# 3D ISAR Imaging of Realistic Target Model Based on General Purpose EM Simulators

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**Abstract**— Recent progress in computation performance and computational electrodynamics allows various analyses on many problems related to electro-magnetic (EM) waves using general purpose EM simulators. In this paper, we describe and demonstrate 3D ISAR image generation of a realistic target using FEKO, which is one of the representative general purpose EM simulators on the commercial market. This method can benefit us many advantages like building the database of many targets for target recognition with cost-and-time effective way and designing a radar and evaluating its performance under more realistic situations.

## 1. INTRODUCTION

Inverse synthetic aperture radar (ISAR) has been widely used in many applications for its high resolution capability. In the traditional operation of ISAR, the coherent system directs the antenna to the target and gathers the wideband reflected energy at various look angles of the target, normally by utilizing the rotational motion of the target. Representing the target's cross-sectional area in various range points and Doppler frequencies (or cross-range points) generates the 2D ISAR image of the target [1–3]. Similarly, a 3D ISAR image of the target can be acquired when the translational and rotational motion components of the target can be measured or at least estimated precisely so that the target's profiles for two different orthogonal look angles are collected.

Recent studies on 3D ISAR imaging concept have been mainly focused on two different approaches [3]. The first approach is based on interferometric ISAR principle, where multiple antennas are used at different heights such that the second cross-range dimension is able to be resolved [4–6]. This approach has many limitations, including its high sensitivity with respect to glint noise of the target and the lack of multiple height information for a selected range cross-range point. On the other hand, the second approach that utilizes single ISAR antenna can yield radar cross section (RCS) profiles at multiple heights and multiple range cross-range points. Some of the 3D ISAR imaging algorithms are listed in [3].

In this paper, we will present 3D ISAR imaging of a realistic target using the EM simulation data from FEKO EM simulator for small frequency-bandwidth and small-angle approximation.

## 2. 3D ISAR IMAGING

The 3D ISAR image actually presents a 3D profile of a target in range and two cross-range domains (azimuth and elevation). Therefore, the backscattered field data must be gathered for various frequencies and different azimuth and elevation angles. The gathered data occupy a finite space in the spatial frequency domain ($k_x$, $k_y$, and $k_z$). If the backscattered electric field data are collected within a small bandwidth of frequencies, $B$ (or $BW_k$), and width of viewing angles, $BW_\phi$ and $BW_\theta$, the data grid in the spatial frequency ($k_x$, $k_y$, $k_z$) space becomes an equally spaced linear grid. This assumption enables to use Fast Fourier Transform (FFT) in reconstructing the 3D ISAR image.

The point scatterer to be imaged is located at $P(x_o, y_o, z_o)$. The radar illuminates the target with a wavenumber vector of $\mathbf{k} = k\hat{\mathbf{k}}$. The direction of illumination makes an angle of $\theta$ with the $z$-axis. It also makes an angle of $\alpha$ with $x$-$y$ plane. Taking origin as the phase center of the scene, the far-field backscattered $E$-field from a point scatterer $P$ at azimuth angle $\phi$ and elevation angle $\theta$ can be written as $E^s(k, \phi, \theta) = A_o e^{-j2\mathbf{k}\cdot\mathbf{r}_o}$. At this point we assume the backscattered signal is collected within a frequency bandwidth, $B$, that is small compared to the center frequency of operation, $f_c$. We further assume that the angular bandwidths in both $\theta$ and $\phi$ directions are also small. If the radar is located around the $x$-axis, the following approximations are valid: $k \approx k_c$, $\cos\alpha\cos\phi \approx 1$, $\cos\alpha\sin\phi \approx \phi$, $\sin\alpha \approx \alpha$. Then, the scattered electric field from point $P$ is approximated as [3]

$$E^s(k, \phi, \alpha) = A_o e^{-j2k\cdot\cos\alpha\cos\phi\cdot x_o} e^{-j2k\cdot\cos\alpha\sin\phi\cdot y_o} e^{-j2k\sin\alpha\cdot z_o} \approx A_o e^{-j2k_c\cdot x_o} e^{-j2k_c\cdot\phi\cdot y_o} e^{-j2k_c\alpha\cdot z_o}$$

