation of the sampling grids are giving a new perspective to near-field acquisitions [28, 29]. Also optimized controllers are being devised, profiting of the non-regular sample positions to access a significant increase in the average probe speed between two consecutive points even in continuous acquisition schemes [30]. As far as point #7 is considered, the acquisition in the very near field, with a non-significant perturbation of the working conditions of the AUT, could permit a significant reduction of the size of the scanned area with beneficial effects on the overall acquisition time. Obviously, the sampling in the very near field represents an open problem, which should take into account for contribution from both visible and invisible domains, but should profit as much as possible of non-regularity to reduce the number of needed sampling locations. At the same time, non-invasive probes are required in very near field acquisitions, with a reduced mutual coupling with the AUT. Concerning point #8, typically, traditional systems attempt to retrieve the radiation behaviour from near-field samples with full resolution. In some cases, a fast snapshot can be useful, particularly at preliminary characterization steps. In some cases, a multi-resolution characterization could be useful, returning full-resolution only wherever needed, but rougher details where sufficient. Obviously, not requiring the full resolution could reduce the amount of measured data and speed up the acquisitions. Moreover, in other cases (see point #9), full-resolution characterizations, but at prescribed cuts of the radiated field, can be very appealing, particularly when this comes with a dramatic reduction of the needed field samples [31, 32]. Finally, parallel probes, already exploited by standard, regular sampling techniques, could introduce a further improvement in speeding up non-regular acquisitions.

Conclusion. Field sampling in the near-field exploiting non-regular distributions of the samples has paved the way to several significant improvements in antenna characterization/diagnostics with amazing outcomes. Significant reductions of the overall acquisition time have been obtained, with strong relapse in the applications, but solutions to some relevant open problems are expected to provide a further practical impact.

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Post Processing for Antenna Diagnostics and Spurious Signals Cancellation

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This contribution provides a brief overview of recent developments related to post processing of measured antenna radiation data for diagnostics applications and cancellation of spurious signals. Traditional post processing methods such as back-projection have been known and used for decades, but limiting factors such as low resolution makes these methods inadequate for some applications. Here we review a Method of Moments (MoM) based method that can instead be applied that offers superior resolution and 3D reconstruction, but is more computationally demanding. New accelerated MoM current reconstruction methods that are presented in this work open up the possibility for performing antenna diagnostics of electrically large and complicated antennas, reducing the prototype cycles and increasing the quality of the antenna prototype.

Introduction. The accuracy of antenna measurement test ranges has improved significantly in the past decades. In addition to many hardware improvements, also advances in the computational methods used to process the acquired measured data have greatly enhanced performances. Despite all the mentioned advances, it may be the case that the measured radiation pattern of an antenna under test (AUT) differs from the designed/expected results, and that the cause of this discrepancy can not be easily identified. In the past, a trial and error procedure has commonly been utilized. Today, larger and more complicated antenna designs are being utilized, such as passive/active array antennas, large deployable antennas and complex science instruments; antennas are often mounted on platforms such as cars, satellites and ships, where the antenna surrounding has a non-negligible effect on the antenna performance. In these cases, the trial and error antenna prototyping approach can be very costly and time consuming.

Post processing techniques of the measured antenna radiation are indispensable tools for digging deeper and finding the source of discrepancies in the radiated field, and thus shorten the prototyping cycle of antenna designs. A specific post processing technique that has been very successful for this purpose is the equivalent current reconstruction technique (also referred to as source reconstruction). It consists of computing equivalent currents with a known location that radiate a given complex vector field [8]. The equivalent currents are typically computed at a surface in front of, or enclosing, the AUT. Once these equivalent currents have been found they can be used for a number of applications such as antenna diagnostics [33, 34, 35], near-field to far-field transformation (e.g. [36]) filtering of spurious signals in the radiated field [37], antenna placement investigations [38], and performance analyses of 5G devices [39].

Different approaches of using the equivalent current technique for solving the inverse problem of finding the radiating currents from measured fields have been developed in the past two decades. The first type of methods are based on modal transformations, for example plane wave to plane wave (PW-PW) transformations (microwave holography) or spherical wave to plane wave (SW-PW) transformations [40]. These methods are fast and well suited for electrically large problems, but only reconstruct the currents on a planar surface. While PW-PW transformations provide a spatial resolution limited to half a wavelength, SW-PW transformations can provide higher spatial resolution than half wavelength with noise free measurement data, but in practice this is difficult to be achieved with a typical 60 dB signal to noise ratio (S/N).

The second type of methods is based on representing the inverse problem as integral equations that are solved by some kind of Method of Moments (MoM) based implementation [35, 41, 42, 43] These methods can operate on measured data sampled on regular, irregular as well as truncated surfaces, and reconstruct equivalent currents on 3D surfaces of general shapes. The spatial resolution of the reconstructed currents is in general high and may be better than half a wavelength, even in the presence of noise, indicating that the 3D reconstruction methods are superior to traditional microwave holography, especially for array antennas [44]. Moreover, 3D reconstruction allows filtering of undesired radiation and scattering, which is not possible with microwave holography. Two examples of commercial software products based on this type of current reconstruction methods are *DIATOOL*[1] by TICRA and *Insight*[2] by MVG. Drawbacks with the 3D reconstruction methods are that their computational requirements are generally high, and their baseline versions scale poorly with frequency and the electrical size of the problem. However, a number of new developments have been made in recent years to meet the challenge of applying this approach to large antennas; in this work, alternative methods are presented for accelerating the computational solutions to the equivalent current reconstruction problem.

Theory. In order to solve the inverse source reconstruction problem numerically, using measured field in amplitude and phase as input, the reconstruction surface and the unknown currents are discretized as a linear system of equations

$$\bar{\bar{A}}\bar{x} = \bar{b} \tag{1}$$

where $\bar{\bar{A}}$ is a matrix representing the radiation from the unknown currents $\bar{x}$ on the reconstruction surface S that generate the measured fields in $\bar{b}$. For applications with diagnostics purposes, the source reconstruction equations should be augmented with Love's condition of zero fields inside a surface enclosing the sources. This condition ensures that the found currents provide a unique solution that represents the actual tangent fields (i.e. physical currents) on the structure. The mathematical problem

[1] DIATOOL Software, website: https://www. ticra.com/software/diatool/.
[2] Insight Software, website: https://www. mvg-world.com/en/products/antenna-measurement/ software/insight.

to solve can thus be formulated as

$$\min_{\bar{x}} \|\bar{\bar{A}}\bar{x} - \bar{b}\|_2 \tag{2}$$

$$\text{s.t. } \bar{\bar{L}}\bar{x} = \bar{0} \tag{3}$$

where $\bar{\bar{L}}$ is the matrix representation of Love's condition. The problem in (2)–(3) is solved iteratively to find the currents $\bar{x}$.

Recent numerical improvements for source reconstruction.
(a) Calderon projections for fast antenna diagnostics: An alternative solution procedure to the problem in (2)–(3) was initially indicated in [8], and recently pursued in [45]. Instead of solving the data equation in (2) by including (3) in each iteration, the unique current condition enforced by (3) is represented by a projection operator $\bar{\bar{T}}$ that is applied a single time, *after* the solution to (2) has been found. We refer to this final step as a Calderón mapping[3]; a possible way to effect that is to restate (2)–(3) simply as a preconditioned Least Squares problem

$$\min_{\bar{z}} \|\bar{\bar{A}}\bar{\bar{T}}\bar{z} - \bar{b}\|_2, \quad \bar{x} = \bar{\bar{T}}\bar{z} \tag{4}$$

An implementation tailored for electrically large problems has been introduced in [46] and applied to large reflector antennas for space applications in [47]. This implementation leads to a complexity scaling at most as $\mathcal{O}(N \log N)$ per iteration, where N is the number of unknowns, with drastic improvement with respect to standard approaches. Furthermore, the method employs higher order basis functions on higher order quadrilateral mesh elements, with a significant reduction in the number of unknowns required for a given problem with respect to Rao-Wilton-Glisson (RWG) basis functions.

An example application of the Calderón method is presented in Fig. 2, where equivalent electric and magnetic currents have been computed on a conformal reconstruction surface enclosing a satellite with three reflector antennas, where one antenna is radiating at 10 GHz. This equivalent current reconstruction problem consists of roughly 3.2 million higher-order unknowns (corresponding to about 15 million RWG unknowns) and only require a RAM allocation of 60 GB.

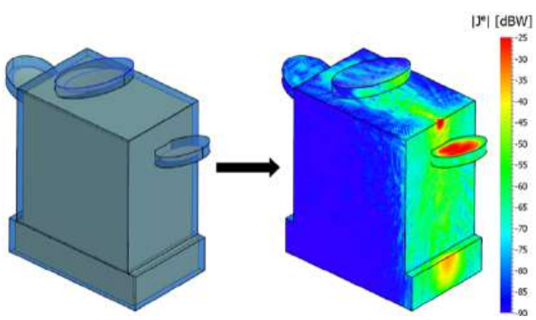

Figure 2: Reflector antennas on a satellite platform enclosed by a conformal reconstruction surface (left) and reconstructed equivalent electric current density (right).

[3] In [8] this approach was not indicated by this name, but as "field boundary integral identities"

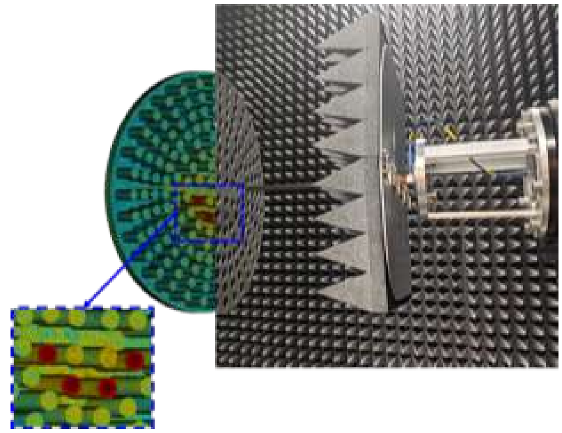

Figure 3: Diagnostics of a Planar Wave Generator (PWG) large array: the AUT in the measurement setup and Ring n.2 excitation verification.

(b) Fast multilevel Low-Rank solver: The original numerical problem (2)–(3) closely resembles the MoM problem for a penetrable body; hence, as mentioned above, it can be accelerated by fast factorization schemes with $\mathcal{O}(N \log N)$ complexity per iteration. The main, relevant difference to standard MoM problems is that the essential testing condition happens on the measurement surface, significantly farther away from the reconstruction surface; on it testing points due to measurements are typically much more spaced that in MoM problems (close to $\lambda/2$ in the ideal sampling case): this renders the standard application of fast factorizations less efficient. This can be obviated by an ad-hoc algebraic factorization [48, 49, 50] that has been tested on a large and complex structure as in Fig. 3; the improvement is above a factor of 35 in memory and time with respect to standard implementation [51].

Conclusion. We have reviewed baseline and advanced equivalent currents methods, that have witnessed a constant improvement in application, theory and implementation - as well as new challenges.

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Antenna Measurement Uncertainty

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Introduction. Antennas are an inherent part of any wireless transmission. Especially their efficient use of energy and ultimate utilization of the electromagnetic spectrum are essential requirements for various applications such as remote sensing, radar, next generation wireless systems with high-speed and high link reliability. A raft of emerging wireless technologies such as ultra-massive multiple-input-multiple-output (UM-MIMO), Orbital Angular Momentum (OAM), etc. is increasingly arising in the arena of modern devices and system design [52]. Furthermore, technology advancements together with spectrum scarcity has driven the exploration of new radio frequency (RF) spectrum suitable for upcoming wireless technologies in the millimetre wave (mm-wave), terahertz (THz) and even optical frequency bands.

All types of omni-directional and directional antenna measurements have their associated uncertainties, which are unavoidable due to limitations of the measurement instrument capabilities. Their measurement results can only be relied upon with confidence when all the uncertainties associated with them are fully understood and known. Therefore, it is important to evaluate their measurement uncertainty to quantify the reliability of the measurement result. The traditional 18-term sources of uncertainty errors that have a direct impact on the accuracy of the far-field measurement of an antenna under test (AUT) measured in the near-field has been given in [53]. This uncertainty analysis can be extended to far-field (see example in Table 1 [54]) and compact range measurements (see example in Chapter 13 in IEEE Standard 149 [55]).

In practice, the antenna calibration process involves the measurement of the ratios of powers and as such a power ratio measurement system is required with sufficient dynamic range and suitable linearity to achieve the required uncertainties. For determining the gain of an antenna, the most accurate of the many measurement techniques is the three-antenna extrapolation technique [56]. By using three antennas to make the measurement, one does not require an a priori knowledge of the gain of any of the antennas used. When measuring the antenna radiation pattern, the antenna-to-range interface (including antenna feed, positioner, etc.) can have a large effect, for example for omni-directional antennas without balun or adequate match, as they are prone to unwanted common mode currents on the coaxial cable used to feed the antenna during the measurement. They radiate and interfere with the radiation of the antenna, which can cause differences between the measured pattern and the expected pattern [57]. The designer can spend fruitless efforts redesigning without insight of the actual cause, which can limit the uptake of these technologies. Antenna radiation efficiency is an important attribute of antennas as it has a significant effect on the performance, reliability, and efficiency of wireless communications systems. The recently revised IEEE Standard 149 [55] include the measurement techniques such as pattern integration, Wheeler cap and reverberation chamber methods. In the following, we discuss the current measurement challenges and future developments required for improving antenna measurement uncertainty.

Gain Budget Error Term	Uncertainty (dB)
1. Probe Relative Pattern	0.00
2. Probe Polarisation Radio	0.00
3. Calibrated Probe Gain	0.15
4. Probe Alignment	0.00
5. Normalisation Constant	0.16
6. AUT Impedance Mismatch	0.06
7. AUT Alignment	N/A
8. Data Point Spacing	0.02
9. Data Truncation	N/A
10. Sphere Radius Errors	0.00
11. Sphere Theta/Phi Errors	0.01
12. Higher Order Coupling	0.03
13. Receiver Amplitude Non-Linearity	0.00
14. System Phase Errors	0.03
15. Receiver Dynamic Range	0.00
16. Room Scattering	0.01
17. Cable Leakage	0.00
18. Repeatability and Random Errors	0.00
Gain Total Uncertainty (RSS)	**0.23**

Table 1: Gain uncertainty budget example [54].

Current and Future Challenges. With the industrial exploitation and adoption of complex new radio (NR) signals, energy efficient devices and large-scale multi-antenna beamforming technologies at different RF bands in emerging wireless systems, several worldwide industries, research communities and standard bodies are now facing new measurement challenges on efficient and accurate verification of NR products that meet desired performance parameters for fulfilling the diverse technical requirements set by ITU-R [58], especially, for high-volume beam-reconfigurable issues [59].

Typical antenna measurands are antenna factor, gain, axial ratio, efficiency, radiation pattern, etc., but as wireless technologies evolve and modern antennas are becoming highly integrated into wireless systems, there is a shift towards an over-the-air (OTA) radiated testing approach (due to the lack of antenna connectors) measuring some other integrated power pattern metrics such as total radiated power (TRP), total isotropic sensitivity (TIS), effective isotropic radiated power (EIRP) and effective isotropic sensitivity (EIS). The 3rd generation partnership project (3GPP) defines three OTA test methods, namely, the Direct Far-Field (DFF), Indirect Far-Field (IFF) and Near-Field to Far-Field Transform (NFTF) in TR 38.810 [60]. However, other potential candidates, such as mid-field [61] and reverberation chamber methods [62] are missing. Moreover, measuring the performance of the devices or systems with adaptive antennas and characterising the propagation channel creates further challenges at mm-wave bands, where innovative test methods and novel measurement equipment are required throughout research and development stages.

While on the one hand the accuracy of the measurement directly depends on the named 18 error term models [53], on the other hand the properties of the measurement laboratory itself as well as the measurement method play an important role. Therefore, the error description of an antenna in a particular measurement laboratory remains incomplete as long as it has not been validated against other measurements performed in other measurement facilities [63]. Validation and accreditation of different facilities can be achieved with inter-comparisons and careful evaluation of error budgets and different measurement standards. A crucial factor here is a robust reference antenna that consistently performs under different measurement environment conditions. An example of the requirements and design for such robust reference antenna is given in [64] for the DTU-ESA mm-wave Validation Standard (VAST) antenna.

To fulfil the needs of new technologies, new measurement campaigns are constantly being launched. For example, there are several on-going inter-comparison measurement campaign activities carried out under the measurement working group of the European Association on Antennas and Propagation (EurAAP), IEEE technical committee on antenna measurements, etc. focusing on antennas with different characteristics like both narrow and wide-band antennas within different frequency ranges, omni-directional and highly directional antennas. Also, an international comparison for antenna gain measurement of two Ku-band standard gain horn (SGH) antennas that involved 12 national measurement institutes (NMIs) has been carried out [65] whereby a variety of measurement techniques such as extrapolation, far field, gain transfer and reciprocity were used. A similar international comparison for antenna pattern measurement that involved eight universities and industry was also performed in 2004 and 2005 with the DTU-ESA 12 GHz VAST antenna at 12 GHz [66] using different measurement techniques and antenna facilities, including spherical near-field, compact range, planar near-field and far-field facilities. In 2019-2022 a measurement campaign with DTU-ESA mmVAST for 19.76 GHz, 37.80 GHz and 48.16 GHz was conducted with 13 participating facilities [67]. Pictures of the two DTU-ESA devices are given in Fig. 4. More details on facility comparisons are also given in the Section entitled “EurAAP and IEEE Standardization and Facility Comparison”.

New ranges with higher flexibilities, like robotic antenna test ranges are of upcoming importance within the past few years. Due to the higher mechanical flexibility, the measurement uncertainties differ from the known uncertainty terms from well-established ranges [68]. In addition, non-classical or irregular measurement geometries outside of spheres, cylinders and planes can be applied, which also require further consideration. On the other hand, such higher flexibility also allows for more degrees of freedom in alignment correction. Besides the robotic test ranges the use of Unmanned Aerial Systems (UASs), so called drones, is an emerging technology in antenna measurements, due to their portability and the need to measure electrically large antennas in situ. Despite the higher degrees of freedom UASs can offer, it is important to note that additional uncertainty may incur due to the precise positioning in environmental conditions like wind and gust [69].

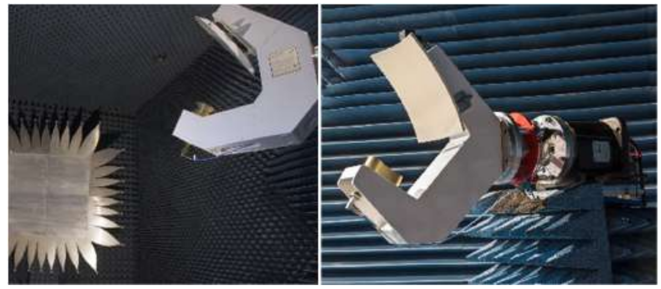

Figure 4: DTU-ESA 12 GHz VAST (left) and DTU-ESA mm-wave VAST (right) antennas.

