The EurAAP Working Group on Antenna Measurements: Highlights over Two Decades

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***Abstract*—Over the past two decades, many measurement facilities have been involved in various international comparison campaigns led and supported by the European Association on Antennas and Propagation (EurAAP) working group (WG) on measurements (WG5). Its activities cover various areas of antenna measurements. These activities play an important role for the documentation and validation of laboratory proficiency and competence, helping to improve the antenna measurement procedures/protocols in facilities and standards such as ISO 17025, IEEE 149, IEEE 1720. The analysis and data elaboration have promoted discussions among the antenna measurement community experts and have led to modernization of comparison techniques. This paper highlights some selected EurAAP WG5 activities including, for example, international antenna measurement intercomparisons, self-assessment measurements of facilities, outreach collaborations and outcome disseminations (e.g., revisions of international standards for antenna measurements).**

I. INTRODUCTION

A raft of emerging wireless technologies is progressively arising in the arena of modern devices and system design [1]. Antennas are an inherent part of any wireless transmission, and their measurements represent a crucial phase during the design, development, and verification processes of any wireless system to ensure the compliance with all specifications. Antenna's efficient use of energy and ultimate utilization of the electromagnetic spectrum are essential requirements to support the ever-increasing and all-pervasive demand for modern communication, sensing, power transfer and other applications.

The importance of the development of novel antenna measurement techniques and technologies increases with the industrial exploitation and adoption of new complex antenna technologies at different frequency bands in emerging wireless systems. Several worldwide standard bodies, industries, and research communities are facing numerous near-future antenna measurement challenges [2]. In particular, on efficient and accurate verification of these products that meet desired performance parameters for fulfilling the diverse technical requirements set by ITU-R [3].

The European Association on Antennas and Propagation (EurAAP) [4] working group (WG) on measurements (WG5) [5] was founded in 2009. It originates from various institutions previously involved in the works initiated in 2004 on defining some reference antennas to be used for different antenna measurement intercomparisons and conducted within the Sixth Framework Program of the European Union (EU) Antenna Center of Excellence (ACE) during the 2004-2008 period [6]. The works continued under the management of EurAAP supported by the European Cooperation in Science and Technology (COST) in the programs ASSIST (Antenna Systems and Sensors for Information Society Technologies) IC0603 [7] and VISTA (Versatile, Integrated, and Signal-Aware Technologies for Antennas) IC1102 [8].

EurAAP WG5 constitutes a framework for cooperation to advance research and development of antenna measurements in support of the ever-increasing use of wireless technology in modern society. This WG has been pursuing several long-term objectives such as antenna measurement techniques for new wireless technologies, standard procedures for different antenna measurement techniques, standard procedures for benchmarking of antenna measurement facilities, sharing of technical resources, educational activities for universities and industry, and cooperation & networking with other professional organizations. Its activities cover various areas of antenna measurements and are sub-divided into different tasks [5].

This paper highlights some selected EurAAP WG5 activities over the past two decades and is organized as follows: Section II presents some selected antenna measurement facility intercomparisons and self-assessments, Section III describes some of the WG outreach and outcome disseminations activities. Conclusions are drawn in Section IV.

II. Antenna Measurement Facility Intercomparisons and Self-Assessments

Antenna measurement facility intercomparison activities have become mandatory to achieve or maintain official accreditation such as ISO 17025 [9] whereby the self-assessment activities allow any antenna measurement facility needing accreditation but haven't been involved in the intercomparison activities by comparing their measured data with the existing reference data obtained in the closed intercomparison campaigns. This can be achieved by the use of highly accurate reference antennas. The main goal of such activities is to provide a formal opportunity for the participants to validate and document their laboratory proficiency and competence by comparison with other facilities. They constitute a crucial foundation for validation of measurement accuracy among participants and provide an important prerequisite for certification of facilities as well as inputs to standards and research on measurement uncertainties.

The EurAAP WG5 international intercomparison campaigns cover a frequency range starting from ultra-high frequency (UHF) band up to V band using different reference antennas. Each campaign is conducted by a campaign leader or institution. During the proposed period of facility intercomparison campaigns, the selected reference antenna travels among the participating facilities whereby the measured data is collected and processed by the campaign leader. This activity has been supported by the EurAAP WG5 that covered the transportation costs and insurance for shipment from one laboratory to another. The required typical antenna performance figures common to most measurement campaigns are: 1) Peak gain (IEEE definition) at discrete frequencies, 2) Directivity/Gain patterns, 3) S-parameters, 4) Description of measurement facility and measurement procedure, 5) Description of mechanical and electrical setup and alignment, 6) Uncertainty budget.

