International Journal of Engineering Innovation & Research
Volume 9, Issue 2, ISSN: 2277 – 5668

Bistatic MIMO Radar System Design and the Effects of Antenna Placement on Parameter Estimation

David Ebregbe
Department of Electrical and Electronic Engineering, Niger Delta University. Wilberforce Island Bayelsa State, Nigeria.
Corresponding author email id: ebregbed@gmail.com

Date of publication (dd/mm/yyyy): 25/03/2020

Abstract **– In this paper a bistatic Multiple Input Multiple Output (MIMO) ground based air surveillance radar system is designed for a maximum target range of 150 kilometers from the transmitter and 175 kilometers from the receiver, a range resolution of 7.5m, the overall detection rate is 90% and the False alarm rate (FAR) = 1e-6. The radar operating frequency is 10 gigahertz. The design focuses on implementation of angle estimation and the effects of antenna placement on angle estimation performance. Most literatures on bistatic MIMO radar systems assume equal transmit and receive antenna elements with half wavelength inter element spacing for both arrays. An antenna placement scheme for varying the number of transmit and receive antenna for good angle estimation performance is proposed. Matlab simulations were performed to evaluate the performance of the proposed method.**

Keywords **– Bistatic MIMO Radar, False Alarm Rate, Detection Rate, Angle Estimation, Maximum Unambiguous Range.**

I. INTRODUCTION

Bistatic MIMO radar operates with separated transmitting and receiving antennas. Applications are not only limited to the military, bistatic radar can be used in ocean wave-spectra and also to detect atmospheric echo for meteorological applications and recently, in wireless mobile communications at the base station to increase the capacity and quality. Traditionally, DOA estimation performance depends on the size of the array's aperture [1]. If for budgetary considerations due to hardware cost only a few sensors are available to transmit a certain transmitter power, nyquist spatial sampling restrictions of less than or equal to half wavelength inter element spacing and an associated aperture size necessitates the use of minimum redundancy linear arrays (MRLAs). MRLAs minimize the number of redundant spacing in an array without degrading the angle resolution of the resultant array pattern and also reduces the spatial side lobes [1, 2, 3, 4]. Monostatic MIMO virtual arrays can be constructed to be sparse or filled [5, 6]. MRLA concepts are applied to monostatic MIMO to produce sparse arrays that meet the nyquist spatial sampling requirements but with non uniform inter element spacings and at the same time produce a large aperture size for improved angle estimation. These sparse (Thinned) MIMO arrays are formed from uniform linear arrays by turning off some of the array elements. However, they produce high grating lobes that can be reduced by distorting the periodicity of the non uniformity in the array [5]. For a monostatic MIMO radar, a filled virtual array is obtained from a sparse transmit and/or receive array. The sparse arrays are constructed by selecting elements from a one dimensional grid (vector) of nyquist spacing. In [7], the author uses the algebraic concept that convolutions and polynomial products are directly related and developed a procedure to decompose the convoluted virtual array into various transmit and receive antennas. The particle swarm optimization algorithm is used in ref. [8]. In our simulations using the monostatic MIMO procedures of creating filled virtual arrays from sparse arrays on either or both the transmitting and receiving arrays results in angle ambiguities. Angles are correctly paired only when both the transmit and receive ULAs are filled arrays.

However, in this study we propose a method of varying the numbers of transmit and receive antennas by first making sure that both the transmit and receive array apertures are equal. This can be done by constructing a one dimensional grid structure (vector) with nyquist spacing for both the transmit and receive array. Keeping one of the arrays as a filled array, the number of elements on the other array can be varied and at the same time select the antenna positions that produce the best angle resolution. In our implementation, the transmit array is sparse and represented as a vector grid of ones and zeros with a value of ‘1’ if there is an antenna located at that position and ‘0’ otherwise. The transmit array steering vector for the full grid is then multiplied by the weight vector of ones and zeros. Since transmit beam forming can be achieved with MIMO while processing and without the use of phase shifters, weighting functions can be included as complex amplitudes in the form of a taper vector.

II. BISTATIC MIMO RADAR DESIGN

A. *Design Equations*

A bistatic MIMO radar system is designed for a maximum target range of 150 kilometers from the transmitter and 175 kilometers from the receiver with specifications of a maximum unambiguous range of (175+150)/ 2 km, a range resolution of 7.5m, the overall detection rate is 90% and the FAR = 1e-6. The radar operating frequency is 10 gigahertz

Table 1. Design Specifications.

Item	**Value**
Maximum Range	(175+150)/2 = 162.5km
Range Resolution	7.5m
Probability of false alarm (Pfa)	10^{-6}
Probability of Detection(Pd)	0.9
Radar Operating Frequency	10GHz
Number of targets (All in the same range bin)	15

Based on the design specifications stated above (table 1), the pulse repetition frequency (PRF), the bandwidth of the waveform and the radar pulse width assuming rectangular pulses are computed as follows.

Pulse repetition interval (prf) = c/(2 x Range sum) where, c = 3 x 10^8 is the speed of light and the Radar pulse width = (2 x resolution)/c.

