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Orthogonal MIMO Radar Waveform Performance Analysis with Ambiguity Function

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Abstract*— *In this paper, the basic Multiple Input and Multiple Output ambiguity function tool is used to analyze the performance of orthogonal waveforms for MIMO radar antenna system. The orthogonal waveforms like modified Discrete Frequency Coding Waveform Linear Frequency Modulation (DFCW_LFM), Polyphase and Discrete Frequency Coding Space Time Waveform (DFCSTW) waveforms are considered. The resolution performance is governed and controlled by the system on transmit using orthogonal waveform diversity. The resolution performance is illustrated using MIMO radar orthogonal waveforms.

Index Terms*—*Ambiguity Function (AF), Discrete Frequency Coding Space Time Waveform (DFCSTW), Discrete Frequency Coding Waveform Linear Frequency Modulation (DFCW_LFM), Orthogonal waveforms, Polyphase Waveforms.

I. INTRODUCTION

MODERN radar systems are designed to be highly accurate for their intended purpose. Designers and engineers are required to know the level of resolution expected from a particular radar configuration. The Ambiguity Function (AF) is a powerful tool for fulfilling and widely recognized for evaluating the performance of a radar waveform by directly determining the position of target and velocity and the resolution of the position. It is also well known that the AF is a useful tool for evaluating performance metrics of radar, such as delay and Doppler resolutions and the probabilities of detection and false alarm.

Multiple Input Multiple Output (MIMO) antenna systems have the potential to dramatically improve the performance of communication systems over single antenna systems MIMO radar [1]. The AF of MIMO radar could directly determine the position of target, velocity and the resolution of the position is higher when more transmitters and receivers were used. The MIMO radar ambiguity function characterizes the resolutions of the radar system. The range resolution typically depends on the bandwidth of the system, whereas the cross-range resolution is determined by the combined contribution of the relative motions and the topology of sensors. It is noted that, a number of parameters are involved in the MIMO AF, such as the waveform, the bandwidth, the topology of the sensor array, and the relative motions, which jointly impact the radar resolving performance in different ways. By choosing different waveforms, a different MIMO ambiguity function can be obtained. Therefore the MIMO radar waveform design problem is to choose a set of waveforms which provides a desirable MIMO ambiguity function.

In MIMO radar, the transmitted signals are required to be mutually orthogonal [2]. At each of the receiver, the received signals are matched filtered for each of the transmitted waveforms forming multiple channels. The ambiguity function of MIMO radar is a combination of the AF of bistatic radar.

The transmitted waveforms are orthogonal and consist of multiple shifted narrow pulses using Frequency-Hopping Waveforms [3, 4]. The SA algorithm is used to search for the frequency hopping codes which minimize the sidelobes of the ambiguity function. In the phase modulation of the signal when the envelopes of the signal and its spectrum are specified, is a solution is given for the large time bandwidth product case to avoid range ambiguities [5, 6].

The properties of the MIMO radar AF [7] and the cross ambiguity function are to have max amplitude at zero position, to characterize on energy spread, symmetry condition and shear-off effect of the LFM waveform which improves the range resolution.

MIMO radar delay-Doppler ambiguity function, which is the sum of all auto- and cross-ambiguity functions of a set of waveforms operations in distributed clutter. The "volume-clearance" [8, 9] condition shows that for signals of equal energy, bandwidth, and duration, the largest "clear area" around the main peak of the MIMO ambiguity function cannot be improved upon.

The statistical behavior [10] of sidelobe-ambiguity arising in location estimation in distributed coherent MIMO radar, a model is developed to analyze the statistics of the localization metric under random sensor locations.

The Hybrid MIMO Phased Array Radar (HMPAR) [11] for a multisensor radar architecture combines elements of traditional phased-array radar with the emerging technology of MIMO radar. A HMPAR comprises a large number of subarrays of elements of T/R elements. The ambiguity function is a function of time delay, Doppler frequency shift, and two or more spatial variables.

The several properties of the auto-ambiguity and cross-ambiguity function of weighted pulse trains with Oppermann sequences [12]. A clear region analysis of usable range-Doppler space based on a coherent MIMO ambiguity function for MIMO radar transmitting N waveforms there is a reduction of the clear area by a factor of 1/N [13]. Signal design for beampattern and spatial ambiguity function synthesis for colocated MIMO radar [14]. The Synthesis of the waveforms based on the crosscorrelation and covariance matrix method to MSE.

