# DTU-ESA Millimeter-Wave Validation Standard Antenna (mm-VAST) – Detailed Design

Oleksiy S. Kim[1], Sergey Pivnenko[1], Olav Breinbjerg[1],
Rolf Jørgensen[2], Niels Vesterdal Larsen[2],
Kim Branner[3], Peter Berring[3], Christen Malte Markussen[3],
Maurice Paquay[4]
[1]Department of Electrical Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark, Email: osk@elektro.dtu.dk
[2]TICRA, Copenhagen, Denmark, Email: rj@ticra.dk
[3]Department of Wind Energy, Technical University of Denmark, Roskilde, Denmark, Email: kibr@dtu.dk
[4]ESA/ESTEC, Noordwijk, the Netherlands, Email: Maurice.Paquay@esa.int

***Abstract*—A design of a well-characterized, mechanically and thermally stable multi-frequency VAlidation STandard antenna for mm-wave frequencies (mm-VAST) developed in an ESA project is presented. The antenna will facilitate inter-comparison and validation of antenna measurement ranges at K/Ka and Q/V bands in response to on-going deployment of satellite communication services at 20/30 GHz (K/Ka-band) as well as future commercial use of the 40/50 GHz bands (Q/V-band).**

***Index Terms*—antenna measurements, reflector antenna, millimeter waves.**

## I. Introduction

Numerous antenna measurement facility comparison campaigns conducted in the past three decades clearly show advantages of having dedicated VAlidation STandard antennas (VAST) specifically designed for these purposes. Being mechanically and electrically stable a VAST antenna excludes uncertainties associated with an antenna under test (AUT), and thus allows a measurement range and a measurement procedure to be readily verified [1].

A new multi-frequency mm-wave VAST antenna (mm-VAST) is being developed for inter-comparison and validation of antenna test ranges at higher GHz frequency bands (K/Ka-band and Q/V-band) intended for upcoming broadband satellite communications. The project involves electrical, mechanical, and thermal design as well as manufacturing and testing of the antenna. Here, the synergy of the respective expertizes of three parties involved in this project comes into play:

- Electromagnetic Systems (EMS) Group of the Department of Electrical Engineering at the Technical University of Denmark (DTU) — expertise in antenna measurements and antenna measurement techniques; operates DTU-ESA spherical near-field (SNF) antenna test facility [2];
- TICRA — expertise in computational electromagnetics; reflector antenna analysis and design; developer of the reflector antenna analysis software GRASP and the feed horn design software CHAMP;
- Wind Turbine Structures (WTS) and Composite Materials Sections of the Department of Wind Energy at DTU — expertise in dynamic loads and structural design as well as in composites and materials mechanics.

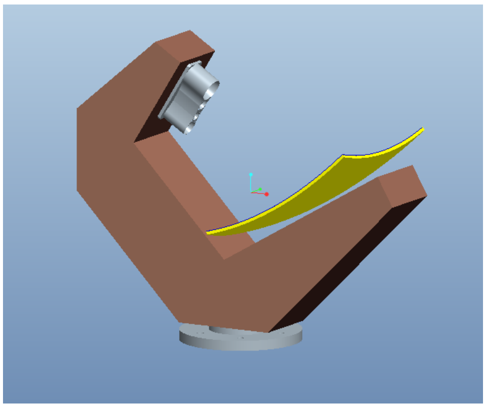

Fig. 1. DTU-ESA mm-VAST antenna

## II. Requirements to the mm-VAST antenna

The main challenges of the project include not only multi-frequency capabilities of the mm-VAST antenna, but also very stringent requirements on the gravity and temperature induced uncertainties of the measured characteristics. It is required that any deformities of the mm-VAST antenna during tests, assuming the antenna is rotated and the temperature varies $\pm5°$C, introduce an error ten times less than the measurement accuracy being sought. With the measurement accuracy of the peak directivity attained at the DTU-ESA SNF range of 0.03 dB ($1\sigma$), deviations should not exceed 0.003 dB ($1\sigma$). In combination with a short wavelength (6 mm) at the highest operational frequency, this requirement results in maximum acceptable deformations of the antenna structure of the order of microns. The main requirements are summarized in Table I.

