Microwave Imaging Using Sub-SpaceBased TR-MUSIC Method for Security Applications

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ABSTRACT: *Microwave imaging technologies are widely investigated in the biomedical field where they rely on the imaging of dielectric properties of tissues. The key challenge in security applications using the microwave imaging is the image reconstruction methods adopted in order to gain clear image of illuminated objects inside human bodies or underneath clothing, Therefore in this paper we present subspace based TR-MUSIC algorithms for point targets and extended targets. The algorithm is based on the collection of the dominant response matrix reflected by targets at the transducers in homogenous background and use the MUSIC function to image it. We used the FDTD method to model the transducers and the objects to process its response matrix data in Mat lab. Clear images of metal dielectric properties have been clearly detected.*

Keywords: Microwave imaging, Security Imaging, Dielectric properties, Subspace based TR-MUSIC, Image reconstruction

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1. Introduction

Microwave imaging systems exist under different types of technologies have been found applications in the medical imaging systems. There are already several papers discussing the use of microwave imaging via the analysis of dielectric properties of tissues using different techniques [1,2]. The microwave imaging has non-ionizing, non-invasive, sensitive and low-cost features [3], which is a promising technology for applications in security areas, such as border control in airports. Although the resolution of microwave imaging is not as high as X-ray, it has the advantage of being capable of imaging physiological changes [4,5]. The preferred illumination level in frequency for microwave imaging make it safe and non-destructive for operator customer, avoiding the hazard of X-ray radiation used in airport securities. This paper will illustrate the possible application of Security Imaging Systems using microwave frequencies between 0.9 GHz to 3GHz, which has already been attracted research interest in the medical field [6]. In the active microwave imaging methods there are two types of possible detection method for contraband materials: the microwave tomography and UWB radar techniques which has been investigated in the medical field as well as in the security systems [14]. The Microwave tomography has been successful in measuring the dielectric properties of the object to be imaged by solving nonlinear invers scattering problem [10], where the UWB techniques used to measure the targets are only from the back scattering signals [11]. The UWB technique on its own has failed to get the best resolution needed [12], where time reversal MUlti-static Signal Classification (MUSIC) technique has found its gap within the UWB to gain a higher resolution. The time reversal with electromagnetic inverse scattering imaging method has been used in many applications such as ultrasonic imaging in medical application, underground mine detection and other targets detection using a radar or sonar system. The MUSIC algorithm is used to describe the theoretical and experimental measurement of the scattered wave received at multiple antenna arrays located in arbitrary positions around the illuminated targets which calculates the number of signals, directions of arrivals, strength of the scattered wave, polarization and level of noise interference [13]. The key ideas behind this algorithm are (1) physical representation of the scattered field matrix, (2) filtration approach constructed on the resolution of the array and the singular value decomposition of the response matrix. The method proposed in this paper can be used to analyze the dielectric properties of the target, using different waveforms e.g. a point source or plane wave and using near or far field data. This method calculates the amplitude modulation of the signals coming from the dominant scattered field and then time reverses it in conjunction with MUSIC algorithm. The ideas of the image reconstruction algorithm is similar to the concept of the multi-static radar system by transmitting electromagnetic wave of single or multiple frequencies towards the targeted area and receiving a matrix of scattered field data, then being analyzed and viewed as an image. This method of measuring scattered wave field received at the transducers (receiver's antenna) is suitable for the security application of detecting image target location and its geometry. This approach is more straightforward and simpler than the usual approaches of an inverse problem where the whole medium is regarded as unknowns. Solving a nonlinear inverse problem will image the targets, but it takes a long time because of iteration method that usually be used to solve a nonlinear optimization and also expensive which requires a huge computation process. In a homogeneous medium with each iteration, solving adjoin forward problem as well as shape regularization is needed to find the shape derivative. The subspace-based TR-MUSIC direct imaging algorithm proposed in this paper will locate the target as well as its shape where dominant scattering wave field is detected. Moreover the target has its own dielectric properties which distinguish itself from the background medium. In heterogeneous media the detection of the target depends on two factors: (1) position of the dominated scattering event at the boundary of the target in the medium; (2) the fact that how well the Green function of the medium can be approximated. The image reconstruction formulation is based on the Helmholtz equation where all the transmitters send out pulses to the target and the scattered wave called the response matrix is recorded at the receivers. Then iterated time reversal procedure is used as well as the Singular Value Decomposition to extract the dominant scattered events that characterize the shape information of the target. The algorithm proposed in this paper can be used to analyze the dielectric properties of the target, use different waveforms e.g. point source or plane wave and using data near field or far field. The concerns raised about this imaging system were how to construct them cost effectively and with less radiation emission. The microwave imaging used to face the issue of expensive hardware and insufficient computing power, but now the technologies have advanced, and have indicated a brighter future for microwave systems, especially with the knowledge of the interaction of electromagnetic waves between human body tissues and their dielectric properties [7, 8]. The current human body inspection systems in airports are metal detectors, which can only detect metals concealed in the person's clothing, but they are ineffective if the person is hiding other illegal materials such as plastic explosives or drugs. There are additional machines at the airports which use a high dosage X-ray radiation, but it is very harmful for both the scanned person and the operator. Moreover, the goal of our research is to find the contraband materials within a human body, but at this stage we only investigate the strength of another image reconstruction method to find concealed metallic weapons within a human body and then this algorithm will be developed to find extreme small hidden targets within the human body using dielectric properties analysis. Compared with microwave tomography, wave front reconstruction and Delay-and-Sum algorithms, subspace-based TR-MUSIC algorithm is supposed to feature in super resolution, simplicity and generalizability. In this paper, we propose a multi-static radar system to visualize concealed metallic weapons with in human body clothing and it will later be extended to dielectric objects detection. And we will discuss the possibility of microwave imaging techniques for security applications using a Subspace-based TR-MUSIC algorithm. This paper is organized as follows: Section II discusses the data of dielectric properties of human body, Section III describes the minimum resolution and micro-wave frequency to be used in the imaging for security applications, Section IV describes the simulation configuration of the model and imaging scenarios, Section V discusses the mathematical principles of the algorithm, Section VI describes the numerical simulation and Section VII concludes the paper.