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In the computation of the ambiguity function, the effect of the crosscorrelation of the radiated waveform with a Doppler shifted replica of itself is dispersed by a factor of two [15]. However, the "pulse" duration is itself a function of angle and the distortion of the ambiguity function is severely distorted as a function of steering angle.
The Generalized Ambiguity Function (GAF) [16] to characterize the effects of array geometry and waveform sets on resolution performance. GAF of MIMO SAR is characterized by the configuration of antennas and the correlation properties. The overall performance of the MIMO system is the combination the individual factors, are the signal-related factor, the relative motion factor and the topology factor in resolving performance of the system. The radar sensors are sparsely or closely deployed in 2-D/3-D space with various spatial configurations, which provide the designer with an extra degree of freedom. The Wideband/UWB MIMO radar, the range resolution typically depends on the bandwidth of the system, whereas the cross-range resolution is determined by the combined contribution of the relative motions and the topology of sensors [17]. The design of orthogonal, Doppler tolerant waveforms for diversity waveform radar (e.g. MIMO radar) that remains orthogonal when they are received [18]. The focus is on: (1) developing sets of waveforms that are orthogonal on both transmit and receive, and (2) ensuring that these waveforms are Doppler tolerant when properly processed. The formulation of the ambiguity functions of Phased–MIMO radar and its properties [19]. The properties of the ambiguity function is maximum and constant along the line and can be controlled by changing the number of subarrays, the total energy of the ambiguity function is also a constant and independent of waveforms, but again controllable by number of subarrays, the function is symmetry along τ and ν axes and the shearing effect on the ambiguity function. In this paper the orthogonal waveforms are developed and extended to MIMO radar AF. Section II provides the design for orthogonal waveforms for MIMO radar antenna system like modified Discrete Frequency Coding Waveform Linear Frequency Modulation (DFCW_LFM), Polyphase and Discrete Frequency Coding Space Time Waveform (DFCSTW) waveforms. In Section III the signal model used for MIMO radar and AF are discussed. Section IV will show some resolution performance is governed and controlled by the system on transmit. Finally in section V conclusion is draw.

II. ORTHOGONAL WAVEFORMS

Consider a MIMO radar system with a Tx transmitting antennas. Let x_i where i={1,2,…Tx) denote the position of Tx transmitting antennas located at an angle θ_i when viewed from an origin. Each element may transmit N coding frequencies on each subpulse of a waveform. Each Rx receives and processes the signal from all the Tx transmitters. The received signals are return signal from a target and clutter. Each element transmits N pulses with a Pulse Repetition frequency (PRF) of f_r.

A. Polyphases waveforms:

Consider the orthogonal polyphase code set consists of Tx orthogonal waveforms, each represented by a sequence of N samples with M phases. The t^{th} waveform of Tx orthogonal waveform set is as follows [20, 21]

$$\left\{ s_t(t) = e^{\frac{j2\pi\,\Phi_t(n)}{M}}, n = 1,2,\ldots\ldots\ldots\ldots N \right\}, \qquad (1)$$

$$t = 1,2,\ldots\ldots\ldots Tx,$$

Where $\Phi_t(n) \in \{\Psi_1, \Psi_2, \Psi_3, \Psi_4\} = \{0,1,2,3\}$ is the phase of subpulse n of signal t. The polyphase code set S as shown in (2), with code length of N, code set size of Tx, and distinct phase number M, one can concisely represent the phase values of S with the following Tx*N phase matrix.

$$S(Tx,N,M) = \begin{bmatrix} \Phi_1(1),\Phi_1(2),\ldots\ldots\ldots,\Phi_1(N) \\ \Phi_2(1),\Phi_2(2),\ldots\ldots\ldots,\Phi_2(N) \\ \\ \Phi_{Tx}(1),\Phi_{Tx}(2),\ldots\ldots\ldots,\Phi_{Tx}(N) \end{bmatrix}$$

(2)

