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Digital Beamformation Technology in Scan Radar and Its Essentiality for Achieving Predefined Surveillance under Air-borne Operations

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Authors' contributions

This work was carried out in collaboration between all authors. Author DB designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript and managed literature searches. Authors RB, MG and SD managed the analyses of the study and literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Aims: To develop a precise Digital Beam Forming control at the receiver of a Digital RADAR under clutter condition.

Place and Duration of Study: Electronics & Communication Engineering Department, Sikkim Manipal Institute of Technology, Sikkim, India, between March 2012 and May 2012.

Methodology: Under a slow motion clutter environment, the target dimension is being varied i.e., appearing different targets with descending order RCS, the receiver performance is tested in terms of detectability of the target. Then at each case it has been observed how the target peak is gradually reduced w.r.t the decreasing RCS of the target. But, after employing the precise Digital Beam Formation at the receiver towards the lowest RCS target, it has been observed that by what extent, the target peak is improved in order to get a sustainable target to clutter ratio.

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Results: In Case-1, Digital Beamformation is done in an arbitrary direction & the Signal-to-Clutter Ratio (SCR) is noticed for larger as well the smaller dimension target. In Case-2, the Tx and Rx Beamformation is done towards larger dimension target. Keeping the dimension of the larger target constant, the dimension of the smaller target is gradually decreased and the decreasing SCR is noticed at the output of the receiver beamformer. At a certain decreasing value of smaller target RCS, the target gets hidden in clutter and not being detected. Under Case-3, the receiver Beamformation direction has been switched towards the smaller target so as to successfully retrieve the smaller target from clutter.

Conclusion: By the precise Digital Beam Forming control at the receiver, the Signal-to-Clutter Ratio (SCR) of the smaller target as discussed in Case 3, is improved by a great extent. Due to the limitation of the system dynamic range the smaller RCS target can't be distinguished from clutter, but at this condition, if the precise Digital Beam Forming (DBF) towards an optimum direction can be formed, it may help at a great extent to find the smaller RCS target being distinguished from the clutter. The simulation results in this paper prove the fact with vivid depictions and clarifications.

Keywords: Digital beam forming; radar RCS; clutter; target; signal-to-clutter ratio.

1. INTRODUCTION

Digital Beamforming is a signal processing technique used in sensor arrays for directional signal transmission or reception. This is achieved by combining elements in the array in a way where signals at particular angles experience constructive interference and while others experience destructive interference. Beamforming can be used at both the transmitting and receiving ends in order to achieve spatial selectivity. The improvement compared with an omnidirectional reception/transmission is known as the receive/transmit gain (or loss).

Beamforming can be used for both radio and sound waves. It has found numerous applications in radar, sonar, seismology, wireless communications, radio astronomy, speech, acoustics, and biomedicine. Adaptive Beamforming is used to detect and estimate the signal-of-interest at the output of a sensor array by means of data-adaptive spatial filtering and interference rejection [1].

Beamforming takes advantage of interference to change the directionality of the array. When transmitting, a beamformer controls the phase and relative amplitude of the signal at each transmitter, in order to create a pattern of constructive and destructive interference in the wave front. When receiving, information from different sensors is combined in a way where the expected pattern of radiation is preferentially observed.

Digital Beamforming is provided for use with electronically scanned radar. In an aspect, the present invention provides enhanced sensitivity, wide angle or field of view (FOV) coverage with narrow beams, minimized number of receivers, reduced side lobes, eliminated grating lobes and beam compensation for target motion [1,2]. In an aspect, the present invention employs a uniform overlapped sub array feed network, a time multiplexed switch matrix, and a restructured digital signal processor. Antenna channels share a receiver, rather than maintain a dedicated receiver for each antenna element, as in conventional systems. In an aspect, Doppler/frequency filtering is performed on each antenna element or sub array output prior to Digital Beamforming. Further, Doppler compensation is employed following Doppler/frequency filtering, followed by Digital Beamforming. An antenna having a tiled architecture with overlapping sub array in two dimensions is disclosed. Each tile has two orthogonal ports and there is no physical interconnection between adjacent tiles. The outputs are coupled to individual receivers. The outputs of ports from n adjacent tiles are digitally combined to form an overlapping sub array [3].

2. SCHEMATIC DESIGN OF DIGITAL BEAM FORMER IN ASCAN RADAR

The Digital Beam Formation is applicable to a Phased Array Antenna System. Now there should be a brief illustration on what is Phased Array Antenna System. A phased array is an array of antennas in which the relative phases of the respective signals feeding the antennas are varied in such a way that the effective radiation pattern of the array is reinforced in a desired direction and suppressed in undesired directions. An antenna array is a group of multiple active antennas coupled to a common source or load to produce a directive radiation pattern. Usually, the spatial relationship of the individual antennas also contributes to the directivity of the antenna array [4].

At each antenna element of the receive phased array antenna there is a receiver whose analog signal is digitized by the 10-bit A/D converter as shown in Fig.1. Once the digital numbers are obtained at each element, they can be used for many purposes simultaneously. Spatial beam forming is done first to provide N fixed receiving beams.