Future developments to satisfy these challenges. With the use of new ranges like the robotic antenna test range the uncertainty budget is envisaged to change. For every new test range and testing method the well-known uncertainty terms [53] have to be revisited, revised and maybe supplemented or replaced. The same applies to new testing methods like OTA and the measurements of active antenna systems where other parameters (e.g., TRP, EIRP, etc.) are measured or the uncertainties of the antenna systems itself have to be considered.

New methods like the test-zone field compensation technique [70] can be used and established to improve measurement accuracy and enable precise antenna measurements even with non-ideal reflectivity of the measurement environments. Whereas the evaluation of a complete uncertainty budget using measurements can be extremely time consuming, with increasingly powerful computation and enhanced simulation algorithms, simulation tools can be used to support and accelerate measurements. This would also allow uncertainty budgets and measurement environment properties to be determined more quickly and accurately in the future.

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Large Satellite Antenna Measurements at Airbus

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Large deployable satellite antennas and respective structures can hardly be characterized w.r.t. their RF performance using state-of-the-art antenna measurement systems such as compact ranges or cylindrical / vertical planar near-field scanners, which are usually implemented in the integration and test areas of the spacecraft manufacturers. This is mainly due to the size of the reflecting surfaces, but also by its gravity sensitive elements like meshes or deployment booms, which require complicate gravity compensation devices to bring them into their representative in-orbit configuration during on-ground testing. Consequently in some cases those antennas have even not been fully RF-measured before being placed into orbit. To overcome this limitation Airbus Defence and Space has developed the so-called PAMS (Portable Antenna Measurement System), which enables pattern and gain measurements of large antennas without the need of moving the test object by means of precise positioners or scanning systems. The core idea is to utilize an especially modified overhead crane as a coarse near-field scanner driving a gondola with an integrated RF probe at the crane hook. The gondola and its probe are commanded by a controller to sample the near-field data along a roughly pre-defined trajectory above or around the device under test. The versatility in the scan surface allows for measurements of a motion free test antenna. The sampling in irregular intervals requests for an innovative, advanced near-field to far-field transformation algorithm, which incorporates precise knowledge of the probe orientation and position into a set of equations that is solved for the unknown plane wave modes. This algorithm was developed at the TU München. The exact probe location information is obtained in up to six dimensions from a laser tracking system, which is following a target mounted on the lower part of the gondola. The sample density needs typically to be in the order of $< 0.4\lambda$; the scan speed is about 200 mm per second.

The novel RF-test system has been qualified in several frequency bands between L- and Ka-Band. Therefore well-known reference antennas have been measured with the PAMS as well as in the classical Compensated Compact Range at Airbus Defence & Space GmbH, Taufkirchen. As an example the set-up of a PAMS-based test campaign in Ka-Band is shown in Fig. 5. The test object is mounted on a fixture in front of an absorber wall being coarsely levelled horizontally. Exact levelling or placement of the test object is not mandatory as the antenna coordinate system is aligned with optical targets. The laser tracker needs to be placed such that the respective target is always visible during the nearfield scanning. The data resulting from the nearfield to farfield transformation have demonstrated an excellent level of agreement with those achieved in the classical compact range set-up. Typically the error contribution was in the order of -40 dB [71].

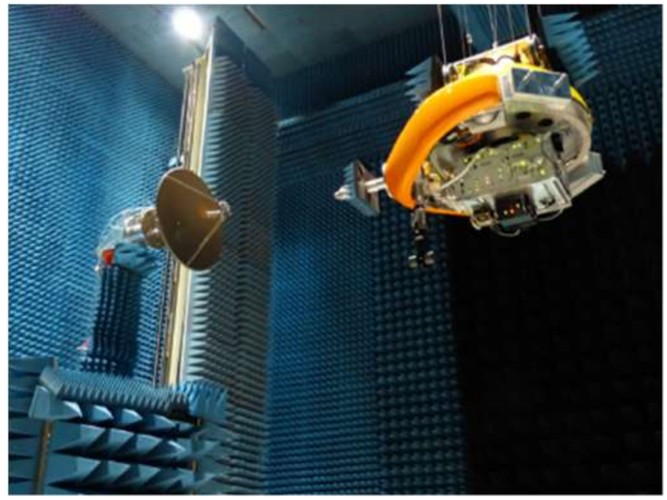

Figure 5: PAMS Gondola with calibrated test probe and removed bottom cover during Ka-Band Test.

Following the successful system qualification itself the PAMS has been applied in different RF-test campaigns for the performance verification of large deployable mesh or panel based reflector antennas. A typical example is shown in Fig. 6.

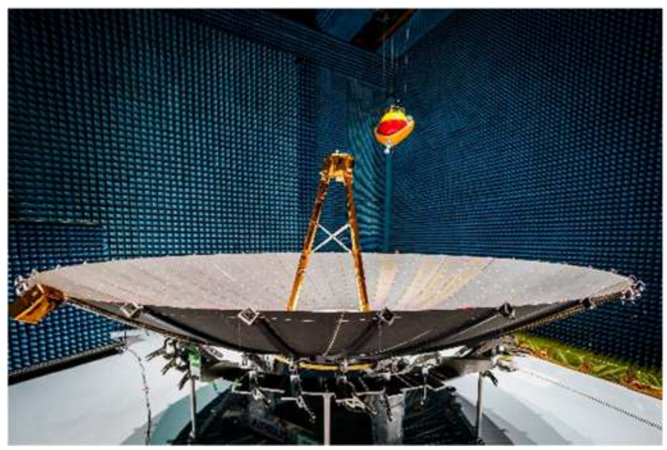

Figure 6: PAMS test configuration for a large antenna structure (5m Deployable Reflector developed by Airbus Defence & Space GmbH, Friedrichshafen).

The comparison of the measured RF-pattern with predictions based on well-known antenna analysis software routines such as GRASP developed by TICRA, Denmark, has revealed a very good agreement [72].

Large Satellite Antenna Measurements at JPL

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Introduction. The history of the Mesa Antenna Measurement Facility at the Jet Propulsion Laboratory (JPL) goes back to the early 1960s. The location was chosen due to the topology being a mesa overlooking the JPL campus, which provides both multi-path advantages for outdoor antenna testing and a quieter RF environment. At the time, all measurements were Far Field (FF), which provided relatively quick feedback of the pattern cuts. With lesser computational power than what is available today, some parameters, such as the feed position on a reflector antenna, were empirically optimized by real time adjustments. Some of the antennas operated above 100 GHz, but most were at or below Ka-band. Over time, as Near Field (NF) processing developed and NF range hardware matured, JPL's antennas started being tested in indoor NF chambers as opposed to the FF ranges outdoor. The first NF chamber on the JPL Mesa was a custom-conversion from an indoor 12.2 m FF range, which ultimately became a cylindrical NF chamber, optimized for the long and narrow antenna elements used for NSCAT, after being used as a plane-polar NF scanner for the 4.8m Galileo antenna. This chamber has served faithfully through many projects, including CloudSat [73] (see Fig. 7), which operated at W-band. Note that this NF chamber, and the one cited below, support conventional NF data acquisition and processing. This NF range was also used to measure Ku-band 1:10 scale models of the AQUARIUS and SMAP [74, 75] (see Fig. 8 and 9) instrument antennas with excellent results when compared with predictions calculated with TICRA GRASP and Ansys HFSS.

Emerging challenges. As the demand for NF measurements increased, an adjacent 18.3 m indoor FF chamber was chosen to be converted into a NF chamber via the acquisition of an NSI, Inc. 9.1 x 4.6 meters planar scanner. In 2017, this was upgraded to include spherical NF capacity. Most of JPL's projects require the planar scan capability, but the spherical capability has proven to be useful for lower gain antennas and feeds. The current frequency range of the planar scanner is 1 to 40 GHz. However, by using custom electronics, we have obtained reasonable co-pol only measurement results at 130 GHz and 168 GHz. With future JPL mission concepts planned for W-band and above, the Mesa is currently planning to acquire upgrades for up to 170 GHz, and possibly higher. The necessary equipment includes RF electronics, probe fixtures, and standard gain horns for each band. The equipment is available from the range manufacturer and is relatively easy to install.

Future developments to satisfy these challenges. In the pursuit of always better RF performance, sensitivity, and spatial resolutions, current and future projects at JPL are pushing the antenna technology toward larger antennas and at the same time higher frequencies. While our facilities offer limited accommodation in terms of antenna size, we are working toward upgrading our NF scanners with the latest instrument packages to be able to handle antennas at W-band and higher. Moving to higher frequencies has the added benefit of making our chambers inherently larger and therefore we can accommodate larger apertures in terms of wavelengths.

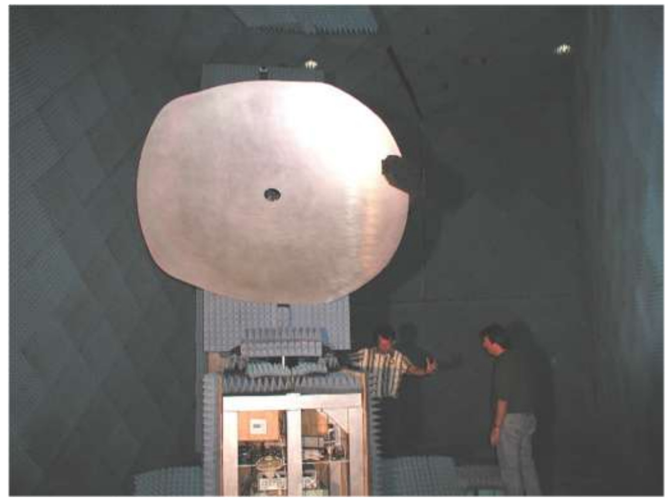

Figure 7: The CloudSat W-band offset reflector being measured in the 12.2 m (40 ft) chamber at JPL.

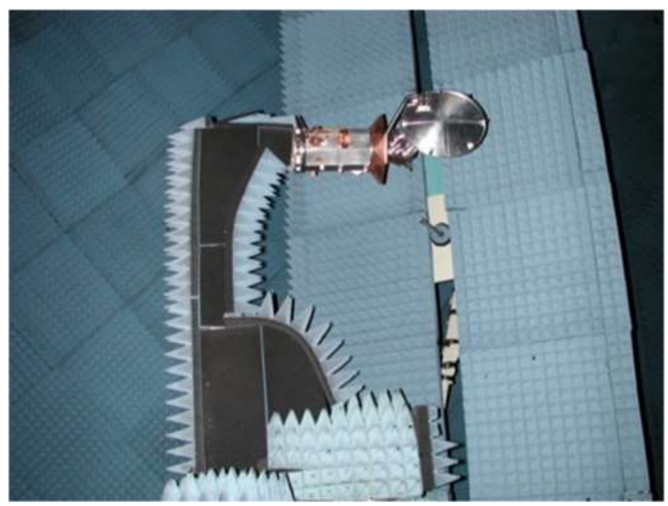

Figure 8: AQUARIUS 1:10 scale model being measured in the 12.2 m (40 ft) chamber at JPL.

We recently tested a prototype antenna from Tendeg that approached the limits of our 18.3 m chamber capabilities. The deployable mesh reflector, which is parabolic on one axis and flat on the other (Fig. 10) offers some interesting RF performance with its 7.1 m length. The unit fits inside our 6.1 x 18.3 m chamber even though it required a somewhat complex Ground Support Equipment (GSE) structure and about two wavelengths of spacing for the probe aperture to clear the center mounted feed. The pattern, measured on the planar NF scanner at 5 GHz, showed repeatability below -40 dB.

On the opposite side of the spectrum, plans are underway to

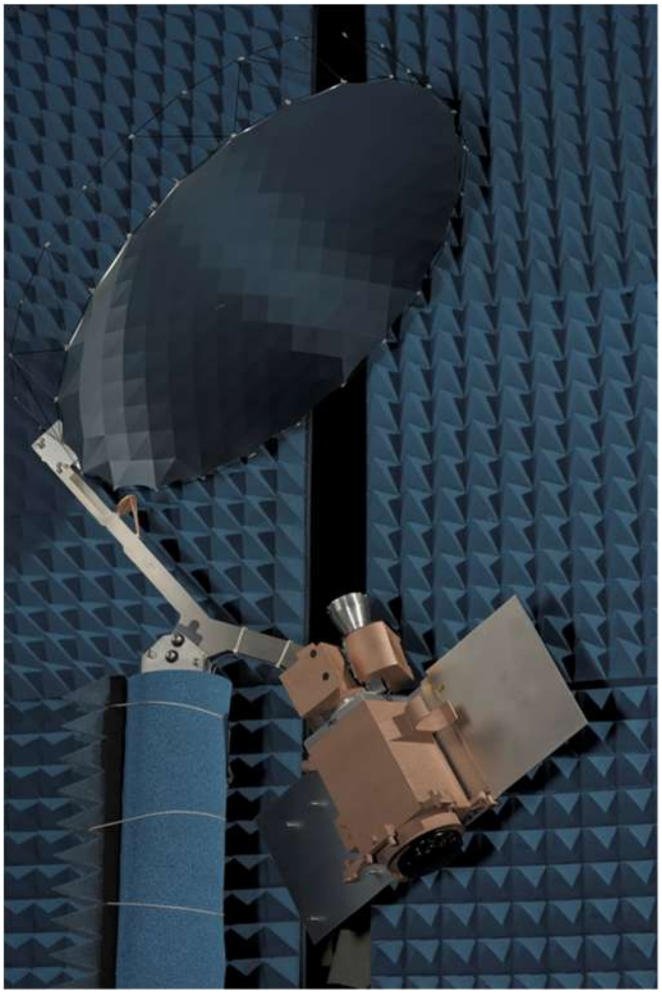

Figure 9: SMAP 1:10 scale model being measured in the 12.2 m (40 ft) chamber at JPL.

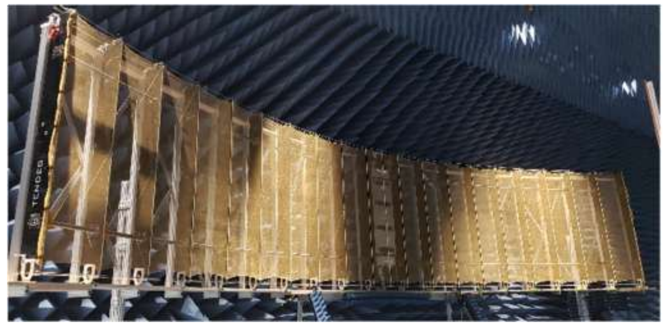

Figure 10: A 7.1m long Tendeg deployable mesh reflector being tested in the 18.3 m (60 ft) chamber at JPL.

replace the absorber in the 12.2 m chamber with material suitable for UHF frequencies, and to replace the aging cylindrical range with a planar/spherical range. Several future JPL projects are aiming to use UHF for telecom and instrument applications. The upgrade would enable the measurements currently performed outdoors to be done indoors.

Conclusion. Adding test capabilities does not come without challenges as it is always the case with indoor ranges. As mentioned above, we are planning to upgrade our existing planar/spherical range electronics to be able to test at higher frequencies, from 90 GHz to 170 GHz. While ad-hoc set-ups have been done in the past, we need a more standard and reliable approach for these frequencies. In our other chamber, we are planning to add a new planar/spherical range with large absorber to test antennas at UHF frequencies, which until now have always relied on outdoor ranges. These upgrades will enable our Mesa Antenna Test Facility to continue to play its vital role of ensuring mission success for JPL telecom and instrument antennas.

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Robotic Antenna Measurements

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Outline. Robots excel at manipulating objects with 6 degrees of freedom movement. A combination of well-defined kinematics, optimized control loops, and robust mechanical architecture make robots a versatile and capable *platform* for a range of applications where controlled movement throughout space is needed. The requirement to manipulate antennas of various form factors accurately and precisely over a volume of space is especially important for antenna testing. The use of robots to address measurement challenges in today's wireless world has continued over the past decade with new types of systems and antenna measurements being realized. This contribution exposes the reader to key aspects of current and emerging directions of research in robotic antenna measurements so that they can explore this exciting and continually evolving area of metrology.

Introduction. In the context of radio-frequency metrology, the pre-defined and well-established boundary conditions offered by waveguides and connectors do not exist in the same way for free-space antenna measurements. Rather, boundary conditions are defined through the action of dynamically placing antennas at multiple poses (position and orientation) in space often times to within a fraction of the operating wavelength [55, 76]-[79]. Furthermore, the dynamic placement of antennas must be coordinated in space and time with other equipment within an automation infrastructure. With the prevalence of wireless systems, the need to test antennas using multiple measurement techniques over a large range of frequencies (roughly 1 GHz-to-1 THz) has never been more relevant. This need puts a high demand on antenna measurement facilities with regards to measurement setup flexibility, working volume, payload, positional accuracy, repeatability, and sampling strategy for characterizing a device under test (DUT). One of the main components of any antenna test facility is the positioning system used to move and place antennas. The capability of the positioner dictates the type of measurements that can be performed (e.g., canonically a plane, sphere, or line). Furthermore, it is paramount that the positioner maintain the alignment of antennas to specified coordinate systems and to a specified tolerance as defined by the method of measurement. The use of a system of ad-hoc stacked motion stages such as linear slides and rotary tables has long been used to achieve the role of the positioner in antenna test facilities [76]. This metaphorical mechanical representation derived from the literal mirroring of antenna motion from a specific measurement method geometry (i.e., plane, sphere), while effective in specific cases, is limiting in its utility to manipulate antennas in 6 degrees of freedom (6Dof) and becomes unwieldy. Conversely, the use of robotics allows for a compact mechanical system that abides by a well described kinematic model to achieve 6Dof motion in a more general manner while, maintaining payload, stiffness, and accuracy. This approach breaks away from a literal metaphorical mechanical positioner construction, opening up new antenna range design possibilities and new ways of doing antenna measurements.

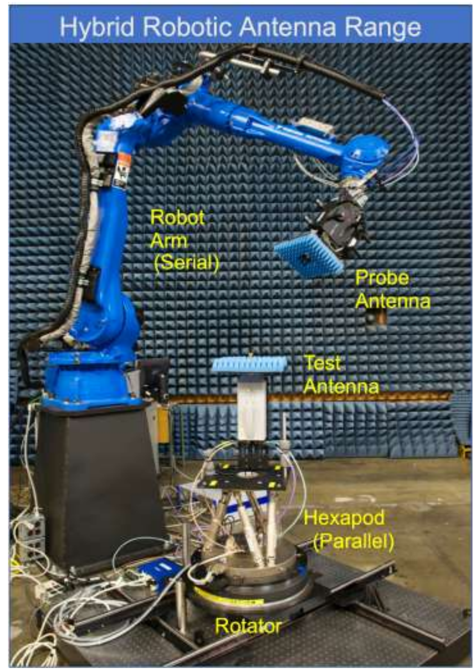

Figure 11: The CROMMA, a hybrid-robotic antenna range.

