2019-2022 ESA-EurAAP Facility Comparison Campaign with the DTU-ESA mm-VAST Antenna – Towards a Reference Pattern

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***Abstract*—The ongoing 2019-2022 ESA-EurAAP Facility Comparison Campaign with the DTU-ESA mm-VAST antenna involves 12 European institutions and 13 spherical near-field and compact range measurement facilities. The mm-VAST antenna is employed in three operational configurations at 19.76 GHz, 37.80 GHz, and 48.16 GHz, including both linear and circular polarization. This paper presents results of 10 out of 13 expected measurements from the campaign, from which a set of reference measurements of the mm-VAST will be derived. As a first step towards this task, a comparison of the radiation patterns, and several metrics of difference between these patterns are presented. These comparisons aim to identify those measured patterns most suitable to be incorporated in the future mm-VAST reference pattern, and which should be discarded as outliers.**

***Index Terms*—antenna measurements, validation, facility comparison, mm-VAST.**

I. Introduction

Antenna measurements are a critical step in the development and validation of a wireless radio-frequency system. Despite the improving accuracy of EM-modelling and technology, the increasing complexity of modern antennas in terms of functionality and topology, and the stringent specifications of performance mean that antenna measurements remain an important tool for verification and validation of antenna performance. This importance is reflected in the ever increasing demand for antenna measurements.

The primary objective of many antenna measurement facilities is to provide a measurement of a specified accuracy of the antenna under test (AUT). Several well-known measurement techniques exist to this end, based on well-known theories, see [1]. Ideally, the result of an AUT measurement should not depend on the specific measurement technique. In practice, this is not the case and the choice of measurement technique and its individual implementation in terms of laboratory, equipment and procedures, as well as the human factor will introduce different sources of uncertainty, either of random or of systematic nature. The uncertainty of the measurement thus depends of the specific measurement facility.

This uncertainty affects both the precision and the accuracy of a measurement facility. While precision (quality of measurement process) can be easily assessed through repeatability measurements, accuracy (quality of measurement result) may be evaluated by the establishment of an error budget, a process which requires detailed insight in the effect of all sources of uncertainty, or, alternatively, by a comparison with reference results or with independent measurements of the same antenna [2]. The latter case constitutes a comparison campaign, which is the foundation of the current mm-VAST campaign.

A comparison campaign where several measurement facilities contribute measurements of one antenna provides each of the facilities with a means to assess its own accuracy by comparison with results from other independent facilities, and to validate its capability to provide measurements with the specified accuracy of said facility. In addition to this, comparison campaigns can offer the antenna community useful insight into the uncertainties associated with different measurement techniques and implementations, a knowledge which can be valuable in standardization of antenna measurements. An example of a previous measurement campaign with the DTU-ESA VAST12 antenna, can be found in [3].

This paper reports current results of the ongoing ESA-EurAAP 2019-2022 facility comparison campaign with the DTU-ESA mm-VAST antenna. The campaign involves 12 European facilities producing 13 measurements of the mm-VAST antenna, specifically designed as a validation standard. The campaign is supported by the European Space Agency (ESA) and the European Association on Antennas and Propagation (EurAAP), and coordinated by the DTU-ESA Spherical Near-Field Antenna Test Facility at the Technical University of Denmark (DTU).

At present, 11 out of 13 facilities have delivered results of the mm-VAST antenna measured in its various configurations, while the 2 measurements that remain for the finalization of the campaign are expected to be conducted before the end of 2022.

This paper is organized as follows: Section II describes the mm-VAST antenna, Section III summarizes the methods used for producing an averaged measured pattern, Section IV presents and compares measurement results, Section V presents several figures of merit for quantitative comparison of patterns, and Section VI gives a brief summary.

