UAV-Based Calibration for Polarimetric Phased Array Radar

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ABSTRACT

Calibrating dual polarization in phased array radars is an important aspect of risk mitigation in moving towards a nationwide multifunctional phased array radar (MPAR) system for weather surveillance and to track aviation. Since dual polarization was implemented into the WSR-88D, the new products have been vital for hydrometeor classification. The calibration of scan-dependent polarization in phased arrays is a primary goal in achieving the same products provided by traditional dish-based systems. There are many challenges to the calibration process, including isolating the horizontal and vertical polarizations that are sent by the radar and making sure that their amplitudes are identical. In the project described herein, the focus is on the calibration of the radar's receive patterns, the first step in the overall calibration process. An unmanned aerial vehicle (UAV) has been developed to facilitate scan-dependent calibration of a fixed phased array, and the focus of this part of the project is on the so-called "Twitching Eye of Horus" circuit. It provides a means for transmission of calibrated horizontal (H) and vertical (V) electric fields towards the radar in a controlled manner from the UAV, but in and of itself it requires its own processing and calibration procedures. Removal of the frequency offset between the circuit and the radar is a primary challenge. This study takes a look at the process of calibrating the radar's receiver using a UAV and the Twitching Eye of Horus, as well as presenting initial results.

1. INTRODUCTION

Phased array radars are the future of weather radar surveillance, but they currently lack proven polarimetric capabilities. Dual polarization is a requirement for future phased array radars, and the calibration for errors in dual polarization has become a high priority because of the advantages it can provide. In lieu of indirect measurements supporting the calibration of the radar's receive patterns vs. scan angle, a UAV-based sensor and transmission circuit have been developed to help with the calibration. Calibration of the transmit patterns is a separate task that will be a future capability of the UAV platform.

In 2011, the National Weather Service (NWS) began upgrading the WSR-88D to include dual polarization capabilities. They completed the upgrade in 2013, and there have been many significant advantages with the polarimetric radar products enabled by this upgrade. These products include differential reflectivity (Z_{DR}), correlation coefficient (ρ_{HV}), and specific differential phase (Φ_{DP}) (Warning Decision Training Branch, 2012). Hydrometeor Classification (HCA) algorithms were also derived from these products, as well as the Melting Layer Detection algorithm, improved Quantitative Precipitation Estimation (QPE), and improved detection of Tornado Debris Signatures (TDS) (Berkowitz et al. 2013).

Phased array radars are fairly new when it comes to applying them to weather, but they have been used in the military for decades. In 2005, a National Weather Radar Testbed (NWRT) was formed to develop a phased array radar for weather (Zrnic et al 2007). Phased array radars offer advantages that dish antenna radars do not offer. The phased array fulfills the need of frequent observations, as it can scan and receive observations every minute and potentially faster. The ability of fast adaptive scanning can focus on the feature of interest and place emphasis on scanning in that area (Zrnic et al. 2007). Absence of beam smearing offers better ground clutter

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detection as well as narrowing the beamwidth. The multiplexing beam allows for the ability to create vertical wind profiles (Zrnic et al. 2007). Also, phased array radar improves rainfall estimation by reducing sample errors and retrieving refractivity of the beam (Zrnic et al. 2007).

With the goal of a multifunction phased array radar (MPAR) system in mind, adding polarimetric capabilities to phased array radars is a high priority. An MPAR system would provide radars that are used for weather observations, aircraft surveillance, and tracking non-cooperative aircraft (Weber et al. 2007). The OU team proposes the use of an unmanned aerial vehicle (UAV) as the basis of calibration. Dual-pol must be operational for the MPAR system because of the important data it provides. It has been the most challenging part of weather surveillance for the system, and will be examined further in this text (Weber et al. 2007).

