Antenna Rotation Effects and its Compensation in Radar Signal Processing

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Abstract —Signal processing in radar is used for extraction of target parameters. Rotating antennas can cover wide area during surveillance. Similarly wide beam antennas have an advantage of simplicity and more data reception. If the radar has a wide beam antenna which rotates, the effects are such as in accurate Doppler and parameter estimation. So these effects need to be compensated. The antenna rotation Doppler is modeled and compensated by using data shifting method in the processor. It is a very effective method and the results show that it works correctly. In this manuscript, the mathematical model of antenna rotation effects are presented for array antenna. The simulations were carried out in Matlab to implement the radar rotation and moving targets. The simulation results are shown with rotating antenna and its effects. The results are also shown after compensating the antenna rotation effect. The results verify the effectiveness of the compensating algorithm.

Index Terms—Rotation, doppler, radar, antenna, compensation, algorithm, doppler adjustment, linear array, signal processing.

I. Introduction

Radar signal processing algorithms need to be accurate for error free estimation of target parameters. Rotating antennas are used for scanning a large area. DOA estimation technique for UCA (Uniform circular array) is presented in [1] which is designed for a rotating array. The antenna rotation effects are partially modeled which are helpful for rotating radars' modeling. The rotating antenna has effects on parameters estimated such as Doppler and need to be compensated. Antenna rotation compensation for arrays is discussed in [2] but it requires compensators before signal processing.

In rotating antenna radars, the radar processor's performance and sensitivity are reduced due to two effects. Firstly successive time samples from the same source originate at different angles relative to the antenna normal, so all radiation sources appear to be extended. Secondly the antenna rotation imparts a Doppler spread to radar returns since samples received at one edge of the rotating antenna exhibit a positive Doppler shift, and samples received at the opposite edge experience a negative Doppler shift and the intermediate samples being uniformly spread in between these extremes. If these effects are not compensated, it leads to significant degradation to the performance of a processor [2]. The most important effect due to antenna rotation is the Doppler shift [3]. If this rotation effect is not compensated, errors occur in target parameter estimation. In this chapter, the rotation effects are described with two compensation techniques proposed.

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II. Rotating Antenna Model

For linear array rotating radar, consider monostatic radar with a two-element antenna that rotates with angular speed ω_a rad/s. The center of the array is the axis of rotation, which is also considered the origin of the array. The elements labeled as m = -1, +1 are separated by a distance $d = \lambda / 2$ where λ is the mean wavelength of the transmitted signal.

Fig. 1 shows the two element antenna array. The same antenna is used for transmission as well as reception. However, the role of antenna is different for the two processes. The two processes are multiplexed in time as in conventional monostatic radars with same antenna.

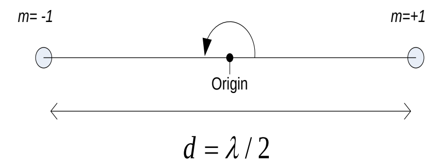

Fig. 1. Rotating linear antenna array.

Let the origin of the array labeled O, P_1 and P_2 are the waves incident on the element after reflection from the target for pulse l = 0 and l = 1 respectively. Let θ_o be the angle of incidence for first pulse i.e. $l = 0$, as illustrated in Fig. 2. The antenna element m = +1 moves from a point A to point B at the time of second pulse i.e. l = 1 as the antenna undergoes a rotation of angle $\theta_r = \omega_a T$. The wave front travels a shorter distance to reach the element m =+1 with angle of incidence θ_1. Simple trigonometry shows that the difference in path lengths is $d\left(\sin\theta_1-\sin\theta_o\right)/2$. As a consequence, a Doppler shift is introduced in the echo due to the antenna motion. The same reasoning applies to element m = -1 with opposite direction of antenna motion.

