Clutter property analysis and clutter suppression for HyperSonic Airborne Radar

Zheng LIU, Yi CHEN, Rong XIE, Lei ZHANG
National Laboratory of Radar Signal Processing
Xidian University
Xi’an, China, 710071
Email: lz@xidian.edu.cn

Abstract—Clutter property of a forward-looking array radar on Hypersonic Vehicle is analyzed and a method for clutter suppression using multi-stage space-time adaptive processing (STAP) is proposed. This method employs the elevation degree of freedom of the planar array to extract various range ambiguous clutter. Then range-unambiguous non-stationary clutter is compensated by using Doppler Warping (DW) algorithm, and finally STAP in azimuth-Doppler domain is used to suppress the residual clutter. Simulation results are given to demonstrate the validity of the presented method.

Keywords—HyperSonic Vehicle; forward-looking array radar; clutter suppression; elevation dimension; STAP;

I. INTRODUCTION

HyperSonic Vehicle (HSV) draws people’s attention for its attractive military and civilian application prospects, so it has a promising future in the development of 21st worldwide aerospace[1], while forward-looking array radar might be an active detection device for battle reconnaissance and target detection. Therefore, it is of great significance to research into target detection with hypersonic platform airborne radar (HSV-R). HSV employs forward-looking array radar, which would be influenced by severe clutter during downward-looking. To obtain better performance of target detection, clutter signal should be suppressed effectively. A forward-looking array radar generally adopts space-time adaptive processing[2-7] (STAP) to suppress strong clutter, but it is hard to achieve for hypersonic platform for following reasons: First, due to high platform height, the limitation of antenna aperture and transmit power, and a large elevation angle of radar beams, range dependence of clutter signal is rather serious. Second, due to the high altitude and high speed of hypersonic platform, pulse repetition frequency (PRF) cannot meet the requirements of both range unambiguity and Doppler unambiguity. Medium pulse repetition frequency (MPRF) is a compromise in clutter suppression of hypersonic platform, and range ambiguity or Doppler ambiguity undoubtedly exists for the clutter signal with MPRF. To solve this problem, reference [8] puts forward the Doppler Warping (DW) algorithm, which aligns the peaks of the Doppler spectrum by simple linear phase compensation. The method is simple and effective in the condition with low PRF and without range ambiguity. However, if there exists range ambiguity, the DW method is no longer suitable to range-dependent compensation. In recent years, the elevation degree of freedom (DOF) of the plane array has been introduced into STAP to solve non-stationarity problem, which is referred to as 3D-STAP[9]. 3D-STAP has good performance of clutter suppression, but it needs high computational complexity and large number of range secondary data, which is hardly to be satisfied in the practical case. Reference [10] proposes a method which firstly removes short-range non-stationary clutter by elevation prefiltering and then employs STAP in azimuth and time domain. It can effectively suppress the near-range clutter and the far-range clutter; besides, the computation burden is far less than that of 3D-STAP. However, it is not suitable in the case of large elevation angle. In this paper, based on the movement features of hypersonic platform, a scheme for clutter suppression of forward-looking array radar is proposed. The clutter with range ambiguity are separated and suppressed by employing the planar array’s elevation DOF. Then the clutter range non-stationarity is compensated by the DW algorithm. Finally, clutter is suppressed via STAP in azimuth-time domain. The scheme proves to be effective by simulation results.

II. CLUTTER PROPERTY OF HSV-R

A. Range non-stationarity of HSV-R clutter

HSV usually flies in the near space from 20km to 100km at the speed more than 5 times of sound velocity. Being high both in altitude and in speed, the clutter property of HSV during downward-looking is different from that of conventional airborne radar. The geometric relationship between airborne radar and a scatterer is shown in Fig.1. Airborne radar adopts forward-looking array. Assume that the plane flies along x axis, and the antenna is a rectangular plane array; the number of array elements is $M \times N$, where $M$ stands for the antenna’s row number and $N$ the column number. $\theta$ and $\varphi$ are the azimuth angle and the elevation angle (downward-looking angle) of clutter scatterers in the coordinate system, respectively.
The elevation angle of the clutter scatterer can be expressed by platform height $H$ and the slant range $R$:

$$\varphi = \arcsin(H/R) \quad (1)$$

The Doppler frequency of the clutter scatterer is given as follows:

$$f_d = \frac{2v}{\lambda} \sin \theta \cos \varphi \quad (2)$$

where $v$ is the aircraft velocity and $\lambda$ is the wavelength.

