DTU-ESA Millimeter-Wave Validation Standard Antenna – Requirements and Design

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Abstract — **Inter-comparisons and validations of antenna measurement ranges are useful tools allowing the detection of various problems in the measurement procedures, thus leading to improvements of the measurement accuracy and facilitating better understanding of the measurement techniques. The maximum value from a validation campaign is achieved when a dedicated Validation Standard (VAST) antenna specifically designed for this purpose is available. The driving requirements to VAST antennas are their mechanical stability with respect to any orientation of the antenna in the gravity field and thermal stability over a given operational temperature range. In addition, VAST antennas must possess electrical characteristics that are typical for satellite antennas and challenging to measure.**

A multi-band millimeter-wave VAST (mm-VAST) antenna for the K/Ka-bands and Q/V bands is currently under development in collaboration between the Technical University of Denmark (DTU) and TICRA under contract from the European Space Agency. In this paper, the electrical and mechanical requirements of the DTU-ESA mm-VAST antenna are discussed and presented. Potential antenna types fulfilling the electrical requirements are briefly reviewed and the baseline design is described. The emphasis is given to definition of the requirements for the mechanical and thermal stability of the antenna, which satisfy the stringent stability requirement for the mm-VAST electrical characteristics.

I. INTRODUCTION

Inter-comparison and validation of antenna measurement ranges either with readily available antennas or with dedicated VAST antennas have been carried out for at least three decades [1-5]. These activities have proven to be very useful as these allow finding and help correcting major and minor problems in the measurement procedures, thus leading to an improvement of the measurement accuracy of the involved ranges and facilitating better understanding of the measurement techniques.

The early experience gained from the campaigns demonstrated that readily available antennas can be used for this purpose, but they only partially meet the requirements of a validation campaign. The maximum value from a validation campaign is achieved when a dedicated Validation Standard (VAST) antenna specifically designed for this purpose is available. The widespread use of the known VAST-12 antenna (working at 12 GHz), developed by the Technical University of Denmark (DTU) and operated by the DTU-ESA Facility since 1992, demonstrates the long-term value of the dedicated VAST antennas [5]. The VAST-12 antenna has been used extensively for measurement facility comparison and validation over many years; in particular within the EU Network of Excellence ACE – Antenna Centre of Excellence which led also to important recommendations for future VAST antennas and comparison campaigns [5].

The driving requirements of VAST antennas are their mechanical stability with respect to any orientation of the antenna in the gravity field and thermal stability over a given operational temperature range. The mechanical design shall ensure extremely stable electrical characteristics with variations typically an order of magnitude smaller than the measurement uncertainty. At the same time, it must withstand high g-loads under frequent transportations and it shall also support convenient handling of the VAST antenna (practical electrical and mechanical interfaces, low mass, attachment points for lifting, etc.). Also, the VAST antenna must allow for precise definition of at least one coordinate system to which all pattern measurements must be referred.

Today, there is a well identified need for increased operational frequencies to get access to large bandwidth for broadband communication. Upcoming satellite communication services utilize up/down link at K/Ka-bands, while the use of Q/V bands is contemplated for the feeder links in the coming years. In response to this need, a multi-band millimeter-wave VAST (mm-VAST) antenna covering K/Ka/Q/V-bands is currently under development in collaboration between DTU and TICRA under contract from the European Space Agency.

In this paper, the electrical and mechanical requirements of the DTU-ESA mm-VAST antenna are discussed and presented. Potential antenna types fulfilling the electrical requirements are briefly reviewed and the baseline design is described. The

emphasis is given to definition of the requirements for the mechanical and thermal stability of the antenna, which satisfy the stringent stability requirement for the mm-VAST electrical characteristics.

II. REQUIREMENTS TO MM-VAST ANTENNA

In order to increase the outcome from facility comparisons, the VAST antenna electrical characteristics should possess a series of features combining both representative characteristics of typical satellite antennas and complex details challenging the measurement. Many typical errors in antenna measurement ranges can be seen from the location and shape of the pattern peak, the shape and level of the near and far sidelobes, the cross-polar pattern, the location and level of the nulls. It is also preferred that the pattern is asymmetric, with its peak slightly offset from the axes of the coordinate system allowing detection of problems in its definition.

