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A high-precision SAR echo simulation method based on FDTD

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ABSTRACT

Synthetic aperture radar (SAR) echo simulation offers a low-cost and convenient way to obtain high-resolution images of targets, and plays an important role in system design and algorithm validation. Although high frequency approximation simulation is widely used, it is considered to be imprecise when calculating scattering field of fine structures, such as exhaust pipes and groove structures, especially in low frequency band. In this paper, a finite-difference time-domain (FDTD) based method is proposed for high-precision SAR echo simulation. In this method, scattering process of electromagnetic wave is accurately simulated to obtain equivalent electric and magnetic current on the surface of the target. Also, a near-to-far-field transformation is applied to the equivalent electric and magnetic current to calculate the field at the receiving antenna. In this transformation, a waveform forming method is introduced to simulate stripmap SAR echoes. By introducing this method, the usage of FDTD in one single simulation can be greatly reduced. The experiments show that proposed method can significantly improve the efficiency of the simulation while maintaining echo accuracy.

Key Words: SAR echo simulation, waveform forming, FDTD

1. INTRODUCTION

Synthetic aperture radar (SAR) echo simulation is a method to obtain the SAR echo of the target by computer simulation. It has been researched and investigated in a large number of publications in last decades. It provides a convenient and low-cost way to obtain the SAR images of targets, so as to assist the design of the system and algorithm.

To simulate the echo of SAR, one important way is calculating the electromagnetic field at the receiving antenna by computational electromagnetics algorithms, such as high-frequency approximation methods and full-wave electromagnetic computation methods. Although high-frequency approximation simulation, such as physical optics (PO) and geometric optics (GO) method, is widely used because of its low computational complexity[1-5], it is considered to be inaccurate when calculating the scattering field of electrically large targets with fine structures such as exhaust pipes and groove structures, especially in low frequency band. In contrast, full-wave electromagnetic computation methods[6-9], such as finite-difference time-domain (FDTD), can generate high precision simulation results. However, the computational complexity and computing time are unacceptable in many cases.

In this paper, a high precision SAR echo simulation method is proposed. In order to obtain high-precision SAR simulation echo data, firstly, FDTD is used to replace the commonly used high frequency simulation method to improve the simulation accuracy. Secondly, the extrapolation boundary is set on the surface of the target to calculate the equivalent electromagnetic

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current on the surface of the object. As will be seen later, this strategy is the premise to improve the efficiency of simulation. Finally, a waveform forming method is proposed to reduce the usage of FDTD in one single simulation for stripmap SAR. The reliability of our method is verified by experiments, which show that proposed method can significantly improve the efficiency of the simulation while maintaining echo accuracy.

2. METHODOLOGY

2.1 Overall simulation process

SAR is usually installed on a mobile platform such as an airplane or a satellite. The platform moves at a constant speed along a certain track and the radar emits electromagnetic pulses to the ground at a certain interval. Then, the electromagnetic wave reaches the ground after space transmission and is scattered by the target. The scattering field is detected by the receiving antenna to obtain the echo of the target. The physical process of echo acquisition is shown in Figure 1.

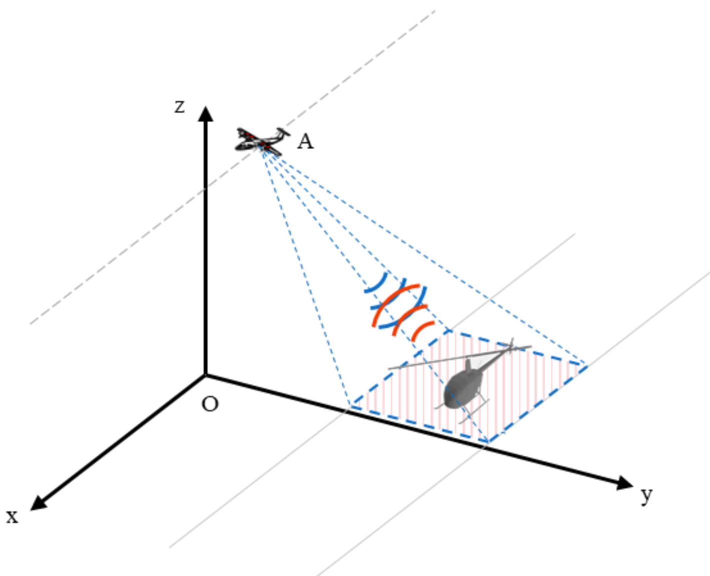


Figure 1. The physical process of echo acquisition.

