DUAL-POLARIZATION PERFORMANCE OF THE PHASE-TILT ANTENNA ARRAY IN A CASA DENSE NETWORK RADAR

Jorge L. Salazar, Eric J. Knapp and David J. McLaughlin
Engineering Research Center for Collaborative Adaptive of the Atmosphere (CASA)
Dept. of Electrical and Computer Engineering, University of Massachusetts, USA
210 Knowles Engineering Building, 151 Holdsworth Way, Amherst, MA 01003
(jlsalaza@engin.umass.edu, knapp@ecs.umass.edu, and mclaughlin@ecs.umass.edu)

***Abstract*—In this paper the evaluation of dual-polarized scanning performance of a large planar array antenna for a solid state radar for weather is discussed. The antenna array is designed to operate at 9.36 GHz ±50 MHz, and the transmission and reception mode is configured to work alternatively. The antenna array architecture based on a series-fed array configuration of Dual-Polarized Aperture Coupled Patch Antennas (DP-ACPA) was designed and implemented to achieve the required radar polarimetric performance at low cost. Measured patterns of the array in the elevation and azimuth plane are used to evaluate the two principal polarimetric radar parameters (Z_{dr} and LDR) over the scanning range in azimuth plane. It is shown that the biases in the differential reflectivity due the cross-polarization of this antenna configuration are negligible in comparison with the biases produced for the mismatch antenna patterns (H and V).**

***Index Terms*—Low cross-polarized phased array antenna, aperture-coupled patch antenna, dual-polarized array antenna and solid sate radar, CASA radar**

I. INTRODUCTION

Polarimetric observations are increasingly being considered in weather radar systems. For example, in the US, the NEXRAD system is being outfitted with dual-polarization capability. Moreover, at the X-band wavelengths, the use of polarimetric observations is strongly indicated as one of the primary means to compensating for attenuation. Well matched co-polar beam patterns at vertical and horizontal polarizations and low cross-polarization levels are desired in polarimetric weather radars. While phased-array radars have many advantages in scanning agility, they present a new challenge for polarimetric radars because co-polar main beam patterns, sidelobes and cross-polarization isolation changes with scanning beam position, which can result in larger biases in the measured differential reflectivity in comparison with a dish antenna. Since Z_{dr} values range from 0.1 dB (drizzle and dry snow) to 3-4 dB (heavy rain), it is desirable that the measured bias errors for Z_{dr} be less than 0.1 dB. A quantitative evaluation of the measurement accuracy due to system polarization limitations that's convey in a further system specification of polarization requirements for a single conventional dish antenna is described in [1]. According to this analysis, cross-polarization isolation levels better than -20 dB and -25 dB are needed to avoid contamination of less than 0.1 dB in Z_{dr} for alternated and simultaneous polarization modes respectively.

A new dual-polarized weather radar design concept being investigated by the NSF Center for Collaborative Adaptive Sensing of the Atmosphere (CASA) [2] confronts this phased-array radar issue. The CASA Phase-Tilt radar uses a planar array of dual-polarized columns that performs electronic phase-steering only in the azimuth direction, while mechanically steering in the elevation plane.

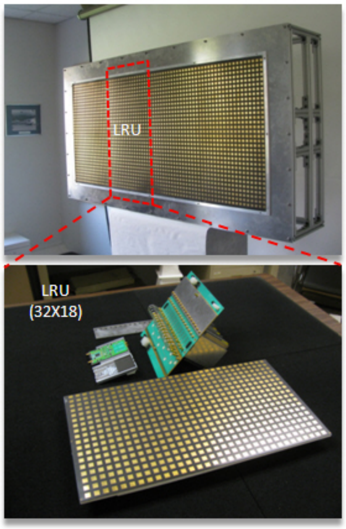

Figure 1: Phase-Tilt array antenna sub-system

The purpose of this paper is to present the preliminary performance of the phase-array antenna for the CASA solid state radar. Emphasis on the polarimetric bias errors due to the mismatch of the co-polar patterns and the isolation of the fields in H and V with respect to beam position in the azimuth plane is presented. Section II presents a brief description of the antenna and the solid state radar system requirements. Section III discusses the antenna performance in the elevation and azimuth planes for H and V polarizations, respectively. Section IV discusses the effect of the mismatch, sidelobe roll-off and cross-polarization isolation on the differential reflectivity Z_{dr} and linear depolarization ratio (LDR).

