118019 POLARIZATION SELECTION FOR PHASED ARRAY WEATHER RADAR

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1. INTRODUCTION

Precipitation estimates can be made from the relative returns of vertical and horizontally polarized radar interrogations, Doviak (2000); Zhang (2006). Conventionally this is done with a mechanically scanned, fixed-beam antenna with "vertical" and "horizontally" polarized feeds. Phased Array Radars (PARs) improve weather forecast lead times by providing coverage over the scan volume at rates much quicker than can be done mechanically, Shapiro (2003). Dual polarized Phased Arrays can be used to determine quantitative precipitation estimates (QPE) in a similar fashion to the up-graded WSR-88. However, a clear understanding of the differences the Phased Array main-beam characteristics (beamshape and polarization) is critical to translating the algorithms from conventional to PAR systems. This is true not only for application to current weather metrology, but it especially if the projected advantage of real-time, radar-stimulated models to extend the lead-times in hazardous weather forecasts is to be realized.

This paper describes the polarization characteristics of Phased Array radiating elements and looks at alternative Array/Module design performances compared to the conventional Dual Polarized Dish antennas.

There are a number of significant cost versus performance issues that must be answered by assessing operational performance requirements for PAR systems over the next several years. Some of these can be studied with the existing National Weather Radar Testbed system; others will be better answered with a prototype dual polarized phased array antenna supplementing the system.

2. DUAL POLARIZED PHASED ARRAY MODULE

Figure 1 is a sketch of a solid state phased array showing a TR module feeding a dual polarized radiating element. Polarization of the phased array is determined by the selection of co-located, orthogonally polarized radiating elements. Polarization behavior observed in the array far-field will depart from the ideal, especially at wide scan angles owing to element type(s), array mutual coupling effects and fabrication tolerances. Linearly polarized arrays are routinely calibrated to assure good phase alignment between corresponding elements to steer the main-beam of the array and to achieve low sidelobes. For a polarimetric antenna, it may also be necessary to calibrate the polarization. This can be done by adjusting the relative amplitude and phase of the separate polarization channels to achieve the required orthogonal polarization performance at peak of beam. However, there can be a residual error for angles about the center of the beam. An analysis below will examine this error for an idealized radiating element.

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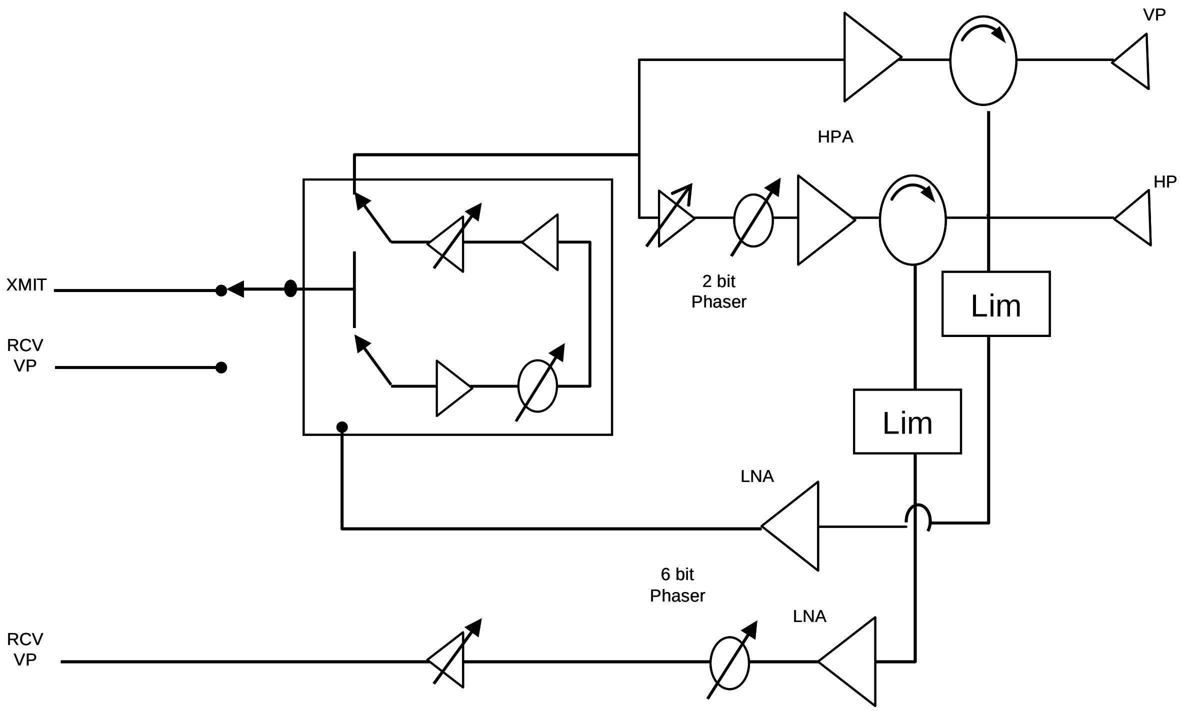