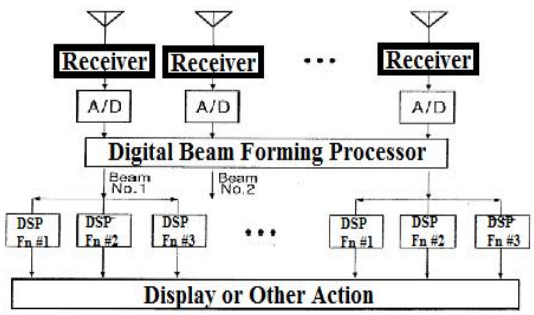

Fig. 1. Multi DSPs involved in Receiver Digital Beam Formation

The Digital Beam Formation is a DSP technique which is done within the Workstation dedicated after the Receiver (Vector Signal Analyzer) section of the Scan RADAR utilizing rectangular phased array antenna system [4]. So, in digital beam forming there is no actual radiation pattern in space. The "pattern" resides in the computer and is evident as the variation of the output response of the signal processor as a function of the angle of arrival of the received signal. At the output of each beam there are multiple digital signal processors to simultaneously provide the various radar functions. In Air-borne applications, phased array radars utilize this Digital Beam Former at its receiver computer, because (1) it can perform multiple functions simultaneously and (2) its radiated signal can be considerably more difficult to intercept because of its much lower peak power.

Multifunction air-defense radar systems usually have different ranges and different data rates. An air defense radar might have to perform the following:

- Long range surveillance at low data rate. The revisit time might be 10 or more seconds. The range to a target might be from 100 to over 200 nmi.
- Surveillance and target acquisition at medium ranges. Medium ranges might be below about 100 nmi and revisit times about 4 s.
- Short-range surveillance (pop-up targets). This might be at ranges from 10 to 20 nmi or less, with revisit time of about one second.
- Weapon control. A high data rate (short revisit time of about 0.1 s) at short and moderate ranges, up to 30 to 40 nmi (but could be more).
- Noncooperative target recognition. This is desired at any range and can require relatively long dwell times.

3. MATHEMATICAL MODELLING TO EXTRACT WEIGHT VECTOR OF A DIGITAL BEAMFORMER

With narrow-band systems the time delay is equivalent to a "phase shift", so in this case the array of antennas, each one shifted a slightly different amount, is called a phased array. A narrow band system, typical of radars, is one where the bandwidth is only a small fraction of the centre frequency. With wide band systems this approximation no longer holds, which is typical in sonars.

In the receive beamformer the signal from each antenna may be amplified by a different "weight." Different weighting patterns (e.g., Dolph-Chebyshev) can be used to achieve the desired sensitivity patterns. A main lobe is produced together with nulls and sidelobes. As well as controlling the main lobe width (the beam) and the sidelobe levels, the position of a null can be controlled. This is useful to ignore noise or jammers in one particular direction, while listening for events in other directions. A similar result can be obtained on transmission. For the full mathematics on directing beams using amplitude and phase shifts, see the mathematical modeling and illustrations under this section [5,6].

Beamforming techniques can be broadly divided into two categories:

- Conventional (fixed or switched beam) beamformers
- Adaptive beamformers or phased array

- Desired signal maximization mode
- Interference signal minimization or cancellation mode

- Conventional Beamformers use a fixed set of weightings and time-delays (or phasings) to combine the signals from the sensors in the array, primarily using only information about the location of the sensors in space and the wave directions of interest. In contrast, adaptive beamforming techniques generally combine this information with properties of the signals actually received by the array, typically to improve rejection of unwanted signals from other directions. This process may be carried out in either the time or the frequency domain.
- As the name indicates, an Adaptive Beamformer is able to automatically adapt its response to different situations. Some criterion has to be set up to allow the adaption to proceed such as minimising the total noise output. Because of the variation of noise with frequency, in wide band systems it may be desirable to carry out the process in the frequency domain.

If we assume, the antenna array as symmetric then, for every antenna element at location 'd_n' there is an antenna element at location '$-d_n$', both multiplied by the same weight w_n.

One more assumption can be made, that the array lies along the z-axis and is centered at z=0 and has a uniform spacing equal to 'd'.

The array factor can be given by:

$$AF = \sum_{n=1}^{M} w_n e^{-jk(2n-1)\frac{d}{2}\cos\theta} + \sum_{n=-M}^{-1} w_n e^{-jk(2n-1)\frac{d}{2}\cos\theta} \quad \text{(even array)} \qquad \text{………………(1)}$$

The array is even if there are even number of elements (no element at the origin) or odd if there are an odd number of elements (an element at the origin).

