Optimizing the Cross Polarization Performance of a Compact Test Range by Conjugate Matched Field Concept

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***Abstract*—Single reflector and dual cylindrical reflector Compact Test Ranges (CTRs) are well known for having a high cross-polarization level in the quiet zone (QZ), limiting their measurement performance. A new three element feed array is developed. By adding two adjacent open waveguide antennas a conjugate matched field is generated leading to a superposed field in the QZ, having lower cross-polarization level. The ideal excitation values for each element is calculated by a nonlinear, numerical optimization, which also considers the limited performance of the experimental feeding network. A validation of the feed array concept is done by field probe scans in the CTR of the German Aerospace Center (DLR), showing an improvement of better than 8 dB over 900 MHz in the X-band.**

***Index Terms*—Antenna Measurement, Compact Range, Cross Polarization Optimization**

I. INTRODUCTION

The Microwaves and Radar Institute at the German Aerospace Center (DLR) operates a Compact Test Range (CTR) for antenna and radar cross section measurements. The CTR's principle bases on two parabolic, cylindrical reflectors, shown in Fig. 1 [1]. Its co-polar performance is extensively analyzed in [2], but not the cross-polarization properties. With the ongoing research in full polarimetric radar systems, the cross-polarization of the CTR is a topic of increasing interest. It limits the capability of measuring antennas with a high cross-polarization suppression, since there is limited dynamic.

Except for compensated CTRs, the offset geometry causes a depolarization of the field distribution in the aperture, even if the feed antenna is purely polarized. For double curved reflector antennas this is proven analytically in [3]. A similar behavior is found for dual parabolic, cylindrical systems, like the CTR at the DLR. The influence of this type on the depolarization is studied extensively in [4]. Similar as for double curved parabolic systems an increase in the offset angle, see γ in Fig.1, is directly related to a higher cross-polarization in the quiet zone (QZ).

The QZ is the area in the CTR, where the co-polar field has plane phase fronts and a uniform amplitude. The same properties as in true far field appear and the antenna under test (AUT) is placed in this area. Contrarily the generated cross-polarization is not distributed uniformly in the QZ and it is increasing, especially along the y-direction. In the symmetry plane (xz-plane in Fig. 1) of the chamber no depolarization occurs, but towards greater distance from the origin, the cross-polarization is getting higher. As a consequence, small AUTs can be measured with high cross-polarization purity in the xz-plane. The cross-polar measurement of large antennas is error prone, since the complete QZ is not cross-polarization free. Same holds true for AUTs, which do not allow a placement in the symmetry plane, like complete satellite systems with multiple antennas.

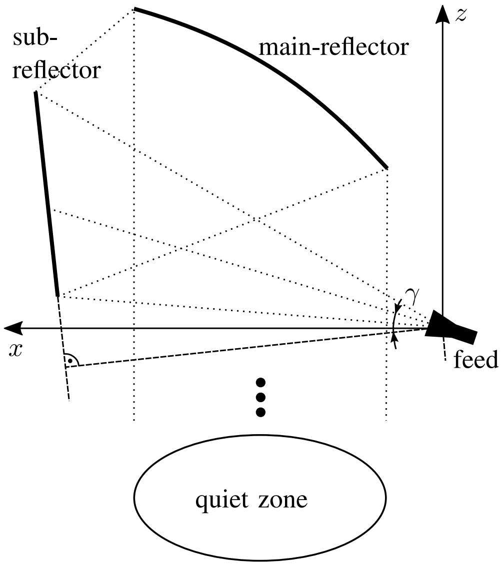

Fig. 1. Geometry of the CTR, adapted from [4].

The paper presents the development of a new feed array antenna for the CTR at the DLR, which reduces the cross-polarization level in the QZ. It is capable of generating horizontal and vertical polarized fields and bases on the conjugate matched field principle, which is described in section II. The weighting factors for the individual array elements are calculated via nonlinear optimization. All theoretical considerations are validated by field probe measurements.