Figure 1. Block Diagram of Dual Polarized TR Module

In the transmit mode, the input signal to the PAR module is amplified and phase shifted through a common (to transmit and receive) leg circuit, through a power divider, final amplification, and a duplexing circulator. Separate feeds are required for each of the dual polarized radiating elements. The 2 bit phase shifter can be used to controls the relative transmit phase between the co-located radiating elements in a way that provides either switched linear or switched circular polarization. In the receive mode, signals from the two antenna ports are feed to two separate paths, each with phase and gain control circuits. Sufficient amplitude and phase control is provided in this module to control both scanning calibrated polarization control.

3. THE NEED FOR DUAL POLARIZATION: TARGET MATCH

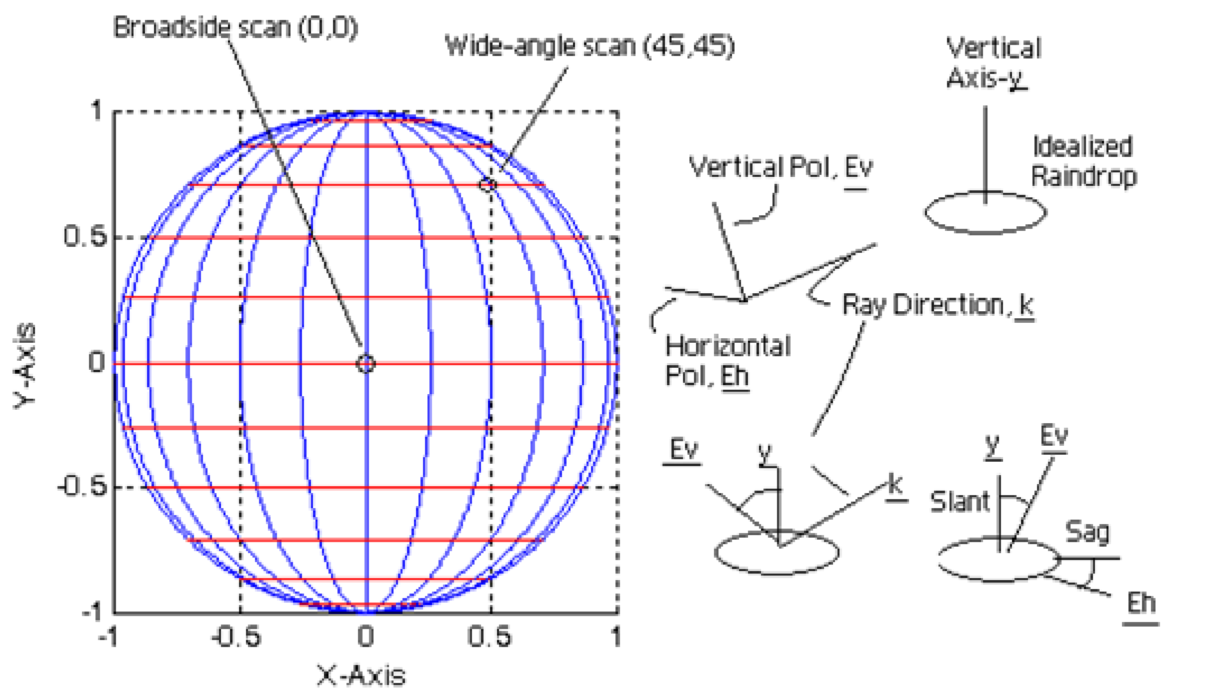
Motivation for dual-polarized weather radar derives from the observation that rain-drops tend to flatten in the vertical dimension when falling thru the atmosphere. The radar cross section (RCS) or brightness (dBZ) is different for radar beams with electric fields polarized perpendicularly or parallel to this axis of symmetry. It is argued that if all the constituent reflectors in a range cell have similar aspect ratios, then the back-scatter from the entire cell will behave similarly to the RCS of the deformed drops contained in the cell.