It was observed in the facility comparison campaign carried out with the VAST-12 antenna [5] that scattering from the antenna positioner may have noticeable effect when its illumination is significant. Thus the VAST antenna radiation towards its support structure should be minimized by proper design or by proper location of the mounting flange.

Another very important requirement is the high stability of electrical characteristics ensuring that the differences in the measurement results from different measurement ranges and techniques are not coming from the deformations of the antenna itself. Stability of the electrical characteristics of the antenna is directly dependent on its mechanical stability, e.g. structural deformations due to gravity changes when the antenna is rotated, and its thermal stability, e.g. antenna thermal expansion due to changed temperature. To this end, variations of the antenna characteristics due to the above factors an order of magnitude smaller than the expected measurement uncertainty are required. In the state-of-the-art measurement facilities, an achievable measurement uncertainty for an antenna with some 30-40 dBi directivity is typically about 0.03 dB (1σ) referenced to the peak directivity [5, 6]. Thus the value characterizing the electrical stability of the VAST antenna is taken to be 0.003 dB (1σ).

The main electrical and mechanical requirements to the mm-VAST antenna are summarized in Table I.

TABLE I. ELECTRICAL AND MECHANICAL REQUIREMENTS.

Parameter	Description
Co-polar pattern	Near sidelobes (1st-3rd) shall be present in the range 18-25 dB below the pattern peak. Deep nulls are desirable. The radiation towards a support structure (to be specified) shall not introduce uncertainty larger than 0.01 dB (1σ). An asymmetry visible in the first few sidelobes shall be present at least in one plane of the radiation pattern. The beamwidths in the orthogonal planes shall differ. Flat-top or split main beam in one of the planes.
Cross-polar pattern	The cross-polarization level in the main beam shall be lower than 20 dB below the co-polar level within the −1 dB contour at a selected operational frequency in each band.

	The cross-polar pattern shall have a null in the main beam; quantified as a level of some 50 dB below the co-polar peak.
Polarization	Reconfigurable between linear and circular polarization for all operational frequencies.
Operational frequencies	One frequency within each of Band 1: 17.5-20.2 GHz Band 2: 27.5-31.0 GHz Band 3: 37.5-40.5 GHz Band 4: 47.2-50.2 GHz These bands comply with the Primary allocations for Fixed Satellite Service.
Gain	Within 30-35 dBi for bands 1 and 2 and within 33-38 dBi for bands 3 and 4.
Input impedance	The reflection coefficient shall be between -10 dB..-20 dB for the operational frequencies.
Feed arrangement	No feed horn mounting/dismounting is allowed when changing the frequency band. Waveguide components are allowed to be remounted for changing the frequency band and/or polarization.
Electrical interface	The electrical interface shall be standard rectangular waveguides: • WR42 for band 1 • WR28 for band 2 • WR28 or WR22 for band 3 • WR22 or WR19 for band 4
Stiffness and robustness	The antenna shall be rigid enough to withstand the amount of handling and transportation to which it will be subjected.
Mechanical and thermal stability	The antenna shall be stiff enough such that any deformities of the antenna during test, assuming that the antenna is to be rotated, introduce an error not larger than 0.003 dB (1σ) in the peak directivity.
Temperature and humidity ranges	Operational temperature range from 15ºC to 25ºC Survivability temperature range -10ºC to +50ºC Long time relative humidity limits 40% to70%
Weight	Less than 50 kg.
Dimensions	No specific requirement.
Coordinate system definition	Optical CS defined by a mirror cube. Mechanical CS defined by the mounting flange and spirit level.
Hardware development	Use of components-of-the-shelf is preferred. Compatible with class 100.000 .
Handling and transportation	Necessary lifting and handling tools. Shock level detection sensors included. Dedicated transport container.
Mech. interface	Compatible with the VAST-12 antenna.

