Space-Time Adaptive Processing Techniques (STAP) for Mitigation of Jammer Interference and Clutter Suppression in Airborne Radar Systems: A MATLAB Implementation-based Study

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***Abstract*— Radar Systems are used for the detection of objects by transmitting the electromagnetic waves in the free space. They operate in environments where there is a high possibility that the desired echo signal interferes with the signals from other sources. These signals include clutters and jammer signals. The jammer is a device that continuously emits the wideband radio signals in the radar environment, to saturate the receiver with noise or false information. Thus, the total received signal has three components- returns from target, clutter, and jammer combined i.e. it is a three-dimensional signal. The use of conventional signal processing techniques is not desirable, as they cannot separate the desired echo signal from the other components, because the statistics of these components present in the received signal is not known. This problem needs to be accounted for, in airborne surveillance radars, as they have to identify and locate the targets in multiple interference environments. The Space-Time Adaptive Techniques (STAP) is a combination of spatial and temporal filtering that can nullify the jammer signal, and recognize the slow-moving targets. These techniques filter the signal in the angular and the Doppler domain for suppressing the unwanted signals. This paper presents a theoretical study of space-time adaptive coding techniques, and the MATLAB implementation of STAP algorithms; namely, SMI, DPCA, and ADPCA, to suppress clutter and jammer interference in the received pulse.**

Keywords—component, formatting, style, styling, insert (*key words)***

I. INTRODUCTION

STAP is a method for signal processing, very commonly used in radar systems. In this method, the adaptive array processing algorithms are used for detecting the target. The STAP techniques are exclusively used in the scenarios where there is interference from other sources i.e. ground clutter, jamming, etc. Using STAP, the receiver can be made sensitive for reliable target detection [1].

A. REQUIREMENTS OF STAP [2]

STAP radar processing is a combination of temporal and spatial filtering used for the cancellation of jammer signals, and the detection of slow-moving targets. The targets with lesser radial velocity are usually not detected by the radar [2]. The clutter and jammer effects in the Doppler space are shown in Fig. 1[2] shows that there is an erroneous value of the Doppler frequency at the output of the receiver due to the presence of multiple components other than the echo signal corresponding to the actual target.

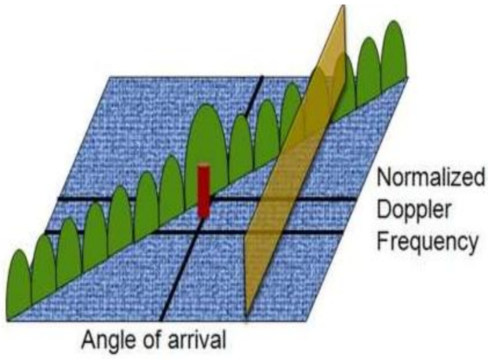

Fig.1 Clutter and jammer effects in the Doppler Space [2]

i. <u>Phased Array Antenna</u> [1-2]: STAP uses a multi-dimensional filtering technique that uses a phased array antenna comprising of multiple spatial channels. These channels are coupled with the pulse-Doppler waveforms, hence the name ‘space-time’ [1]. The array antenna necessary for STAP radar is shown in Fig.2 [2].

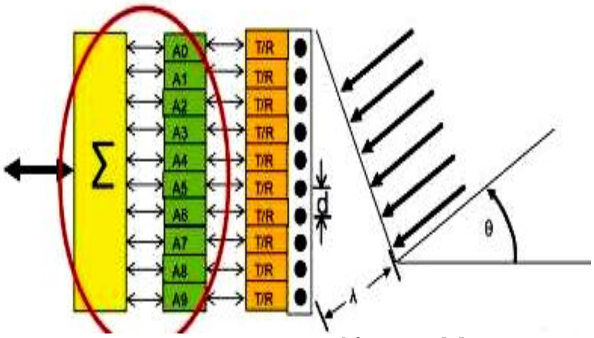

Fig.2 Array Antenna required for STAP [2]

As shown in Fig.2 [2], the raw data is fetched to the STAP Radar Processor. However, there is no involvement of the antenna processor in beam-steering, phase-rotation, or the combined steps. The steering of the antenna beam in this array is possible in both azimuth and elevation [2].

ii. *<u>Formation of weight vector for array signal processing</u> (from [1-2]):* To separate the desired echo signal from the unwanted signal components, the interference environment –statistics is needed. Using the statistics, an adaptive STAP vector is generated, shown in Fig. 3. The adaptive vector represents a series of data which is used to train the receiving signal function in the radar receiver.