Robots for Antenna Testing. In using robotics for antenna measurements a core concept is that robots provide a *platform* for doing so and allow one to control, program, and automate a multitude of measurement scenarios which can be tailored to a large set of measurement requirements. Two classes of robots have emerged which have proven useful for antenna testing, able to provide both positional accuracy and requisite working volume among other desirable attributes. These being the serial 6-axis (and 7-axis) robotic arms [80, 81] and parallel 6Dof Stewart-Gough platforms (a.k.a. hexapods) [82, 83] (See Fig. 13). Due to their fundamentally different kinematics (i.e., links in series vs. links in parallel) these tend to excel in different ways as antenna range components, with serial robotic arms excelling at long range motion of several meters with high payloads (10's of kg) and nominal accuracy around 70 μm (shown [84] to be reduced to < 25 μm with optical feedback and calibration), and hexapods excelling at smaller range motion (a few centimeters) but significantly higher stiffness, smaller resolution, and better accuracy (~ 1 μm). Hybrid robotic manipulators [85, 86] combine attributes from both serial and parallel robotics and provide advantages from both adding further flexibility and utility. Shown in Fig. 13 is a multi-purpose (near-field, gain extrapolation, and polarization) mm-wave hybrid-robotic antenna range [84, 87] capable of both high accuracy scanning of < 25 μm and DUT alignment resu-

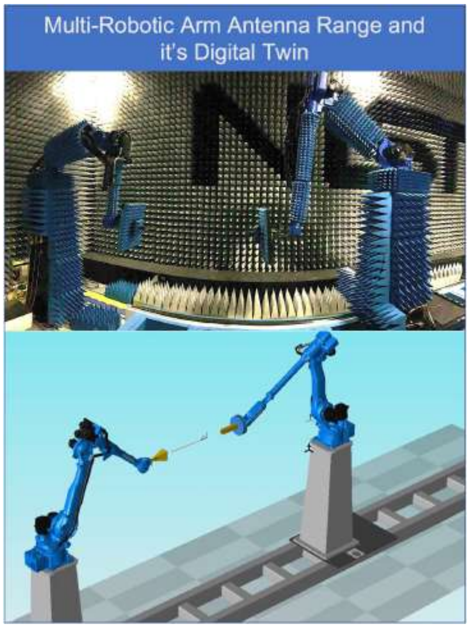

Figure 12: Photo of multi-robot antenna range (top), digital twin representation (bottom).

lution of $\sim 1\ \mu$m. Other hybrid configurations suited for lower frequency applications (i.e., where far-field distances grow over 1 m) implement a long linear slide and multiple robotic arms [88],[89] (see Fig. 12). The added slide increases the degrees of freedom to 13 and allows one to achieve large scan areas in various orientations.

Calibration and Uncertainty Analysis. Another key aspect of robotic platforms is the ability to work directly with the underlying kinematics to optimize performance. Representations based on Denvait-Hartenberg [80], Hayati [81] parameters and unified parameterizations for hybrid systems [86] from spatial measurements (e.g., laser tracker data) can be employed to develop models and implement calibration of robotic positioners with uncertainties. The ability to employ measurement-based approaches for robot calibration provides a powerful frame work for improving off-the-shelf positional accuracy, improved control and automation, and the ability to develop an uncertainty analysis based on robust robotic kinematics, thus exposing the full capability of robotic antenna testing platforms to the user.

Practical Benefits. It is worth mentioning a few important practical benefits that are less often discussed in the literature. Time consuming tasks like antenna mounting and alignment are quicker to achieve with increased repeatability. Climbing scaffolding to mount and align antennas, as is the case with fixed positioners in legacy systems, are mostly unnecessary as the robots can readily be commanded to easily reachable locations and moved back into position, and antenna alignment poses can be stored in local variables in the controller. Measurement planning using digital twins can be done offline allowing, in essence, multiple virtual antenna ranges to exist simultaneously. In mm-wave applications, setups can be simplified as entire RF systems can be mounted on robot positioners and rotated as needed, thus eliminating the need for rotary joints and improving measurement quality. Robot-based antenna range designs can be scaled up or down in size as the kinematics remain the same regardless, and robot positioners sharing the same kinematics can be swapped out for others with little or no change in performance. In the case of multi-robot antenna ranges, the roles and duties of individual robots can be reassigned or shared between positioners through simple programming, thus expanding automation possibilities and workflow efficiency.

Application Trends: Current and Future. Robotic antenna measurements span a wide range of emerging applications and provide a paradigm to perform freshly-imagined configurations and measurements. Performance boundaries are being expanded beyond what was once accessible. The capability of scanning hardware is no longer limiting the theoretical tools that have been developed, thus making predicted measurements a reality. The generatrix of a near-field scan surface now formable through robotic path planning into near arbitrary geometries for instance. This allows one to extended the viewing angle of a planar scan (e.g., from $\pm 45^\circ$ to $\pm 135^\circ$) and exploit advanced processing techniques on arbitrary surfaces [90]. More efficient sampling strategies based on path optimization applied to near-field scanning have been used to reduce scanning time by 16% for instance, using spline-based motion sequences [91] managed by the intelligence of the robot controller. The use of robotics is also enabling one to extend antenna measurements far beyond the physical laboratory with concepts like digital twins (Fig. 12) and Model Based Systems engineering and Design (MBSE/MBSD) [89] by bridging computational electromagnetic and physical measurements. The configurability afforded by robotics combined with MBSE/MBSD approaches allow optimization and reduced uncertainties of test configurations not achievable with legacy static test-range configurations. Applications in 5G and 6G advanced communications are also benefiting from the use of robotics. Serial robotic arms are enabling compact synthetic aperture systems for improved OTA measurements with uncertainties [92]. Multi-robot multi-purpose testing platforms [93] able to perform a suite of measurements including channel sounding and OTA for 6G sub-THz applications are emerging to tackle wireless testing challenges of the future. Portable compact robotic antenna test ranges are also being realized where the antenna test range can be brought *to* the device for in-vio measurements of antennas integrated to larger systems and test beds while combining with other measurements like thermal testing of active phased arrays [94]. Multi-purpose calibration facilities [88],[89] for antenna gain, polarization, and electric-field strength have been revolutionized by hybrid robotic systems.

Conclusion. Robotics brings a new paradigm giving unfettered access to 3D space with sophisticated automation and a multitude of possibilities for new antenna measurements, uncertainty analysis, and approaches. Current and future antenna measurement challenges across a wide range of applications benefit from this approach with one's imagination being the ultimate driver of what new things this platform will enable.

Extreme Temperature Space Antenna Measurements

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Introduction. Operational conditions in space pose several challenges to the design of space antennas, in particular to materials, mechanical and thermal design. The former are chosen carefully to withstand the harsh space environment, such as vacuum and large temperature excursions. Due to their nature and function, space antennas are accommodated on the outer structure of the spacecraft and as such they may experience very diverse conditions, depending on the application. For example, an antenna on a satellite orbiting Mercury is exposed to a very distinct thermal environment when compared with a satellite in an geostationary orbit around Earth. One way to ensure that the antenna will perform as expected throughout the difference environments it will be subject to is through on-ground testing. This typically happens throughout the antenna development and can take place during a qualification phase, but also sometimes as early as feasibility studies and material selection phases.

When the temperature effects on the antenna performance knowledge are limited to the thermoelastic deformation of its mechanical structure and elements, one technique is to characterise such deformations inside a thermo-vacuum chamber and use the results to build an electromagnetic model that represents the antenna under those conditions [95, 99]. This technique is particularly suitable for large and complex space antennas and instruments, but its often limited to pattern and pointing knowledge.

For complete performance assessment, characterising antennas under extreme temperature conditions typically entails performing antenna testing while the antenna is experiencing the thermal environment.

State-of-the-art: Testing space antennas under representative thermal environments is seen as significant developments which allow not only to cope with the various environments, but also enable testing in various schemes such as Compact Ranges, Near Field test facilities and also testing at material sample level. Typical antenna parameters that are characterised under temperature are radiation pattern and gain/ohmic losses, phase centre estimation, group delay variation, pointing error and Passive Inter-Modulation (PIM) performance. There are application specific parameters which can also be evaluated, such as Radiometric Performance, for remote sensing instruments, or Signal-in-Space (SIS) performance for navigation payloads.

The large majority of tests under temperature fall in one of two categories: a test setup that constrains the environment in a transparent enclosure where the antenna under test (AUT) is and is used in a traditional/standard anechoic chamber, and a test setup that is integrated inside a vacuum chamber capable of recreating the required space environment.

(a) RF transparent enclosures: Transparency of enclosures at microwave frequencies is commonly achieved by using low dielectric materials and foams that have some structural capability such as dense closed cell foams. From a thermal point of view, when aiming for low temperatures, the challenge is to keep the temperature of the outer surface of the enclosure above the dew point, to prevent condensation. Reaching further down to -100°C and below, the material, and its thickness, need to ensure that icing does not occur. In this case, the duration of the test and the lowest temperature inside the enclosure also play a role. In the hot cases, the main challenge becomes maintaining the structural integrity of the enclosure as these materials tend to loose their strength and become soft at high temperatures, typically above 150°C. When testing at temperatures above 200°C, such as for space antennas on board of satellites for planetary science in close proximity to the sun (e.g. Solar Orbiter and BepiColombo), extrapolation techniques are then used [96] and in some cases the tests are limited to sample tests [97] to infer critical antenna parameters such as ohmic losses. The interest to expand usability of such domes for relatively large antenna dimensions and compatible with a more generalised acquisition scheme such as spherical near field is growing as demonstrated by recent developments [100].

(b) Testing under vacuum The move into a vacuum environment is preferred for high frequencies (due to vacuum chamber sizes) and allows getting a thermal environment very close to the real scenario as the thermal flows are more representative (conducted and radiated). Typical thermal-vacuum chambers are closed systems, where a device can be cycled through a series of temperatures and simple monitoring such as device temperature can be recorded. To incorporate free space RF measurement with such a facility, there are many additional challenges to solve that depend on the facility architecture chosen.

The design of the Low-temperature Near-field Terahertz Chamber (LORENTZ) brings the entire measurement system inside a vacuum chamber. This chamber was designed to operate between 80 and 400K and can cover a frequency range of 50 to 1500GHz. It includes a planar near-field scanner with a 1 by 1m scan range, can accommodate instruments up to 300kg and has a 2 meter internal diameter. The facility successfully measured the Engineering Model (EM) and Flight hardware for the Sub-millimetre Wave Instrument (SWI) on JUICE satellite.

Figure 13: LORENTZ Antenna Test Facility.

It is also possible to test the antenna inside a vacuum chamber, while keeping the measurement system in a standard lab environment. This requires one or two RF transparent windows into the facility, that allow for an antenna to transmit out of or a gaussian beam to pass through to characterize materials, keeping this way the measurement system in a room pressure and temperature environment. The challenge with this approach is to design a sufficient sized RF window that is transparent in RF, but does not thermally load the whole chamber. This is typically done at sub-mm wave frequencies, where such windows have been perfected for astronomical telescopes. This becomes challenging for lower frequencies and larger devices as the size of the window must increase. Regardless of the operational frequency, such a window is never truly transparent and will always introduce some loses and additional reflections into the measurement.

Emerging and Future Needs. For the next generation of Cosmic Microwave Background (CMB) and far-infrared telescopes, there is the requirement to fully quantify the systematic error of the full end-to-end instrument as well as individual components. At component level there are various common technologies currently in development and each require their own test configuration: dielectric lenses and Half Wave Plates (HWP) are being considered as part of the antenna optics, but both need to be actively cooled down to cryogenic temperatures and thus will require dedicated testing techniques and facilities. To this end, calibrated (but re-configurable) test benches for reflective and refractive optics will need to be developed to allow radiated tests of such devices and for the full instrument large cryogenic facilities will be required, capable of reaching temperatures down to 4K in vacuum.

The size of focal plane receivers proposed are greatly increasing, with some missions proposing arrays with thousands of detectors. The individual detector will be coupled with a horn or lens to the sky, each of which has to have its antenna pattern and gain characterised in representative environmental conditions: several detector technologies, need to be cooled below 1 Kelvin which makes testing extremely challenging.

With the growth of available large deployable reflectors in the market, especially metal mesh-based reflectors like those proposed for future earth observation missions such as CIMR, there is the need to accurately calibrate performance of the antenna, taking into account its thermal environment which, for such large apertures, may include a gradient through the reflector surface. Such reflectors, when used for multi-band missions, will also require PIM performance assessment and despite PIM testing at feed or antenna array element is commonly done today, such characterisation for large apertures will require large thermal enclosures in an anechoic environment which are yet to be developed.

In addition, the use of reconfigurable payloads for future generation of navigation satellites will likely require precise antenna phase centre and group delay knowledge for multiple thermal scenarios and payload configurations, with unprecedented accuracy.

Establishing and quantifying uncertainties related with performance over temperature is a challenge on its own and it is foreseeable that new developments will be necessary to support the developments on the testing techniques and facilities. These might include antenna gain standards built with materials with low Coefficient of Thermal Expansion (CTE) which are relatively temperature insensitive and integration of Electromagnetic Modelling (EM) tools with multiscale/multiphysics simulation software to allow optimisation of complex antenna digital designs, taking its thermal environment, transient and steady-state behaviours into account at an early stage.

Automotive Antenna Measurements at VISTA

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Introduction. Measurements of the radiation patterns of automotive antennas present a special challenge. On the one hand, there is a large number of antennas – more than 20 for a middle-class passenger car, the number of which will increase in view of future technologies like automated and connected driving, 6G, or combined terrestrial and non-terrestrial network coverage. This requires a concept of efficient and accurate antenna testing. On the other hand, the antennas must be characterized in their installed state, since the mounting environment has a significant influence on the radiation, especially at lower frequencies. This requires measurement equipment capable of accommodating entire vehicles. This paper presents the automotive antenna test facility VISTA - Virtual Road Simulation and Test Area at the Thuringian Center of Innovation in Mobility at TU Ilmenau. The semi-anechoic chamber is equipped with a multiprobe arch for fast antenna measurements. After a description of the setup, current and prospective measurement and post-processing steps that can be performed in VISTA are sketched.

The Automotive Test Range VISTA. VISTA is a test facility operated at TU Ilmenau and equipped with an antenna measurement system from MVG (Fig. 14) [101]. Its outer shielding dimensions are 16 m x 12 m x 9 m (LxWxH). Walls and ceiling are lined with 60" pyramid foam absorbers. The metallic floor can be covered with absorbers of sizes suitable for the respective testing process (8" to 60"). A 6.5 m turntable is embedded in the floor, which contains a 4-wheel-roller dynamometer. One of the centerpieces of the chamber is an antenna measurement arch of 4 m radius. Its left part contains 111 dual-pol probes covering the co-elevation range from θ=0° (zenith) to 110° operating in the frequency range 400 to 6000 MHz. The right part consists of 22 dual-pol probes with 5° angular spacing, covering the frequency range 70 to 400 MHz. The center of the arch is 2.3 m above the floor, making it necessary to raise the car under test on a scissor lift. The space beneath the car can be lined with absorbers to emulate free-space conditions. Another alternative is to use a specific construction mimicking a perfect electrical conductor [102] or, prospectively, more realistic materials like asphalt or even artificial road surfaces. The measurement usually proceeds such that the vehicle rotates on the turntable underneath the fixed arch. For each azimuthal angle, the antenna under test (AUT) is measured along an elevation cut with the LF or HF arch. Upon a complete turn of 0 to 360°, the electric field strength in amplitude and phase is obtained for all elevation and azimuth angles of the upper hemisphere down to -20° below the horizon. The co-elevation range is truncated below the vehicle, i.e. θ=[110° to 180°].

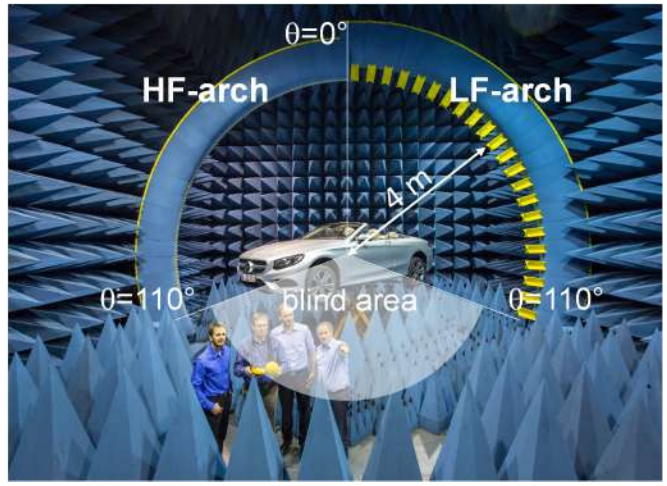

Figure 14: VISTA antenna measurement chamber at ThIMo/TU Ilmenau with multiprobe antenna measurement arch and a car raised into the center of the arch with a scissor lift (orange).

Measurements Capabilities.
(a) 3D Antenna Patterns. Radiation pattern measurements imply the characterization of the directional variation of the radiated power density and, after calibration (i.e. gain substitution method [55, 103]), the derivation of gain and radiation efficiency as well as derived parameters like the total radiated power or total isotropic sensitivity. A "passive measurement" is applied if the antenna feed points are accessible. In this case, the AUT is connected to the ports of a vector network analyzer (VNA), and the transmission coefficient S21 is measured for each angular position. Some challenges arise when performing and evaluating such automotive measurements. First, considering that not the AUT alone is radiating but parts of the car chassis as well, the probes are not in the far-field (FF) for most frequencies of interest (e.g. mobile communications). Instead, the measurements take place in the nearfield (NF), and thus the multiprobe antenna arch acts as a spherical nearfield system (SNF). Hence, the measured data must be transformed to FF with a post-processing step. This transformation is based on the spherical wave expansion (SWE) theory [76, 2]. The conventional SWE-based NF-to-FF transformation becomes critical, when the AUT is located outside the "equivalent sampling sphere" (ESS), which is defined by the frequency and the angular separation of the probes on the arch [104]. For example, at 6 GHz, the ESS at VISTA is approx. 3 m, hence smaller than a typical vehicle. In cases where the AUT is outside this sphere (i.e., mounted in the rear spoiler), advanced processing tools [104, 105] can be used to move the ESS to the fed antenna location, in order to capture most of the radiated power (i.e. local measurement approach [104]). Another important aspect is the truncation of the scanning area which could compromise the measurement accuracy especially at low frequencies such as 70 to 400 MHz and near horizon [106]. Simply replacing the missing field samples with zeros generates a discontinuous field which is difficult to represent in the SWE domain due to

the limited number of available spherical wave modes [106]. To mitigate such type of error methods like the iterative modal filtering (IMF) or the equivalent current technique (EQC) can be considered [106]. Gain calibration is yet another important aspect. The above-mentioned substitution method allows the calibration of the whole measurement system without the need of accessing individual components of the RF chain. However, the gain measurement of the reference antenna is also affected by errors, for example due to residual reflectivity of the anechoic chamber and/or truncation of the scanning area. To improve the accuracy of the gain calibration, the known efficiency of the reference antenna can be used instead of its gain [103]. Indeed, since the efficiency is an integral quantity, it allows to smoothen the measurement errors showing up in form of ripples. More specifically, considering the upper hemispherical efficiency, truncated spherical NF systems, like the one at VISTA, can be accurately calibrated [103]. If the RF feed points of the antenna are not accessible, the simple VNA measurement principle must be replaced by an "active measurement". This means that a signaling link to the AUT must be established using a communication tester, for example. Instead of measuring the amplitude and phase of the AUT in transmit mode, which needs special consideration of phase retrieval, an alternative is to operate the AUT in receive mode and measure communication parameters like the reference signal received power (RSRP) instead. A low mean error of 0.2 dB between VNA and RSRP measurements was shown [107].