Complex-exponential formula for the cosine function.

$$\cos(x) = \frac{e^{jx} + e^{-jx}}{2} \qquad \text{………………..} \quad (2)$$

The array factors can be rewritten as:

$$AF = \sum_{n=1}^{M} w_n \cos[(2n-1)u] \quad \text{(even array)}$$

$$AF = \sum_{n=0}^{M} w_n \cos(2nu) \quad \text{(odd array)}$$

$$u = kd\cos\theta/2 \qquad \text{…………..(3)}$$

The no. of A/D conversion bits control the angular resolution of the synthesized beam out of the phased array and thereby affects the variable 'u'. Higher the no. of A/D conversion bits, the more will be the spatial (angular) resolution. The Dolph–Chebyshev function has been actually constructed by using the well-known Chebyshev polynomials and was first used by Dolph (1946) to solve the problem of designing a radio antenna having optimal directional characteristics (Kraus 1988) [6]. The Chebyshev polynomials are defined by the following equations:

$$T_n(x) = \begin{cases} \cos(n\cos^{-1} x), & |x| \le 1; \\ \cosh(n\cosh^{-1} x), & |x| > 1; \end{cases} \qquad \text{……….} \quad (4)$$

From the definition, the following recurrence relation follows immediately;

$$T_0(x) = 1, \quad T_1(x) = x,$$
$$T_n(x) = 2xT_{n-1}(x) - T_{n-2}(x), \quad n \ge 2 \quad \dots \quad (5)$$

The following properties are easily derived from the definition: $T_n(x)$ is an n^{th}-order polynomial in x, even or odd accordingly as n is even or odd; $T_n(x)$ has n zeros in the open interval (-1, +1) and n+1 extrema in the closed interval [-1, +1]; $T_n(x)$ oscillates between -1 and +1 for x in [-1, +1]; $T_n(x)$>1 if x>1; for large x, $T_n(x)$ ≈ 2n-1xn.

Let's match the expression in equation (3) to the above Chebyshev polynomials (eq. 4) in order to obtain an equil-sidelobe design of the Digital Beamformer.

To do this, we recall some trigonometry which states relations between cosine functions

$$\cos(2u) = 2\cos^2 u - 1$$
$$\cos(3u) = 4\cos^3 u - 3\cos u$$
$$\cos(4u) = 8\cos^4 u - 8\cos^2 u + 1$$
$$\cos(5u) = 16\cos^5 u - 20\cos^3 u + 5\cos u$$
$$\vdots \qquad . \qquad (6)$$

Let's substitute these expressions into the Antenna Array Factors given in equations (1) and (3), and introduce a substitution:

$$\cos(u)t_0 = t \qquad (7)$$

By this method, the Array Factor (AF) can be constructed and the AF is a polynomial. We can now match this polynomial to the corresponding Chebyshev polynomial (of the same order), and determine the corresponding weights, w_n.

The parameter 't_0' is used to determine the sidelobe level. Suppose there are N elements in the array, and the sidelobes are to be a level of S below the peak of the main beam in linear units (note, that if S is given in dB (decibels), it should be converted back to linear units SdB=20*log$_{10}$(S). The parameter 't_0' can be determined simply from:

$$t_0 = \cosh\left[\frac{\cosh^{-1}(S)}{N-1}\right] \qquad (8)$$

The Dolph-Chebyshev method can be introduced for having an optimal directional characteristic of the phased array Receiver antenna system or in other way to achieve highly accurate Digital Beamformation that is significant during airborne scanning radar operation. In this part, we'll run through an example. Let's consider a N=6 element array, with a sidelobe level to be 30 dB down from the main beam (S=31.6223). Let's also assume the array has half-wavelength spacing, and recall that the Dolph-Chebyshev method requires uniform spacing and the array to be steered towards broadside. The array has an even number of elements, so the array factor can be written as:

$$AF = \sum_{n=1}^{3} w_n \cos[(2n-1)u] \qquad \text{……….} \quad (9)$$

$$u = \pi \cos(\theta / 2) \qquad \text{……….} \quad (10)$$

Using the trigonometric identities for the cosine function, the above equation can be rewritten as:

$$\begin{aligned} AF &= w_1 \cos(u) + w_2 \cos(3u) + w_3 \cos(5u) \\ &= w_1 \cos u + w_2 (4\cos^3 u - 3\cos u) + w_3 (16\cos^5 u - 20\cos^3 u + 5\cos u) \\ &= \cos u (w_1 - 3w_2 + 5w_3) + \cos^3 u (4w_2 - 20w_3) + \cos^5 u (16 w_3) \end{aligned} \qquad \text{………} \quad (11)$$

Now, for the above case, i.e., considering N=6 element array & a sidelobe level to be 30 dB down from the main beam (S=31.6223), the parameter 't0' is calculated as:

$$t_0 = \cosh[\cosh^{-1}(31.6223)/(\text{N-1})] = 1.3641 \qquad (12)$$

So, from eq.(7), it can be written as: cos(u) = (t/1.3641). Now the cos(u) in equation (11) can be substituted by (t/1.3641). As, in the above design, it has been considered that the phased array has N = 6 no. of elements, so, we have a polynomial of order N-1 = 5, so we'll use the Chebyshev polynomial T5(t), and equate that to the new array factor (AF):

$$\begin{aligned} AF &= \left(\frac{t}{1.3641}\right)(w_1 - 3w_2 + 5w_3) + \left(\frac{t}{1.3641}\right)^3 (4w_2 - 20w_3) + \left(\frac{t}{1.3641}\right)^5 (16w_3) \\ &= T_5(t) \\ &= 16t^5 - 20t^3 + 5t \end{aligned} \qquad \text{………}(13)$$

The above equation is valid for all values of t. Hence, the terms that multiply t must equal, the terms that multiply t cubed must be equal, and the terms that multiply t to the 5th power must be equal. As a result, we have 3 equations and 3 unknowns, and we can easily solve for the weights:

$$w_1 = 15.9778; \quad w_2 = 10.9243; \quad w_3 = 4.7231;$$

The resulting normalized Array Factor (AF) is plotted in the following Figure.

