Displaced Phase Center Antenna Processing For Airborne Phased Array Radar

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***Abstract*—Clutter suppression is paramount to detect slow-moving ground targets by an airborne radar. Ground clutter in the case of airborne radars is not centered on zero Doppler frequency due to the mobile radar platform, making the detection of slow-moving targets difficult. These targets appear very close to the main lobe clutter in the Doppler dimension. Thus, the main lobe ground clutter competes with the slow-moving targets raising the minimum velocity at which targets can be detected. Conventional radar signal processing methods can be used to filter out the clutter but at the cost of eliminating the signals of interest. In this paper, Displaced Phase Center Antenna (DPCA) concept has been utilized to suppress clutter for an airborne phased array radar. DPCA is a non-adaptive technique that eliminates clutter by electronically shifting the phase center of antenna array and subsequent subtraction of successive pulses. The benefit of DPCA lies in its simplicity and computational efficiency. DPCA algorithm extenuated clutter and increased the probability of detection of slow-moving targets. With DPCA processing, we were able to detect targets with velocities as low as 5 m/s.**

***Keywords*— (DPCA, clutter, airborne radar)**

I. Introduction

The advent of Active Electronically Scanned Array (AESA) radar has galvanized new research avenues in the field of radar signal processing. AESA radar steers the antenna beam electronically, which augments the revisit time exponentially. Moreover, multiple modes can be envisaged in a time-interleaved fashion. The RF front end of an AESA radar involves multiple antenna elements, which can be exploited to adaptively null jammers and ground clutter. To harness maximum benefits afforded by spatial diversity, there is a dire need to develop optimum algorithms viable in real-time.

Pulse-Doppler radars extract position and velocity information by processing the returned signal from a target and illuminated patch of ground. The unwanted reflections from various objects give rise to ground clutter that impedes target detection.

Radar return comprising an undesired signal component is a nuisance for radar engineers. The clutter component is strong enough to obscure the target of interest. Traditionally, high pass filters, large antenna apertures and long CPI have been employed to counter clutter. However, AESA radar with multiple apertures and fast scan times affords an innovative solution. It involves spatial and temporal diversity to accrue the requisite information with high levels of confidence interval.

Airborne radar possesses significant advantages over a ground radar. The horizon range is extended and the radar signal suffers lower attenuation as it travels in the upper atmosphere. Airborne platforms extend imaging techniques like synthetic aperture radar. Whilst airborne radar has some advantages, it faces a seriously challenging environment. The extended horizon entails a large extent of clutter. Owing to the higher depression angle, clutter intensity is usually high. Platform motion-induced Doppler shift and spread of clutter pose a serious threat to easy detection of targets [1-2]. In the case of ground radars, all of the clutter is essentially stationed around zero Doppler, since the radar is stationary.

Many techniques have been presented in the literature to suppress ground clutter. Space-Time Adaptive Processing (STAP) eliminates clutter by evaluating inner product of the covariance matrix inverse and desired target response for the cell under test [3-6]. Theoretically, it is an optimum technique, however, computational complexity and availability of requisite training cells are the limiting factors [7-10]. In Time Averaged Clutter Coherent Airborne Radar (TACCAR), the received signal frequency is shifted based on platform velocity [11-12]. This method displaces the main lobe clutter frequency to DC in the Doppler spectrum. However, spectral widening of the clutter cannot be mitigated with this technique.

DPCA is a non-adaptive technique that suppresses clutter by processing signals from different antennae but the same physical location [13-14]. In this paper, DPCA processing for an airborne phased array radar is presented. An airborne phased array radar is modeled and ground clutter in the side-looking mode of airborne radar is successfully eliminated utilizing the DPCA technique.

Airborne Radar geometry has been explained in section II. The Space-Time model and clutter model have been briefly introduced in section III and IV respectively. Furthermore, clutter spectrum has been described in section V. DPCA has been introduced in section VI followed by results and discussion in section VII.

