Super Resolution Signal Processing Algorithm for Ground Penetrating Radar

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ABSTRACT:

Ground Penetrating Radar (GPR) has been approved as very successful sensing device for various kinds of investigations & detection of buried targets like pipe, (Water, Gas, Electric) cable, archaeological objects, voids, unexploded ordinances (UXO) etc. Such GPR using electromagnetic pulse is required to reduce pulse-width for high resolution and increase transmitting power for signal enhancement because the signal received from the radar is normally very weak and indescribable. Improvement of resolution is the challenging issue in GPR and that is greatly desired to increase for clear imaging of very closely buried targets. In this paper, super resolution technique MUSIC (Multiple Signal Classification) algorithm has been implemented because of its superior results. Moreover, the conventional FFT (Fast Fourier Transform) has been utilized to get higher precision receiving signal level. Combined Processing Method (CPM) of time domain response of MUSIC and IFFT (Inverse FFT) has been proposed to get high resolution and high precision receiving signal level. Simulation and experiment have been performed to support the proposal.

Key words: Subsurface Radar, FFT, MUSIC Algorithm, Super Resolution Signal & Image Processing.

1. INTRODUCTION

In the past decade, spectral estimation techniques have been approved as a unique tool for signal and image processing of radar. There are different spectral estimation techniques, in which conventional FFT has been widely used for real-time measurement due to higher computational efficiency and produces high precision receiving signal level for a large class of signal processes. However, there are several inherent performance limitations of the IFFT approach like low frequency range, i.e., ability to distinguish the spectral response of the two- or more signal is very low and implicit windowing of the data, i.e., the energy of the main lobe of a spectral response leaks into the side lobes.

Generally, GPR is a narrow bandwidth device and radar range is normally high, wide bandwidth is desired to enclose all target image. It is difficult to make wide bandwidth because the bandwidth is limited by antenna size in low frequency range and also wide bandwidth is limited by underground propagation characteristic in high frequency range. In order to overcome such problem, improvement of frequency resolution is greatly desired. Moreover, improvement of resolution is very important for GPR to trace out closely buried targets like gas pipe, water pipe, cables etc in urban area and also to detect the buried landmine that causes thousands of human life every year throughout the world. Therefore, in this paper, super resolution spectral estimation technique MUSIC algorithm [3] and conventional FFT has been implemented for signal processing of GPR for high resolution and high precision signal level.

2. THEORETICAL CONSIDERATIONS

The **MU**ltiple **SI**gnal **C**lassification (MUSIC) algorithm is a nonparametric spectral estimation technique, which estimate multiple scattering center from the observed voltage received on an array of antenna utilizing the eigenvector. The eigenvectors can be used to compute a spectrum with DOA (Direction of arrival) and estimate delay time of high frequency spectrum [3]. Eigen value of diagonal matrix helps to estimate the numbers of reflected signal.

The model vector for MUSIC can be expressed as

$$\boldsymbol{x} = \boldsymbol{Af} + \boldsymbol{w} \tag{1}$$

Where,

$$\boldsymbol{x} \cong [x_1, x_2 ....x_L]^T \tag{1a}$$

$$\boldsymbol{Á} \cong [\boldsymbol{a}(\boldsymbol{t}_1), \boldsymbol{a}(\boldsymbol{t}_2).........\boldsymbol{a}(\boldsymbol{t}_K)]^T \tag{1b}$$

$$\boldsymbol{a}(\boldsymbol{t}_K) \cong [e^{-j2pf_1 t_K}, e^{-j2pf_2 t_K} ....e^{-j2pf_L t_K}]^T \tag{1c}$$