II. The DTU-ESA mm-VAST Antenna

The DTU-ESA millimetre-Wave VAlidation STandard (mm-VAST) antenna was developed by DTU and TICRA for ESA [4]-[7] and is mantained at the DTU-ESA Spherical Near-Field Antenna Test Facility, wich acts as an ESA external reference laboratory for high-accuracy antenna testing. It is an antenna well suited as a validation standard due to its high mechanical and thermal stability, challenging radiation patterns over several frequency bands, and its polarization reconfigurability.

The mm-VAST antenna (Fig. 1) is an offset single-reflector antenna with an astigmatic paraboloid of different focal lengths in the orthogonal offset and transverse planes resulting in different beam widths in these planes and thus an elliptic main beam. The reflector is illuminated by a feed cluster of four low cross-polarization Pickett-Potter horns, one for each of the four operational frequencies of 19.76 GHz, 30.04 GHz, 37.80 GHz, and 48.16 GHz. The antenna can be configured for circular as well as linear polarization. A summary of its main features is found in [4], Section III. For this measurement campaign, three configurations of the mm-VAST are considered: configuration 1 at 19.76 GHz and linear polarization, configuration 2 at 37.80 GHz and circular

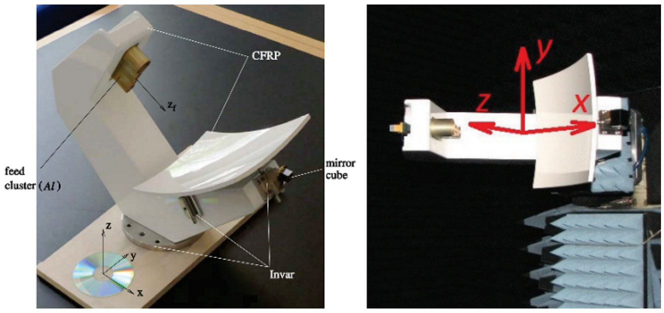

Fig. 1. mm-VAST reflector antenna shown in side-view and during measurements at DTU-ESA Facility with associated coordinate system.

polarization and configuration 3 at 48.16 GHz and linear polarization

Changes of the radiation pattern due to deformations of the antenna caused by changes of the gravity field and/or the temperature are less than one tenth of the typical measurement uncertainty, e.g. for the peak directivity, with a typical measurement uncertainty of 0.03 dB (1σ) at the DTU-ESA Facility; the gravitation and temperature variations will give rise to a change of less than 0.003 dB (1σ).

III. Averaging of radiation patterns

One objective of the ongoing campaign is to produce a reference radiation pattern of the mm-VAST antenna. This reference pattern will essentially be obtained as an average of the various patterns of each configuration measured during the campaign. However, additional factors beyond a simple averaging must be considered. Importantly, since each facility delivered measurements with varying degrees of uncertainty, it is an obvious thought to include these as weighing factors in the averaging, such that measurements of lower-uncertainty have more weight in the reference pattern than measurements with higher-uncertainty. However, since not all facilities submitted an uncertainty figure this is not a possibility unless the corresponding measurements are excluded from the average. It is also necessary to identify possible outlier data in the set of measurements, patterns which should not be included in the reference pattern as not representative.

Currently, two measurements of the mm-VAST antenna are yet to be delivered, and a reference radiation pattern of definitive validity cannot yet be produced. Additionally, due to limited space we consider only configuration 1 of the mm-VAST antenna. This is the configuration most extensively tested, with 10 individual measurements submitted.

In this paper, we refer to an *averaged* pattern aggregating the measurements currently available as a reference for the purpose of the different comparisons presented in Sections IV and V. The pattern is averaged in the linear domain with no weighing based on uncertainty.

The averaged pattern over the forward hemisphere ($\theta \in [0°, 90°]; \phi \in [0°, 360°]$) is calculated from 8 individual patterns, which were provided by the various participants with a sampling density of $\Delta\theta = 1°, \Delta\phi = 1°$. 2 of the 10 submissions did not include full forward-hemisphere information, and thus were not included in this average.