Shnidman’s equations [9] provide an empirical fit to the receiver operating characteristic (ROC) curves for non fluctuating, swerling 1-4 fluctuating signals and square law detection. We use shnidman’s equations to determine the minimum required SNR to achieve the desired probability of detection Pd, given, the false alarm probability Pfa, and a swirling 2 target fluctuation

$$
\begin{aligned}
&SNR = X + C \\
&where\ X = \eta\left(\eta + 2\sqrt{N/2 + \left(\alpha - 1/4\right)}\right) \qquad (1) \\
&\eta = \sqrt{-0.8 In\left(4P_{fa}\left(1 - P_{fa}\right)\right)} + sign\left(P_d - 0.5\right)\sqrt{-0.8 In\left(4P_d\left(1 - P_d\right)\right)}
\end{aligned}
$$

Where $a = 0$ for $N < 40$ and $a = {}^{1}/_{4}$ for $N \geq 40$. C is specified in terms of C_1 and C_2 as $C_1 = (((17.7006P_d - 18.4496)\,P_d + 14.53339)\,P_d - 3.525)\,/\,K$ and $C_2 = \exp\,(27.31\,P_d - 25.14)\,/\,K + (P_d - 0.8) \times [0.7 \log\,(10^{-5}\,/\,P_{fa}) + (2N - 20)\,/\,80]\,/\,K$

Where K is the Swerling fluctuation parameter with $K = 1$corresponding to Swerling I, $K = N$ to Swerling II, $K = 2$ to Swerling III, $K = 2N$ to Swerling IV. The correction term C = C_1 for $0.1 \leq P_d \leq 0.872$ and C = $C_1 + C_2$ for $0.872 < P_d \leq 0.99$.

The SNR obtained is 7.07dB for one transmit and N receive antenna pulses for a swerling 2 fluctuating target required to achieve the probability of false alarm (Pfa) and the Probability of detection (Pd) specified.

$$(SNR)_{SIMO} = \frac{N(\text{Signal Power})}{\text{Noise Power}} \tag{2}$$

$$(SNR)_{MIMO} = \frac{MN(\text{Signal Power})}{\text{Noise Power}} = M\,(SNR)_{SIMO} \tag{3}$$

Using 6 antennas for the transmit array there would be an increase in the SNR of 10 log 6 = 7.78 dB after match filtering as compared to a single isotropic antenna using transmit power equal to the sum of all the individual MIMO transmit antennas (i.e., 6 times the power of a single MIMO antenna).

We then estimate the required peak transmitting power from the bistatic radar equation [10] as

$$P_t = \frac{(SNR)_{SIMO}\,(4\pi)^3\,R_t^2 R_r^2 LkTBF}{G_t G_r \lambda^2 \sigma} \tag{4}$$

Where the terms in the equation are:

P_t - Peak transmit power in watts.

G_t - Transmitter gain in decibels.

G_r - Receiver gain in decibels. If the radar is monostatic, the transmitter and receiver gains are identical.

λ - Radar operating frequency wavelength in meters

σ - Target's non fluctuating radar cross section in square meters =10m^2.

L - General loss factor in decibels that accounts for both system and propagation loss = 3dB.

R_t - Range from the transmitter to the target.

R_r - Range from the receiver to the target.

k - Boltzmann's Constant (1.38×10^{-23} J/°Kelvin),

T - System Temperature (usually 290°Kelvin),

B - Receiver Bandwidth (Hz).

F - Noise Figure = 4dB.

The transmitter and receiver gains are chosen as 40 and 40 db respectively.

The computed total peak transmit power is 620KW and the power per transmit antenna is 103.3KW. The computed radar parameters and antenna parameters are shown in table 2.

Table 2. Computed Radar Parameters and Antenna Parameters.

Item	Value
Transmit antenna Gain (Gt)	40dB
Receive antenna Gain(Gr)	40dB
Radar Pulse width	50ns
Pulse Repetition frequency (prf)	923Hz
Length of Binary code (Q)	64
BPSK Bit Period	50ns
BPSK Signal Bandwidth	1/(50ns) = 20MHz
IF frequency	300MHz
Sampling frequency	(300MHz x 4) = 1.2GHz
Transmitter power (Pt)	620KW
SNR (Minimum)	7.07dB
Number of Transmit antennas (M)	6
Number of Receive antennas (N)	8

B. *Radio Frequency Circuit Design*

In this implementation, the transmitter elements are fed with signals which are modulated by a set of Binary orthogonal codes designed in [11]. These codes have good auto-correlation and cross correlation properties. The IF frequency is chosen to be 300MHz, the chip rate is 20MHz. The codes are transmitted using a Binary Phase Shift Keying (BPSK) modulation. Fig. 1 shows the MIMO array block diagram. The Digital front end and Digital Back end circuits are implemented using Matlab's Digital Up Conversion (DUC) and Digital Down Conversion (DDC) Sub-systems that includes interpolation/decimation filters. The baseband signal utilizes a 300MHz intermediate frequency (IF) which is added and removed from the 10GHz carrier frequency [12]. The DUC system at the transmitter consists of a cascade of three interpolation filters and an oscillator up samples the signal from 600MHz to 10GHz. At the receiver the signal is brought back to 300MHz, using a digital down converter (DDC). The Digital down Converter consists of an oscillator at the same frequency as the transmitter oscillator and converts the input signal from 10GHz to 300MHz.