II. PHASE-TILT SYSTEM DESCRIPTION

The solid state radar was designed to operate in X-band (9.36 GHz) using electronically scanning in only one dimension (Azimuth-plane) while a fast servo motor is used for the other dimension (Elevation-plane). A maximum electronic scanned range of ±50°can be performed using phase-shifters in the array antenna. Dual-polarized capability based in alternate transmit and alternate receive mode is implemented, a low cross-polarization isolation ports isolation ports better that -20 dB is performed for the all scan volume required. A simple antenna architecture using series-fed array linear array antennas in the elevation plane permit the reduction of the number of TR modules from 2048 to only 64, having a great impact in the cost reduction of the overall system, since the TR modules represent about 40% of the total cost of the array antenna. Similar than in CASA IP1 network [2], each radar is controlled by a Meteorological Command

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and Control Center (MC&C), which is responsible for translating and transfering the user's needs trough commands to the radar system level. The Host Computer is responsible for update and translation to the Array Formatted Board and also produces the weather products. The Array Formatted Board (AFB) breaks down commands from the host computer and disseminates in data files to the TR modules. The radar transceiver is based in a commercial Vaisala's RVP900 board where the radar transmitted waveforms and the digitization of the received signals are implemented as well as the up/down converter. Figure 1 shows a picture of the full array antenna (72x32 elements) and also the picture of one LRU (18x32 elements) with the backplane and TR modules.

III. ANTENNA ARRAY PERFORMANCE

The antenna is a planar array of 64x32 Dual-Polarized Aperture Coupled Patch Antennas (DP-ACPA) designed to operate at 9.36 GHz ±50 MHz . The columns are fed by a 1.25 W transmit and receive module that features 360° of phase control with 5.6° of resolution, and 31.5 dB of amplitude control with 0.5 dB of resolution. A maximum peak power of 80 W is provided for the 64 TR modules, considering the losses of the cables and the array antenna efficiency, the antenna array can deliver a maximum peak power of 50 W. In this section the measured results of the antenna such as s-parameters, active element patterns, and linear (1x32) and planar array (18x32) are presented.

A. Elevation plane antenna patterns

In the elevation plane the array is composed of 32 DP-ACPA elements interconnected in series using two serpentine lines for V and H polarizations. In order to obtain a good compromise between beamwidth and side lobe level, Taylor -25dB ($\overline{n}$=2) coefficients were used. The procedure to design this linear array antenna was based on the synthesis technique developed and discussed in detail by Salazar in [3]. Figure 2 shows the measured patterns of the linear array antenna embedded in the planar array of 18x32 elements for both polarizations (H and V). The elevation patterns for 9.36 GHz and for the frequency range (9.3 GHz - 9.4 GHz) shows the first sidelobes are below -24 dB and the pattern roll-off decays rapidly as far as it is from broadside. The cross-polarization, presents values of -35 dB and -32 dB at broadside for V and H respectively. Also when those are integrated across ±90°, values of -21.3 dB and -21 dB are obtained for V and H respectively. The impedance bandwidth measured at -10 dB return loss of the array antenna is about 120 MHz for V and 200 MHz for H port. The beam position shifted 3° from broadside is due to alignment issues during the measurring process.

B. Azimuth antenna patterns

The planar array antenna composed of 64x32 elements is designed in 4 sub-panels called Line Replacement Units (LRUs) in an effort to facilitate the assembly, and also to reduce the fabrication cost and maintenance. Each sub-panel consists of 18 columns of 32 elements. In the complete array 8 columns (4 in each side only in the azimuth direction) are used as dummy elements, in order to minimize the diffraction of the fields because the edges of the antenna. The lattice spacing in azimuth-plane of 17 mm ($0.53\lambda_\circ$) is also the same for the elevation-plane was determined according with limited space available to accommodate the serpentine fed lines and SMP connectors for each polarization. Besides the effort to reduce the spacing in the azimuth plane to avoid grating lobes in the visible region, the coupling between feed lines compromise the cross-polarization performance of the antenna. A trade-off between the cross-polarization and maximum scanning range was performed in order guarantee good performance in cross-polarization at maximum scanning range. The next sub-sections show the performance of the cross-polarization at a±45° scanning range even with the presence of the grating lobe at 62.5° in the azimuth plane.