$$\boldsymbol{f} \cong [f_1, f_2 .... f_K]^T \tag{1d}$$

$$\boldsymbol{w} \cong [w_1, w_2 ....w_L]^T \tag{1e}$$

Here, T represents transpose. Again $\boldsymbol{a}(\boldsymbol{t})$ vector can be decleared by its time. So, it is called mode vector. Matrix $\boldsymbol{A}$ has K numbers of array and L^{th} element of row. So, K can be regarded as number of signal.
The position (delay time) of each reflection point can be estimated by searching the peak position of the MUSIC function (P_{music})

$$P_{music}(\boldsymbol{t}) = \frac{\boldsymbol{a}(\boldsymbol{t})^* \boldsymbol{a}(\boldsymbol{t})}{\boldsymbol{a}(\boldsymbol{t})^* \boldsymbol{E}_N \boldsymbol{E}_N^* \boldsymbol{a}(\boldsymbol{t})} \tag{2}$$

Where * denotes complex conjugate transpose, $\boldsymbol{a}(\boldsymbol{t})$ is a delay time mode vector and $\boldsymbol{E}_N$ is noise $Lx(L-K)$ matrix whose columns are the $(L-K)$ noise eigenvector.

Ground Penetrating Radar signal are generally coherent signal. MUSIC doesnot work properly when the signal are coherent. Smoothing process should be performed in order to eliminates the problems encountered with coherent signal. So, MUSIC is preprocessed by Spatial Smoothing Processing (SSP) method [2]. Let's consider the frequency domain array with L reflection coefficient that is extended from $(1,2,3..N, N+1,..L-1, L)$ making M number of overlapping sub-array or snap shot having length N. Relation among L, M and N can be formulated as following.

$$L = N + M - 1 \tag{3}$$

Consequently, x_1 be the first snap shot having length N, x_2 be the second snapshot and extended up to x_M

overlapping snap shot. Phase is changed in each snap shot. The spatially smoothed covariance matrix is defined as the sample means of the sub array covariance and expressed as

$$\boldsymbol{S}_{SSP} = \frac{1}{M}\sum_{k=1}^{M} \boldsymbol{S}_k \qquad (4)$$

This SSP method has been implemented to decorrelate the signal in both simulation and experimental data.

3. SIMULATION

Computer simulation has been performed using Band Pass Filter before preceding the experiment. This Band Pass Filter impulse response is considered as radar signal [4]. The bandwidth is considered 125 MHz and the number of target considered is two with the delay time of 20ns and 40ns respectively. Signal level (amplitude) of the second target is set half of the first target, as second target is assumed to be much deeper than first one.

This frequency domain spectrum of radar signal as shown in Fig. 1(a) is first performed IFFT processing. In the mean time, same radar signal is performed MUSIC processing and the results are comparatively studied. Consequently, frequency domain data is converted in to time domain data in both cases. Combined Processing Method (CPM) of time domain response of IFFT and MUSIC is carried out using the following expression.

$$Z(t) = \frac{X\left|\frac{\partial Y}{\partial t}\right| + Y\left|\frac{\partial X}{\partial t}\right|}{\sqrt{\left|\frac{\partial Y}{\partial t}\right|^2 + \left|\frac{\partial X}{\partial t}\right|^2}} \qquad (5)$$

where, $X(t)$ is the complex time domain data of IFFT response, $Y(t)$ is the time domain data of MUSIC response and $Z(t)$ is the complex time domain data of combined result