2. Dielectric Properties Of Human Body

Here we are going to investigate the best sources of dielectric properties of human body which will help to create simulated model to be imaged using the proposed algorithm. Dielectric properties of the human body have been discussed by several researchers. The most reliable data was produced by Gabriel 1996[8], under variable tests of microwave frequencies. Semenov and his group have used Federal Communication Commission tabulated values for the human body's dielectric properties in their simulation experiments [6]. This dielectric data will help to easily distinguish it from other dielectric properties of contraband materials, where it will show difference in the image results after any image reconstruction method applied. The advantage here of dielectric property analysis is that the dielectric properties values of explosive or drug materials are lower than the tissue of a human body tissue which contains blood and water. This difference of dielectric properties will be reported in another paper using this successful subspace-based TR MUSIC algorithm method in locating targets as shown later.

3. Resolution and Frequency for Microwave Imaging

In general there was always a concern about the resolution of microwave imaging systems. In fact, the answer to this question is that the resolution of the illuminated object by microwave imaging is affected by factors such as: microwave wavelength, reconstruction algorithms, and signal-to-noise ratio adjustments in microwave imaging systems, number of emitters and receivers and dielectric properties of biological objects. The resolution of microwave imaging has been investigated by Sergueiet al [7]. Their microwave operating frequencies were between 0.9 and 2.36 GHz, with a signal-to-noise ratio was 30 dB. They concluded that the resolution between 6.3-7.8 mm was achieved at 2.36 GHz. Therefore, knowing that the wavelength in water at 2.36GHz is equal to 1.44 cm, the spatial resolution achieved was better than half of the wavelength $\lambda/4$ = 8.3 mm. They also concluded that resolution between 7.3-9.5 mm was achieved at 0.9 GHz. Therefore, knowing that wavelength in a medium at 0.9 GHz is equal to 3.32 cm, the spatial resolution resulting experimentally was better than the quarter of the wavelength The above has demonstrated that the microwave resolution is not limited by the wavelength in medium, the smallest object which could be detected is 6.3mm and therefore, that is the minimum resolution achievable for microwave security applications. For ordinary security control of contrabands, 6.3 mm diameter or higher is the required resolution to detect any illegal object hidden in a human body. In the current simulation we have used 3 GHz frequency radiation to increase the possibility of better resolution.