(b) Over The Air Testing. Like in 3G/4G/5G cellular networks, over-the-air (OTA) testing, where the transmitter or receiver are part of the AUT, is becoming essential also in the automotive industry. In these cases, the feed point of the antennas is not accessible, hence an active measurement setup must be considered. Classical NF measurement techniques cannot be applied in conventional OTA testing because of the lack of phase coherence between TX and RX. In fact, OTA tests are usually performed in a far-field setup, where the plane wave condition is achieved by placing the TX and RX antennas at sufficiently large distance (direct FF) or by using a compact antenna test range (CATR, indirect FF). The disadvantages of these two solutions are mainly associated to the high costs needed to implement a large measurement distance in an anechoic environment or to realize an effective CATR for automotive applications. On the other hand, performing automotive OTA testing at reduced distance (e.g. 4 m as in the multiprobe system in VISTA) is an appealing solution as long as the measurement uncertainty is not compromised. In [108], preliminary results of OTA measurements of vehicle installed antennas were presented, showing that good accuracies can be achieved for typical automotive OTA figures-of-merit such as partial radiated power/sensitivity. Moreover, it was shown in [109] how the parallax compensation technique can be exploited to improve the accuracy in case of offset mounted antennas.

(c) Virtual Drive Testing. The impact of wireless sensing and communication technologies on safety-relevant applications in mobility require scenario-based safety assurance testing including the vehicle, the road and traffic environment, as well as the electromagnetic wave propagation. To cope with the enormous complexity and deficiency of real drive tests, virtual drive tests (VDT) present the only solution to test automotive system in virtual environment with real hardware (vehicle-in-the-loop) [110, 111]. The complexity related to a full emulation of a realistic scenario can be significantly alleviated by the combination of measurements and simulations [112]. Performing electromagnetic full-wave simulations of the vehicle with antennas integrated is not always possible due to protected intellectual property rights related to antenna design and signal processing. On the other hand, the effort to perform full vehicle measurements with the antenna in different positions is prohibitive. A valuable alternative is to measure the antenna in a stand-alone configuration, compute the equivalent currents on a Huygens box including that antenna and use the EQC in a simulation software containing the vehicle structure [112]. Such a co-simulation can also be applied to other use cases such as the evaluation of human exposure to the radiated field inside cars [113] or virtual verification and validation of automotive radar [114]. Evaluating the radiation performance of a vehicle over infinite flat dielectric ground (like asphalt) is often a test requirement which can be met by combining SNF measurements of the vehicle performed under free-space conditions with image theory [115, 116]. Even more complex scenarios like urban traffic environments can be emulated by co-simulation techniques, where the EQC of the whole car are numerically derived from measurement and then inserted into advanced electromagnetic simulation tools emulating the scenarios of interest [111].

Conclusion. The development of modern automotive antennas and wireless transmission systems requires fast and accurate measurements of the whole vehicle to reduce design and test cycles [111]. The state-of-the-art multiprobe spherical nearfield facility implemented in the automotive test range VISTA at TU Ilmenau, Germany, was described, and promising approaches to address upcoming challenges related to the combination of measurements and simulations and virtual verification and validation in virtual environment were outlined.

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Drone-aided In-situ Antenna Measurements

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Introduction. The use of Unmanned Aerial Vehicles (UAVs) allows for in-situ characterization of antennas in outdoor settings. Moreover, their adaptable nature provides opportunities to conduct various diagnostic techniques that were previously unfeasible. This article explores works carried out in this field until now and highlights some future potential applications.

Current status. In-situ measurements have been mostly reported for radio telescopes, radar and satellite antennas, mobile and TV tower antenna systems. Early measurements with modern UAVs have been reported since 2014 [117], thereafter publications succeeded with rapid growth. So far, the operating frequencies ranged from HF band [118] up to Q-band [119].

Testing of radio telescopes undoubtedly represents an ideal scenario for in-situ UAV-based measurements. UAVs allow the calibration and characterization of modern radio telescopes based on phased-array technology – such as the Square Kilometre Array (SKA) – at both the element and instrument levels (end-to-end verification). Experiments have been reported on a 6 m×6 m array prototype of the SKA-mid instrument at 350 MHz [120], on a 16-elements demonstrator of the SKA-low instrument from 50 MHz to 350 MHz [121], and on two 48-elements arrays located at the Murchison Radio-astronomy Observatory from 50 MHz to 320 MHz [122]. Measurements have also been performed on operating radio telescopes such as the LOFAR low-band array from 32 MHz to 70 MHz [123, 124] and high-band array from 124 MHz to 180 MHz [125]. As far as radio astronomical reflector antennas are concerned, UAV-based measurements have been reported on 5-m dishes at 1 GHz [126], on a 15-m reflector at 2 GHz [127], and an offset-parabolic reflector at 14.5 GHz [128].

Speaking of radar and satellite antennas, measurements have been reported on coastal HF oceanographic radars from 3 MHz to 50 MHz [118], on a naval surface-wave radar at 13 MHz [129], and on a folded dipole for the Europa Clipper mission spacecraft at 60 MHz [130]. Finally, broadcast tower antenna systems have been measured at 177.5 MHz, 226 MHz and 598.5 MHz [131].

As far as the UAV is concerned, the payload generally consists in a radio frequency transmitter, i.e., the UAV represents the flying test source and the AUT operates in receiving mode. An example is shown in Fig. 15. The simplest transmitter consists in a continuous wave (CW) generator, but also more complex solutions have been occasionally adopted, e.g. a pulse transmitter in [124], whereas [126] used a flat-spectrum noise source of about 2 kg carried by a 11 kg hexacopter.

Airborne receivers have been adopted in some cases; they mostly consist in portable spectrum analyzers [131, 132] or miniaturized power sensors [133]. In this case, the UAV shielding from external interference represents a critical aspect [131]. A further approach aims at minimizing the payload complexity by carrying on the UAV only a probe antenna with some basic electronics, thus avoiding the presence of both transmitter and receiver. In this case, a wired or fiber-optic link will tether the drone to a ground equipment, e.g. a Vector Network Analyzer (VNA) [127].

Figure 15: QuadSAT's UAV-based measurement platform.

In both cases, the measured data is generally represented by the power level received either at the AUT port or at the UAV. The AUT pattern calculation requires the knowledge of both the UAV attitude and position during the measurement and, of course, the radiation properties of the UAV-mounted payload. The former is generally measured by Inertial Measurement Units (IMUs) onboard the flight controller with an accuracy of few degrees. As far as the UAV positioning is concerned, modern UAVs can take advantage of Real Time Kinematic (RTK) devices to reach a centimeter-level accuracy.

As far as the antenna on board the UAV is concerned, wire antennas represent the most practical solution at the lowest frequencies (HF and VHF). They can be fixed to the UAV frame so that their orientation coincides with the UAV attitude. In these cases, the onboard antenna can be strongly coupled with the UAV metal parts, therefore the overall electromagnetic behavior must be accurately studied to maximize the measurement accuracy. On the other hand, the smooth pattern of electrically small antennas generally mitigates the measurement errors generated by the limited IMU accuracy. As the operating frequency increases, directive and/or calibrated antennas and even horns can be used. Directive antennas can be mounted on gimbals [126], [134], in this way the onboard antenna always points toward the AUT regardless of the UAV maneuvers, simplifying the data processing.

The most common flying platform consists in a 4-to-8-rotor multicopter with a variable mass (generally within 3 kg) and a flight autonomy between 15 and 25 minutes. Fixed wing UAVs have been employed to cover large distance with long flight duration [118]. Generally speaking, multicopters provide more versatility in terms of flight strategies, lift capacity and possibility to control the horizontal orientation of the vehicle (the yaw angle), which is of great important as far as the characterization of the polarization properties of the antenna are concerned.

Emerging challenges. In the simplest measurement configuration, the distance between the AUT and the UAV satisfies the far field (FF) criteria. This is the case of most of the cited works. In the far field, the AUT radiation pattern can be easily extracted from the measured received power through the well-known Friis equation.

Near-field (NF) strategies become necessary when the Fraunhofer distance is incompatible with the applicable flight regulations. The conventional approach to compute the AUT radiation pattern from near-field data is to apply a NF to FF transformation. Traditional algorithms use the phase information of the received signal in order to perform the transformation. This is particularly challenging in UAV-based measurements, as the flying instrumentation and the ground one generally do not share a common frequency reference, impeding phase measurements. Even when obtaining a reliable phase measurement, the position accuracy of the RTK receivers limits the applicability of NF-to-FF transformations to *S*-band. Furthermore, transformation algorithms will deal with a highly irregular spatial domain compared to conventional regular grids of motorized positioners (e.g. Cartesian, cylindrical or spherical).

In [135], the EM model of a 30-m wide LOFAR station has been validated in the near field. In particular, the geometrical model of the station incorporated both the array elements and the flying test source. The measurements were then compared with the transmission coefficient simulated taking into account the real UAV flight path and attitude. This represents, however, an unconventional and computationally heavy approach.

A phaseless transformation technique has been adopted in [133]. In that case, a UAV equipped with a power sensor was used to measure the radiation pattern of a 2-horn array in *S*- and *C*-band through cylindrical scans in the near field. The measurement setup is highly simplified as the phase information is not acquired (i.e., magnitude-only measurements were made). However, phaseless methods generally minimize a nonlinear and non-convex cost functional, potentially leading to an ill-posed problem that suffers of local minima.

A conventional approach based on a NF-to-FF transformation with phase information has been adopted instead in [127]. A VNA on the ground fed the AUT (a 15-m parabolic reflector at 2 GHz) while the received signal was transmitted from the UAV to the ground thanks to a RF-over-Fiber (RFoF) link, obtaining reliable phase measurement regardless of the UAV movement. A laser tracker was present to obtain sufficiently accurate position data, and the Fast Irregular Antenna Field Transformation Algorithm (FIAFTA) was used to deal with the irregular sampling grid.

A further approach aims at applying NF to FF transformation avoiding the need of tethered flights. It uses an additional known reference antenna to retrieve the phase information. A common receiver samples the signals from both the AUT and the reference antenna, allowing to compute the phase difference and eliminating the phase drift caused by the frequency offset between receiver and transmitter. In [125], the radiation patterns of the LOFAR high-band array have been measured in the proximity of the beam axis, exploiting the near-field focusing method. Such a technique avoids both the time-consuming $\lambda/2$ sampling of the aperture field and the application of computationally-heavy NF to FF transformations. One of the central elements of the array was used as phase reference. In [121], the phase reference antenna was instead placed in the proximity of a 16-elements SKA-low prototype to retrieve a near field phase pattern. A NF-to-FF transformation was then applied. Of course, this method assumes the reference antenna phase pattern to be known from simulations. It is to note that the two field components needed by the transformation were acquired with different flights and were therefore sampled on different sets of points.

Finally, the flexibility of UAVs allow for further antenna diagnostics other than measurements of the radiation pattern, such as the evaluation of the tracking performance of an AUT for satellite communications [136]. In this case, the pass of a satellite is projected to a shorter distance from the AUT and emulated by the UAV, matching its velocity and radiated power, and compensating for Doppler effects. Since the position and attitude of the UAV are known in all moments, they can be compared to the known pointing angle of the AUT for diagnostics and refinement purposes. The main advantage of this method is the repetition of the pass at will, without needing to wait for the satellite, and even the diagnostic of tracking problems before a satellite is even launched.

Future developments. The use of UAVs for antenna measurements has proven to be a valuable tool in outdoor environments. However, there is still room for future research and development in this area. One possibility is to incorporate software-defined radios (SDRs) to transmit/receive signals with the drone, or to both transmit and receive allowing for a more comprehensive examination of the antenna characteristics. Additionally, phaseless measurements with phase retrieval algorithms may be improved to allow measurements in the near-field region using UAVs without additional equipment for the measurement of the phase. Another possibility, assuming reception from the UAV side, is the use of drone swarms to expedite measurements through the acquisition of multiple parts of the measurement surface simultaneously. Furthermore, advanced measurement strategies can be implemented by using the processing capabilities of the microcomputer onboard the UAV, thus using the *live* processing of the measurement data for the modification of the measurement path. Finally, the use of RTK-aided IMUs to increase attitude accuracy in yaw/pitch/roll could lead to uncertainties below 1°, further improving the quality of the collected data. These possibilities illustrate the potential for continued advancement and innovation in the field of antenna measurements using UAVs.

Fast Antenna Measurement Techniques for 5G Personal Devices and Beyond

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Introduction. Modern personal devices, such as mobile phones, are equipped with a range of antennas and sensors to ensure optimal performance and connectivity. The evaluation of devices has undergone significant changes, with regards to performance metrics assessment such as coverage/radiation patterns both with and without user interference.

Early testing of 1G/2G/3G devices often involved mechanically rotating the device while it was held in a test fixture. This resulted in high levels of interaction with the fixture, potentially distorting the results. The launch of one of the most popular smartphones in history in 2010 was a pivotal moment for the testing industry. The incident, known as ”antenna-gate” brought attention to the importance of precise representation of devices during testing, as well as a comprehension of the effects of user interference on performance. This paved the way for systems based on non-invasive device positioners enabling access to both standalone and user-influenced performances. This contribution provides an overview of current testing methods used for the evaluation of 4G/5G/6G devices.

OTA Testing. Traditionally, the transmit and receive performances of wireless devices have been measured by directly connecting the device to test equipment. However, this is no longer possible in today’s technology where transmitter/receiver are part of the device. Instead, testing is done through a remote connection using over-the-air (OTA) methods.

Test parameters for personal communication devices are defined in the far field (FF), which presents a challenge for OTA testing. Ensuring a high-quality FF condition in the test environment is essential, and compact test environments with low spatial losses are generally preferred. Striving to achieve measurements that closely approximate the FF condition presents a paradox, as most communications supported by antennas and devices occur at a finite distance and often in the near field (NF). However, the FF state provides a convenient reference condition that enables traceable and comparable results from different measurement ranges and systems. In OTA testing, spatial power quantities related to radiated power and device sensitivity are typically measured to characterize the transmitting and receiving properties of a device.

Testing Challenges. In [137], it was reported that the human body can significantly impact the performance of personal devices, particularly in mmWave frequencies. This is due to the strong shadowing effect that occurs, which reduces the coverage efficiency of the phased array. Unlike lower frequencies like GSM and UMTS, where fields can curve around the user and still provide decent 3D coverage, the shadowing effect at mmWave frequencies is more pronounced. To overcome this challenge, modern devices now come equipped with multiple arrays placed in different parts of the device to ensure full coverage is achieved through selection. This effect can be tested using head and/or hand phantoms or life person testing of the devices as shown in Fig. 16.

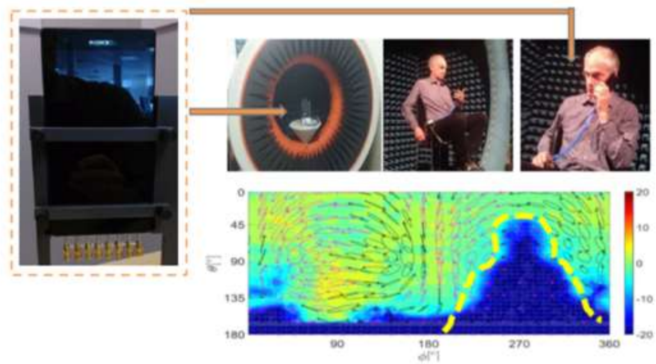

Figure 16: Measurements of shadowing effect by user and efficiency of array switching on 5G enabled device at mmWave frequencies [137].

Another testing challenge is MIMO OTA testing which aims to determine system-level parameters such as data throughput with received power at a device in a realistic and complex scenario using a standardized channel model in a multi-probe anechoic chamber (MPAC). To achieve this, a channel emulator and a probe array are used to reproduce the RF and spatial contributions to the signal, respectively. The RF contribution consists of various elements such as modulation, polarization, temporal delay, and doppler profile, while the spatial contribution is represented by plane waves with a certain angular spread. A typical test setup is shown in Fig. 17. More details on MIMO OTA testing using MPAC solution is outlined in [138].

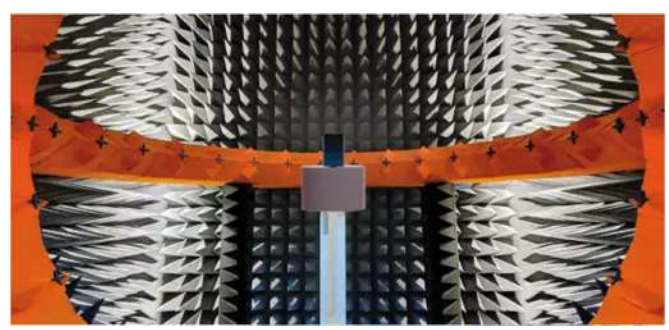

Figure 17: Measurements of MIMO OTA performances using a typical MPAC solution.

At mmWave frequencies the required number of probes for a full MPAC solution becomes prohibitive as the electrical size of the device growths. This is a key challenge for the testing. A potential solution is to limit the angular space of the testing reducing the overall number of probes required

Testing Solutions and Challenges. The standard NF and FF measurement solutions used for personal device testing are described in [55, 76]. The techniques, as shown in Fig. 18, are commonly referred to as direct FF, indirect FF and NF techniques.

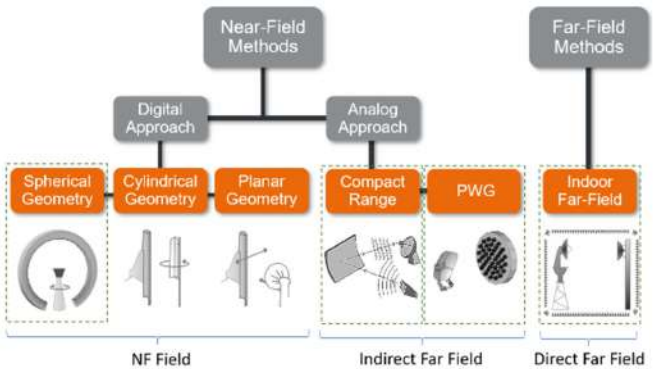

Figure 18: Overview of testing solutions for personal devices.

Due to the lower interaction with the test fixture, NF techniques have generally been preferred for testing of personal devices designed to radiate in all directions. NF techniques require a full scan of the measurement surface to determine performance. For this reason, the multiprobe systems shown in Fig. 16 were developed. Measurement speed is significantly increased from the substitution of the mechanical probe movement with the electronically scanned multi-probe array.