2. CALIBRATION CHALLENGES

Polarimetric radars send out pulses in the horizontal (H) and vertical (V) polarizations to gather information about the target and to return a cross-section. This helps distinguish the type of hydrometeor. The main challenge is isolating the H and V signals as they are being cross-coupled and mismatching with each other (Fulton et al. 2013). They also have to be calibrated separately. The signal that is sent out in H, must reach the target in H and be returned to the radar in H perfectly. The V signal must be returned only in V as well. This is important, since polarimetric radar products are calculated using the differences between the H and V signals in both amplitude and phase (Zrnic et al. 2013).

The dish antenna calibration techniques cannot be adapted to phased array due to differences in scanning, waveform, and pulsing techniques. Also, the calibration for phased array radars must be scan-dependent, and the beam must be individually calibrated for each scan angle (Fulton et al. 2013). The dish antenna only needs to be calibrated once at the center of the beam. In an array, the calibration must also occur on all of the array elements since it is a fixed radar.

There are also other issues with calibration. A narrow beamwidth must be maintained through calibration, as well as low sidelobes. The gain is another important factor to consider when calibrating. All of these issues need to be considered during calibration to fix the bias given by polarimetric products and technology.

3. METHODOLOGY

3.1 *UAV and Twitching Eye of Horus*

A UAV, built by the Advanced Radar Research Center (AARC), is being used to calibrate a generic phased array radar (Fig. 1). It is an octocopter drone that has an S-band array to act as a transmitter for the H and V polarizations. The UAV is a source for the phased array radar and is located in the far-field of the radar. The UAV is moved in the far-field for calibration to calibrate all scan angles, as the radar beams must capture targets in any direction. Also, this gives the ability to calibrate all four faces of a planar phased array radar. The UAV is representing a calibration tower that can be moved. A dish antenna radar can be moved to capture targets at a fixed location, while a phased array radar cannot.

Figure 1: The UAV built by the ARRC for use in the calibration of the phased array radar.

A circuit, named the Twitching Eye of Horus, is located on the UAV (Fig. 2), providing a polarization reference source for the radar. A SynthHD signal generator produces the signal into the input of the circuit. The circuit, which is made up of capacitors, a 555 timer, and an RF switch, sends out signals in H and V alternately. The timer and switch alternate between the two outputs on the order of a fraction of a millisecond. The first output sends a horizontal polarization while the second output sends out a vertical polarization back to the radar. The radar then receives these pulses, and these received signals are then used to calibrate the radar (Fig. 3).

3.2 *Calibration*

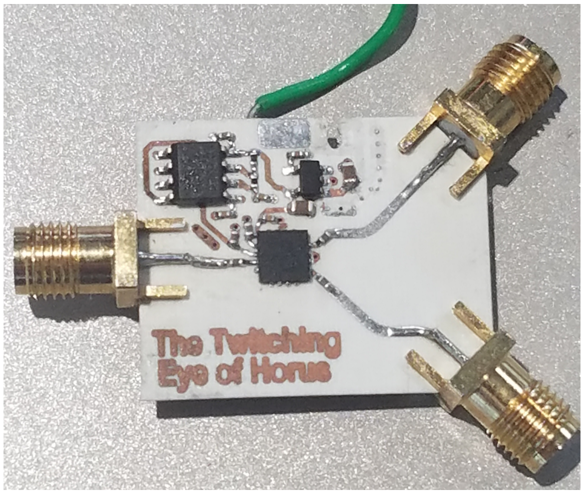


Figure 2: The Twitching Eye of Horus circuit located on the UAV.

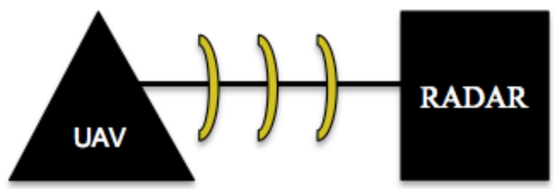


Figure 3: The concept of operations for the H and V polarizations sent from the UAV and Twitching Eye of Horus to the radar.