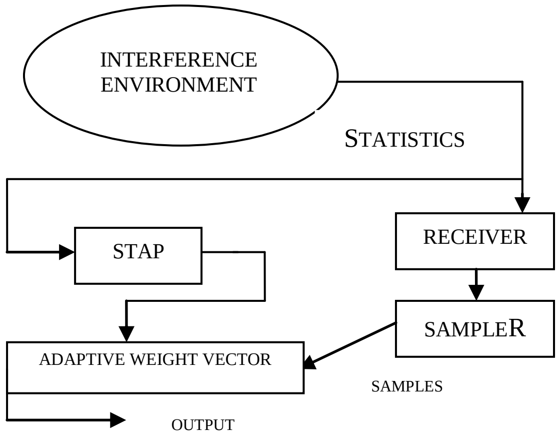

Fig. 3 Schematic Representation of Signal Processing in STAP (drawn from [1])

The received signal from the interference environment is given to the STAP Processor consisting of an adaptive weight vector. The received signals are sampled and applied to the weight vector. After this, the final output is generated.

B. HISTORY AND MOTIVATION [1]

The roots of the theory of STAP, lie somewhere in the year 1959. The theory of STAP was proposed by Lawrence. E. Brennan and Irving S in the early1970s. At these times both of them were at Technology Service Corporation (TSC). The theory was officially put forward in the year 1973 [1].

In ground-based radar, there are clutter signals at the receiver comprising of low frequencies or DC components. It is necessary to distinguish the target from these signals, which is done by using a Moving Target Indicator (MTI) Radar. For this purpose, a notch filter at the zero-Doppler bin is used [1].

i. Problems with Airborne Applications [1]: In airborne radar applications, there is a fair possibility of a relative clutter motion, which is influenced by factors dependent on the angle; which causes the angle-Doppler coupling at the input side. In this case, the filtering of the signal in a single dimension is not sufficient, as the unwanted echo signal overlaps with the Doppler component of the desired target from the multiple directions. The interference of clutters with the desired echo signal in the Doppler domain is called a ‘clutter ridge’, as it forms the angle-Doppler domain. The other sources of interference are the narrowband jamming signals with a considerable amount of spatial correlation. The effect of interference and noise affects the performance; and hence, the detection processors must be designed with the consideration that SINR (Signal to Interference-Noise Ratio) should be maximum [1].

C. THEORY OF STAP (refered[1], also discussed in[3-4])

STAP is a technique of filtering the signal in the ‘space-time’ domain. It implies deploying the filters that can separate the component of echo signals corresponding to the desired target from the clutter and jammer signals present in multiple dimensions. To design a STAP filter, it is needed to find the optimal weights in an M-N dimensional space where M = No. of elements or spatial degrees of freedom, N= Pulse Repetition Interval (PRI) taps or time degrees of freedom

A STAP Filter is equivalent to a two dimensional FIR filter connected in cascade with a bank of one dimensional FIR filters (one filter for each channel). These channels are steered spatially by an array antenna. Ideally, the STAP filters can be designed in such a way that the array response is steered to the response of the ideal target. However, the antenna is steered over the 2-D angle-Doppler plane at discrete points for the potential targets. The procedure is repeated for the all range bins in the system.

Fig .4[1] shows the functional diagram of a two-dimensional STAP processor.