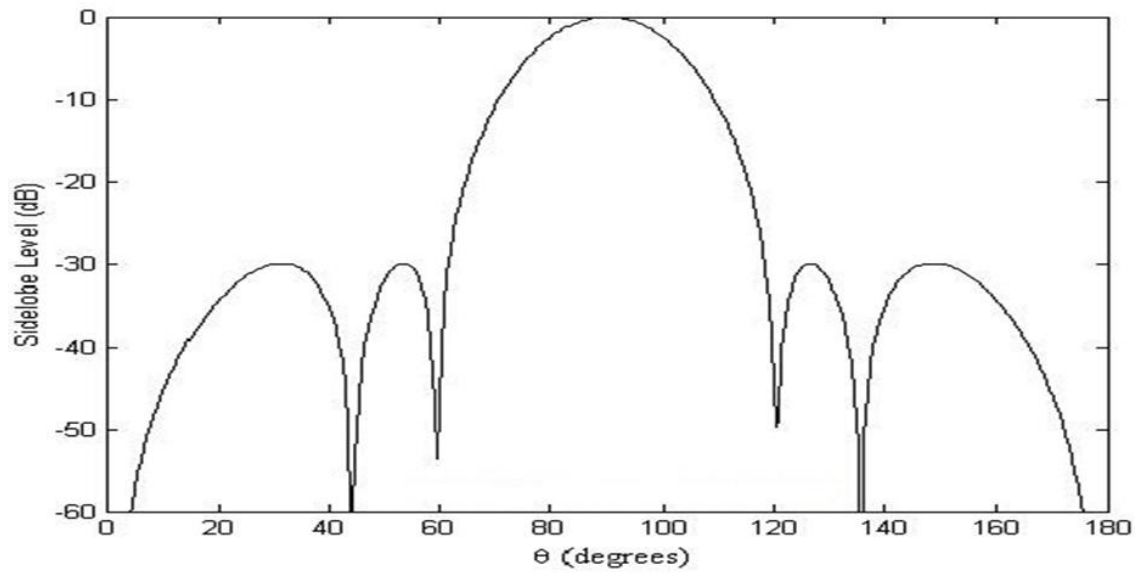

Fig. 2. Normalized array factor with sidelobe level around -30dB

The sidelobes are equal in magnitude and 30 dB down from the peak of the main beam. The beamwidth obtained here (approximately 60 degrees) is the minimum possible beamwidth obtainable for the specified sidelobe level. The weight vector for Digital Beam Formation is used as calculated above (i.e $w_1 = 15.9778; \quad w_2 = 10.9243; \quad w_3 = 4.7231$).

So, if any desired Target signal exists in front of the scan Radar, the main-lobe would be responsible for acquiring it, whereas the unwanted events like clutter or jammer signal will automatically fall under the null-point between the sidelobe & main-lobe of the Digitally Beam Synthesized pattern as obtained in Fig. 2.

4. DESIGN ASPECTS & PARAMETERS

For detecting multiple targets through Airforce Scan RADAR, we follow the Digital Beamformation Technique at the RADAR Receiver. Here, we have considered two stationary targets at the War-Field, and the Airborne RADAR is moving with a supersonic speed of 300 m/sec above the sky [7].

Here, Digital Beamformation is done for three cases:

- ✓ First at an arbitrary angle
- ✓ At an angle directed towards the target with bigger RCS
- ✓ At an angle directed towards the target with smaller RCS

4.1 Modeling the Target & Target Return Propagation Channel

4.1.1 Matlab programmatic approach used for realization

Here, we define object for two targets whose mean RCS are 1.1 m2 and 3 m2, operating frequency is 1.45 GHz, initial position at [10000; 500; 200] and [5500; 100; 0] respectively, with zero velocity. Also, we calculate the range, angle, and speed of each target. The code designing has been done in MATLAB for simulating the War-Field stationary targets and its corresponding Return signal propagation channel up to the Scan Radar Receiver front end. At the receiver front-end, the temperature stability is maintained through a precise LNA whose noise figure is typically 1.4 dB. The team at SMIT worked for this experiment using the effects of DBF at the receiver side of the scan RADAR depending on the RCS variation of the corresponding War-Field targets.

Now, by using Matlab embedded class phased. Free Space (.), we define propagation channel for each target. There, the parameter 'f_s' takes the value for which the baseband waveform sampling rate is matched and the no. of A/D conversion bits fit with the target spatial resolution.