C. *Signal Processing Chain*

Fig. 5 shows the spectral properties of one of the transmitted orthogonal codes. The other 7 orthogonal codes are similar. At each receiver antenna as shown in Fig. 2, the signals from the transmitter antennas are processed separately and in parallel, allowing for DOA processing. Since it is assumed that all fifteen targets are in the same range bin, only one pair of correlators (I and Q) is shown for each receive antenna processing block, otherwise each antenna processing block would contain fifteen pairs of correlators implemented in parallel, so that range scans are processed simultaneously with each correlator spacing equal to the range resolution. This also means that there will be one correlator per pulse for each range gate with their corresponding subpulse accumulations in order to extract Doppler information for moving targets. For CFAR processing down the chain, multiple transmissions of the same waveform for each transmit antenna would increase the SNR before CFAR processing.

Since this paper focuses on DOA processing only, we have assumed stationary targets all in the same range bin and the system flowchart is shown in Fig. 3.

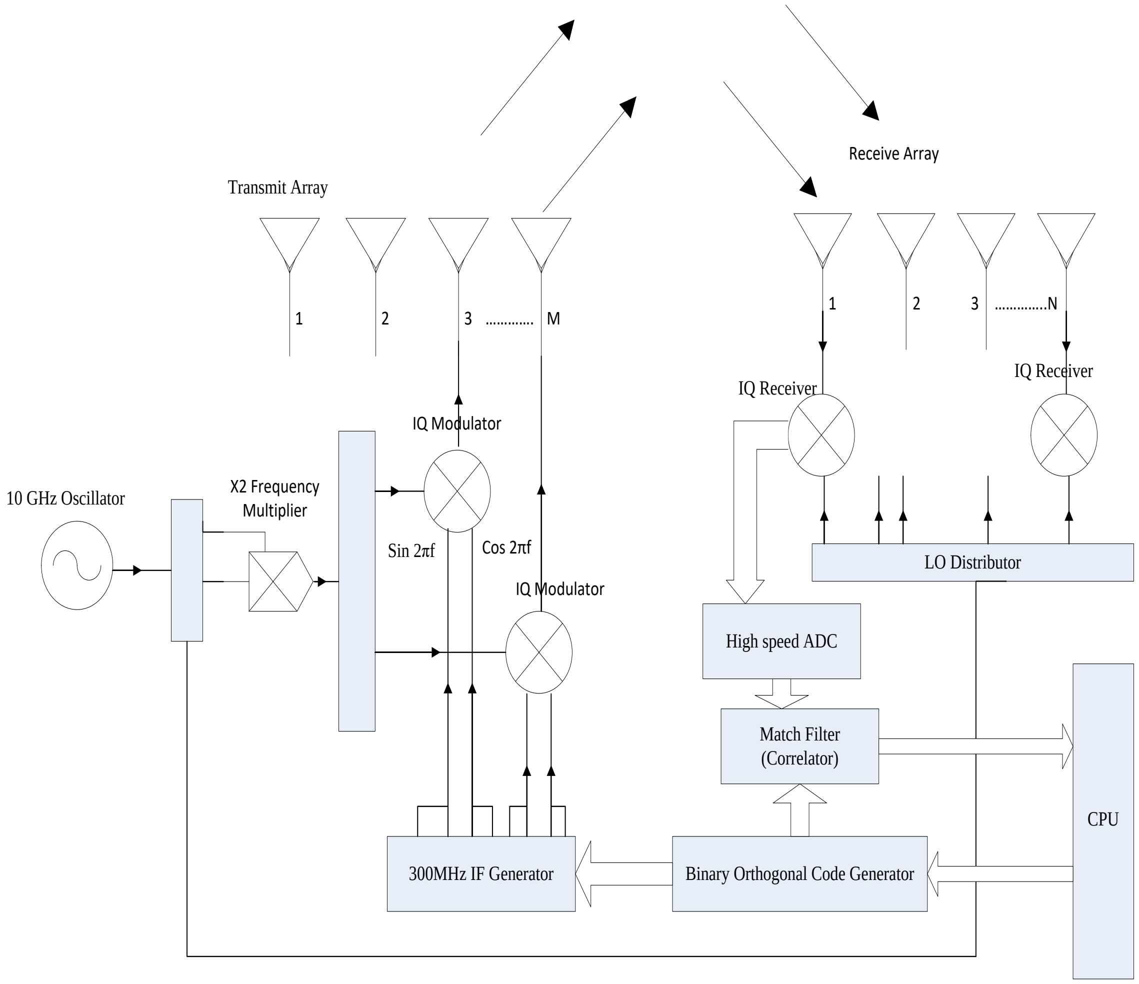

Fig. 1. Block diagram of the Bistatic MIMO(Adapted from ref. [12]).

