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Nonuniform Three-dimensional Configuration Distributed SAR Signal Reconstruction Clutter Suppression

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Abstract

This paper deals with the problem of clutter suppression in spaceborne distributed synthetic aperture radar (D-SAR) with nonuniform three-dimensional (3D) configuration geometry. In order to make a breakthrough of the configuration limitation of the traditional space time adaptive processing (STAP) based on uniform array and improve the inhomogeneous clutter suppression performance, this paper considers signal reconstruction technique using array interpolation to process the D-SAR signal. An array interpolation signal reconstruction method based on pitching-partition is derived then a signal reconstruction 3D-STAP clutter suppression method applied to nonuniform 3D configuration is proposed. In particular, the proposed method is compared with conventional methods and the performance analysis is carried out based on simulations. The improvement factor (IF) for clutter suppression is imported and reported as a benchmark on the clutter suppression effect.

Keywords: distributed synthetic aperture radar; nonuniform 3D configuration; clutter suppression; signal reconstruction; STAP

1. Introduction

Spaceborne distributed synthetic aperture radar (D-SAR) is an increasingly expanding space-based radar system allowing for many functions of earth observation with different configurations. These configurations tend to be nonuniform and three-dimensional (3D), i.e., the spaces between satellites are unequal, and the satellites are not arranged in one single plane [1-2]. For instance, American Space Concept Design Center (CDC) carries out the system-level design according to the system task of "TechSat21", and this system is composed of 35 satellite groups (each group contains 8 satellites) locating in 7 different orbit planes. The Air Force Research Laboratory (AFRL) launched 3 satellites to a near-circular orbit, and the relative distances between the satellites are unequal changing from 100 m to 5 km. During the task period, the configurations of the 3 satellites are changing for carrying out experimental research on many key technologies of the distributed satellites. This kind of nonuniform 3D configuration can provide multi-directional spatial degrees of freedom in ground moving target indication (GMTI), and has got a wider field of view and a further detection range. Unfortunately, because of the extremely complicated configuration geometry of this configuration, it is difficult to model the echo, and the clutter suppression technology based on uniform linear array (ULA) cannot be applied to the nonnuniform configuration. Thus, the research on clutter suppression of nonuniform 3D configuration is rarely to be mentioned.

Conventional space time adaptive processing (STAP) clutter suppression technology based on ULA assumes that the interferences in the training samples and the test samples are independent and identically distributed (IID). In this way, using the samples of the other range gates we can estimate the statistical char-

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acteristics of the interferences in the test range gate accurately, and the clutter can be suppressed effectively. However, the practical clutter circumstances faced by the radar are mostly inhomogeneous. Corbell, et al.[3] pointed out the inhomogeneous interferences could affect the performance of STAP, and the investigation shows that the conventional STAP cannot suppress the inhomogeneous interferences changing with the pitching angle effectively. Corbell proposed 3D-STAP based on uniform planar array to tackle the inhomogeneous clutter suppressing problem [4]. Then, Hale and Corbell, et al. discussed 3D-STAP further, and derived the pitching Doppler frequency expression [5-6].

The above mentioned approaches show satisfactory performance when a uniform array configuration is available. Unfortunately, in practical situations, the uniform configuration is rarely encountered [7-8], so the performance of the approaches above is limited. Therefore, several approaches based on interpolated array have been recently suggested in the literature. Friedlander and Weiss studied the regional partition and the placing rule of the virtual array in array interpolation method [9]; Sidorovich and Gershman extended array interpolation method to the planar array, and applied this technique to the target arrival angle estimation problem [10]; Martorella and Littleton applied the array interpolation techniques to resolve the phase retention problem in phase estimation of the multi-baseline InSAR systems [11]. However, these above mentioned approaches are studied based on linear or planar configuration, so they cannot be applied to 3D configuration.

In this paper, an array interpolation signal reconstruction method based on the pitching dimension partition is proposed, i.e., the multi-planar signal reconstruction is realized through slicing the nonuniform 3D configuration array into several layers in pitching dimension, and calculating the interpolation matrix according to the steering vectors before and after the interpolation. Thereby, the actual nonuniform configuration signal can be reconstructed into the virtual uniform configuration signal, so that clutter suppression can be carried out on the virtual signal using 3D-STAP.

