Deceptive jamming against multi-channel SAR-GMTI

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Abstract: Aimed at the problem that the deceptive jamming against synthetic aperture radar ground moving target indication generated by single jammer cannot work effectively in multi-channel SAR, a novel deceptive jamming against multi-channel SAR-GMTI based on two jammers is studied. First, signal model of the novel deceptive jamming is built. Then, based on three-channel clutter suppression and interferometry processing, the amplitude and interferometric phase of deceptive moving target generated by the novel deceptive jamming are derived. Last, simulation experiment validates that the novel deceptive jamming can generate false moving targets with the controllable radial velocity and located azimuth position in the multi-channel SAR.

1 Introduction

Synthetic aperture radar ground moving target indication (SAR-GMTI), which can realise the detection, location and imaging of moving targets in hotspots [1–3], has improved the information sensing capability of SAR greatly and brought an austere challenge for SAR jamming, thereby being one of the indispensable reconnaissance tools in military application. So, jamming techniques against SAR-GMTI has already been hot research issue in radar electronic countermeasure (ECM) area.

The jamming technique against SAR-GMTI can always be divided into barrage jamming and deceptive jamming. Barrage jamming can reduce the detection rate of moving targets via concealing the real targets in barrage plaques or strips [4–7]. On the other hand, deceptive jamming makes it difficult to distinguish fact from fable by generating deceptive moving targets which have the similar characteristics of scattering and motion with real ones. Due to the high fidelity and the low recognition rate, deceptive jamming is always a hot topic in SAR ECM community. Nowadays, most of deceptive jamming methods against SAR-GMTI focus on generating deceptive moving targets with a given motion state exploiting single jammer, and the jamming effect is always evaluated by whether deceptive targets can be detected as moving targets after clutter cancellation [8–11]. However, most multi-channel SAR-GMTI systems have the capacity of velocity measurement and location [12–15], so it is necessary to study the rationality of the radial velocity and located position of deceptive moving target. In fact, the signals of deceptive moving targets received by the radar have the same radiation resource, while the echoes of real moving targets are scattered by real targets with different position, that is, the Doppler phase of deceptive moving target is decided by both the radial velocity and the azimuth position, while the Doppler phase of real moving is only decided by the radial velocity. According to the difference between deceptive moving target and real one, literature Zhang et al. [16] points out that the radial velocity and located azimuth position of deceptive moving target are not controllable after multi-channel SAR-GMTI image processing, and deceptive moving target cannot simulate the spatial and motion characteristic of real moving target.

To address the aforementioned issue, profiting from the three-dimensional scene generation based on two jammers [17], we propose a novel deceptive jamming thought against multi-channel SAR-GMTI based on two jammers in this paper. The paper is organised as follows: Section 2 introduces the signal model of the novel deceptive jamming in multi-channel SAR-GMTI. In Section 3, we derive the amplitude and interferometric phase of deceptive moving target generated by the novel deceptive jamming. In Section 4, simulation results are presented to verify the validity of the novel jamming method. Finally, conclusions are presented in Section 5.

2 Signal model of the novel deceptive jamming

This section will introduce the signal model of the novel deceptive jamming.

Without loss of generality, here, a three-channel SAR-GMTI as shown in Fig. 1 is considered, which has three antennas \( J \), \( m \) and \( r \) with equal interval \( d \) along with the motion direction; the antenna \( m \) transmits signal, whereas all antennas simultaneously receive echoes. The system moves at a speed of \( V_T \) along with the \( X \)-axis which represents the azimuth direction. There are two jammers \( J_1 \) and \( J_2 \) in the imaging scene. The origin \( O \) of the Cartesian coordinate system \( OXY \) is the position of \( J_1 \). The closest distances between the antenna \( m \) and \( J_1 \) and \( J_2 \) are \( R_{J_1} \) and \( R_{J_2} \), respectively. The azimuth coordinate of \( J_2 \) is \( \Delta \chi (\Delta \chi \neq 0) \). Assuming that both \( J_1 \) and \( J_2 \) generate an arbitrary deceptive moving target located at \( (x_T, y_T) \), the radial velocity, tangential velocity, and scattering coefficient are \( v_r \), \( v_t \) and \( \sigma(x_T, y_T) \), respectively. Let \( R_T \) represents the closest distances between antenna \( m \) and deceptive target, where \( R_T = R_{J_1} + y_T \).

According to Fig. 1, the instantaneous distances between the jammers and the antennas are:

\[
R_{J_1}(t) = \sqrt{R_{J_1}^2 + (V_T^2 + x_1^2)} \approx R_{J_1} + \frac{(V_T^2 + x_1^2)}{2R_{J_1}}
\]

\[
R_{J_2}(t) = \sqrt{R_{J_2}^2 + (V_T^2 + \Delta x + x_2^2)} \approx R_{J_2} + \frac{(V_T^2 + \Delta x + x_2^2)}{2R_{J_2}}
\]

where \( \eta \) is the slow time, \( i \in \{ l, m, r \} \) represents the sub-antenna channel, and \( x_1 \) represents the azimuth distance between sub-antenna and middle antenna, where \( (x_v, y_v, x_1) = (–d, 0, d) \).