The goal of this project is that of calibrating the radar's receiver. In normal operation, the target is a volumetric scatterer that produces a scattering matrix dependent on distance (r), composition, elevation, and azimuth angles, S(r, θ, Φ). The scattering matrix is the measurement that the radar gets from hydrometeors in the field, and is different for different hydrometeors.

$$S(r, \theta, \Phi) = \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad (1)$$

For the purpose of calibration, however, the target is a sphere; a sphere has a known scattering matrix that is proportional to an identity matrix, so the co-polar values, S_{HH} and S_{VV}, equal 1 and the cross-polar values equal 0 (Fulton and Chappell 2010a).

The radar's receiver matrix is dependent on the elevation, azimuth, elevation scan and azimuth scan angles, R $(\theta, \Phi, \theta_s, \Phi_s)$.

$$R = \begin{bmatrix} R_{HH} & R_{HV} \\ R_{VH} & R_{VV} \end{bmatrix} \quad (2)$$

The receiver matrix, which is being measured in the current project, is normalized to R_{HH}. The equation for solving for the H and V components of the polarization goes as follows:

$$F = RXST \quad (3)$$

$$F = \begin{bmatrix} F_{HH} & F_{HV} \\ F_{VH} & F_{VV} \end{bmatrix} \quad (4)$$

$$X = \begin{bmatrix} X_{HH} & X_{HV} \\ X_{VH} & X_{VV} \end{bmatrix} \quad (5)$$

$$T = \begin{bmatrix} X_{HH} & X_{HV} \\ X_{VH} & X_{VV} \end{bmatrix} \quad (6)$$

where F is the pattern matrix of the array elements and X is the antenna matrix measurements for the sensor of the UAV, which is assumed to be perfect after it is calibrated carefully in an anechoic chamber. When the UAV represents a receiver calibration target, the equivalent representation is

$$F = RX \quad (6).$$

R can be calculated once X is measured in the chamber and solved by

$$FX^{-1} = R \quad (7)$$

giving the co-polar and cross-polar values of the receiver. The corrected R matrix must have low cross-polar values and equal co-polar values.

The transmit and receive patterns must have narrow beamwidths and low co-polar and cross-polar terms in the sidelobes.

4. DATA/MEASUREMENTS

4.1 *Measurement Procedures*

The radar's receiver is calibrated by the polarizations sent from the Twitching Eye of Horus. A linear phased array antenna was used for the test. In the test, the anechoic chamber (Fig. 4) acts to provide a realistic, echo-free environment for the signals produced by the Twitching Eye of Horus (Dash, 2005). The radar's antenna will be measuring the co-polar and cross-polar elements from H and V for the X matrix as seen through a perfect R matrix (in the chamber). The data gathered from the receiving matrix is used to accurately determine R.