From the autocorrelation and crosscorrelation properties of orthogonal polyphase codes, we get

$$A(\Phi_m,k) = \begin{cases} 1/N \sum_{n=1}^{N-k} \exp j[\,\Phi_m(n) - \Phi_m(n+k)] = 0 \;, 0 < k < N \\ 1/N \sum_{n=-k+1}^{N} \exp j[\,\Phi_m(n) - \Phi_m(n+k)] = 0 \;, -N < k < 0 \end{cases},$$

$$m = 1,2,\ldots..Tx$$

(3)

$$C(\Phi_p,\Phi_q,k) = \begin{cases} 1/N \sum_{n=1}^{N-k} \exp j[\Phi_q(n) - \Phi_p(n+k)] = 0, 0 < k < N \\ 1/N \sum_{n=-k+1}^{N} \exp j[\Phi_q(n) - \Phi_p(n+k)] = 0, -N < k < 0 \end{cases}, \qquad (4)$$

$$p \neq q, p, q = 1,2\ldots\ldots Tx$$

Where $A(\Phi_m,k)$and $C(\Phi_p,\Phi_q,k)$ are the aperiodic autocorrelation function of polyphase sequence S_m and the crosscorrealtion function of sequences S_p and S_q, and k is the discrete time index. Therefore, designing an orthogonal polyphase code set is equivalent to the constructing a polyphase matrix in (2) with the $A(\Phi_m,k)$and $C(\Phi_p,\Phi_q,k)$ in (3) and (4).

B. Modified DFCW_LFM

DFCW is still is the most popular pulse compression method. The basic idea is to sweep the frequency band B linearly during the pulse duration T. B is the total frequency deviation and the time bandwidth product of the signal is BT. The spectral efficiency of the LFM improves as the time-bandwidth product increases, because the spectral density approaches a rectangular shape. The modified DFCW_LFM waveform is proposed in this paper and is defined as

$$S_p(t) = \begin{cases} \sum_{n=0}^{N-1} e^{j2\pi f_n^p (t-nT)} . e^{j\pi k t^3} & 0 \le t \ge T \\ 0 & \text{elsewhere} \end{cases}, \qquad (5)$$

$$p = 1,\ 2\ldots\ T_x$$

Where, T is the subpulse time duration. k is the frequency slope, k=B/T. N is the number of subpulse that are continuous.f_n^p=n Δf is the coding frequency of subpulse n of waveform p in the (6).Δf is the frequency step. Each line is a LFM pulse, the B and T for each pulse remains a constant.

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The Δf values are called frequency steps. Each LFM pulse has a different starting frequency. The choice of BT, T.Δf and B/Δf values are crucial for the waveform design. Different lengths of firing sequence, N, have different values for each of the above mentioned parameters are taken from [22].

Considering a DFCW_LFM code set S as shown in (2.5), with code length of N, set size of W. The frequency values of S is represent with the following W*N frequency matrix.

$$S(T_x,N)=\begin{bmatrix} f_1(1),f_1(2),\ldots\ldots\ldots\ldots,f_1(N) \\ f_2(1),f_2(2),\ldots\ldots\ldots\ldots,f_2(N) \\ \\ \\ f_{T_x}(1),f_{T_x}(2),\ldots\ldots\ldots,f_{T_x}(N) \end{bmatrix} \quad (6)$$

$$A(s_w,\tau)=\frac{1}{N}\int_t S_w(t)S_w^*(t-\tau)dt\begin{cases}=1 & ,\tau=0\\ =0 & ,otherwise\end{cases} \quad (7)$$

$$w=1,2,\ldots\ldots.T_x$$

$$C(S_p,S_q,\tau)=\frac{1}{N}\int_t S_p(t)S_q^*(t-\tau)dt=0 \quad (8)$$

$$where\ p\neq q\ and\ \ p,q=1,2,\ldots\ldots.T_x$$

Where $A(S_w,k)$ and $C(S_{p,}S_q,k)$ are the aperiodic autocorrelation function of DFCW_LFM sequence S_w and the crosscorrealtion function of sequences S_p and S_q, and t is the discrete time index. Therefore, designing an orthogonal DFCW_LFM code set is equivalent to the constructing a DFCW_LFM matrix in (6) with the $A(S_w,t)$ and $C(S_{p,}S_q,t)$ in (7) and (8).