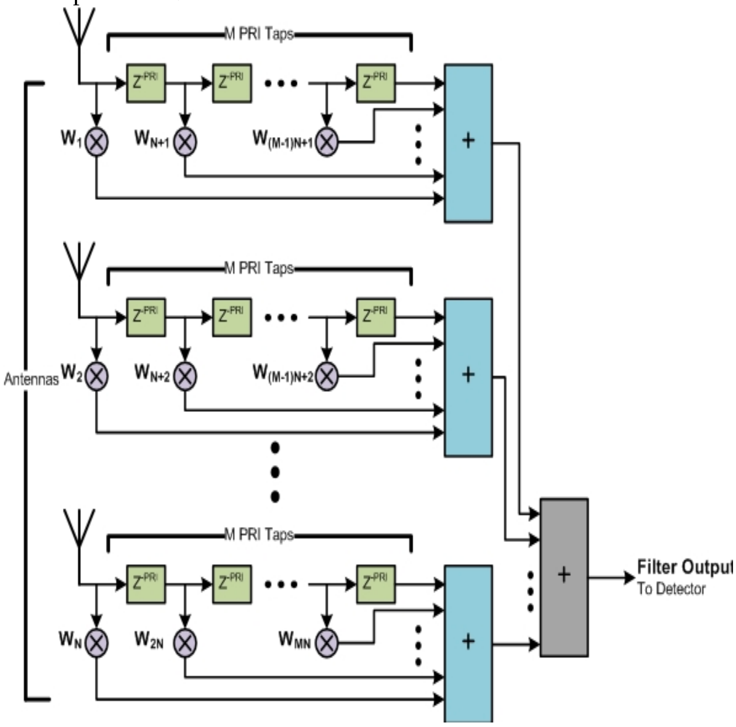

Fig.4 Block Diagram of STAP Processor [1]

The steps involved in a STAP processor are illustrated in Fig.4 [1]. There are multiple receiving antennas in which the signal arriving from the free space will be intercepted. The received signal is then passed through a delay block Z_{PRI}. At the input of each block, the signal will be multiplied by a weight W_N to W_{MN} (for N^{th} antenna element). The output from all the multipliers will be summed up together and fetched to an adder. There will be N such adders corresponding to each element, the output from all the N adders will be summed up and fetched to a detector. The detector-output is the final output. The weights are ordered from W_1 to $W_{MN.}$ These are the degrees of freedom for which the solution has to be found. The Z_{PRI} delay element corresponds to a one-dimensional filter used for steering one antenna channel [1]. The role of STAP is to find the optimal weights maximizing the SINR. These weights are calculated by (1), [1].

$$W = k \times R^{-1} \times s \qquad (1)$$

In (1), k is a scalar; it does not affect the SINR of the received signal. s is the steering vector. The output of the optimal detector is given by (2), [1].

$$y = W \times x \qquad (2)$$

In (2), x is the space-time shot of the input data.

The operation of a two-dimensional STAP filter is summarized in Fig. 5 (refer to the flow-chart).