In addition to this, 7 out of the remaining 8 also provided a densely sampled cut of the offset plane ($\phi = 0°$) of the mm-VAST antenna, with a sampling density of $\Delta\theta = 0.1°$ over the entire θ range of 360°. From these 7 offset cuts an averaged cut of the densely-sampled offset plane was obtained. The 8th participant only supplied this dense cut in the forward hemisphere and thus could not be included in this average, but is nevertheless included in some of the comparisons of Section V.

IV. Radiation Patterns

In Fig. 2, the averaged far-field pattern is shown in the offset plane. For each θ-point, the maximum and minimum among all averaged values are also plotted (blue and red lines, respectively). These two curves of maximum deviation from the average towards higher and lower values define for each θ an interval of maximum deviation, which is shown in Fig. 2 as a grey shaded area. The co-polar component exhibits relatively low variation across the forward hemisphere, while the large variation in the backward hemisphere is expected and carries little meaning. The cross-polar shows large variation, which is also expected, but noteworthy given the significantly large variation in the main-beam. The 50th percentile line of the cross-polar component lies closer to the line of minimum values than to the averaged cross-polar pattern, indicating that most patterns have a cross-polar level which is closer to the minimum than to the maximum of all counted measurements. The reason for the higher level of the averaged cross-polar pattern is thus the presence of outliers in the averaged set with disproportionately large cross-polar component, which strongly influence the on-axis cross-polar of the averaged pattern to higher levels than in the majority of the individual patterns.

In Fig. 3 all individual measurements are shown in a narrower region around the main beam of the mm-VAST antenna in the offset plane, and in Table I the peak directivity values and directions are stated. From the table it can be seen that pattern CATR4 is a clear outlier with a significantly larger level of maximum co-polar of 33.06 dB, compared to the average peak directivity of 32.68 dB. Fig. 3 also reveals that this pattern (purple line) has a broader main beam, to the extent that the line of maximum deviation towards higher values largely corresponds to this pattern alone. As for the cross-polar component, it is seen in Fig. 3 that pattern SNF6 (grey line) exhibits a disproportionately high value of cross-polar component; this cross-polar strongly replicates the co-polar component and thus is likely the result of a polarization misalignment of the antenna in the measurement coordinate system. All in all, it is possible to identify two outliers, CATR4 and SNF6, based respectively on their co- and cross-polar components deviating excessively from the remaining measurements.

V. Figures of Merit

The qualitative observations in the previous section are complemented with several quantitative measures in the form of three figures of merit of the studied patterns. The main reference for the figures of merit presented hereby is [3]. The figures of merit (arithmetic mean, standard deviation and 50th percentile) seen in Fig. 4 are calculated over the difference in logarithmic scale of two patterns:

$$\Delta_{log}(\theta,\phi) = 20\log_{10}|F_1(\theta,\phi)| - 20\log_{10}|F_2(\theta,\phi)| \quad (1)$$

The figures of merit are calculated over the different levels of the pattern with intervals of ±3dB, by a summation over all θ, ϕ values for which the directivity lies in the interval. In Fig. 4 the figures of merit of each individual pattern compared to the averaged pattern are shown. The plots show the arithmetic mean (Fig. 4a), standard deviation (Fig. 4b) and 50th percentile (Fig. 4c) of the difference Δ_{log} (Eq. 1) between the averaged pattern and each of the 8 individual measurements considered in Table I, over the forward hemisphere. In the plots, it is observed that most of the patterns follow a similar trend compared to the averaged pattern. It is intuitively understood that for high normalized pattern levels the figures remain low, indicating the overall good agreement of the patterns with the average. At lower levels, the effect of measurement perturbations such as noise becomes more relevant resulting in higher values of these merit figures. The change in the levels of the figures of merit vs the normalized pattern level, particularly in the case of the arithmetic mean, is not very linear, although a linear component of negative slope can easily be identified. The deviation of these figures from a purely linear model indicates that there are significant sources of inaccuracy, other than noise, which affect these measurements [3]. In particular, the arithmetic mean (Fig, 4a), deviates significantly from a linear trend for pattern values between -20 dB to -40 dB, with large values in most of the measurements. This can be due to the fast θ-variation of the directivity in this interval, which in Fig. 2 is seen to encompass the slopes around the main beam with a multitude of side-lobes. In this region, small changes

