Design and Verification of Cross-Polarization Compensation Feed for Single Reflector Compact Antenna Test Range over a Wide Bandwidth

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Abstract— **Measurement applications using a Compact Antenna Test Range (CATR) often require low cross-polarization or high polarization purity of the Quiet Zone (QZ). This requirement is often the main motivation for choosing the more complex and thus expensive compensated dual reflector system as opposed to the simpler and cheaper single reflector system. In this paper, a novel wide-band, conjugate matched feeding concept is presented. The concept aims at the cancellation of the geometrical optics cross-polar component in the QZ of a single reflector CATR. The concept is valid for both side and edge fed configurations of the CATR in dual simultaneous polarizations.**

The conjugate matched feeding concept, suitable for a standard CATR system, is described in detail and the cross-polarization cancellation properties of the proposed wide-bandwidth feed system is discussed. The concept is initially verified and the solution consolidated using numerical simulation of the reflector and full wave simulation of the feed system. The achievable wide-band cross-polar discrimination of 40dB in the QZ is confirmed on an operational bandwidth of 1:1.5. The conjugate matched feeding concept is then validated by a reduced hardware demonstrator and measurements. The target cross-polar discrimination of 40dB is confirmed by QZ probing of a standard single reflector CATR system.

Keywords— Compact Range, Quiet Zone, Cross Polarization Compensation

I. INTRODUCTION

Antenna measurement accuracy in CATRs depends on the amplitude and phase uniformity of the Quiet Zone (QZ) field and its polarization purity. It is well known that offset parabolic reflector systems induce undesired cross polarized field degrading the quality of the measurement [1-2]. Other than reflector geometry adjustment, different options have been presented in the literature to improve the cross polar performance of the single reflector CATR [3-6].

One such solution is the insertion of a polarization selective grid between the feed and the reflector. The layout of the curved strip grid is determined by the geometry of the reflector and each polarization has a different shape. This approach was demonstrated to provide QZ cross-polar performances similar to the dual reflector system on a decade bandwidth. The drawback of this solution is that orthogonal polarization components cannot be measured simultaneously since a different polarizer grid is required for each polarization [3-4].

Other techniques, based on measurement post processing, aim at improving both amplitude/phase taper and cross polarization. Processing techniques are based on numerical modeling of the range [5] or by de-convoluting the measured pattern with a predetermined range response based on QZ probing [6]. The drawback of these methods are the finite accuracy of the post processing, increased measurement complexity and the difficulty to measure active antenna systems.

Recently, the application of conjugated matched feeds for cross-polar reduction in space application have received attention in the literature [7-12]. Various solutions have been devised to excite conjugate field matching. Recognizing, that the cross polar contribution induced by the offset reflector geometry has a focal plane distribution very similar to the higher order modes in feed horns, various techniques have been devised to excite compensating feed modes. Although a very elegant technique, the drawback is that the feed polarization must be constrained by the offset reflector configuration, therefore the cross-polar compensation is possible only for one polarization using this kind of approach and the achievable bandwidth is limited.

A different concept of conjugated matched excitation, overcoming the dual polarization and partially the bandwidth limitations, has been introduced in [13-14] based on a patch array feed system. However, this implementation is aimed at applications with different beam-width in the principle planes.

In this paper, we propose a conjugate matched array of 3x1, dual-linearly polarized elements designed to achieve cross-polar compensation in a standard single reflector CATR for both polarizations. The central element of the array, produce the co-polar component radiation in the QZ, while the two side elements, suitably excited, provide the cross-polar cancellation. Since the cancellation principle is enforced by the array geometry, the cancellation can be achieved on a much larger bandwidth than what can be achieved by a single matched feed.

II. OFFSET PARABOLIC REFLECTOR CROSS POLARIZATION

In offset parabolic reflector systems, the cross polarization proprieties can be predicted using Geometrical Optics (GO) theory [2]. If the polarization is defined according to Ludwig's third definition [1], the secondary cross-polar pattern of a parabolic reflector antenna that is illuminated by a linear polarized source, arise from the asymmetry of the primary pattern with respect to the principal planes of the secondary field polarization references. In fact, it is well known that the parabolic reflector antenna either in off-axis or on-axis configuration, will not induce cross polarization if both of the following conditions are satisfied:

- Primary rotationally symmetric radiation pattern;

- Feed axis coincident with the axis of the reflector.