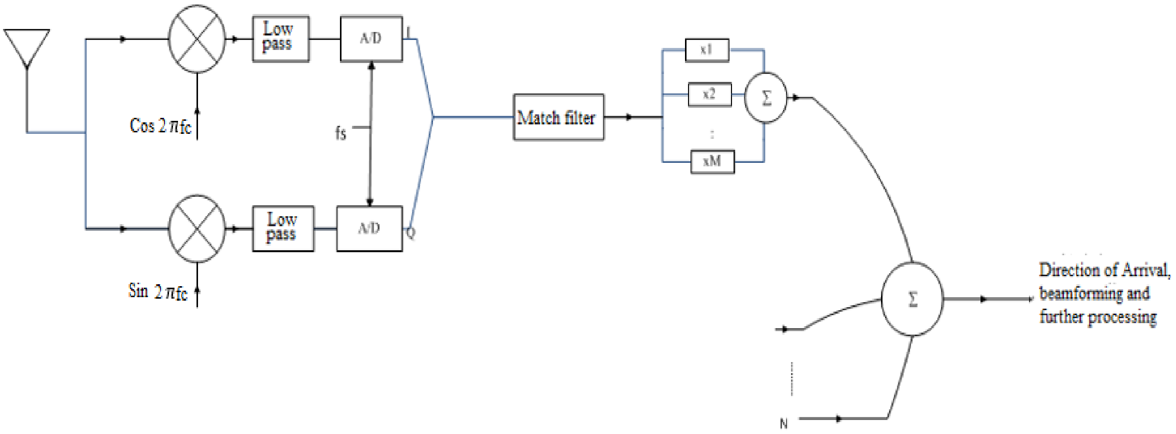

Fig. 2. Signal processing of the nth receive antenna for all transmitted waveforms.

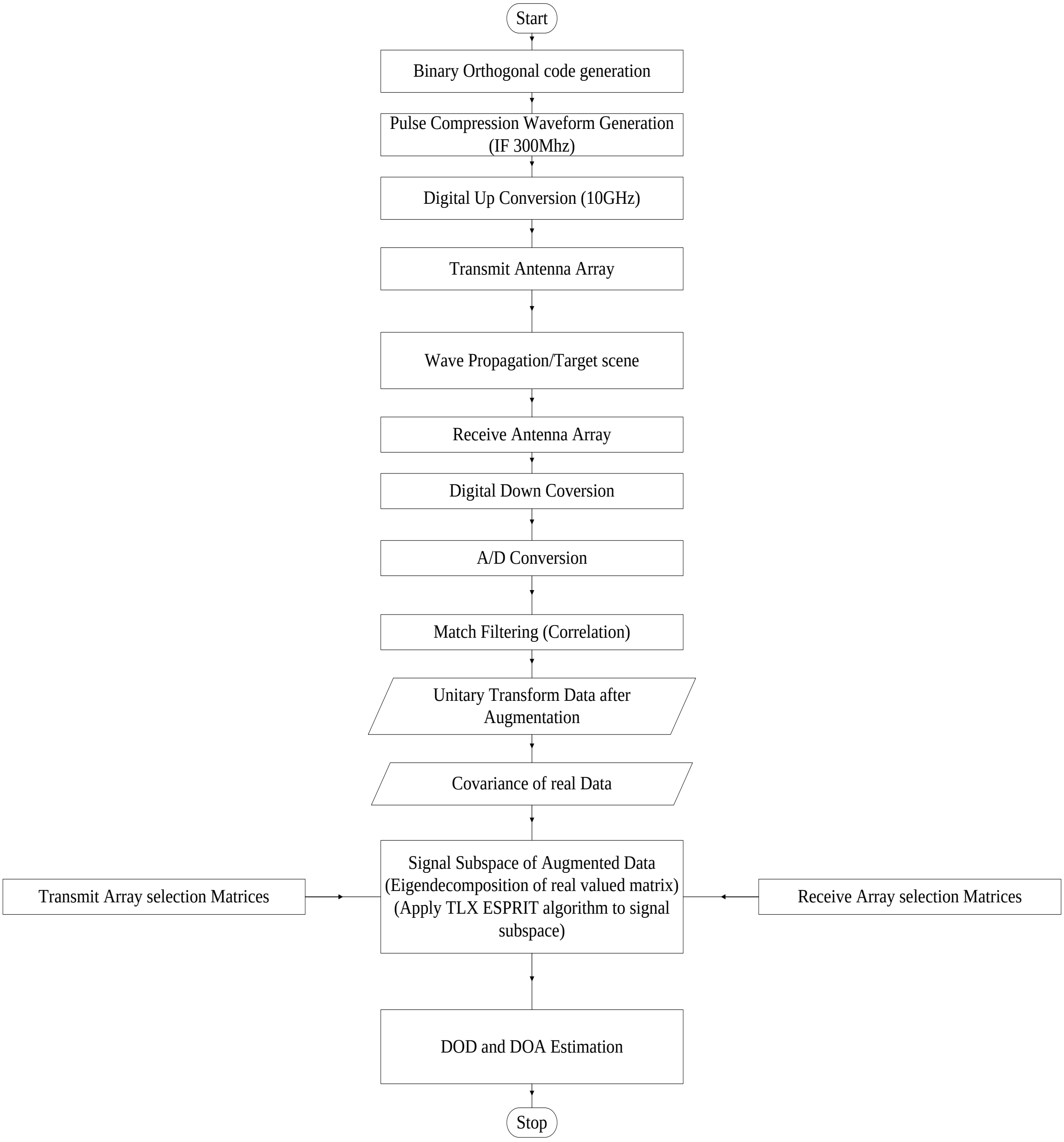

Fig. 3. System Design flowchart.