In practice, quantitative precipitation estimates (QPE) radar scans are made at elevation angles near the horizon (nominally less than 5-degrees). This is done for 2-reasons: 1) The precipitation at high elevation angles may evaporate before reaching the ground, and 2) The aspect ratio of the raindrops is greatest for interrogations made perpendicular to the foreshortened height of the raindrop deformation.

4. PARABOLIC REFLECTOR ANTENNAS (DISHES): RADIATION PATTERN CHARACTERISTICS

Conventional and PAR radars are both capable of simultaneously transmitting and receiving dual polarizations. Whereas the beam-shape and polarization characteristics of a conventional radar are fixed with respect to the direction the dish is pointed, the PAR main-beam shape and polarization can change as a function of scan angle. The PAR beam can be electronically repositioned to any point over a large sector (say a 45-degree cone) around the direction the normal to the aperture is physically pointed. Significant differences can be observed in both the beam-shape and polarization characteristics of these two system types. The Phased Array Aperture designer is allowed several choices of radiating element types to implement dual polarization. The nature of these choices is discussed in this section, and the impact is described in the following section.

A conventional weather radar antenna, such as the WSR-88D, produces a narrow beam in both elevation and azimuth. The Electric Field of waves emanating from (or received by) the antenna are polarized in a plane that contains the vertical axis of the aperture and a line along the direction of the main beam. A dual polarized reflector antenna produces a second (and entirely independent) main beam with essentially the same shape, but with the electric field perpendicular to that of the primary (vertically polarized) mode. The shape of the main beam will always be the same regardless of pointing angle. **Figure 2** illustrates the fact that this beam-shape, say a circle or an ellipse, is the same for any pointing angle. Azimuth and elevation beamwidths are determined by the width and height of the reflector, and the nature of the feed-horns located at the reflector focal point.



a) Coordinate/Polarization Contours

b) Beam/Raindrop Geometries, showing
Tilt: between Vertical axis and Wavefront
Sag: between Eh and Horizontal Plane
Slant: between Ev and z-k plane

Figure 2. Elevation and Azimuth Contours showing typical beam locations for mechanically scanned, reflector array radar. The inset b) shows the geometry of the foreshortened raindrop with an incident, polarized ray.

The orientations of both the vertical and horizontally polarized components are found to be nearly constant over the region of the main beam. However, these polarized fields are not both vertical and horizontal in the truest sense except at the horizon.

The example of a dish antenna located at the origin (x=y=z=0) and pointed along the z direction is shown in **Figure 2**. We have superimposed constant azimuth (blue) and elevation (red) contours about the antenna at some constant radius where a target might be located. Typical beam locations are shown at azimuth, elevation coordinates including [0, 0] and [45, 30]. Each of these points will be illuminated every 6-minutes by a dual polarized WSR-88. The horizontal polarization incident the target at each of these positions is oriented along the constant elevation (red) contours. This polarization is indeed "Horizontal" or parallel to the ground. The maximum value of the electric field for the vertically polarized wave is oriented along constant azimuth (blue) contours. This direction is not truly "Vertical", but rather is in the direction along the spherical blue lines. The angle between this polarization vector and the "Vertical" axis increases degree-for-degree with the elevation scan angle of the radar until the point when the antenna is pointed straight up; the vertical polarized component is actually parallel to the ground (Horizontal).