II. Airborne Radar Geometry

Airborne radar geometry is critical to space-time concepts and operations. Fig 1 represents an inclusive geometrical model for an airborne radar with a uniform linear array. In the subsequent simulations, it is assumed that the aircraft is moving in a straight and level flight with uniform velocity. Moreover, the airborne platform maintains constant height during simulation. In Fig 1, aircraft is moving in the x-direction. The radar antenna illuminates a stationary clutter point P on the ground. The slant range to the clutter point is R_s and ground range is R_g. The clutter point subtends azimuth angle φ and elevation angle θ, with the antenna beam. The angle between the antenna axis and the aircraft velocity vector is defined as crab angle Ψ. For side looking radar antennas, the crab angle becomes 0º whereas for front looking it is 90º. The angle between the radar beam and antenna axis is β, whereas α is the angle between the velocity vector and the radar beam.

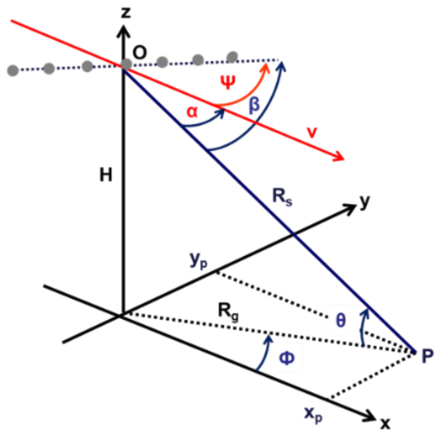

Fig 1. Airborne Radar Geometry

III. SPACE-TIME MODEL

Phased array radar stores IQ samples in the form of a data cube. Visualization of radar samples in the form of data cube presents an intuitive model to understand fundamental radar signal processing operations.

The data cube has three dimensions; fast time, slow time and spatial axis. The received IQ samples are sampled by ADC for each spatial channel. The sampling rate is set according to Nyquist criteria. Typically, the sampling rate is equal to twice the bandwidth of the transmitted signal. The total number of range bins is equal to the product of the sampling rate and PRI (Pulse Repetition Interval). The starting range interval is determined by the radar blind zone or in the case of airborne radars, it is adjusted according to the altitude of the airborne platform. The radar blind zone is a function of the pulse width. Radar range resolution is also determined by pulse width, however, the resolution of fast time is defined by the ADC sampling rate. Each sample in the range bin corresponds to a specific range.

In general, radar transmits a series of coherent pulses. The total time interval for the pulses is called Coherent Processing Interval (CPI). The data cube dimension across the pulses is categorized as slow time. PRI is the sampling interval across slow time. Desired Doppler resolution is the main determinant of the number of pulses in a CPI. Doppler spectrum is obtained by undertaking FFT across the slow-time dimension.

A phased array comprises thousands of antenna elements. Antenna elements may be followed by a receiver channel or not, depending on the particular requirement. The number of receiver channels determines the third dimension of the data cube. To satisfy the Nyquist criteria, the spacing of the antenna elements should not be less than lambda/2.

IV. CLUTTER MODEL

Clutter refers to signal components received from volume or surface scatterers. Such signal components may be the desired signal in some cases such as synthetic aperture radar; however, in our case, it is categorized as interference. Generally, returns from cloud and ground are classified as volume and surface scatterers respectively. Clutter modeling is paramount in terms of radar signal processing. Clutter returns may have spatial and temporal correlation. Moreover, clutter returns depend upon the radar parameters as well as the geometry of the platform.

The radar range equation takes different forms for point, area and volume scatterers. Reflections from the ground, forest, and other surfaces are modeled through area scattering. RCS parameter differentiates each of the three forms of radar range equation.

Radiation from the antenna is bounded by azimuth and elevation beam width. The area illuminated on the ground by radar beam is determined by down range and cross-range extent. Azimuth beam width establishes the cross-range extent of the illuminated area. While, in the case of downrange, there could be two possibilities. It could be either limited by the pulse width or elevation beam width. It means that if the projection of pulse width on the ground is smaller, downrange would be determined by pulse width and vice versa.

The reflectivity factor $б^0$ is strongly affected by the type of terrain, surface conditions such as its roughness, grazing angle, dielectric properties, engagement geometry and radar parameters. Extensive research has been carried out to model $б^0$ and its dependence on the above parameters. The reflectivity factor generally increases with an increase in frequency for a constant grazing angle. $б^0$ values range from -60 dB to -20 dB typically. $б^0$ also varies with surface roughness, generally, its values are greater for rough surfaces than smooth surfaces. Different values of $б^0$ are reported in the literature for sea, woods, forests, mountains and deserts. The reflectivity factor which is also called normalized RCS, greatly depends on grazing angle. It increases rapidly at very low and high grazing angles. The variation of $б^0$ is relatively mild in the middle region, which is also called plateau as depicted in Fig 2.