Figure 3 shows the measured E-plane and H-plane embedded element pattern of the unit cell in a planar array composed for 18x32 elements (corresponding to one LRU) for the vertical (a) and horizontal (b) polarizations. The plots show only the center frequencies of the bandwidth required (100 MHz). In azimuth plane each element corresponds to one column (32x1 linear array), and for this measurement each polarization was excited independently while the other ports of the 17 columns were terminated in 50 Ohms. In the azimuth plane, where the scanning is performed (H-plane for V polarization and E-plane for H polarization) the co-patterns shows a constant amplitude with a variation in amplitude (ripple) less than ±0.8 dB, in the range of ±45°. The ripples presented in H are due to the fact the mutual coupling is strong when the electric fields are collinearly oriented and the ripple level will be reduced when the antenna will be composed of the 4 LRU's (64 element in azimuth plane). For both ports the cross-polarization level at broadside is better than -31 dB.

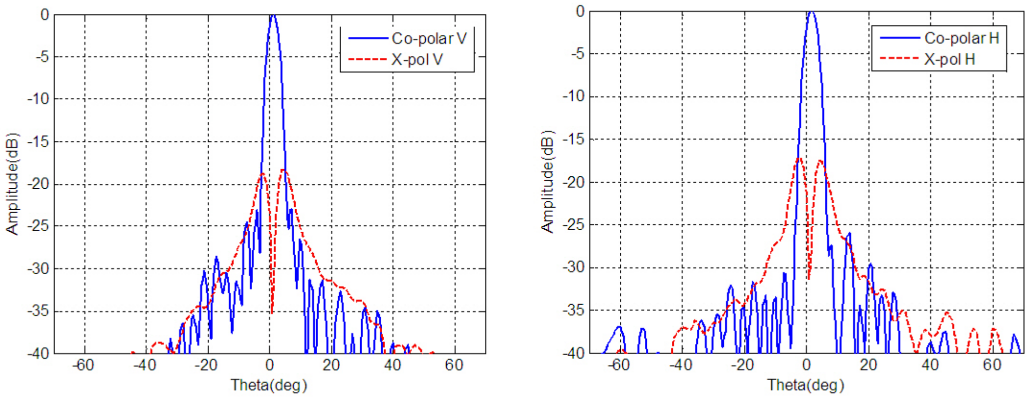
IV. EFFECT OF THE ANTENNA PERFORMANCE IN POLARIMETRIC VARIABLES Z_{dr} AND LDR

To improve the precision of the polarimetric measurements it is necessary to minimize errors in the radar system, especially when phased-array antennas are used, where the co-polar beam patterns and cross-polarization levels changes significantly with beam position. In this context, the ideally matched co-polar beam patterns and very high polarization purity are desirable but not realistic. Matched co-polar beam patterns for H and V are very difficult to obtain, even more when the antenna elements are designed based on multilayer substrates where the presence of surfaces waves and mutual coupling can affect the performance of the patterns and increase the cross-polarization levels. For the Phase-tilt array antenna these two considerations have been accounted for and the principal design consideration consisted of minimizing the surface waves and optimizing the cross-polarization to obtain levels below -20 dB for the whole scanning range. To evaluate the polarization performance two parameters are used as a figures of merit to evaluate the performance of the antenna in a polarimetric system. First is the differential reflectivity (Z_{dr}) and the second is the linear depolarization ratio (LDR). If those parameters are evaluated over a uniformly filled volume with identically spherical scatterers then the measured values Z_{dr} and LDR would be considered an error caused by the antenna only. When this happens, Z_{dr} can represent differential reflectivity bias error (Z_{dr}^b) and LDR is called two way integrated cross-polarization ratio ($ICPR_2$). The expressions of the Z_{dr}^b and for the $ICPR_2$ are defined in equation (1) and (2) taken from [4], [5]

$$Z_{DR}^b = \frac{\int \mid f_{Hc_T} f_{Hc_R} + f_{Hx_T} f_{Hx_R} \mid^2 d\Omega}{\int \mid f_{Vc_T} f_{Vc_R} + f_{Vx_T} f_{Vx_R} \mid^2 d\Omega}, \tag{1}$$

