A Hybrid Antenna Pattern Synthesis Method for the Polarimetric Atmospheric Imaging Radar (PAIR)

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***Abstract*—Polarimetric Phased Array Radar (PAR) technology is a candidate radar architecture capable of providing rapid volumetric weather observations. In this paper, we present a hybrid optimization method for synthesizing phase-only PAR beam patterns using individually measured antenna element patterns to account for practical antenna performance. We investigate a phase-only pattern synthesis method for the C-Band Polarimetric Atmospheric Imaging Radar (PAIR) developed at the Advanced Radar Research Center (ARRC). Preliminary results show that the Bézier surfaces can be used to parametrize the phase excitation across the array to synthesize imaging beams. Key results indicate that the synthesis of two independent H/V transmit beams may be needed to maximize mainlobe matching and mitigate co-polar biases in polarimetric weather measurements.**

***Index Terms*—element pattern, pattern synthesis, phased array radar, polarimetric radar, radar imaging**

I. Introduction

Phased Array Radar (PAR) technology is rapidly rising as a candidate technology of future weather radars capable of providing tailored high-quality meteorological observations, needed to advance understanding of atmospheric phenomena. Due to the limited visible region of a single-face planar PAR (typically $\pm 90°$ in antenna-boresight-relative θ and ϕ spherical coordinates), either multiple PAR faces (3 or 4) or mechanical scanning in azimuth are needed to provide full radar coverage. The single-faced Rotating PAR (RPAR) architecture consists of a compromise solution to provide full coverage at a more affordable cost in comparison to a stationary four-faced PAR [1], at the expense of mechanical rotation in azimuth.

Dual-polarization capability has become essential for weather radar observations. It involves the transmission and reception of electromagnetic waves in both Horizontal (H) and Vertical (V) polarizations, which are used to estimate weather radar variables (namely, spectral moments and polarimetric variables). In the Simultaneous Transmit Simultaneous Receive (STSR) mode, adopted by most operational and research weather radars worldwide, the H- and V-polarized waves are transmitted simultaneously to estimate polarimetric variables. However, producing accurate polarimetric weather measurements with RPARs in the STSR mode has been a challenge due to the co- and cross-polar radiation pattern biases induced by the antenna when steering the beam off the boresight [2, 3]. Given that electronic beam steering and digital beamforming (DBF) are RPAR capabilities critical for producing rapid, high-quality, polarimetric observations, these biases must be mitigated.

The C-Band mobile Polarimetric Atmospheric Imaging Radar (PAIR) is being developed by the Advanced Radar Research Center (ARRC) at the University of Oklahoma (OU) with funding from the National Science Foundation (NSF) to produce rapid-update, full-volume, polarimetric observations of meteorological events. The concept of operations for the PAIR radar involves using *radar imaging* in elevation while mechanically rotating the antenna in azimuth [4]. Radar imaging involves synthesizing a wide antenna radiation pattern on transmission to illuminate a large sector and using DBF to simultaneously form multiple receive beams from signals within the illuminated sector [5].

In this paper, we present progress towards a hybrid optimization method for synthesizing beam patterns using phase-only weights driven by the measured antenna embedded element pattern. Phase-only synthesis weights are preferred over magnitude weights to maximize transmit power. A combination of phase and constrained magnitude (to control the gain loss) weights could also be considered. Smooth phase excitations across the array are expected to produce low sidelobe levels, and are modeled here using a Bézier-surface