There are three reasons for this proposal. First, this approach is desirable to enable the use of the clutter suppression algorithms, for uniform configuration array have demonstrated the best performance in term of accuracy and computational efficiency in the uniform configuration case such as 3D STAP. Second, the acquisition geometry is mostly determined by mechanical, structural, or orbital considerations which are not directly related to the GMTI requirements. In fact, such considerations will often result in a nonuniform sampling. Third, nonuniform 3D configuration could provide more multi-direction degrees of freedom, wider view field and detection range, which are beneficial to GMTI. Therefore, this paper proposes signal reconstruction-3D-STAP(SR-3D-STAP) based on nonuniform 3D configuration to tackle the above mentioned problem.

2. Nonuniform 3D Configuration Clutter Signal Model

In order to study the clutter suppression method based on nonuniform 3D configuration, the clutter signal model should be established in this configuration above all. We suppose that two array elements of the nonuniform 3D configuration distribute in the space as Fig. 1 shows.

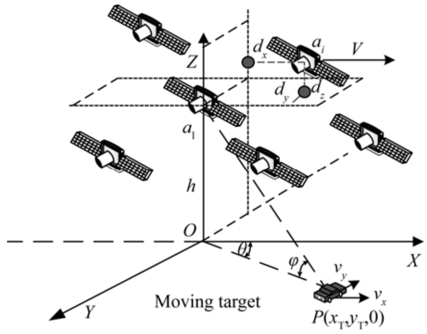

Fig. 1 Distributed SAR spatial geometry model.

In Fig. 1, a_1 is the reference satellite, and a_i an optional element of the configuration. The system is h kilometers from the ground and moves at a constant speed V in a straight line along the X axis. Here, we assume that the antennas in the array work in the multiple-input multiple-output (MIMO) mode. a_1 is located at (0, 0, h), and a_i at (d_x, d_y, $h+d_z$). The ground moving target P is located at (x_T, y_T, 0), and moves at the speed of $[v_x \quad v_y \quad 0]$. θ and φ are respectively the azimuth angle and the pitch angle of the moving target according to the reference satellite.

It is different from the traditional signal model which is established in one single plane. According to the geometry in Fig. 1, we can obtain the relative distance between the moving target and the ith radar of the configuration, at the slow-time kT (T is the pulse repetition period, and k the number of transmitted pulse):

$$R_T(i,kT) = \{(h+d_z)^2 + [(x_T + v_x kT) - (VkT + d_x)]^2 + (y_T + v_y kT + d_y)^2\}^{1/2} \tag{1}$$

The relative distance between the stationary target (x_c, y_c, 0) and the ith satellite of the configuration at the slow-time kT is

$$R_C(i,kT) = \{(h+d_z)^2 + [(x_c - (VkT + d_x)]^2 + (y_c + d_y)^2\}^{1/2} \tag{2}$$

So, the moving target echo signal received by the ith array elements after quadrature demodulation and range pulse compression can be obtained:

$$s(i,kT) = \mathrm{psf}(t - 2R_T(i,kT)/c) \cdot \exp[-\mathrm{j}4\pi f_c R_T(i,kT)/c] \tag{3}$$

where f_c is the carrier frequency, psf(·) is the point spread function after the range pulse compression [12-13],

c is the speed of light. In the real observation scene, there are a mass of clutters besides the moving target signal. Suppose that the jth clutter cell is located at (x_{cj}, y_{cj}, 0), so the clutter signal received by the ith radar is

$$c(i,kT)=\sum_j \sigma_j(i,kT)\cdot \\ \mathrm{psf}(t-2\sqrt{h^2+y_{cj}^2+(VkT-x_{cj})^2}/c)\cdot \\ \exp[-j4\pi f_c\sqrt{h^2+y_{cj}^2+(VkT-x_{cj})^2}/c] \quad (4)$$

where $\sigma_j(i, kT)$ is the response function of the jth clutter cell according to the ith radar.

The actual received signal is composed by three parts: target echo (may exist), clutter signal and noise. So the echo signal after range compression received by the ith radar at kT is

$$z(i,kT)=s(i,kT)+c(i,kT)+N(i,kT) \quad (5)$$

where $N(i, kT)$ is the additivity white noise.