In the proposed simulator, the physical process is precisely simulated by FDTD, as shown in Figure 2. Before starting the calculation, three kinds of input parameters are needed, which are excitation source signal parameters, excitation source position parameters, and target shape and material parameters. For SAR, these three kinds of parameters correspond to SAR transmitting signal parameters, SAR motion parameters and target parameters respectively. The first two kinds can be summarized as radar parameters. Subsequently, FDTD algorithm calculates the electromagnetic field near the target in each time step. Using the equivalence principle, the equivalent electric and magnetic current on the surface of the target is calculated. Then, a waveform forming method is introduced. It is the upgrade method of the near-to-far-field transformation. By using this method, the execution number of FDTD will be greatly reduced. After waveform forming, scattering field of all transmitted pulses at the receiving antenna can be obtained, which can be arranged as a two-dimensional scattering echo. In order to observe and evaluate the result of echo simulation conveniently, the I/Q demodulation and imaging operation are needed to obtain the simulated SAR images.

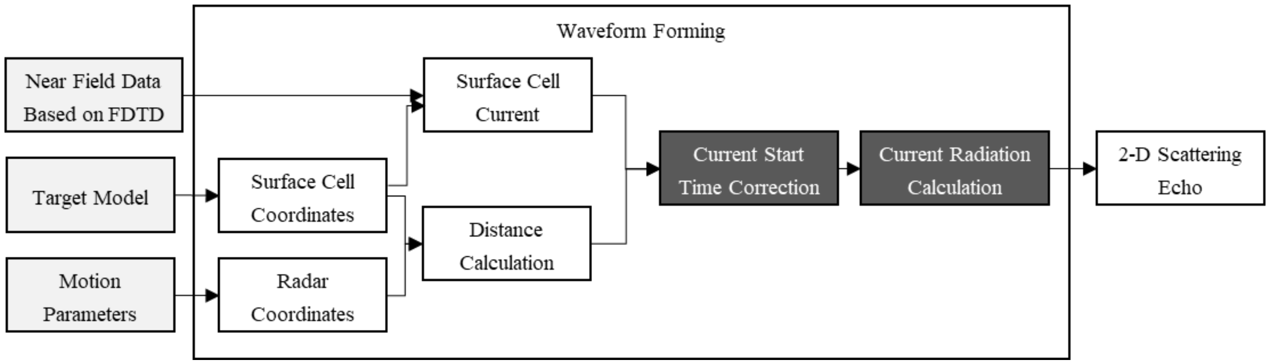


Figure 2. The overall simulation process of the proposed SAR echo simulation method.

2.2 Waveform forming

By using FDTD method, the electromagnetic field near the target is obtained. Based on this, the equivalent electric and magnetic current on a closed surface surrounding the target, called extrapolation boundary, can be obtained according to surface equivalent principle.

$$\begin{aligned} \vec{J}_s &= \hat{n} \times \vec{H} \\ \vec{M}_s &= -\hat{n} \times \vec{E} \end{aligned} \tag{1}$$

Where $\vec{H}$ and $\vec{E}$ represents the magnetic field and electric field on the extrapolation boundary, and $\hat{n}$ is the external normal vector of the extrapolation boundary. The equivalent electric and magnetic current will be used to calculate the far field, which is called near-to-far-field transformation.

For the convenience of calculation, the extrapolation boundary is generally defined as the surface of a cuboid enclosing the target. The advantage is that the extrapolation boundary is composed of six regular rectangular surfaces, which simplifies the near-to-far-field transformation. And this regular extrapolation boundary is applicable to most simulation cases. However, it should be noted that the extrapolation boundary is a virtual surface. Scattering does not occur on the extrapolation boundary, but on the surface of the target. In fact, the electromagnetic field on the extrapolation boundary is also the result of the superposition of scattering fields from multiple cells on the surface of the object. Therefore, the regular extrapolation boundary can not reflect the actual scattering of each surface element.

