IDENTIFICATION OF INTRA PULSE MODULATION SIGNAL IN THE PRESENCE OF NOISE

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ABSTRACT

In Electronic Warfare systems, Low Probability of Intercept (LPI) radar signals are used for identifying the targets in the selected region of operation. LPI radars are designed to minimize the chances of being intercepted or detected by passive radar receivers. Advanced signal processing techniques become an essential requirement when these signals are used for the detection and separation of multiple targets in a noisy environment. In this work, a noisy Stepped Frequency Modulated (SFM) waveform is detected by using high resolution spectrum estimation techniques. To improve the detection capability of the noisy SFM, two level filtering is used as pre-processing step. The filtered SFM signal is analysed using Root MUSIC and Eigenvector algorithms and the multiple target frequencies are estimated. The proposed method is successful in detecting the parameters of the SFM signal in the low Signal Noise Ratio conditions up to -9dB with an accuracy of 99%.

Keywords: stepped frequency FM, root MUSIC algorithm, eigenvector method, denoising filters, electronic warfare.

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1. INTRODUCTION

Radar is a vital and versatile tool for many applications because it can operate in all weather conditions. Radar images captured by satellites have a wide range of applications, such as visualizing the surface of the Earth from orbit, studying asteroids, and exploring the surfaces of other planets. It can also be used for assisting with navigation in the air and on the water, assisting in the detection of military forces, enhancing traffic safety, and providing scientific data [1]-[3]. Radar is a tool used by military forces to target different kinds of weapons as well as track the movement of troops, missiles, and aircraft in the Electronic Warfare field.

Electronic warfare (EW) system uses electromagnetic energy to detect, exploit, or prevent hostile use of the electromagnetic spectrum. The primary two problem that EW receivers encounter is determining a theoretical bound for a receiver that can process two simultaneous signals. The second problem is to find the dynamic range and frequency resolution of the radar signals. This problem should be answered with real time signal processing in mind This problem should be addressed with real-time signal processing techniques. Because of the increase in signal processing speed, digital receivers are employed in EW systems to detect the targets [4]-[7]. Most of the users of radar systems are employing LPI radar signals as tactical requirements for Electronic Warfare applications [8]-[10]. A.B.Glenn in 1984 proved that the most significant improvement in LPI performance may be obtained by operating at extremely high frequency ranges. The basic purpose of an LPI capability for a communication system is to prevent the enemy from locating our communication systems, which will reduce the effect of electronic attacks and physical attacks [11]. R.K.Niranjan and B.Rajendra Naik proposed Digital IQ Method for detecting complex pulsed radar signals. The modulation techniques used in pulsed radar are Inter-Pulse Modulation and Intra-Pulse Modulation. For intrapulse analysis, it measures immediate parameters including phase, frequency, and amplitude, while for interpulse analysis, it measures pulse width and pulse repetition interval. With the suggested approach, different radar signal waveforms can be handled [12]. Since the range resolution is inversely proportional to the signal bandwidth, therefore the modulation improves range resolution without narrowing pulse width. In Inter-Pulse Modulation, modulation is applied from pulse to pulse. It is classified into two types Frequency modulated signal (Stepped FM) and Phase Modulated signal [13]-[18].

In stepped FM, the frequency is varied in the form of steps which is constant with Δf. It can achieve a large bandwidth for high range resolution by repeatedly changing carrier frequency over pulses. Wide bandwidth signals are required in high resolution radars to achieve a narrow main lobe width [19]. The generation of such wide bandwidth signals raises the system's cost and complexity. To overcome these constraints, the wide bandwidth signal is divided into a group of narrowband signals that are transmitted and received separately. The effect of a wide bandwidth signal is obtained by coherently merging narrow band signals. Such narrow band signals are called Stepped FM waveforms frequency jumped train or synthetic wide band waveforms [20]-[21]. The majority of digital receiver systems employ the FFT to determine the radar signal spectra. This method of spectral analysis is highly effective and yields acceptable outcomes for a wide range of signal processing applications [22]. Apart from these advantages, it has several performance limitations. The most prominent limitation is that, if there are multiple signals with frequencies that are very close in range, the FFT operation gives a spurious response that, one flat peak containing the response of multiple signals. Many alternative spectral estimating methods have been proposed to overcome the drawbacks of the FFT methodology such as MUSIC (MUltiple SIgnal Classification), Root MUSIC, Eigenvector method, and ESPRIT algorithms [23]-[25].