The inset in **Figure 2b** shows the geometry of the reflector antenna's main-beam direction (**k)** and its V and H polarization directions; all shown with respect to the local axes of the targeted raindrop. The vertical axis of the raindrop is indeed "Vertical", indicated by **y.** The direction of the main beam propagation is represented by the vector **k** (shown at some azimuth and elevation angles [θ,ϕ]**.** The orientations of the vertically and horizontally polarized electric fields are represented by the vectors $\mathbf{E}_v$ and $\mathbf{E}_h$. As noted above, the vertically polarized electric field is tilted with respect to the Vertical axis, in this case at a tilt angle of ϕ. We have shown a sag angle, measured between the horizontally polarized electric field and the Horizontal axis in this figure, although this angle will generally be zero for mechanically positioned antennas. We also define a slant angle between the vertical field, $\mathbf{E}_v$, and the plane containing the y-axis and the propagation vector, **k.**

5. PAR DUAL POL RADIATING ELEMENT CHOICES

The polarization characteristics of a phased array are dependent upon the type of radiating element selected. Vertical and horizontal polarizations can be generated by properly orienting either an electric dipole or a circular loop antenna (often referred to as a Magnetic Dipole). A dual polarized PAR will use two orthogonally polarized radiating elements for each module in the aperture. These element pairs will be collocated at the face of each module. The polarization of any collimated beam from arrays of these like-oriented element pairs will be defined by the isolated behaviors of the separate element types. There are a number of ways to realize radiating elements that behave (from a polarization perspective) as electric or magnetic dipoles. Selection will depend on their gain (or lack of loss), their ability to be co-located with another element type, manufacturability, and bandwidth.

A vertical electric dipole element, placed at the center of the coordinate system shown in **Figure 2**, will produce an electric field parallel to the constant azimuth (blue) contours shown in the figure. Vertical Electric (VE) elements used in planar phased arrays will maintain this polarization characteristic, but the gain or sensitivity of the element will decrease as a function of the azimuth and/or elevation angles away from the normal to the face of the array. A heuristically derived expression for the electric field from a VE element VE dipole over a ground plane at the center of the coordinate system x', y', z' is:

$$\underline{\mathbf{gVE}} = \underline{\mathbf{a}}_{\phi'} \cos^{\tau 1} (\sin^{-1}(\sin\theta'\cos\phi')) \cos^{\tau 2}(\phi') \qquad (1)$$

where θ' and ϕ' are the azimuth and elevation angles shown in **Figure 2**, and $\underline{\mathbf{a}}_{\phi'}$ is a unit vector pointing in the direction along a constant azimuth contour (the blue lines). We use the primed coordinate system here, to allow for the condition that the elements may-or-may-not be aligned with the system coordinates (x, y, z). The exponents τ_1 and τ_2 determine the approximate rates of decay of the field from an electric dipole in planes perpendicular to the polarization (in the x'-z' and y'-z' planes) respectively. The electric field nominally goes to zero everywhere in the x'-y' plane for such elements in a planar array (dipole over a ground plane).

The complementary element to the VE is a Horizontal Magnetic (HM) dipole. Some types of HM can be co-located with a VE element at each module. At **broadside** (along the normal to the array), the HM element will generate a horizontally polarized electric field. The Electric field from this HM dipole will ideally be parallel to the constant elevation (red) contours of **Figure 2**. For a HM element over a ground plane at the center of the x', y', z' coordinate system, the element pattern for the HM dipoles can be written as:

$$\underline{\mathbf{gHM}} = \underline{\mathbf{a}}_{\theta'} \cos^{\tau 3} (\sin^{-1}(\sin\theta'\cos\phi')) \cos^{\tau 4}(\phi') \qquad (2)$$

where $\underline{\mathbf{a}}_{\theta'}$ is a unit vector pointing in the direction along a constant elevation contour (the red lines). Here, again, the sensitivity or gain of the element will be a function how far the beam is scanned away from the element normal. This time with beamwidth coefficients τ_3 and τ_4 in the x-z and y-z planes, respectively. Note that the field lines for the HM dipole are everywhere perpendicular to the electric field lines for the VE dipole. The VE/HM dipole elements are thus a complementary element pair.