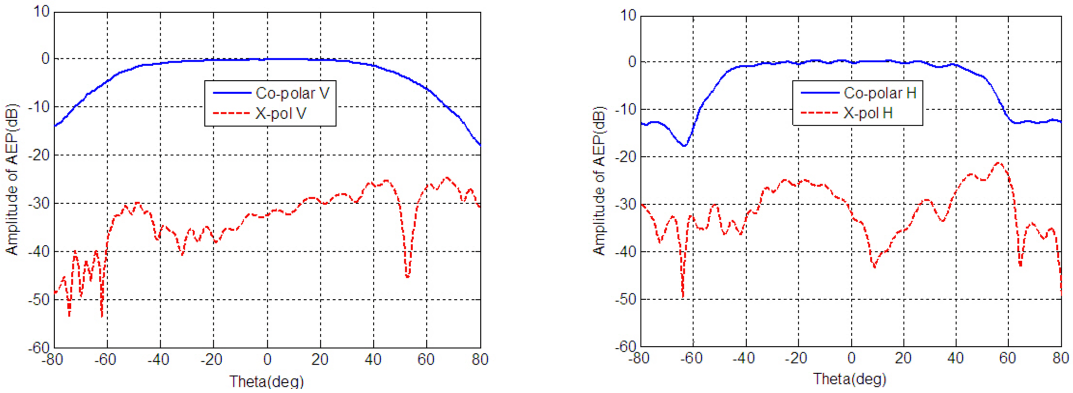
$$ICPR_{2H} = \frac{\int \mid f_{Hc_T} f_{Hc_R} f_{Hx_T} f_{Hx_R} \mid d\Omega}{\int \mid f_{Hc_T} f_{Hc_R} \mid^2 d\Omega}, \tag{2}$$

where, f_{Hc_T}, f_{Hc_R}, f_{Vc_T} and $f_{Vc_R}$are the co-polar patterns for H and V and f_{Hx_T}, f_{Hx_R},$f_{Vx_T}$and f_{Vx_R} represent the cross-polar patterns for H and V, both in transmission and reception, respectively. The azimuthal antenna patterns for the array were obtained based on the measured AEP and the array factor for each scan beam position.



(a) (b)

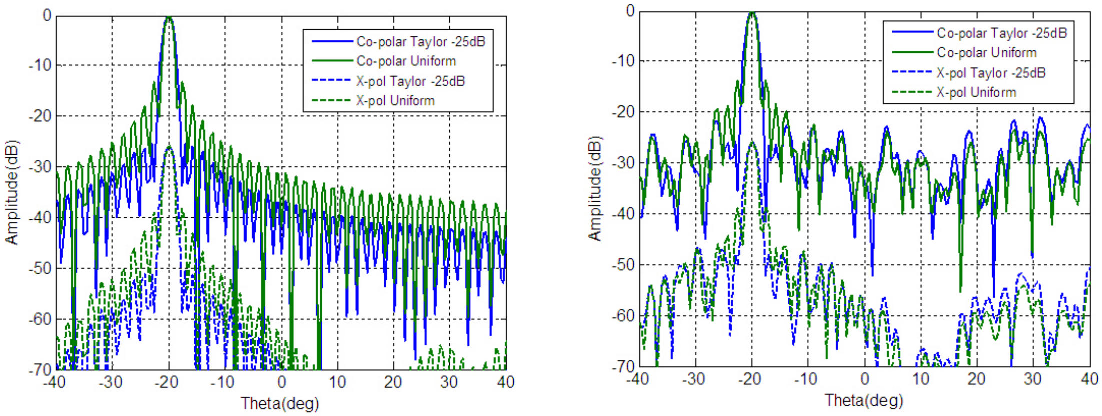
Figure 2: Measured co-polar and cross-polar antenna patterns of linear array of 1x32 embedded in a planar array of 18x32 (LRU) for a) Vertical and b) Horizontal



(a) (b)

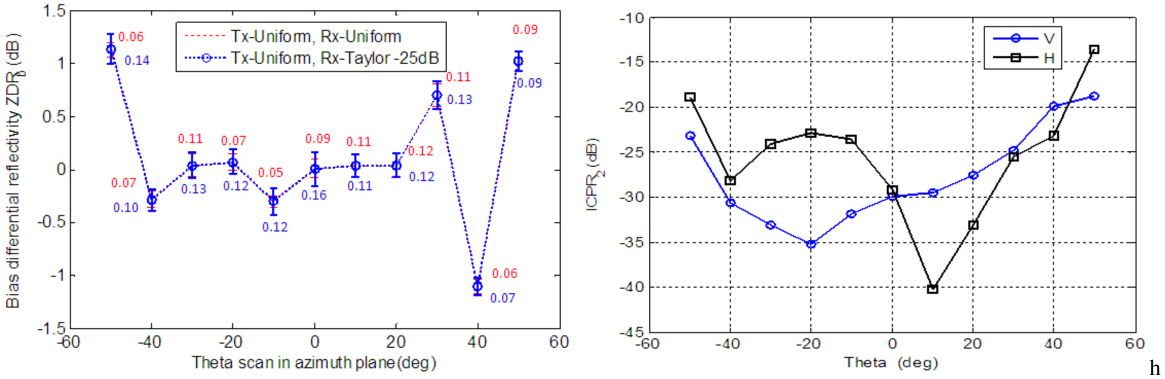
Figure 3: Measured co-polar and cross-polar element patterns embedded in a planar array of 32x18 elements for a) Vertical and b) Horizontal polarizations