4. Simulation Configuration and Imaging Scenarios

The imaging geometry and configuration is demonstrated in Figure 1. The object is surrounded by a circular N-element array with radius R and inside is the imaging region with length L and width W. Each element antenna transmits electromagnetic wave towards the imaging region in turn and all the elements receive all-directional wave front scattered by the object. This means that each antenna is a transducer. The obtained scattering data is then processed to reconstruct the position and shape of the object.

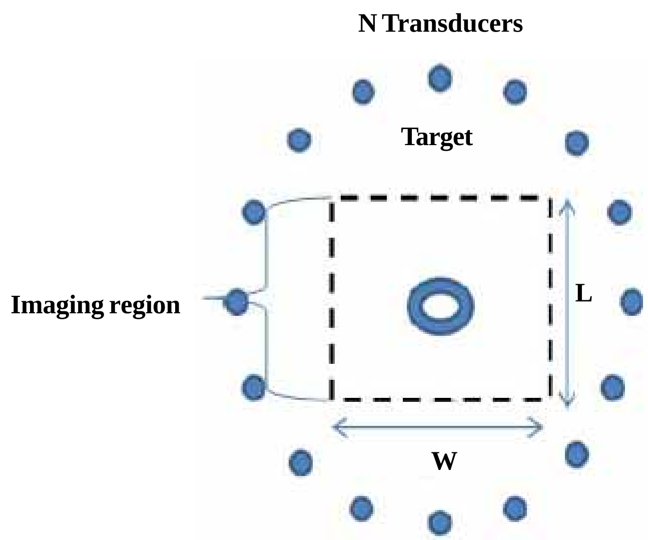


Figure 1. Imaging Geometry and Configuration

5. Subspace - Based TR-Music Algorithm

5.1 Time-Reversal (TR) Principle

In the wave equation of lossless and stationary medium, the quadratic differential relationship between field component and time keep the invariance to the sign of time, upon which the concept of Time-Reversal is based upon. If $E(x, t)$ is the solution to the wave equation in (1) $E(x, -t)$, is also its solution, which is called the time-reversal field of $E(x, t)$.

$$\nabla^2 \mathrm{E}(x,t) - \mu\varepsilon \frac{\partial^2}{\partial^2 t}\mathrm{E}(x,t) = 0 \quad (1)$$

where $E(x, t)$ is the electric field component at position $\boldsymbol{x}$ and time t, μ and ε are the permittivity and permeability of the medium, respectively. The wave propagation process means that the time-reverse field $E(x, -t)$ would precisely retrace the path of the original wave $E(x, t)$. If $E(x, t)$ is the divergent scattered field, then $E(x, -t)$ is the convergent wave which will focus on the source with physical or computational TR process. In the frequency domain, the TR process can be implemented by phase conjugation, using $\overline{E(x, \omega)}$ to replace , where the superscript bar denotes complex conjugation $E(x, \omega)$ and is the Fourier transform of $E(x, t)$

4.2 Multi-static Response Matrix (MRM) and TR operator

For the array of N transducers in Figure 1, we can define the inter-element impulse response $h_{ij}(t)$ to be the signal received at the ith transducer with an impulse sent out from the jth transducer, the matrix.