Majid Pourahmadi, Mansor Nakhkash, and Ali Akbar Tadaion (2013) explained in their work that the role of noise is crucial in the determination of the true dimension of signal subspace in the MUSIC algorithm. In the presence of noise MUSIC method performance degrades and even fails to identify the frequencies of closely spaced targets. In such a case, a denoising system is needed to reduce the impact of noise on the estimating system when there is noise in the system, the performance of MUSIC can degrade. Stoica, Petre, and Randolph L. Moses, 2005 have explained that the RootMUSIC algorithm, the Eigenvector method, and the MUSIC method are similar in some ways. It uses the properties of the signal subspace to estimate the spectrum. These spectrum estimation techniques cannot establish the precise location of the targets in the absence of denoising, whereas the denoising method can well separate targets from each other [26]. Denoising filters generally used are Wavelets, Moving Average Filter, Median, Savitzky - Golay (SG) filter, and Mean filter [27]. In this paper, firstly the complex Radar signal i.e., Stepped FM is generated. To test the functionality of the algorithm random noise is added to the signal. Detection of noisy stepped FM signal is carried out by using denoising filters and spectrum estimation algorithms. The codes for generation and detection algorithms have been written in MATLAB.

2. GENERATION OF STEPPED FREQUENCY RADAR SIGNAL

To generate the stepped frequency modulated radar signal, the detailed algorithm is explained in below flow chart Fig.1 below. Select the number of samples that are used for choosing the sampling rate of the signal. Decide the number of steps wanted to generate, for example as N=4. As in the stepped frequency waveform, the carrier frequency is changed from pulse to pulse with the fixed step frequency, set the carrier frequency and step frequency. By using the number of samples (n)and the number of step frequencies time duration of the pulse is calculated for example n/N =256, here it is considered as the pulse repetition interval is 256. For the corresponding frequency and period, the signal is generated. The flow diagram gives the steps to perform the simulation of stepped frequency modulation.

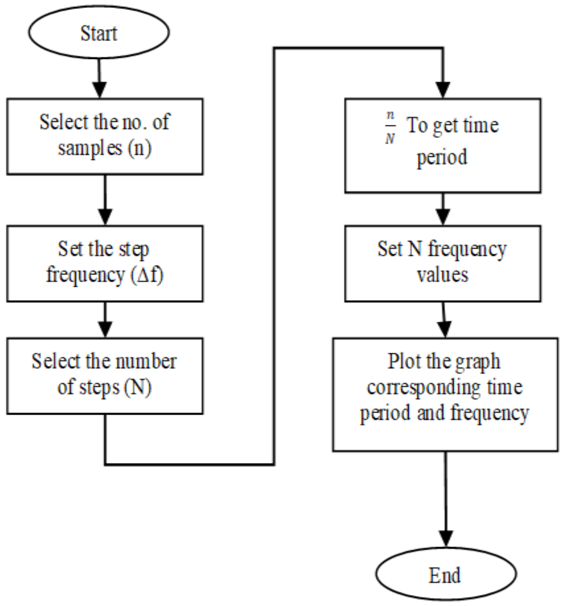

Figure-1. Flowchart of generation of the stepped frequency radar signal.

The stepped frequency radar waveform is generated with the characteristics given in Table-1. Frequency variation from pulse to pulse is known as frequency agility and by observing the fall count of sample frequency, it can be understood that there are four (fall count+1) steps presented in the received data are shown in Figure-2(a). Frequency varies from 100 MHz to 160 MHz in four steps with a step frequency of 20MHz and 1024 samples per cycle each. An increase in the frequency with fixed steps frequency of 20 MHz can be found in the Spectrogram which is shown in Figure-2(b). Spectrum estimation with FFT is shown in Figure-2(c). By comparing every sample frequency raise or fall counts we can know the number of steps present in the received data. Frequency variation means finding the frequency difference from pulse to pulse in received data. Frequency variation can be defined as Δf. The mathematical expression to find the difference frequency is given by eq. (1)

$$\Delta f = f2 - f1 Hz \quad (1)$$

Table-1. Stepped frequency radar waveform details.

S. No.	Signal parameter	Details
	Sample number	1024 per pulse
	Starting frequency	100 MHz
	Step frequency (Δf)	20 MHz
	Number of step frequencies	4

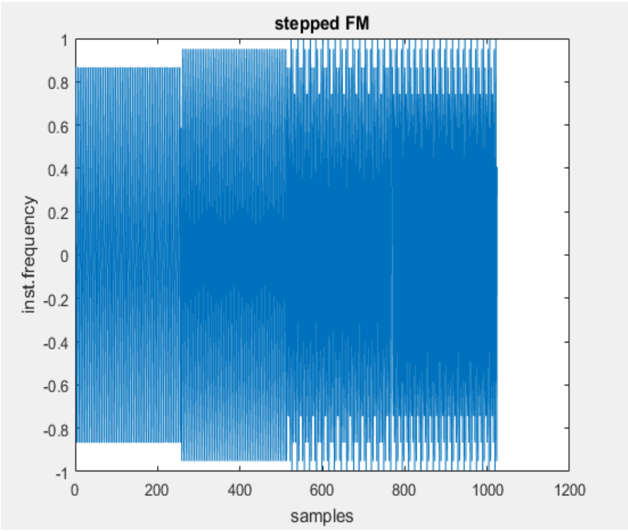

Figure-2(a). Input SFM signal.