As the reflected signals are received by an array, we use a beamformer pointing to an arbitrary angle (in the first case i.e., CASE 1) to obtain the combined signal. To Create the steering vector for transmit beamformer, the Matlab inbuilt class ‘phased. Steering Vector (.)’ has been utilized.

To Create the receiving beamformer, another Matlab class viz. ‘phased. Phase Shift Beamformer(.)’ has been used.

CASE 1: Beamformation takes place at an arbitrary angle [100; 300] i,e [azimuth; elevation] to form a narrow sharpened beam (see above Fig. 3).

At each token of outgoing pulse, the Matlab ‘step(.)’ function has been implemented for achieving the steering vector directed towards an a desired angle. And finally Digital Beamformation is obtained at the receiver of the scan RADAR.

After this, we do matched filtering and pulse integration on the [200 x 10] data matrix obtained after DBF at an arbitrary angle. The receiver DSP is involved to do this DBF.

5. RESULTS ANALYSIS

The Fig. 4 depicts the pulse integrated signal after the Beamformation and matched filtering. The signal to clutter ratio is 17.17 dBm for target with larger RCS and 13.75 dBm for the target with smaller RCS.

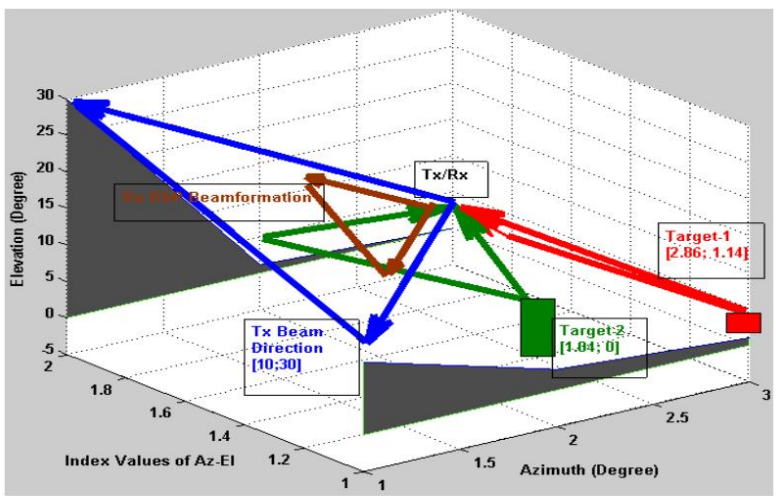

Fig. 3. Beamformation direction for Tx & Rx not alligned with any of the targets

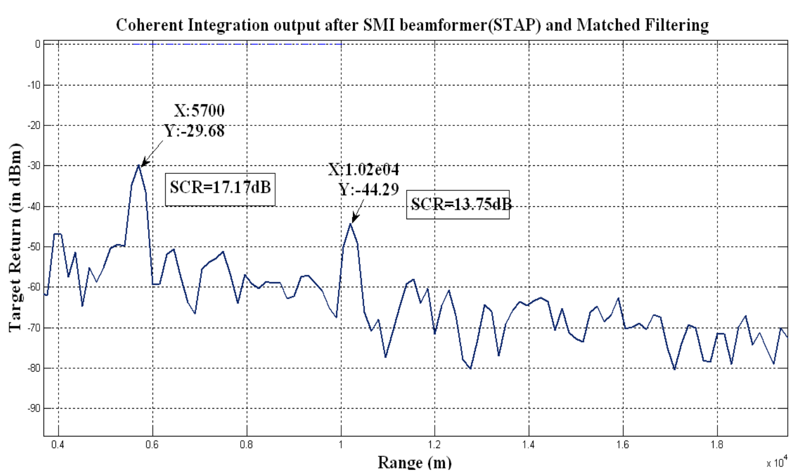

Fig. 4. Coherent pulse integration output after receiver digital beamformer and matched filtering

The Slow motion Clutter has been considered while the phased array RADAR from Air-Defence Plane looks onto the battle ground for predefined surveillance zone like Army base communication point/ war-field communication control networking center, at that time, the slow moving War-Tankers are considered as clutter to the Airborne RADAR flying with a supersonic speed 300m/sec on the sky [8]. The DBF processing at the receiver of the scan RADAR can generate a [200 x 10] complex data matrix. It is then passed through the next processing stage where Matched filtering and coherent pulse integrations are done but the angle-Doppler response is extracted with pulse Doppler filtering of the complex valued matrix achieved after DBF above. So, the Doppler information of the slow moving clutter w.r.t its angle of arrival from the battle-ground is processed by FFT based Moving Target Detection method. The outcome is the Angle-Doppler Response Pattern as shown below in Fig. 5.

CASE 2: Now we move on to the next case in which the Beamformation is done in the direction of the target having larger RCS. Keeping the RCS of the larger target constant and varying the RCS of the other target (which has smaller RCS) we record and compare the pulse integrated outputs of all cases. The changes reflected in the graphs are (see Fig. 6-8.6).