$$H(t) = [h_{ij}(t)]_{N \times N} \qquad (2)$$

is called the multi-static response matrix in time domain. Due to the space reciprocity of the static medium, the matrix H(t) is symmetric, i.e. $h_{ij}(t) = h_{ij}(t)$. For a source signal distribution

$$S(t) = [s_1(t), s_2(t),..., s_N(t)]^T \qquad (3)$$

The received signals at the array are

$$R(t) = [r_1(t), r_2(t),...,r_N(t)]^T = H(t) * S(t) \qquad (4)$$

where the star sign denotes convolution in time domain. In the frequency domain, it becomes

$$R(\omega) = H(\omega)\, S(\omega) \qquad (5)$$

P(ω) is called multi-static frequency response matrix at frequency ω. The Hermitian operator

$$K(\omega) = H^{\dagger}(\omega)\, H(\omega) \qquad (6)$$

is also called time-reversal matrix, where superscript † denotes complex conjugation transpose. Because $K(\omega)S(\omega) = H^{\dagger}(\omega) H(\omega) S(\omega) = H(\omega) R(\omega)$ means the received signals are back propagated after phase conjugated, according to the TR principle mentioned above, toward the source positions where they come from.

There exists singular value decomposition (SVD) for matrix H(ω)

$$H(\omega) = U\Sigma V^{\dagger} \qquad (7)$$

with m singular values $\sigma_1 \geq \sigma_2 \geq ...\sigma_m \geq 0$, where m = rank (H), U and V are left singular vectors and right singular vectors, respectively. The first m columns and the last N - m columns of V span the row space and nullspace of H(ω), respectively, and the first m columns of U span the column space of H(ω), the last N - m columns of U span the nullspace of $H^T(\omega)$, respectively. And it can be showed that the orthonormal columns of U and V are eigenvectors of $H(\omega) H^{\dagger}(\omega)$ and $H^{\dagger}(\omega) H(\omega)$, respectively. And the eigenvectors of TR matrix K(ω) can be showed to correspond to different targets in a one-to-one manner. So the singular vectors of H(ω) play the same role as the eigenvectors of K(ω). That is the reason why the subspace-based MUSIC method is also called TR-MUSIC method. Mathematically and practically, SVD of H(ω) is preferred compared to the eigenvalue decomposition (ED) of K(ω), because: (1) SVD uses orthonormal bases whereas ED uses a basis that generally is not orthonormal; (2) All matrices (even rectangular ones) have a SVD and not all matrices (even square ones) have an ED.

4.3 MRM matrix structure for point targets in electromagnetic scattering problems

Electromagnetic wave propagation is dominated by the Greens function $g^o(x_1, x_2)$ of the background medium, where x_1 denotes the field point and x_2 the source point. And due to spatial reciprocity of homogenous background, the x_1 and x_2 can be exchanged, that is $g^o(x_1, x_2) = g^o(x_2, x_1)$.

Assume that there are M point scatterers located at $x_1, x_2,...,x_M$ in the imaging region with isotropic reflectivity 1 and the array element antenna locate at $\xi_1, \xi_2,..., \xi_M$ respectively. If Born approximation is applied, i.e. neglecting the multiple scattering effect, H(ω) can be written

$$H(\omega) = \sum_{m=1}^{M} G^0(x_m)\, G^0(x_m)^T$$

$$= \begin{bmatrix} \sum_{m=1}^{M} g^0(\xi_1, x_m) g^0(x_m, \xi_1) & \cdots & \sum_{m=1}^{M} g^0(\xi_1, x_m) g^0(x_m, \xi_N) \\ \vdots & \ddots & \vdots \\ \sum_{m=1}^{M} g^0(\xi_N, x_m) g^0(x_m, \xi_1) & \cdots & \sum_{m=1}^{M} g^0(\xi_N, x_m) g^0(x_m, \xi_N) \end{bmatrix} \tag{8}$$

Where $G^o(x_m)$ is called illumination vector for x_m, defined by

$$G^o(\boldsymbol{x}_m) = [g^o(\boldsymbol{\xi}_1, \boldsymbol{x}_m), g^o(\boldsymbol{\xi}_2, \boldsymbol{x}_m),...,g^o(\boldsymbol{\xi}_N, \boldsymbol{x}_m)]^T \tag{9}$$

According to (8), it is clear that H(ω) is a linear combination of M illumination vectors $G^o(x_1)$, $G^o(x_2)$, ..., and $G^o(x_M)$, and furthermore rank(H) = min(M, N).