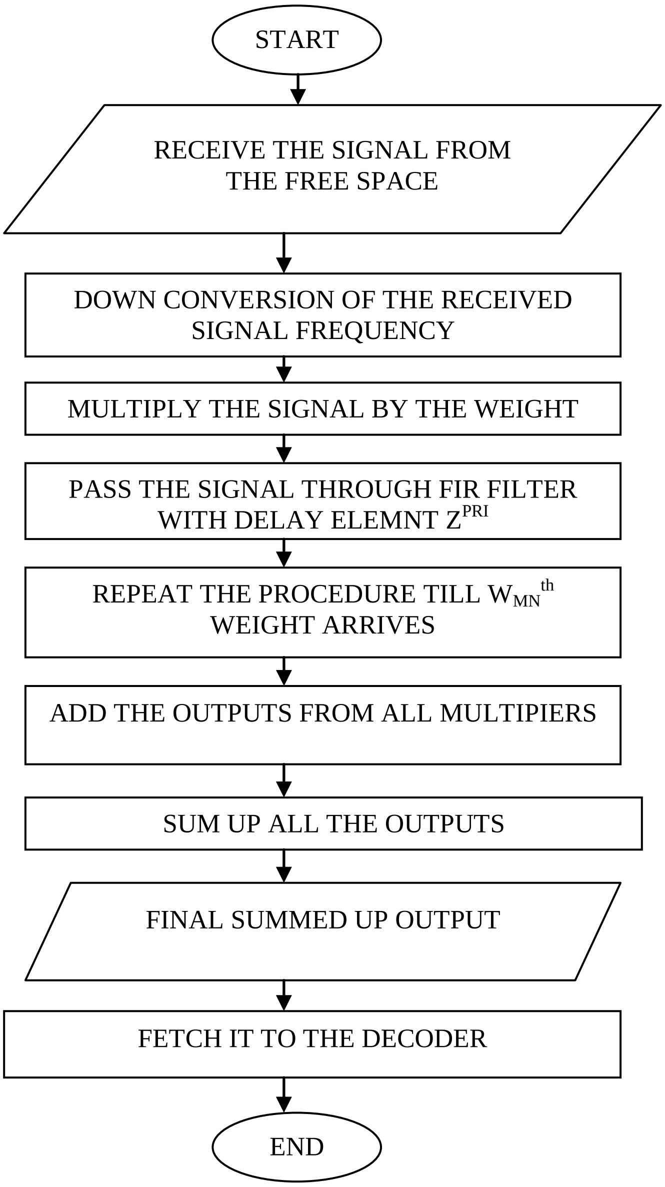

Fig.5 Flow-chart for the steps involved in the STAP Processor (drawn by using information from [1])

D. *DIFFICULTIES IN STAP [1]:*

- i. Solving the unknown covariance matrix $\dot{R}$ and. finding the mathematical inverse of it is difficult.
- ii. If the covariance matrix is not properly conditioned, the inversion of it leads to some absurd numerical value. Thus, it becomes mathematically unstable.
- iii. The computational time and the memory requirement, both are more.
- iv. There is a possibility that steering losses may occur with the antenna elements if the actual target does not lie within the two-dimensional angle Doppler domain, is sampled with the steering vector (s).

E. *APPROACHES FOR STAP[1]:*

The classification of the approaches for STAP can be done in the following two ways, mentioned in [1].

- i. Based on processing taxonomy [5]
- ii. By simplification of the data resources [3]

Fig. 6 [1] shows the classification of the approaches for STAP.

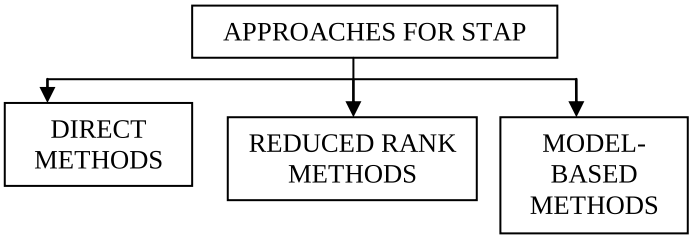

Fig. 6 Classification of the approaches for STAP (drawn from [1])

i. *Direct Methods [1]:* If we exploit all the degrees of freedom, by the optimal processing using the adaptive STAP filter on antenna elements, the solution for the STAP can be obtained. In the direct methods, Simple Matrix Inversion (SMI) is used to obtain the covariance matrix 'R'. This version of the matrix is the estimated version of the matrix and not the actual ones. If the actual covariance matrix is known, there is no need to compute the estimated ones. The values of the optimal weights are decided earlier, and they remain constant. This is known as 'data-independent variation'. In the data-dependent variation, the interference covariance matrix 'R' is estimated from the data. A training sequence is used for this purpose in MIMO. If R is known, the clairvoyant detector is defined by (3), [1].

$$R_k = E\,[x_{k\times}x_k^{H}]|_{H0} \tag{3}$$

In (3), x_k = space-time shot of the statistic for k^{th} range of the cell and H_0 is known as 'the interference only hypothesis'.

Incorporating the effect of interfering noise, clutters, and jammers, the equation (3) can be rewritten as

$$R_k' = 1/P \times \Sigma_{m=0}^{P-1}(x_m \times x_m^{H}) \tag{4}$$

In (4), x_m = the training data set obtained from the input processor of m^{th} range cell. Thus, the average of the space-time shots surrounding the required range is taken. Usually, the space-time shot corresponding to the range of the required cell or an additional cell is not included. This is done to prevent the addition of the white noise to the statistics [1].