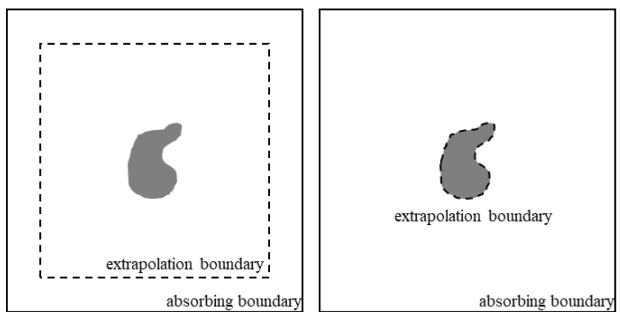
For the case of SAR, if regular extrapolation boundary is used, the expression of echo can be rewritten as

$$\begin{aligned} E_\theta(\eta,t) &\approx -U_\phi(\eta,t) - Z_0 W_\theta(\eta,t) \\ E_\phi(\eta,t) &\approx U_\theta(\eta,t) - Z_0 W_\phi(\eta,t) \end{aligned} \tag{2}$$

$$\begin{aligned} \vec{W}(\eta,t) &= \frac{1}{4\pi r(\eta) c} \frac{\partial}{\partial t}\left[\iint_S \vec{J}_s\left(\eta, t - \frac{r(\eta) - \vec{r}' \cdot \hat{r}(\eta)}{c}\right) ds' \right] \\ \vec{U}(\eta,t) &= \frac{1}{4\pi r(\eta) c} \frac{\partial}{\partial t}\left[\iint_S \vec{M}_s\left(\eta, t - \frac{r(\eta) - \vec{r}' \cdot \hat{r}(\eta)}{c}\right) ds' \right] \end{aligned} \tag{3}$$

The integral operation is performed on a regular extrapolation boundary S, where t represents fast time, η represents slow time. In formula (3), slow time variables η are added to represent the equivalent electric and magnetic current at the extrapolation boundary calculated by FDTD at slow time η. Similarly, formula (2) represents the scattering echo simulated at each azimuth. It means that because the equivalent electric and magnetic current on the regular extrapolation boundary can not reflect the scattering mechanism of the target, FDTD simulation needs to be carried out again and again to simulate the echo of each pulse when the target is in the radar beam, even if the incident angle between different pulses changes little. This will result in a huge amount of computation.

In this paper, we propose two strategies to solve the problem. The first strategy is to adjust the extrapolation boundary and set the extrapolation boundary as the target surface, as shown in Figure 3 (b). In this way, the equivalent electric and magnetic current on extrapolation boundary can reflect the actual scattering of each surface element. The second strategy is to introduce a waveform forming method. After adjusting the extrapolation boundary, by using this method, it is not necessary to simulate the echo direction by direction.



(a) (b)

Figure 3. The extrapolation boundary of (a) traditional method and (b) proposed method.

In waveform forming, the scattering problem of single azimuth is considered first. As shown in Figure 4 (a). At the time η_c, the radar emits an electromagnetic pulse. When the pulse reaches the target through space propagation, it is approximately a plane wave. Through FDTD, we can obtain the current of the surface cell of the target excited by the plane wave. As shown in Figure 4 (b), the current waveform of cell 1 and cell 2 starts at the same time, because they are excited by electromagnetic waves at the same time. After a period of time, the radar transmits another electromagnetic pulse in azimuth B. Similarly, when the pulse propagates to reach the target, it is approximately a plane wave as well, but the incident direction is slightly different from time η_c, as shown in Figure 4 (a).