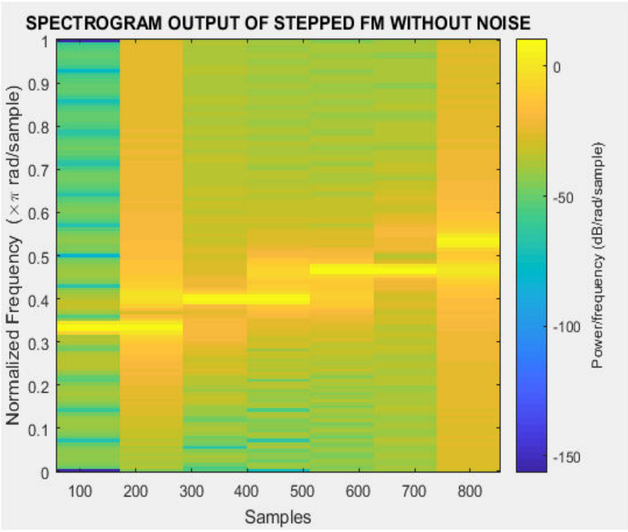

Figure-2(b). Specgram of the SFM signal.

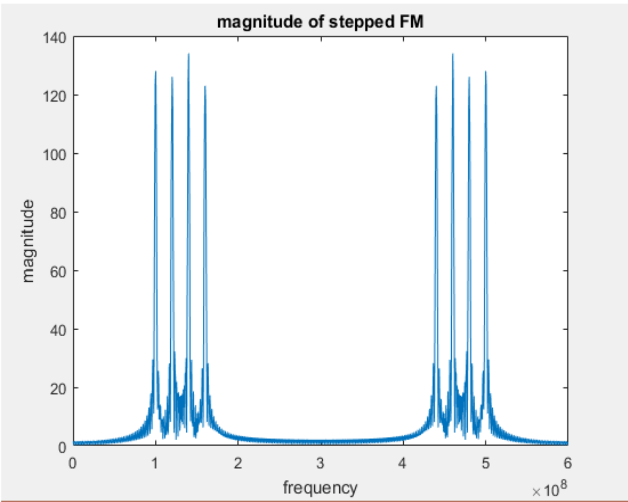

Figure-2(c). FFT of the SFM signal.

3. DENOISING FILTERS

In real time signal analysis, when the signal is transmitted from transmitter to receiver, many obstacles can obstruct its path, and corresponding noise will be added to the signal as it reaches the receiver antenna. Hence, detection of stepped frequency modulated radar signal is carried out by two major steps, which are using denoising filters and high resolution spectrum estimation methods. Denoising filters are used to reject or lessen the impact of noise. To identify and differentiate objects in different environmental conditions spectral estimation methods are generally preferred. Denoising filters, the Eigenvector method, and the Root Music algorithm are used for detection purposes. Median and SG filters are mostly preferred filters for smoothing out the noise.

3.1 Median Filter

The Median Filter is a common non-linear digital filter used to reduce noise in images or signals. It is particularly effective at reducing random noise, especially when the noise has long tails in its probability density or when there are periodic patterns in the noise. The filter works by moving a small window (M by M neighborhood) over the input image or signal. For each position of the window, the Median Filter substitutes the median value of the pixel intensities within that window for the corresponding center pixel in the output image or signal. By using the Median instead of the mean (average) of the pixel intensities, the Median Filter is robust against outliers and can effectively eliminate noise spikes or sudden variations in pixel values that might be caused by noise. It is a pre-processing method for noise reduction and to improve the results of later processing techniques. The Median filter's nonlinear function can be written with a filter length of $Nd=2k+1$ as given in eq. (2).

$$d(n)=med[r(n-k),r(n-k+1),\ldots,r(n),\ldots,r(n+k-1),\ldots\ldots r(n+k)] \quad (2)$$

where
$d(n)$ - the output signal
$r(n)$ - the input signal
Nd - Length of the input data
k - Order of the kernel window

3.2 Savitzky Golay (SG) Filter

The core idea behind Savitzky-Golay filtering is to find the best-fitting polynomial within the moving window, considering the assumption that the data points are locally well-approximated by the chosen polynomial. This local polynomial fitting allows the method to smooth the data while preserving the underlying features, such as peaks and other signal frequencies. By sliding the moving window through the entire data set and performing polynomial fitting at each position, Savitzky-Golay filtering effectively smooths the data without losing significant resolution, making it a useful technique for denoising and preserving important features in noisy signals. For getting a better smoothing effect as depicted in eq.(3), the length of the window should be higher than O.