If a real target locates at \( (x_T, y_T) \) with the radial velocity \( v_r \) and the tangential velocity \( v_t \), the instantaneous distance between target and antenna \( m \) can be expressed as:
\[ R_T(\eta) = \sqrt{(R_T + \nu \eta)^2 + (x_T - v_T \eta - V_T \eta)^2} \] 
\[ \approx R_T + \nu \eta + \frac{(x_T - (V_T + \nu \eta))^2}{2R_T} \] 
\[ \approx R_{T1_m}(\eta) + \Delta R_T(\eta) \] 
\[ \approx R_{T1_m}(\eta) + \Delta R_T(\eta) \] 
\[ \Delta R_T(\eta) = \gamma_T + \nu \eta + \frac{(x_T - (V_T + \nu \eta))^2}{2R_T} - \frac{(V_T \eta - \Delta \chi)^2}{2R_T} \] 
\[ \Delta R_T(\eta) \approx \gamma_T + \nu \eta + \frac{(x_T - (V_T + \nu \eta))^2}{2R_T} - \frac{(V_T \eta - \Delta \chi)^2}{2R_T} \]

According to the principle of SAR deceptive jamming, the jammer can generate a deceptive target located at \((x_T, y_T)\) via delaying the intercepted SAR signal with a specific time interval and modulating appropriate amplitude, so the double-trip distances of SAR jamming signal received by antennas can be expressed, respectively, as
\[ 2R_{T1_m}(\eta) \approx R_{T1_m}(\eta) + R_{T1_m}(\eta) + 2\Delta R_T(\eta) \]
\[ = 2R_T + \frac{x_T^2 + 2V_T \eta}{2R_T} \] 
\[ 2R_{T2_m}(\eta) \approx R_{T2_m}(\eta) + R_{T2_m}(\eta) + 2\Delta R_T(\eta) \]
\[ = 2R_T + \frac{x_T^2 + 2V_T \eta}{2R_T} \] 

Supposing that SAR signal is \( s(t) \), the jamming signal of antennas can be modelled by
\[ S_{J_1}(\tau, \eta) = \sigma_1(x_T, y_T) \delta\left(\frac{\tau - 2R_{T1_m}(\eta)}{c}\right) \otimes s(t) \] 
\[ + \sigma_1(x_T, y_T) \delta\left(\frac{2R_{T1_m}(\eta)}{c}\right) \otimes s(t) \] 

From (6), it can be seen the jamming signal received by SAR-GMTI is the summation of the jamming signals generated by \( J_1 \) and \( J_2 \).

3 Amplitude and interferometric phase of deceptive moving target

In this section, the amplitude and interferometric phase of deceptive moving target will be analysed via three-channel clutter suppression and interferometry (CSI) [3, 13–15]. Three-channel CSI is a mature method combines the advantages of displaced-phase centre antenna (DPCA) and along track interferometry (ATI), which has been widely used in a lot of SAR-GMTI systems such as AN/APY-7, AN/APG-76, RadarSAF-2 and so on.

Based on SAR imaging principle, the images of antennas can be derived as
\[ S_{J_2}(\tau, \eta) \approx S_{J_2}(\tau, \eta) \exp\left(-j \frac{2\pi d(y_T - V_T \eta)}{\lambda R_T}\right) \]
\[ + S_{J_2}(\tau, \eta) \exp\left(-j \frac{2\pi d(y_T - \Delta \chi)}{\lambda R_T}\right) \]

where \( S_{J_1}(\tau, \eta) \) and \( S_{J_2}(\tau, \eta) \) are the jamming images in antenna \( m \) generated by \( J_1 \) and \( J_2 \), respectively, and can be expressed, respectively, as

\[ S_{J_1}(\tau, \eta) = S_{J_1}(\tau, \eta) C_{J_0} - S_{J_2}(\tau, \eta) \]
\[ \approx S_{J_1}(\tau, \eta) \exp\left(-j \frac{2\pi d(V_T \eta)^2}{\lambda R_T}\right) \]
\[ + S_{J_2}(\tau, \eta) \exp\left(-j \frac{2\pi d(V_T \eta - \Delta \chi)}{\lambda R_T}\right) \]