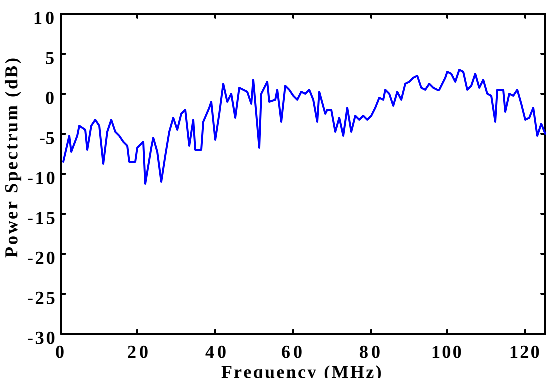


Fig. 1(a) Frequency spectrum of radar signal

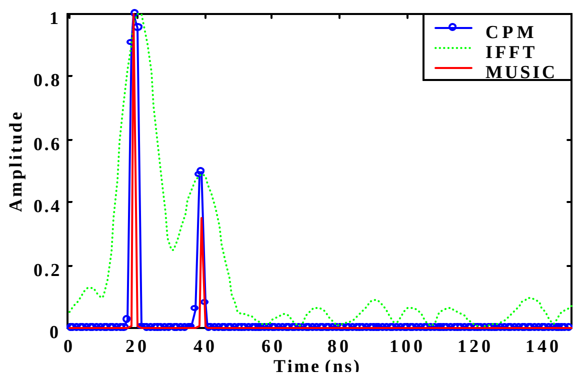


Fig. 1 (b) IFFT MUSIC and CPM Response

It is observed (Fig.1(b)) in IFFT response that the amplitude of the second signal is almost half of the first signal, which means IFFT gives correct amplitude but resolution is low. In MUSIC response, output signal is very sharp and resolution is very high as it is estimated from the peak of the MUSIC function. However, the second signal level is very smaller than the first one. That means MUSIC processing receiving signal level is lacking. Combined Processing Method (CPM) response gives high resolution as well as correct signal level.

3.1 SNR (Signal to Noise Ratio) Analysis

Generally, subsurface radar signals are enveloped inside the noise when the targets are deeply buried. Consequently, the signal to noise ration (SNR) will be very small as SNR is proportional to the depth of the target. Improvement of SNR is desired for minimum detectable signal to investigate deep target. Practically, minimum detectable signal is based on threshold level which should be set properly, otherwise false alarm might be consequence if threshold level were set too low and weak target echo might not be detected if threshold level were set too high. Therefore, SNR of input signal and each IFFT; MUSIC and CPM responses have been calculated and analyzed in order to set proper threshold level. However, number of snapshots M has been changed while performing MUSIC processing to investigate the effect of M with respect to SNR.

Input SNR in dB	SNR of IFFT Response in dB	No. of Snap Shots (M)	SNR of MUSIC response in dB	SNR of CPM Response in dB
-15.22	17.65	30	11.35	10.41
-5.80	17.74	30	13.58	11.11
-5.59	15.5	235	41.45	39.79
-5.04	17.01	100	32.08	23.59
-4.87	21.78	50	14.17	13.43
-4.46	20.26	10	10.85	11.12
+2.23	18.97	30	12.58	11.83

Table 1. Simulation results to investigate the SNR ration.

Simulation results have been shown in Fig. 2 at input SNR is -5.8dB, number of overlapping snapshots M is 30, frequency bandwidth is selected 250 MHz, sampling point is 250, sampling frequency is 1 MHz. The comparison is difficult due to great discrepancies observed in the amplitude of IFFT and MUSIC responses. So, MUSIC response has been normalized with IFFT response according to its the maximum value of signal level

In table 1, the simulation results have been presented varying input SNR ratio. It has been realized that minimum detectable signal –15.22 dB. The SNR response of IFFT, MUSIC and CPM at this input SNR has been achieved 17.65 dB, 11.43 dB and 10.41 dB respectively. In this case, SNR of IFFT response exhibit superior than SNR of MUSIC response.

It is observed from the simulation results that M play an important role in improvement of SNR, M is varied for smoothing while performing MUSIC processing. When M is increased, decorrelation performance will be improved and SNR will also be improved but resolution will be decreased. On the other hand, decrease in M degrades decorrelation performance as well as SNR but increases resolution. It can be illustrated by the simulation result shown in Table 1. When M is set 30 SNR of MUSIC responses is 13.58 dB at input SNR –5.8 dB and when M is increased to 100 SNR of MUSIC response increases up to 32.08 dB at input SNR –5.04 dB.