## III. Electrical Design of the mm-VAST antenna

The mm-VAST antenna will be a reflector antenna, as this configuration has proven its viability through 20-year long

TABLE I
REQUIREMENTS TO THE MM-VAST ANTENNA

| | |
|---|---|
| Operational frequencies | Frequency 1 in the band 17.5–20.2 GHz |
| | Frequency 2 in the band 27.5–31.0 GHz |
| | Frequency 3 in the band 37.5–40.5 GHz |
| | Frequency 4 in the band 47.2–50.2 GHz |
| Gain | Frequency 1 and 2: 30–35 dBi |
| | Frequency 3 and 4: 33–38 dBi |
| Polarization | Reconfigurable between linear and circular at all operational frequencies |
| Co-polar pattern | Challenging to measure:<br>• near-sidelobes (1st-3rd) in the range 18–25 dB below peak<br>• deep nulls<br>• far-out sidelobes at least 30 dB below peak<br>• an asymmetry<br>• different beamwidths in the orthogonal planes<br>• flat-top or split main beam |
| Cross-polar pattern | • XPD $>$ 20 dB in the main beam region<br>• null in the main beam region |
| Spillover loss | $<$ 0.35 dB |
| Return loss | 10–20 dB |
| Coordinate systems | Optical and mechanical |
| Temperature range | $20 \pm 5°$C |

TABLE II
GEOMETRICAL PARAMETERS OF THE MM-VAST ANTENNA

| | |
|---|---|
| Aperture | 230 $\times$ 230 mm |
| Focal lengths | $F_x = 167$ mm |
| | $F_y = 220$ mm |
| Offset | 200 mm |
| Offset angle | 57.6° |

operability of VAST-12 — a validation standard antenna for 12 GHz also developed by DTU [3].

The optimized design of the mm-VAST antenna is sketched in Fig. 1. The reflector surface is defined by the following equation

$$z = \frac{x^2}{4F_x} + \frac{y^2}{4F_y}, \quad (1)$$

which describes a paraboloid with different focal lengths in the orthogonal planes, $F_x$ and $F_y$. This reduces the variation of the directivity over the large frequency span from Frequency 1 to Frequency 4 and at the same time ensures different beamwidths in the orthogonal planes. The square aperture facilitates the near-sidelobes in the specified range (18–25 dB below peak) and moderate spill-over loss. The main geometrical parameters of the antenna are provided in Table II.

## IV. FEED SYSTEM OF THE MM-VAST ANTENNA

The feed system consists of four Picket-Potter horns [4] — one for each of the operating frequencies. These are simplified versions of classical Potter horns [5]; they have narrower

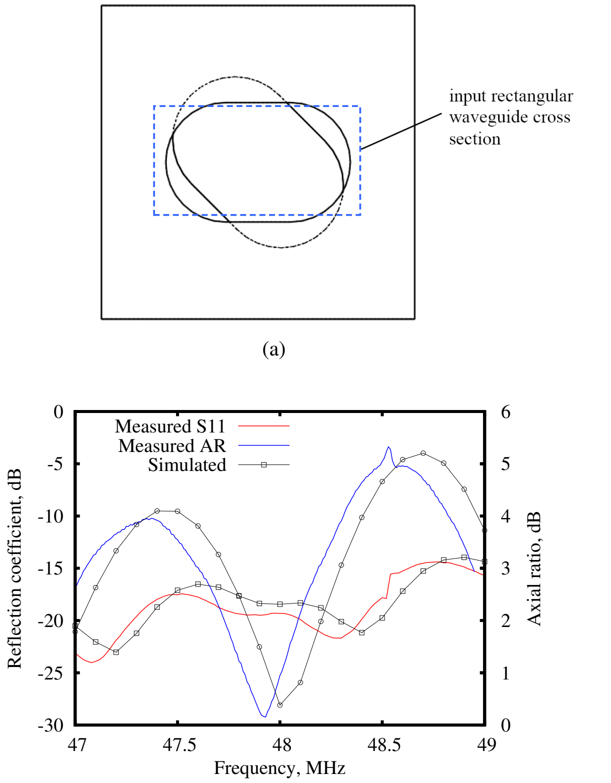


Fig. 2. Geometry of a simple LP to CP polarizer (a) and simulated and measured reflection coefficient and axial ratio (AR) for a manufactured prototype (b).

bandwidth, which however is more than sufficient for a single-frequency operation required from each of them. The horn apertures are placed in the same plane, while the horn axes are parallel and located in the antenna symmetry plane (see Fig. 1). The former eases the manufacturing, whereas the latter guarantees null of the cross-polarization in linear polarization (LP) operation mode.