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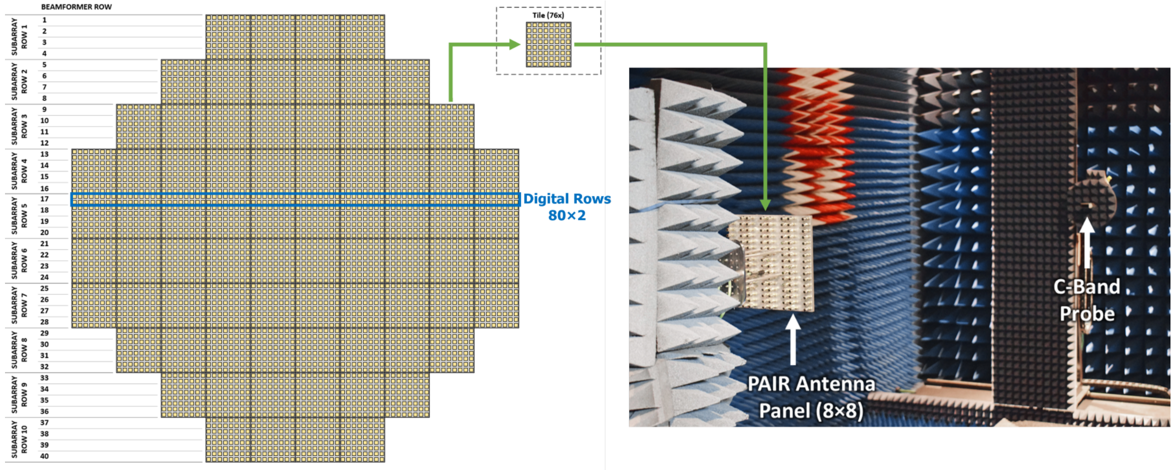

(a) (b)

Fig. 1. (a) PAIR antenna geometry, capable of scanning a broadside pencil-beam with a 1.5° beamwidth. Digital channels are produced for every 2 rows, (b) Back view of the PAIR panel mounted in the anechoic chamber positioner.

parametrization. The goals of the paper are to evaluate if the Bézier surfaces can be used to parametrize the phase of the array excitation to shape the transmit beam, and to investigate the potential for designing independent weights for the H/V channels such that the synthesized beams are matched. This key aspect of the pattern synthesis method proposed could help mitigate copolar-pattern-induced biases in polarimetric weather measurements.

II. The PAIR Antenna

The ARRC was awarded a project by the National Science Foundation (NSF) to design, fabricate, and commission the PAIR radar system [6]. The PAIR antenna is composed of 4,864 active dual-polarization stacked microstrip-patch antenna elements [7] arranged in a rectangular lattice using 8×8 antenna panels to form an approximately circular antenna geometry as illustrated in Fig. 1(a). This arrangement of elements spaced by half wavelength produces a broadside pencil beam with 1.5° beamwidth (the angular width in degrees within which the microwave radiation is greater than one-half of its peak intensity) in azimuth and elevation. The PAIR has 40 digital channels per polarization, one every two rows of elements, which gives the system advanced DBF capabilities. The PAIR concept of operations involves transmitting a wide imaging beam in elevation and digitally forming narrow pencil beams within the transmit, while mechanically rotating the antenna in azimuth, to complete a volume scan in seconds. PAIR is intended to be a shared system with the potential to enable important research findings through rapid observations (∼10-s volumes), critical for observing events such as hail, lightning, microbursts, tornado-producing convective supercells, wildfires, and hurricanes [8].

A. Element pattern measurements

The PAIR antenna element patterns were characterized in the ARRC's precision anechoic chamber using the spherical far-field scan mode. One 8×8 dual-polarization antenna panel was mounted on a positioner that rotates in the spherical coordinate system, for full (two-dimensional) characterization of the element patterns. The setup is illustrated in Fig. 1(b).

The C-band probe used by the chamber scanner received signals transmitted from the PAIR panel. With this setup, the performance of each antenna element was individually measured with $5° \times 5°$ sampling in the spherical system for a total of 64×2 = 128 measurements. While each individual element was being measured, all others were terminated with matched impedances to emulate the behavior of a fully connected panel (although only one element was excited at a time). It is important to note that this setup can only characterize the passive behavior of the antenna, as it does not include the transmit-receive modules, the analog beamformer, and other connectors/attenuators in the signal path to the radar receiver. These effects will be characterized next year after array integration and calibration. Magnitude and phase measurements were obtained for each element at 21 frequencies (5.35 GHz to 5.55 GHz, in steps of 0.1 GHz; centered at 5.45 GHz), and for the co-polar and cross-polar antenna radiation patterns. For example, when transmitting a horizontally polarized wave, the co-polar radiation is in the intended H-plane, and a small level of cross-polar radiation is transmitted in the V-plane (contamination). The PAIR antenna includes novel design techniques (e.g., balanced anti-symmetric feeds) to minimize cross-polar radiation and improve polarimetric weather data quality.