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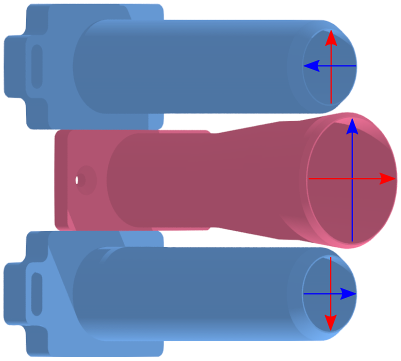

Fig. 2. Drawing of the new feed array, the colored arrows indicate the direction of polarization, blue is vertical polarized.

II. COMPENSATION TECHNIQUES

Reducing the cross-polarization level can be achieved by postprocessing techniques, like presented in [5]. It requires additional correction data, gathered by simulations or field probe measurements. Drawbacks are the additional processing and a limited accuracy.

A second method of compensation technique is the conjugate matched field concept. If the CTR is fed by an antenna with a circularly symmetric radiation pattern, the cross-polarization in the QZ is exclusively generated by the offset geometry. The cross-polar radiation pattern of the feed is modified, that it cancels out the offset-generated cross-polarization, by destructive interference. In [6] it is suggested to use special formed polarization grids in front of the feed, to ensure the desired compensation. It is not possible to use the same grid for horizontal and vertical polarization.

The conjugate matched field can be generated directly by the feed itself. For single reflector systems this was proven successfully in [7] by a so called tri-mode feed horn. A major drawback is the limited bandwidth. This limitation is overcome in [8], by using a linear three element array, where two outer elements generate the conjugate matched field.

III. CONJUGATE MATCHED FEED ARRAY

Currently, for measurements in the X-band, a corrugated circular horn is used at the DLR. It causes a high cross polarization level in the QZ. Inspired by the findings in [8] a new feed array is developed for the X-band. It is shown in Fig. 2. The central element generates the co-polar field, while the blue elements are orthogonal polarized to compensate the depolarization. In Fig. 2 the red colored arrows indicate the polarization for the horizontal case, and the blue colored arrows indicate the vertical polarization state.

The conical horn's diameter is a trade off between optimum illumination of the sub-reflector and distance between the outer elements. It is found to be 40 mm, without additional corrugations. The radiation pattern is not perfect rotationally symmetric, but in simulations, and later in measurements, it is shown that the co-polar performance is preserved.

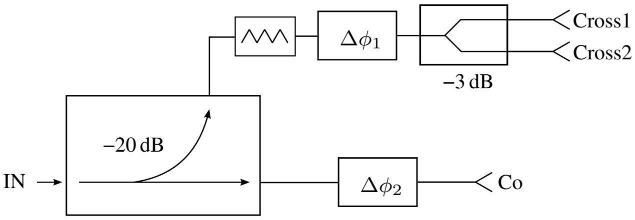

Fig. 3. The schematic of the feeding network.

The outer two horns are used in combination, to generate a monopulse radiation pattern. It matches adequately the distribution of the offset-generated cross-polarization in the QZ. The axial spacing between both elements has a direct influence on the monopulse pattern. It is obtained geometrically and optimized in simulations to 84 mm. Since the distance is significantly larger than the wavelength, the pattern suffers from grating lobes [10]. A circumstance, which needs to be considered in measurements. Both open waveguide antennas have a standardized opening diameter of 23.86 mm.

An optimum excitation of the three elements is ensured by the feeding network, schematically depicted in Fig. 3. For a first proof of concept the complexity is reduced. The simplified design has a direct impact on the broadband optimization, shown in section IV.

IV. NUMERICAL OPTIMIZATION

As a last step in the synthesis of the feed antenna, the weighting coefficients of the excitation is determined. For each feeding signal this is done in amplitude and phase by a numerical optimization. In [9] an application of numerical optimization in antenna synthesis is shown, where the far field pattern is adapted. The same principle is now applied to the conjugate matched feed array: The distribution of the cross-polarization, $s(x, y)$, in the QZ is simulated for each element individually and collected in

$$\mathbf{s}(x,y) = \left[s_{\text{co}}(x,y), s_{\text{cross},1}(x,y), s_{\text{cross},2}(x,y)\right]^{\mathrm{T}}.$$