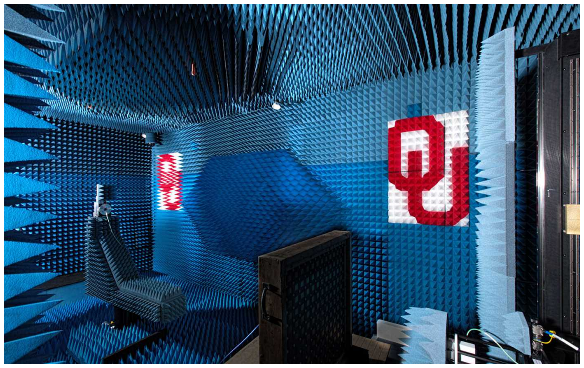
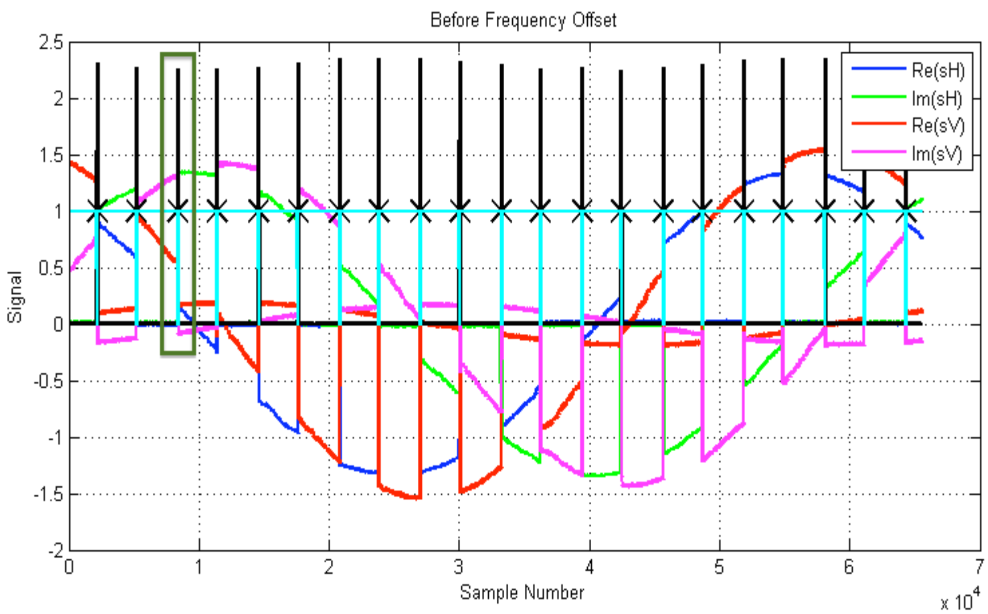


Figure 4: ARRC/University of Oklahoma's Anechoic Chamber.
Source: University of Oklahoma's ARRC

4.2 *Finding Pulses*

The horizontal and vertical pulses transmitted by the Twitching Eye of Horus are recorded, as seen by either the radar (in operation) or a calibrated dual-pol probe (during calibration). In either case, the overall amplitude is estimated and than normalized in H and V to the amplitude. After the amplitudes are normalized, the pulse jumps between H and V are detected. These jumps are the peaks of the moving average derivative (Fig. 5). These pulse jumps occur during the transition period as the Twitching Eye of Horus is switching between the H and V pulses. The data inside the jump must be masked off and ignored because the data is transient.



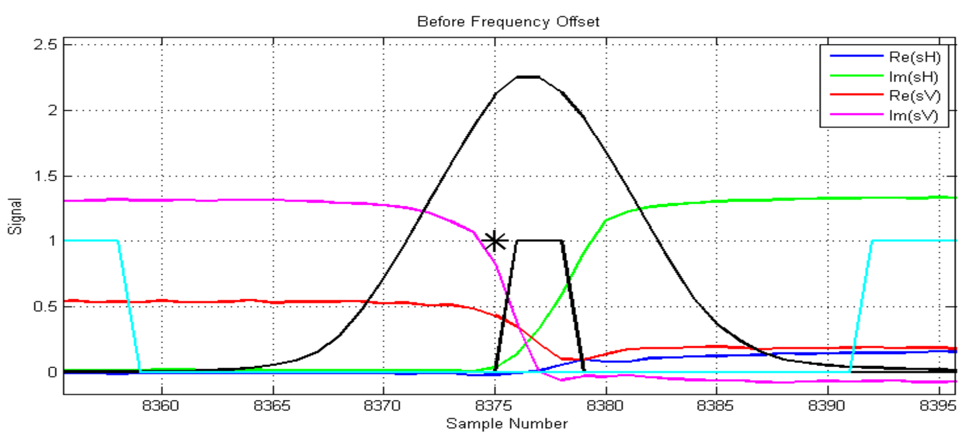


Figure 5: The signal before frequency offset (top) with a zoomed in area (bottom) of a peak of the moving average derivative (black) used to detect the pulses. The mask (cyan) shows where the data is ignored when it equals 0. The pulse (trapezoid) changes at the star.