4.4 Subspace-based MUSIC algorithm

In the MUSIC algorithm, for M < N case, since rank(H) = M, The first M columns of U span the column space of H(ω) in terms of SVD theory, which is defined the signal space V^S, and the last N -M columns of V span the nullspace of H(ω), defined the noise space V^N, which is the orthogonal complement of V^S. For arbitrary search point x in the imaging region, its illumination vector is $G^o(x)$, if it collocates with any point among $x_1, x_2,..., x_M$ then $G^o(x)$ belongs to V^S and V^N its projection to equals to zero, otherwise the projection of $G^o(x)$ to V^N is finite. According to this finding, a pseudo-spectral imaging function can be constructed as

$$I(x) = \frac{1}{\| P_V NG^o(x) \|^2} = \frac{1}{| \sum_{k=M+1}^{N} | v_k.G^o(x) |^2} \tag{10}$$

Where v_k is the kth column vector of V. This imaging function will peak greatly at the positions of point targets and super-resolution characteristic can be expected.

4.5 TR-MUSIC algorithm for extended targets

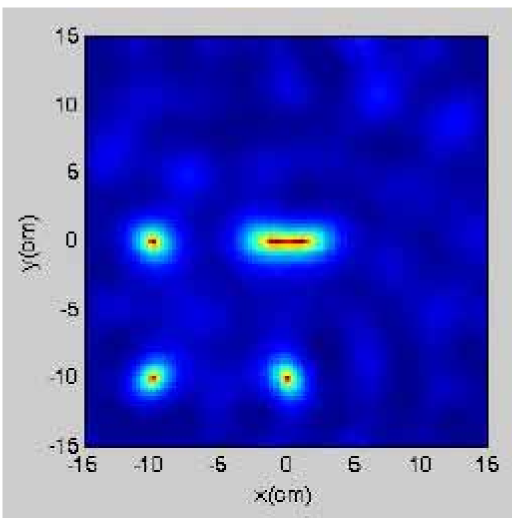
It can be assumed that when there is noise in measurement or extended target, the performance of TR-MUSIC algorithm is degraded, but it can be applied in these circumstances. The key issue is how to decide the optimal M value to obtain the best imaging results if the array element number is big enough. For extended targets, the peaks of the imaging function don't correspond to the point targets one-by-one anymore and maybe exist on the target boundary or inside of the object due to physical resonance and dielectric property of the objects. In this scenario, TR-MUSIC can be used to sketch the shape of extended targets, which is demonstrated in the following simulation examples.

6. Numirical Simulations and Results

Microwave imaging technique is adapted here to test 2D object by subjecting them to multi-static single frequency excitation of microwave rays from an arbitrary antennas array around the object and analyzing the image created. This program has been developed in Matlab. The simulation was carried out to prove the concept of detecting different objects in homogenies backgrounds such as air. After projecting the microwave ray onto the developed Models of objects using FDTD method there will be an image reconstruction algorithm using Subspace-based TR-MUSIC to calculate the scattered field absorbed by the arbitrary antenna array. To demonstrate the usage of TR-MUSIC algorithm in microwave imaging applications, the 2D scattered fields are calculated by FDTD method to get the MRM H(ω) to be processed. The zero-order Hankel function of 2nd kind $H_0^{(2)}(k_o\rho)$ in 2D free space is used as the Greens function $g^o(x_1, x_2)$ in the illumination vector $G^o(x)$, where $k_o = 2\pi / \lambda$ is wavenumber and ρ is the distance between the field point and source point. The probing array is consisted of N =14 isotropic point transducers equally distributed on the circumference of radius R = 30cm.The frequency of electromagnetic wave is 3GHz and the wavelength λ = 10cm. The imaging region is 30cm × 30cm. And some typical imaging results are listed in the following figures.

6. 1 Multiple point targets

In numerical experiment for point targets imaging, the H(ω) MRM is calculated directly by Hankel function but not FDTD method. The 5 point targets located at the coordinates of (-10,0), (-1,0), (1,0), (-10,-10) and (0,-10), and their unit are cm. The imaging result is showed Figure 2 using 2D and 3D views. It should be noted that the vertical axis is linear scaled in 2D view but logarithmic scaled in 3D view, and all the following figures are the same. It can be observed that TR-MUSIC algorithm can resolve them completely even from the smallest distance which is only 2cm less than λ / 4 . This super-resolution is obtained only from the single frequency scattering information and better resolution can be expected for multiple frequency or wide-band data.