3. Nonuniform 3D Configuration Signal Reconstruction Clutter Suppression

Based on the nonuniform 3D configuration signal model derived above, this section mainly derives how to reconstruct the above mentioned signal to uniform 3D configuration signal using array interpolation technique, then suppress the clutter with 3D-STAP. This new clutter suppression technique could be named SR-3D-STAP.

3.1. Nonuniform 3D configuration array interpolation signal reconstruction

Array interpolation technique can estimate the desired virtual array output from the real array output. It is different from traditional array interpolation based on linear array or planar array that this paper derives the interpolation method based on nonuniform 3D configuration starting with the pitching of the configuration. Here, we suppose there are N elements in the nonuniform 3D configuration shown in Fig. 2, whose coordinates are $(x_1, y_1, z_1), \cdots, (x_n, y_n, z_n), \cdots, (x_N, y_N, z_N)$, respectively. $\boldsymbol{V}_a$ is platform speed.

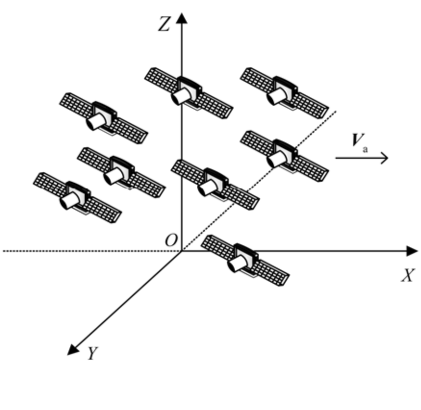

Fig. 2 Nonuniform 3D configuration.

The array interpolation technique can reconstruct the output signal of the nonuniform array above to that of the uniform array according to the least squares using linear interpolation. The virtual uniform array after the interpolation is shown in Fig. 3.

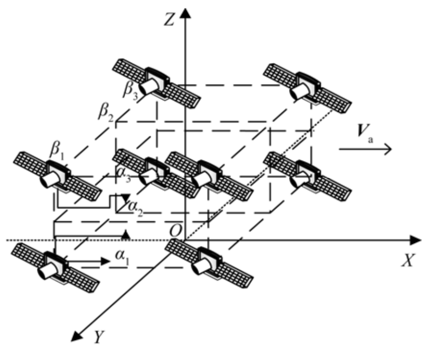

Fig. 3 Uniform 3D configuration.

Here, we suppose there are M elements in the array, and the coordinates are $(x'_1, y'_1, z'_1), \cdots, (x'_m, y'_m, z'_m), \cdots, (x'_M, y'_M, z'_M)$.

In order to ensure the rationality and a higher precision of the signal reconstruction, we can calculate the distance between the elements of the array before and after the reconstruction:

$$d_n=\sqrt{(x_n-x'_m)^2+(y_n-y'_m)^2+(z_n-z'_m)^2} \quad (6)$$

where $n=1,2,\cdots,N, m=1,2,\cdots,M$. We confirm m firstly to test which element of the real array is the nearest one to the m element of the virtual array. After that, we match the nearest element x_n in real array with the element x'_m in virtual array. Then confirm the relationship between other real elements and virtual elements according to this method.

Set the nethermost planar sub-array of the virtual array (α_1 shown in Fig. 3) as the reference plane, and define the pitching Doppler frequency of the lth planar sub-array relative to the jth echo cell as

$$f_{plj}=\frac{2\pi d_{zl}}{\lambda}\sin\phi_j \quad (7)$$

where ϕ_j is the pitch angle of the jth echo cell, λ the wavelength of the carrier frequency, and d_{zl} the distance between the lth planar sub-array and the reference plane, l=1,2,⋯,L. Thereby, we can obtain the pitching steering vector of the whole nonuniform 3D configuration array relative to the jth echo cell:

$$\boldsymbol{S}_{pnj}=\begin{bmatrix}1 & e^{jf_{p2j}} & \ldots & e^{jf_{pLj}}\end{bmatrix}^{\mathrm{T}} \quad (8)$$

In the observation scene, the pitching steering vector matrix of the clutter cells and target under the nonuniform 3D configuration is

$$\boldsymbol{A}_p=[\boldsymbol{S}_{pn1}\ \boldsymbol{S}_{pn2}\ \cdots \boldsymbol{S}_{pnJ}] \quad (9)$$

where j=1,2,⋯, J is the number of the echo cells, so $\boldsymbol{A}_p$ is a $L\times J$ matrix.