The horns were designed by EMS using TICRA's CHAMP software and combined in a cluster. Only one feed horn operates at a time; others are terminated with a well-defined load (short circuit). A feed chain for each feed horn consists of a rectangular to circular waveguide transition mounted directly to the feed cluster in the LP operation mode. In the circular polarization (CP) operation mode, the transition is substituted by an LP to CP waveguide polarizer.

Since each polarizer is required to operate at a single frequency, a simple geometry composed of two sections of rounded rectangular waveguides was selected (Fig. 2a). The first section aligned with an input rectangular waveguide matches the latter to the rest of the feed chain. The second section is rotated by $45°$ with respect to the first one for polarization conversion. Parameters of both sections were optimized for each horn individually taking into account its complex reflection coefficient at the respective operating frequency. The polarizer for Frequency 4 was manufactured and measured together with the respective horn; the resulting

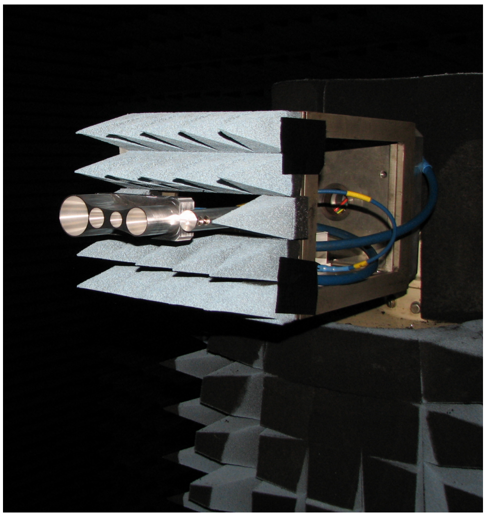

Fig. 3. Feed cluster of four Picket-Potter horns under measurements

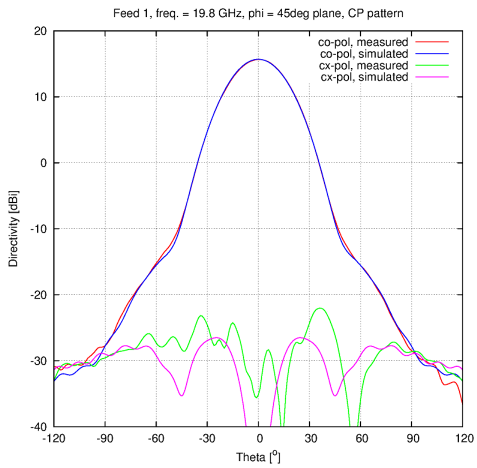


Fig. 4. Measured and simulated radiation patterns of the horn 1 in the feed cluster operating at 19.8 GHz

reflection coefficient and the axial ratio (AR) agree very well with the predictions (Fig. 2b). The minimum AR of 0.15 dB is achieved at 47.93 GHz with the reflection coefficient of $-19.4$ dB. The observed 0.2% frequency shift with respect to the simulations does not present any problem, as the operating frequency can be freely selected as long as it lies within the band specified in the requirements (see Table I).

The rectangular to circular waveguide transitions for LP are simple sections of rounded rectangular waveguides.

A prototype of the designed feed cluster was manufactured at the EMS workshop and measured at DTU-ESA SNF antenna test facility (Fig. 3). The simulated and measured radiation patterns for the horn operating at Frequency 1 are presented in Fig. 4. A good agreement between simulations and measurements is observed.