The limitations of the direct method are listed below [1]:

1. The major limitation of this method is that there is a computational complexity in the estimation and inversion of covariance matrices of all degrees of freedom.
2. For multidimensional systems, a large number of errorless range cells are required; and, it is difficult to fulfill this requirement.
3. It is necessary that the neighboring cells must consist of stationary statistics as a function of the range, which is an assumption to obtain large number of cells. Example- for optimal, clairvoyant STAP Processor, 2×M×N cells are required for 3 dB degradation in SNR, where (M×N) is the order of the covariance matrix.

For radar systems, it is desirable to have high gain and narrow beams, for long detection, tracking range, and accurate measurement of direction. Hence, the steering losses should be as low as possible. If the steering loss increases; there will be severe performance degradation.

ii. *Reduced Rank Methods [1]:*

Reduced rank methods are designed to overcome the computational complexity of Direct Methods. This is done by reducing the dimensions of the data or rank of the covariance matrix. To achieve this, we form beams and use the STAP with the beam-space. In the beam-space, we can use both pre and post Doppler methods. Some Doppler methods like DPCA (Displaced Phased Center Antenna) are used on the full antenna element input and the data reduction, in this case, takes place in one dimension only. In airborne applications, the radar moves over discrete periods; as a consequence, the clutter is Doppler-free. Hence, the beam should be stationary. In this method, the phase error may degrade the system performance, as the algorithm is non-adaptive to the data obtained from returns. Several other methods operate by reducing the rank of the interference-covariance matrix. Post Doppler methods reduce the STAP problem s follows: MN × MN adaptive filter is reduced to M individual adaptive filters of length N. The adaptive filters are made spatial by using the fixed Doppler processing schemes. These methods also reduce the number of training data frames to estimate the matrix R [1]. These methods are inherently sub-optimal. The example of a technique that compares the direct methods and reduced rank method is given by (5), [1].

$$L_{S,2} = (SINR|_{W=W'}/SINR|_{W=Wopt}) \qquad (5)$$

The numerator of (5) represents the SINR of the system evaluated with sub-optimal weights and the denominator represents the SINR evaluated with optimal weights.

iii. *Model-based Methods[1]*:

In these methods, the covariance interference matrix-structure is used. These methods are generally used to exploit the structure of the covariance interference matrix. The purpose is to model the interference at the point at which it can be processed by using the principal component analysis techniques or diagonal loading SMI techniques. In the SMI techniques, a small magnitude random diagonal matrix is used to stabilize R, before finding R^{-1}. There are two advantages of it, listed below [1]:

1. It de-correlates the Interference Sub-space Leakage (ISL)
2. It resists the Internal Clutter Motion (ICM)

The Principal Component Analysis (PCA) method can be used to estimate the diagonal Eigen values and Eigen vectors after which a covariance taper is applied, followed by the addition of an estimated noise floor. This is represented by equation (6), [1].

$$\widetilde{\mathbf{R}}_{\mathbf{PC-CMT}} = \left(\sum_{m=0}^{P-1} \lambda_m v_m v_m^H \right) \circ T + \sigma_n^2 \qquad (6)$$

In equation (6), [1], λ_m is the m[th] Eigen-value estimated using PCA, T is the estimated covariance matrix taper and σ^2 is the estimated noise floor. After computing the taper matrix, it is applied to the simple form of SMI adaptation of CMT given by equation (7), [1].

$$\widetilde{\mathbf{R}}_{\mathbf{SMI-CMT}} = \widetilde{\mathbf{R}}_{\mathbf{SMI}} \circ T + \delta I \qquad (7)$$

In equation (7), R'_{SMI} is the typical SMI matrix obtained using the approximate method, δ is the diagonal loading factor, and 'I' is the identity matrix of the appropriate dimensions. This is done to improve the standard SMI method, where SMI uses a smaller number of range bins in its average than the standard SMI technique. The matrix is stabilized by the diagonal form of loading, as fewer samples are used in training the data. In some cases, the modeling of the interference is done to enforce the Toeplitz structure, and it makes the system computationally simple. The limitations of these methods are given below [1]:

1. These methods may suffer from the problem of model-mismatch.
2. During the process of fitting the model to Toeplitz matrix and the order estimation, the computational savings may be lost due to the model-mismatch problem.