The traditional comparison of data involved the comparison of boresight gain and directivity values for different frequencies; however, the measurement differences and their sources are often better understood by direct inspection and comparison of the patterns. Since the direct comparison of large amount of measured pattern data is unfeasible by inspection of pattern differences alone, a statistical approach was implemented that allows the comparison of data in a simple form. The measurement postprocessing of the intercomparison campaigns consists in the computation of a reference value and an associated Equivalent Noise Level (ENL) as reported in [10]. The reference value can be defined as the common best value among different measurements, and it can be obtained by averaging the different measurements with a simple or weighted mean. In some cases, the weighting is related to the obtained measurement uncertainty. The ENL is a figure of merit that helps to understand the level of correlation between each measurement and the reference value.

Some of the test setup of the reference antennas tested in the comparison campaigns are shown in Figure 1. Table I provides some example highlights over different intercomparison campaigns. An example of multiple pattern acquisition is shown in Figure 2. The reference pattern is computed from all the independent measurements acquired by the different participants and its correlation with each measurement is expressed through the ENL. Upon completion of the activity the measured data is analysed and made available to the participants and usually targeting to publish the outcomes in peer-reviewed journals.

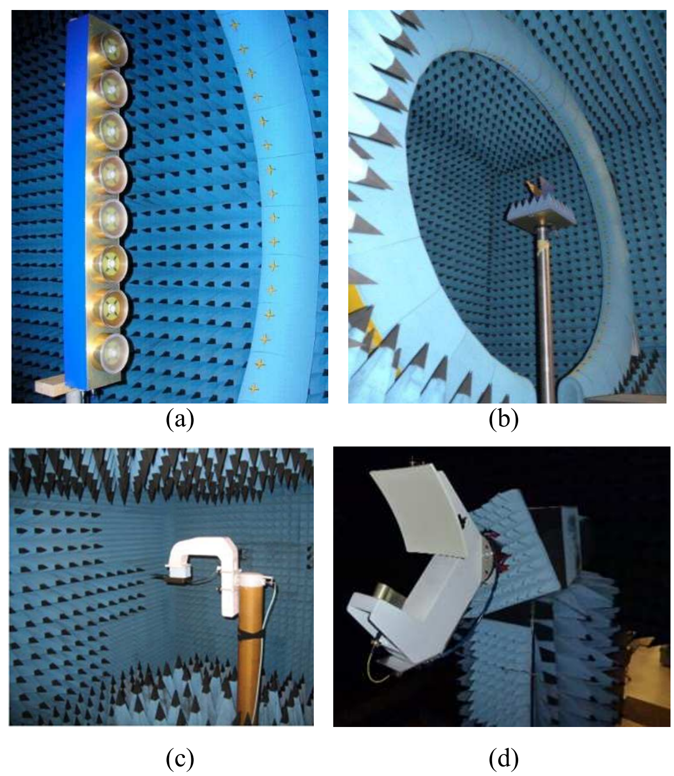
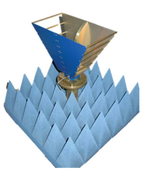
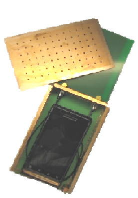
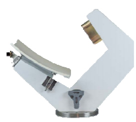
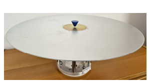


Figure 1. Reference antennas for antenna measurement facility intercomparisons: (a) MVI/SATIMO base station (BTS) 1940-01; (b) MVI/SATIMO SH800 ultra-wideband antennawith absorbers plate; (c) MVI/SATIMO MIMO (Multiple-input-multiple-output) antenna; (d) DTU-ESA mm-VAST (millimeter-wave validation standard) antenna.