4. FIELD EXPERIMENT

Field experiment was performed at the research field of Koden–electronics Company, Yamanashi, Japan, using Network Analyzer that has a capability of measuring high precision data. The experimental field is ordinary soil with relative permittivity e_r and conductivity s of about 36 and 0.02 S/m respectively, a grass landscape with steel pipes having diameter 10 cm, buried under the earth at the horizontal separation of about 2 m and vertical separation of 50cm.

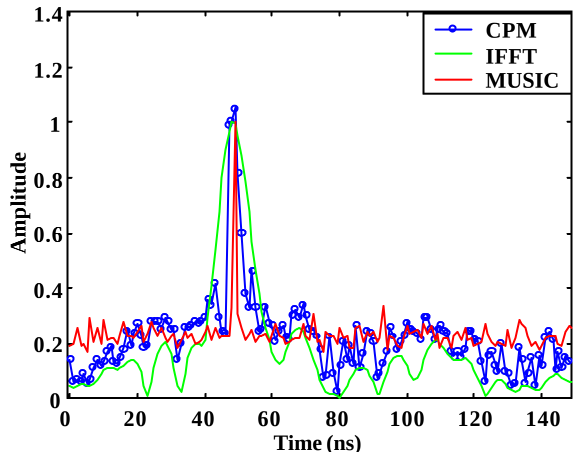


Fig. 2 IFFT, MUSIC and CPM response of signal plus noise at input at SNR –5.8 dB and M=30

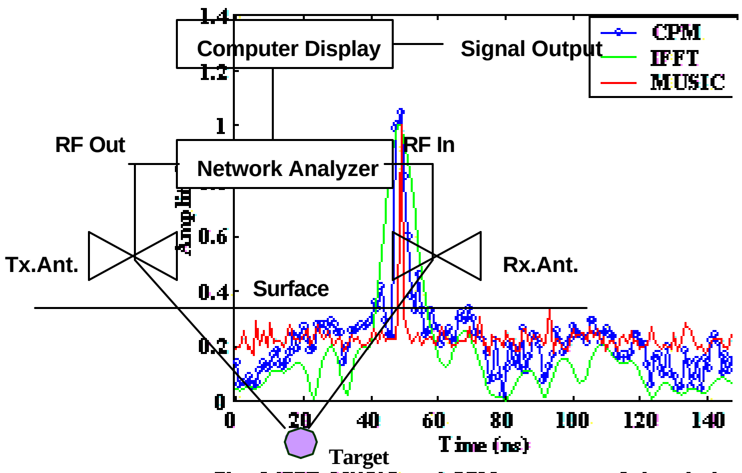


Fig. 2 IFFT, MUSIC and CPM response of signal plus noise at input at SNR –5.8 dB and M=30