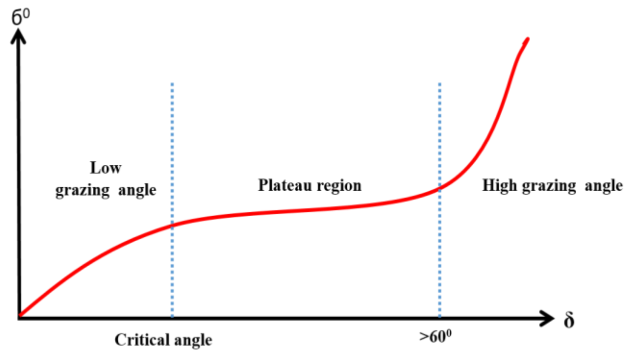

Fig 2. Clutter Model

To characterize clutter in the plateau region, the constant gamma model is used in literature which is given by the following equation.

$$б^0 = ɣ \sin\delta \tag{1}$$

The parameter Gamma γ depends on terrain type, frequency of operation and polarization. This model adequately predicts the reflectivity behavior in the plateau region. However, its accuracy is less when the grazing angle δ is very less or high. In this paper, the constant gamma model has been employed to model clutter. It is assumed that the earth model is flat. This means that the grazing angle and depression angle are congruent.

V. Clutter Spectrum

The illumination of ground terrain by the antenna beam generates clutter. The angle of the antenna beam and its beamwidth determine the extent of ground clutter both in range and swath.

In the case of ground moving target indication applications, clutter is mainly dominated by the main lobe return. It may be noted that the signal of interest is also embedded in the main lobe return signal. Additionally, sidelobe and altitude line clutter further complicate the extraction of the signal of interest. Altitude return can be masked with the knowledge of platform height while sidelobe returns can be attenuated by antenna tapering and sidelobe blanking. The clutter spectrum distribution for an airborne radar is shown in Fig 3.

The clutter Doppler frequency f is predicated by the look angle φ, platform velocity v and operating wavelength λ.

$$f = \frac{2v}{\lambda}\cos\varphi \quad (2)$$

Bandwidth Δf of the main lobe clutter is found by differentiating (2).

$$\Delta f = \frac{2v}{\lambda}\sin\varphi \quad (3)$$

The angle φ between the platform velocity and radar beam is not the same for every clutter patch of the ground, thus the main beam clutter occupies a band of frequencies.

Clutter bandwidth also depends on the antenna beam width. Doubling the beam width roughly doubles the clutter spread. Also, both the clutter center frequency and bandwidth vary directly with the velocity of the mobile radar platform. The width and center frequency of the clutter band vary inversely with the wavelength of the radar. The spread of the band also varies with the antenna scan angle. Targets are difficult to detect in case of airborne radars because of the strength, variability and spread of clutter.

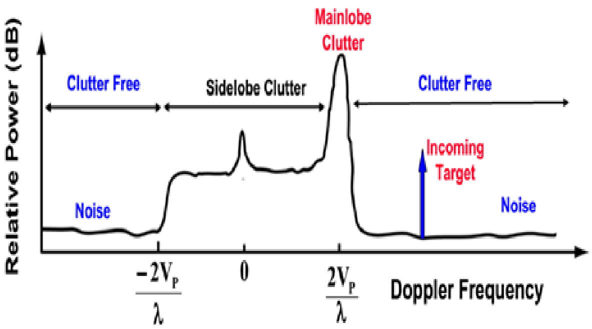

Fig 3. Ground Clutter Spectrum

Radar Pulse Repetition Frequency (PRF) determines the extent of range and Doppler ambiguities. A low PRF radar is unambiguous in range but ambiguous in Doppler while a high PRF radar is unambiguous in Doppler but ambiguous in range. Range and Doppler ambiguities further compound the problem of clutter suppression. Ambiguity causes clutter profiles in range and Doppler to overlap with each other. The selection of PRF for a particular radar operation is a critical one. In general, low PRF is used in airborne radars for the detection of slow-moving targets on the ground.