Measurement	Max D [dB]	(theta, phi)max	Uncertainty
SNF1	32.64	(11.17, 179.81)	0.04
CATR2	32.58	(11.26, 178.97)	0.12
SNF3	32.59	(11.2, 179)	0.02
CATR4	33.06	(11.2, 179.6)	-
CATR5	32.8	(11.2, 180)	0.1
SNF6	32.59	(11.25, 181.5)	-
SNF7	32.59	(11.3, 180.3)	0.22
CATR8	32.84	(11.2, 180)	0.07
CATR9	-	(11.3, 180.3)	-
CATR10	33.3	(11, 180)	0.5
Averaged	32.68	(11.0, 180.0)	-

TABLE I
PEAK DIRECTIVITY AND DIRECTION OF PEAK FOR EACH MEASUREMENT OF MM-VAST, CONFIGURATION 1. MEASUREMENTS IN RED WERE NOT INCLUDED IN THE AVERAGED PATTERNS. MEASUREMENT IN ITALIC WAS NOT INCLUDED IN AVERAGE OFFSET PATTERN.

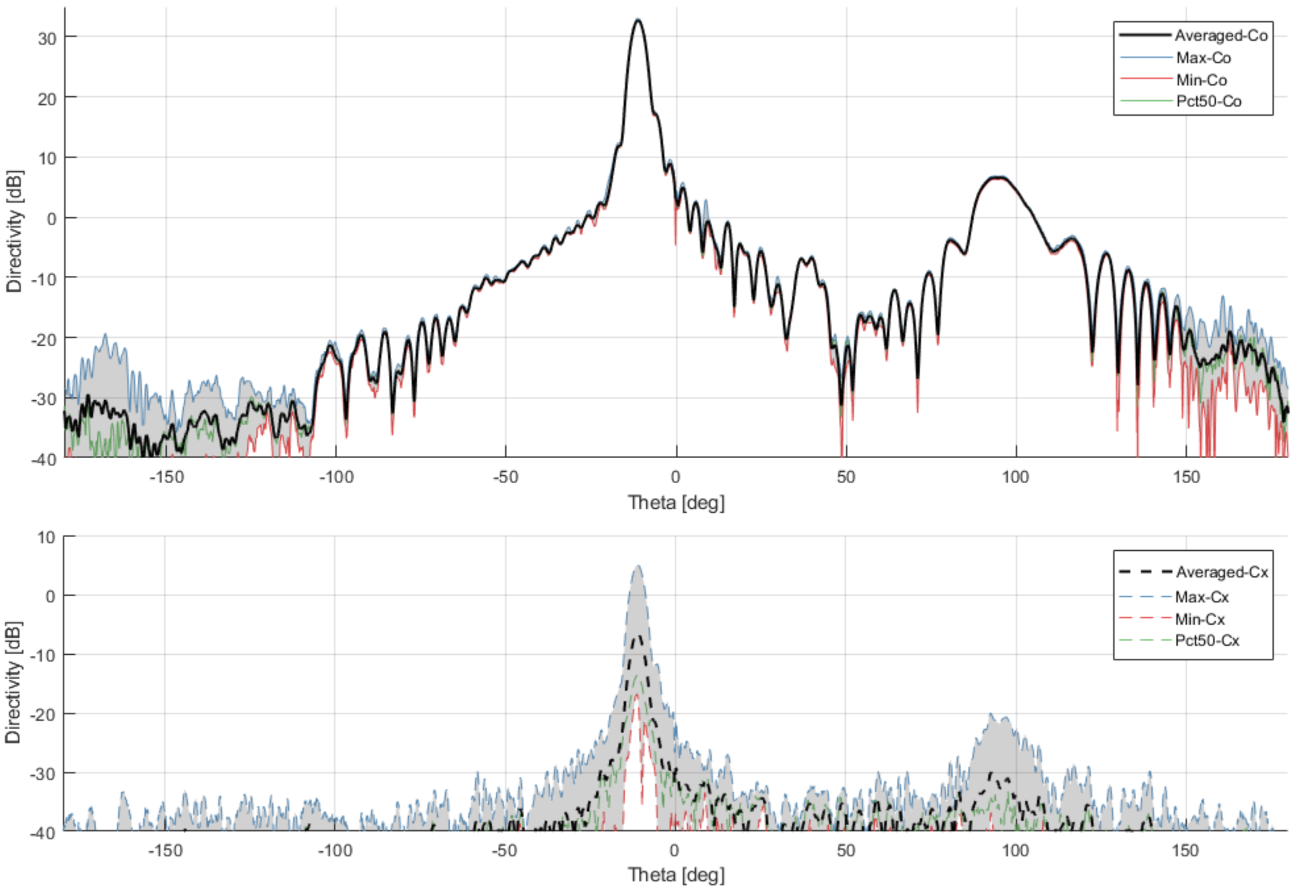

Fig. 2. Averaged radiation patterns of densely sampled ($\Delta\theta = 0.1°$) mm-VAST antenna offset plane of configuration 1 (f = 19.76 GHz, linear polarization). The blue and red lines show respectively the maximum and minimum of all averaged values for each θ. These two lines of maximum deviation towards upper and lower values define a shaded area between the two curves which is the interval of total variation. The 50th percentile for each point (green) is also given.

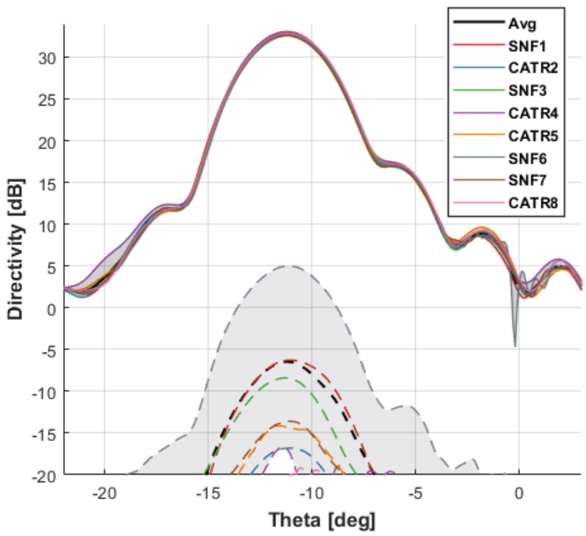

Fig. 3. Main beam of 8 densely sampled ($\Delta\theta = 0.1°$) offset-plane patterns of mm-VAST antenna of configuration 1 (f = 19.76 GHz, linear polarization). Solid/dashed color-paired lines denote co/cross-polar components of a given measurement, respectively. Also shown is the interval of maximum deviation for each θ.

in the direction of observation, e.g. due to differences in the alignment of the coordinate system can easily translate to large pattern differences in logarithmic scale, resulting in the large values of Fig. 4a.

The character of patterns CATR4 and SNF6 as outliers can be supported by the values of the figures of merit in Fig. 4. Particularly, CATR4 shows larger values of mean and standard deviation of the co-polar Δ_{log}, and SNF6 has large mean and 50th percentile values of the cross-polar difference for high directivity levels. Fig. 4 also shows a clear outlier in pattern CATR8 (pink line), with atypically large levels of all three figures of merit across the entire pattern. Close inspection of the data reveals that this is caused by a more marked rippling of both the co- and cross-polar patterns compared to the other studied measurements, as well as the overall lowest level of the main-beam cross-polar, resulting in very large values of the figures of merit at the corresponding intervals.