III. ANTENNA TYPES SUITABLE FOR MM-VAST

Due to the main requirements to the mm-VAST antenna – such as high mechanical and thermal stability, durability, minimum research and development (R&D), maximum use of components-of-the-shelf (COTS) – certain antenna types can be immediately ruled out:

- Waveguide/waveguide-slot arrays – involves large R&D, COTS can hardly be used, challenging to make multi-band;

- Printed phased arrays – in addition to the problems above, a PCB substrate can be a problem with respect to the thermal stability as well as durability;

- Printed reflectarrays – same problems as above;
- Wideband horns cannot be used due to their low directivity.

Thus, a reflector antenna presents a natural choice for the mm-VAST. The experience gained from the development and operation of the VAST-12 confirms that a reflector antenna can be made mechanically and thermally stable, durable for decades, and at the same time the R&D work is reduced to minimum, as the reflector and the feed support structure are the only parts, which need to be designed.

A. Single reflector, prime focus

This configuration exhibits a good cross-polar performance. However, significant scattering from the feed(s) and the massive feed support structure can increase the far-out sidelobes to an unacceptable level. Attempts to minimize these effects will compromise the mechanical stability of the support structure. Moreover, additional uncertainties are introduced in the measurements due to feed cables arbitrarily located in the high field of the main reflector.

B. Dual reflector, prime focus

It potentially exhibits excellent cross-polar performance as well as very low spill-over losses and back radiation. The support structure carrying only sub-reflector can be made simpler and lighter than for a feed, and thus the pattern disturbing effects due to the scattering are less significant. Feed ports and cables are hidden behind the main reflector, thus reducing the measurement uncertainty. On the other hand, this configuration requires highly directive feed(s), and thus large feed aperture(s) and larger offsets from the focal point, if a multiple-feed set-up is chosen. Compared to a single reflector configuration, a dual reflector system is inherently more costly in design and manufacturing. Another disadvantage is the feed return loss due to the feed sub-reflector interaction. This is especially a problem for small main reflector diameters (expected diameter in this case is 20λ-30λ).

C. Dual reflector, offset

The feed sub-reflector scattering problems are reduced significantly as no reflected (only diffracted) rays will hit the feed and sub-reflector. However, the offset geometry will create high cross polarization on either side of the symmetry plane. This cross-polarization can be reduced by applying cross polarization compensated geometries such as Gregorian, front-fed Cassegrain and side-fed Cassegrain. On the other hand, the first configuration will give rise to higher side lobes in the ±20° range, due to the feed/sub-reflector radiation directly to the far field, while in the latter two configurations, the feed direct radiation will increase the sidelobes in the back and side region, respectively. Furthermore, the manufacturing cost of the front-fed or side-fed Cassegrain antennas is more than twice of that of a single reflector system, as the main and sub-reflectors are nearly of the same size, which in addition require a bulky frame to ensure mechanical stability.

D. Single reflector, offset

This configuration does not suffer from the disadvantages of the single-reflector, prime focus configuration. The cross-polar performance is worse, which however can be mitigated by the increased focal distance to diameter (f/D) ratio. During the initial design phase of the VAST-12, this configuration went through a thorough comparison study (together with a dual reflector, prime focus configuration) and was selected as the most appropriate one. Subsequent development, tests, and operation of the VAST-12 have confirmed the validity of this choice.

Therefore, a single reflector, offset configuration, has formed the baseline for the development of the mm-VAST.

IV. FEED CONFIGURATION

As the mm-VAST antenna has to operate at four widely separated frequencies, within the Ku-, Ka- Q-, and V-bands, the first quite natural choice is to use a dedicated narrowband feed for each frequency.

Another option is to use a single wide-band feed covering all four bands of interest. However, known wideband antennas that can be used as the feed will require a custom designed transition to a standard waveguide for each of the four bands. This is associated with a lengthy development as well as costly manufacturing and testing and thus not considered suitable within this project.

The possibility of using only two conical horns, with each one working in two neighboring bands was also considered, but due to large difference of the beamwidth and possible excitation of the higher-order waveguide modes this configuration was discarded.