If the first condition is not fulfilled, the feed will have an associated cross-polar component resulting in a reflected cross-polar component of the secondary field. Unfortunately, feeds with a perfect rotationally symmetric radiation and thus very low cross polar in wide view angles are very hard to achieve. The optics of most CATR are thus also designed to reduce the primary cross-polar component intercepted by the reflector.

If the second condition is not fulfilled, the offset angle between the feed axis and the axis of the reflector will lead to asymmetry of the primary radiation pattern and the reflector will induce a secondary cross polar component. Assuming that the polarization reference vector of the feed and secondary co-polar component are either parallel or orthogonal to the plane of reflector symmetry the cross polarization distribution in the plane of the reflector can be described as in Fig. 1. The reflector depolarizes the incident co-polar field into a rotated field vector related to the secondary co-polar component reference vector [1].
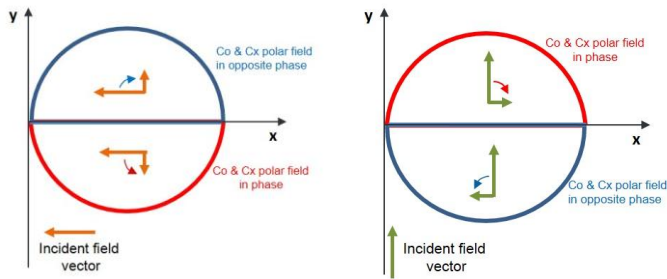

Fig. 1. Illustration of depolarization in offset reflector due to offset angle between the feed axis and the axis of reflector (contained in the xz-plane)

As shown in Fig. 1, there is no depolarization effect in the symmetry plane of the geometry but the depolarization increase along the orthogonal plane. Moreover, the secondary field vector of both principal components rotates in opposite sense with respect to the plane of symmetry. Consequently, the co-polar components and the cross-polar component (due to the offset) are in phase on one side of the plane of symmetry and in opposite phase on the other side.

III. THE CONJUGATE MATCHED FEED ARRAY

The proposed conjugate matched 3x1 element feed array consist of two types of elements, the cross-polarized radiators, referred to simply as "cx-feeds", which produce the conjugate field matching and a central element referred to as "co-feed" producing the Co-polar field component. The cx-feeds are aligned orthogonally to the plane of symmetry of the reflector with the same focal offset. The proposed array configuration is shown in Fig. 2. The concept can be used in both side fed and edge fed CATR configurations.
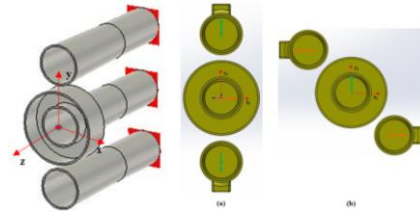

Fig. 2. Conjugate matched feed array consisting of two side elements and a central element. Feed coordinate reference system with origin in the focal point. a) Side-fed CATR configuration. b) Edge-fed CATR configuration.

The conjugate feed array concepts is illustrated on a common single reflector, side fed, CATR configuration using Physical Optics (PO) calculation on the reflector and full wave simulation of the feed(s). The calculated QZ cross polar discrimination with and without the proposed conjugate feed array concept is shown in Fig. 3. The results are similar for either of the two polarization components.