VI. Summary

The mm-VAST comparison campaign is approaching its completion, with 11 out of 13 scheduled measurements

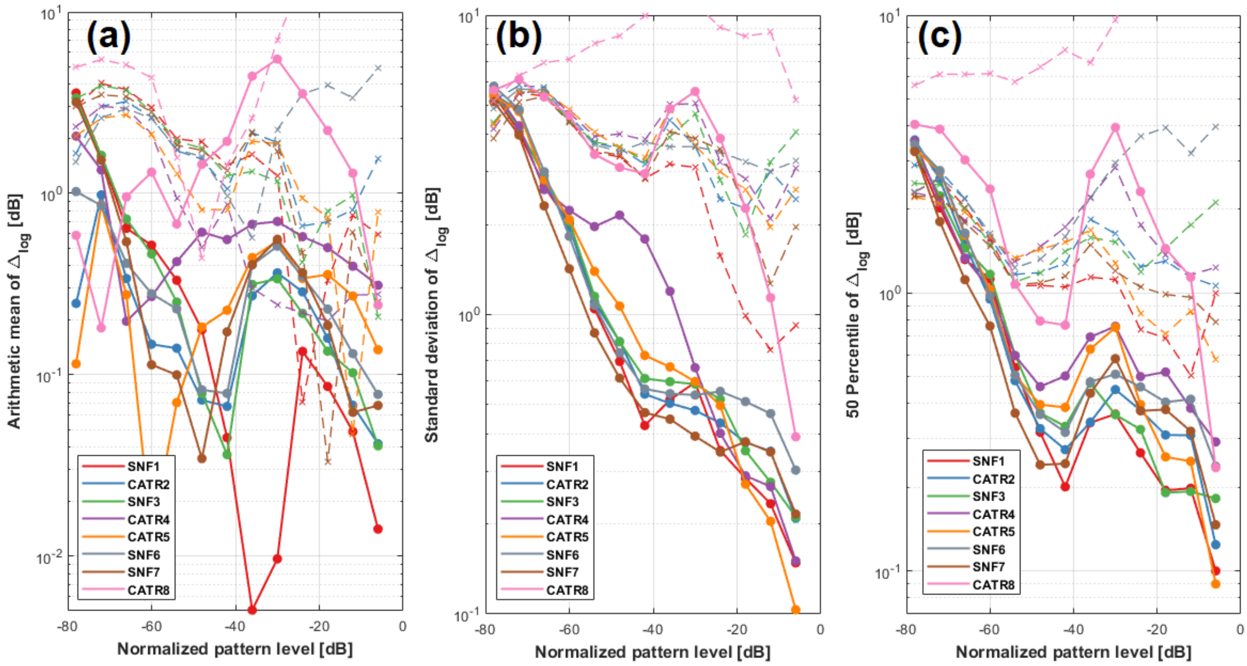

Fig. 4. Figures of merit of each of the measurements in Table I, compared to the averaged measurement over the forward hemisphere. Solid/dashed lines denote co/cx-polar components, respectively. Lines are color-coded similarly to Fig. 3.

delivered. This paper documents present measured data corresponding to configuration 1 (19.6 GHz, linear polarization). An investigation into the task of producing a mm-VAST reference pattern is conducted. It consists of a comparison of the different patterns to identify the outlier measurements which deviate from the representative majority of measurements. Qualitatively, two possible outliers have been identified; based respectively on larger peak co and cross-polar directivity than the majority. This is confirmed by the presented figures of merit which evidence a deviation from the general trend. Furthermore, a third outlier was identified based on these figures of merit which was not readily identified by qualitative evaluation of the patterns. According to these considerations, 5 of the patterns hereby presented will be incorporated into a final measured reference pattern of the mm-VAST antenna, while 3 patterns should not.

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