To be able to use the advantages of FT, we can reorganize the above equation as follows:

$$E^s(k,\phi,\alpha) \approx A_o e^{-j2\pi\left(\frac{2f_c}{c}\right)\cdot x_o} e^{-j2\pi\left(\frac{k_c\cdot\phi}{\pi}\right)\cdot y_o} e^{-j2\pi\left(\frac{k_c\alpha}{\pi}\right)\cdot z_o}$$

Then the 3D ISAR image in the spatial domain $(x,\ y,\ z)$ can be obtained by taking the 3D inverse Fourier Transform of the above equation with respect to $(\frac{2f_c}{c})$, $(\frac{k_c\cdot\phi}{\pi})$ and $(\frac{k_c\cdot\alpha}{\pi})$ as follows:

$$\begin{aligned}
ISAR(x,y,z) &= A_o\cdot F_1^{-1}\left\{e^{-j2\pi\left(\frac{2f_c}{c}\right)\cdot x_o}\right\} F_1^{-1}\left\{e^{-j2\pi\left(\frac{k_c\cdot\phi}{\pi}\right)\cdot y_o}\right\} F_1^{-1}\left\{e^{-j2\pi\left(\frac{k_c\alpha}{\pi}\right)\cdot z_o}\right\}\\
&= A_o\cdot\left[\int_{-\infty}^{\infty} e^{-j2\pi\left(\frac{2f_c}{c}\right)\cdot x_o}\cdot e^{j2\pi\left(\frac{2f_c}{c}\right)\cdot x} d\left(\frac{2f_c}{c}\right)\right]\\
&\quad\cdot\left[\int_{-\infty}^{\infty} e^{-j2\pi\left(\frac{k_c\cdot\phi}{\pi}\right)\cdot y_o}\cdot e^{j2\pi\left(\frac{k_c\cdot\phi}{\pi}\right)\cdot y} d\left(\frac{k_c\cdot\phi}{\pi}\right)\right]\\
&\quad\cdot\left[\int_{-\infty}^{\infty} e^{-j2\pi\left(\frac{k_c\cdot\alpha}{\pi}\right)\cdot z_o}\cdot e^{j2\pi\left(\frac{k_c\cdot\alpha}{\pi}\right)\cdot z} d\left(\frac{k_c\cdot\alpha}{\pi}\right)\right]\\
&= A_o\cdot\delta(x-x_o, y-y_o, z-z_o)
\end{aligned}$$

The backscattered electric field from a target can be approximated as the sum of scattering from a finite number of single point scatterers, called scattering centers, on the target as shown below

$$E^s(k,\phi,\alpha) \approx \sum_{i=1}^{M} A_i e^{-j2\mathbf{k}\cdot\mathbf{r}_i}$$

The backscattered electric field from a target is approximated as the sum of backscattered field from $M$ different scattering centers on the target. While $A_i$ represents the complex backscattered field amplitude for the $i$-th scattering center, $\mathbf{r}_i$ is displacement vector from the origin to the location of $i$-th scattering center. Then, the ISAR image of the target can be found via the following inverse 3D Fourier integral

$$ISAR(x,y,z)=\iiint_{-\infty}^{\infty} E^s(k,\phi,\alpha)\cdot e^{j2\pi\left(\frac{2f_c}{c}\right)\cdot x} e^{j2\pi\left(\frac{k_c\cdot\phi}{\pi}\right)\cdot y} e^{j2\pi\left(\frac{k_c\alpha}{\pi}\right)\cdot z} d\left(\frac{2f_c}{c}\right) d\left(\frac{k_c\cdot\phi}{\pi}\right) d\left(\frac{k_c\cdot\alpha}{\pi}\right)$$