F. APPLICATIONS OF STAP[1]:

The STAP techniques are mainly developed for RADAR. They can also be used for communication systems. The modern applications of STAP are listed and discussed below.

i. MIMO Communications [1,6]:

In MIMO systems, for dispersive channels, the STAP solution can be formulated. The signal at the receiver can be computed by equation (8). [1].

$$S' = W'^T \times Z \qquad (8)$$

In equation (8), W' is the weighting matrix and Z is the space-time input.

ii. MIMO Radar [1,7]:

The STAP techniques are used in MIMO Radar for the improvement of the spatial resolution of the clutter.

The theory of STAP has been fully discussed in Section I of the paper. The organization of the rest of the paper is as follows: In Section, the methods of STAP for the clutter suppression and reduction of jammer interference, their MATLAB implementation, and the results are discussed. Section III concludes the paper followed by References.

II. STAP METHODS FOR RADAR, IMPLEMENTATION, AND RESULTS

In radar systems, two things affect the performance of a receiver:

1. Clutter
2. Jammer

Both the above factors affect the SINR of the received signal. The received signal contains the echo signal reflected from the target; in addition to it, it also comprises the returns from the surface of the earth. These components present in the received signal are called 'ground clutters' or 'clutters'. For Moving Target Indicator (MTI) Radars, the Doppler component from the return is non-zero. It is also angle-dependent and carries the energy across the Doppler spectrum. Hence, the clutter cannot be filtered with respect to the Doppler frequency. Jamming is also a strong interference-source disturbing the radar signal. Jamming is the process of releasing the Radio Frequency signals into the free-space so that they contaminate the radar signal with the noise or wrong information. STAP Techniques are capable of suppressing the clutter and jammers, as the filtering of the signal is carried in the angular as well as the Doppler domain [8].

The STAP methods used for Clutter and Jammer Suppression in radars (especially airborne radars) are listed and explained below [8].

1. Clutter Suppression with DPCA Canceller
2. Clutter and Jammer Suppression with SMI Beam-former
3. Clutter and Jammer Suppression with ADPCA Canceller

The first method listed above, the Displaced Phased Center Antenna (DPCA) is considered to be first or the initial algorithm of STAP to be used in radar systems. Using this algorithm, the platform motion can be compensated using the shift in the antenna aperture. Thus, the removal of the clutter component is accomplished by subtraction of two consecutive radar pulses. This algorithm can be used if the below-listed conditions are satisfied:

1. Clutter should be stationary for all the radar pulses
2. The equation (8), [9] must be satisfied by the target.

$$v \times T = 0.5 \times d \qquad (8)$$

In (8), v is the radial velocity of the target, T is the Pulse Repetition Time (PRT), and d is the distance between the neighboring antenna array-elements.

The second method is used to suppress clutter and jammer simultaneously. The SMI beam-former works similarly to the DPCA Canceller. But, the additional information of the guard cells and training cells is needed. The reason for is that the space-time covariance interference matrix R is exactly not known, the SMI algorithm is used. The samples in the training cells are used to compute the interference. In this method, there exist separate cells other than the target cells. These cells are known as ''guard cells'. The number of training cells must be even and equally divided in front of the target and the backside of it. Note that the number of training cells is directly proportional to the quality of the interference estimate.

The third algorithm functions similarly to DPCA, but in addition to the clutter suppression, it minimizes the jammer interference too. Since only two consecutive pulses are used, the computational cost is less.

The MATLAB-implementation of the algorithms was carried out by referring to the MathWorks examples [8-10].