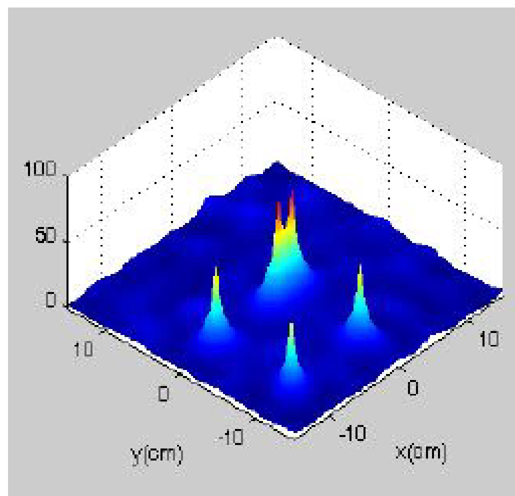


Figure 2. Multiple point targets imaging: (left) 2D view; (right) 3D view

6.2 Small metal cylinder

In the second numerical experiment, it is assumed that the target could be a metallic gun underneath the terrorist clothing, therefor a small metal cylinders was created in 2D FDTD with radius R = 2 cm and reconstructed by TR-MUSIC algorithm. In Figure 3, the cylinder is located at the coordinate of (0, 0), it can be seen that the small cylinder looks like a point target due to radial symmetry. When the cylinder is moved to (0,6) in Figure 4, it looks like a point target as before but there is a negligible virtual point at the y-axis imagery position, which maybe is caused by calculation error in FDTD codes. When the same two cylinders coexist in Figure 5, the image becomes a little complicated because of multiple scattering between them, although they can be still distinguished clearly from each other.

6.3 Extended target

Figure 6 is for another metal cylinder with R = 20cm and Figuer 7 is for a metal rectangle cylinder whose dimension is 20cm ×10cm, respectively. These two objects are extended targets compared to the wavelength. It can be seen that the image peaks or spotlights located on the boundary and inside the metal, the TR-MUSIC images sketch the shape for the illuminated objects which conclude thatthe "*large*" targets can be represented by their main scattering centers as radar targets characteristics.

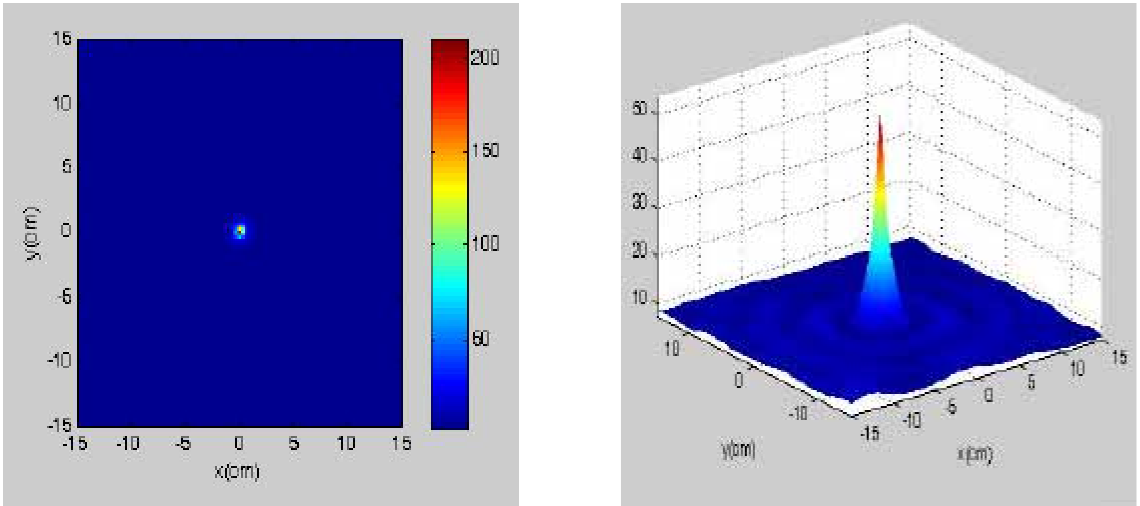


Figure 3. Small metal cylinder located (0, 0)