Through digital post-processing, data from corresponding polarizations were properly beamformed and compared to ANSYS HFSS panel simulations to verify the patterns of the PAIR panel. The measured cross-polarization level (with respect to the co-polar peak) at the intended transmit frequency (5.45 GHz) was -50.3 dB on broadside.

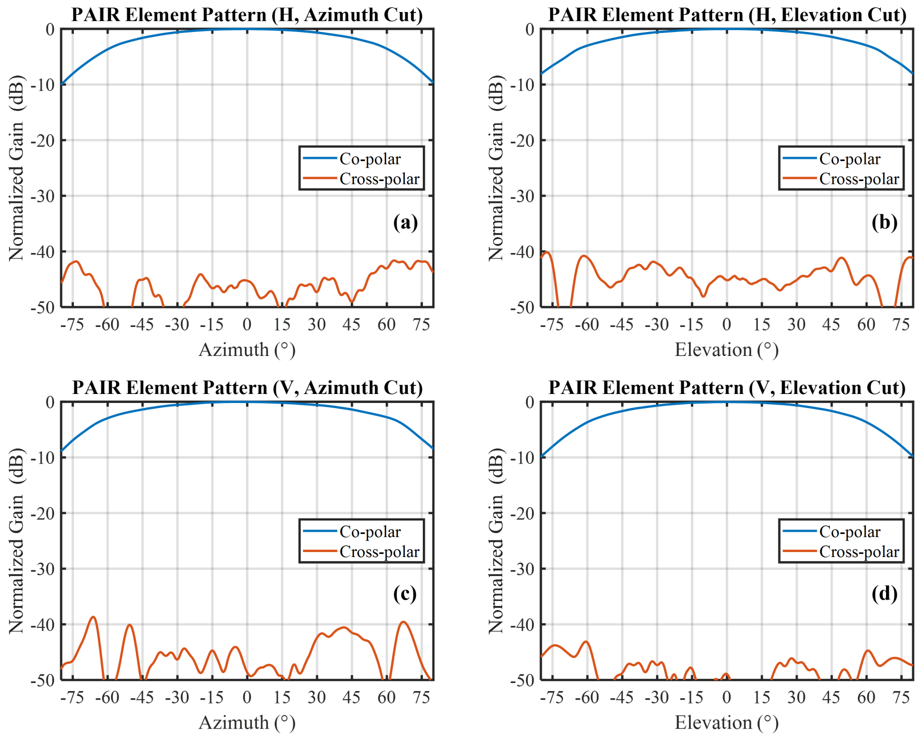

Fig. 2. Estimated PAIR embedded element pattern cuts: (a) and (b) H-polarization, (c) and (d) V-polarization.

B. Derived embedded element pattern

The embedded element patterns are critical to characterize any phased array. Using the individual PAIR element patterns measured, we derived the embedded element patterns of the antenna shown in Fig. 2. Note that these are presented in the Ludwig-2I coordinate system (azimuth/elevation)[9]. These measurements serve as a basis for full array patterns to be calculated. A qualitative comparison of the co-polar patterns (panels *a* and *d* in Fig. 2), indicates good matching between the H and V patterns.

The embedded element pattern also provides key information about cross-polarization levels that can be achieved with the array, which ultimately determines polarimetric-estimation performance. This is especially the case at steering angles away from the array's principal planes, given that cross-polarization levels increase with angle moving away from these planes. The element patterns show cross-polar levels on the order of -40 dB along the principal planes. Normally, these levels are lowered when thousands of elements are arranged in the array, as random phase errors create incoherent interference, producing deeper nulls.

Having individual H and V embedded element patterns allows the prediction of different steered and tapered antenna array patterns, but more importantly, allows modeling the full PAIR array. Using these measurements and the PAIR antenna architecture as described at the beginning of this section, full array pattern are simulated using the procedure outlined in [10].