## V. Electrical Characteristics of the mm-VAST Antenna

The radiation patterns of the mm-VAST antenna obtained using GRASP are presented in Fig. 5. The peak directivity meets the specifications (see Table I) at all four operating frequencies. Pattern features challenging to measure, such as different beamwidths in the orthogonal planes and flat-top main beam, are present at Frequencies 2-4. Requested near-sidelobes in the range 18–25 dB below peak (red area on the plots) as well as deep nulls can be observed. The cross-polarization level is at least 20 dB below peak within –1 dB main beam contour, as required. In general, almost all the requirements are met at all frequencies for both LP and CP; the few noncompliances are minor and deemed acceptable.

## VI. Mechanical Design of the mm-VAST Antenna

The mechanical design of the mm-VAST antenna has been carried out by WTS based on the antenna electrical design and maximum acceptable tolerances identified by TICRA via full-wave simulations. As noted above, the latter are of the order of few microns for feed and reflector displacements, while the acceptable rotations of the reflector are of the order of few ten-thousandths of a degree.

To meet these stringent specifications, the support frame and reflector are made of 8-mm thick monolithic carbon fiber reinforced plastic (CFRP) panels. The feed cluster mounting interface, the antenna mounting flange, and other metal parts are made in Invar. These materials are chosen in order to provide the optimum combination of mechanical strength and thermal stability, as they have very low thermal expansion coefficient and high stiffness.

The mechanical modelling of the antenna was carried out using the commercial finite element package MSC.Patran (version 2012.2) and MSC.MARC was applied as a solver in all analyses. The numerical load configurations (rotations in gravity and temperature variations) were scaled with a factor of 100 compared with the nominal design load cases, as the displacements response of the antenna model, when subjected to the nominal design load cases, were too small to compute with an acceptable precision. It was assumed, and also verified by the analyses, that the response of the antenna is linear and therefore the scaling as well as superposition of the computed displacements and rotations are valid. Fig. 6 illustrates the result of one of the simulations for a thermal load case.

The overall results of the simulations validate the design showing that the displacements and rotations of the antenna parts due to arbitrary orientation of the gravity force and temperature variations lie within the limits set by the maximum acceptable measurement uncertainty introduced by the antenna deformations under test (0.003 dB ($1\sigma$) in peak directivity).

There will be two coordinate systems – mechanical and optical. The mechanical coordinate system will be defined by the normal to the antenna mounting flange and a spirit level attached to the support frame. The optical coordinate system will be defined by a mirror cube placed behind the reflector.