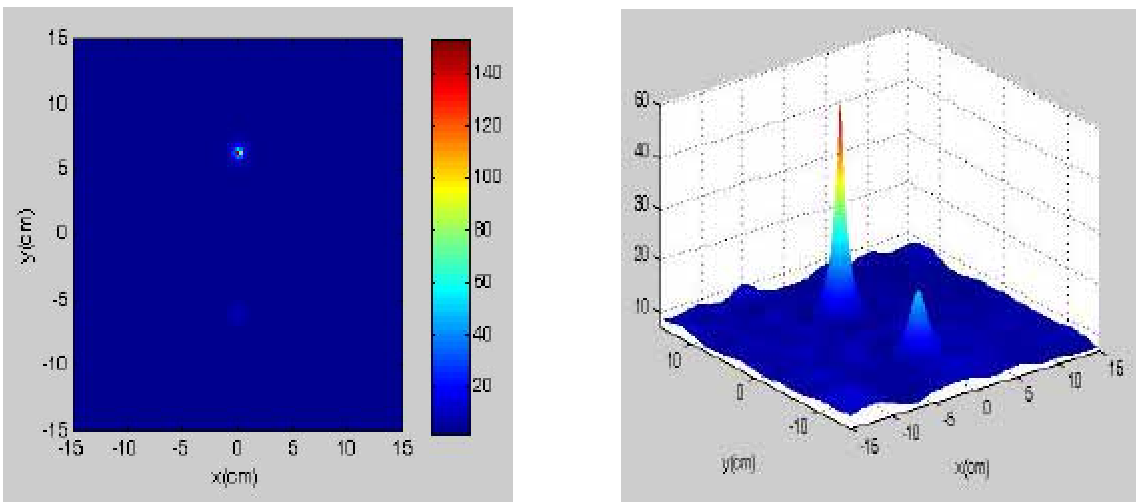


Figure 4. Small metal cylinder located (0, 6)

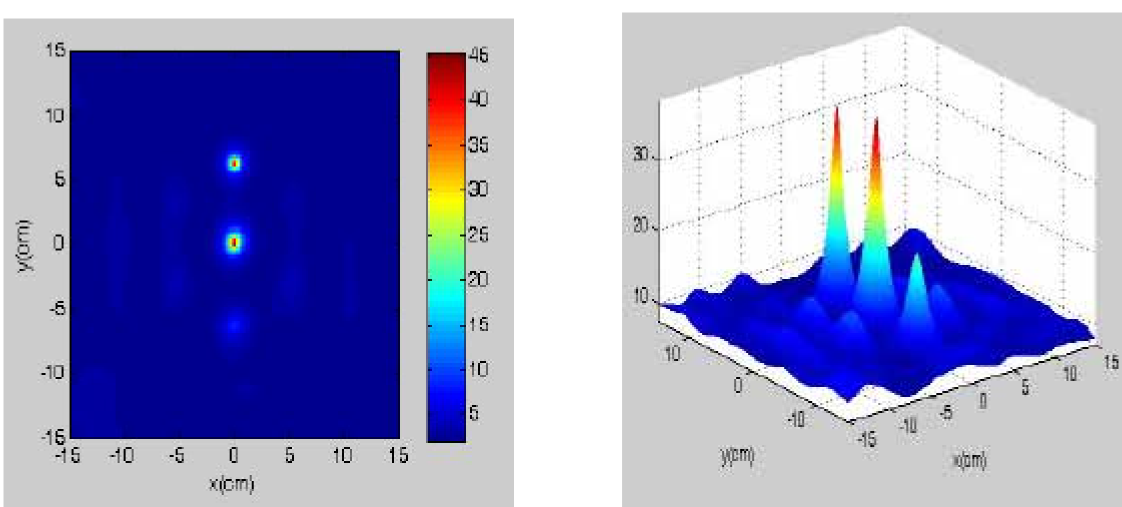


Figure 5. Two small metal cylinders located (0, 0) and (0, 6)