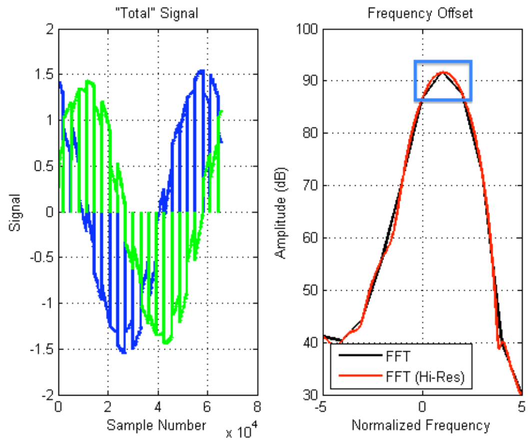
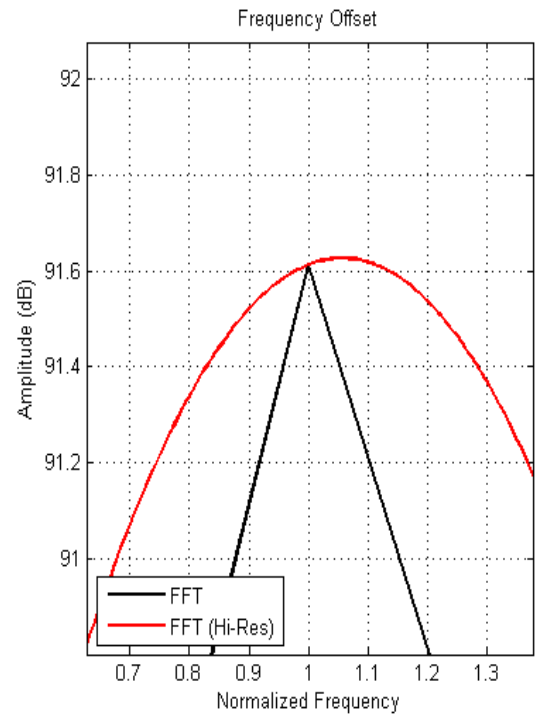


Figure 6: Total Signal (left) shows the track of the co-polar to make one signal. The Frequency Offset (center, right) shows the fast Fourier transform (FFT) and the fast Fourier transform at a higher resolution (FFT (Hi-Res)).



4.3 *Frequency Offset*

A frequency offset is evident due the difference of the frequencies sent by the Twitching Eye of Horus and the oscillator frequency of the radar's receiver. The Twitching Eye of Horus is transmitting its own pulse at ~3 GHz, while the radar's receiver is expecting to receive a 3 GHz pulse as well. The difficulty is to get the oscillations to match because the Twitching Eye of Horus' oscillator is not tied to the radar. The radar's receiver is expecting to receive the same signal frequency it sent.

The frequency offset estimation is used to estimate the difference between the frequency transmitted and the frequency of the radar receiver. The peaks of the spectrum are not at a zero normalized frequency, signifying the difference of the frequency offset (Fig. 6). The estimate is then removed to alter the frequency of the received signal from the Twitching Eye of Horus to match the frequency of the radar's receiver.

4.4 *The Estimated Receive Matrix*

After the pulse jumps are detected and the frequency offset is eliminated (Fig. 7), the receiver is calibrated. The removal of the frequency offset allows for estimates of the received signals during H and V transmission to be averaged. The estimated receive matrix is normalized with respect to its first entry, R_{HH}. The receive matrix consists of the averages of the horizontal and vertical signals' real and imaginary numbers. Ideally, the receive matrix should be an identity matrix, but planar phased arrays always deviate from this in practice. Low cross-polar characteristics are important for calibration to minimize the contamination between the horizontal and vertical pulses to produce accurate calibration. The signal averages are taken from outside of the mask to provide a better pattern estimate for the receiver (Fig. 7).