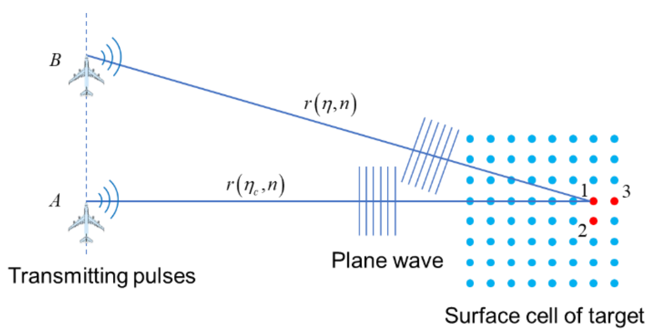
For the target, the incident direction of the electromagnetic wave emitted by radar almost does not change between several adjacent transmitting pulses. The scattering characteristics of the target are almost unchanged. especially for stripmap SAR, because the azimuth beam is very narrow, and its direction does not change when the platform is moving, it can be considered that the incident direction of electromagnetic wave does not change during the whole process of the target being irradiated. Therefore, if the extrapolation boundary is set on the target surface, the equivalent electric and magnetic current of each cell on the boundary will have a strong correlation between different azimuths, which can be approximately considered as unchanged, with only one time delay difference. As shown in Figure 4 (a), the waveform at time η has a delay compared with that at time η_c. And for different cells, the delay time is different. For example, at time η_c, the waveforms of cell 1 and cell 2 start at the same time. However, under the excitation of the plane wave at time η, cell 1 is first excited, and then cell 2 is excited. Obviously, the delay time in these two cases is different. Take cell 1 as an example. The distance between radar and cell 1 is $r(\eta,n)$, in which n is the cell's number. The time delay of pulse propagation to cell 1 is $r(\eta,n)/c$. However, since FDTD is carried out at time η_c, the time delay of the current calculated by electromagnetic calculation is $r(\eta_c,n)/c$. Therefore, we must delay the current obtained by FDTD for another period of time, which is τ_d.

$$\begin{aligned} \tau_d &= \frac{r(\eta,n)-r(\eta_c,n)}{c} \\ r(\eta,n) &= r(\eta)-\vec{r}'\cdot\hat{r}(\eta) \\ r(\eta_c,n) &= r(\eta_c)-\vec{r}'\cdot\hat{r}(\eta_c) \end{aligned} \tag{4}$$

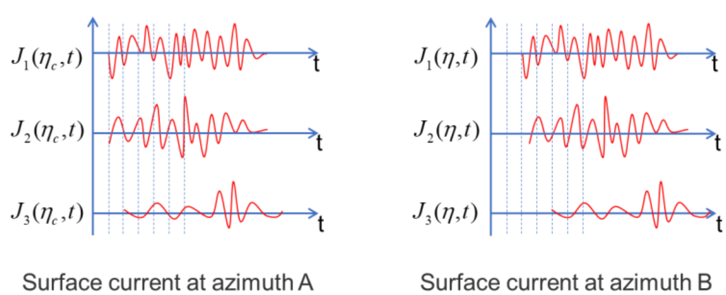
Thus, the surface current of cell 1 at time η can be obtained approximately. By doing the same treatment for all the other cells, the distribution of current at time η can be obtained. Because η is arbitrarily selected, the current distribution on the target surface in each azimuth can be obtained. Write as

$$\begin{aligned} \vec{J}_s(\eta,t) &\approx \vec{J}_s(\eta_c,t-\tau_d) \\ \vec{M}_s(\eta,t) &\approx \vec{M}_s(\eta_c,t-\tau_d) \end{aligned} \tag{5}$$

Where η_c is the slow time when the target is at the beam center, and $\vec{J}_s(\eta_c,t-\tau_d)$ is the surface current of the target at η_c, which is calculated by FDTD. And τ_d is the difference of time delay from radar to surface cell between slow time η and η_c, as shown in Figure 4.



(a)



(b) (c)

Figure 4. The illustration of waveform forming. (a) Interaction between radar pulse and target surface cell. (b) Current of surface cells at azimuth A, which is obtained by FDTD. (c) Current of Surface cells at azimuth B, which is obtained by the time delay of the current in azimuth A.

Then the formula (3) can be rewritten as

$$\vec{W}(\eta,t)=\frac{1}{4\pi r(\eta)c}\frac{\partial}{\partial t}\left[\iint_S \vec{J}_s\left(\eta_{c,}t-\tau_d-\frac{r(\eta)-\vec{r}'\cdot\hat{r}(\eta)}{c}\right)ds'\right]$$
$$\vec{U}(\eta,t)=\frac{1}{4\pi r(\eta)c}\frac{\partial}{\partial t}\left[\iint_S \vec{M}_s\left(\eta_{c,}t-\tau_d-\frac{r(\eta)-\vec{r}'\cdot\hat{r}(\eta)}{c}\right)ds'\right] \quad (6)$$

Under the effect of this property, only one transmitting pulse needs to be simulated by FDTD. The distance between the target surface cells and the receiving antenna can be calculated in every azimuths, so the scattering echo of each azimuth can be extrapolated according to the formula (6). In other words, FDTD simulation result of one azimuth is used to form multi-azimuth scattering echoes, that is, waveform forming method. This greatly reduces the simulation time.