III. GEOMETRY OF BISTATIC MIMO RADAR AND ANTENNA PLACEMENT

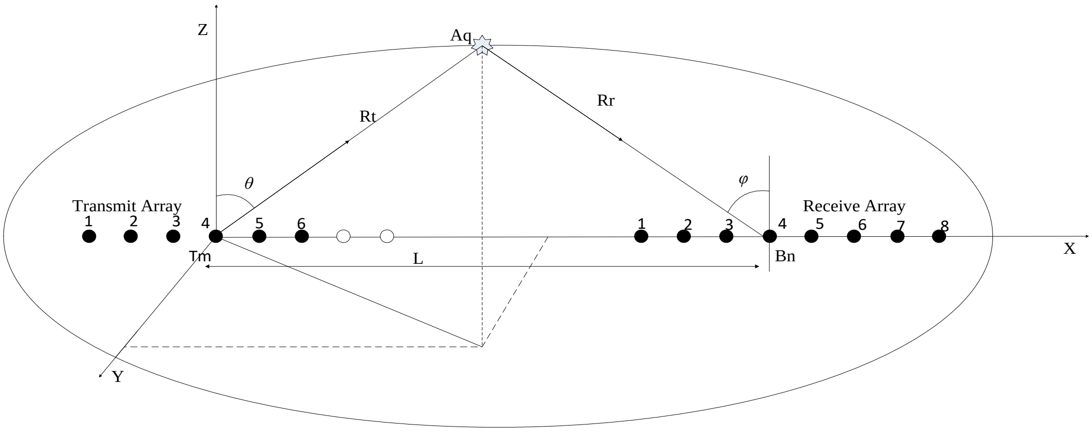

Fig. 4. Geometry of Bistatic MIMO radar.

Fig. 4 shows an illustration of the radar configuration and target scene in this design. The antennas are placed on a one dimensional Uniform linear grid structure of half wavelength spacing and of the same size for both the transmitting and receiving array. This geometry supports sparsity with fewer elements if needed. All targets are assumed to be in the same range bin (i.e. range sum 175 +150 = 325km). The target scene is illuminated by M =6 transmitting omnidirectional antennas located at coordinate $T_m = (x_{tm}, 0, 0)$, $m = 1\ldots\ldots\ldots M$. The scattered signals are collected by N = 8 antennas at some distance away at coordinates $B_n = (x_{rn}, 0, 0)$. P = 15 targets are located at coordinate $A_p = (x_p y_p \; z_p)$ with transmit angles θ and receive angles ϕ as shown in table 5.3. Geometry of antennas and targets in the coverage region is very important in the number of targets that can be accurately localized. The maximum number of uniquely identifiable targets for MIMO radar is MN. The bound is $[M + N -1, MN – 1]$.

IV. SIMULATION RESULTS

In this section we perform several simulations to verify our design. The parameters used for the simulation are as shown in tables 1 and 2. The bistatic MIMO radar configuration is as shown in Fig. 4 with M = 6 transmitting antennas and N = 8 receiving antennas. Both are ULAs with half wavelength inter element spacing implemented on one dimensional half wavelength spaced 8 number grid structures as shown in Fig. 4. The receive array is a filled array while the transmit array has only 6 antennas on the grid thereby creating a sparsely distributed array. The transmit array is represented as a vector $\mathbf{W}_t$ which contains 0 and 1 entries with a 1 indicating the presence of an antenna in that location and 0 otherwise.

Table 3. Target Parameters.

Targets	**DODs(θ)**	**DOAs(φ)**	**Arbitrary Phases**	**Reflection coefficients(β)**
1	50	-50	0	0.1
2	-20	-40	$\pi/2$	0.3
3	-10	0	$\pi/3$	0.5
4	-40	40	$\pi/4$	0.7
5	60	20	$\pi/6$	0.8
6	30	-15	$\pi/8$	0.6
7	10	20	$\pi/7$	0.4
8	40	30	$\pi/9$	0.7
9	0	70	$\pi/11$	0.8
10	20	50	$\pi/5$	0.5
11	10	-30	$\pi/12$	0.6
12	-8	30	$\pi/16$	0.3

13	40	80	π	0.8
14	-50	-20	π/17	0.4
15	30	25	π/18	0.3

The steering vector associated with these antenna positions is obtained as $\tilde{\mathbf{a}}_t(\theta) = \mathbf{W}t \odot \mathbf{a}_t(\theta)$ where $\odot$ denotes the Hadamard (element-wise) product and $\mathbf{a}_t(\theta)$ is the transmit array steering vector for the full 8 number grid structure. The signal - to- noise ratio used here is obtained from (3)

$(SNR)_{MIMO} = \frac{MN\,(\text{Signal Power})}{\text{Noise Power}} = M\,(SNR)_{SIMO} = 7.07dB + 7.78dB = 14.85dB$, there are $P = 15$ stationary targets with parameters as shown in table 3. The target model is a fluctuating swerling 2 model. Angle estimation for the 15 targets utilizing the algorithm for non circular signal model for Unitary ESPRIT developed in [8] and the transmit waveforms designed in [11] is implemented for various positions of transmit antennas in the vector **W**t.