The two critical components of the Savitzky-Golay filtering method for producing the smoothing effect are:

a) Moving Window (W): Savitzky-Golay filtering applies a moving window over the data points. The window size is typically odd and represents the number of adjacent data points used for the smoothing process.

b) Polynomial Fitting(O): Within the moving window, a polynomial function is fitted to the data points. The degree of the polynomial can be chosen based on the characteristics of the data and the desired level of smoothing. The most commonly used polynomial degrees are 2 (quadratic) or 3 (cubic).

$$W > (O + 1) \quad (3)$$

4. SPECTRUM ESTIMATION TECHNIQUES

4.1 Eigenvector Method

This method is based on Schmidt's eigenspace analysis technique, which estimates the pseudo spectrum from a signal or a correlation matrix using a weighted version of the MUSIC algorithm [23]. It finds applications in various fields such as radar signal processing, wireless communications, and seismic data analysis, where identifying signal frequencies from noisy measurements is crucial. The algorithm takes an input signal or a correlation matrix as its input. The signal is typically represented as a vector of data points or a matrix of data points collected over time. If a correlation matrix is not provided as input, the algorithm estimates it using the Singular Value Decomposition (SVD) technique. The correlation matrix provides information about the relationships between different components (e.g., sensors in an array) of the signal. The algorithm performs an eigenspace analysis on the correlation matrix. This involves finding the eigenvalues and eigenvectors of the matrix. The eigenvalues represent the variance explained by each eigenvector, and the eigenvectors provide the direction of the principal components of the data. The pseudo spectrum of the signal is estimated based on the eigenvalues obtained from the eigenspace analysis. The pseudo spectrum provides information about the frequencies present in the signal and their strengths.

The eigenvector method yields a pseudo spectrum estimate, which is given by eq. (4)

$$P_{ev}(f) = \frac{1}{\sum_{l=M+1}^{k} \left| V_l^H \, e(f) \right|^2 / \lambda_l} \quad (4)$$

Where

k - the dimension of the eigenvectors

V_l - l^{th} eigenvector of the correlation matrix of the input signal

M - the dimension of the signal subspace/ the number of input signals

4.2 Root MUSIC Method

Root-MUSIC" stands for "Root-Multiple Signal Classification," and it is a signal processing technique used in the field of array processing and direction-of-arrival (DOA) estimation. It is a high-resolution algorithm that can accurately estimate the spectrum and DOAs of multiple signals even when they are closely spaced. It provides accurate and robust results, making it a popular choice in various applications, including wireless communication, radar systems, sonar, and more, such as locating the source of a signal or tracking the movement of objects. The key idea behind Root-MUSIC is to analyze the eigenvalues and eigenvectors of the covariance matrix of the received signals. The "root" in Root-MUSIC comes from the fact that the method involves calculating the square roots of the eigenvalues of the covariance matrix. The working procedure of the Root MUSIC algorithm for finding the spectrum of the received signal is given below

Working procedure:

Step 1: Find the input data to create a Correlation matrix.

Step 2: Generate a correlation matrix of received data using the Covariance matrix.

Step 3: Construct the covariance matrix, R, of the received signals. If the received signal matrix is ‘x’, then the covariance matrix is given by eq. (5)

$$R = xx^H \quad (5)$$

where H represents the Hermitian (conjugate transpose) operator.

Step 4: Use the Eigenvalue Decomposition method to compute the eigenvalues and eigenvectors of the covariance matrix R as shown in eq. (6)

$$R = Q\Lambda Q^H \quad (6)$$

Here, Q is a matrix of eigenvectors, and Λ is a diagonal matrix of eigenvalues.

Step 5: Based on eigenvalues, construct the noise subspace and signal subspace.

Step 6: Construct the spatial spectrum using the signal subspace/noise subspace.

Step 7: Polynomial Root-Finding: Formulate a polynomial using the spatial spectrum.

Construct the spatial spectrum (Root-MUSIC spectrum) using the eigenvectors. For a given angle θ, the spatial spectrum value, P(θ), is computed as eq. (7)

$$P(\theta) = 1/|a(\theta)|^2 \quad (7)$$

Where a(θ) is the steering vector for the given angle.