Yet another option is to use two specially designed wideband corrugated horns, each one covering two neighbor bands, with approximately the same beamwidth in each band. The designs of such horns with 1:2 relative bandwidth are available for 20-30 GHz [7, 8]. Detailed analysis of this configuration has shown only little improvement over the four narrowband feed and thus it was ruled out.

In conclusion, it was found that the best solution is to use 4 conical horns each one working in one of the 4 frequency bands.

V. ELECTRICAL BASELINE DESIGN

A series of extensive simulations for an offset reflector was carried out using GRASP software [9] with varying parameters such as reflector diameter, focal distance, feed offset, reflector surface shape, rim shape, and feed configuration. The obtained results were summarized in a compliance matrix versus the electrical requirements described in Table I.

For the chosen preliminary reflector parameters, all considered feed configurations showed rather similar performance potentially meeting the requirements. However, when using the wideband horns or conical horns in the neighbor bands, excitation of the higher-order modes in the higher-frequency band may potentially give rise to problems with repeatability of the results after changing from linear (LP) to circular polarization (CP) and from band to band. Thus the configuration with four narrow-band feeds arranged along the symmetry plane of a dual-focus reflector with a rectangular aperture was finally selected, see Fig 1. The parameters of the optimized configuration are summarized in Table II.
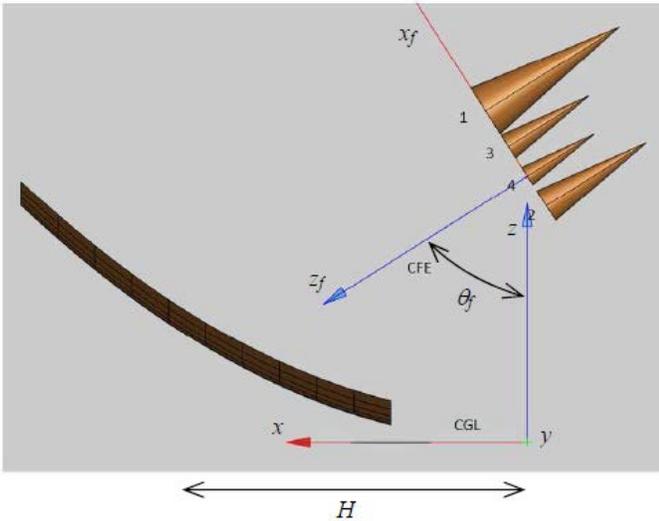
Figure 1. Optimized configuration of the mm-VAST antenna: CGL – global coordinate system, CFE – feed cluster coordinate system.

TABLE II. OPTIMIZED REFLECTOR PARAMETERS.

Aperture	230 mm x 230 mm
Focal lengths	$F_x = 167$ mm
	$F_y = 220$ mm
Offset H	200 mm
Offset angle θ_f	57.6°
Feed coordinate system (CFE) origin	(0.0, 0.0, 167 mm)

Further analysis has shown that using Potter horns allows significant improvement of the cross-polar performance at CP. Thus the final feed configuration was selected as being a cluster of four Potter horns with the apertures placed in the same plane, while the horn axes are parallel and located in the antenna symmetry plane. The order of the 4 feeds is chosen to minimize the electrical offset from the focal point in the offset plane; thus, the V-band horn is located at the focal point, with the Q-band and Ka-band horns on each side, and the K-band horn next to the Q-band horn.

The radiation patterns around the main beam and first few sidelobes for the LP and CP and for all four bands are shown in Fig. 2 and Fig. 3.