If the cx-feeds are excited in opposite phase and with optimum attenuation X_{dB} with respect to the co-feed, primary cross polar field is generated to match exactly in amplitude the unwanted cross-polarization induced by the reflector geometry. From the phase distribution of the cross polar field, induced by the offset and the array factor formula, in can be seen that a ±90° phase shift is required between co-feed and cx-feeds for achieving the conjugate matching condition. The right image in Fig. 3 show the achievable cross polar discrimination of the QZ with optimum amplitude and phase excitation of the cx-feeds.
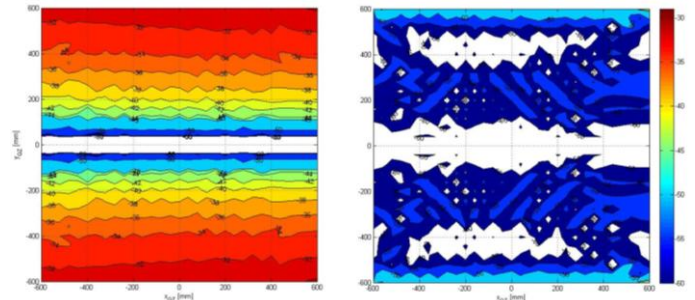

Fig. 3. (*Left*) Example of the typical cross polar discrimination in QZ due to reflector offset. (*Right*) Cross polar discrimination in QZ using the proposed 3x1 conjugate matched feed with optimum excitation.

IV. IMPLEMANTATION IN A STANDARD SINGLE REFLECTOR CATR SYSTEM AND COMPUTATIONAL CONSIDERATIONS

The achievable performance and ease of implementation of the proposed feed system in a standard single reflector CATR is investigated using the Orbit/FR AL-24404. This system consist of a standard offset, side-fed, single reflector with serrated edges. The system is scalable to different dimensions depending on the desired size of the QZ. The solid model and the reference coordinate systems are shown in Fig. 4. In this example, reflector dimensions of 1.6m diameter, serrations of 0.7m have been considered providing a cylindrical QZ region of about 1.2m diameter. The feed polarization reference vectors are defined according to the feed x_f-axis (H) and y_f-axis (V).
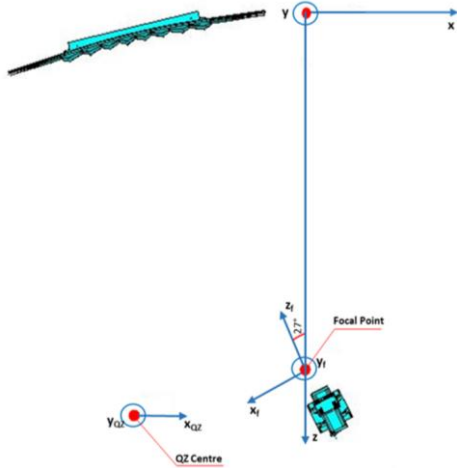

Fig. 4. Relative dimensions of Orbit/FR AL-24404 single reflector, side fed, CATR with indication of feed, reflector and QZ coordinate systems.

Computational tools based on Physical Optics (PO) and Method of Moments (MoM) have been used in the QZ performance analysis of the serrated edge reflector. In the PO modeling, the impact of the edge serrations of the reflector can be approximated by a proportional attenuation of the induced currents to the area of the serrations. The PO approach leads to a very rapid calculation of the QZ fields. This approximation was validated comparing PO results with the more accurate full-wave MoM calculation of the complete CAD geometry of the reflector [15].
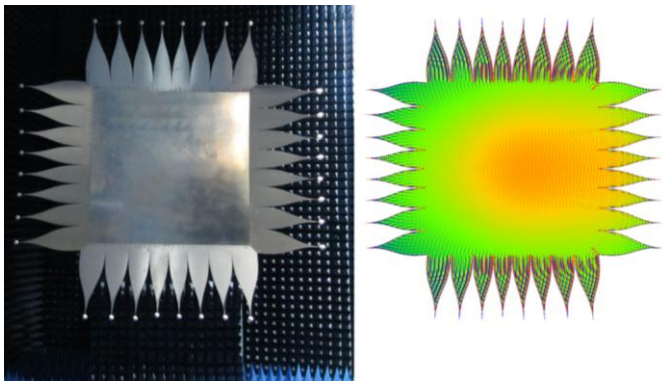

Fig. 5. (*Left*) Orbit/FR AL-24404 single reflector with serrated edges. (*Right*) Plot of induced currents using MoM calculation @ 10GHz.

An image of the Orbit/FR, AL-24404 installed in the Orbit facility in Israel (Left) and a plot of the total reflector current distribution determined by full-wave MoM calculation (Right) is shown in Fig. 5. The calculation has been performed at 10GHz using a standard illumination feed and polarization along the symmetry plane of the reflector. The effect of the edge serrations are clearly visible in the current distribution.