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The number of distinct roots corresponds to the number of signal sources or target frequencies.

5. DETECTION OF STEPPED FREQUENCY RADAR SIGNAL USING PROPOSED ALGORITHM

The initial procedure starts with signal collection from the targets and the flowchart of the detection algorithm is shown in Figure-4. Let x be the noisy signal from the Radar receiver as given eq. (8). To estimate the spectrum of the signal, the signal data is converted from analog to digital form using the covariance method. Formation of correlation matrix R_m as indicated in Figure-3.

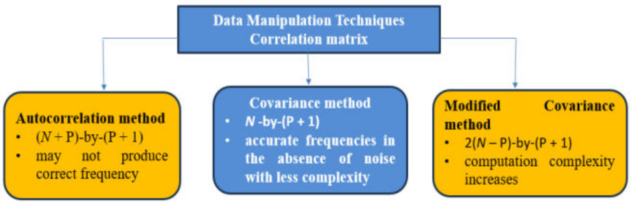

Figure-3. Data manipulation techniques.

In most cases, the Modified covariance method is used for forming the digitized data matrix from the received noisy signal data x(0),x(1),…..,x(N-1). For decreasing the effect of noise (z), Median and SG filters are employed as denoising methods, and these are very effective in decreasing noise in the received signal information. Next, this signal is converted to digital form by using the Covariance matrix technique to perform Eigenvalue decomposition (EVD). If M is the number of step frequencies and Nd is the input data length, it selects the model parameter of the matrix 'P' performing EVD as represented in eq. (9).

$$x = Ys + z \tag{8}$$

here $Y=[y(\omega_1), y(\omega_2),\ldots.y(\omega_M)]$ and 's' is the amplitude vector

$$P \geq 2M+1 \tag{9}$$

To perform EVD analysis, the covariance matrix is generated by taking 'P' as '9'. The procedure for EVD analysis and the calculation of the eigenvectors and the eigenvalues of the correlation matrix are explained clearly in Ref. [24]. From the output of EVD, signal subspace information (M) is obtained. This information is the most important parameter in high resolution spectrum estimation methods Root MUSIC and Eigenvector methods to identify the positions of the multiple step frequencies nearby. Finally, the spectrum of the signal frequencies is estimated using eigenvalues of the matrix.

The detection process is done to verify whether the received data is stepped frequency or not and to find signal parameters like instantaneous frequency, step frequency, number of pulses, and number of samples.

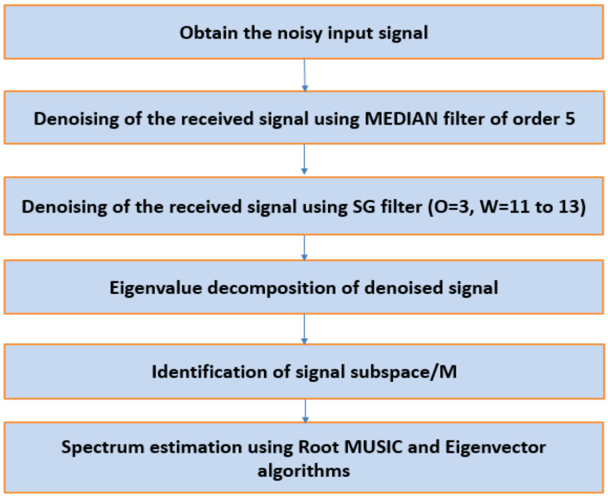

Figure-4. Flowchart of the detection algorithm.

6. RESULTS AND DISCUSSIONS

Figure-5(a) shows the FFT of a signal with a signal-to-noise ratio (SNR) of -6dB and a sampling frequency of 600MHz. The spectrum indicates that it's difficult to identify the signal frequencies due to the presence of noise. To mitigate this, the signal is passed through a Median filter of order '5' and an SG filter with a polynomial order and window length of '3' and '11' respectively. Figure-5(b) depicts the signal's spectrum using a Median filter, which is unclear to identify the peak frequencies. The estimated frequency results of SG and Median plus SG filters are shown in Figure-5(c) and Figure-5(d). The result is showing the correct number of step frequencies in Figure-5(d). For Stepped FM, the simulated signal using the Eigenvector method is presented in Figure-5(e). It shows that frequency varies from 160 MHz to 100 MHz with a fixed step frequency of 20 MHz and a sample length of 1024 ns in each pulse. The output four step frequency values measured using the Root MUSIC algorithm are indicated in Table-2.