Fig. 3 Simple diagram of Radar

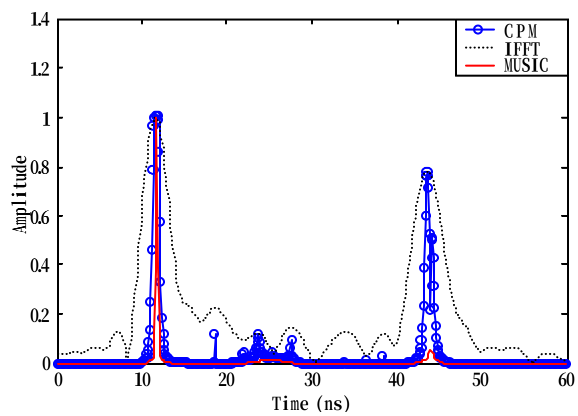
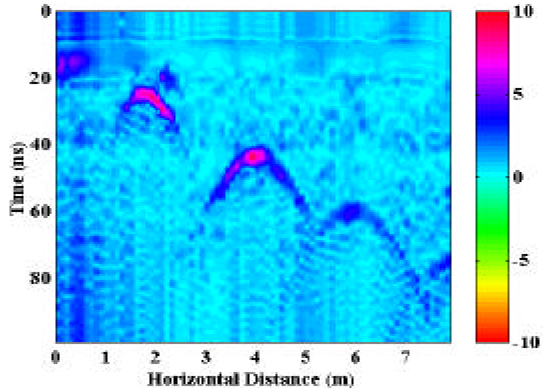
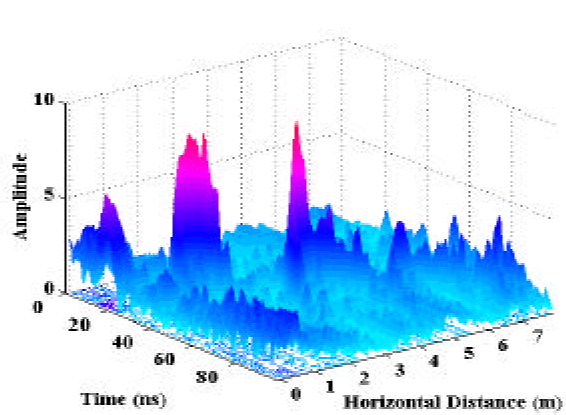


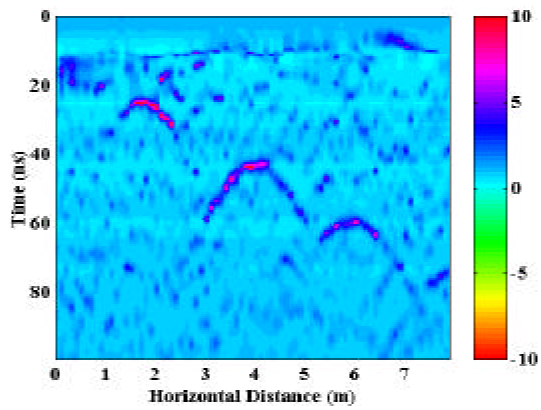
Fig. 4. IFFT, MUSIC and CPM Response of Experimental Data.