The near fields are calculated in complex phasor form and therefore $\mathbf{s}(x, y)$ is also complex valued. The individual weighting factors of each element are summarized in

$$\mathbf{w} = \left[w_{\text{co}}, w_{\text{cross},1}, w_{\text{cross},2}\right]^{\mathrm{T}} \in \mathbb{C}^{3\times 1}.$$

Based on the definitions the general optimization problem is formulated

$$\begin{aligned} \min_{\mathbf{w}} \quad & \text{mean}\left\{\left|\mathbf{w}^{\mathrm{T}}\mathbf{s}(x,y)\right|\right\} \\ \text{s.t.} \quad & |w_{\text{co}}| = 1, \\ & |w_{\text{cross},1}| = |w_{\text{cross},2}|. \end{aligned} \tag{1}$$

It corresponds to minimizing the arithmetic mean of the cross-polarization level. For side constraints the amplitude exciting the central horn is normalized to 1 W. Additionally, both outer horns must have the same amplitude. Equation (1) is a nonlinear optimization in three variables.

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The optimization problem is solved numerically by an algorithm based on the interior points method. In [9] the problem statement is strictly convex, ensuring the calculated local minimum is a global minimum. For (1) this is not generally the case, since it strongly depends on the near field distribution, $\mathbf{s}(x, y)$. A nonconvex optimization means that the minimum found by the algorithm is not necessary global. This can be overcome by choosing an adequate starting point. By applying a priori knowledge from the simulated cross-polarization it is ensured that the optimization algorithm is iterating towards the global minimum.

The previous presented optimization is only valid for a single frequency point. In order to have a compensation over a larger bandwidth the limitations of the feeding network in Fig. 3 must be considered:

For all frequency points in the X-band the optimized phase difference between both outer horns is approximately 180°. This value is ensured frequency independent, by rotating the coax to waveguide transition of both outer horns contrarily. A second limitation is the fixed attenuation, which allows only a constant value for $|w_{\text{cross},1}|$ and $|w_{\text{cross},2}|$ over frequency. It is calculated by averaging the optimized amplitudes over the X-band. The use of discrete attenuators permits only a stepwise variation of $|w_{\text{cross},1}|$ and $|w_{\text{cross},2}|$. The phase shift in the network is performed by varying the length of transmission lines. It is well known that the phase of such elements is a linear function over frequency. Therefore the optimized values for phase$(\mathbf{w}_{\text{co}})$ are approximated by a linear regression.

V. RESULTS

A proof of concept demonstrator is build to validate the performance in the CTR of the DLR. It is manufactured in the institute's mechanical laboratory. The distance between the outer horns can be adjusted arbitrarily, allowing a fine tuning for a specific frequency. In Fig. 4 the finalized prototype is shown.

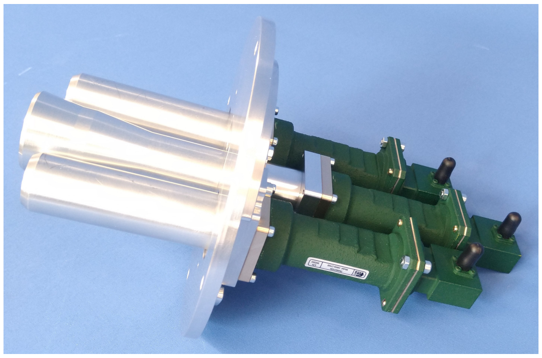

Fig. 4. The manufactured feed array.

In the following, the measurement results of the conjugate matched feed are presented, exemplary for horizontal polarization. Applying the numerical optimization in section IV gives for $|w_{\text{cross},1}|$ and $|w_{\text{cross},2}| = 1.16\,\text{mW}$ (compared to $|w_{\text{co}}| = 1\,\text{W}$). The properties of the feeding network do not allow an adjustment for the optimized phase distribution, phase(w_{co}). It is adjusted to provide best suppression around 10 GHz.