At mmWave frequencies the higher directivity of the antenna arrays incorporated in the devices allow testing using indirect FF techniques such as Compact Antenna Test Range (CATR) or Plane Wave Generators (PWG). The advantage of these systems is speed, from the possibility to determine FF performance in a given direction from the measurements of a single point [76, 139, 111]. An implementation of the PWG designed specifically to be able to perform device testing including live or phantom users is shown in Fig. 19.

Figure 19: Personal device testing including live user experience using movable PWG. Additional PWGs can be mounted to emulate simultaneous connectivity points.

Other test solution is the reverberating chamber [55]. It allows to determine integral performance values of devices but does not provide information on the spatial performance or user interference.

Future Developments. The time to market is a critical factor in personal communication. The development of new technologies necessitates thorough testing, with advancements in measurement speed, accuracy, and convenience serving as important driving forces. These factors actively propel the progress of testing methodologies. With the rapid evolution of technology, there is a clear and notable shift moving away from traditional testing techniques such as [55] and [76]. Instead, there is a growing emphasis on adopting more specialized methodologies that focus on optimizing device performance in realistic scenarios. This shift is primarily driven by the increased demands arising from research and development (R&D) activities. Conducting realistic user experience testing has become indispensable in the process of device development. Such testing plays a key role in identifying areas that require improvement, ultimately leading to the enhancement of overall device performance.

As both testing and numerical modelling techniques are continuing to develop individually to meet new design challenges, measurements post processing technology is under refinement to facilitate the use of a measured data on specific devices as sources in larger scale simulations. This integration of measurements and numerical techniques in R&D development is becoming increasingly important, as it improve development speed and efficiency [139, 111].

Public safety using personal communication devices is also an area important area of new developments. Until recently the standard approach was to mimic device and user interaction using phantoms and measure the power dissipation within human tissue equivalent materials. These legacy methods are likely to continue to be in use for type approval testing of devices below 6GHz. Newer methods are already now preferred for R&D purposes based on multi-sensor techniques giving access to much faster, reliable testing and data specifically useful for further development of the devices. At frequencies beyond 6GHz, the legacy methods are no longer useful, but as personal communication move to higher frequencies new testing method to ensure public safety are required. These methods are mainly based on post-processing of the measured device and are currently under development. They aim to determine if power densities in the close vicinity of the devices are within acceptable health limits when operated.

By incorporating new testing methods, we can not only verify but also achieve the optimum performance of personal communication devices.

Conclusion. Modern device testing methods prioritize fast and accurate performance measurement with minimum of interaction with test fixture and including the user's impact on device functionality. This important shift in testing methodology will lead to improved device performance and more reliable results and increased safety for consumers.

Over-the-Air Testing of Communication Systems

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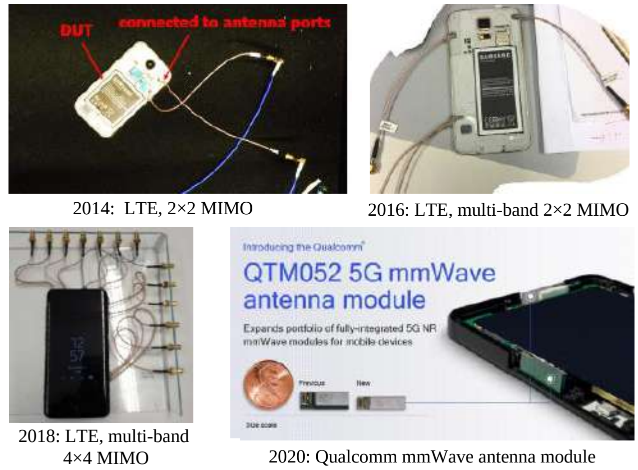
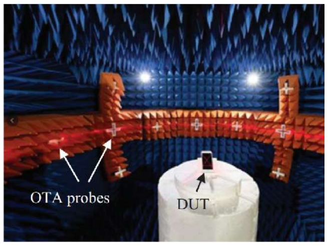


Figure 20: Cabled testing for LTE phones and integrated antenna for 5G FR2 phones.

Introduction. Wireless radio access technologies continue to evolve, as technologies like 5G and Wi-Fi 6 reach mainstream adoption and the industry begins to look towards 6G and Wi-Fi 7. To increase the available bandwidth and overall performance, these systems utilize adaptive radio systems with multi-antenna technologies that use digital, analog, or hybrid beamforming mechanisms as well as employing concepts like massive MIMO, in addition to exploiting wider bandwidths in both incumbent spectrum allocations and newly opened regulatory bands in the microwave and millimeter-wave (mm-Wave) frequency ranges. Radio endpoints typically undergo thorough conformance and interoperability testing to ensure that they meet the specifications of the design standard for the given radio access technology. Traditionally, most of these tests have been performed using a conducted setup to evaluate the radio performance independently from that of the antenna(s) in the system. Over-the-air (OTA) testing was introduced initially as a final step to evaluate the radiated transmit and receive performance of the device through the antennas [141]. Later, the introduction of multiple-input/multiple-output (MIMO) technologies made it impossible to isolate the device performance from the radio environment in which it operates, resulting in the need for RF environment simulation that could evaluate the behavior of a complex antenna system over the air [142, 143]. With the advent of advanced phased array technologies at mmWave and microwave frequencies (for base stations), the radio performance has become much more tightly tied to the behavior of the antenna system [144, 145, 146]. As the radio transceiver becomes more compact and highly integrated, cabled access to the radio circuitry becomes impractical if not impossible, leading to the need to perform all of the traditional conformance test cases through the antenna system using an OTA testing approach. A photo of why testing will move towards OTA mode is shown in Fig. 20. Advanced radio technologies also pose huge challenges on their OTA performance and conformance testing, due to the high system complexity, high implementation cost, long measurement time, and high measurement uncertainty.

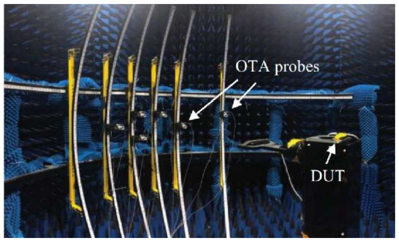
Current State-of-Art. OTA testing of wireless device performance was initialized for single antenna (single-input single-output, SISO) mobile terminals in CTIA and 3GPP, where figures of merits (FoMs) total radiated power (TRP) and total isotropic sensitivity (TIS) were selected to characterize the transmit and receive capability of the mobile terminals [141]. However, SISO OTA testing was deemed not sufficient to capture the performance of MIMO-enabled mobile terminals, since the performance enhancement introduced by multi-antenna, e.g. spatial multiplexing and transmit diversity, are determined by the propagation channels as well as the antenna design. To tackle this problem, OTA testing of 2×2 MIMO terminals was initiated in [142, 143], with a focus on introducing realistic and representative spatial fading channel conditions. Using a base station emulator (BSE) and a channel emulator (CE) with appropriate measurement setups in the anechoic chamber, OTA radiated performance testing evaluates the wireless system's performance and reliability in a controlled laboratory environment that emulates realistic real-world fading channel conditions. Several MIMO OTA methods were proposed and extensively discussed, including the later standardized radiated two-stage (RTS) and the multiprobe anechoic chamber (MPAC) solutions [142, 143, 146, 147]. Throughput (i.e. data-rate) was selected as the FoM for MIMO OTA testing. 3GPP TR 38.827 specification studies the performance metrics, measurement methodologies, channel models, and validation procedure for MIMO performance evaluation of 5G mobile terminals [145]. The test methods, originated from 4G MIMO OTA were extended to support OTA testing of 5G mobile terminals. Specifically, the MPAC solution has been selected as the reference testing method for 5G frequency range 1 (FR1) UEs up to 4×4 MIMO, while the RTS method can be utilized as well if consistent results with the reference MPAC solution can be achieved. Fig. 21(a) and (b) show the setup for 5G FR1 UE OTA testing with MPAC and RTS methods, respectively [148, 149]. For 5G FR2 UEs, only the simplified 3D MPAC solution has been selected, as shown in Fig. 21(c) [148], with limited capability to emulate spatial channels. Although arbitrary channel models can be emulated by the RTS method in principle, the RTS method has been only validated for 2×2 MIMO mobile handsets in FR1. OTA performance testing of base station under realistic fading conditions is still in its infancy in the standardization.

OTA radiated conformance testing evaluates a wireless system's capability with respect to the transmitter (e.g. power, signal quality, unwanted emission, etc) and the receiver (e.g. dynamic range, sensitivity, selectivity, and blocking, etc) [150, 151]. Several measurement systems have been employed for radio frequency (RF) OTA metric measurement for directional



(a)

(b)



(c)

Figure 21: Measurement setup for OTA testing of 5G NR: (a) The MPAC setup for 4×4 MIMO terminals at FR1 [148]. (b) The wireless cable setup for 4×4 MIMO terminals at FR1 [149]. (c) The MPAC setup for 2×2 MIMO terminals at FR2 [148].

testing, i.e. direct far-field method (DFF), compact antenna testing range (CATR), plane wave generator (PWG) and near-field to far-field transformation (NF-FF) techniques and non-directional testing (e.g. TRP and TIS measurement in reverberation chamber) [152]. The required measurement distance to meet the far field assumption in the DFF setup increases significantly for 5G radios as the antenna electrical dimension continues to grow, which makes it impractical for massive deployment due to physically large testing setup and link budget issues. CATR, which can reduce the measurement range compared to the DFF, has been employed for BS testing currently. However, it still suffers from high cost and large test chamber as the BS antenna aperture gets larger. Recently, a multi-feed CATR was designed to generate plane wave from several distinct directions, which is promising for radio resource management (RRM) measurements of 5G radios [153]. PWG offers a shorter measurement range and lower cost compared to the CATR. However, its supported bandwidth cannot cover the required 1.7 GHz to 7.2 GHz due to the limitation of the phase shifters. Furthermore, its application in the mmWave bands is still not mature. Significant efforts have been taken to make the PWG a reality, e.g. support for ultra-wideband bandwidth and mmWave frequency band, generation of a spectrum of oblique incident plane waves, PWG in non-anechoic deployment environment and cost-reduction by reducing complexity of the PWG feeding network [154, 155, 156, 157]. NF-FF solutions can further reduce the measurement range. However, it suffers from long measurement time, and it cannot be directly used for modulated signal measurements.

Emerging Challenges and Future Development. The key bottlenecks in standardization for conformance OTA testing are the long measurement time (due to a large-scale antenna configuration and beam-steering capability of 5G radios) and high system cost (due to the demanding and expensive testing chamber environment). The current RF testing methods measure the beams sequentially with a beam-lock function until all available beams are measured. Considering that the antenna array pattern becomes more directive with a larger array configuration, the entire radiation pattern measurement is very time-consuming since very fine spatial resolution is required over the sphere enclosing the antenna for each beam-steered state. Besides the radiation characteristics, it is also of importance to efficiently calibrate the large-scale antenna arrays in practical measurement setups. The conventional “probe and park” solution with the help of mechanical scanner is slow and inaccurate [158]. Recently, array diagnosis and calibration in the all-on mode has been actively discussed to improve the measurement efficiency and accuracy [159].

Another challenge is the measurement deviations introduced by practical setup, e.g. power-only measurements, limited measurement range, non-anechoic chamber environment, hardware impairment, etc. It is highly desirable that we can perform the transmitter and receiver conformance testing of the communication radios in cost-effective measurement setups in a fast and accurate manner. Miniaturization of testing chamber is essential to reduce setup cost, which has attracted great research attention recently, e.g. mid-field solutions, which aim to reconstruct the far-field results from mid-field measurements using compensation or extrapolation algorithms [160]; metamaterial enabled absorber design, which can significantly reduce the absorber dimension while maintaining the same performance as traditional absorber [161]; algorithms to reduce echo in the test environment so that we can retrieve target results in non-anechoic measurements [162].

As more integrated antennas will be employed in future radios, it becomes essential to have radiated OTA access to the digital receivers in the radio systems. This has been achieved for mobile terminals supporting 2×2 and 4×4 MIMO schemes. However, it will become problematic as the MIMO order gets larger. For the MPAC system, the number of required probe antennas (thereby associated CE resource) will increase as more antennas are employed in the DUT, leading to expensive system design. To ensure the channel reconstruction accuracy, we typically have to sacrifice channel emulation flexibility, as done in FR2 MIMO OTA testing [145]. For the wireless cable solution [147], the condition number of the transfer matrix between probe antenna ports and DUT antenna ports will get large as the number of antennas grow, making it difficult to achieve in practice (as it requires inversion of the transfer matrix). It is currently still an open challenge.

Conclusion. In conclusion, we briefly revisited the current standardization for over-the-air testing of communication devices. We explained the new radio technologies introduced for the future radio systems and new challenges on over-the-air testing introduced by the new antenna technologies. Over-the-air testing is seen inevitable for future integrated radio systems. However, strong efforts are required from academia, industry and standardization to make the OTA testing more accurate, fast, and cost-effective.

mmWave Active Antenna Systems Measurements - an Overview

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Introduction. Active Antenna Systems (AAS) have received larger attention lately with the introduction of 5th generation (5G) systems. With a huge paradigm shift with respect to previous generations, 5G systems rely on actively tracking the users within the cell, with a dedicated beam generated by a phased array, in order to maximize the radiated energy to the individual users and to exploit Space Division Multiplexing Access (SDMA) technology within the cell, thus enabling frequency reuse. Moreover, in order to support the increased data rate, larger portions of the spectrum in the mm-wave range (Ka-band and E-band) have been reallocated from point to point legacy systems to wireless access to the 5G network, making larger channels available to users [163].

In a Base Station (BS), the Active Antenna System can be seen as a composition of three main parts: an analog core (usually composed by a set of transceivers - TRXs), a Radio Distribution Network and an Antena array. The TRXs, composed by Variable Gain Amplifiers (VGA) and Phase Shifters (PS) required for antenna reconfiguration, are very often integrated within the same unit as the antenna, eliminating the physical interface between them, and forcing the characterization of the active control section along with the purely radiating section of the antenna.

In this work we will focus on the challenges in the field of antenna measurement brought about by these new systems and discuss some approaches on how to best address these issues.

Antenna measurement set-up. Previous generations of wireless telecommunication equipment all relied, for the most part, on fixed antenna systems to transmit and receive their signals. Point to point radio links in the Ka-band employed, in the vast majority of cases, fixed Cassegrain type double reflectors antennas of standard sizes (30 cm, 60 cm main reflector diameter) while sub-6GHz base station antennas for network access employed fixed arrays. The lack of pattern re-configurability of these antennas and their passive nature made their electrical characterization relatively simple by performing standard antenna measurements of fully passive devices, either in anechoic chambers or in open field ranges. 5G antennas, on the other hand, require a more complicated measurement setup as well as an accurate characterization of a whole set of configurations, each corresponding to one specific beam pointing direction. This set of configurations is usually referred to as a codebook and the beams it generates are usually referred to as a Grid of Beams. The individual beams within the grid can be optimized in order to achieve the best network performance. The superposition of the measured beams generated by a codebook forms the so called Radiation Pattern Envelope (RPE) which, while being a non-physical radiation pattern, is of the utmost importance for emission compliance verification and interference assessment during network planning activities.

Given the number of measurements required for an accurate characterization of mm-wave antenna systems and the reduced space required for high-frequency measurements, it is preferable to perform these in an anechoic chamber instead of an open field range. Contrary to older antenna systems, 5G systems not only require a more comprehensive characterization, but also require a more complicated assortment of wires and cables in order to power and configure the Antenna Under Test (AUT). Extreme care must be paid to how these wires and cables enter the anechoic chamber, since every opening in the room's shielding degrades its immunity from external sources of EM noise. Also extremely important is to ensure that none of these cables and wires impede in any way the rotational and translational movement of the measurement axis inside the chamber as this could result into permanent damage of the measurement system or, in the best case, measurement failure. Finally, care must be taken that the digital control signals of the VNAs and PSs do not interfere with the measurement, this is not a trivial concern since the spectral content of high speed digital signals may contain high order harmonics which extend well within the mm-wave spectral range.

Antenna measurement typology. The limited room available in anechoic chambers typically offer the possibility to perform either Compact Antenna Test Range (CATR) or Near Field (NF) measurement. CATR measurements are faster, as they are an indoor replica of open range measurements, with a properly designed reflector positioned in the opposite end of the chamber generating a flat phase front over the quiet zone (where the AUT is measured) when illuminated by the source antenna, but they only provide the far field radiation pattern along one cut on each pass. NF measurements are longer, they can take up to a few hours, as a surface enclosing the AUT needs to be sampled at an interval compatible with the antenna wavelength and aperture size, but they provide a complete description of the fields around the antenna and, from this information, the full 3D far field pattern of the antenna can be derived by applying a spherical wave expansion of the source fields [76]. It is worth noting that, when performing NF measurements, it is of the utmost importance to know the exact position of the sampling probe over the antenna in order to properly compute the spherical wave expansion. Any inaccuracy in the sampling point creates an unwanted phase contribution to the source fields which will affect an accurate far field pattern reconstruction. The positioner accuracy requirement obviously scales with the measurement frequency, since a position error in the range of 1/100th of a wavelength is normally considered as the acceptable limit. For E-band systems this requirement translates into a positioner accuracy in the range of 40 μm from the nominal sampling position. In Fig. 22, an example of an Active Antenna System measured by means of a Near Field test range is shown.

The full knowledge of the fields around the antenna is essential in identifying, for example, faulty elements within the

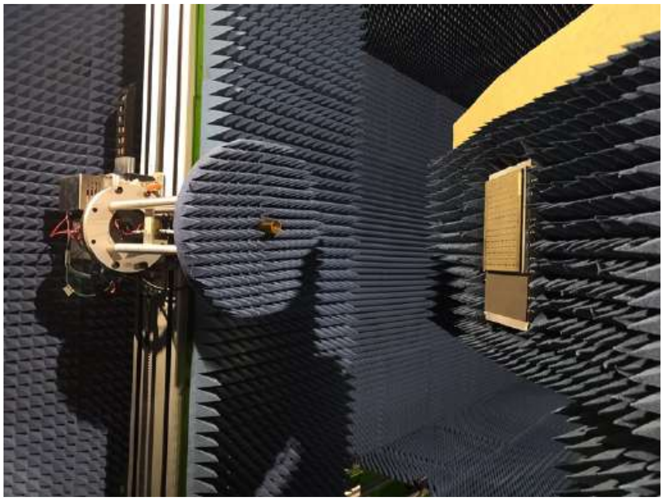

Figure 22: Near Field measurement setup of a mm-wave antenna system. The control electronics is on the backside of the unit properly shielded by absorbing material in order to minimize its impact on the measurement.

array or to verify if all the radiators are properly excited, and it is not available by CATR measurement. NF measurements are also useful when beam forming techniques are used to generate a more complex pattern than a single beam, for example if nulls are required in certain position for interference cancellation, in this case a single 2D CATR scan may not be able to provide all the relevant information regarding the pattern generated by the array. It would not be fair, however, to disregard CATR measurements as a valid option for 5G antenna systems. Indeed, they are extremely useful for specific situations such as a fast pattern verification along defined planes or during production stages where it would not be conceivable to dedicate a few hours of precious chamber time to one single system. In the end it is important to recognize the strength and drawbacks of both measurement methods and to choose the most suited one according to the specific need.