The pitching Doppler frequency of the uniform 3D configuration is

$$f_{pj} = \frac{2\pi d_z}{\lambda}\sin\phi_j \tag{10}$$

where d_z is the element space along the pitching. So the pitching steering vector of the uniform 3D configuration array relative to the jth range cell is

$$\boldsymbol{S}_{puj} = \begin{bmatrix} 1 & e^{jf_{pj}} & \cdots & e^{j(l-1)f_{pj}} & \cdots & e^{j(L-1)f_{pj}} \end{bmatrix}^{T} \tag{11}$$

The pitching steering vector matrix of the uniform 3D configuration can be obtained:

$$\tilde{\boldsymbol{A}}_p = [\boldsymbol{S}_{pu1} \ \boldsymbol{S}_{pu2} \ \cdots \ \boldsymbol{S}_{puJ}] \tag{12}$$

According to the method described by Friedlander and Weiss in Ref. [9], the transition matrix $\boldsymbol{B}_p$ between the virtual array steering vector matrix and the real array steering vector matrix can be obtained by solving the following least square problem:

$$\boldsymbol{B}_p = \arg\min_{B_p} \left\| \tilde{\boldsymbol{A}}_p - \boldsymbol{B}_p^H \boldsymbol{A}_p \right\|_F^2 \tag{13}$$

where $\| \ \|_F$ is the Frobenius norm. Thereby, we can obtain

$$\boldsymbol{B}_p = (\boldsymbol{A}_p \boldsymbol{A}_p^H)^{-1} \boldsymbol{A}_p \tilde{\boldsymbol{A}}_p \tag{14}$$

where H represents conjugation transposition. In this way, the signal reconstruction of the array along the pitching direction has been completed. Now the nonuniform 3D configuration array is parted into several $N\times M$ nonuniform planar arrays distributing along the pitching uniformly, in which N, M are the numbers of elements distributing along the azimuth (X axis) and the range (Y axis), respectively. Similarly, the azimuth transition matrix $\boldsymbol{B}_a$ and the range transition matrix $\boldsymbol{B}_r$ can be calculated according to the array interpolation method based on planar array [10].

Obtaining the three transition matrices $\boldsymbol{B}_a$, $\boldsymbol{B}_p$ and $\boldsymbol{B}_r$, we can reconstruct the slow-time signal $Z=\{z(1,1,1,1), z(1,2,1,1),\cdots,z(n,m,l,k),z(N,M,L,K)\}$ of the real array (nonuniform 3D configuration) derived in Section 2, in which N, M, L and K are the numbers of the elements distributing along the azimuth, range, pitching direction and the number of pulses. It is different from traditional array interpolation signal reconstruction, that the proposed method reconstructs the signal three times from pitching, azimuth and range to obtain the virtual uniform 3D configuration signal. This signal contains the necessary information of the real signal and satisfies the configuration requirement of the clutter suppression method. Thereby, we can carry out clutter suppression on this signal. According to the position of the satellites in the real configuration, we obtain the three transition matrixes with which we can reconstruct the nonuniform configuration signal and suppress the clutter using SR-3D-STAP with these matrixes.

3.2. SR-3D-STAP

The traditional 2D-STAP based on linear configuration cannot suppress the inhomogeneous clutter changing with pitch angle efficiently [9-11]. The proposed SR-3D-STAP based on nonuniform 3D configuration utilizes the 3D steering vector (pitch, range and azimuth) after the signal reconstruction above, rather than 2D steering vector utilized by traditional STAP, so that it is not only suitable for the nonuniform 3D configuration but also increases the degree of freedom on pitch and range direction, therefore, the proposed method possesses the ability to suppress the inhomogeneous clutter.