By entering the scattering center representation for the backscattered field, the small-bandwidth small-angle ISAR image can then be approximated as follows:

$$ISAR(x,y,z) \approx \sum_{i=1}^{M} A_i\delta(x-x_i, y-y_i, z-z_i)$$

Therefore, the resulting ISAR image is the sum of $M$ scattering centers with their own electromagnetic reflectivity coefficients. In practical cases, the limits of the integral will be limited to finite frequency bandwidth and finite angular intervals. So, the impulse function will be blurred to the sinc function.

## 3. SIMULATION RESULTS

Simulation was implemented under the following environment: FEKO EM simulator v7.0 [7], Microsoft Windows™ 7 Professional (64 bit), Intel™Xeon™CPU E5-2667 2.9 GHz, RAM 64 GB. The target model for the simulation is 6.8 m in length, 17.78 m in width, and 1.64 m in height as shown in Figure 1. The direction of body length is $Z$ axis and range direction, the direction of wing is $Y$ axis and cross-range direction, and down direction is $X$ axis. The angles from $Z$ axis and $X$ axis are $\theta$ and $\phi$, respectively.

The EM simulation for frequency step $\Delta f = 1.96$ MHz, angle step $\Delta\theta = 0.3915$ degree and $\Delta\phi = 0.095$ degree under the following conditions of transmitted frequency $f_c = 9.65$ GHz (9.5∼981 GHz), transmitted bandwidth $B = 310$ MHz (small bandwidth), linear polarization, look angle interval $\theta = 9.9833$ degree (−5∼4.9833 degree), $\phi = 5.985$ degree (−3∼2.985 degree) (small angle scan), gives total $157\times256\times64$ data samples ($N_x = 157$, $N_y = 256$, $N_z = 64$) with "Large PO" setting in FEKO. The reason for the selection of PO method is to reduce the computation time and memory

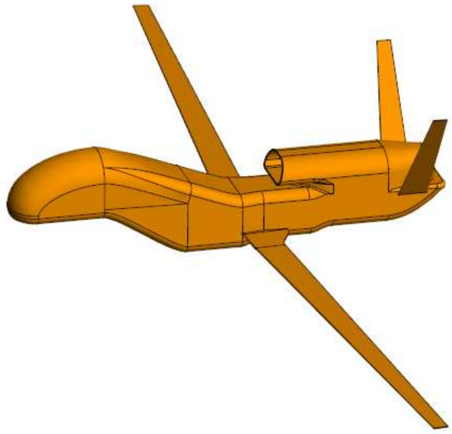

Figure 1: Target model.

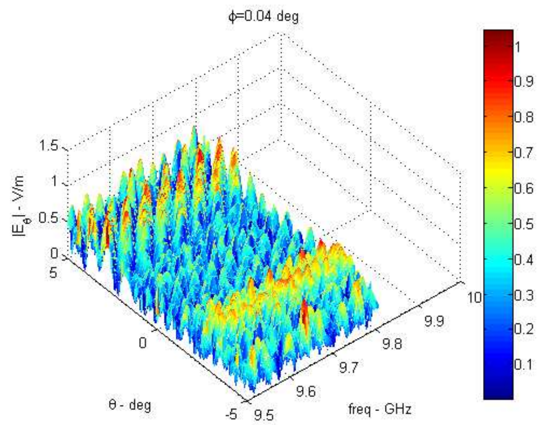


Figure 2: Electric field 2D spectrum in theta direction.