There are two other element types that can be used to produce orthogonally polarized radiation pairs: Horizontal Electric (HE) and Vertical Magnetic (VM) dipole elements can be used to produce complementary electric fields with the polar axis lying parallel to the x-axis. Basically these elements produce the same type of fields as the VE and HM dipoles, but with each of them tilted 90-degrees in the plane of the aperture. Mathematically these element patterns are given by

gVM = $-\mathbf{a}_{\theta''} \cos^{\tau 3} (\sin^{-1}(\sin\theta''\cos\phi'')) \cos^{\tau 4}(\phi'')$ (3)

gHE = $\mathbf{a}_{\phi''} \cos^{\tau 1} (\sin^{-1}(\sin\theta''\cos\phi'')) \cos^{\tau 2}(\phi'')$ (4)

Here, the double-primed coordinate system has its pole along the x'' axis, and ϕ'' is measured as longitudes away from the x''-z'' plane and ϕ'' is measured latitudinally from the y''-z'' plane.

Figure 3 shows that polarization orientations produced by VM/HE elements (magenta lines and green lines respectively) do not lie along the constant azimuth/elevation (blue/red) contours used by weather radar systems. In the principal planes ($\theta''=0$ or $\phi''=0$ with z'' and x'' parallel the z and x-axes) the polarization vectors do lie along the respective az/el contours.

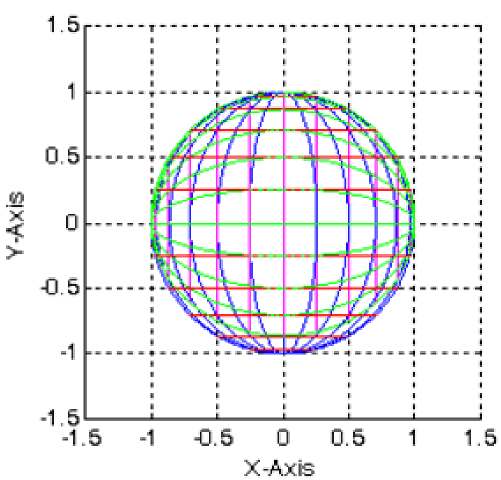


Figure 3. Polarization Orientation of Vertical Magnetic (magenta) and Horizontal Electric (green) dipole fields, superimposed on mechanically scanned coordinate system of constant azimuth (blue) and elevation (red). Note that the E-fields are only parallel to the constant az/el contours in the principal planes (az or el =0).

In these principal planes, we can also produce orthogonal electric fields with a combination of Vertical Electric and Horizontal Electric dipoles or with Vertical Magnetic and Horizontal Magnetic dipoles. Polarization performance may degrade at wide scan angles, However these VE/HE or VM/HM combinations may provide advantages in producibity (cost) or sensitivity (gain) that would warrant consideration.

The polarization orientations of the VE/HM element combination is exactly the same as we saw from the mechanically scanned dish … so long as the normal to the face of the array is pointed toward the horizon. Ground-based PAR antennas are seldom aligned facing the horizon for a number of reasons. The extent of the scan is limited first by the reduced gain experienced as the beam scans from normal, and then by the possible excitation of grating lobes at wide scan angles: both result in undesirable conditions. Since we wish to cover as much as the upper hemisphere as possible, the array is normally tipped upward. The extent of this tipping is tempered downward by the need for maximum range (gain) at the horizon, and by the need to sufficiently cover all azimuths near the horizon with high gain. So, if we need to cover to 45 degrees in elevation, we may not tip the aperture up to 22.5-degrees, but to some lesser amount, say half-that. An aperture designed to cover the full hemisphere might be tipped upward by as much as 20- to 30-degrees.