C. Discrete Frequency Coding Space Time (DFCSTW) Waveform:

The Discrete Frequency Coding Space Time (DFCSTW) Waveform defined as

$$S_p(t)=\begin{cases}\sum_{n=0}^{N-1}e^{j2\pi\ f_n^p(t-nT)}.b(t)a(x) & ,0\leq\ t\ \geq T\\ 0 & elsewhere\end{cases},$$

$$p=1,\ 2\ldots\ T_x$$

$$b(t)=e^{j\pi st^2}$$

$$a(x_i)=e^{j2\pi\ \theta_i(N-1)\ f_n/c},i=\{1,2,\ldots T_x\} \quad (9)$$

Where s is the frequency slope, s=B/T and p= 1, 2,…, T_x. T is the subpulse time duration. N is the number of subpulse that is continuous with the coefficient sequence $\{n_1,n_2,\ldots\ldots.n_{Tx}\}$ with unique permutation of sequence{0,1,2,……N}. f_n^p= n Δf is the coding frequency of subpulse n of waveform p in the waveform DFCSTW. Δf is the frequency step. θ_i denote the angle of the T_x transmitting antennas when viewed from origin.

The cost function is the key parameter to optimize the waveform design. The value of the cost function weights w_1 to w_4 are considered as 1 for all the optimization which means the optimization based on the cost function based on the autocorrelation sidelobe energy, crosscorrelation energy, the Autocorrelation Sidelobe Peak (ASP) and the Crosscorrelation Peak(CP). The energy based cost function to be used for MIMO radar signals design is as follows.

$$CF=w1.\sum_{l=1}^{Tx}\max|A(\Phi_m,k)|+$$
$$w2.\sum_{p=1}^{Tx-1}\sum_{q=p+1}^{L}\max|C(\Phi_p,\Phi_q,k)|$$
$$+w3.\sum_{l=1}^{Tx}\sum_{k=1}^{N-1}\max|A(\Phi_m,k)|^2+ \quad (10)$$
$$w4.\sum_{p=1}^{Tx-1}\sum_{q=p+1}^{Tx}\sum_{k=-(n-1)}^{N-1}|C(\Phi_p,\Phi_q,k)|^2$$

III. SIGNAL MODEL

Then, the received signals of a target for MIMO radar can be formulated in.

$$r_i=S_i{*}T_i+S_i{*}Cl_i+V_i,\ \ i=1,2,\ldots R_x$$

(11)

Where, S is the transmitted code matrix Eq. (1). $T_i=[T_{i1},\ldots\ldots\ldots,T_{iTx}]^T$, i=1,2,……Rx are the complex values accounting for both the target backscattering. $V=[V_{i1},\ldots\ldots\ldots,V_{iTx}]^T$, i=1,2,……Rx are noise component. $r_i=[r_{i1},\ldots\ldots\ldots,r_{iN}]^T$, i=1,2……..Rx are the echo signals of the i^{th} receiver antennas contaminated by the clutter. The clutter vectors n_i are assumed as compound Gaussian random vector i.e., [22]

$$Cl_i=\sqrt{\alpha_i\beta_i},i=1,\ldots\ldots\ldots\ldots R_x \quad (12)$$

The texture α_i is non negative random variable which models the variation in power that arises from the spatial variation in the backscattering of the clutter and the speckle components β_i are correlated complex circular Gaussian vectors and independent to each other. This α_i is independent Zero-mean complex circular Gaussian vector with covariance matrix.

$$R_i=E[n_in_i^H\ ]=\alpha_ir_o \quad (13)$$

Where $r_o=[Cl_iCl_i^H]$ is the covariance structure. Where H is complex conjugate.

AF represents the time response matched to a given finite energy when the signal is received with a delay τ and a Doppler shift ν relative to the normal value expected by the filter. The ambiguity function is defined as

$$|\chi(\tau,\upsilon)|=\left|\int_{-\infty}^{\infty}S(t)\ \ S^*(t+\tau)\ \ \exp(j\ 2\nu\ t)\ \ dt\right| \quad (14)$$

Where S(t+τ) = r (received signal)

The MMO AF is defined as

$$\Theta_{MIMO}=\sum_{i=1}^{T_x}\sum_{j=1}^{R_x}|\chi_{ij}|^2 \quad (15)$$

IV. RESULTS

The orthogonal waveforms are generated with (10) as the objective function using ACC_PSO algorithm [23] [24] as the orthogonal waveforms sequences. ACC_PSO algorithm is beyond the scope of this paper. Using those sequences the orthogonal waveforms are generated.

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The 2X2 MIMO models with two targets are considered to plot AF. Three different waveforms are designed and considered to plot AF. In case I the AF is plotted with modified DFCW_LFM {Tx=2, Rx=2, N=40} in fig 1 and contour fig is plotted for the same in fig 2. In fig 1 it can be observed that the resolution of the targets is clear and same can be observed in fig 2 & fig 3 where fig 3 is the 2D plot of the AF.