Consider an airborne platform modeled by a five-element Uniform Linear Array (ULA). The array elements have the distance (d) = 0.5 ×λ at 3 GHz. Suppose that the transmitter emits eight rectangular pulses of 2 microseconds in duration with a PRF of 6 GHz. The target has a cross-sectional area of 0.5 m^2 and moves with a constant velocity of the vector (15. 15, 0) [9]. The echo signals will arrive at the radar pulse-by-pulse i.e. every transmitted pulse will have a corresponding echo pulse. All the echo pulse will be collected by the receiver and integrated. The non-coherent method of integration used for it. A non-coherent integrator will combine the N-radar pulses and after the integration is done, the threshold checking is done. The received signal is first applied to the matched filter (IF Amplifier). The IF frequency is the intermediate frequency-value to which the received signal is down-converted. After the down-conversion is complete, the signal undergoes square-law detection. During the process of amplitude detection, the phase-information gets lost. The output of integrator is fetched to a threshold detector. Now, the comparison of the signal with the threshold value is done, to get the final output. The non-coherent integration of the 1^{st} Pulse at the five-element ULA (Uniform Linear Array) is shown in Fig.7.

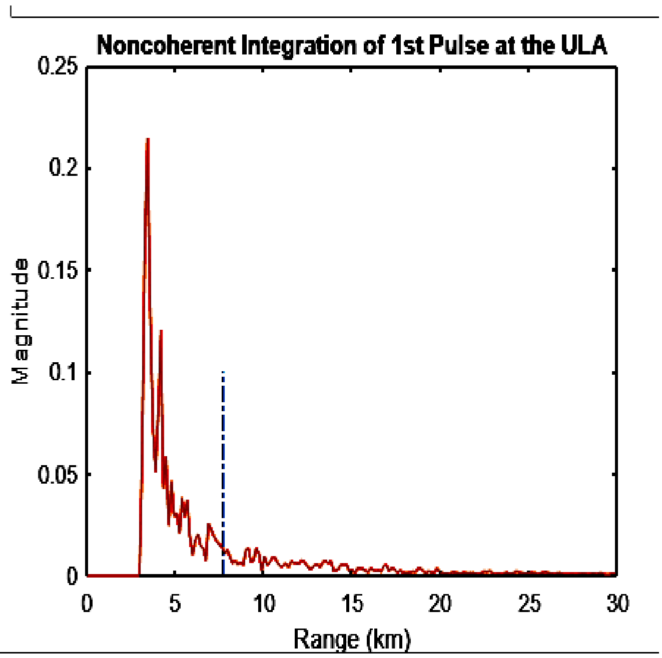

Fig. 7 Non-coherent Integration of 1^{st} Pulse at ULA

The maximum amplitude of the received pulse is 0.2146 at the range of magnitude 3.448 kilometers.

It becomes difficult to detect the target as the amplitude of the clutter in the received signal is large. By applying DPCA, the clutter is suppressed. The DPCA canceller output is shown in Fig.8.

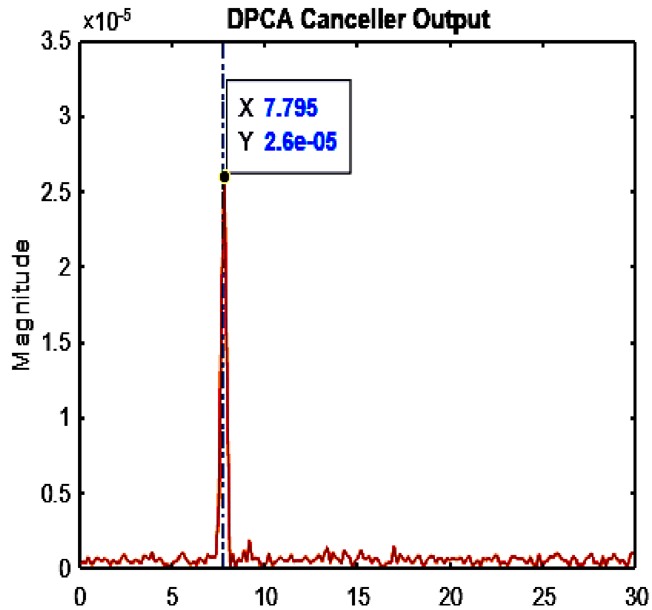

Fig. 8 DPCA Canceller Output

The amplitude of the clutter has brought down the amplitude of the clutter to 2.6×10^{-5} and the range is increased to 7.795 kilometers. Suppose that the barrage jammer situated at (3.5e3, 1e3, 0) with EIRP = 1 kW. A SMI beam-former using 100 training cells equally distributed on each side of the target with 4 guard cells is built. It has two range gates. Fig. 9 shows the output of the beamformer after beam-forming. The output of the SMI beamformer for two sets of data is plotted, seen in Fig. 9