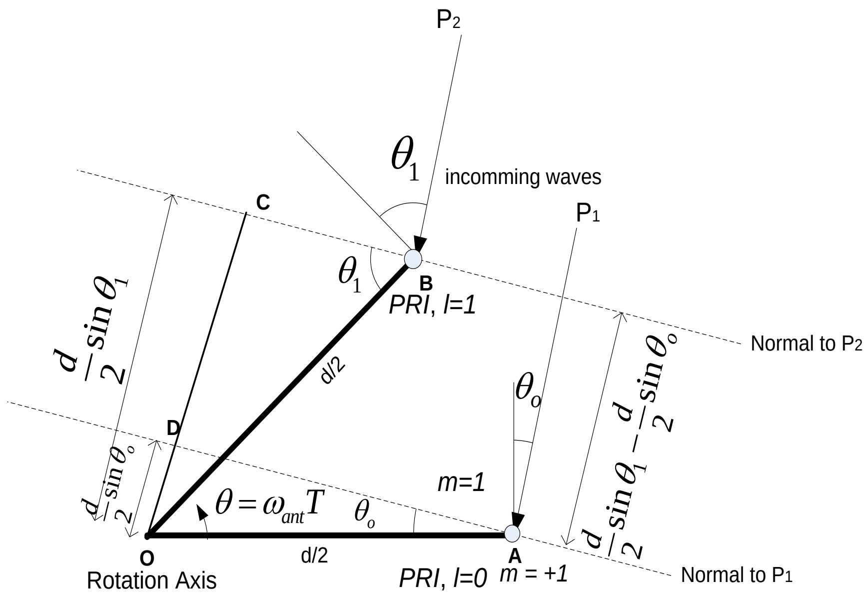

Fig. 2. Rotating antenna array showing signal for different pulses.

The antenna elements receive the echoes independently. The echo from the target contains information about target velocity (Doppler), range (delay) and direction (DOA). The signal reflected back to the antenna m = +1is

$$x_{+1}(t)=P_r\times\begin{bmatrix}2q(t-t_o)e^{j\left(2\pi\left(f+2f_d^t+f_d^a\right)(t-t_o)\right)}\\ \cos\left(2\pi f_d^a\left(t-t_o\right)\right)\end{bmatrix} \quad (1)$$

Received power is given by $P_r=P_tG_tA_rRCS/(4\pi)^2R^4$ [3] where P_t is power of the transmitter, G_t is a gain of the transmitter, $A_r=G_r\lambda^2/4\pi$ is the effective aperture of the receiver, RCS is radar cross section and R is range of target from the radar . Similarly, the signal reflected back to the antenna m = -1 is

$$x_{-1}(t)=P_r\times\begin{bmatrix}2q(t-t_o)e^{j\left(2\pi\left(f+2f_d^t-f_d^a\right)(t-t_o)\right)}\\ \cos\left(2\pi f_d^a\left(t-t_o\right)\right)\end{bmatrix} \quad (2)$$

The antenna Doppler is $f_d^a=v_a/\lambda=v_{\text{tang}}\cos\theta_l/\lambda=r\omega_a\cos\theta_l/\lambda$. For antenna separation $d=\lambda/2$, the radius $r=\lambda/4$, thus $f_d^a=\omega_a\cos\theta_l/4$ which is independent of λ. The total Doppler shift will be $f_d=f_d^t+mf_d^a$.

Since the radar signal processing algorithms are implemented in digital domain, so the data received by the antennas is passed through analog to digital converter (ADC) with a sampling rate of $f_s = 1/T_s$. We can write $x_m(t)\big|_{t=nT_s}=x_m(nT_s)=x_m[n]$, where subtle issues in the process of analog to digital conversion are ignored for brevity and simplicity sake. The antenna scans [5] the azimuth, and L pulses (echoes) are received within a beamwidth [5].

III. Antenna Doppler Adjustment

In this proposed technique, the antenna rotation is compensated at processing stage. This Doppler shift can have two parts: an integer part and a fractional part. The received data is stacked in matrix form, after taking FFT along columns, the Doppler shift is obtained. But it will also include the antenna rotation Doppler. If the resulting data matrix after taking FFT is then shifted along Doppler axis to compensate for the integer part of Doppler due to the antenna rotation (see Fig. 3(b))

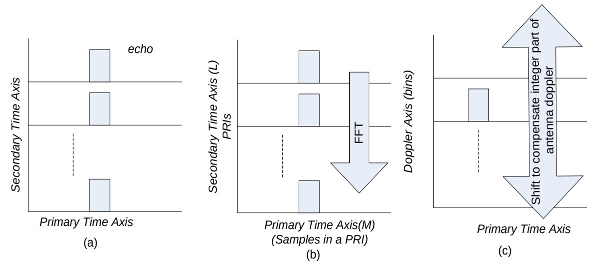

Fig. 3. Compensation in processor.

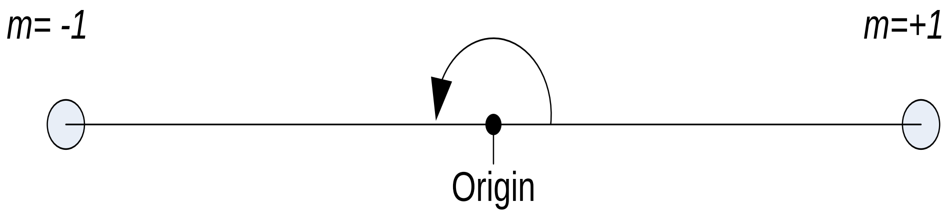

Fig. 4. Two element rotating array.