VI. DPCA

The main aim of DPCA is to make the antenna phase center stationary for a fixed target. In this technique, platform velocity v is tied to radar PRF such that the platform traverses a half phase center during one Pulse Repetition Interval (PRI). This constraint is given by (4), in which d is the inter-element spacing.

$$v \times PRI = d/2 \quad (4)$$

Assuming a dual-phase center antenna, alternate pulses are transmitted with the red and blue phase centers of the antenna at times T1 and T2, as shown in Fig 4. Both pulses illuminate the same geographical area and hence clutter can be canceled with a two-pulse canceler scheme.

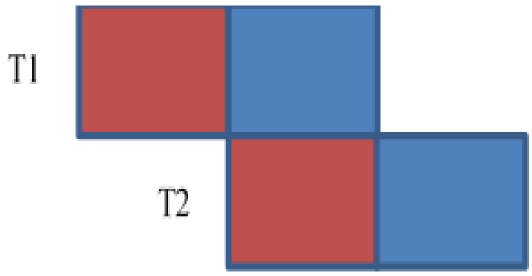

Fig 4. Antenna Array at time T1 & T2

The radar return of the first pulse from the front part of the antenna is delayed by PRF. The second pulse is then subtracted from this pulse as depicted in Fig 5. In this way motion of the aircraft could be compensated and the strength of ground clutter could be reduced.

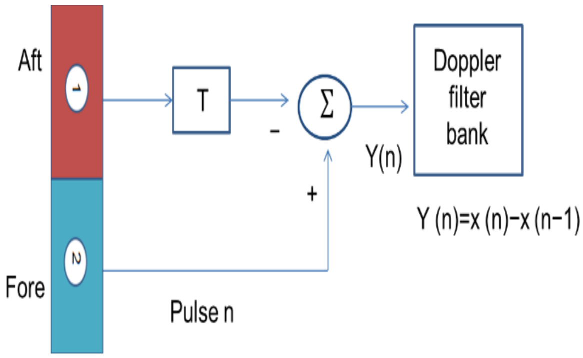

Fig 5. DPCA block diagram

VII. Results & Discussion

A side-looking X-band airborne radar was modeled in Matlab. The PRF and platform velocity were adjusted to achieve the DPCA condition. Furthermore, clutter was assumed to be unambiguous in range and Doppler. Constant Gamma model was used to simulate clutter that approximates clutter reflectivity in the plateau region. A rectangular waveform was transmitted using a uniform linear array of six isotropic antenna elements. The transmitted signal bandwidth was narrow enough so that spatial and Doppler responses were approximated by phase shifts. The simulation parameters for radar and target are listed in Table 1.

TABLE 1. SIMULATION PARAMETERS

Parameter	Value
Sampling Rate	1 MHz
Pulse Width	2 μs
PRF	2 kHz
Target RCS	2 m^2
Target Range	8 km
Target velocity	5 m/s
Platform Height	3000 m

Ten pulses were transmitted to collect the return signal from the target and ground patch. The complete CPI comprised 10 pulses and 6 spatial samples. The raw data signal received for a single PRI is depicted in Fig 6 below.

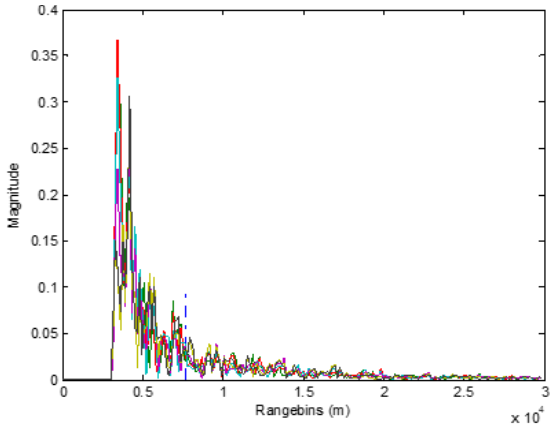

Fig 6. Raw data for the first antenna element

From Fig 6, it is quite evident that the target is not visible and the magnitude of the clutter signal is large. To improve the SNR (Signal to Noise Ratio), match filtering was carried out. Match filtering reduced the noise level and overall signal purity was improved. After that ten pulses were non-coherently integrated to further improve SNR. Non-Coherent pulse integration further decreased the noise level. But the target was still not visible. The blue line in Fig 6 & 7 represents the target location which has been masked by the clutter. The output of matched filtering and non-coherent pulse integration is depicted in Fig 7.