It is seen from Figs. 2-3 that the electrical requirements in Table I are satisfied in this baseline design. The only comment is that for LP the level of cross-polarization is just below the goal of −20 dB in the bands 2 and 4. It is expected that the feed support structure may result in degradation of this value, and some further fine tuning of the reflector parameters is planned taking into account the effects of the feed support frame. On the other hand, it is noted that for the strongly elliptic shape of the main beam it is rather difficult to ensure this cross-polar level within the -1 dB contour, even though the on-axis cross-polar level has a deep null.
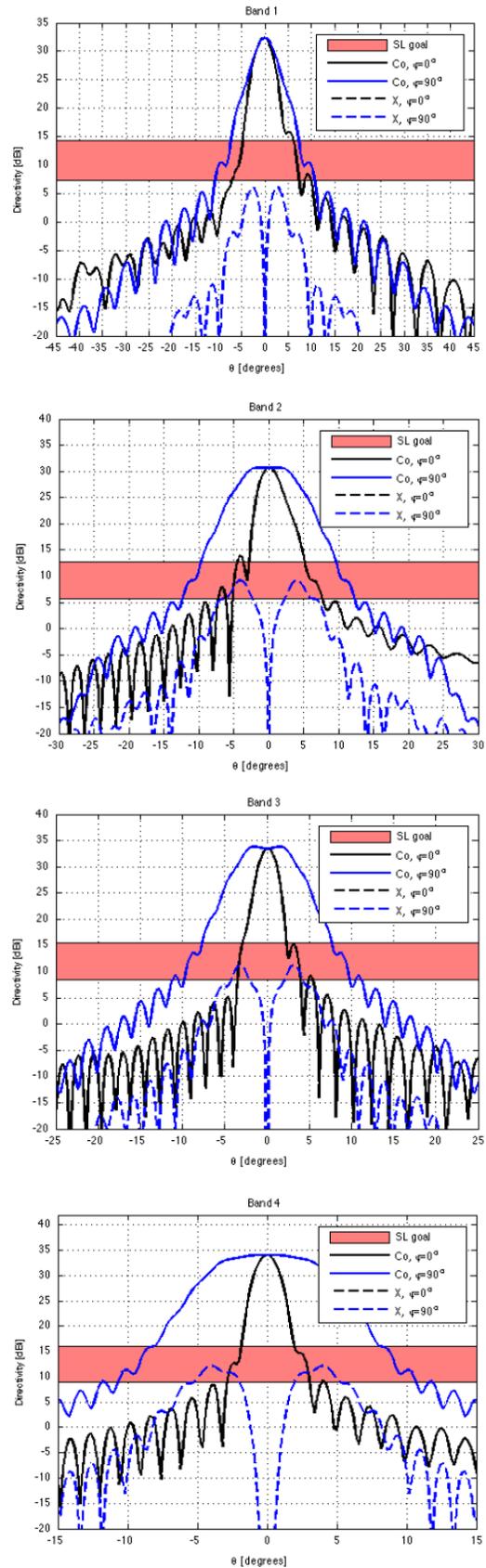
Figure 2. Simulated mm-VAST patterns for the LP.
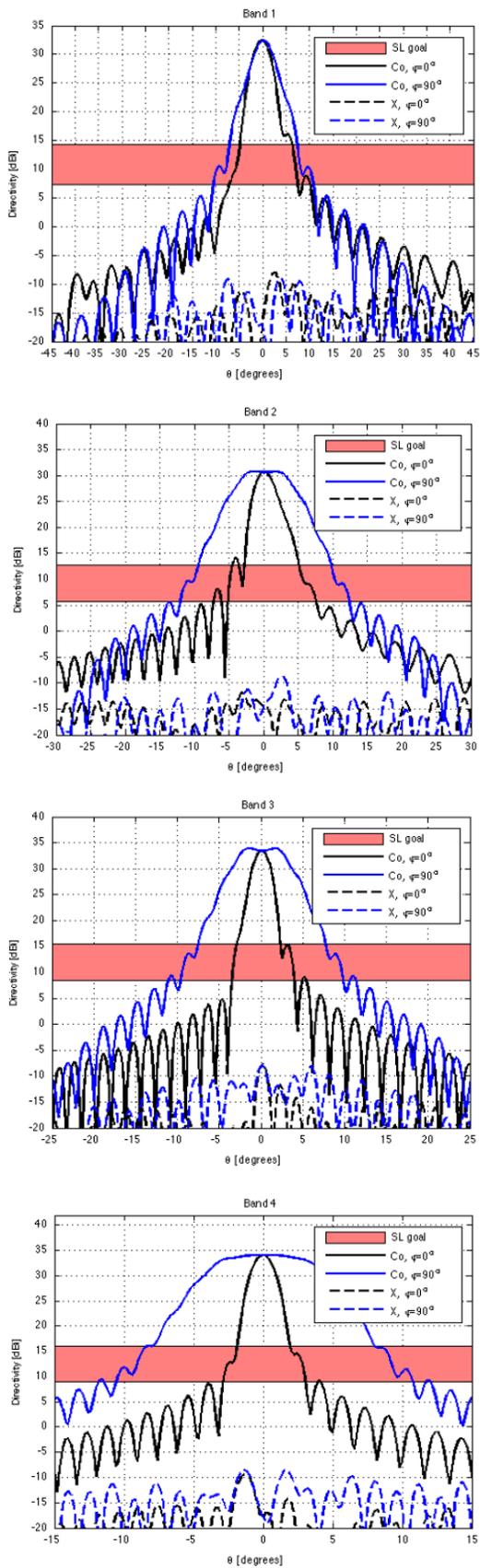
Figure 3. Simulated mm-VAST patterns for the CP.