Since the AEP includes the effect of the mutual coupling the co-polar and cross-polar patterns can be considered as a good approximation for the azimuth plane. Figure , shows the antenna array patterns of H polarization of the array in azimuth plane. Uniform amplitude distribution was used to illuminate the azimuth pattern in transmit mode, in order to maximize the output power and also to have narrow beamwidth. Amplitude distribution corresponding to Taylor -25dB was used in receive mode in order to reduce the side lobe level and avoid contamination from the first side lobes in the azimuth plane. Figure 5a, shows the bias in the Z_{dr} incurred by the antenna patterns with e-scan position of the Phase-tilt antenna in the azimuth plane. The biases range from few tenth of 1 dB to ±1.2 dB when the beam is scanning up to $\pm50^\circ$. Those large biases in the Z_{dr} are attributed principally to the mismatch of the co-polar patterns and not to cross-polar pattern contamination, since the cross-polarization levels are below -20 dB (for the overall scanning range). It is clear that these biases are not tolerable for weather radar, nevertheless since the antenna co-polar patterns can be characterized for each beam position a calibration process in post-processing can be used to compensate for these biases because of the antenna mismatch for H and V polarization. Influential effects, such as temperature, humidity and mechanical stress can introduce some errors in the estimated bias Z_{dr}. In order to evaluate the effect of these errors, standard deviation of the bias Z_{dr} of a set of patterns affected by random errors have been analyzed. Figure 4b shows the co-polar and cross-polar patterns for H polarization at 20°affected for the maximum tolerable errors in phase for Taylor -25dB for a planar array of 64x32 elements. Note that the introduced errors affect the sidelobes, the pattern roll-off and as a result a mismatch between the patterns for H and V that can introduce uncertainty in the bias Z_{dr}. Similar procedure using equation (1) and the patterns affected the errors were used to evaluate the standard deviation, which indicates the worst case scenario of the bias reflectivity for this antenna configuration. Figure 5a, shows the bias Z_{dr} and the standard deviation for each scan angle because the additional errors introduced in the excitation phase of the antenna. It indicates that for the pecause the antenna imperfections and influence effectshase-tilt antenna array, the worst case scenario of uncertainty to correct the bias Z_{dr} can be no more than ±0.12 dB when antenna uniform illumination is used to transmit and receive, and no higher than ±0.16 dB when the antenna transmit in uniform and receive using Taylor -25dB illumination. Figure 5b show the $ICPR_2$ versus scan angle for H and V polarizations using azimuth array antenna patterns base on measured element patterns embedded in a planar array of 32x18 elements.



(a) (b)

Figure 4: Co-polar and cross-polar antenna patterns of planar array of 64x32 in azimuth plane for Horizontal polarization a) Calibrated and b) With maximum errors in phase tolerable using Taylor -25dB for 64 elements separated 1.7 cm apart.



(a) (b)

Figure 5: a) Bias differential reflectivity base on measured AEP patterns assuming maximum errors tolerated by the antenna array. In red when the antenna transmit and receive using Uniform illumination. In blue when the antenna is transmitting using Uniform illumination and receiving in Taylor (-25dB for n=2). b) $ICPR_2$ versus scan angle for H and V polarizations using azimuth array antenna patterns base on measured AEP.

V. CONCLUSIONS

This paper has described the performance of the Phase-Tilt antenna array (64x32) pattern in elevation and azimuth plane for H and V polarizations. Measured results of the second prototype presents significant improvements in the scatterers parameters and elevation and azimuthal patterns, principally in the cross-polar patterns. The mismatch of the co-polar patterns and cross-polarization isolation has been evaluated and quantified for two polarimetric variables (Z_{dr} and LDR) for the whole scannin range in the azimuth plane. It is shown that large bias in the Z_{dr}, are produced principally for the mismatch co-polar patterns and those can be corrected using the radar calibration in post-processing using the characterized beam patterns for each beam position. Uncertantly analiysis of $Z_{dr}$is performed to determine the possible additional errors that the array antenna can incurr in the worst case scenrio.

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