The predicted QZ co-polar field using full-wave MoM calculation and the faster PO approximation is compared in Fig. 6. Similar results have been found for the cross-polar correlation. The correlation in the 1.2m diameter QZ between the two numerical techniques confirm the validity of the PO approximation, allowing to use the faster PO approach in the synthesis and optimization of the conjugate matched array.
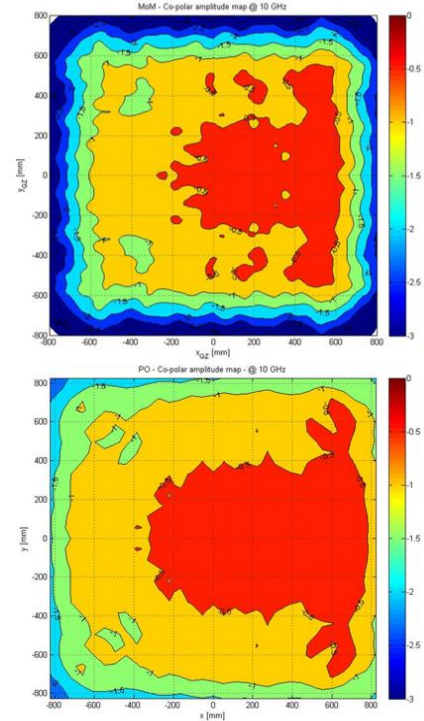

Fig. 6. (*Top*) MoM calculation of the QZ Co-polar field. (*Bottom*) prediction of the copolar QZ field using the PO approximation @ 10GHz.

V. SYNTHESIS OF THE MATCHED FEED 3x1 ARRAY AND PERFORMANCE PREDICTION

The dimensions of the three element feed array of Fig. 2 was optimized for the standard geometry of the Orbit/FR AL-24404, considering dual polarization operation and an operative bandwidth of 10-15 GHz. The array has been dimensioned using CST MWS [16] considering an ideal waveguide feeding. Array factor considerations of the 3x1 array show that the effectiveness of the cross polarization compensation, degrade if the inter-element distance, D, between the cx-feeds, does not satisfy the upper bound:

$$D \le \lambda / (2 \cdot sin\ (\theta_0)) \qquad (1)$$

In (1) λ is the operative wavelength and θ_0 is the angle of semi-view of the portion of reflector projected from the QZ region. The above constraint on the cx-feed spacing constitutes

the upper limit of the size of the co-polar aperture. Since the cx-feeds compensate the cross-polar induced by the off-set geometry but not the cross polar component from the co-feed, the polarization purity of the co-feed should be sufficient to avoid significant cross-polar field in the QZ region. A single choke conical horn is therefore the ideal compromise between performance and physical size of aperture as shown in Fig. 2. The Co-polar component arising from cross polar radiation from the cx-feeds gives an insignificant contribution to the QZ Co-polar ripple and this effect can be ignored in the design phase. By eliminating the choke on the cx-feeds the inter-element distance, D, can be further reduced to increase the bandwidth of the final array. The optimum dimensions of the 3x1 element array for the considered geometry are summarized in Table I.

TABLE I. OPTIMIZED DIMENSIONS OF THE 3X1 ELEMENT DEMONSTRATOR

Dimensions (mm)	Co-feed	Cx-feed
Aperture inner diameter	21.0	21.0
Choke inner diameter	39.2	x
Inter-element distance (D)	x	70.0

Since cross-polarization due to the reflector offset is a Geometrical Optics (GO) effect, the required phase of the cx-feeds for cross polar cancellation is constant +90°/ -90° with frequency. However, the optimum amplitude X_{dB} of the cx-feeds is frequency dependent and decreases linearly with frequency. Considering an external feeding network as shown in Fig. 7 a compromise between cancellation efficiency and achievable bandwidth must be sought.
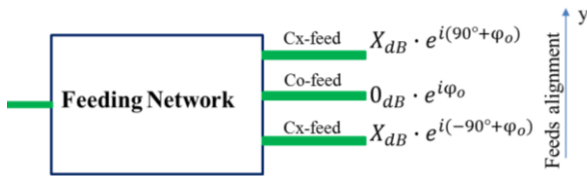

Fig. 7. Model of the feeding network. A separate feeding network is needed for each polarization.