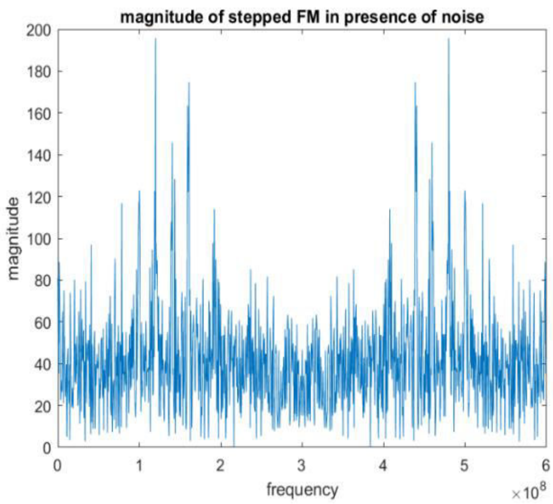

Figure-5(a). Output signal in the presence of noise SNR=-6dB.

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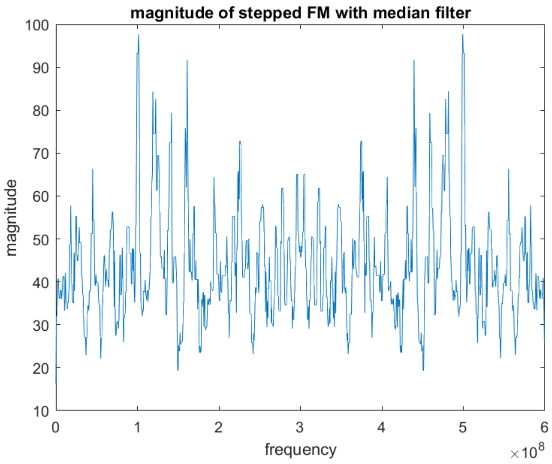

Figure-5(b). Output of signal with Median filter for SNR=-6dB.

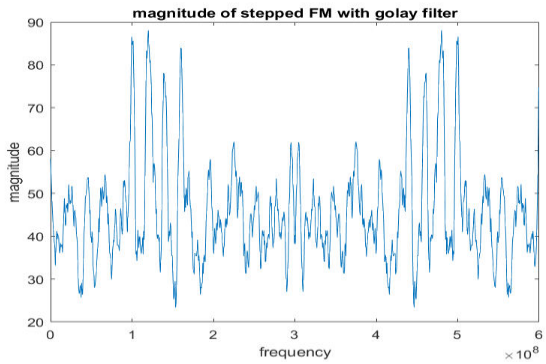

Figure-5(c). Output of Stepped FM signal with SG filter for SNR=-6dB.

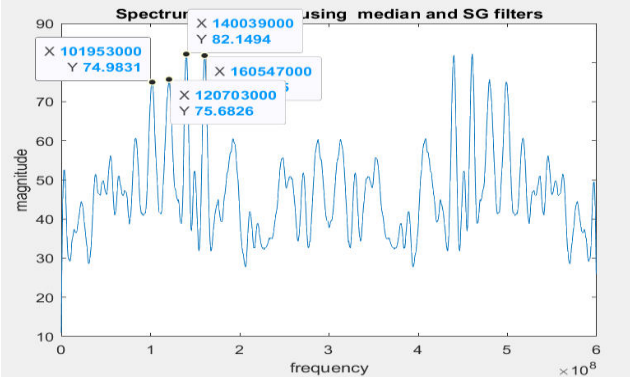

Figure-5(d). Output of Stepped FM signal with Median plus SG filter for SNR=-6dB.

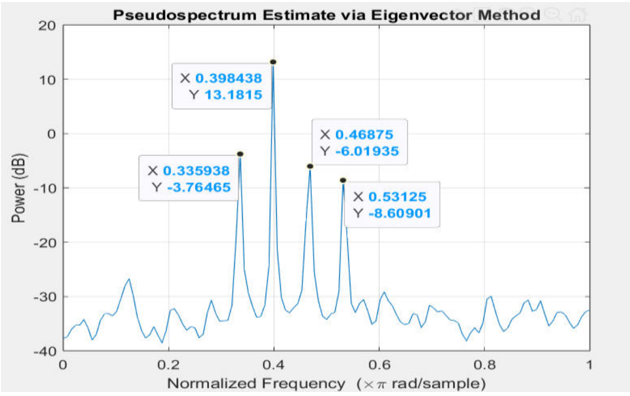

Figure-5(e). The output of Stepped FM signal using the Eigenvector method for SNR=-6dB.

Table-2. Estimation of output signal frequencies using spectrum estimation techniques for SNR= -6dB.