III. Beam Pattern Synthesis

Through element-level control of the magnitude and phase of transmitted signals, active RPARs allow the synthesis of custom antenna radiation beam patterns on transmission and reception. This capability can be used to produce imaging beams on transmission, to effectively increase the beam coverage. This comes at the expense of increased antenna pattern sidelobe levels, reduced antenna gain, and slightly increased beamwidth, when compared to a two-way pencil beam. It is desirable to use phase-only weights to synthesize the imaging beams and minimize gain loss, especially for relatively low-powered solid-state weather radars. This in turn maximizes system sensitivity, considering that signals received from meteorological scatterers are relatively weak. Various methods have been developed for the solution of the phase only synthesis problem [11], although none have considered design requirements for accurate polarimetric measurements. Further, although it is preferable to use phase-only weights, this may limit the degrees of freedom for beam shaping and the attainable sidelobe levels. A constrained-magnitude and phase synthesis method could also be explored.

The array factor of a planar PAR can be computed as,

$$AF(\theta,\phi) = \sum_{m=1}^{M}\sum_{n=1}^{N} w_{mn} e^{j\alpha_{mn}} e^{-jm\Psi_x} e^{-jn\Psi_y} \qquad (1)$$

where w_{mn} and α_{mn} are the magnitude and phase weights for the element in row m column n, $\Psi_x = kd_x \sin(\theta)\cos(\phi)$, $\Psi_y = kd_y \sin(\theta)\sin(\phi)$, $k = 2\pi/\lambda$ is the wavenumber, λ is the wavelength, d_x and d_y are the element spacings in x and y, and θ/ϕ are the steering angles. We are interested in searching for optimal α_n's, and therefore, $w_n = 1 \, \forall \, n$.

The array pattern can be approximated using the embedded element pattern as,

$$F^{pq}(\theta,\phi) = F_e^{pq}(\theta,\phi)\,|AF(\theta,\phi)|^2 \quad (2)$$

where $F_e^{pq}(\theta,\phi)$ represents the embedded element pattern, and p and q could be either h or v representing the horizontal or vertical polarizations. With the previous expression, we can obtain the four pattern components in the polarization scattering matrix, namely, F^{hh} (co-polar H), F^{hv} (cross-polar H), F^{vv} (co-polar V), and F^{vh} (cross-polar V).

We propose a genetic-algorithm optimization to search for phase weights that produce a synthesized beam with maximum efficiency and meeting a prescribed antenna pattern envelope function. An efficiency metric is introduced as the ratio of the synthesized pattern gain over the pencil-beam gain (i.e., uniform weights) to quantify the synthesis gain loss. A pattern envelope function is designed to control 1) the 3-dB width of the transmit beam, and 2) the expected sidelobe levels as a function of azimuth and elevation in the visible region. The optimization is posed as follows,

$$\min_{\alpha_n \in [-\pi/2, \pi/2)} \quad \mathrm{IC}^2 \quad (3a)$$

$$\text{subject to} \quad w_n = 1, \quad (3b)$$

$$\eta \geq -2 \text{ dB}, \quad (3c)$$

where the integrated contamination (IC) is the volume of the synthesized pattern that exceeds a predefined pattern design envelope, $E(\theta,\phi)$, defined in dB as,

$$\mathrm{IC} = 10\log_{10}\left[\frac{1}{2\pi^2}\int_{-\pi/2}^{\pi/2}\int_{-\pi}^{\pi}\frac{\max\left[F^{hh}(\theta,\phi), E(\theta,\phi)\right]}{E(\theta,\phi)}d\theta d\phi\right],$$

and η is the efficiency factor defined as the beamwidth-normalized ratio of the 3-dB averaged synthesized pattern gain over the 3-dB averaged pencil-beam gain.

Given the relatively large number of antenna elements that would need to be optimized for a planar RPARs, phase weights are parametrized using Bézier surfaces [12]. These surfaces are defined by a small number of "control points" that use Bernstein polynomials as basis functions to produce smooth surfaces over a desired domain. In the proposed optimization, one control point is placed every 4 elements in each array dimension, although this number was arbitrarily set and can be changed. We plan on investigating the best number of control points to use in the future. An example set of phase weights for the PAIR antenna obtained using Bézier surfaces is shown in Fig. 3.