TABLE I. ANTENNA MESUREMENT FACILITY INTERCOMPARISONS

Reference Antenna	Activities, Period & Status	Participating Institutions, Country	Highlights
VAST-12 (12 GHz validation standard) *Photo*: 	Intercomparisons, 2004 – 2005, Closed	1. Saab Microwave Systems, Sweden 2. France Telecom R&D, France 3. RUAG Aerospace Sweden, Sweden 4. Technical University of Catalonia, Spain 5. Technical University of Denmark, Denmark 6. Universidad Politécnica de Madrid (UPM), Spain	• *Campaign Leader*: The Technical University of Denmark (DTU) • *Antenna*: High directive reflector antenna (designed by DTU [11] for European Space Agency (ESA) as validation standard antennas) • *Operating Frequency*: 12 GHz • *Antenna Design Features*: 1) The offset shaped-parabolic reflector, with different focal points in the two principal planes, and the corrugated circular feed horn provide a pattern with elliptical main beam and several challenging characteristics; 2) The Carbon Fiber Reinforced Polymer (CFRP) foam structure ensures thermal and mechanical stability against differences in temperature and gravity orientation, respectively, between the participating facilities. • *Measurands*: Co- & Cross-polar patterns in Ludwig's 3rd definition • *Facilities*: compact antenna test ranges (CATR), far field systems (FF), spherical near field systems (SNF) and planar near field systems (PNF) • *Note*: The reference antenna was measured at 8 different facilities and two measurements at the beginning and the end of the campaign were performed at DTU.
BTS 1940-01 Base station antenna *Photo*: 	Intercomparisons, 2009 – 2016, Closed Self-Assessment, 2021 – 2023, Request-based	1. Saab Microwave System, Swiden 2. DTU, Denmark 3. Universidad Politécnica de Madrid (UPM), Spain 4. Microwave Vision Group (MVG), France 5. Microwave Vision Italy (MVI), Italy 6. CellMax Technologies, Swiden 7. Universidad de Oviedo, Spain 8. Valencia Polytechnic University, Spain	• *Campaign Leader*: SATIMO (MVI, Italy) • *Antenna*: Linear GSM1800 and UMTS band array antenna [12] • *Operating Frequency*: 1.71 GHz – 2.17 GHz • *Antenna Design Features*: Dimension – 1.4 m x 0.2 m. Dual slant ±45° polarized elements with directive elevation beam and wide azimuth beam in the direction of the boresight axis and return loss ≤ -15 dB throughout the operational bandwidth • *Measurands*: Full 3D gain measurement • *Facilities*: CATR, Spherical NF, multi probe SNF (Stargate-64), Cylindrical NF (CNF) • *Note*: Three individual self-assessments were performed between 2021 and 2023
SH800 Ultra-Wideband Antennas *Photo*: 	Intercomparisons, 2013– 2016, Closed Self-Assessment, 2022 – 2023, Request-based	1. DTU, Denmark 2. Microwave Vision Group, USA 3. Microwave Vision Group, France 4. Universidad de Oviedo, Spain 5. Universidad Politécnica de Madrid (UPM), Spain 6. Saab Ericsson Space, Sweden 7. IMST, Germany 8. National Centre for Scientific Research, Greece 9. RWTH Achen, Germany 10. University of Vigo, Spain 11. Microsoft, USA 12. Boeing, USA 13. Loughborough University, UK 14. Yebes Observatory 15. Fraunhofer Institutes, Germany	• *Campaign Leader*: SATIMO (Microwave Vision Group, Italy) • *Antenna*: Medium gain linearly polarized L, S and C bands dual-ridge horn with absorbers plate (designed by SATIMO [13]) • *Operating Frequency*: 0.8 GHz and 6 GHz • *Antenna Design Features*: Flat gain response (typically 7- 15 dBi) with low return loss and cross polar in a 1:15 frequency range. The design suppresses any possible excitation of higher order modes in the aperture and maintains a well-defined smooth radiation pattern in the boresight direction throughout the operational bandwidth • *Measurands*: Co- & Cross-polar Directivity and Gain patterns • *Facilities*: SNF, multi probe SNF (Stargate-64), combined FF-SNF test range, Cylindrical NF, Planar NF, FF, and CATR • *Note*: An absorber plate has been added behind the antenna to eliminate the sensitivity to the measurement setup. The weighted directivity and gain reference pattern has been computed according to the 2σ uncertainties. Two individual self-assessments were performed between 2022 and 2023
Multiple-input-multiple-output (MIMO) antennas: *Photo*: 	Intercomparisons, 2013– 2016, Closed	1. MVI, Italy 2. IMST, Germany	• *Campaign Leader*: SATIMO (MVI, Italy) • *Antenna*: CTIA (Cellular Telecommunications Industry Association) 2 × 2 long term evolution (LTE) [12] • *Operating Frequency*: 2.62 GHz – 2.69 GHz (LTE Band 7) and 0.746 GHz – 0.756 GHz (LTE Band 13) • *Antenna Design Features*: Planar inverted-F antennas (PIFAs) • *Measurands*: Full 3D gain measurement • *Facilities*: SNF (StarLab) and FF • *Note*: The intercomparison campaign have been compared with simulations from software vendors with different numerical methods [13]. For example: 1) EMPIRE: Finite-Difference Time-Domain method (FDTD); 2) WIPL-D: Method of Moments (MoM); 3) FEKO: Finite Element Method (FEM) & MoM; 4) ANSYS: FEM; 5) FASANT: Multilevel Fast Multiple (MLFMM), Macro basis functions, Geometrical Theory of Diffraction (GTD), & Physical Optics (PO).