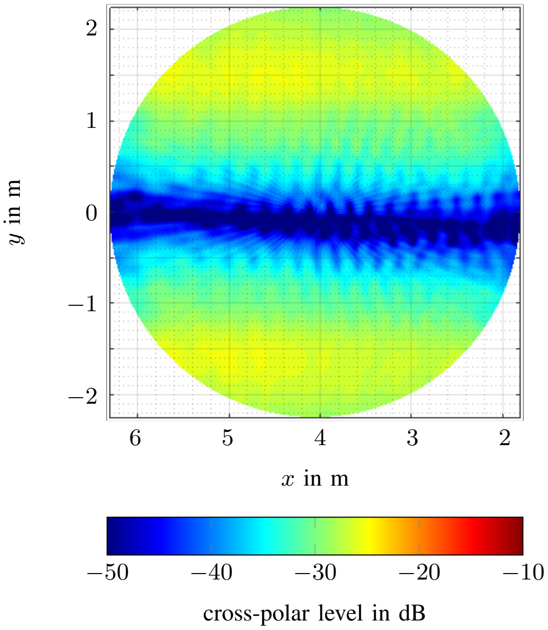

Fig. 5. The measured cross-polarization with the reference corrugated feed.

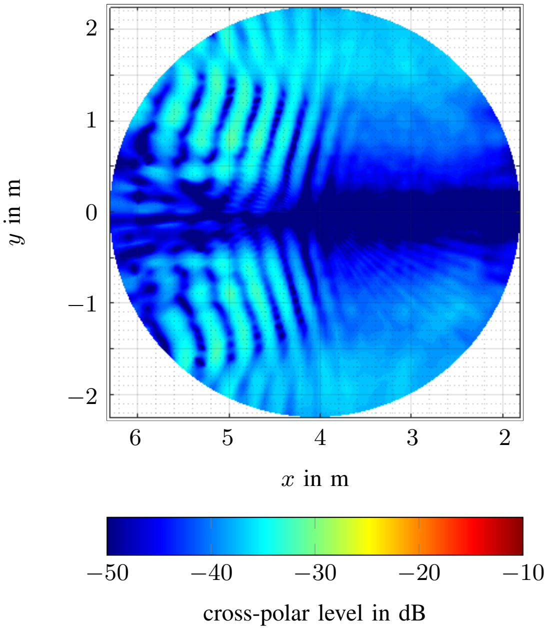

Fig. 6. The cross-polarization resulting from the conjugate matched feed.

By scanning the QZ with a standard gain horn, the concept is validated. For comparison first the CTR is fed with the currently used corrugated horn. The corresponding cross-polarization suppression is shown in Fig. 5. Inside the QZ the mean cross-polar level is −32.4 dB. The optimized conjugate matched feed's performance is visible in Fig. 6, having a mean cross-polar level of −41.8 dB. In both plots the co-polar field is

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horizontal polarized and at a frequency of 10 GHz. Especially towards the upper and lower edge of the QZ the improvement due to the conjugate matched field clearly visible. The unwanted illumination of the main reflector, is suppressed in both figures by a software time-gating. Additionally, in Fig. 5 an appropriate impedance wall is installed.

An effective suppression in the cross-polar level is achieved from 9.8 GHz to 10.7 GHz. This is a direct consequence of the limited performance of the feeding network. In simulation, where the optimum linear regression curve for phase(w_{co}) is applied, the cross-polarization is effectively reduced in the entire X-band.

For the relative comparison of the measured data only the so called "random measurement errors, repeatability" has to be considered [11]. Especially the accuracy of both rotational axes of the positioning system has an substantial impact on the uncertainty. Giving the theory this simplified approach gives an uncertainty of the cross-polar level of better than −59 dB.

VI. CONCLUSION

A method of reducing the cross-polarization for the CTR at the DLR, by a new developed conjugate matched feed, is presented. The feed consists of three individual antennas, their excitation values are calculated via nonlinear, numerical optimization. The results, obtained by field probe scanning, show an improvement of better than 8 dB over a bandwidth of 900 MHz in the X-band.

Further steps include, the development of a more sophisticated feeding network. This allows to extend the bandwidth over the entire X-band, like proven in several simulations. Additionally a convenient impedance wall will be designed, to reduce the parasitic illumination, without need of short time-gate. Finally the concept will be validated by measurements for the vertical polarized case as well.

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