The requirement to the electrical stability of the mm-VAST antenna is set to be 0.003 dB (1σ) referenced to the peak directivity. From this value, the requirements to the mechanical stability of the feed support structure, i.e. maximum acceptable displacement of the feed with respect to its nominal position has to be determined.

Feed displacement orthogonal to its symmetry axis causes mainly a reflector main beam shift proportional to the feed displacement angle. A series of simulations were carried out for the measured patterns of the VAST-12 antenna having about 30 dBi directivity and a reflect-array antenna [8] having about 40 dBi directivity. The far-field patterns of these antennas were calculated in a coordinate system shifted by 0.01º and 0.003º for the VAST-12, and by 0.005º and 0.002º for the reflect-array, separately in a symmetry plane and in an offset plane. A complex difference between the far fields obtained with the nominal and displaced feed was then calculated. This difference in the logarithmic scale represents the equivalent error (difference) signal (EES) between the fields from the nominal feed position and the displaced feed. The EES level corresponding to the 0.003 dB (1σ) pattern uncertainty is −60 dB. The VAST-12 radiation pattern in the offset plane with the EES level corresponding to the 0.003º pattern displacement is shown in Fig. 4.
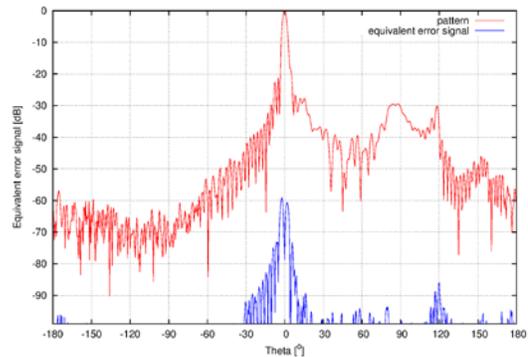
Figure 4. VAST-12 offset plane, 0.003º displacement.

It is seen from Fig. 4 that for the VAST-12 antenna for the feed displacement of 0.003º the EES level reaches the −60 dB limit, while for the 40 dBi antenna (not shown here), this limit is achieved at about 0.0017º feed displacement. The calculated maximum angular feed deviations can be transferred to maximum feed translation by calculating tangent of the found angle times the focal distance (assuming the deformation happens in one point where the feed support is attached to the reflector). For the focal distance of 167 mm, it is: $167 \times \tan(0.0017º) = 0.005$ mm = 5 μm.

A similar investigation for the feed displacement carried out with GRASP have shown very similar maximum feed displacement values orthogonal to the feed axis, but much smaller value, 1 μm, for the feed displacement along the feed axis for the same EES level at −60 dB. Such tight tolerance is very difficult to achieve from the mechanical point of view and thus another series of simulations was carried out to clarify the effect of the longitudinal feed displacement on the far-field

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pattern obtained from a typical near-field antenna measurement.