The horizontal spatial frequency $f_s$ is a function of both the azimuth and elevation angle:

$$f_s = \cos \psi = \cos \theta \cos \varphi \quad (3)$$

From (2) and (3), the relationship between normalized Doppler frequency $F_d$ and spatial frequency $f_s$ is given by:

$$\left(\frac{\lambda f_d}{4v}\right)^2 F_d^2 + f_s^2 = \cos^2 \varphi \quad (4)$$

where $f_s$ is the PRF, and $F_d = 2f_d / f_s$ is the normalized Doppler frequency.

Equation (4) indicates that the space-time clutter ridge of the forward looking array radar clutter is an ellipse, and the long axis and the short axis of the ellipse vary with range which validates the clutter range non-stationarity. Besides, the clutter non-stationarity is more serious in the case of short range $R \leq 5H$ (large elevation angle). It is seen that the range non-stationarity in the forward-looking array radar mainly locates in the area where the slant distance $R \leq 5H$ ($H$ is the altitude of the hypersonic platform), while in the area where slant distance $R > 5H$, the non-stationarity is unobvious, which can be approximately considered to be stationarity clutter. Since the altitude of the hypersonic platform $H$ is high, and the detection range $R$, restricted by radar aperture and antenna transmit power, is usually less than $5H$, the range non-stationarity is very serious. The clutter space-time spectrum distributions of HSV-R for different range bins are shown in Fig.2.

![Figure 1. Geometric relationship between airborne array and clutter scatterer](image1)

![Figure 2. Distribution of clutter spectrum](image2)

Fig.2 shows the clutter space-time spectrum distributions with the range being 80km, 90km, 100km, and 110km, respectively. It is shown that the clutter distributions of four range bins are different. Thus, the clutter is range dependent. Range dependent clutter makes STAP difficult to obtain the identically independent distributed secondary data. If these range dependent clutter are used for covariance matrix estimation, the clutter property reflected by the estimated covariance matrix is not accord with the true clutter property. Thus, clutter statistic mismatch occurs and performance degradation is unavoidable.

**B. The space-time 2D distribution of HSV-R clutter**

It is hard for PRF to meet the requirements of unambiguous range and unambiguous Doppler simultaneously with the HSV being both high in altitude and speed. Using MPRF is a compromise for HSV-R, where Doppler ambiguity and range ambiguity of clutter exist simultaneously. Fig.3 shows the space-time 2-dimensional (2D) clutter spectra with R being 100km.

It is seen from Fig.3 that there are multiple clutter patches from different spatial frequencies in single Doppler frequency due to the presence of Doppler ambiguity. Thus, the clutter rank increased greatly. Compared with the Doppler unambiguity case, more spatial DOF are required to suppress these Doppler-ambiguous clutters. Under the same spatial DOF, clutter suppression performance of the Doppler ambiguity case is worse than that of the Doppler unambiguity case.
Similarly, range ambiguity also increases the clutter rank due to the fact that the spatial frequencies of different range bins are not the same. Thus, more spatial DOF are required to suppress these range-ambiguous clutter. Additionally, the presence of range ambiguity makes range non-stationary compensation unfeasible since the linear compensation-based algorithms, e.g., the DW algorithm, can not compensate more than one Doppler frequency simultaneously. To compensate the non-stationarity clutter when range ambiguity exists, other array resources can be used (such as the elevation DOF).

### III. Suppression Method of HSV-R Clutter

#### A. Suppress the range ambiguous clutter utilizing elevation DOF\(^{[10]}\)

As range ambiguity exists in clutters, the \(l\)th range cell is the superposition of the clutter of multiple ambiguous ranges. Since the elevation angle is proportional to range, the range-ambiguous clutter can be considered as multiple clutter signals from multiple elevation angles. If the planar array is employed, the elevation DOF can be obtained to resolve the elevation space, which means that it is possible to resolve multiple range-ambiguous clutter or suppress arbitrary range-ambiguous clutter. Here we employ elevation filtering to reserve the clutters with the same range ambiguity and eliminate others.