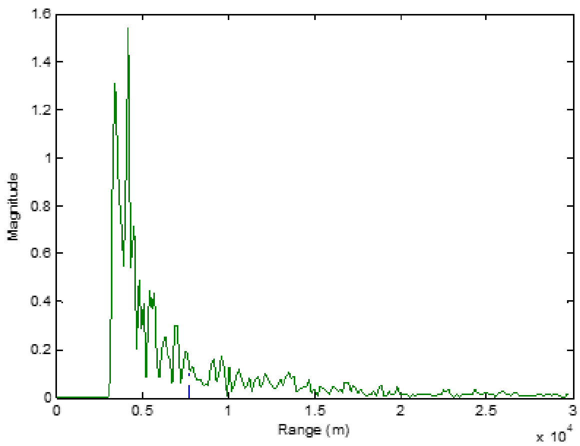

Fig 7. Signal after Matched filtering and pulse integration

DPCA processing entails the subtraction of successive pulses to suppress signal elements without any phase shift. DPCA was applied to the non-coherently integrated signal and the result obtained is depicted in Fig 8. It can be observed that clutter has been eliminated and the target is detected at a range of 8 km.

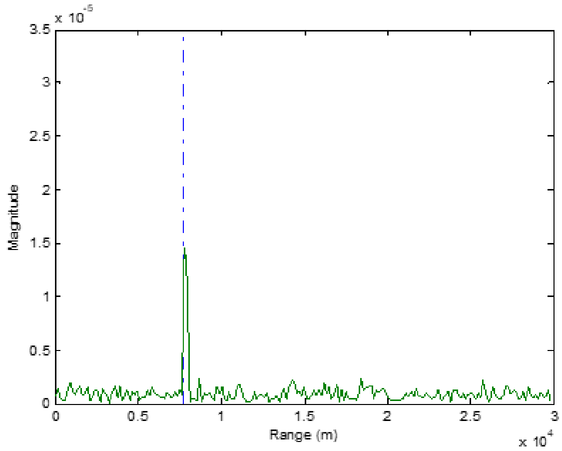

Fig 8. Processed signal after DPCA

In the case of a side-looking radar, the angle between platform velocity and look angle is 90º. Thus clutter manifests itself in the form of a diagonal clutter ridge in the angle-Doppler domain. A diagonal clutter null is visible in DPCA weights response depicted in Fig 9. The clutter null suppresses ground clutter in the angle-Doppler domain. It is important to note that clutter null is narrow enough so that it eliminates clutter only and the desired signal of interest is not attenuated. The strength of the DPCA technique lies in the fact that it operates in the angle-Doppler domain. Unlike DPCA, MTI filter implements a high pass filter in the Doppler dimension which may extenuate a moving target along with clutter.

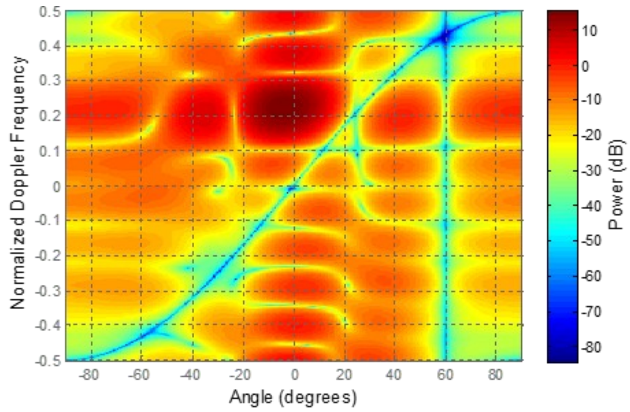

Fig 9. DPCA weights response

VIII. CONCLUSION

In the case of airborne radars due to mobile platform, slow-moving targets are difficult to detect, because they fall in the proximity of main lobe clutter. To discern these slow-moving targets, the DPCA algorithm was used instead of MTI techniques that fail to perform in airborne radar platforms. DPCA uses successive pulses from the front and back portion of the antenna array to compensate for the motion of the airborne radar platform. Using DPCA main lobe clutter was removed and the slow-moving target was detected.

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