Antenna calibration. The information derived by a NF scan can also be used to perform the calibration of the phased array control elements, which is fundamental for the proper functioning of the active antenna. In fact, the control elements of the array (named beam-formers) are essentially mm-wave VGAs with Gain in the range of 30dB placed after mm-wave PSs capable of achieving full 360° of phase rotation, both VGAs and PSs usually being controlled by a 5 or 6 bits word giving them 32 or 64 independent states.

Since mm-wave devices are affected by a high degree of parameters dispersion, it is very unlikely that all the beam-formers in a single system align perfectly to feed the respective radiating elements with the desired phase and amplitude combination synthesized by the base band (Fig. 23), even choosing to neglect any additional misalignment generated by the Beam Forming Network (BFN). The NF sampling of the fields in front of each element provide the information needed to equalize all the radiators within the array and to compensate for the dispersion of the respective control chains.

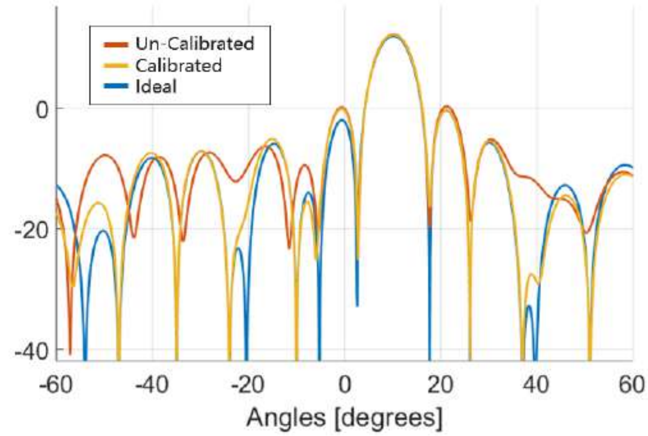

Figure 23: Measured radiation patterns of calibrated and un-calibrated active array versus target pattern (numerically obtained with ideal excitation set).

Antenna measurement standards. The novel architecture of active antennas introduced by 5G systems have also had an impact on long-lasting standards of antenna measurement [55]. Integrated active antennas with the radiating section on the top layer of a circuit board and distributed amplification on the backside of the board, with no accessible interface to characterize the antenna, have required a new set of Key Performance Indicators (KPI) to be defined for antenna characterization.

Traditional parameters such as Gain and Directivity have been replaced by Total Radiated Power (TRP) and Equivalent Isotropic Radiated Power (EIRP) as it is not trivial to separate the contributions by the antenna to those by the active devices when performing Over The Air (OTA) measurements [164]. As a matter of fact, in integrated active antennas the EIRP (that is defined as the antenna realized gain times the net power accepted by the antenna) can be measured with the support of properly characterized reference antenna and power source. On the contrary the accepted power and therefore the realized gain of the antenna, cannot be accurately calculated. In this case the AAS gain declared by the Original Equipment Manufacturer (OEM) is essentially derived as the EIRP divided by the output power configured in the system.

Conclusion. In this brief contribution, the application scenario for mm-wave active antenna systems within the 5th generation ecosystem was discussed. We then explored the issues that arise when setting up the measurement of an integrated active antenna system operating in the mm-wave range in an anechoic chamber, the conditions which influence the choice of CATR or NF measurement and the factors which can affect the quality of the measurement. The need for an appropriate calibration of the active antenna system was briefly discussed and finally an overview of how traditional measurement standards are impacted by the new integrated active systems and we presented the new standards introduced by the NGMN (Next Generation Mobile Networks) recommendation.

Millimeter and Sub-millimeter Antenna Measurements

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Introduction. Antenna testing at frequencies greater than 30 GHz are typically regarded as millimeter and sub-millimeter (mmW) testing. The test techniques deployed at these frequencies do not fundamentally differ from those used at lower frequencies, but typically vary in terms of implementation. RF instrumentation and mechanical implementation is driven by significantly higher RF loss in guided wave paths and tighter mechanical tolerancing required to control phase uncertainty driven by the shorter wavelengths. Radiation characterization concerns any type of antenna, but specific topics have to be mentioned as they refer to unique research activities or development of industrial applications, and these highlight the principal constraints for testing: embedded antennas (Antenna In Package, Antenna On Chip)[165] and mono/multi-beams antennas [166] for example. In the first case interaction between the measurement system and antenna under test is key. In the second case, mechanical and motion accuracies dictate the effort required. In both cases, several solutions, mixing software and hardware topics, have been proposed to overcome existing limitations of classical measurement systems, or to implement new measurement systems appropriate for mmW frequencies.

Antenna technology. Compared to low frequency range applications, mmW range applicable technologies are deeply impacted by physical size of the antennas and the relevant feed structure losses. The use of coaxial cables and connectors is limited, due to their maximum effective frequency of use, their losses, and their physical size compared to the antenna size. In fact, most commercial RF connectors are electrically large at mmW frequencies, inducing parasitic effects that can adversely affect the antenna performance. A solution to this problem is integration of the antenna in or on the operational platform. This has led to on-chip integration of antennas, which complicates testing of the antenna. This either requires special probes that are used to excite the antenna at chip level (which often requires microscopic positioning of the probe) or a system-level test approach where the antenna cannot be separated from the accompanying sub-system (also referred to as active antenna testing). In the THz domain, integrating frequency generation modules (diodes and photo-diodes) on the antenna is a research topic of interest. This integration introduces a specific problem for radiation characterization as the RF signal cannot be synchronized to classical RF systems, or optical-based measurement systems do not provide phase information (frequency-domain spectroscopy). This constraint requires the use of specific magnitude-only measurement procedures and related phaseless processing algorithms [167]. This limitation applies to source/antenna integrated systems dedicated to communications or automotive radar applications.

RF Sub-system. Generating and detecting mmW signals lie at the heart of making measurements at these high frequencies. A limited ability to generate power or to amplify that power becomes a severely restrictive aspect. Also, path loss, albeit free space or guided wave loss, limits the minimum detectable signal at the receiver. A proven technique to largely overcome these guided path loss limitations is frequency up and down conversion at well selected locations in the RF subsystem [168] by using a distributed RF sub-system. Using this type of RF design also has the added benefit of minimizing the mmW components (including receivers operating at intermediate frequencies (IF)) required to make such high frequency measurements. It also opens the path for a high degree of modularity, in terms of banded mmW solutions. Addressing the RF power and loss problem focuses on magnitude-only measurements and although this would address the majority of test cases, the ubiquity of near-field measurement test systems [169] that require a complex signal to be measured, make the detecting of phase in mmW measurement systems an essential capability. Fortunately, the use of frequency conversion techniques and coherent IF receivers make this possible. However, the detection of signal phase at mmW frequencies is highly affected by temperature variation, mechanical vibration, cable flexing and overall RF stability and these factors become uncertainty inducing parameters into mmW measurement systems [170]. In order to mitigate coupling between the Antenna Under Test (AUT) and the measurement probe, Electro Optic Systems have been developed [171, 172]. Even if further development is needed, their implementation in next generation measurement systems will offer a clear benefit for near-field applications.

Test Facility Types. Test facility types can be divided into amplitude-only and complex signal classes. In many cases amplitude-only test systems will be instrumented with phase capable RF sub-systems (e.g. Vector Network Analyzers) but the phase would simply be discarded. However, it is possible to also use scalar instruments like power meters or spectrum analyzers which do not allow for a complex measurement to be performed and the purpose would be to reduce RF sub-system cost. Examples of such test systems would include: Direct far-field illumination range (FF): This type of range represents the simplest (conceptually) test solution where the transmitter and receiver is separated by a distance such that the AUT experiences an effective far-field condition. An appropriate RF sub-system designed for the range length and a mechanical positioner allowing for the desired motion of the AUT during testing is required. This solution is very practical and in common use in industry today up to frequencies of 1 THz. Compact Range (CR): This type of range can be viewed as a direct far-field illumination range where the range length is reduced by using a feed/reflector combination to create a suitable test zone. The instrumentation required is identical to that of the FF range. However, the biggest challenge for this type of range is the fidelity of the reflector being used. Machining and finishing a reflector surface to support mmW frequencies is challenging (e.g. surface accuracy of < ±30 µm RMS to support 200 GHz [173]) and CR systems supporting measurements above 100 GHz are not common in industry (Fig. 24 shows a machined CR reflector with near-optical surface finish). Despite this stringent constraint, this type is of main interest as it enables direct analysis of the measured data [174] and can be coupled to an interpolation algorithm to provide efficient 3D characterization [175].

Figure 24: CR reflector with measured ±50µm RMS surface tolerance offering a reasonable optical reflection.

Hologram: To overcome CR limitations but following the same philosophy of generating a plane wave in a limited physical space to create a well-defined test area volume (the Quiet Zone) in which the antenna under test must be located during the measurement process. An example solution has been developed using a transmission-type hologram [176]. This solution mitigates the geometrical accuracy needed by the collimating element but impacts the frequency range of measurements (i.e. limits the bandwidth). Plane wave generator (PWG): Generation of a plane wave for test applications can be achieved using CR techniques or arrays of discrete radiators. Practical examples of the latter have not been commercially implemented at mmW frequencies. Recent 5G developments require the design of new measurement systems to characterize spatial beam reconfigurability in a multi path link scenario and CR techniques are deployed to address this [177]. This application is in the lower part of the mmW band and it can be expected that higher frequency coverage will be required in the near future. Near-Field range (NF): Near-field test systems at higher frequencies are principally limited by the ability to measure RF phase accurately. Technology is available today to measure complex RF signals in excess of 1 THz. However, maintaining RF phase stability during antenna or NF probe motion becomes the next major challenge and this is true for planar [178], spherical [179, 180] and multi-axis robotic test systems [181]. Figure 25 shows a SNF scanner implementation suitable for mmW antenna testing.

Errors. Measurement uncertainty associated with the various test systems described can be determined through a Range Assessment and reported in an industry norm 18-term framework as described in [3]. Parameters that typically drive the overall uncertainty are mechanical position accuracy of both the NF probe and the AUT [170], RF sub-system stability and dynamic range as well as RF/LO cable performance. Additional factors that also impact high frequency test systems are temperature and foundation stability. Both of these factors impact RF phase stability most (since motion induced translates to phase variation) and this aspect requires tight control of these environmental parameters. Since most mmW test solutions push the boundaries of mature RF technology today, measurement uncertainty is often higher than what is desired. Implementation therefore revolves around understanding and controlling the factors most adversely driving the measurement uncertainty budget. Using the uncertainty budget as a guide during implementation is key to success.

Figure 25: Articulating arm SNF scanner.

Chambers/Anechoic Environments. Radiation characterization is impacted by any source of corruption of the signal to be measured. Close attention must be paid to the near and far surroundings of the AUT. Specific material treatments must be made to minimize specular and multiple reflections in the measurement chamber. Relative size of the AUT and the facility positioner requires that special attention be paid to the region close to the AUT. For both problems, a classical solution is to use absorbing material, which then requires characterization of this material in the mmW range [182, 183].

Conclusion. Antenna testing at mmW frequencies do not fundamentally differ from those at lower frequencies. However, high RF losses, short wavelengths and the electrical size of commercially available cables and connectors make special implementations essential. These can often be as simple as tighter mechanical tolerances, but can also be more sophisticated accuracy enhancements through software correction techniques or phase-less NF solutions. This short write-up attempts to give the reader a broad view of the solutions that are available in industry today or are being pursued through research to expand the boundaries of possibilities in the future.

Phaseless Antenna Measurements

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Introduction. Antenna measurement based on near field to far field transformation requires precise knowledge of amplitude and phase data on a prescribed surface. Phaseless or phase retrieval or amplitude-only techniques typically refer to far-field pattern characterization when only amplitude data of the near field is available due to the high impact of phase error in high frequency measurements [185] (e.g., flexing cables at frequencies above 100 GHz) or due to a complete lack of phase-measurement hardware. Even, phaseless techniques can be used as alternative to probe position error correction methods [184]. One approach of phase retrieval techniques classification would lead to three categories: four magnitudes techniques, indirect holography techniques, and multiple scan techniques by means of iterative and optimization schemes. Others can be seen as combination or variations of such techniques. In the four magnitudes techniques, the phase difference between two complex signals can be determined from four magnitude measurements. The two signals can be selected as probe and reference channel, two probes at different positions, two orthogonal polarizations, etc. With this technique, the phase difference can be determined from the magnitude values of such signals and linear combinations of such signals and phase delayed representations of such signals. A general description as well as hardware and calibration limitations can be found in [186]. Implementations of multi-probe cylindrical near-field have been proposed [187]. Indirect off-axis holography, also known as Leith-Upatnieks holography [188], is an interferometric technique based on the acquisition of the amplitude of two or more interfering signals, which is adapted from optical holography to amplitude-only antenna measurements. In indirect off-axis holography, the measurement setup includes not only the AUT and a probe antenna but also a reference branch with a "reference antenna" (Fig. 26). In addition to the signal transmitted by the AUT (EAUT), a fraction of the generator signal, using a directional coupler, is transmitted by a reference antenna (Er) separated from the AUT. To balance the amplitudes of the signals radiated from both branches and, therefore, increase the dynamic range of the acquired signal (hologram), an attenuator or amplifier is usually inserted in the reference branch.

$$h(x,y) = |E_{AUT}(x,y) + E_r(x,y)|^2 \quad (5)$$

Both signals are received by the probe antenna to create the hologram (h in Eq. 5) from which the complex pattern of the AUT (and, hence, its phase) can be retrieved by means of appropriate filtering. This conventional indirect holography requires a complete characterization of the radiated field of the reference antenna. Some variations and improved techniques over the conventional indirect off-axis holography are summarized in [189]. One is the modified hologram, based on the removal of the autocorrelation terms of the hologram before the filtering process (for example by means of an extra measurement to characterize the amplitude of E_{AUT}), deriving in some advantages as the diminishing of overlapping, the reduction of the bandwidth in the k-space (and thus, the sampling requirements) and the reduction of size of the setup. Other is the synthesized reference field off-axis holography [190], in which the reference branch is composed by a phase shifter that synthesizes a plane wave that is added to the acquired field of the AUT using a power combiner at the receiver frontend (an alternative way for generating such phase delays can be performed by mechanical shifts of the probe antenna). Progress in broadband antenna characterization has been set with the broadband off-axis indirect holography, in which a frequency interference hologram is composed at each acquisition point from measurements on a frequency range, being compatible with non-redundant sampling techniques and suitable for non-canonical acquisition surfaces. Another alternative is the use of a reference signal produced by the AUT and collected by a second probe moving simultaneously over the near-field scanning surface. The complex signals measured by the two probes are summed, both in phase and in quadrature, by two hybrids mounted on the same circuit board. The squared amplitudes are detected by four diodes [187] and subsequently processed to retrieve the unknown phase.

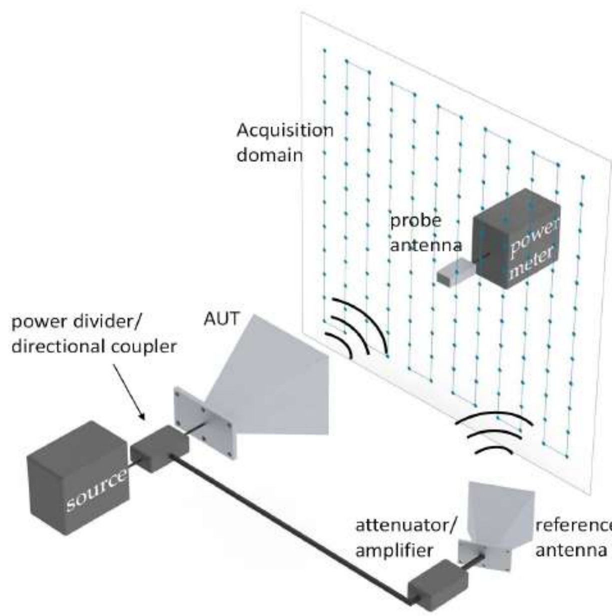

Figure 26: Indirect off-axis holography setup for phase retrieval antenna measurement [189].

Regarding the two-scan techniques, one of first approaches, the Gerchberg-Saxton algorithm [191], alternated substitutions and back-substitutions of the magnitude using Fourier transform. In [192], the algorithm is formulated as alternating projections onto convex or non-convex sets and the "stagnation" interpreted as due to local minima of the objective functional. The mentioned approaches inspired more refined phaseless antenna testing methods ([193], [194]). The two-scan techniques exploit two amplitude acquisitions and can be grouped in two families of algorithms. The first class aims at recovering the missing phase of the data while the second sets up a relation between the antenna features and the amplitude patterns and then recovers the features from the measured data. Both classes involve iterative procedures. The first class of algorithms (e.g. [194]) starts from an initial guess for the field phase of the first pattern; then, the complex field is "propagated" to the second scan and the new numerically obtained phase is attached to the second measured amplitude pattern; finally, the estimated complex field for the second scan is "back-propagated" to the first scan and the process is iterated. The procedure stops when the propagated/backpropagated and measured amplitude patterns become close enough. Such an approach is named Plane-To-Plane (PTP) and the two scans typically involve measurements over two different scanning surfaces. For the latter class ([195, 196]), the unknown is a feature of the antenna to be characterized, for example, its fields at the aperture or equivalent currents around the antenna. A radiating model links the unknown to the measured amplitude patterns and the distance between the latter and the numerically predicted one is minimized. Measurements over two scanning surfaces [195] or by two probes scanning the same surface have been proposed to achieve uniqueness. Differently shaped antennas with different scanning geometries have been considered [196]. Regarding optimization techniques, the phase retrieval problem can be also expressed as the solution of the following equation:

$$|Ax| = |b| \tag{6}$$

where x is the source representation of the antenna (typically equivalent currents [196] or spherical wave coefficients [197], b the collected measurement samples, and A some discretization of the radiation operator. Eq. 6 can be used to model any antenna phaseless measurement problem in matrix notation. This facilitates the application of non-linear optimization methods to find the solution vector x. Some forms of the iterative two-scan method have been formulated as an optimization problem of a properly defined functional ([195, 196]).