The effect on tipping a dual pol aperture is shown in **Figure 4**. This figure shows the apparent "distortion of VE/HM dipole polarizations (green and magenta, resp) that has been tipped back by 30-degrees. The 'vertical' (VE) and 'horizontal' (HM) polarization vectors are only parallel with the constant azimuth (blue) and elevation (red) contours in the Azimuth=0-degree plane. In the upper hemisphere, the 'vertical' signal is slanted outward and the 'horizontal' sags downward with respect to the polarization planes of the conventional weather radar.

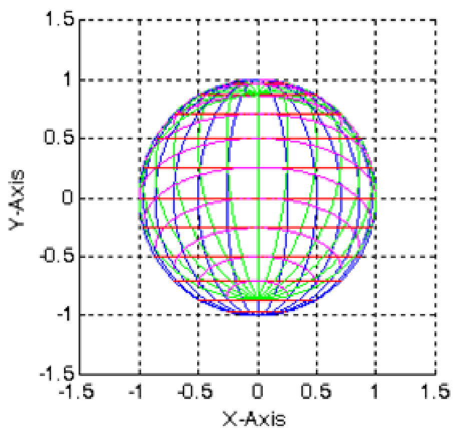


Figure 4. Polarization orientation of a VE/HM dipole pair tilted back 30-degrees in elevation with respect to Azimuth/Elevation boresight.

It should be noted that tipping an HE/VM dipole pair up or down in elevation does not change the relative orientation of the polarization vectors to the local az/el coordinates anywhere in the visible region.

Tilt, Slant and Sag angles are presented in **Table 1** for a number of scan angles over a typical coverage region. Polarization performance for a mechanically scanned aperture and for a VE/HM PAR tipped back at 0, 15, and 30-degrees is shown. With this selection of elements and a moderate aperture tip-back, the polarization inclination from the desired axes is less than 10 degrees for scan angles near the horizon and up to 30 degrees from broadside in azimuth. Low-angle QPE scans (near the horizon) will not be significantly degraded with four-faced or mechanically positioned phased arrays. Degradation at higher angles will require further investigation.

Polar Align	El	Elevation = 0-deg			Elevation = 30-deg			Elevation = 45-deg		
	Az	0	30	45	0	30	45	0	30	45
Pointed Dish Antenna	Tilt	0	30	45	0	30	45	0	30	45
	Slant	0	0	0	0	0	0	0	0	0
	Sag	0	0	0	0	0	0	0	0	0
VE/HA 0-deg Tipback	Tilt	0	30	45	0	30	45	0	30	45
	Slant	0	0	0	0	0	0	0	0	0
	Sag	0	0	0	0	0	0	0	0	0
VE/HM 15-deg Tipback	Tilt	0	30	45	0	30	45	0	30	45
	Slant	0	7.63	10.72	0	7.87	11.16	0	8.79	12.69
	Sag	0	1.01	1.99	0	1.05	2.14	0	1.36	2.77
VE/HM 30-deg Tipback	Tilt	0	30	45	0	30	45	0	30	45
	Slant	0	16.1	22.21	0	14.50	20.88	0	15.2	22.3
	Sag	0	4.41	8.21	0	3.59	7.29	0	3.95	8.29

Table 1. Polarization Tilt, Slant, and Sag angles for a mechanically pointed and a VE/HM electronically scanned array with various tip-backs.

In the following section, we will describe means to align the polarization with the desired coordinate planes.