The best angle estimation resolution as shown in Fig. 6 is obtained with antenna placements represented by weight vector $\boldsymbol{W}_t = [\mathbf{1\ 1\ 1\ 1\ 1\ 1\ 0\ 0}]$. Figs. 7, 8 and 9 show other optimal placements while Figs. 10 and 11 reveal angle estimation ambiguities at some target locations. It is clearly exhaustive to search for arrays by testing antenna placements this way. As a suggestion for further studies we therefore propose an optimization algorithm to obtain the optimal antenna placements.

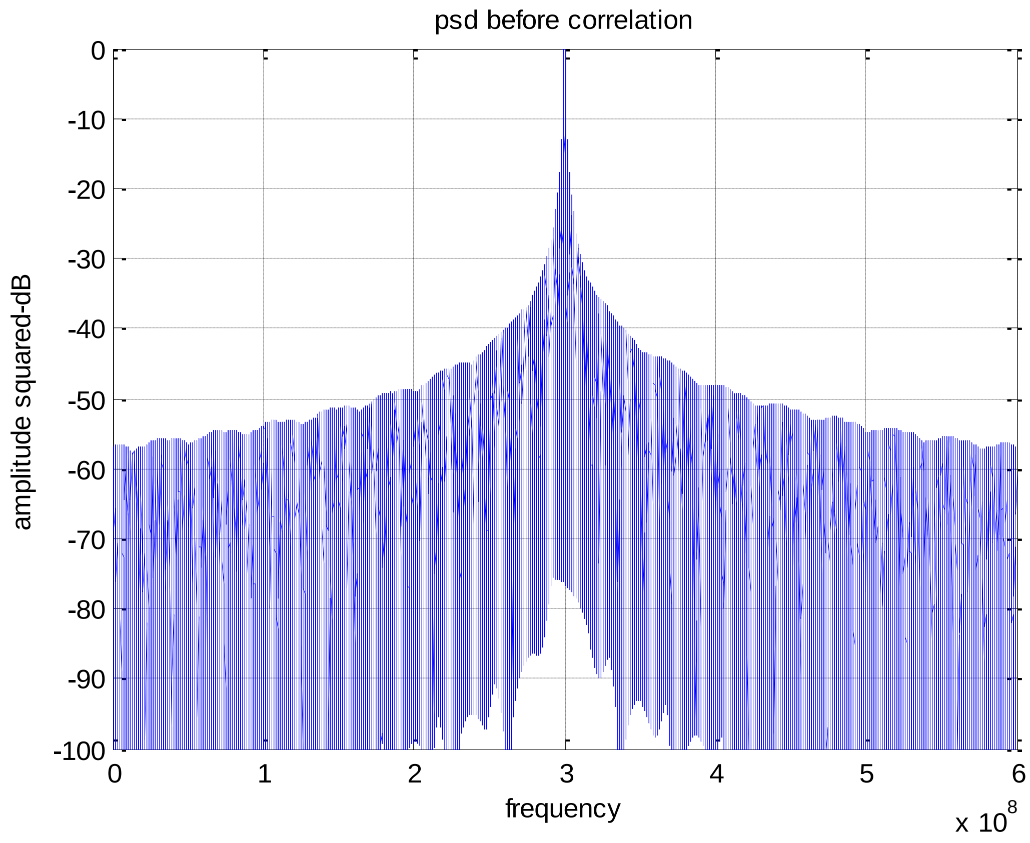

Fig. 5. Power spectral density of transmitted signal.

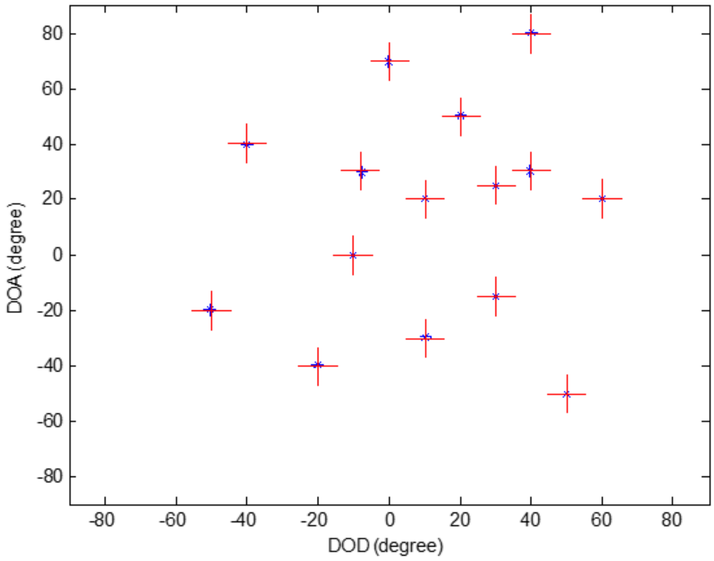

Fig. 6. Automatically Paired angle estimates for 15 targets.