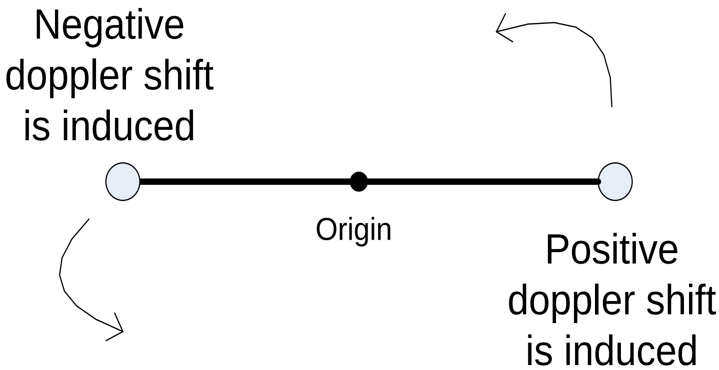

Fig. 5. Doppler effect of array rotation.

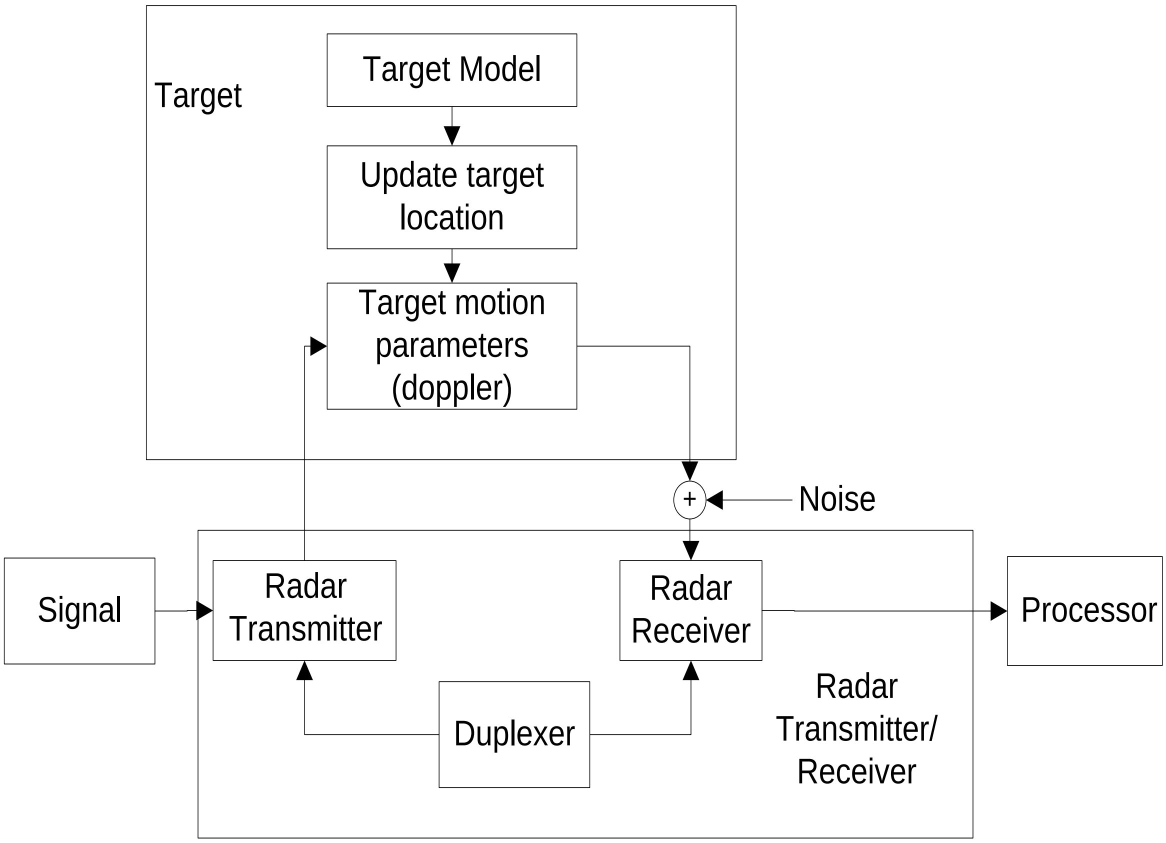

Fig. 6. Simulation diagram

When multiple elements are present, the shifting depends on the position of element with respect to center of array. In Fig. 4, a two element array is considered. During rotation, element $m = +1$ adds right shift and element $m = -1$ shifts left as shown in Fig. 5. For a rotation Doppler of 10 Hz, it is shown in Fig. 7 that the shift for compensation depends on the position of element in array.