Reference Antenna	Activities, Period & Status	Participating Institutions, Country	Highlights
mm-VAST (millimeter-wave VAlidation STandard) *Photo*: 	Intercomparisons, 2019 – 2022, Closed	1. Airbus Defence & Space, Germany 2. Airbus Defence & Space, Spain 3. ESA-ESTEC (European Space Research and Technology Centre), Netherland 4. MVI, Italy 5. Orange Innovation, France 6. University Côte d'Azur, France 7. RWTH Aachen University, Germany 8. Universidad Politécnica de Madrid (UPM), Spain 9. DTU, Denmark 10. Telecom Italia, Italy 11. Thales Alenia Space, France 12. Universidad de Oviedo, Spain 13. University of Rennes, France	• *Campaign Leader*: DTU, Denmark • *Antenna*: Offset single reflector antenna (designed by DTU and TICRA [14] for European Space Agency (ESA) as validation standard antennas) • *Operating Frequency*: 19.76 GHz, 37.80 GHz, & 48.16 GHz • *Antenna Design Features*: With an astigmatic paraboloid having different focal lengths in the orthogonal offset and transverse planes. The antenna can be configured either for circular or linear oplarization. • *Measurands*: Co- & Cross-polar radiation patterns & S-parameters • *Facilities*: CATR, and SNF • *Note*: The 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
Internet of Things (IoT) antenna *Photo*: 	Intercomparisons, 2023 – 2024, On-going	1. National Physical Laboratory (NPL), UK 2. University of Liverpool, UK 3. MVI, Italy 4. Bluetest, Sweden 5. Antennex, Netherlands 6. National Institute of Metrology, China 7. General Test Systems (GTS), China 8. Beijing Institute of Radio Metrology and Measurement (BIRMM), China 9. Nanjing University of Aeronautics and Astronautics (NUAA), China	• *Campaign Leader*: NPL, UK • *Antenna*: RUN mXTEND IoT antenna (designed by ignion [15]) • *Operating Frequency*: 0.824 GHz–0.96 GHz & 1.71 GHz–2.69 GH • *Antenna Design Features*: Electrically small Omnidirectional Multiband antenna for IoT applications • *Measurands*: Total efficiency • *Facilities*: FF, SNF, and Reverberation Chamber (RC) *Note*: This campaign is carried out in collaboration with the EurAAP software and modeling tool WG with the aim of promoting the benefits of the synergy between measurement and simulation modelling tools)
SMC2200 Monocone antenna *Photo*: 	Intercomparison, 2024 - 2025, On-going	1. MVI, Italy 2. DTU, Denmark 3. Universidad Politécnica de Madrid (UPM), Spain 4. IMST, Germany 5. KTH Royal Institute of Technology, Sweden 6. RWTH Aachen University, Germany 7. Volkswagen, Germany 8. AGC, Belgium 9. GTS, China 10. Antennex, Netherlands 11. Demokritos, Greece	• *Campaign Leader*: MVI, Italy • *Antenna*: Monocone [12] • *Operating Frequency*: 2.2 GHz – 6.0 GHz • *Antenna Design Features*: Monocone on a circular ground plane • *Measurands*: TBD • *Facilities*: TBD *Note*: For the first time a low directivity antenna is being considered for intercomparison as new challenge to meet the needs of increasingly less directional antenna measurements such as in the automotive industry

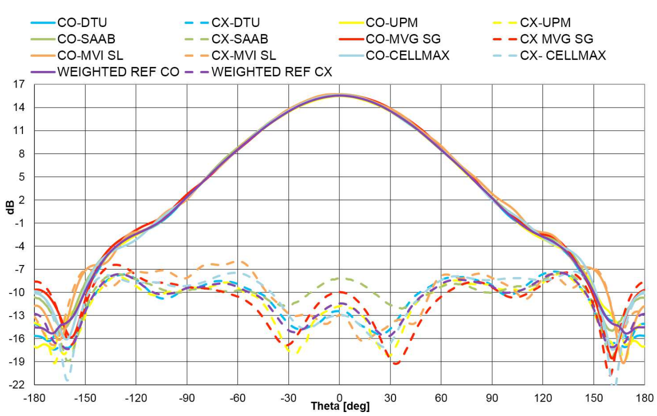


Figure 2. Example Intercomparison of Gain radiation pattern of the MVI/SATIMO BTS 1940-01 Base station antenna (Fig. 8 in [16]).