In case II the AF is plotted with Polyphase {Tx=2, Rx=2, N=40, M=4} in fig 4 and contour fig is plotted for the same in fig 5. In fig 4 it can be observed that the resolution of the targets is clear and same can be observed in fig 5 & fig 6 where fig 6 is the 2D plot of the AF but resolution is lesser then case I.

In case III the AF is plotted with DFCSTW {Tx=2, Rx=2, N=40} fig 7 and contour fig is plotted for the same in fig 8. In fig 7 it can be observed that the resolution of the targets is clear and same can be observed in fig 7 & fig 8 where fig 8 is the 2D plot of the AF but resolution is lesser then case I and Case II.

As the length of the sequence increase the resolution is better in case I when n is of 40 lengths and can be observed in fig 1 and fig 10. As the time period of each sequence of the waveform decreases the sidelobes increases when can result in the decease of resolution and can be observed in fig 1 and fig 11. As the number of transmitting and receiving antennas decreases the resolution decreases and can be observed in fig 1 and fig12.

V. CONCLUSION

In this paper, the orthogonal DFCW_LFM, polyphase and DFCSTW waveforms are designed and illustrated with AF. The DFCW_LFM shows better resolution than polyphase and DFCSTW orthogonal waveforms. It can also be observed that the as the value of sequence number N and number of transmitting and receiving antennas increases the resolution is better in both the cases.

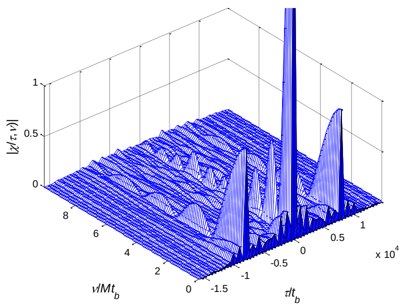

Fig1. Plot of 2X2 MIMO radar AF with orthogonal modified DFCW_LFM (N=40)

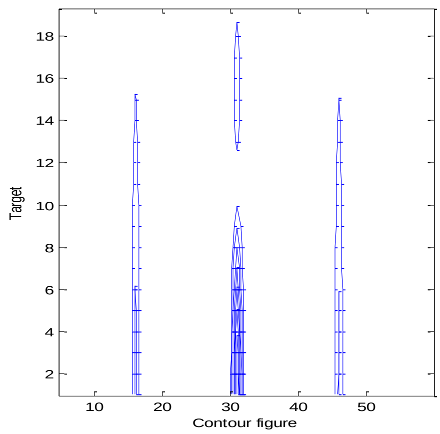

Fig2. Plot of Counter figure of 2X2 MIMO radar AF with orthogonal modified DFCW_LFM

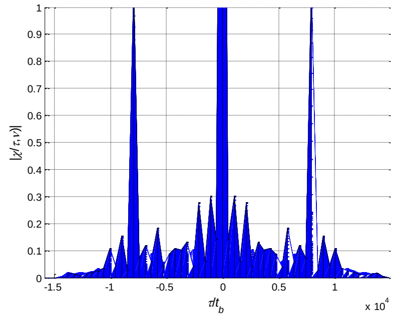

Fig3. Plot of 2D figure of 2X2 MIMO radar AF with orthogonal modified DFCW_LFM

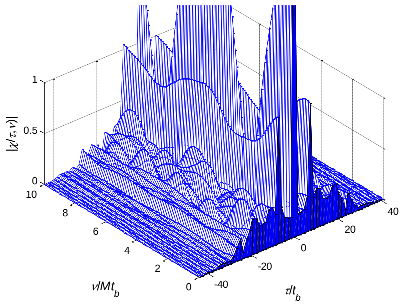

Fig4. Plot of 2X2 MIMO radar AF with orthogonal Polyphase Waveform

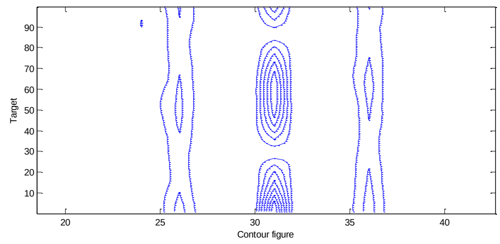

Fig5. Plot of Counter figure of 2X2 MIMO radar AF with orthogonal Polyphase Waveform