6. MAIN-BEAM POLARIZATION CONTROL FOR PAR ANTENNAS

Polarization characteristics of a phased array will be determined by the selection of the radiating elements, choosing the orientation of the face of the array, and the architecture of the active module used to excite the elements. Algorithms for QPE depend on simultaneous radiation of both these primary senses of linear polarization. The presumption is that beam interactions with the rain cell will not cross-couple the return. That is V transmit begets V return with no return in the H polarization (and vice versa). In general, either pair of complementary elements (VE/HM or HE/VM) will allow simultaneous excitation of both vertical and horizontal polarizations. Economic considerations may drive consideration of other combinations.

Using a pair of perpendicularly oriented Electric Dipole antennas to generate both V and H beams will result in these beams being aligned with the raindrop coordinates only in the principal planes. This “turnstile”, (4) type of antenna can also be developed by using a crossed pair of Magnetic Dipoles. Either choice results in good performance in the principal planes with degradation in alignment as the beam is scanned in any diagonal plane. Simultaneous excitation of either of these pairs can be controlled in a way to provide either sense of vertical polarization at beam center. Control of the receive channels can similarly be used to align a receive beam polarization to the same orientation.

Selected vertical or horizontal polarization can be generated on a beam at any scan angle by controlling the relative amplitudes of excitation of an electric turnstile element pair. That is, Ramsay (1962)

$$\underline{\mathbf{E}}_{\phi}(\theta,\phi) = \underline{\boldsymbol{gVE}}(\theta,\phi) + K_1(\theta_0,\phi_0)*\underline{\mathbf{gHE}}(\theta,\phi) \quad (5)$$

$$\underline{\mathbf{E}}_{\theta}(\theta,\phi) = \underline{\boldsymbol{gVE}}(\theta,\phi) + K_2(\theta_0,\phi_0)*\underline{\mathbf{gHE}}(\theta,\phi) \quad (6)$$

Where the targeted beam centroid is scanned to the angles (θ_0,ϕ_0), and where

$$K_1(\theta_0,\phi_0) = -\underline{\mathbf{a}}_{\phi}(\theta_0,\phi_0)\bullet \underline{\boldsymbol{gVE}}(\theta_0,\phi_0) \div \underline{\mathbf{a}}_{\phi}(\theta_0,\phi_0)*\underline{\mathbf{gHE}}(\theta_0,\phi_0) \quad (7)$$

$$K_2(\theta_0,\phi_0) = -\underline{\mathbf{a}}_{\theta}(\theta_0,\phi_0)\bullet \underline{\boldsymbol{gVE}}(\theta_0,\phi_0) \div \underline{\mathbf{a}}_{\theta}(\theta_0,\phi_0)*\underline{\mathbf{gHE}}(\theta_0,\phi_0) \quad (8)$$

The correction required is a function of scan angle. The correction will be effective at beam center and a residual error in the polarization will exist at angles away from the peak of beam.

The magnitude of this error has been assessed for the case of an idealized model of crossed electric dipoles. **Figure 5** shows the result of a calculation of the error in calibration as a function distance in degrees from the center of the beam. A one degree beam ($\pm$0.5 degrees) would have an error of approximately 0.1 dB at the beam edges for a nominal broadside beamwidth. The error would be greater for large scan angles due to bream broadening. Note that the polarization loss is a function of the physical offset angle from beam peak so that the larger the beamwidth, the larger the effective polarization loss.