IV. Optimized Transmit Patterns

In this section we illustrate the performance of the proposed optimization to produce phase-only synthesized transmit beams. First, we derive a two dimensional envelope function

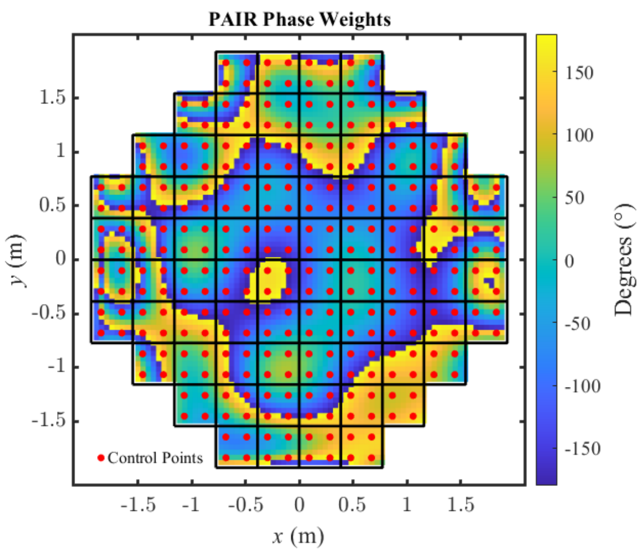

Fig. 3. Example set of phase weights for the PAIR antenna obtained using Bézier surfaces.

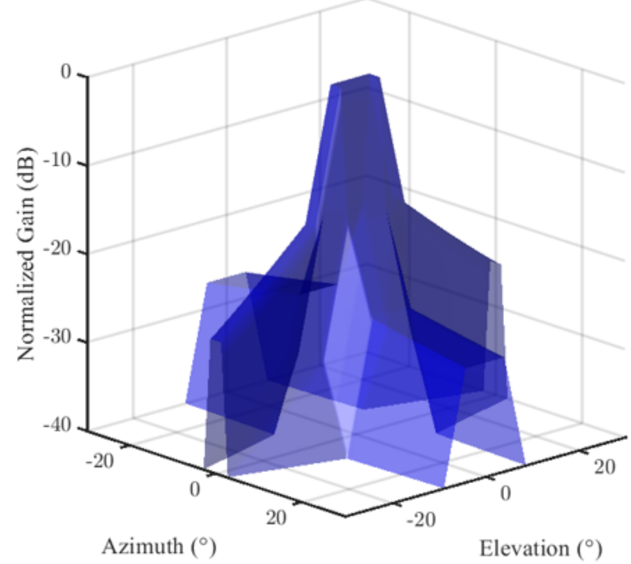

Fig. 4. Example antenna pattern envelope used to design a 10°-wide transmit beam using only phase weights.

to design a beam with a 1.5° beamwidth in azimuth, a 10° beamwidth in elevation, and peak one-way sidelobe levels of -15 dB (shown in Fig. 4).

In search for a feasible solution to the optimization problem posed in (3a), the genetic-algorithm solver converged to feasible solution. The outcome is two-dimensional set of phase weights, which result in the synthesized beam shown in Fig. 5.

A close look at the left plot in Fig. 5 shows a wide transmit beam, with -14 dB and -22 dB sidelobes levels in azimuth and elevation, and a relatively small ripple across the mainlobe peak. Looking at the bottom right panel, it can be seen that the IC of the optimized pattern is not identically zero, as some sidelobes exceed the envelope in