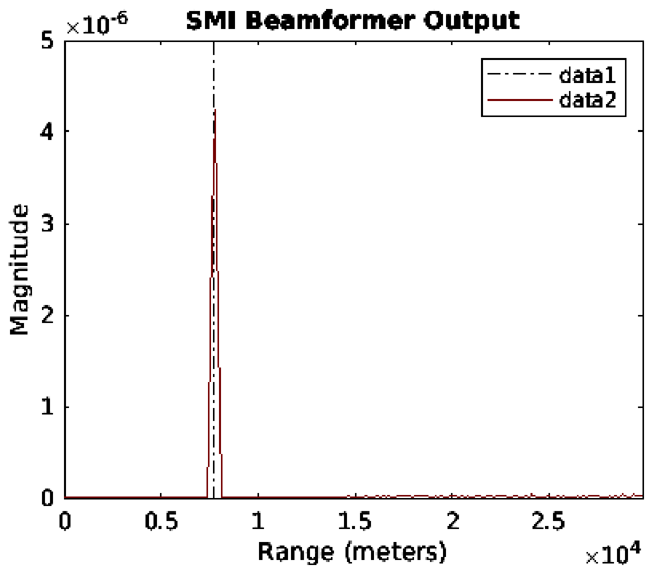

Fig. 9 The output of SMI beam-former

The amplitude of the clutter is reduced to 4.235 $\times 10^{-6}$. The SMI Weights Angle-Doppler Response at zero degree elevation is shown in Fig. 10

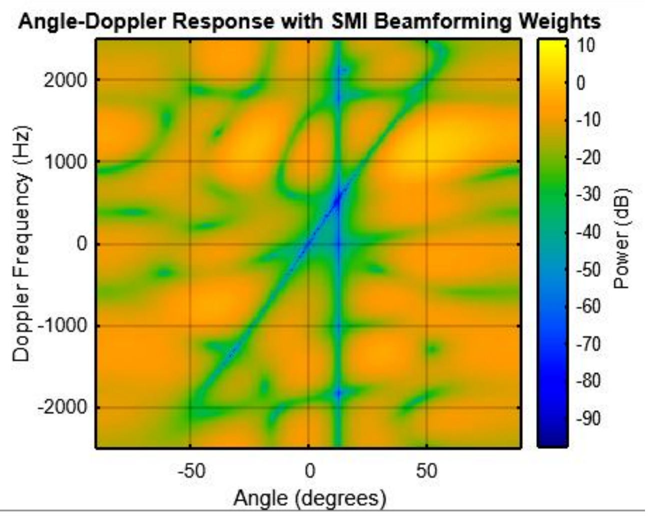

Fig .10 Angle-Doppler Response with SMI Beamforming Weights

From Fig. 10, it is clear that the SMI beam-former can separate the clutter and jammer signals in the radar return. It is seen from the Doppler pattern that there is a big null along the jammer direction. The simulation performed in the MathWorks example [8], shows that the Angle-Doppler response is the same for the ADPCA Canceller.

In ADPCA Method, the results of the simulation performed in the MathWorks example [8], show that in the output of the canceller (with Jammer), the magnitude of the unwanted signal components present in the return is reduced by maximum value.

III. CONCLUSION

In this paper, Space-Time Adaptive Processing (STAP), and the algorithms based on it for the clutter and jammer-reduction in airborne radar systems is discussed. Using the MathWorks Examples [8-10], the simulation was performed, and it was observed that the algorithms DPCA and SMI can be used to reduce the magnitude of the clutter and jammer in the radar-return to a substantial level. The Angle-Doppler response of the SMI beamformer shows that it can isolate the clutter and the jammer signal, and nullify the two.

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