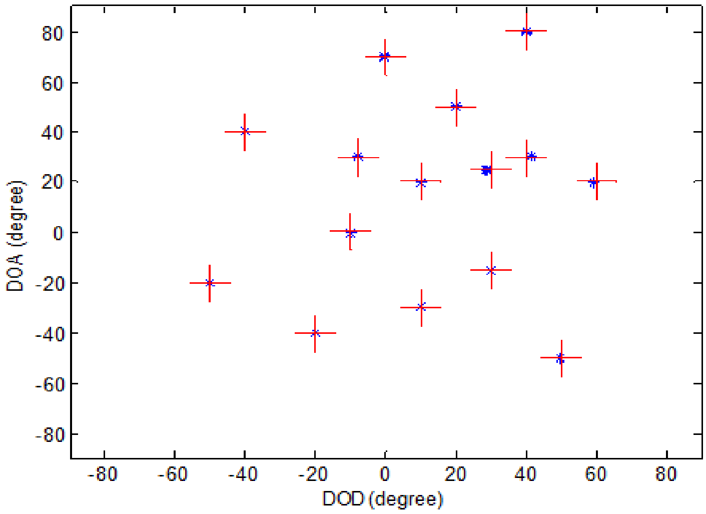

Fig. 7. Angle estimation for a weight vector $W_t = [0\ 0\ 1\ 1\ 1\ 1\ 1\ 1]$.

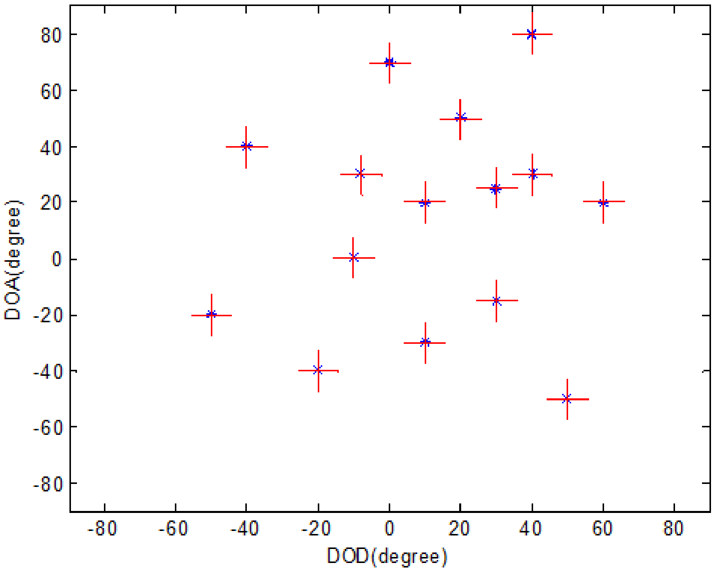

Fig. 8. Angle estimation for a weight vector $W_t = [0\ 1\ 1\ 1\ 1\ 1\ 1\ 0]$.

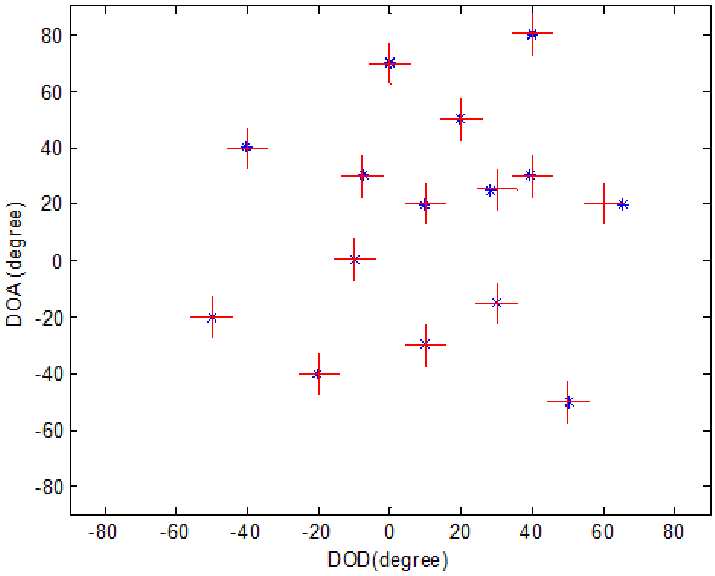

Fig. 9. Angle estimation for a weight vector W_t = [1 1 1 0 0 1 1 1].

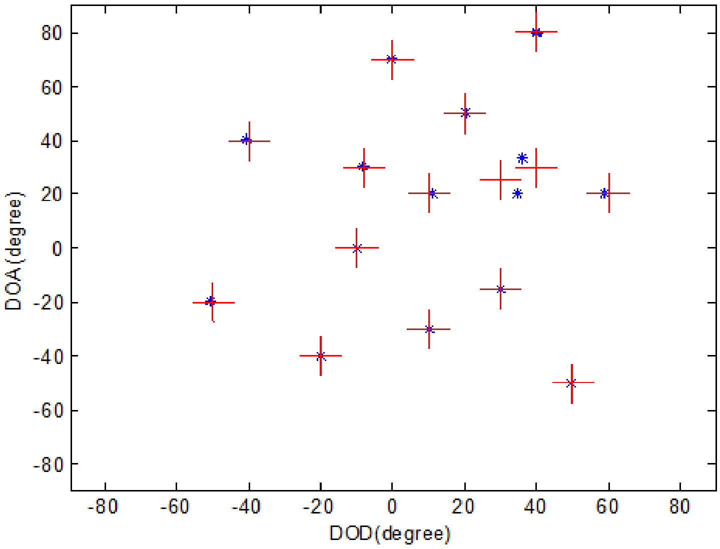

Fig. 10. Angle estimation for a weight vector W_t = [1 1 1 1 0 1 0 1]