The accuracy of the receive matrix determines the accuracy of the calibration of the dual polarization. Therefore, the accuracy of the receiver matrix limits the accuracy of products like Z_{DR}, ρ_{HV} and Φ_{DP}. These products can only be as accurate as the receive matrix warrants. MPAR systems have very strict accuracy requirements when it comes to polarimetric capabilities to ensure accurate science.

5. CONCLUSION

Polarimetric capabilities would be a major upgrade to the current capabilities of phased array radars. The idea of UAV-based calibration and the use of the Twitching Eye of Horus circuit have demonstrated progress towards practical calibration of a polarimetric phased array radar.

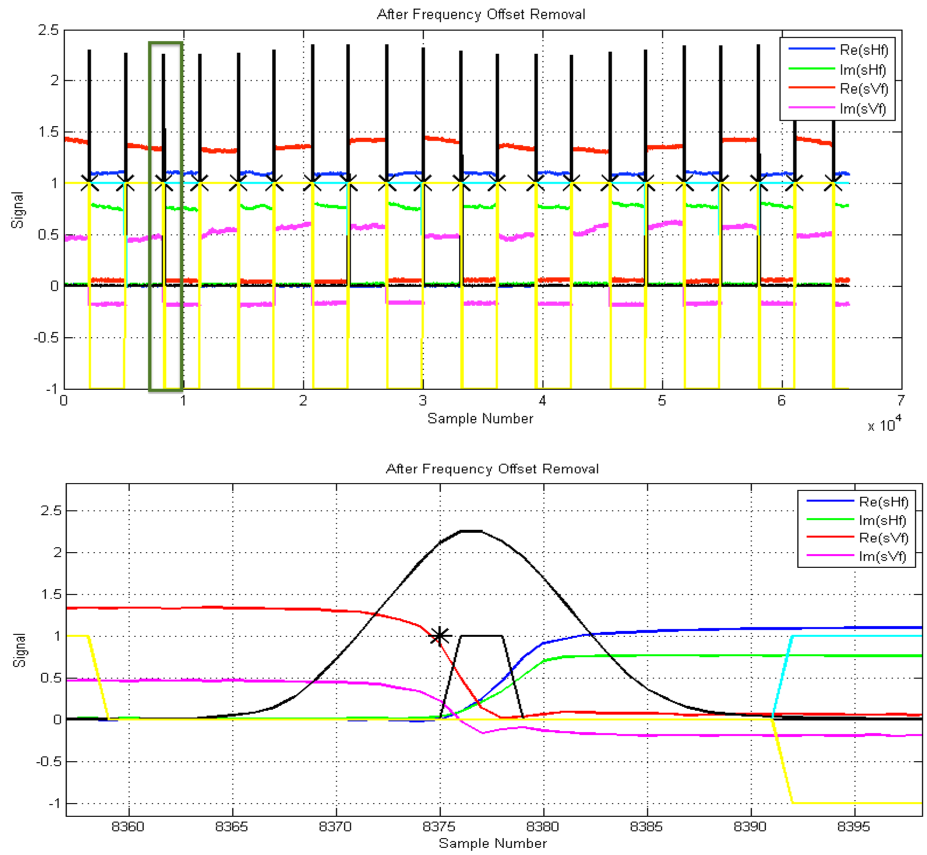


Figure 7: Signal after frequency offset (top) with zoomed in on a moving average derivative peak (bottom). The HV line (yellow) is 0 when the signal is transitioning between the horizontal and vertical polarizations, 1 for vertical pulse and -1 for horizontal pulse.

The frequency offset removal corrects for a shift in frequency between the UAV-based transmitter and the radar receiver. This process is a critical part of the test, but is also very difficult. In the present work, the offset removal works well enough to provide promising results in its early stages. There are plenty of improvements that can be done for the frequency offset process, as it is not robust yet. As it stands, this early work is providing a foundation for better calibration of the X matrix, which, in turn, will lead to better calibration of polarimetric phased array radar systems in the future.

6. ACKNOWLEDGMENTS

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