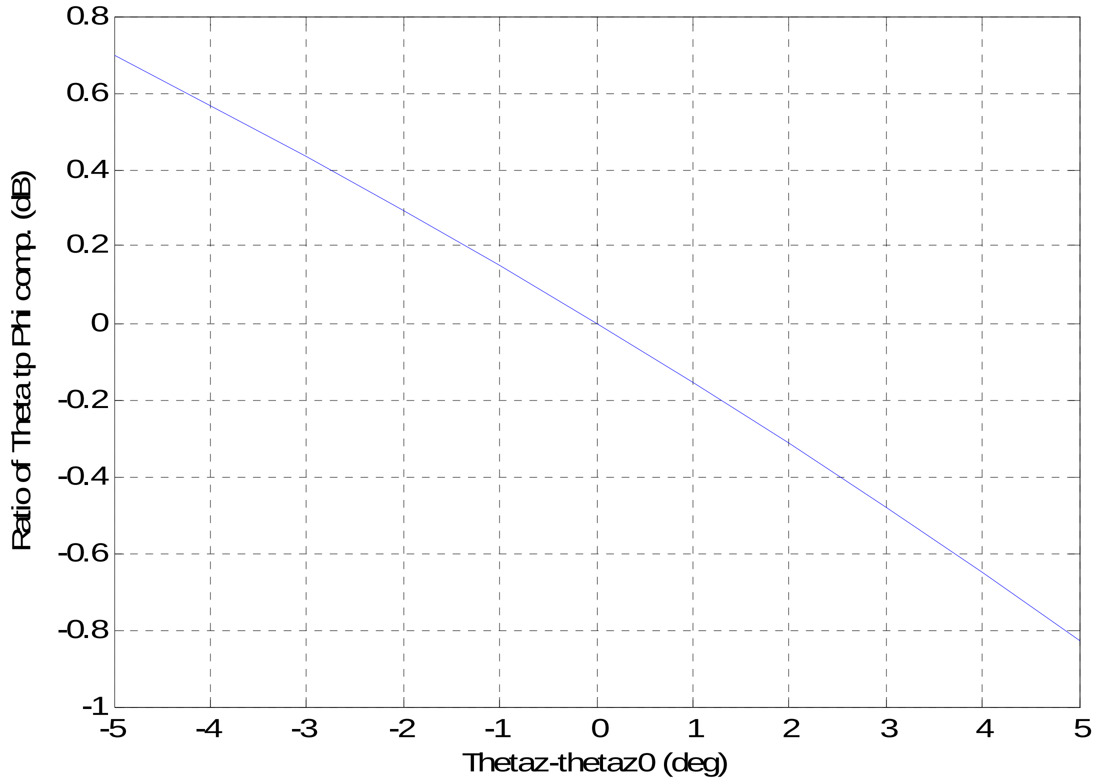


Figure 5. Polarization Loss of corrected, wide angle scanned beam as a function of distance from the center of the beam.

Excitation of complementary element pairs will allow simultaneous correction of vertical and horizontal beam components. These, too will be subject to polarization losses across the main beam, owing to differing rates of change of the respective components in either the elevation or azimuth direction. The extent of these errors is dependent on the same factors. The advantage of this element choice is simultaneous access to V and H so that the same range cell can be observed with both polarizations on the same (rather than on sequential) radar dwells.

7. CONCLUSIONS:

Dual Polarized (DP) Phased Array Radar (PAR) performance and cost are greatly influenced by the radiating elements selected and the architecture of the module. The performance can be dynamically optimized for a particular scan angle using a'priori knowledge of the characteristics of the radiating elements. The effectiveness of this strategy and the degree of difficulty in implementing it depend on major system decisions regarding scan volume, target objective (minimum detectable signal), and cost.

Algorithms used today focus heavily on relative Vertical and Horizontal polarization backscatter at elevation angles near the horizon. If, in the future, PARs are used in conjunction with real-time atmospheric models that are initiated and updated by the radar, it may be important to know precipitation states at high angles. The strategies for marrying the beam agility of Dual Polarized PARs to real-time models has not yet been studied and has certainly not been demonstrated over wide angles of scan. What we do know is that shortening the revisit time in volume surveillance of wind fields has a marked effect on the length of time a model can predict wind fields at future. Phased Array requirements for the next 30 years must certainly look forward to the possibility of interaction with hydrometeors over the entire volume, not just at low angles.

Experience with weather observation with wide-angle scanned, dual polarized phased array radars has yet to be gotten. A few key parameters can be studied with existing systems (e.g. the National Weather Radar Testbed and the DP WSR-88). However, understanding of the full potential (and limitations) for weather metrology will require experimentation with a Dual Polarized PAR against an array weather targets. The greatest benefit will be gained frm an experimental system capable of simultaneous transmission and reception of both senses of linear polarization.

8. ACKNOWLEDGEMENTS

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