According to the Doppler frequencies expression of the nonuniform 3D configuration deduced hereinbefore, we can define $\boldsymbol{p}_i$, $\boldsymbol{q}_i$ and $\boldsymbol{F}_i$ as space (azimuth) steering vector, time steering vector and space (pitch) steering vector respectively. N, M and K are the numbers of line sub-arrays, row sub-arrays and the pulses in one coherent processing interval, respectively. The 2D Fourier-steering vector $\boldsymbol{S}_i$ is defined as the Kronecker product of the vector $\boldsymbol{p}_i$ and $\boldsymbol{q}_i$:

$$\boldsymbol{S}_i = \boldsymbol{p}_i \otimes \boldsymbol{q}_i \tag{15}$$

3D steering vector is

$$\boldsymbol{S}_{3D} = \boldsymbol{S}_i \otimes \boldsymbol{F}_i \tag{16}$$

In the nonuniform 3D configuration, the clutter is relevant to the range. Since the zero-crossing points of the clutter are located at different frequencies according to different ranges, the clutter covariance matrix $\boldsymbol{R}_N$ is

$$\boldsymbol{R}_N = \frac{1}{NKM}\sum_{i=1}^{NKM} \boldsymbol{S}_{3D}\boldsymbol{S}_{3D}^H \tag{17}$$

Suppose the data vector $\boldsymbol{X}$ received by the array is defined as Eq. (5). In order to minimize the SNR, we set the whole space-time adaptive filter weight vector as $\boldsymbol{W}$, and then the filter output is

$$y = \boldsymbol{W}^H \boldsymbol{X} \tag{18}$$

The choice of $\boldsymbol{W}$ has a significant impact on the detection performance. An inappropriate weight cannot reduce the environment interference and improve the signal clutter noise ratio(SCNR) efficiently. SR-3D-STAP calculates the weight based on the interference environment statistical characteristics, and according to the maximum SNR criterion, theoretically the optimal system weight is

$$\boldsymbol{W}_{opt} = \boldsymbol{\mu}\boldsymbol{R}^{-1}\boldsymbol{S}_{3D} \tag{19}$$

in which

$$\boldsymbol{R} = \boldsymbol{B}_r \boldsymbol{B}_a \boldsymbol{B}_p \boldsymbol{R}_N \boldsymbol{B}_r^H \boldsymbol{B}_a^H \boldsymbol{B}_p^H \tag{20}$$

where $\boldsymbol{R}$ is the reconstructed clutter covariance matrix, and the non-zero normalized complex constant $\boldsymbol{\mu}$ is

$$\boldsymbol{\mu} = 1/(\boldsymbol{S}_{3D}^H \boldsymbol{R}^{-1} \boldsymbol{S}_{3D}) \tag{21}$$

In this way, the nonuniform configuration signal is reconstructed in Eq. (20) and the clutter can be suppressed in Eqs. (18)-(19).

4. Performance Analysis of Inhomogeneous Clutter and Suppression Method

4.1. Analysis on essence of pitching angle dependent inhomogeneous clutter

2D-STAP can suppress the homogeneous clutter efficiently. However its performance degrades sharply when facing the inhomogeneous clutter. 3D-STAP, which possesses more system degree of freedom can suppress this kind of clutters efficiently [3]. This section mainly analyses its causes. Distributed SAR clutter signal frequency expression can be written as follows:

$$\begin{cases} f_\mathrm{d} = \dfrac{2|\boldsymbol{V}_\mathrm{a}|\cos\theta\cos\varphi}{\lambda_0 f_\mathrm{r}} \\ f_\mathrm{a} = \dfrac{d_x\cos\theta\cos(\varphi-\psi)}{\lambda_0} \\ f_\mathrm{p} = \dfrac{d_z\sin\theta}{\lambda_0} \end{cases} \tag{22}$$