As shown in Fig. 1, the actual range of the \(n\)th ambiguous range of the \(l\)th range cell is:

$$R_{c}(l, n) = \frac{c}{2f_s} l + \frac{c}{2f_s} n$$  \((5)\)

where \(f_s\) is the sampling frequency. In the same range cell, the elevation angle of different ambiguity times \(\phi_{l,n}\) is:

$$\sin \phi_{l,n} = \frac{H}{R_{c}(l, n)} + \frac{H^2 - R_{c}^2(l, n)}{2R_c(l, n)} \ (6)$$

where \(R_c\) is the earth radius.

Fig. 4 gives a comparison among the elevation sine values at 334th, 667th and 900th range cell with different ambiguity times. Due to the high airborne altitude, there are significant differences between the elevation sine values of different ambiguous clutter in the same range cell, so elevation filtering can be used to separate the range ambiguous clutter.

Suppose that the \(m\)th ambiguous clutter is reserved and the other ambiguous clutter should be suppressed. The elevation steering vector of the \(m\)th ambiguous clutter is:

$$S_m = \left[ 1 \ e^{j x \sin \phi_{l,n}} \ ... \ e^{j (N-1) x \sin \phi_{l,n}} \right]^T \ (7)$$

And the elevation dimensional steering vector of the \(n\)th ambiguous clutter is:

$$S_n = \left[ 1 \ e^{j x \sin \phi_{l,n}} \ ... \ e^{j (N-1) x \sin \phi_{l,n}} \right]^T, n = 1, 2, \ldots P \ (8)$$

where \(P\) is the number of unwanted range ambiguous clutter. The elevation filtering weight \(W\) can be designed by:
\[
\begin{align*}
W^H S_n &= 1 \\
W^H S_i &= 0 \\
&\quad \vdots \\
W^H S_p &= 0
\end{align*}
\]  

The result of (9) is:

\[W^H = \begin{bmatrix} 0 & \cdots & 0 \end{bmatrix} [S_1 \cdots S_s S_n]^T \]  

where \([\cdot]^T\) stands for the generalized inverse operation.

B. Clutter non-stationarity compensation

After elevation filtering, the clutter signals with the same range ambiguous times are obtained. However, as a result of large elevation angle of HSV-R, the extracted clutter signal is still range dependent. Thus range non-stationarity needs to be compensated. Fortunately, the extracted clutter signal is range unambiguous, and thus many existing methods for clutter non-stationarity compensation can be utilized. The DW\(^{(8)}\) algorithm is employed in this paper to compensate range non-stationarity.

The DW algorithm aligns the peaks of the Doppler spectrum by shifting the Doppler center frequency to compensate the clutter non-stationarity. To compensate the non-stationarity for various range cells is to change the compensation into the function related to slant distance. Equation (5) indicates that the elevation angle \(\phi_i\) of the \(i\)th range cell, \(n\)th ambiguous range, is:

\[
\phi_i = \arcsin \left( \frac{H}{R_c(l,n)} - \frac{H^2 - R^2_c(l,n)}{2R_cR_c(l,n)} \right)
\]  

The clutter signals of all the \(n\)th ambiguous range were obtained after elevation filtering, so the elevation angles of different range cells are just related to \(l\). For all range cells of the \(n\)th ambiguous range, the Doppler frequency shift value can be determined by the elevation angle \(\phi_i\) of the cell under test (CUT). Assume that the azimuth angle of the look direction is \(\theta_0\), and thus the Doppler frequency shift value \(\Delta_i\) of the \(i\)th range cell is:

\[
\Delta_i = \frac{4v}{\lambda f_c} \left( \sin \theta_0 \cos \phi_i - \sin \phi_i \cos \theta_0 \right)
\]  

From (2) and (12), the normalized Doppler frequency of the \(i\)th range cell after Doppler warping compensation is:

\[F_{di} = \frac{2f_c}{f_c} + \Delta_i = \frac{4v}{\lambda f_c} \sin \theta_0 \cos \phi_i + \frac{4v}{\lambda f_c} (\sin \theta - \sin \theta_0) \cos \phi_i \]  

Equation (13) shows that Doppler center frequencies \((\theta = \theta_0)\) of all range cells tend to be identical after Doppler warping compensation.