Good Co-polar field performances has been obtained for the final array across the band. The distribution of the Co-polar field amplitude and phase in the QZ is shown in Fig. 8
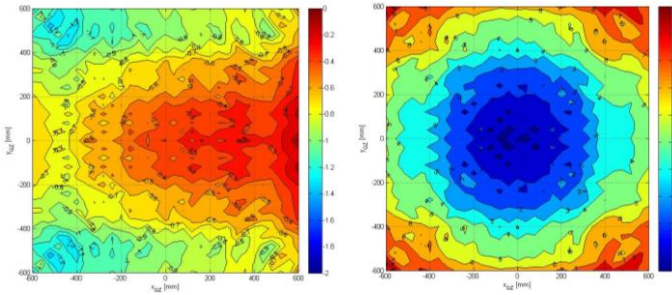

Fig. 8. Co-polar amplitude and phase distribution of the QZ @12.5 GHz. Final 3x1 array. PO calculation and full wave array simulation.
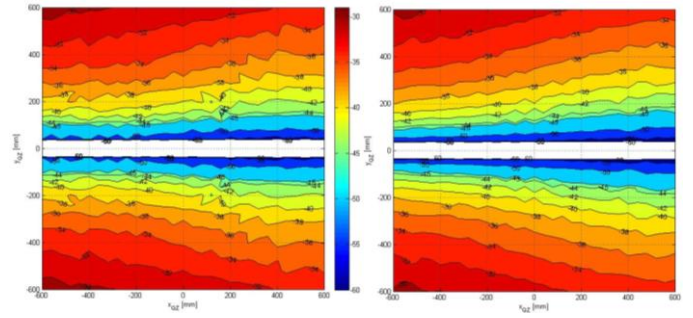

Fig. 9. Cx-polar, QZ discrimination @12.5 GHz before compensation, Horizontal (*Left*) and Vertical (*Right*).

The Cx-polar QZ discrimination before compensation are shown for both Vertical and Horizontal polarization in Fig. 9. The worst case Cx-polar levels are close to 30dB below peak Co-polar levels. Using a fixed amplitude value of -34dB and +90°/-90° phase for each of the cx-feeds, the cross-polar performance of the QZ improves dramatically in the entire 10-15GHz bandwidth for both polarizations as shown in Fig. 10 and Fig. 11 for 10GHz and 15GHz respectively. The worst case cross-polar in the QZ is 40dB below the Co-polar field levels. An improvement of close to 10dB has been achieved.
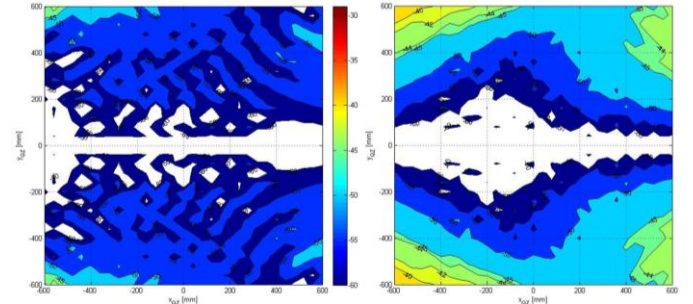

Fig. 10. Cx-polar, QZ discrimination @10 GHz after compensation, Horizontal (*Left*) and Vertical (*Right*).
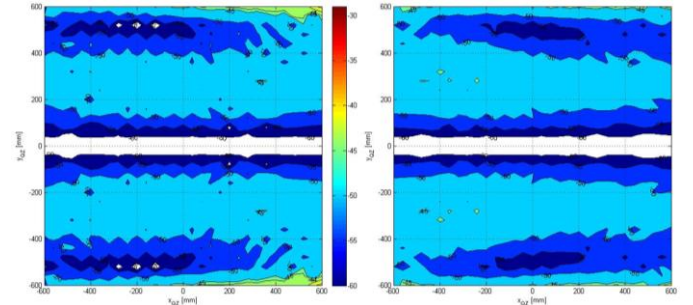

Fig. 11. Cx-polar, QZ discrimination @15 GHz after compensation, Horizontal (*Left*) and Vertical (*Right*).