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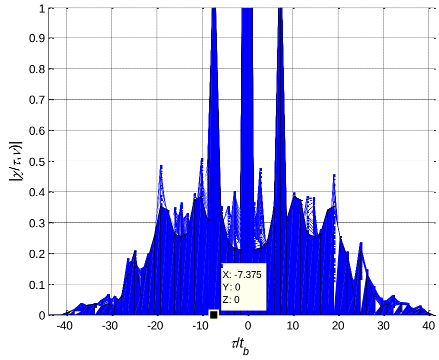

Fig6. Plot of 2D figure of 2X2 MIMO radar AF with orthogonal Polyphase Waveform

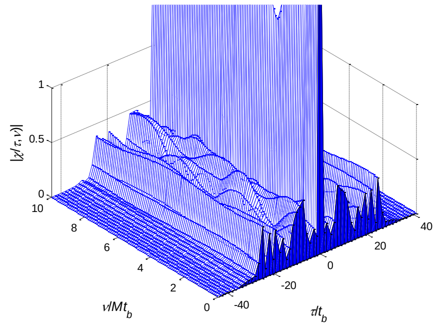

Fig7. Plot of 2X2 MIMO radar AF with orthogonal DFCSTW

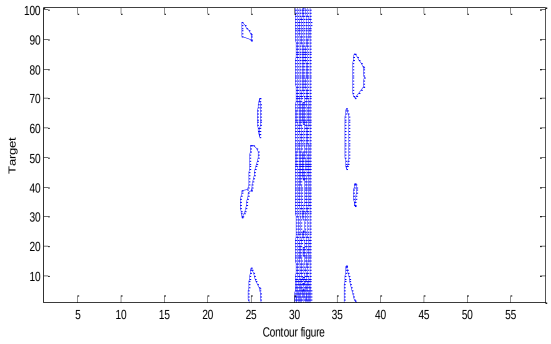

Fig8. Plot of Counter figure of 2X2 MIMO radar AF with orthogonal DFCSTW

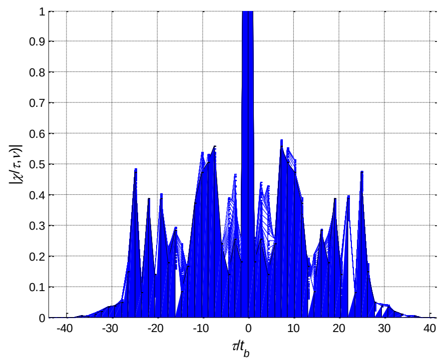

Fig9. Plot of 2D figure of 2X2 MIMO radar AF with orthogonal DFCSTW

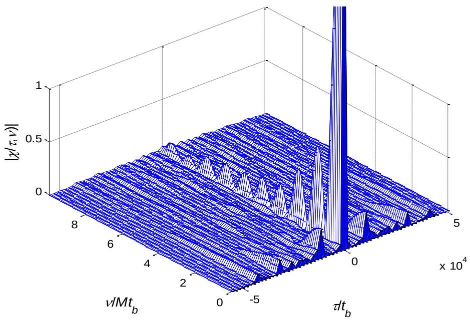

Fig10. Plot of 2X2 MIMO radar AF with orthogonal modified DFCW_LFM (N=32)

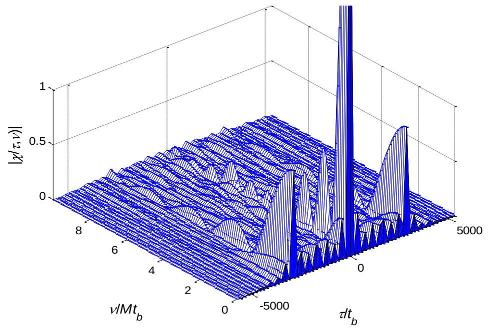

Fig11. Plot of 2X2 MIMO radar AF with orthogonal modified DFCW_LFM (N=40)

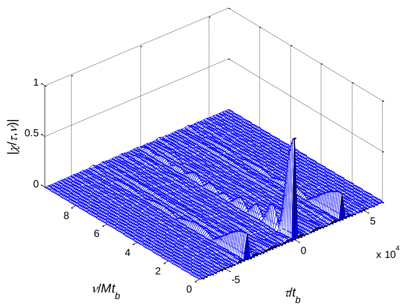

Fig12. Plot of 1 X 1 MIMO radar AF with orthogonal modified DFCW_LFM X1 (N=40)

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