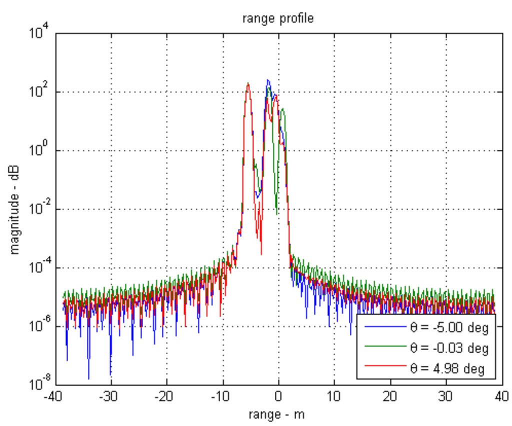


Figure 3: HRRP (high resolution range profile).

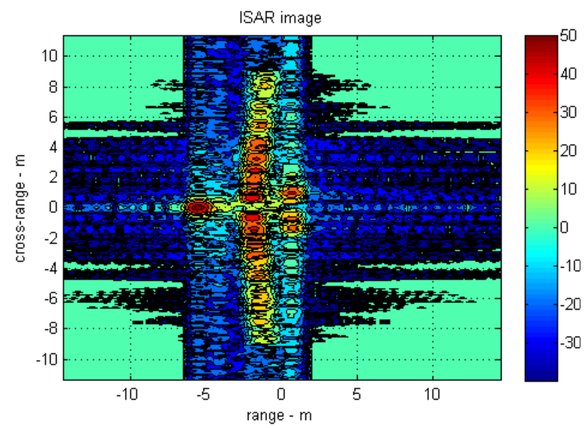


Figure 4: 2D ISAR image.

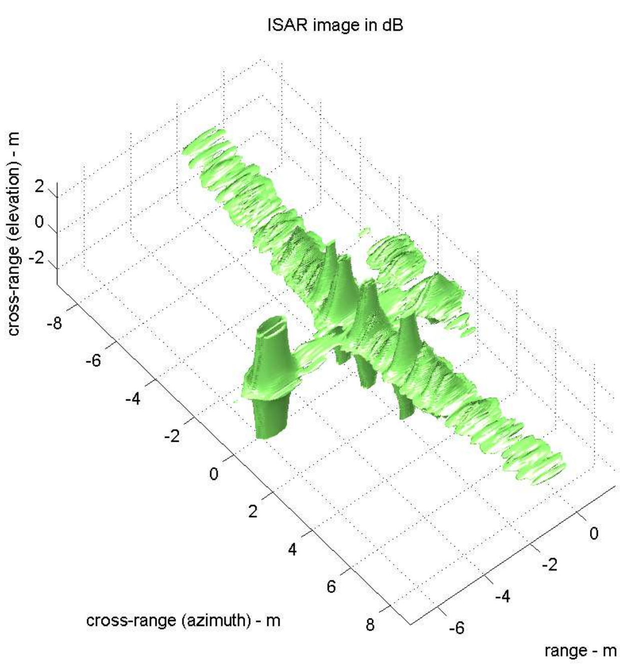


Figure 5: 3D ISAR image.

usage because of the electrically large target size. The number of meshes is 46824. The material of the target is assumed to be a PEC (Perfectly Electric Conductor) for simplicity. The EM analysis result data are saved in FEKO as an FFE file. Figure 2 shows the $E$-field data in $\theta$ axis $E_\theta(f)$ at frequency $f$.

Figure 4 depicts the 2D ISAR image of the given target. Figure 5 shows the 3D ISAR image of the given target reconstructed by 3D inverse Fourier transform under small bandwidth, small angle scan approximation. When comparing with the 2D ISAR image, we can see the 3D ISAR image gives more informative features of the target.

## 4. CONCLUSIONS

In this paper, we described the generation of 3D ISAR images for a realistic target model using a general purpose EM simulator, FEKO. After obtaining the EM simulation data from FEKO, we generated 3D ISAR image using 3D inverse Fourier transform under the small-bandwidth small angle assumptions. This method can benefit us many advantages like building the database of many targets for target recognition with cost-and-time effective way and designing a radar and evaluating its performance under more realistic situations.

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