3. MODELS AND PARAMETERS

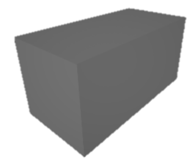
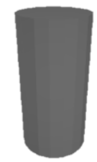
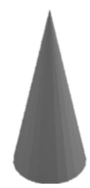
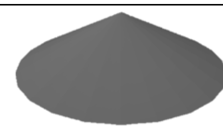
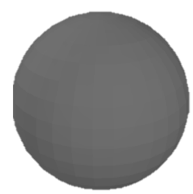
Before echo simulation, according to the imaging principle of SAR and the geometric relationship between SAR and target, a group of airborne L-band SAR parameters are selected to meet the requirements of high resolution imaging, and the existing simulation conditions are taken into account. The simulation parameters are shown in Table 1.

Table 1. Setting of simulation parameters.

Parameters	**Value**
Carrier Frequency	1.5 GHz
Bandwidth	500 MHz
AD Sampling Frequency	600 MHz
Range Resolution	0.3 m
pulse width	20ns
Azimuth Resolution	0.3 m
Platform Velocity	300 m/s
Pulse Number	1536
Squint Angle	0°
Incident Angle	45°
Doppler Bandwidth	1000 Hz
Pulse Repetition Rate (PRF)	1200 Hz

The stripmap SAR echo simulation experiments are carried out for some simple geometries. The geometries used in the experiments include cuboid, cylinder, cone and sphere. In addition, some complex targets are simulated. It should be noted that for complex targets, before simulation, the established models should be meshed in advance to make it conformal with the cubic cell of FDTD. And material information should be added to each cell. In the experiment, all of the targets are made of perfect electrical conductor material. The geometric parameters of targets are shown in the Table 2.

Table 2. Setting of model parameters.

Model	**Parameter**	**Schematic Diagram**
Cuboid	Length: 6 m Width: 3 m Height: 3 m	
Cylinder	Radius: 1.5 m Height:6 m	
Sharp Cone	Radius: 1.5 m Height: 6 m	
Blunt Cone	Radius: 3 m Height: 1.5 m	
Sphere	Radius: 1.5 m	
T90 Tank	Length: 9.58 m Width: 4.01 m Height: 4.02 m	

4. RESULTS

In this section, we use the proposed method to simulate the echoes and images of some standard geometries and complex targets. Some results are presented to illustrate the effectiveness of our method and to evaluate the performance of echo simulation. Furthermore, the simulation results of the proposed method and the traditional method are compared in this section to prove the reliability of the method.

Through FDTD, the electromagnetic field near the targets in one azimuth is calculated. Then, through waveform forming method, the scattering field at receiving antenna in each azimuth can be obtained. It is a set of two-dimensional data. The horizontal axis represents the fast time in the range direction, and the vertical axis represents the slow time in the azimuth direction. By orthogonal decomposition of the received electric field vector, the horizontal polarization component and the vertical polarization component can be obtained. As shown in Figure 5. The two-dimensional complex raw data for imaging can be obtained by I/Q demodulation and AD sampling for horizontal and vertical polarization scattering electric fields. The results of HH polarization are shown in Figure 6. Then, using RD algorithm to image the demodulated raw echo signal, we can simulate the horizontal and vertical polarimetric SAR images of the target. The results of HH polarization are shown in Figure 7.

It should be noted that although the energy of the received signals of the two polarization modes seems to be similar from the image, they are completely different. Because the dynamic range of the two images is different. In fact, the amplitude of co-polarization images is about two orders of magnitude larger than that of cross-polarization images.

At the same time, we also use the traditional method to simulate the SAR echo with the same configuration. The simulation results are shown in the Figure 8. Comparing the simulation results of the proposed waveform forming method with that of the traditional method, it can be found that the difference between the two methods is not significant. And comparing the simulation time of the two methods, it can be found that the simulation time of the proposed method is much less than that of the traditional method. It is proved that the new method can greatly improve the simulation speed without significantly reducing the simulation accuracy.