III. Outreachs and Outcome Disseminations

The EurAAP WG5 has established a long-term cooperation with the different professional organizations and groups. For example, the COST actions in antenna area (specifically COST-VISTA [8]), the antenna measurement techniques association (AMTA), and the institute of electrical and electronics engineers (IEEE). Also, with the aim of promoting the benefits of the synergy between measurement and simulation modelling tools, EurAAP WG5 has extended cooperation since 2022 with the EurAAP working group on software and modelling tools [17] to cross validate both measurements and simulation inter-comparison activities. To promote collaborative research in new and emerging antenna measurement technologies. The EurAAP WG5 has extended its activities to include, for example, multiple-input-multiple-output (MIMO) over-the-air (OTA) measurements using different methods since 2021. Several convened sessions have been organised at European Conference on Antennas and Propagation (EuCAP) and International Union of Radio Science (URSI) conferences.

Results of the EurAAP WG5 activities have led to improvement in antenna measurement procedures / protocols in facilities and standards. For example, together with members from the IEEE and the AMTA, EurAAP WG5 has contributed to the revisions of the IEEE Std. 149 "Recommended Practice for Antenna Measurements" [18] (primary standard covering most antenna measurement techniques) and IEEE Std. 1720 "Recommended Practice for Near-Field Antenna Measurements" [19]. In the revised version of the IEEE Std. 149 standard, many updates, and modern measurement methods were added, for example, reverberation chamber measurements, RF measurements using drones, sensitivity measurements for receive antenna systems and compact range techniques. The IEEE Std. 1720 standard originally published in 2012, dedicated to near-field measurement methods, was created to complement the existing IEEE Std. 149. It is currently under revision and envisaged to be published within 2025. Due to the direct benefits to the participants, the EurAAP WG5 activities have been very successful and partial outcomes have been published in various referenced papers during the years [1], [2], [10], [11], [13]-[16], [18]-[39].

Also, the EurAAP WG5 has collaborated in the organization of several European School of Antennas and Propagation (ESoA) courses: the first ones were in 2005, in Helsinki University of Technology (Aalto University today) entitled "Antenna measurements at millimetre and submillimetre wavelengths" and in Universidad Politécnica de Madrid (UPM), entitled "Antenna Measurements", each one with 9 editions. In 2007, The Technical University of Denmark (DTU) organized a new course about "Spherical Near Field Measurements", and later in 2017, another course was organized by Dassault Systèmes, Microwave Vision Group (MVG), UPM and Politecnico di Torino and Université Paris-Saclay, entitled "Combination of Simulations and Measurements in Antenna Design", in Paris, with already 3 editions. In 2018, the UK National Physical Laboratory (NPL) organized a scientific workshop entitled "5G testbeds, measurements, challenges, and standardisations" in the EuCAP 2018.

It is also remarkable that the first ESoA off-shore courses was the "Antenna Measurements" course, organized twice in Shanghai and twice in Beijing during the years 2014 and 2016. A similar course by ESoA was also organized in Malaysia during 2023 International Symposium on Antennas and Propagation (ISAP 2023) and in (ISAP 2024) as a collaboration between ESoA and AMTA. In 2023, an URSI School for Young Scientists on "Electromagnetic measurements" was organized by NPL, Foundation for Research on Information Technologies in Society (IT'IS) (Switzerland), University of Electro-Communications (Japan), and University of Calcutta (India) at URSI GASS (General Assembly and Scientific Symposium) 2023 in Sapporo, Japan. In 2024, a new AMTA-ESoA course on near-field antenna measurements is being organised by DTU and MVG at ISAP 2024 in Incheon, Korea. Since 2022, EurAAP WG5 has started organized EurAAP convened session in AMTA conference.

IV. Conclusions

In this paper we have presents the highlights of EurAAP WG5 activities over past two decades including highlights of closed and on-going inter-comparison campaigns as well as outreach and outcome dissemination activities. The vast amount of data from different measurements institutions were used to establish a reference pattern for each of the high accuracy reference antennas. The reference patterns and the data from the facility comparison activities has been considered important instruments to verify the measurements accuracies for antenna measurement ranges as well as to investigate and evaluate possible improvements in measurement set-ups and procedures. The analysis and data elaboration has fostered fruitful discussions and led to modernization and harmonization of comparison techniques such as reference pattern, including estimates of the uncertainty and equivalent noise level. The very large set of measured information, collected in the campaigns, constitutes a valuable database of information that could potentially be available to the antenna measurement community for exploitation in further studies and analysis. As a further benefit, the campaigns have initiated a dialogue among different laboratories globally.

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