The complete simulation environment is shown in Fig. 6.

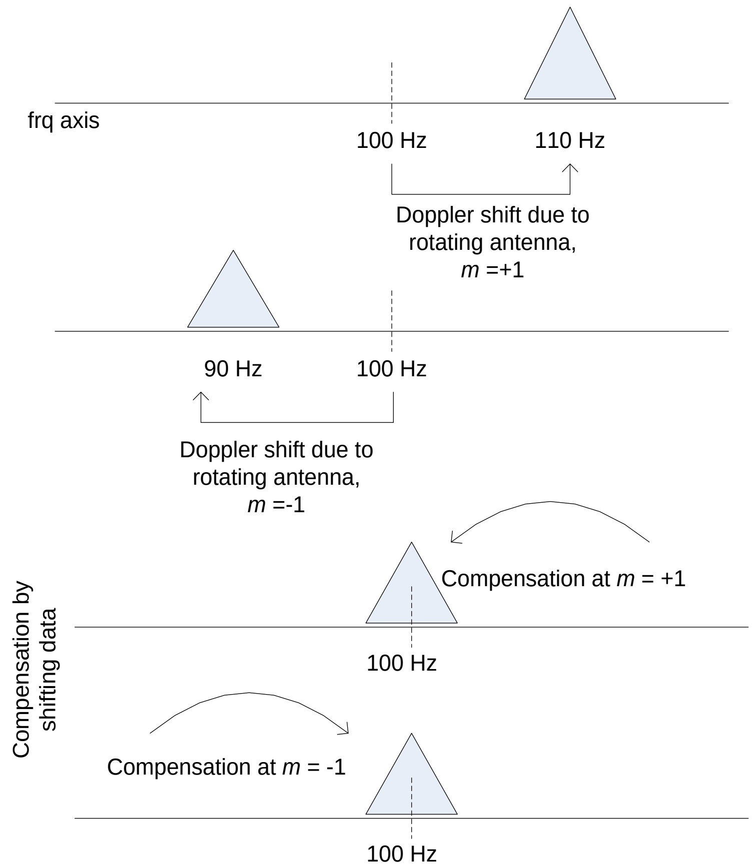

Fig. 7. Compensation of antenna Doppler.

IV. Simulation Results

Consider targets detected. The radar antenna rotates at speed of 90 RPM. Distance between two elements is 1 m. Target 1, having a Doppler of 106.5 Hz, has peaks along Doppler axis at 124.3 Hz and 142 Hz. Two peaks are due to frequency leakage effect across the Doppler bins. Antenna rotation Doppler is added to the actual Doppler of the target. Now if this rotation Doppler is not compensated, inaccurate estimation will be caused. Similar observations can be seen for target 2. Note that the plot is normalized in magnitude.

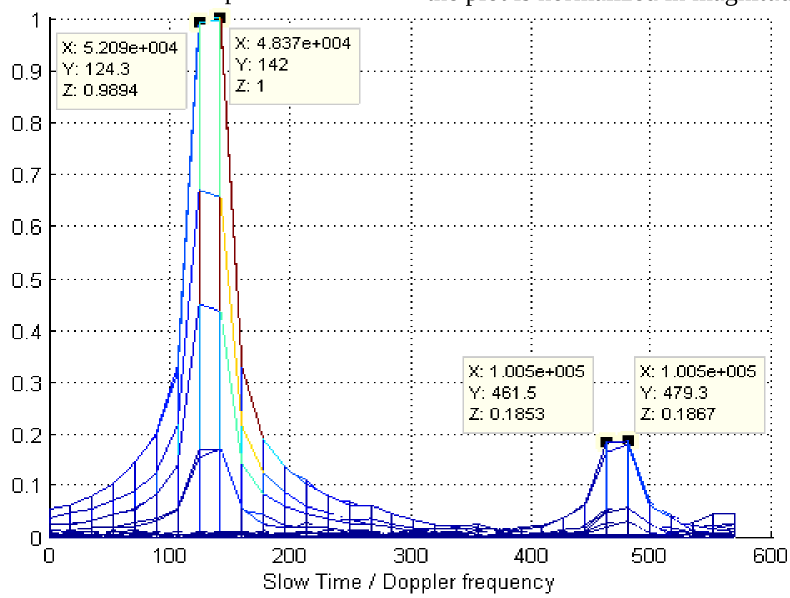

Fig. 8. Target detected without rotation compensation.