S. No.	Input step frequencies	Estimated frequencies of output using Root MUSIC algorithm (MHz)	% Error	Estimated frequencies of output using Eigenvector method (MHz)	% Error
1	100 MHz	99.850000	0.15	100.781400	0.78
2	120 MHz	120.080000	0.06	119.531400	0.39
3	140 MHz	139.820000	0.12	140.625000	0.44
4	160 MHz	160.2100000	0.13	159.375000	0.39

In the second case, the SNR value is reduced to -9dB, with the window length of SG filter '13' for estimating the spectrum using the Root MUSIC and Eigenvector method. Table-3 shows the results of the estimated step frequency values of SFM. The output results with denoising filters and the Eigenvector method are shown in Figure-6(a) to Figure-6(d). The denoised spectrum is unclear to find the number of steps frequencies. Hence it can be observed that when the signals are detected in a cluttered or noisy environment, the data selection and order of filter are very important parameters. The comparative spectrum estimation chart with the percentage of error for SNR=-6dB and SNR=-9dB is indicated in Figure-6(e) to Figure-6(f). It can be observed from the comparative charts that Root MUSIC algorithm is estimating accurately comparing to Eigenvector method with less error in step frequency estimation.

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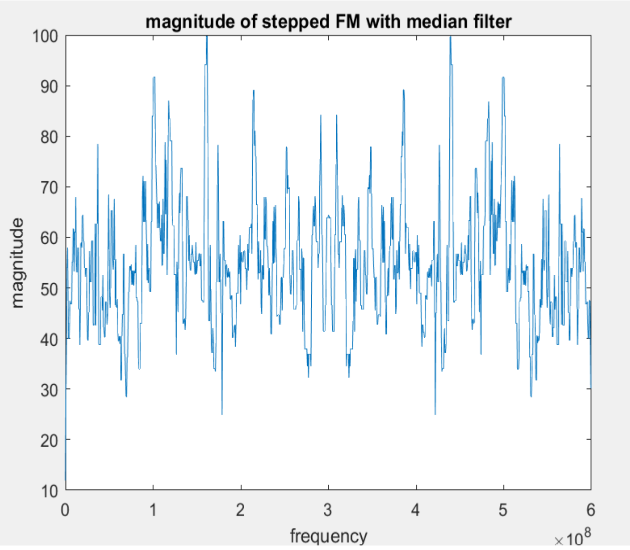

Figure-6(a). Output of SFM with Median for SNR=-9dB.

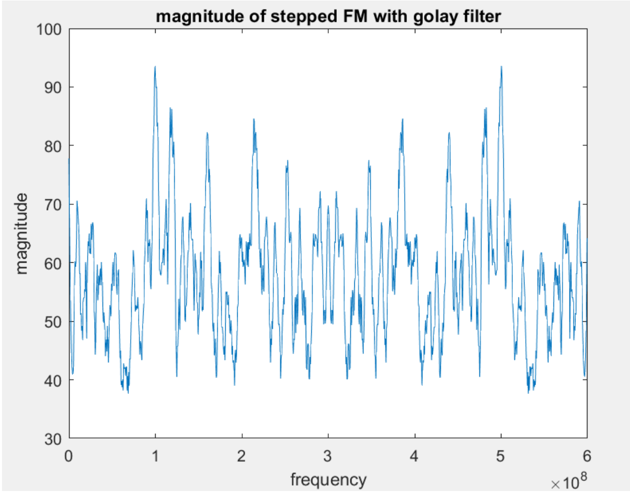

Figure-6(b). Output of SFM with SG filter for SNR=-9dB.

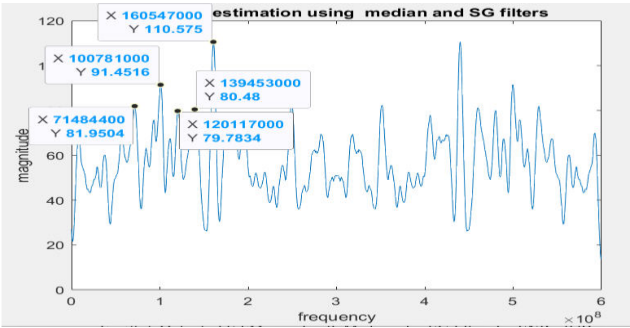

Figure-6(c). Output of S FM signal with Median plus SG filters for SNR=-9dB.

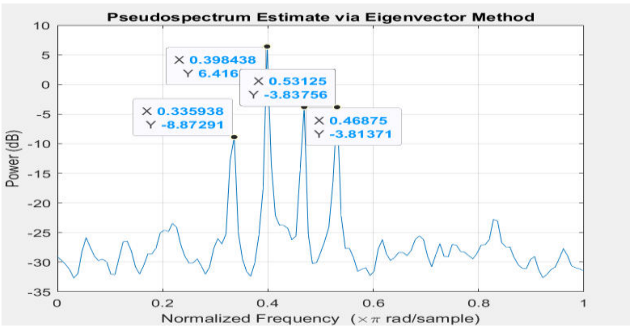

Figure-6(d). Spectrum of output signal with Eigenvector method for SNR=-9dB.