Emerging challenges and future developments. Phaseless antenna measurements continue to draw a lot of attention fueled by the ever-higher operation frequency of antennas and recent advances made in applied mathematics including machine learning. Optimization methods based on convex formulations [198] and non-convex gradient-based techniques combined with a proper initialization have been proposed this last decade to efficiently solve, in an automatic fashion, large-scale phase retrieval problems. The implementation of most of these techniques is readily available online [199] and can be plugged-in electromagnetic modeling tools to efficiently solve phaseless antenna measurement problems [200]. However, none of these techniques can generally prevent from falling into sub-optimal solutions for Fourier-based magnitude-only measurements, such as phaseless antenna measurements. Oversampling can help converging to the optimal solution, as well as increasing the number of independent measurements. For that purpose, the modification of the sensing matrix via various AUT positions [201] or different measurement surface scans, or the acquisition of phaseless samples over multiples frequencies [202] are efficient approaches. Leveraging prior knowledge about the antenna phaseless measurement problem, such as the geometry of the measurement setup and/or the characteristics of the unknowns to be retrieved, enables to go beyond the bare phase retrieval formulation. These so-regularized data fitting problems can be easier to solve. Recent works have shown that deep learning methods can be used to solve a wide range of inverse problems, including non-linear phase retrieval problems [203]. However, if the power of data in fitting models is unarguable, the most reliable and accurate phase retrieval algorithms to come will likely be a combination of data-centric deep learning and model-based optimization having an understanding of the underlying physics.

Conclusion. Due to their many benefits, phaseless measurements have pervaded a wide range of applications and stimulated the development of various experimental configurations and reconstruction algorithms. In the context of antenna characterization, phaseless measurements typically refer to the far-field pattern characterization from the measurement of magnitude-only near field. They avoid the need to accurately measure the phase of the electromagnetic field radiated by the antenna under test, a step that can be delicate and costly, especially at high frequencies. The price to pay to retrieve the missing phase is the need to perform more measurements than necessary for a complex antenna characterization. Thus, phaseless approaches typically resort to several measurements (e.g., the four magnitude and multiple scan techniques) or require the use of a known reference antenna (e.g., the indirect holography approach). Optimization methods have also been developed to solve the notoriously difficult phase retrieval problem and various formulations, initializations and regularizers leveraging prior knowledge have been proposed to help converging to the optimal solution. Finally, despite the significant improvements made in phaseless antenna measurements, there is still work to be done in order to reach the maturity and uncertainty estimation of complex antenna characterization.

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Implantable Antenna Characterization

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Introduction. The characterization of implantable antennas comprises many challenges, as their final place of action is within a living host body [204, 205]. It is thus not possible for evident practical reasons to measure antenna performances in their final setup, in which only system aspects can be determined (e.g. the success of a remote powering or telemetric link). The knowledge of the characteristics of the antenna are nevertheless important in the design and validation phase of an implant, as it is of utmost importance to ascertain that the latter work well before implanting it into a living host.

This issue is addressed by the use of simulation models at different stages of the creation implantable antennas, which are known as phantoms. In the first stages of the antenna development, simulation models or virtual phantoms are included within the software to optimize its characteristics. The purpose is to replicate the environment the antenna is expected to work in by means of adding voxel models with the electromagnetic properties of the involved tissues. This feature is essentially solved and it is a matter of resolution and computing time what affects the quality of the simulations. After manufacturing the antenna, its validation must be carried out in the real scenario or in a realistic one instead. Physical or experimental phantoms emerge at this point when the measurements in the real environment is not possible. There are three main aspects of the communication link that can be assessed thereby: the radiation characteristics of the antenna, i.e., pattern and efficiency [206, 207]; the impact of the body over the radio link in the communications channel, i.e., the path loss [208, 209]; and the specific absorption rate (SAR) [210, 211] of the signals on the body tissues, which must meet the ICNIRP guidelines [212]. Fig. 27 shows a setup for measuring the radiation pattern and efficiency of an on-body antenna with an arm phantom in an anechoic chamber.

Beside the issue of the host body, implantable antennas are usually physically small, and thus often small with respect to the wavelength, which leads to notorious difficulties in measurements [213, 214, 215, 216]. The problem in measuring electrically small antennas are the so-called cable currents, which are at the origin of spurious unwanted radiation. In order to understand the origin of this difficulty, remember that at low frequency components are connected using wires, the latter having negligible dimensions compared to the wavelength. At microwave frequencies, components are interconnected using transmission lines having non-negligible dimensions compared to the wavelength. A component (e.g. an antenna) needs thus

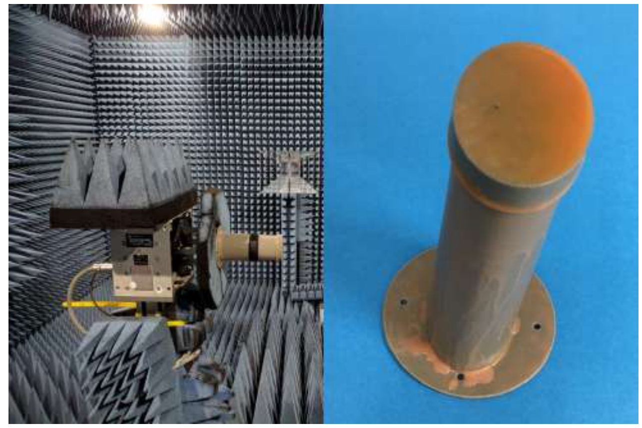

Figure 27: Setup for the measurement of the performance of an on-body device with an arm phantom.

to be adapted to the type of guiding structure (differential or signal to ground) that will be used to connect it to measurement equipment, which is very hard to achieve for electrically small structure. As a result, in the typical case where a coaxial cable is used for measuring the antenna, a spurious current circulates on the mantle of cable. In the case of an antenna radiating into free space, the effect of this current will mainly affect the measurement of the radiation characteristics (gain, efficiency and pattern). The antenna's reflection coefficient or input impedance measurement will suffer less, as the chassis of the measurement equipment will absorb the spurious current. In the case of an antenna implanted in a lossy phantom, there will potentially also be a major effect of the spurious cable current on the measurement of the input impedance or reflection coefficient: Indeed, the medium surrounding the cable will short circuit the spurious current, and reflect it back to the antenna. This may severely affect the measured values [217].

Emerging challenges. An important challenge in the characterization of Implantable antennas is that there is today no clear consensus in the community on the key performance indicators (KPI) of such antennas: Indeed, for antennas radiating into free space, it is general accepted that an antenna can be described e.g. by its input impedance (including bandwidth), gain pattern, polarization and radiation efficiency. All these KPIs enable to link the antenna to a more complex system. A simple illustration is given by the Friis' formula giving the link budget between a transceiver and a receiver:

$$P_r = P_{tr} g_r g_{tr} \left(1 - |\Gamma_r|^2\right) \left(1 - |\Gamma_{tr}|^2\right) \chi_{pol}^2 \left(\frac{\lambda}{4\pi d}\right)^2 \quad (7)$$

where P represents the power, g the antenna gain, Γ the antenna input reflection coefficient, χ_{pol} the polarization mismatch, λ the wavelength and d the distance between antennas. The subscripts r and tr denote the receiver and transceiver, respectively. All the terms in this equation except for the last are linked to antenna characteristics, while the last is linked to the channel (in this case free space) and its effect on the losses. Everything becomes much more complex when implantable antennas and systems are considered, as it becomes difficult to decouple the antennas from the channel. Indeed, let us consider the scenario of Fig. 28:

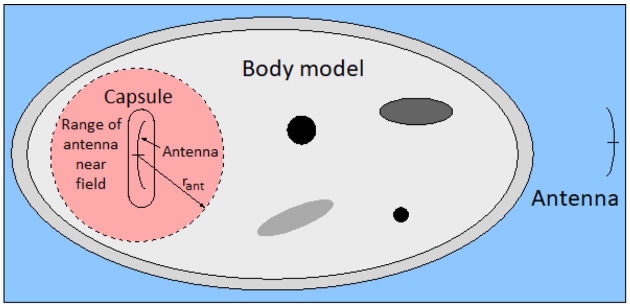

Figure 28: Implanted antennas scenario.

The link budget between the implanted and external nodes depends on many factors (antenna characteristics, in body propagation, out of body propagation, losses) and it is very difficult to decouple the internal antenna from the channel. Indeed, the gain, efficiency and polarization of the implanted antenna depend not only on the antenna itself, but also on the host body. One way to solve this issue is to define the set formed by the antenna and the host body as being the actual antenna, and define the gain, efficiency and polarization of this, from which a link budget to the off-body node can be obtained. Unfortunately, this is not satisfactory as new antenna characteristics need to be obtained for each new position in the host body, or each shape and dimension of the latter. Comparison between different antennas become thus very difficult.

From the experimental assessment side, the main challenge is to replicate the electromagnetic properties of the different body tissues within the whole frequency band of the transmission range of the antenna. The way to achieve this goal is matching the relaxation frequency of the target, which is related to how the molecules can keep polarizing at the same rate as the electric field. This applies to the relative permittivity (ε_r), since relative permeability (μ_r) of body tissues is approximately equal to 1. This was not a problem in the past due to the narrow bandwidths that were used, enough for covering the needs at the time. However, the current trend of rising the data rate and cutting down the latency are moving the technologies to the use of higher bandwidths. In [218], a collection of wideband phantoms is presented and further on reproduced in [209] for channel modeling. Another concern from the scientific community is the phantoms lifetime, considering that these take time for preparing them or are costly, if purchased. It is mainly related to the way of storing them and the type of material used in the phantom elaboration. Solids are normally more durable in time without losing properties, whereas liquids and gels require careful storage. One could think that then, solid phantoms are more convenient, but most tissues contain a considerable amount of water, which normally request liquids to imitate their properties. Once these issues are settled, the challenge lies on the mechanical arrangement of different phantoms for the setup. This can lead to liquid diffusion between different layers that change the dielectric properties of the different tissues.

Future developments to satisfy these challenges. Ideally, future developments would provide means to decouple the antenna characteristics from the host body, at least to some extent, in order to obtain a well-defined interface between antenna and propagation channel, as exists in free space. This would enable to separate the modeling and measurement of in-body channel propagation on one hand and of antennas on the other. The main difficulty to overcome is linked to the coupling between the reactive near field surrounding the antenna and the host body, which generates a non-negligible part of the losses [217]. Those losses depend of course on the antenna and the surrounding medium, but also on the depth of implantation. First models to compute these losses have been proposed in literature for the case of deep implants [217, 219, 220]. In latter case indeed, we can suppose that near field zone around the antenna is entirely located inside the body. In [217], a close form approximation for the near field losses for implanted loops and dipoles, and in [219] the authors propose the very interesting concept of intrinsic radiation efficiency to account for the near field losses.

This work needs to be extended to case of shallow implants, where the antenna near field area reaches outside the host-body, and to more complex antennas. Moreover, models for the reflection at the body-free-space interface also need to be investigated.

As the studies pursue to be as realistic as possible and understanding the phenomena of the electric fields inside the body, phantoms are evolving to multilayer models [221, 222]. Most works are limited to the use basic constituents due to the availability and ease of preparation. However, different chemicals can improve the model versatility to be adjusted to different tissues [218]. Creating the shape of the tissues is currently fostered thanks to the 3D printing capabilities. In this sense, authors are taking advantage of the wide range of materials currently available for creating phantoms [223]. The printed models act as shells for the liquid or semisolid phantoms. This approach deals with two problems, the shape of the tissues, which is certainly key in the scenario, and the lifetime enlargement due to the enclosure. However, there are two challenges here to be addressed: the influence of this external shell in the effective relative permittivity and the chemical compatibility of the printed material and the phantom composition. The first issue is usually resolved by using materials with low relative permittivity values (mostly polymers), and the second one has not been comprehensively targeted due to the aforementioned basic ingredients. As a wider variety of reagents are used, their chemical compatibility with the surrounding materials will be analyzed in terms of degradation.

Conclusion. The characterization of implanted antennas is far from trivial, and many questions still remain open. Most critically, a consensus of relevant KPIs and measurement environment is needed by the community. The phantoms will play an essential role in the validation of these antennas when these need to be tested in realistic scenarios.

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New Measurement Ranges and Instrumentation

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Introduction. In this paper the authors explore the needs that are evolving for both the antenna range or anechoic chamber and the instrumentation required for measuring newer antennas.

Antenna Ranges. Probably the main issue affecting antenna measurement ranges is that there is no universal solution. It is true that you can measure any antenna in a far field configuration. However, this will require in some cases a test range more than 1 km long. Take a 40 λ size antenna operating at 1 GHz. The lower limit of the far field region is 1600 λ or about 480 m [55]. Clearly an outdoor range will be required, however the path loss will be extremely high, requiring higher transmitted power. That higher power comes with the regulatory issues that accompany high-power broadcasting at certain frequencies. For the last 60 years, the world of antenna measurements has orbited around the problem of measuring larger antennas in smaller ranges. Near to far field transforms and compact range development began in the 1960s [224, 225] to contend with the longer far field distances of electrically large antennas. On the other side of the spectrum are the small, lower frequency antennas, that while not electrically large still require long ranges. For example, a 0.5 λ antenna at 200 MHz requires at least a 5 λ distance, or 7.5 m [76]. This is doable in a typical indoor range, but it requires a very large room lined with lots of expensive absorber. To solve these problems, tapered anechoic chambers were introduced in the 1960s as well. All these methodologies are applicable for certain antennas and frequency ranges. Compact Ranges are ideal in the 2 GHz to 100 GHz range. At lower frequencies the size of the reflector becomes the main driver for the cost. At frequencies above 40 GHz, the tolerance of the reflector finish is the driver. Near-Field Systems can be used from lower frequencies, as low as 200 MHz, and as high at the 500 GHz range. At lower frequencies the AUT-to-probe separation and the size of the probe still require a large facility, and at higher frequencies positioning accuracy and stable phase measurement are the critical issues. Common near-to-far-field transforms require accurate phase measurements, and although "phaseless" transform algorithms have been studied, they are not in a mature stage [76]. The phase reference issue is a big problem for testing some integrated antennas such as active arrays with digital outputs and small wireless devices. Tapered ranges are ideal for lower frequencies (100 MHz to 2 GHz), with the lowest frequency being limited mainly by RF absorber technology [226]. Although tapered ranges have been used up to 40 GHz, they have a limit on the electrical antenna size with feed performance and location becoming more critical with rising frequency [226].

Combined Ranges. The future of antenna range design offers a combination of two or more of these technologies into a single range. About 10 years ago, a tapered range with spherical and planar near field capabilities was commissioned (Fig. 29).

Figure 29: A combined tapered, SNF and PNF range seen from the SNF probe location. A dielectric lens is placed at the end of the taper to increase the quiet zone size.

In addition, a variation of the compact range where a dielectric lens is used instead of a mirror to create the plane wave, was introduced to improve the tapered range at higher frequencies [227]. Since then, it has become common to see combinations of compact range and near field, or compact range and far field (Fig. 30), where the ranges share the same AUT (antenna under test) positioner.

Figure 30: A compact range (left) and far field range (right) share the same AUT positioner. This combined range extends the lowest useful test frequency down to 500 MHz.

These ranges are more flexible as they allow for testing a variety of antennas, at a variety of frequencies, with smaller uncertainties since the most suitable approach can be used for the specific antenna under test. Future ranges will certainly follow this path of combining technologies.

Instrumentation. The modern antenna range has become far more complex, especially in the past two decades. The simple range of the past is inadequate for today's antennas that are no longer separable from the electronics behind them. More sophisticated tests are needed to characterize these combinations of antennas, amplifiers, switches, and frequency converters. The antenna range has now become a "subsystem test range," providing capabilities far beyond simple pattern and gain measurements. Similarly, the AUT has now become the UUT (Unit Under Test) to address the wide range of functions and requirements that can be imagined for devices that integrate electromagnetics, mechanics, electronics, firmware, software and other technologies. These integrated antenna subsystems can take on any number of functions depending on the supported product which may be a communicator, transponder, radar, or jammer. Range instrumentation now must support a balance of competing objectives. Some of these are defined by the UUT: wideband operation, higher test frequencies, frequency-converting and non-converting AUTs, high-power RF radiation, pulse mode operation, and interleaved transmit/receive requirements [228]. Others are application-driven: a need for accurate pattern, gain, EIRP, and G/T results based on measured data [229]. Yet others are driven by complexity, cost, and risk considerations: all-at-once acquisitions incorporating multi-frequency, multi-port, dual-pol, and multi-state measurements, and the need to collect all these measurements in the least amount of time. While this level of complexity was once the domain of only the leading-edge firms, it has become common across the middle of the industry as the pace of antenna system development increases alongside innovations in electronics, computation, and RF technology.

Frequency Converting Antennas. It has now become common to see frequency conversion as an inseparable function of many UUT. For example, inspection of a home satellite dish feed assembly (Fig. 31) reveals an integral "block downconverter" that converts Ku- or Ka-band frequencies down to around 1 GHz to send to a receiver. The downconverter includes its own internal Local Oscillator (LO), mixer, and filters.

Figure 31: An integrated feedhorn and low-noise block downconverter (FLNB) used for satellite television reception.

Simple as it is, this antenna-plus-converter offers some challenge to the range instrument designer. Small dish antennas typically used with these feeds are ideal candidates for testing on a planar near field range, but near field testing requires amplitude and phase information to calculate far-field performance. The internal LO in this unit poses a challenge: how to get coherent phase readings given internal LO drift. Additionally, assuming the phase drift problem has been resolved, the challenge is how can it be measured the G/T (Gain-over-Temperature) performance for such an antenna without access to the antenna's RF output port [230]. There are plenty of more-complex antenna systems that present similar challenges. Integration of inseparable amplifiers, frequency converters, and even digitizers is accelerating in the satellite, military, scientific, and even consumer product spaces.

Agile Steerable Antennas. New applications for RF and microwave signals, including Wi-Fi, 5G, IoT, and advanced weather radar, have brought about new growth in low-cost but very capable steered-beam antenna technologies. These agile antennas can sequentially or even simultaneously form a multitude of spatially diversified RF pathways. This offers system designers a way to optimally use limited bandwidth and power to service an ever-increasing number of locations, devices, or users. At the antenna range, of course, there is a cost in the complexity. If the antenna can form sixty-four (or six hundred forty) distinct beams, the range technician will likely need to test all of them. The current explosion of fast control and reconfiguration capabilities presents challenges: test coverage, data volume, measurement timing and electromechanical coordination [231]] (Fig. 32).

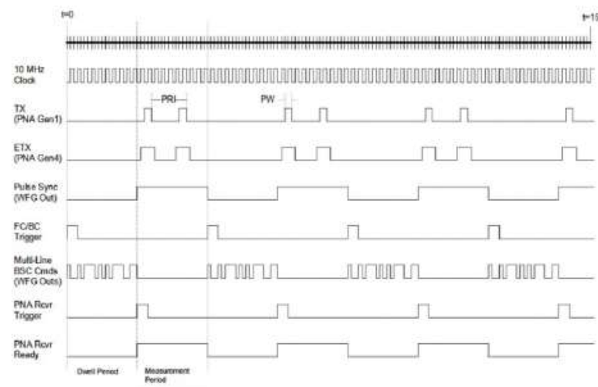

Figure 32: Typical timing sequence for a steerable antenna test using an AUT-specific control sequencer with a standard VNA for the related RF measurements.