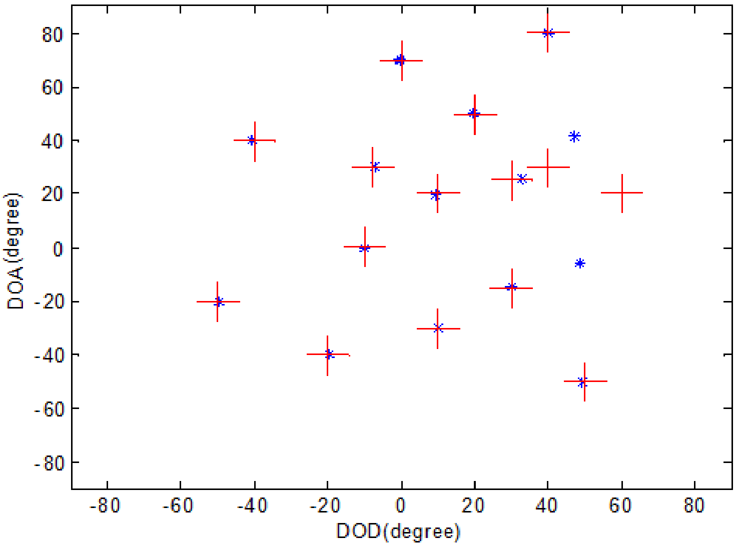

Fig. 11. Angle estimation for a weight vector W_t = [1 0 1 0 1 1 1 1]

V. CONCLUSIONS

In this paper, we designed a Bistatic MIMO radar system and performed angle estimation for 15 slowly moving targets. An antenna placement scheme is proposed and utilized in this design. Simulation results are quite encouraging. The geometry and distance of antenna elements determines the number of targets that can be accurately localized. However, it is clearly exhaustive to search for arrays by testing antenna placements this way. As a suggestion for further studies, an optimization algorithm to obtain the optimal antenna placements is desirable.

REFERENCES

[1] Moffet A, Minimum-redundancy linear arrays, IEEE Trans. Antennas Propag., vol. 16, pp. 172–175, Mar. 1968.
[2] Piya Pal, and P.P. Vaidyanathan, Nested arrays: A novel approach to array processing with enhanced degrees of freedom, IEEE Trans. Signal Process., vol. 58, no. 8, pp. 4167–4181, Aug. 2010.
[3] Rezer K, W. Gropengießer, and A.F. Jacob, Particle Swarm Optimization of Minimum-Redundancy MIMO Arrays. Proceedings of the 6th German Microwave Conference, march 2011.
[4] Chun-Yang Chen and P.P. Vaidyanathan, Minimum Redundancy MIMO Radars, IEEE Int. Symposium on circuits and systems, ISCAS, Pp 45-48, 2008.
[5] Forsythe K. W, D. W. Bliss, and G.S. Fawcett, Multiple-Input Multiple-Output (MIMO) Radar Performance Issues, Proc. 38th IEEE Asilomar Conf. on Signals, Systems, and Computers, pp. 310 – 315, Nov. 2004.
[6] Li J. and P. Stoica, MIMO Radar Signal Processing, John Willey & Sons, 2009
[7] Sammartino P.F, D.Tarchi, C.J. Baker. MIMO radar topology: A systematic approach to the placement of the antennas. Int. conf. on Electromagnetics in Advanced Applications (ICEAA) Pp 114-117, 2011.
[8] Ebregbe D and D Weibo. Exploiting Non Circularity for Angle Estimation in Bistatic MIMO radar Systems. Journal of World Academy of Science, Engineering and Technology (WASET). Issue 78(2013). Pp. 2084-2089.
[9] David A. Shnidman, Determination of required SNR values, IEEE transactions on aerospace and electronic systems. Vol. 38 No 3 july 2002.
[10] Skolnik M., Introduction to Radar Systems, McGraw-Hill, 2001.
[11] Ebregbe D and D. Weibo. Orthogonal Waveform Optimization for MIMO Radar Systems. International Conference on Measurement Technology and its Applications- Journal of Applied Mechanics and Materials. Vols. 239-240 (2013) pp 376-381.
[12] Le Marshall N.W.D., MIMO Radar Array for Termite Detection and Imaging. Progress in Electromagnetics Research B, Vol. 28, 75 94 2011.

AUTHOR'S PROFILE

First Author

David Ebregbe was born in 1963. Lecturer, Department of Electrical and Electronic Engineering, Niger Delta University, Wilberforce Island, Bayelsa State Nigeria. He holds a Bachelor of Engineering (B.Eng) degree from the University of Port harcourt , Nigeria – (1987). Master of Science (M.Sc) in Digital Communications system from Loughborough University. United Kingdom (2002). Doctor of Philosophy (Ph.D) in Communications and Information Engineering, Harbin Institute of technology, Harbin. China – (1913). Research interests include; Radar, Mobile and wireless Communication, Statistical and Array signal processing.