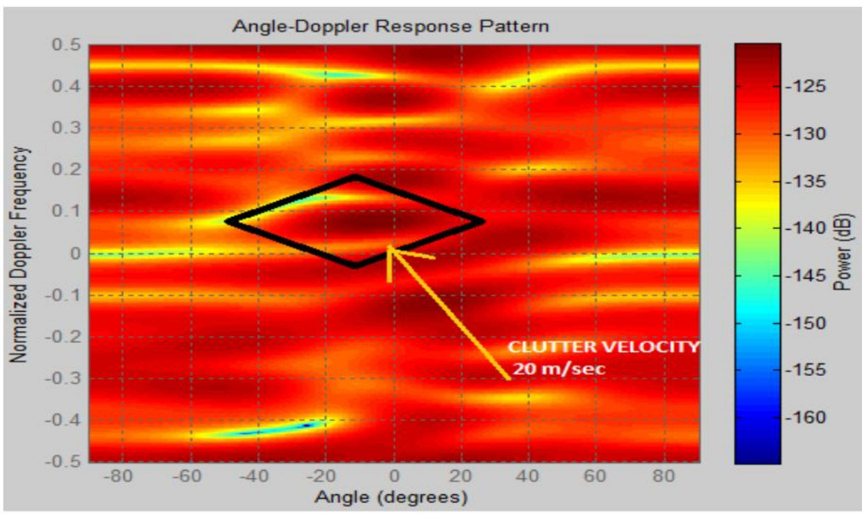

Fig. 5. Angle-doppler response for low clutter velocity = 20 m/sec

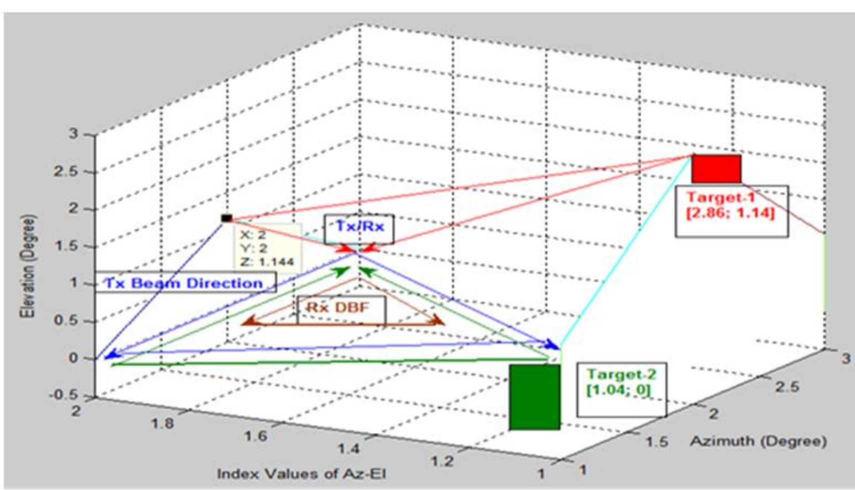

Fig. 6. Beam directions of TX/Rx and target returns

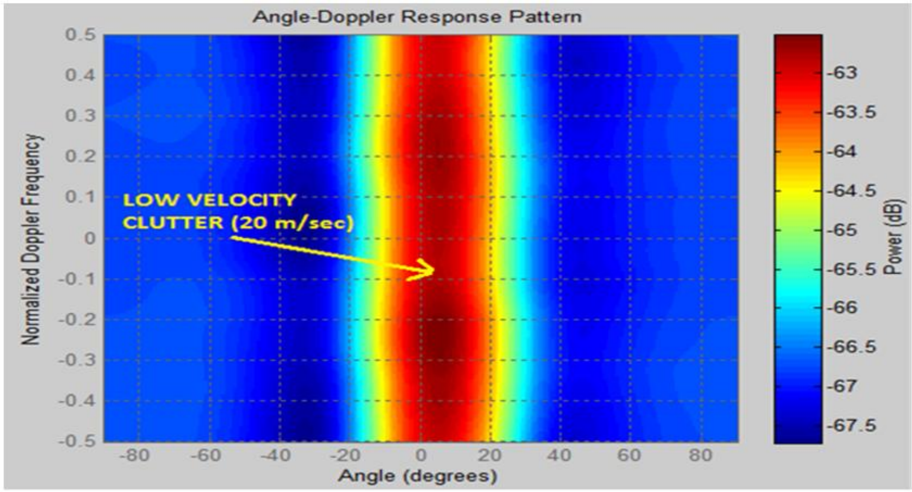

Fig. 7. Low velocity clutter of 20 m/sec

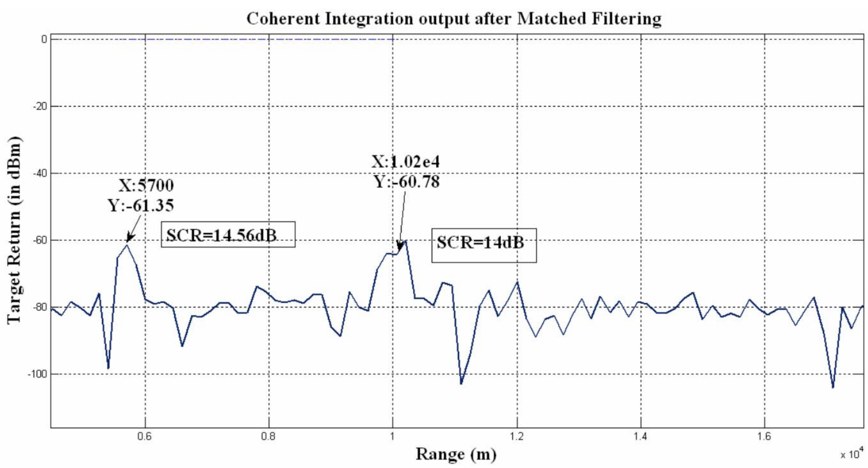

Fig. 8.1. For RCS = 1.1 m^2

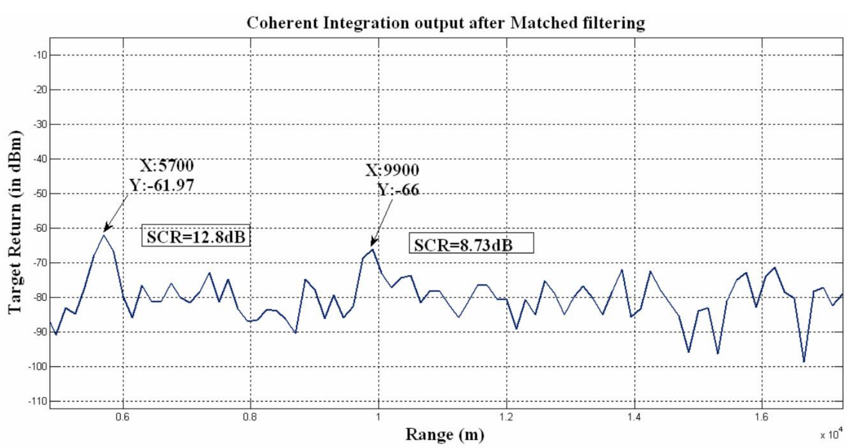

Fig. 8.2. For RCS = 1 m^2

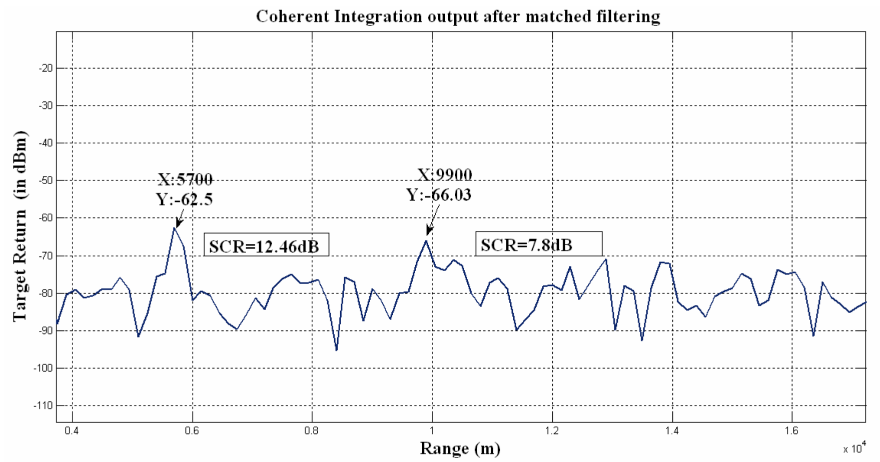

Fig. 8.3. For RCS = 0.8 m^2

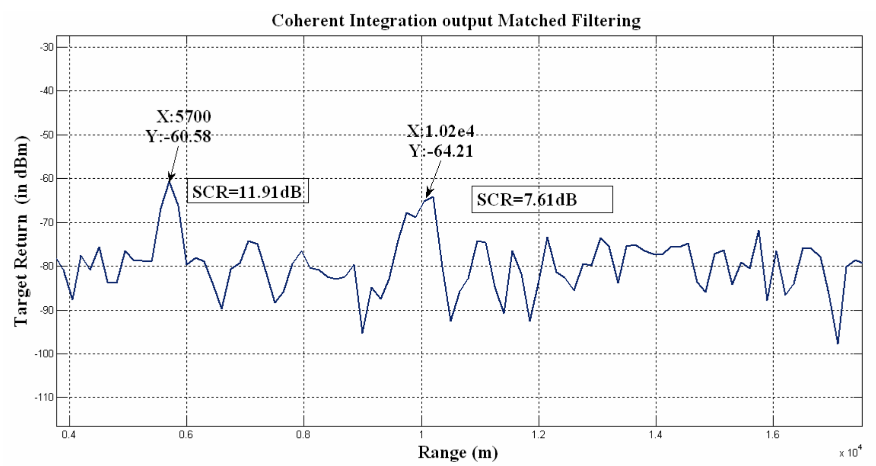

Fig. 8.4. For RCS = 0.6 m^2

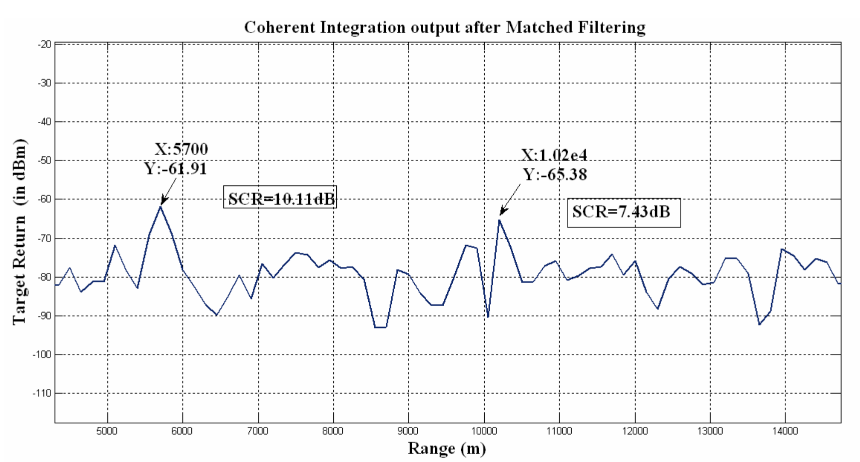

Fig. 8.5. For RCS = 0.4 m^2

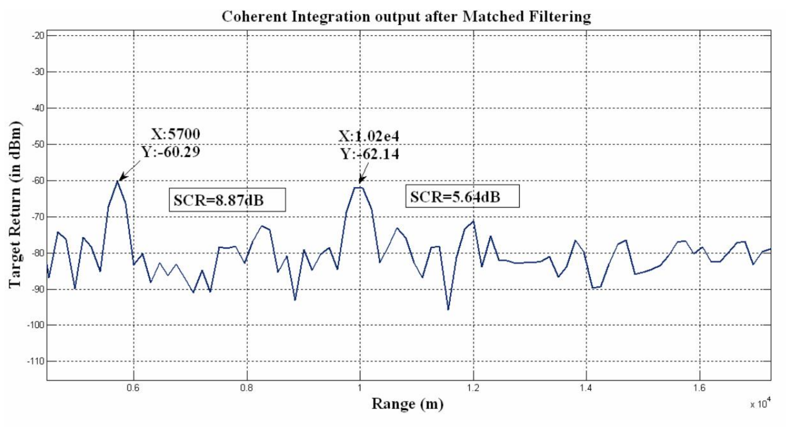

Fig. 8.6. For RCS = 0.07 m^2

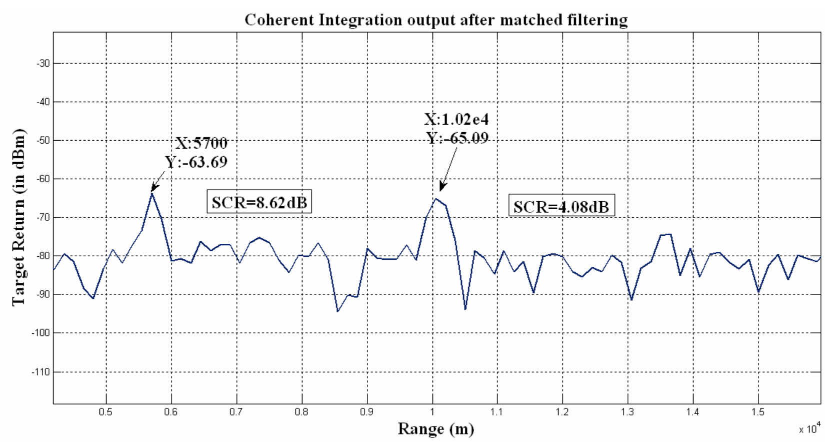

Fig. 9. For RCS = 0.04 m^2

We note that as we keep on decreasing the RCS of the target (which had smaller RCS than the other) it's SCR keeps on decreasing and finally at the dynamic range we cannot distinguish the target signal from the clutter.

CASE 3: At this point, what we do is we change the Receiver Digital Beamforming direction from the previous angle to the direction of the target which had smaller RCS (see above Fig. 9). This is the third case.

We observe a rise in the SCR of the target which had small RCS (as compared with its SCR when directed towards the other target) from 4.08 dB to 5.94dB.

6. CONCLUSION

The Signal-to-Clutter Ratio (SCR) of the smaller target as discussed in Case 3, is improved by proper and precise Digital Beam Forming control at the receiver. The complex weights of the receiver antenna elements are to be carefully chosen to give the desired peaks and nulls in the radiation pattern of the antenna array [9,10]. It should happen in such a way so that the central beam in some desired direction could be created for getting maximum signal strength for that particular target. For two different RCS targets, even if the system dynamic range fails to detect the smaller RCS target from clutter, the precise Digital Beam Forming (DBF) towards an optimum direction may help at a great extent to find the smaller RCS target being distinguished from the clutter. The above simulation results prove the fact with results and plots.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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