Control schemes for agile antennas vary considerably; there are no standard methods, signals, or interfaces. This is likely to continue as differing requirements drive antenna designers to differing solutions. The future for agile-antenna range testing lies in adapting each of the various control schemes to a well-defined "in-between" interface, a task best done by the AUT control designers. The standard interface, published by the test system designers, gives the range unfettered access to AUT capabilities for testing without requiring intimate knowledge of the internal control scheme. Putting the control scheme behind a standard interface has the added benefit of protecting the AUT designer's work which is often proprietary or confidential.

Conclusion. Flexibility is going to be the name of the game moving forward when it comes to range design. If the antenna engineer cannot accept additional uncertainty or error when using non-ideal techniques then the go-to approach will be to build ranges that can support several different techniques: far field, tapered range, compact range, or near field measurements. On the instrumentation side, the equipment, knowledge, and techniques needed to make increasingly complex measurements of agile multi-state and multi-function antennas will be key to staying relevant.

EurAAP and IEEE Standardization and Facility Comparison

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Introduction. Antenna measurements represent a crucial phase during the process of design, development, and verification of any antenna system to ensure the compliance with all specifications. In recent years, emergence and adaptation of new complex antenna technologies has led to specifications even more stringent to comply. This drives continuous research on new measurement technologies to guarantee a required specific accuracy during testing.

Of importance to characterization of antennas are: a consistent and reliable methodology of testing, and assurances of the quality of the measurement system used. Confidence in these two areas is assured by utilizing facilities that follow a set of clear standards backed by an accredited quality process.

Standardization. The Institute of Electrical and Electronics Engineers (IEEE), through its Standards Association (SA) has published many standards governing topics associated with antennas and antenna measurements. The IEEE SA is supported in the antenna technology field by the Antenna and Propagation Society (APS) Standards Committee (SC). This committee is charged with the development and maintenance of standards related to antennas and radar cross section. The standardization of procedures and parameters in antenna measurements is crucial. The efforts of the IEEE are accomplished in collaboration with the work of global working groups consisting of members from the IEEE APS-SC, the Antenna Measurement Techniques Association (AMTA), and the European Association on Antennas and Propagation (EurAAP) working group on measurements (WG5). Two standards addressing the definition of terms associated with antennas are: IEEE Std 211 [232], and IEEE Std 145 [233]. Of these IEEE Std 211 was most recently updated in 2018 and IEEE Std 145 is undergoing revision with a target publication date in early 2024. IEEE Std 149 "Recommended Practice for Antenna Measurements" [55], is the primary standard covering most antenna measurement techniques. This standard was most recently updated and published in 2022 [234] by a working group consisting of members from the IEEE, the AMTA, and WG5. The previous version of the standard was released in 1979 and many updates, and modern measurement methods were added to the standard, such as reverberation chamber measurements, RF measurements using drones, sensitivity measurements for receive antenna systems and compact range techniques as illustrated in Fig. 33. Also important to the field of antenna measurements is IEEE Std 1720 "Recommended Practice for Near-Field Antenna Measurements," originally published in 2012 [76]. This latter standard, dedicated to near-field measurement methods, was created to complement the existing IEEE Std 149 and is currently under revision by a working group consisting of members of AMTA, WG5, and IEEE [235]. Planned publication is in early 2024.

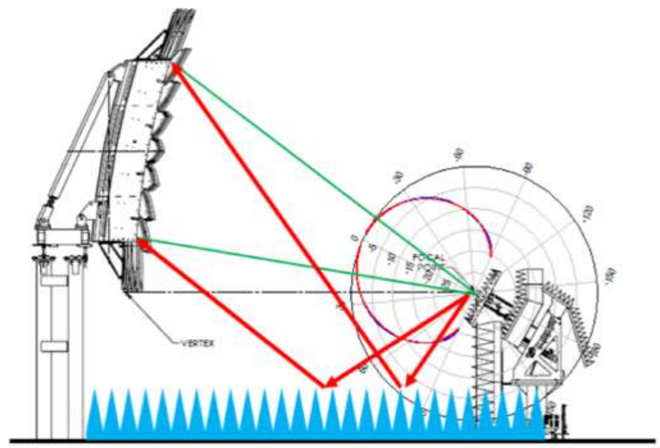

Figure 33: Illustration of primary and secondary field illumination in a compact antenna test range.

The motivation of the activities of maintenance of these standards is IEEE-SA policies specifying that a standard is valid for ten years after its approval. A standard cannot be simply reaffirmed, even if the standard is still considered relevant. The policies specify that a working group must review and revise it, or the standard will expire. There are more than 50 dedicated people from industry, academia, and institutions, who are members of the aforementioned working groups, contributing to update and revision.

Facility Comparison. An important support is provided by the outcomes of measurement campaigns aimed at the intercomparison of antenna measurements since 2005, performed by EurAAP WG5 [236]. Facilities participating to such campaigns have the possibility to demonstrate their measurement proficiency both for internal use and to get or maintain official accreditations, to standards such as ISO 17025 [237]. Intercomparison campaigns can be extremely useful in the estimation of measurement uncertainties that characterize a measurement environment and method [55, 76]. This can be achieved thanks to the measurement of highly accurate reference antennas. During the proposed period of facility comparison campaigns, the selected reference antenna travel among the participating facilities whereby the data is collected. Upon completion of the activity the data is analysed and made available to the participants and usually targeting to publish the outcomes in peer-reviewed journals. Some of the reference antennas tested in the comparison campaigns are illustrated in Fig. 34. The measurement post-processing of the intercomparison campaigns, for the linear array, horn, and reflector antenna shown in Fig. 34, consists in the computation of a reference pattern and an associated Equivalent Noise Level (ENL) as reported in [238]. An example of multiple pattern acquisition is shown in Fig. 35. The reference pattern is computed from several independent measurements by the different participants and its correlation with each measurement is expressed through the ENL.

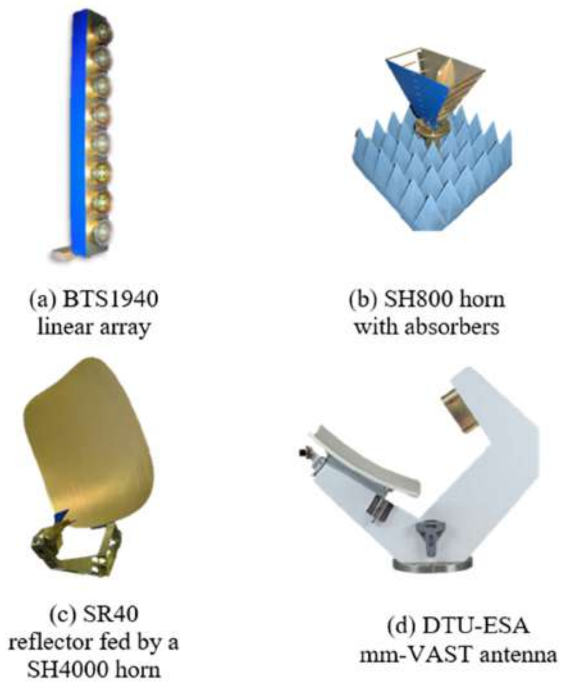

Figure 34: Examples of reference antennas measured during recent intercomparison campaigns.

Additional figures of merit that can enhance the comparison are the Birge Ratio and Escore as reported in [9]. The results of the above described intercomparison campaigns have been published in peer-reviewed journals, see references [238, 239, 240, 241, 242, 243].

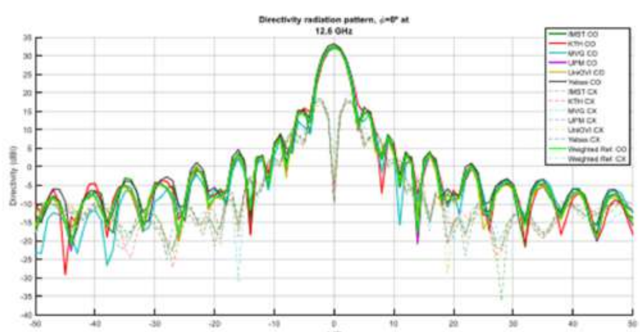

Figure 35: Example of comparison of radiation patterns, a reflector fed by a broadband horn in Fig. 34.

Another relevant comparison campaign has been carried during 2019-2022, with the mm-wave Validation Standard antenna (mm-VAST) shown in Fig. 33. The mm-VAST antenna has been developed by DTU and TICRA in the framework of an ESA project [244, 64, 245, 246]. The measurements have been conducted in three operational configurations: 19.76 GHz, 37.80 GHz, and 48.16 GHz. The objective is to ensure accurate measurements of the next generation communication antennas in the bands K, Ka, Q, and V. Collected data comprise the input reflection coefficient at the waveguide flange; the co- and cross-polar radiation patterns in different planes and the forward hemisphere; the direction of the maximum co-polar pattern; and the 1σ-uncertainty of directivity and gain data. Preliminary results have been presented during the 2022 European Conference on Antennas and Propagation (EuCAP) [247]. The post-processing and analysis of all data has been finalized and the new updated results will be presented afterwards in relevant conferences and journals.

Emerging Challenges. A major challenge for comparison campaigns is to introduce increasingly complex antennas as test objects that are used in the latest and most modern technologies/applications. Measuring at increasingly challenging frequency bands attracts new participants of the campaigns who want to test the capabilities of their measurement facilities. Moreover, increasing the number of participants in measurement campaigns means increasing the variety of the type of various test systems. This can lead to an enrichment of knowledge in antenna measurement procedures, a benefit for the entire community. In parallel, it is important to always keep updated the defined standards on antenna measurements due to the developments of new emerging technologies and applications.

Future developments to satisfy these challenges. Future activities on comparison campaigns consist of proposing new challenging antennas. The selection of a low-directivity antenna would be a new challenge to meet the measurement needs of increasingly less directional antennas, such as in the automotive industry. A future challenge is also to create a stronger bridge of scientific collaboration between the community of antenna measurements and that one operating with numerical simulations. One way is to broaden comparison campaigns not only to measured data, but also to compare the measured reference with simulations made with different numerical methods. Experts on numerical simulations can benefit from the experience of all the long standardization work of so many years on measurements, while experts on antenna measurements will be more confident of the results by simulation tools that were used to make the design of antennas, then manufactured and to be tested. In support of the need for less directional intercomparison testing and comparisons to simulation, the APS-SC is currently undergoing feasibility studies of bi-conical antennas. This work is being done under an IEEE Project Authorization Request (PAR) P2816 "Recommended Practice for Computational Electromagnetics Applied to Modeling and Simulation of Antennas" [248]. Initial antennas have been prototyped by the APS-SC Ad hoc Group on Antenna Measurements and are in preliminary stages of testing. Publication of results are planned for future conferences. Activities to define and maintain standards on antenna measurements will always be continuous in order that the community can benefit up-to-date reference to new emerging technologies and applications.

Acknowledgment. The authors would like to thank all the organizations for spending effort to contribute to the different activities on antenna measurements and to EurAAP for support in keeping existing this working group.

Advanced Antenna Material Measurements

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Introduction. Recent advances in fabrication techniques (e.g., 3D printing [249]) has allowed ever-exotic materials to be constructed for electromagnetic and antenna applications. Materials that are nonlinear, bianisotropic, spatially dispersive, time varying, and nonreciprocal, for example, show promise for enhancing electromagnetic control and antenna performance [250, 251, 252, 253, 254, 255, 256, 257, 258, 259, 260].

In order to understand how electromagnetic waves interact with these complex media, material property tensors must be quantitatively determined. Although electromagnetic material properties may, in some cases, be predicted via computational modeling or by utilizing a lumped-parameter model, experimental measurements are most often employed for the material characterization and validation process [261]. Electromagnetic characterization of simple (i.e., linear, isotropic, homogeneous, and time-invariant) media is well established [262]. However, characterization of the types of complex media mentioned above, requires advanced material measurement techniques and subsequently creates many challenges, which are discussed next.

Emerging Challenges. The electromagnetic measurement and characterization of complex media presents many challenges that are not encountered in simple media. In nonlinear media, harmonic generation (and nonreciprocal behavior) typically occurs. Due to this nonlinear behavior, the traditional linear S-parameters (scattering parameters) cannot be employed in the material extraction process. It can be debated if it even makes sense to assign electromagnetic properties to such a material and whether it would be of use in practice. Equally challenging is the determination of the conditions of uniqueness in the material extraction process. Perhaps even more challenging is developing a proper nonlinear model for a given material.

The measurement of anisotropic and bianisotropic media also presents many challenges, both theoretically and experimentally. Maxwell's equations can become quite complicated and difficult to solve, especially if a Green's function development is needed, which is often the case when performing nondestructive evaluation. The number of measurements required increases (for example, characterization of an anisotropic biaxial material requires six measurements), thus field applicators having sufficient diversity are required. In addition, optical activity or Faraday rotation effects occur, thus an experimental system must have co- and cross-polarization measurement capability. Consequently, known co- and cross-polarization algorithms and standards are necessary for system calibration. Unfortunately, these standards are not readily available. In addition, due to the increased number of unknowns for these materials, calibration and measurement time increases dramatically. The challenges are compounded if measurements in the field or in remote locations are necessary.

Materials exhibiting strong spatial dispersion present many challenges as well (weak spatial dispersion is accommodated more easily [263]). Spatially dispersive media have material properties that are dependent upon the direction/angle in which an electromagnetic wave is impinging and constitutive relations involving spatial derivatives or integrals. As anticipated, Maxwell's equations are more difficult to solve, although Fourier transforms may offer some advantages. The key challenge is to develop an appropriate theoretical material model and to acquire a measurement system capable of multi-angle measurements. As in the nonisotropic case, calibration and measurement time also increases, which can challenge budgetary and allocation resources.

Time-varying media have constitutive relations that are typically not amenable to Fourier transformation, thus analysis, modeling, and measurement must be performed directly in the time domain. In addition, spacetime modulated media can have material properties that change rapidly over time. As a result, the traditional swept-frequency network analyzer (NWA) measurements are rendered practically useless. The challenges are compounded if spacetime modulation is extremely rapid, since these materials are Lorentz-transformed into generally bianisotropic media relative to an observer in a rest frame [258, 259].

Another challenge is the electromagnetic characterization of materials having inherent irregular shapes (e.g., molded materials for antenna applications). What experimental measurement system is most appropriate in this case and what method of theoretical analysis should be used? Although many challenges exist for characterizing modern materials, many technological advances are being made that are capable of accommodating these challenges, as is discussed in the next section.

Advances in Technology to Meet Challenges. Many technological, as well as manufacturing, advances have been made in recent years that make it possible to meet the challenges of the electromagnetic measurement and characterization of modern materials.

Almost all modern network analyzers now have nonlinear measurement capability. Although many nonlinear models exist, X-parameters have become relatively well known [264]. These parameters make it possible to measure harmonics of the excitation frequency, thus making it a possible avenue to characterize nonlinear materials.

Several advances have been made that make the fabrication and measurement of anisotropic and bianisotropic media feasible. First, the advent of 3D printing, as mentioned previously, has now been utilized for fabrication of complex media. As 3D printing capabilities increase, such as 3D printing of metals and magnetic media, ever-more exotic materials will be realized. In addition, these 3D printing technologies now make it easier to rapidly prototype co- and cross-polarization calibration standards. Regarding measurement, precision robots (supporting quad-ridged horn antennas, for example) now make it possible to obtain rapid and accurate multi-measurements. This data collection is assisted via many-port (e.g., 8-port, 16-port, etc.) network analyzers. In addition, these modern network analyzers have common and differential mode capabilities, thus enhancing measurement diversity. Portable NWA's now make it possible to perform these measurements in the field or in remote locations. Multi-axis hot wire cutting machines allow for the fabrication of new diverse measurement systems (see, for example, [261] and Fig. 36). Electronic calibration kits, available from most NWA vendors, reduce measurement time, thereby meeting budgetary and allocation challenges.

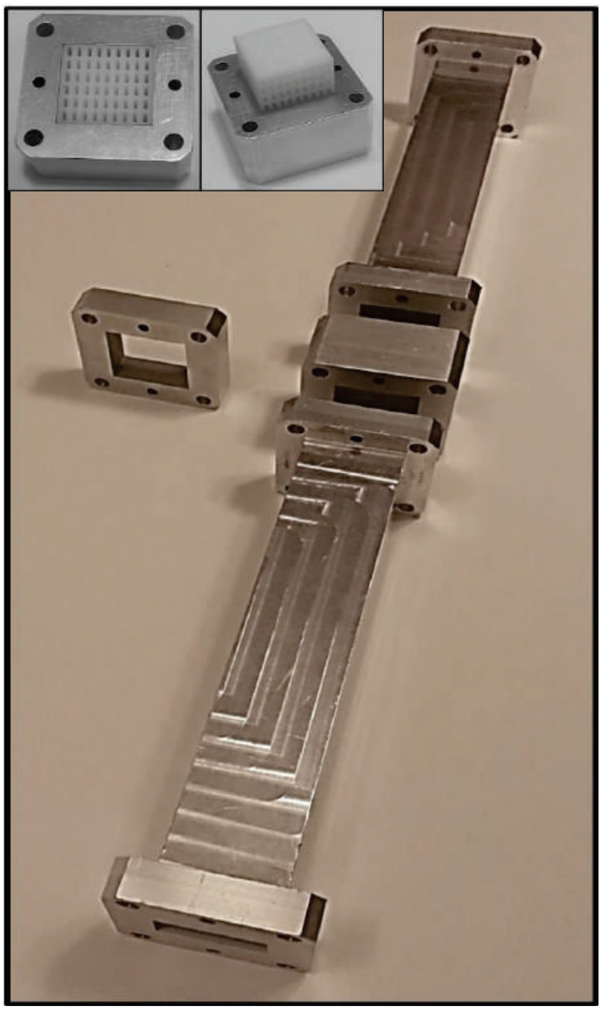

Figure 36: Rectangular-to-Square Waveguide Biaxial Material Characterization System.

The robotic technology mentioned above can also aid in the characterization of spatially-dispersive media since multi-angle measurements can be obtained in a relatively straightforward manner. Improvements in the generation of fast pulse-generation technology provides a path to enable the characterization of modern spacetime metamaterials. In addition, improvements in computer resources and precision scanning technology have made it possible to scan irregular-shaped materials and perform material property extraction via computational electromagnetics [265]. Indeed, computational material characterization is a critical technology that will undoubtedly enable the invention of new material characterization probes and the measurement of antenna materials in ever-more complicated environments.

Although the emphasis above is on technological advances that have enabled new advanced measurement techniques, theoretical developments have also aided in accommodating nonsimple media. For example, scalar potential formulations have lead to more compact electromagnetic field representations, leading to computationally efficient techniques for characterizing nonisotropic media [266]. Future advances in theoretical electromagnetics will likely continue to aid in the development of novel advanced material measurement capabilities.

Conclusion. Interest in advanced materials has flourished in recent years, being enabled by manufacturing and fabrication capabilities as well as the desire to have more control over the electromagnetic field. These modern materials are being integrated in many antenna systems to enhance performance metrics. Advanced material measurements play (and will continue to play) a vital role in antenna system modeling and prediction of operational capabilities. Although many challenges remain in the characterization of advanced materials, these challenges are being met by recent technological advances.

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