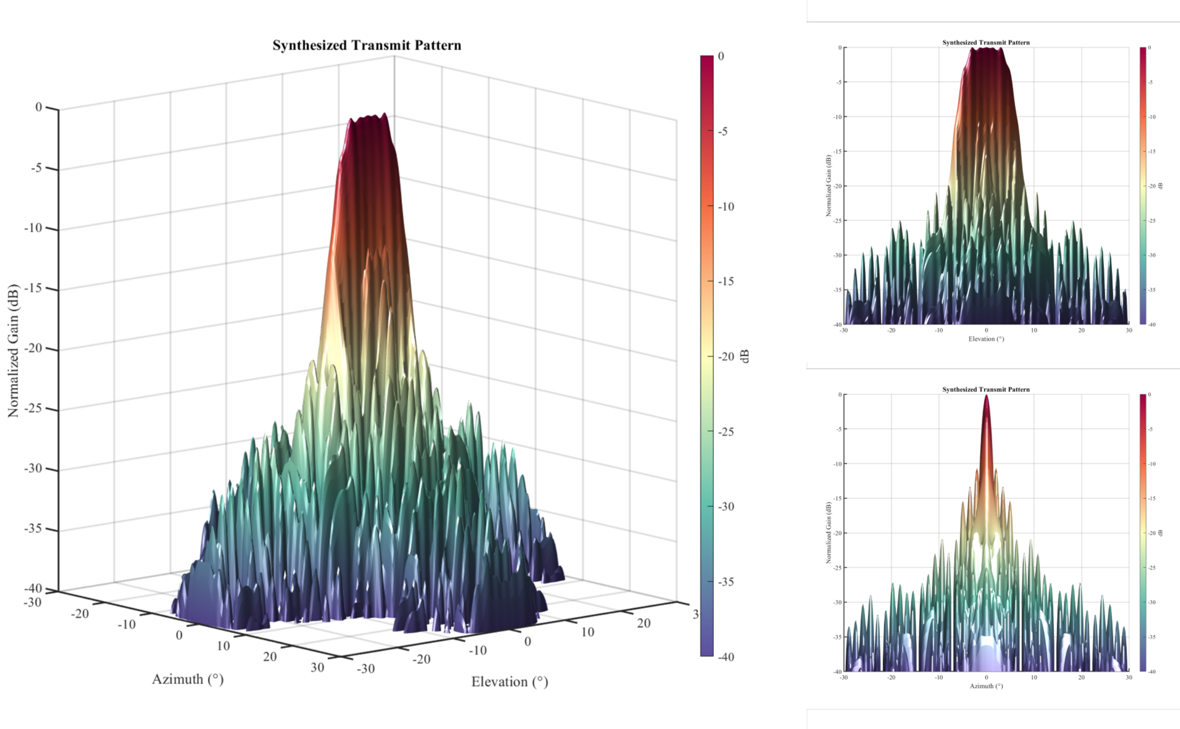

Fig. 5. Synthesized pattern obtained by applying the optimized phase weights to the PAIR antenna. The plots on the right show side views of the pattern in (top) elevation and (bottom) azimuth with the designed envelope.

azimuth. Nevertheless, the synthesized pattern fits well within the envelope in the elevation plane with sidelobe levels below the design requirement (-22 dB). Fig. 6 shows a cut of the pattern in the elevation plane. We note that this is an example beam synthesized with the described method, and other beam shapes (e.g., a cosecant beam) could be designed for a surveillance-type applications. However, broadening the transmit beam can reduce antenna gain considerably, resulting in the loss of sensitivity in detecting relatively weak weather returns.

It is important to note that these are one-way transmit patterns only. Through the use of DBF in elevation to form the receive beams, and the use of amplitude and phase weights to lower sidelobe levels, the sidelobe levels of the two-way beam can be reduced to -50 dB. A similar optimization problem (3a) can be posed to design two-way beams to achieve imaging in elevation and low two-way sidelobe levels. This is left for future work.

Impact on Polarimetric Variables

The PAIR system is expected to produce high-quality polarimetric weather measurements, with negligible biases from co- and cross- polar antenna patterns. Co-polar biases are caused by a combination of scan loss and H/V beam mismatch. These biases are dictated by the embedded element pattern and could be compensated (by synthesizing independent H/V phase-only weights) to alleviate co-polar calibration efforts. Using the optimized phase weights presented in the previous section and a simulation procedure similar to the one in [10], we simulated the full PAIR patterns at two steering angles. These are shown in Fig. 7. First, the beam is steered to Az. = 0°, El. = 20°, and it can be seen that there is very good agreement between co-polar H and V beams. There is a small scan loss (∼0.3 dB) that increases with elevation, as expected. Second, the beam is steered to Az. = 40°, El. = 20°, and it can be seen that there is a considerable difference between H/V beam peaks (∼0.464 dB) on top of a significant scan loss (∼2.5 dB). A larger scan loss was expected for a beam steered off the principal planes, but the difference between H/V beams was not. Although the concept of operations for the PAIR radar consists in maintaining the beams in the vertical plane (i.e., no steering in azimuth), these results show that it is important to quantify polarimetric imaging biases as a function of steering angle.The introduction of a beam-matching metric in the cost function could yield independent H/V phase weights such that polarimetric biases are minimized. This is planned for future research.