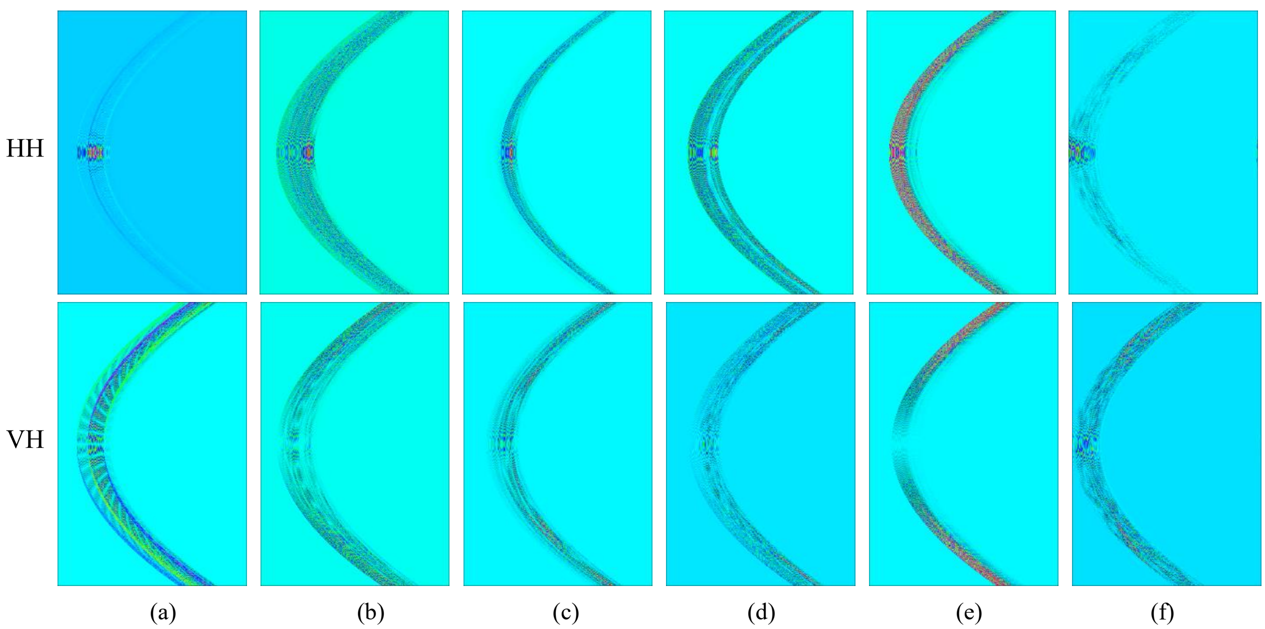
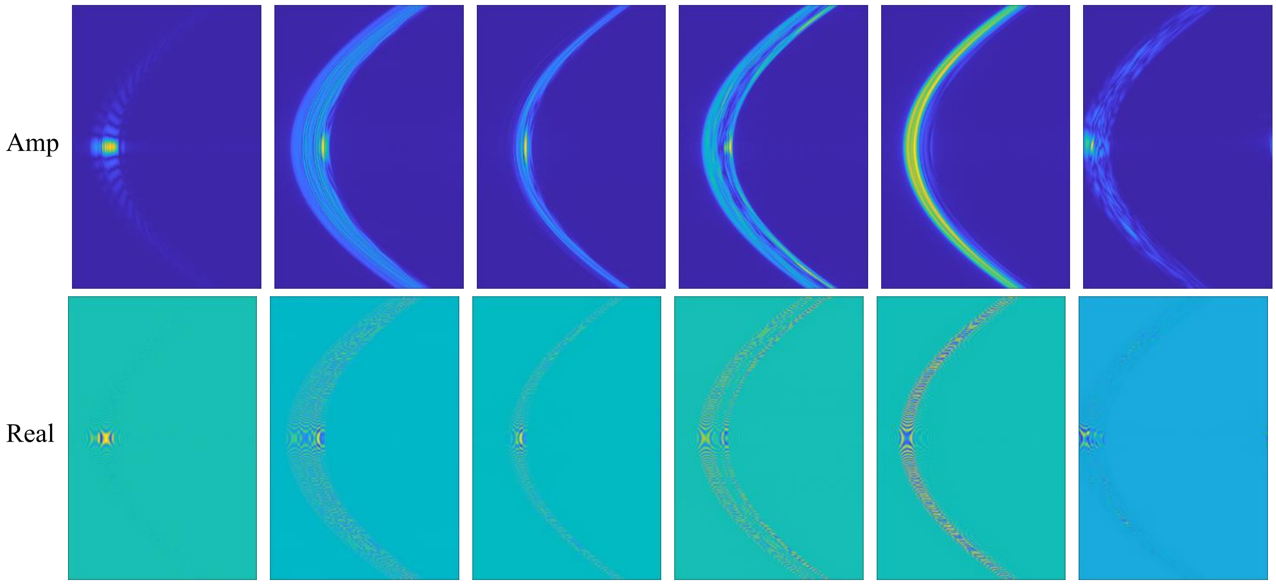
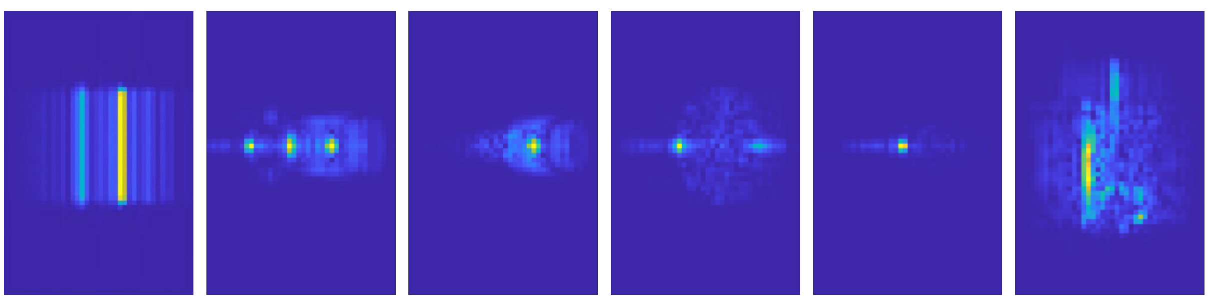