where f_d, f_a and f_p are Doppler frequency, azimuth space frequency and pitching space frequency, respectively; λ_0 and f_r are work wavelength and pulse repetition frequency; d_x, d_y and d_z are the space between elements in azimuth, range and pitch; θ, φ and ψ are pitch angle, azimuth angle and squint angle, respectively. It can be easily found in Eq. (22) that when the configuration is linear and the radar works in vertical side-looking mode, i.e., d_z and ψ are 0, there is a linear relationship between f_d and f_a. In this case, the clutter spectrum distributes along a line crossing the origin point in the f_d–f_a plane homogeneously, and the 2D-STAP can obtain a good clutter suppression effect by learning along the line in the $f_\mathrm{d}-f_\mathrm{a}$ plane [4]; when the radar works in squint side-looking mode, i.e., ψ is not equal to 0, according to Eq. (22), it is easy to find the relationship between f_d and f_a:

$$f_\mathrm{d}^2 - 2f_\mathrm{d}f_\mathrm{a}\cos\psi + f_\mathrm{a}^2 = \sin^2\psi\cos^2\theta \tag{23}$$

Thus the clutter spectrum distributes in a cluster of inclined ellipsoids rather than along a line in $f_\mathrm{d}-f_\mathrm{a}$ plane homogeneously, so that 2D-STAP cannot suppress it efficiently; when the configuration is not linear array and radar works in squint side-looking mode, i.e., neither d_z or ψ is not equal to 0, the relationship between f_d and f_a changing with different values of pitching angle θ and there is a one-to-one correspondence between the pitching angle θ change and f_p change. Therefore, f_d is the function of f_a and f_e at this time. In this case, it is obvious that 2D-STAP only learning in $f_\mathrm{d}-f_\mathrm{a}$ plane cannot suppress the clutter efficiently; on the other hand, 3D-STAP learning in $f_\mathrm{d}-f_\mathrm{a}-f_\mathrm{p}$ space can obtain a better suppression effect (referring to Eq. (17))[5].

4.2. SR-3D-STAP performance analysis

Although 3D-STAP can suppress the inhomogeneous clutter efficiently, it requires the uniform configuration. Therefore, this paper is aimed at proposing a new method on the basis of taking advantage of 3D-STAP and making it suitable for the nonuniform 3D configuration using array interpolation signal reconstruction i.e., SR-3D-STAP.

The essence of the array interpolation signal reconstruction is to estimate the desired virtual array output from the real array output according to the least square algorithm, on the premise of minimizing the interpolation error [9]. In other words, we must calculate a series of weight coefficients corresponding to each real array channel output signal, reasonably, and then weight the real signal with these weight coefficients to obtain each virtual array channel output signal. This process can be described as the mathematical model:

$$\boldsymbol{B}_\mathrm{in}\boldsymbol{A} = \tilde{\boldsymbol{A}} \tag{24}$$

where $\boldsymbol{B}_\mathrm{in}$ is the interpolation matrix, which is composed by the weight coefficients mentioned above. $\boldsymbol{A}$ and $\tilde{\boldsymbol{A}}$ are the matrices of steering vectors of the real array and virtual array respectively and their expressions are shown in Eq. (9) and Eq. (12). These weight coefficients make the interpolation array response $\boldsymbol{B}_\mathrm{in}\boldsymbol{A}$ fit the real array response $\tilde{\boldsymbol{A}}$ as closely as possible. In this case, it changes into a least square problem, and the optimal solution can be obtained from Eq. (14) [10-11]. These virtual signal are estimated based on the real signal according to the least square algorithm, so they reserve the real signal frequency characteristics and satisfy the uniform configuration requirement of the 3D-STAP. Thereby, the SR-STAP combining signal reconstruction with 3D-STAP not only takes advantage of 3D-STAP but also overcomes the configuration limitation.

5. Simulation and Numerical Evaluation

To demonstrate the capability of the proposed method, two simulation experiments are carried out as follows.

Experiment 1 Nuniform 3D configuration clutter echo model establishment. This experiment is designed to validate the heterogeneity of the nonuniform 3D configuration clutter spectrum discussed hereinbefore. According to the system-level design of the "TechSat21" system task carried out by CDC, we assume that the main simulation parameters of the 8 spaceborne radars in one satellite group are shown in Table 1.

Set one satellite as the reference satellite, and the coordinates of the satellites in the configuration are: s_1 (0, 0, 0)m, s_2 (7, 6, 100)m, s_3 (97, −95, 9)m, s_4 (93, 8, 106)m, s_5 (110, 5, 7)m, s_6 (6, −100, 12)m, s_7 (89, −97, 100)m, s_8 (12, −85, 98)m. According to the clutter model in Section 2, the clutter spectrum can be obtained in Fig. 4 and Fig. 5.