IV. SIMULATION RESULT

A. Results of Elevation filtering

According to the parameters given, the clutter signals ranging from 50km to 120km are simulated. The clutter-to-noise ratio (CNR) is 60dB for one array element and one pulse of the array antenna. The range bin with the range being 110km (elevation angle is 27°) is taken as the CUT. After elevation filtering is performed, the 7th range ambiguous clutter is used as the reserved clutter, while others should be suppressed. The response of elevation filtering at the 334th range cell is shown in Fig.5.

![Figure 5. The 334th range cell’s elevation filtering response](image)

Fig.5 indicates that high gain at the elevation spatial frequency of the 7th ambiguous range is obtained by the proposed method. Meanwhile, multiple notches are formed at the elevation spatial frequencies of other range ambiguous clutter. The range-Doppler spectra of HSV-R before and after elevation filtering are shown in Fig.6.

![Figure 6. The range-Doppler spectra of HSV-R before and after elevation filtering](image)

Fig.6 shows that the proposed method effectively retains the 7th times’ range ambiguous clutter and suppress other times’ range ambiguous clutter signals. Additionally, it is observed from Fig.6(b) that the clutter signal is still range dependent. Thus, to obtain a good estimate of the clutter covariance matrix, range dependent compensation is required.
Fig. 6. Clutter range-Doppler spectra

- **a** Before elevation filtering
- **b** After elevation filtering

**B. Results of Doppler warping**

After elevation filtering, the clutter signals are performed by Doppler warping compensation. The range-Doppler spectra of clutter signals after Doppler warping compensation is shown in Fig. 7.

**C. Results of STAP**

Finally, the echoes is processed by STAP in azimuth and time domain (3DT [11] method is utilized). Fig. 8(a) shows the azimuth-Doppler response of STAP by the 3DT method in the first Doppler channel (normalized Doppler frequency is 0). It can be seen that a deep notch is formed in the clutter ridge. Fig. 8(b) gives the Doppler frequency response corresponding to the first Doppler channel (normalized spatial frequency is 0), and Doppler frequency response can form a notch in the clutter Doppler frequency (normalized Doppler frequency is 0.2). Fig. 8(c) shows the adaptive spatial frequency response corresponding to the first Doppler channel. Similarly, the spatial frequency response can also form notches in corresponding spatial frequency (spatial frequency is ± 0.12).
D. IF comparison

Improvement factor\cite{7} (IF) can measure the improvement degrees of system detection performance, which is defined as the ratio of output signal-to-clutter-plus-noise ratio (SCNR) to input SCNR. Fig.9 gives a comparison of IF among the methods introduced in this paper, reference \cite{10} and 3D-STAP. The method in \cite{10} employs STAP directly after elevation filtering; while the 3D-STAP method adopts 8 as elevation DOF and 16 as azimuth DOF. The 3DT method is employed for reduced-dimensional processing of STAP.

Fig.9 shows that the range non-stationarity of clutter signals is still obvious after elevation filtering when the target’s elevation angle is large, and thus performance of the method in \cite{10} decreases with large elevation angle. The performance loss of 3D-STAP is mainly due to the fact that it requires a large number of independent and identically distributed (i.i.d) training samples, but the range samples are not sufficient for covariance matrix estimation. Whereas, the proposed scheme in this paper could achieve better performance improvement in short-range detection.

V. CONCLUSION

The STAP processing for the hypersonic platform with high altitude and speed encounters the problems about non-stationarity clutter, range and Doppler ambiguity which adversely affect STAP performance. Based on the features of the hypersonic platform, this paper puts forward a method that the same range ambiguous clutter is firstly extracted by elevation filtering, and then range-unambiguous non-stationarity clutter is compensated by the DW algorithm, and finally STAP in azimuth-time domain is used to suppress the residual clutter. The method is proved to be effective by simulation experiment. Due to the limited number of elevation elements of planar array radar, performance of elevation filtering decreases when the range ambiguous times is large. Therefore, the future research will be focused on how to suppress clutter signals with serious range ambiguity.

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