Figure 5. The scattering electric field of the target can be decomposed into horizontal polarization (HH) and vertical polarization (VH), in which the targets mainly include (a) cuboid, (b) cylinder, (c) sharp cone, (d) blunt cone, (e) sphere, (f) T90 tank.



(a) (b) (c) (d) (e) (f)

Figure 6. The complex data are generated by I/Q demodulation and AD sampling. The targets include (a) cuboid, (b) cylinder, (c) sharp cone, (d) blunt cone, (e) sphere, (f) T90 tank. For simplicity, only the results of HH polarization are shown here.



(a) (b) (c) (d) (e) (f)

Figure 7. The simulated SAR images of targets, including (a) cuboid, (b) cylinder, (c) sharp cone, (d) blunt cone, (e) sphere, (f) T90 tank.

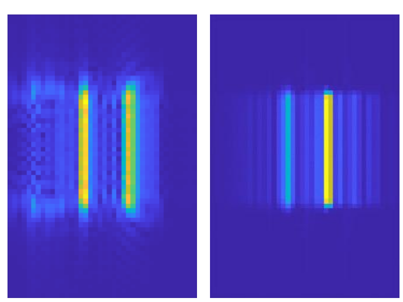


Figure 8. For the same target (brick), the comparison between the (a) traditional method and the (b) proposed method.

5. CONCLUSIONS

In this paper, a high precision SAR echo simulation method based on FDTD is proposed. Echo simulation of electrically large targets has always been an important issue in computational electromagnetics. High frequency methods are often not accurate enough for fine structure simulation. We propose several strategies to solve this problem. First of all, the FDTD method is used in the simulation, instead of high frequency methods, which can improve the simulation accuracy in principle. Secondly, the extrapolation boundary is set on the surface of the object, which can easily obtain the equivalent electric current and magnetic current on the target surface so as to prepare the data for the waveform formation. Thirdly, the waveform forming method is proposed to improve the echo simulation efficiency. Through the experiment, it can be found that the echo simulation method based on FDTD can show more details of targets, and the waveform forming method can improve the simulation efficiency without significantly reducing the simulation accuracy.

Although the waveform forming method can greatly improve the simulation efficiency, the memory occupation is large, which limits the use of the proposed method. In the future, we will focus on this problem and try to reduce the occupation of memory.

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