Taking the far-field pattern of the VAST-12 antenna obtained from a spherical near-field measurement, the corresponding near-field signal at 6 m distance (probe distance at the DTU-ESA Facility) was calculated for the two main scanning schemes: θ-scan and ϕ-scan. The main effect of the longitudinal feed displacement is the phase change of the radiated signal proportional to the electrical length of the displacement. Therefore, the near-field signals were then modified such that a linearly-changing phase shift was added to the near-field signal in each measured point so that the total phase shift at the end of the measurement constituted the desired value, e.g. 1°. This error model corresponds to a linear displacement of the feed along its symmetry axis e.g. with the changing temperature. The modified near-field signals were then processed applying usual near-to-far-field transformation and the obtained far-field patterns with the induced errors were compared to the reference far-field pattern.

Since the developed mm-VAST antenna is expected to have the main beam pointing slightly off z-axis of the mechanical coordinate system, the simulations were done for the main beam pointing along z-axis and also rotated by 5° from the z-axis of the measurement coordinate system along x-axis and along y-axis. In order to make proper comparisons (so that the pattern cuts go through the main beam), the above rotations were then compensated by the reverse rotations before the comparisons. For each antenna orientation, the linear phase shift was adjusted such that the achieved EES was at the level of −60 dB. An example of the EES result together with the pattern itself is shown in Fig. 5. It is seen from Fig. 5 that for the main beam pointing along z-axis the θ-scanning scheme is very sensitive to the phase shift: with only 0.7° total phase shift the EES reaches −60 dB limit. On the other hand, the sensitivity of the ϕ-scanning scheme (not shown here) is very small: the total phase shift of 25° is necessary to reach the −60 dB EES limit.
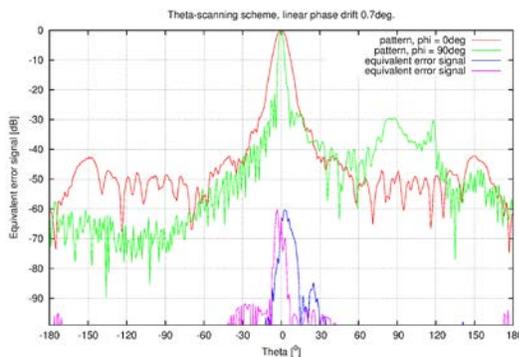
Figure 5. VAST-12, z-axis pointing, θ-scan, 0.7° phase shift.

This behavior is explained by recalling that in the ϕ-scanning scheme, the main beam (pointing along z-axis) is scanned within the first few scans and thus rather large phase changes are necessary to produce an error. In the θ-scanning scheme, the main beam is crossed in every scan and thus the changing phase results in a discontinuity between the first and the last scans, which should be rather small for the given

allowed error level. The results for the 5° rotated main beam (not shown here) have shown even higher sensitivity for the θ-scanning scheme: only 0.25° total phase shift is allowed.

At 50 GHz with 6 mm wavelength the 0.25° phase shift corresponds to the feed longitudinal displacement of: 6mm/360°·0.25° = 0.004 mm = 4 μm. This result is significantly larger than the 1 μm obtained from GRASP simulations, since the effect of the near-field phase change reduces after the near-to-far-field transformation.

VII. Conclusion

A multi-band millimeter-wave VAST (mm-VAST) antenna covering K/Ka/Q/V-bands is currently under development in collaboration between DTU and TICRA under contract from the European Space Agency. A detailed set of electrical and mechanical requirements was established to ensure maximum value of the mm-VAST antenna for facility comparison and validation. The electrical baseline design is based on a single offset reflector antenna fed by a cluster of four Potter horns, one for each of the four frequency bands. A preliminary mechanical end thermal tolerance study has shown that the feed position should not change more than some 4-5 μm. It is planned to use a carbon fiber reinforced polymer, CRFP, for manufacturing the support frame of the mm-VAST antenna in order to achieve the required mechanical and thermal stability. The detailed electrical and mechanical designs are currently on-going at DTU and TICRA, while manufacturing is planned for the winter 2014-2015.

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