Table 1　Main simulation parameters

Satellite Attitude/ km	Satelite Speed/ $(\mathrm{m}\cdot\mathrm{s}^{-1})$	Transmission bandwidth/ MHz	Pulse repetition frquency/ Hz	Wave-length/ m	Side looking angle/ (°)
750	7 481	200	1 496	0.03	30

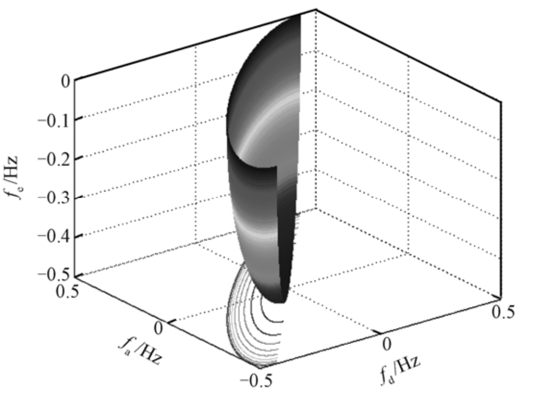

Fig. 4　Nonuniform 3D configuration clutter spectrum.

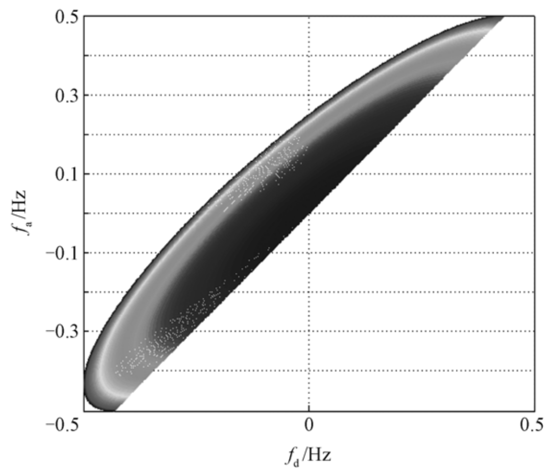

Fig. 5　Clutter spectrum projection on space-time plane.

Figure 4 shows that the nonuniform 3D configuration clutter spectrum is no longer a homogeneous plane along pitching but changes with the variation of pitching Doppler frequency. This point can be seen clearly in Fig. 5 that clutter spectrum does not distribute along a line in the space (azimuth)-time plane. Therefore, the traditional STAP (only learns along the azimuth) cannot obtain a desirable clutter refection performance.

Experiment 2　SR-3D-STAP simulation based on nonuniform 3D configuration. This experiment is designed to validate the clutter suppression performance of the proposed method. According to the system-level design of the “TechSat21” system task carried out by CDC, we assume that there are 8 independent array elements distributing in the space non-uniformly. This paper selects a section of real spaceborne SAR data as the echo data of the reference array element, and its signal parameter is shown in Table 1. The echo data spectrum characteristics of other 7 array elements can be obtained according to the geometry relations between the elements and the reference array element. According to the methods described above, this nonuniform 3D configuration signal can be reconstructed to uniform 3D configuration signal, then the clutter suppression can be carried out using SR-3D-STAP.

In this section of the real echo data, according to the moving target signal model, a moving target with the radial velocity and tangential velocity 10 m/s is added to the center of the scene, so that the half-real D-SAR echo data can be obtained. Using RD imaging, the reference element echo data can image the scene shown in Fig. 6. As the moving target echo is submerged by the clutter, it is not visible in the SAR image.

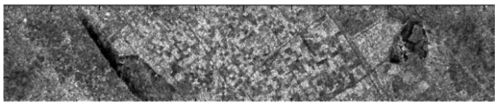

Fig. 6　RD imaging result of reference satellite echo.

We can suppress the clutter in the half-real data using SR-3D-STAP, and the results are shown in Fig. 7. In order to compare the performance, the traditional 2D-STAP is also carried out with the same data, and the results are shown in Fig. 8.