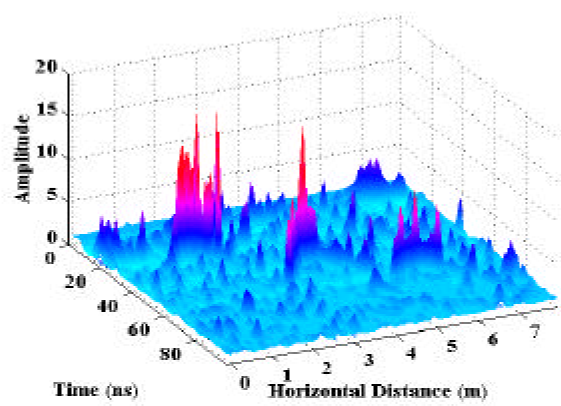




(a). 2-D IFFT Imaging

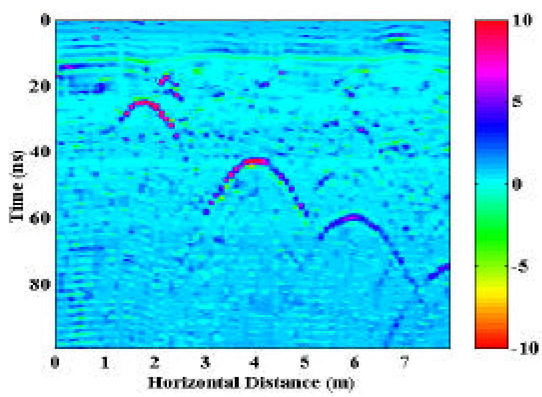
(b). 3-D IFFT Imaging

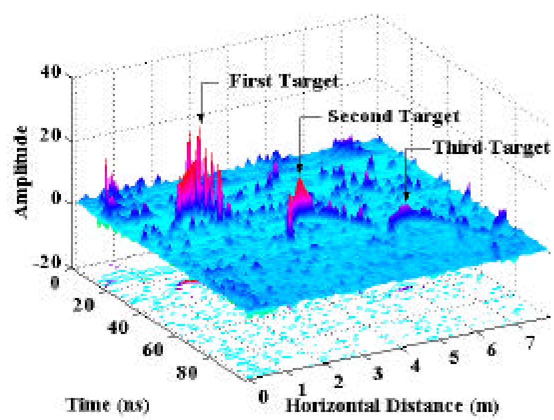




(c). 2-D MUSIC Imaging

(d). 3-D MUSIC Imaging





(e). 2-D CPM Imaging

(f). 3-D CPM Imaging

Fig. 5. Two Dimension and three Dimension images of IFFT, MUSIC and CPM response in linear scale at frequency bandwidth 400 MHz, M=10, L=50.

Basic diagram of experimental setup is shown in Fig 3. This is a Stepped Frequency Continuous Wave (SFCW) radar system based on Agilent RF Network Analyzer. Data range is 1 MHz to 401MHz. Since the point is set 401, the frequency interval is 1 MHz. Different sets of experimental data were taken from 0 to 6 meter at the interval of 10 cm using ferrite covered bow-tie antenna.

Frequency domain data displayed in the Network Analyzer is used to perform IFFT and MUSIC processing simultaneously. Then CPM processing method is performed combining time domain response of IFFT and MUSIC processing as in simulation process. Fig 4 is comparative study of IFFT, MUSIC and CPM processing result when the radar antenna is just above the 1m. The first signal is the coupling between radar antenna and ground & second signal is target signal. The result shows that CPM has both higher resolution and correct amplitude.

Two dimension and three dimension images of IFFT, MUSIC and CPM are presented in linear scale that is shown in Fig. 5. Image of IFFT processing result (Fig. 5(a)) is clear. However, resolution could not be considered high as well as time side lobe could not be ignored, which is undesired.

On the other hand, the image of MUSIC processing is sharp and resolution is very high, which is shown in Fig. 5 (b). Natural clutter has also been remarkably reduced and time side lobe has also been significantly eliminated. Matter of fact, MUSIC uses eigen analysis and the number of eigenvalue helps to estimate the number of signal with high resolution. Generally, the eigen value below the noise level could be discarded. Eigen analysis can be performed varying the value of M (snap shot), L (array element) as explained before in theoretical considerations. Different approach has been taken to approximate the value of M and L during simulation and experimental data processing as it plays vital role to get the good result. In this result (Fig. 5(b)), value of M is set 10 and L is 50, resulting value of N (snap shot length) is 41, which is obtained using equation (3). The frequency range utilized for MUSIC processing is from 150MHz to 350 MHz.

Finally, the image of CPM processing result in Fig. 5(c) shows that resolution has been greatly improved than Fig.5(a) and continuity of target image has also been improved than Fig.5(b). 3-D representation of CPM shown in Fig. 5(e) gives clear vision of the targets and shows that CPM could successfully demonstrate very high resolution, reduction of clutter as well as cancellation time side lobe.

5. CONCLUSIONS

Super resolution technique MUSIC and conventional FFT have been implemented for signal and image processing of GPR. Advantages of FFT and MUSIC algorithm are catered for better performance. CPM yields high resolution and high precision signal level that is realized from simulation. It is found that the improvement of SNR is greatly desired to enhance minimum detectable signal. It is further found from the experimental results that the image IFFT is clear but resolution is not high and presence of noise clutter and time side lobe can't be cancelled. On the other hand, MUSIC gives high-resolution image and significant cancellation of clutter and time side lobe due to eigenvalue analysis. However, MUSIC result could not demonstrate continuous target image. CPM processing has successfully demonstrated the high resolution; clear & continuous target image and significant reduction of clutter as well as time side lobe, which could be considered as a great achievement.

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