VI. PROOF-OF-CONCEPT DEMONSTRATOR

A proof-of-concept conjugated matched feed array was designed and manufactured following the guidelines discuss in this paper. Due to the simplified feeding of the demonstrator, based on the very basic, unbalanced feeding scheme of the elements, the target bandwidth of the demonstrator was reduced to 10-12.5 GHz. The demonstrator was designed for

horizontal polarization only. A mechanical model and image of the final demonstrator is show in Fig. 12.
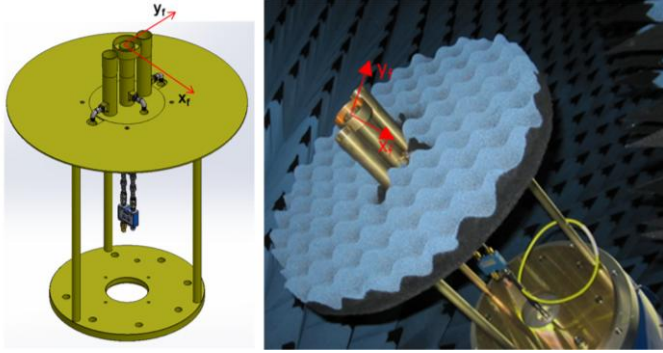

Fig. 12. Mechanical model and image of the proof-of-concept demonstrator with details of the feeding network assembly.

A sensitivity analysis of feeding errors, using the simulated far-field patterns of the demonstrator was performed. It was shown that cross polarization compensation level below -40dB require a max ±0.6dB amplitude excitation errors or ±3° phase shift error between co-feed and cx-feeds across the operational bandwidth. Cross polarization degradation will also occur in the case that cx-feeds are not excited exactly in counter-phase but with an error of ±3° phase error.

The predicted performance of the demonstrator using both PO and MoM simulation and based on a full wave simulation of the 3x1 element array taking into account the measured errors of the BFN is shown in Fig. 13. Both methods confirm that the target cross polar discrimination of 40dB can be meet in the QZ. The minor differences between the predictions show that the Geometrical Optics cross polar component of the reflector has been cancelled very effectively by the demonstrator. The remaining QZ cross polar contributions, more notable in the MoM simulation are probably due to diffracted fields from the serrations.
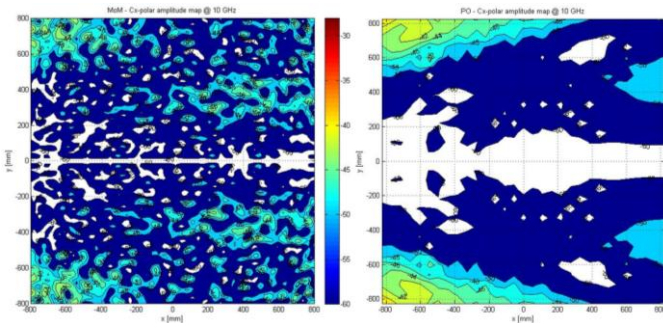

Fig. 13. Cx-polar, QZ discrimination @10 GHz. MoM and PO prediction using the measured performance of the 3x1 proof of concept demonstrator. MoM analysis (*Left*) and PO analysis (*Right*).