V. Conclusion

This paper presents progress towards a hybrid optimization method for synthesizing phase-only beam patterns using actual measurements to account for practical system imperfections. The optimization problem is driven by a two-dimensional angular envelope function that shapes the mainlobe and limits the sidelobe levels, and includes an efficiency factor to reduce ripples in the mainlobe. We use the genetic algorithm solver to search for a global optimum, and to improve convergence time. The number of variables in the optimization is reduced

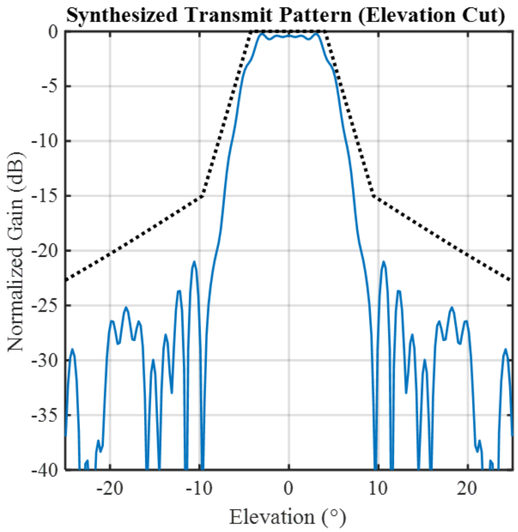

Fig. 6. A cut of the synthesized pattern in the elevation plane.

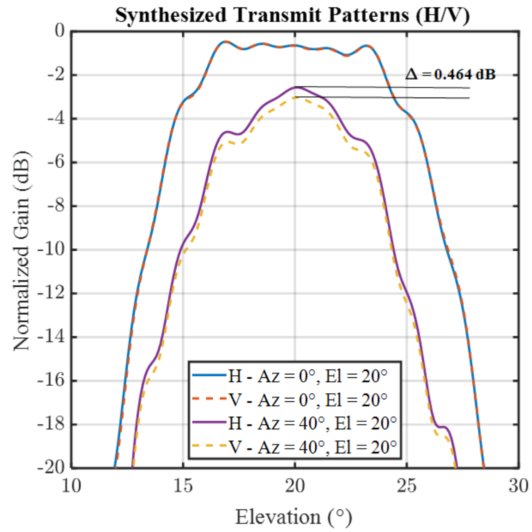

Fig. 7. Comparison of H/V imaging beams for two pairs of steering angles 1) Az. = 0°, El. = 20°, 2) Az. = 40°, El. = 20°.

by parametrizing the phase weights through Bézier surfaces that create smooth phase variations across the face of the array. Preliminary results show that the proposed algorithm can be used to synthesize imaging beam patterns. The technique presented can produce imaging beams with one-way sidelobe levels 20 dB below the pattern peak and that meet a pattern-design envelope function.

The use of identical phase weights to synthesize the H/V beams can introduce biases in polarimetric estimates since the actual H/V embedded element patterns are different. This can be especially important at steering angles far from the principal planes. The PAIR element patterns show good H/V matching in the principal planes, and therefore imaging beams formed with identical phase weights in H/V are sufficiently matched to mitigate biases. However, when steering these beams off the principal plane to Az. = 40°, El. = 20°, a 0.464 dB copolar bias is introduced in differential reflectivity. We are currently expanding the optimization framework to account for these differences and produce matched H/V synthesized beams. It is apparent that the synthesis of independent H/V imaging beams can improve beam matching, consequently mitigating co-polar biases in polarimetric variables.

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