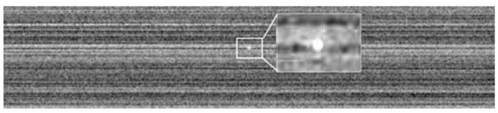

Fig. 7　Clutter depression result of SR-3D-STAP.

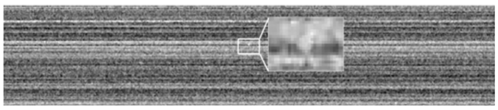

Fig. 8　Clutter depression result of 2D-STAP.

From the figures above, it can be found that after the proposed SR-3D-STAP clutter suppression based on the nonuniform 3D configuration, the moving target at center of the scene becomes visible, i.e. a better clutter suppression result is obtained; under the same simulation conditions, after the 2D-STAP clutter suppression, the moving target is still not well exposed.

In order to evaluate the proposed method performance, we define the improvement factor (IF) as the quotient of the output SCNR and input SCNR:

$$\mathrm{IF}=\boldsymbol{S}^{\mathrm{H}}\boldsymbol{R}^{-1}\boldsymbol{S}\frac{\mathrm{tr}(\boldsymbol{R})}{\boldsymbol{S}^{\mathrm{H}}\boldsymbol{S}} \tag{25}$$

where $\boldsymbol{S}$ is the steering vector. In Fig. 9, we can make IF as the vertical coordinate in the cells of decibels (dB), and make the normalized Doppler frequency $2f_d/f_r$ as the horizontal coordinate.

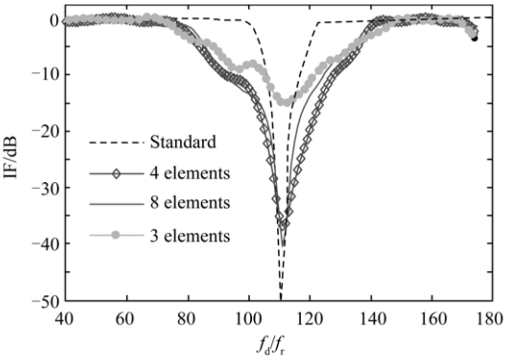

Fig. 9 Comparison of clutter suppression IF.

As Fig. 9 shows, the curve with dots presents the IF of 2D-STAP (suppresses the clutter only along azimuth), and the SCNR improvement is less than 16 dB after clutter suppression, i.e. it can hardly distinguish the clutter signal and the target signal. The dashed curve presents the IF under ideal conditions as reference standard. The curve with blocks presents the 4 elements (nonuniform planar configuration) SR-3D-STAP IF, and it can be found that the suppression performance is improved obviously compared with the traditional method. The solid curve presents the 8 elements (nonuniform 3D configuration) SR-3D-STAP IF. It is easy to find that the notch depth of the 8 element curve is the deepest, i.e. the SCNR improvement is the greatest and its notch width is the narrowest, which demonstrates the proposed method is more sensitive to the moving target velocity.

Furthermore, from the notch depth shown in Table 2, we can find that the clutter suppression performance is different when the element number and configuration are changing, and the clutter suppression effect of the nonuniform 3D configuration is the best among the 3 conditions. It means that high degree of freedom is beneficial to clutter suppression. Thereby it demonstrates the advantage in clutter suppression of the nonuniform 3D configuration with high degree of freedom.

Table 2 Notch depth of different configurations and numbers of elements

	Nonuniform linear configuration	Nonuniform planar configuration	Nonuniform 3D configuration
Number of elements	3	4	5
Notch depth /dB	15.12	37.52	40.57

6. Conclusions

Nonuniform 3D configuration distributed SAR has many advantages in ground monitoring. However, because of the complexity and specialty of its signal, many signal processing techniques with excellent performance cannot be used in practice. This paper combines array interpolation signal reconstruction with 3D-STAP to solve the nonuniform 3D configuration clutter suppression problem. Based on establishing nonuniform 3D configuration signal model, we derive nonuniform 3D configuration array interpolation method and propose SR-3DSTAP clutter suppression method. The advantages and effectiveness of this method are validated in simulation. It is worthy to point out that this method can be extended to other nonuniform 3D configuration distributed SAR problem.

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