VII. VALIDATION OF PROOF-OF-CONCEPT DEMONSTRATOR

The demonstrator was tested in the Orbit/FR, AL-24404, standard, side fed, single reflector CATR system installed in the Orbit facility in Israel as described in paragraph IV and shown in Fig. 14. The side-fed, serrated edge reflector is shown on the left. The proof-of-concept demonstrator and the linear slide for QZ probing are shown on the right.
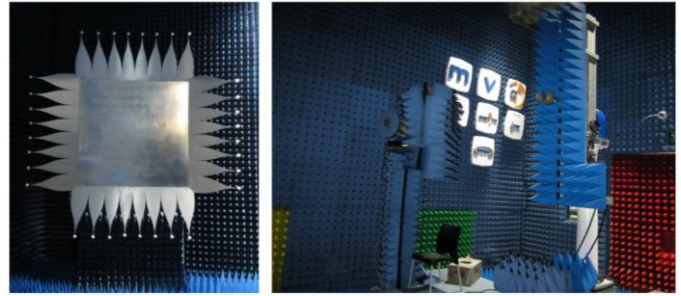

Fig. 14. Orbit/FR, AL-24404, standard, side fed, single reflector CATR system installed in the Orbit facility in Israel.

The reference cross polar performance of the QZ in the Orbit/FR, AL-24404 was determined using the central feed of the demonstrator. This feed has very similar performance to the standard feed used with this system. Using the proof-of-concept demonstrator the QZ probing was repeated. Contour plots of the QZ probing @ 11GHz with and without cross polar compensation are compared in Fig. 15.
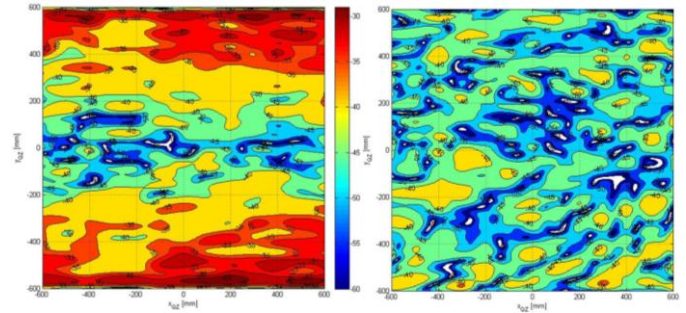

Fig. 15. Contour plots of the QZ cross polar discrimination @ 11 GHz with (*Right*) and without (*Left*) the cross polar compensation.

The improvement of the QZ cross polar performance with the demonstrator is more evident on the vertical cut through the QZ @ 12.5 GHz shown in Fig. 16.
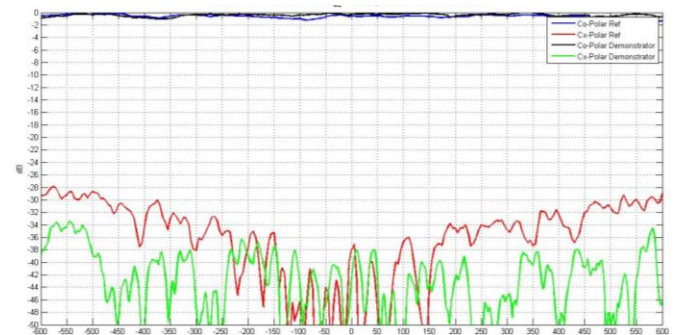

Fig. 16. QZ cross polar discrimination @ 12.5 GHz. Vertical cut in the QZ with (*Green*) and without (*Red*) the cross polar compensation.

VIII. Conclusion

A novel wide-band, conjugate matched feeding concept for common single reflector CATR has been presented. The concept consist of a central Co-polarised feed and two side feeds operating in cross polarisation. The concept aims at the cancellation of the geometrical optics cross-polar component in the QZ of the single reflector CATR by taking advantage of the array characteristics of the two side elements. Since the cancellation principle is enforced by the array geometry, the cancellation can be achieved on a much larger bandwidth than what has been achieved previously.

The proposed matched feed has been designed for standard CATR and can be scaled to arbitrary range dimensions depending on the required QZ. It has been proved by full-wave numerical analysis of the conjugate matched feed array and suitable prediction techniques for the reflector, that QZ cross polar discrimination of 40dB can be achieved across a 1:1.5 bandwidth. This is an improvement of up to 10dB with respect to the reference single feed performance. The performance can be achieved for simultaneous principal polarization use and in both side and edge feed configuration of the CATR.

A reduce scope hardware demonstrator has been designed and manufactured. The demonstrator has been used in an existing standard single reflector CATR confirming the concept of cross polar reduction in the QZ.

IX. Acknowledgements

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