Table-3. Estimated output of SFM signal using Spectrum estimation techniques for SNR=9dB.

S. No.	Input step frequencies	Estimated frequencies of the output of Stepped FM radar signal			
		Root MUSIC algorithm (MHz)	% Error	Eigenvector Method (MHz)	% Error
1	100 MHz	99.800000	0.2	100.7814000	0.78
2	120 MHz	120.140000	0.11	119.531400	0.39
3	140 MHz	139.800000	0.14	140.625000	0.44
4	160 MHz	160.190000	0.12	159.375000	0.39

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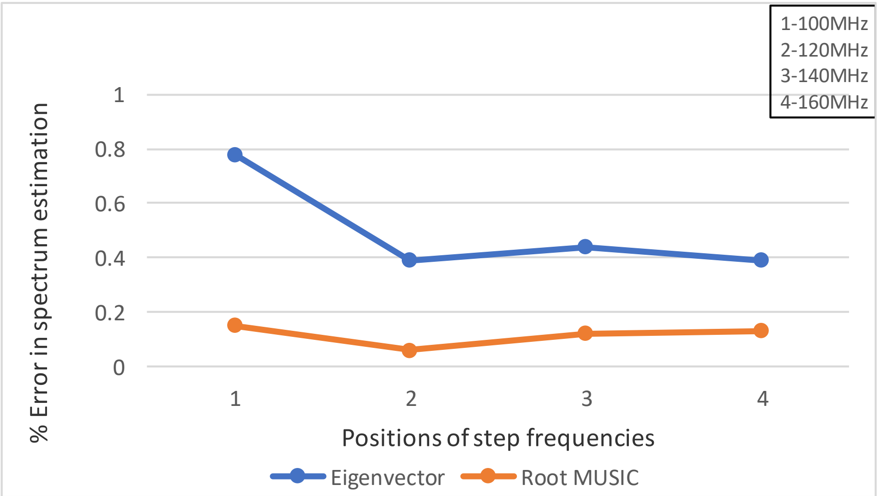

Figure-6(e). Comparative chart of spectrum estimation methods for SNR=-6dB.

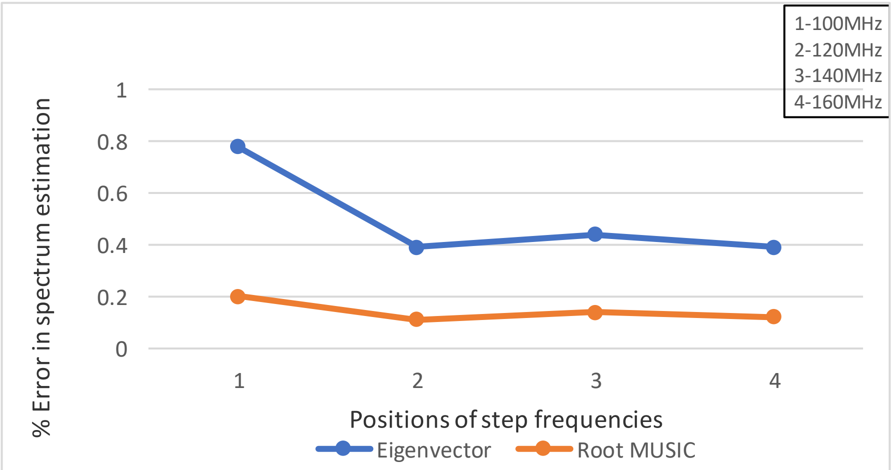

Figure-6(f). Comparative chart of spectrum estimation methods for SNR=-9dB.

CONCLUSIONS

Stepped FM radar signal is used for the identification of the targets because it can achieve fine high range resolution. Detection of the targets from the received signal is done with denoising filters and spectrum estimation algorithms. To reduce the effect of noise in the data, Median and SG filters are used. Denoising filtering is more useful in providing signal subspace information to the spectrum estimation algorithms. High resolution spectrum estimation techniques, Root MUSIC, and Eigenvector algorithm successfully detected the SFM signal by measuring instantaneous parameters step frequency (Δf), and number of step frequencies. The proposed technique is found to be more effective in detecting closely spaced SFM signals with 0.2% error using the Root MUSIC algorithm and 0.8% error using the Eigenvector method (approximately 1%) in the low SNR conditions up to -9dB.

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