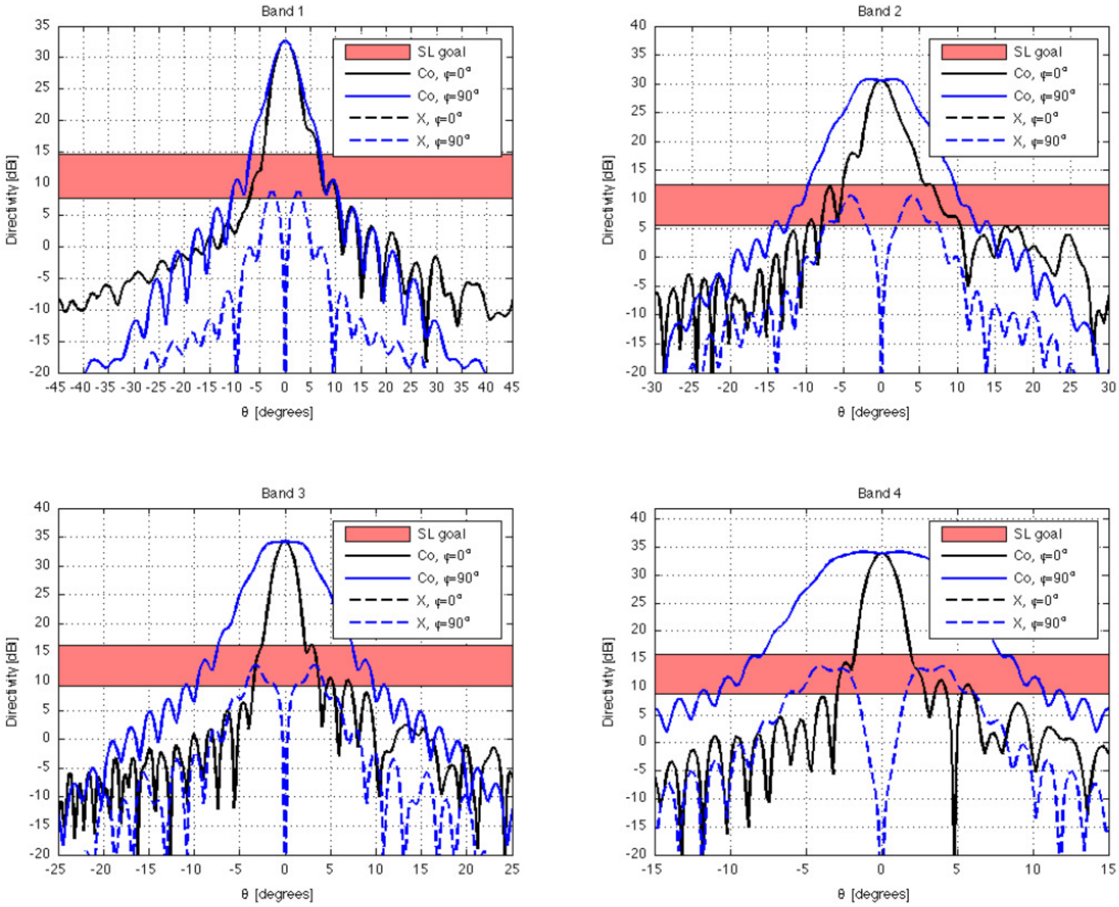


Fig. 5. LP radiation patterns of mm-VAST antenna simulated in GRASP

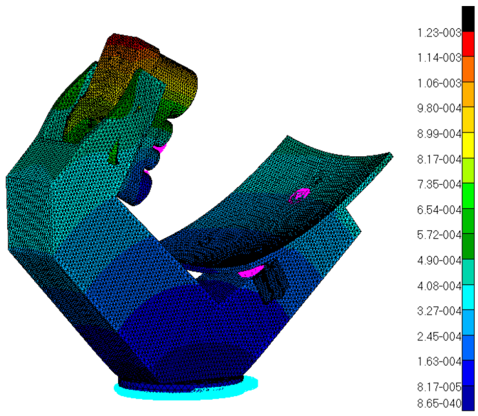


Fig. 6. Deformations in the thermal load case. Displacement magnitude scaled factor by a factor of 100.

## VII. Conclusion

The DTU-ESA mm-wave Validation Standard (mm-VAST) antenna for test range inter-comparisons is under development at the Technical University of Denmark (DTU) in collaboration with TICRA. The results of the final design phase are summarized in this contribution. The antenna is currently being manufactured and further results will be presented at the conference.

## References


[1] S. Pivnenko, J. E. Pallesen, O. Breinbjerg, M. S. Castaner, P. Almena, C. Portas, J. Sanmartin, J. Romeu, S. Blanch, J. Gonzalez-Arbesu, C. Sabatier, A. Calderone, G. Portier, H. Eriksson, and J. Zackrisson, “Comparison of antenna measurement facilities with the DTU-ESA 12 GHz validation standard antenna within the eu antenna centre of excellence,” *IEEE Trans. Ant. Propagat.*, vol. 57, no. 7, pp. 1863–1878, 2009.

[2] DTU-ESA Spherical Near-Field Antenna Test Facility. Homepage, http://www.ems.elektro.dtu.dk/research/dtu_esa_facility.

[3] J. E. Hansen, “Definition, design, manufacture,test and use of a 12 GHz validation standard antenna. executive summary,” Technical University of Denmark (DTU), Tech. Rep., 1997.

[4] H. Pickett, J. Hardy, and J. Farhoomand, “Characterization of a dual-mode horn for submillimeter wavelengths,” *IEEE Trans. Microw. Theory Tech.*, vol. 32, no. 8, pp. 936–937, Aug 1984.

[5] A. D. Potter, “A new horn antenna with suppressed sidelobes and equal beamwidths,” *Microwave J.*, vol. 6, no. 6, pp. 71–78, 1963.