To compensate the antenna Doppler, the FFT processed data is now shifted through the proposed technique. The data matrix is shifted down along Doppler axis. As seen in Fig. 9, the FFT processed [6] data is shifted 2 bins to compensate the integer part of the antenna Doppler. So now from both target Doppler frequencies, the integral part i.e. 2 bins is compensated.

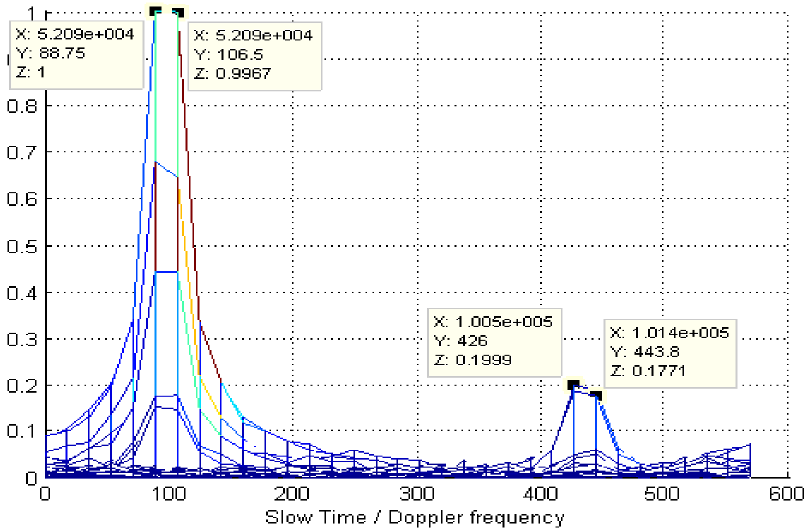

Fig. 9. After antenna rotation compensation.

There is also a frequency leakage. The frequency leakage will be compensated when the data processed from multiple elements is added. To compensate the antenna Doppler, the FFT processed data is shifted through the proposed technique. The data matrix from the element m = +1 is shifted down along Doppler axis and the data matrix from the element m = -1 is shifted up. The FFT processed data is shifted by bins to compensate the integer part of the antenna Doppler. The fractional part will be compensated later on when the processed data from both the elements will be added. So, from both target Doppler frequencies, the integral part i.e. bins is compensated. The frequency leakage will be compensated when the data processed from both the elements' is added in the next step.

The rotation compensation improves the estimation of parameters. The uncompensated parameter estimation of antenna rotation contains errors. The compensation process is completed in the algorithm as shown in Fig. 10

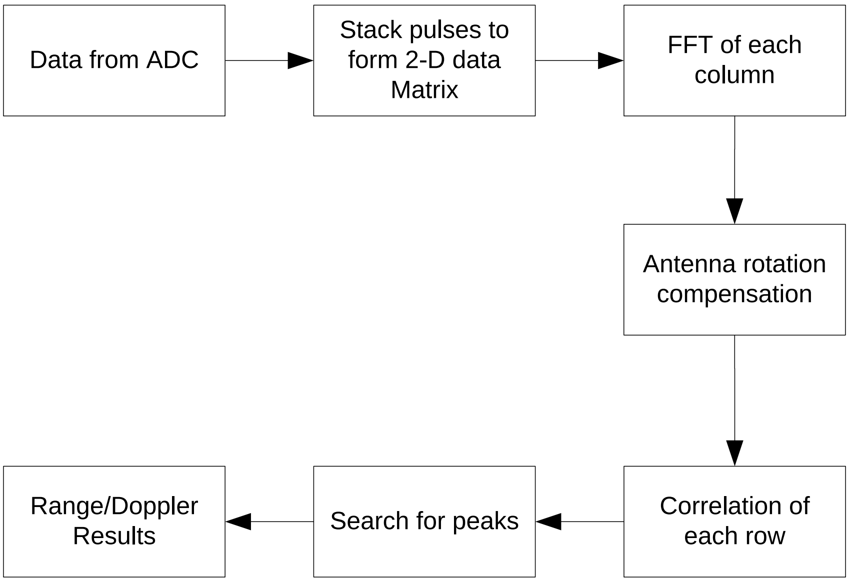

Fig. 10. Antenna rotation compensation block diagram

V. Conclusion

Antenna rotation is modeled completely which is helpful in describing the rotation effects. The proposed antenna rotation compensation techniques are useful for accurate target parameter estimation. Antenna rotation compensation technique is presented in this paper. The mathematical model for rotating antennas is rarely found in literature which is completely presented here. The simulation model was designed to implement rotating radar which was tested for rotating antenna adjustment. The simulation results show that the compensation technique works effectively.

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