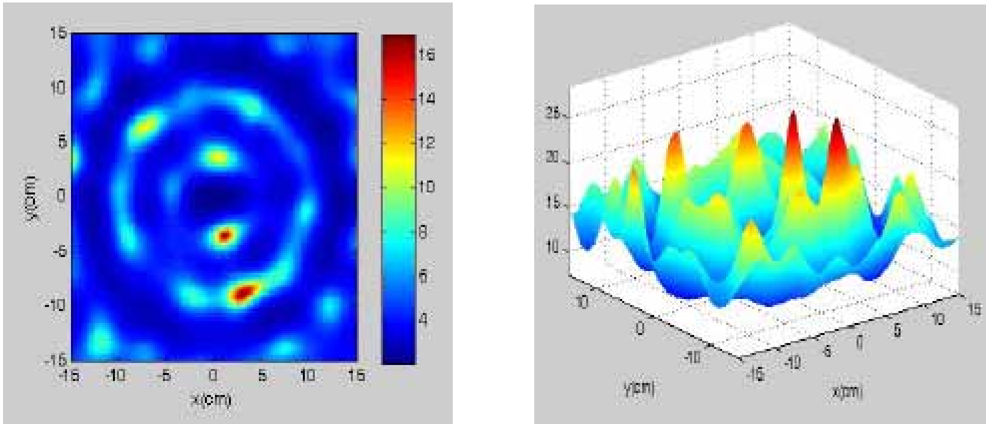


Figure 6. Big metal cylinder with R = 20cm

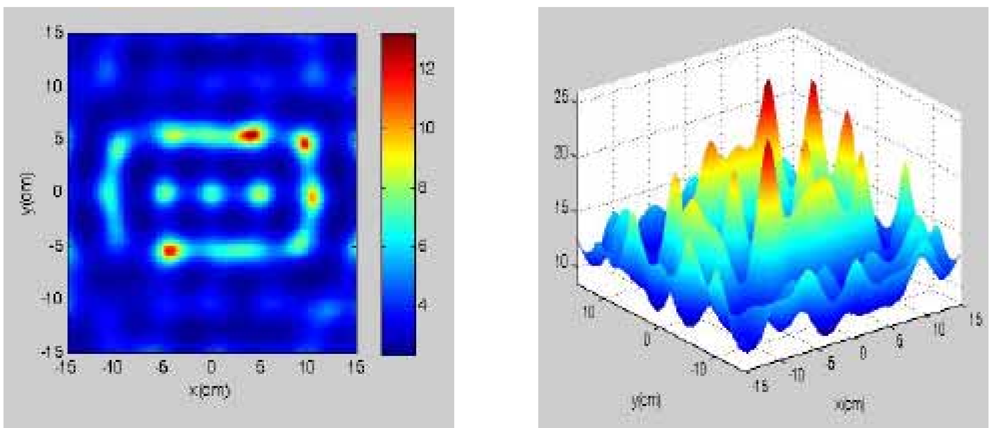


Figure 7 . Metal rectangle cylinder with 20cm ×10cm

7. Conclusions

As seen from the simulation that this method (subspace-based TR-MUSIC) for image reconstruction showed a very clear point targets as well as boundary and inside of the metal objects. It is a direct algorithm, simple and does not need forward solution or iteration. The goal of this algorithm is to locate and visualize a strong scattering field that has been generated by target's response matrix and use the Singular Value Decomposition to collect its information and generate the final image. The simulation assumed here was for single frequency excitation but with multiple frequency excitations the result will be far superior. Consequently it could not be denied that this Algorithm method won't construct the Image of metallic gun if concealed underneath clothing. Therefore the future research work will focus on same scenarios as in Figure 6 and Figure 7 and use more array elements to resolve them to gain a robust and clear image. Also the test of this algorithm will continue to try and build different models of different material properties to match the contraband materials that could terrorist use for threats.

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