From (8) and (9), we can see that the azimuth position of deceptive target is \( \eta_T = x_T/V_T - v_T R_T/V_T^2 \). Substituting \( \eta_T \) into (10) and (11), it can be obtained
\[ \tilde{S}_{J_2}(\tau, \eta) \approx \exp\left(-j \frac{2\pi d(V_T \eta - \Delta \chi)}{\lambda R_T}\right) \]
\[ + \rho \exp(j\phi) \exp\left(-j \frac{2\pi d(V_T \eta^2 - \Delta \chi^2)}{\lambda R_T}\right) \]
\[
\hat{S}_{J,su} \simeq 1 - \exp\left( -\frac{2\pi d}{\lambda R} (x_T - \frac{v_T R_T}{v_T}) \right) \\
+ j \exp(\varphi) \left( 1 - \exp\left( -\frac{2\pi d}{\lambda R} (x_T - \Delta x - \frac{v_T R_T}{v_T}) \right) \right)
\]

where \( \hat{S}_{J,su} \) and \( \hat{S}_{J,su} \) can be considered as the complex residual images of the deceptive moving target. Let \( \varphi_1 = (2\pi d \Delta x / \lambda R) (x_T - (v_T R_T / v_T)) \) and \( \varphi_2 = (2\pi d \Delta x / \lambda R) (x_T - \Delta x - (v_T R_T / v_T)) \), then (12) and (13) can be rewritten, respectively, as

\[
\hat{S}_{J,su} \simeq \exp(\varphi) - 1 + \exp(j\varphi) \exp(\varphi) - 1
\]

(14)

\[
\hat{S}_{J,su} \simeq 1 - \exp(-j\varphi) + \exp(j\varphi)(1 - \exp(-j\varphi))
\]

(15)

It is easy to show that the amplitudes of the deceptive moving target are

\[
\hat{S}_{J,su} \approx \sqrt{a + b + c \cos(\varphi + \Delta \varphi / 2)}
\]

(16)

\[
\hat{S}_{J,su} \approx \sqrt{a + b + c \cos(\varphi - \Delta \varphi / 2)}
\]

(17)

where \( \Delta \varphi = \varphi_1 - \varphi_2 = - (2\pi d \Delta x / \lambda R) \), \( a = 4 \sin(\varphi_2 / 2)^2 \), \( b = 4 \cos^2(\varphi_2 / 2) \), and \( c = 8 \sin(\varphi_2 / 2) \cos(\varphi_2 / 2) \).

The conjugate product of the residual images shown by (14) and (15) is given by

\[
S_{J, su} S_{J,su} = a \cos \varphi_1 + b \cos \varphi_2 + c \cos(\varphi_1 + \varphi_2 / 2) + j (a \sin \varphi_1 + b \sin \varphi_2 + c \sin(\varphi_1 + \varphi_2 / 2))
\]

(18)

So, the interferometric phase of deceptive moving target can be expressed as

\[
\Delta \varphi = \arg(S_{J, su} S_{J,su}) = \arctan \left( \frac{a \cos \varphi_1 + b \cos \varphi_2 + c \sin((\varphi_1 + \varphi_2 / 2))}{a \sin \varphi_1 + b \sin \varphi_2 + c \cos((\varphi_1 + \varphi_2 / 2))} \right)
\]

(19)

If \( \Delta \varphi = -(2\pi d v / \lambda V) \), it is easy to obtain the estimated radial velocity of the deceptive moving target is \( v \), and the located azimuth position is \( x_T \), which are coincident with the setting value. From (19), it can be seen that \( \Delta \varphi \) is the function of \( \rho \) and \( \varphi \), which means the key point of the realisation of the deceptive jamming against multi-channel SAR-GMTI is to find the appropriate complex scattering coefficients ratio \( \rho \exp(\varphi) \) satisfies \( \Delta \varphi = -(2\pi d v / \lambda V) \). It is worth to note that \( \Delta \varphi \) is identical to \( \varphi_1 \) if \( \Delta \varphi = -(2\pi d \Delta x / \lambda R) \). Hence, we should assume that \( \Delta \varphi = -(2\pi d \Delta x / \lambda R) \neq 2k \pi \) to generate deceptive jamming targets with desired interferometric phases.

### 4 Simulation results

In this section, numerical simulations are presented to validate the effectiveness in generating deceptive moving target of the proposed novel deceptive jamming. The main parameters of SAR-GMTI system are listed in Table 1. There are two jammers in the image region with an area of 400 m x 300 m. Jammer J1 locates at the center of the image region, while the azimuth position of jammer J2 is 30 m with the same range position of J1. The position and radial velocity of each deceptive moving target are set as shown in Table 2, and the spatial distribution of the deceptive moving targets is shown in Fig. 2. In the simulation, we can calculate \( \rho \) and \( \varphi \) according to (19) first, then ensure the complex scattering coefficients ratio of jamming templates modulated in the two jammers is \( \rho \exp(\varphi) \) when jammers generate the jamming signal. After three-channel CSI processing, the imaging results are shown in Fig. 3, in which the red circle represents the position of the deceptive moving target in SAR image, the white number is the serial number of the deceptive moving target, the green triangle represents the located azimuth position and the direction of the triangle is the direction of the estimated velocity of deceptive moving target, and the green number is the serial number of deceptive moving target in the GMTI result image. In Figs. 2 and 3, the range is the differential range between the real range and the range of region center.

From Figs. 3a and b, it can be seen that all the generated deceptive moving targets deviate from the setting azimuth position which is caused by the existence of radial velocity, and can be detected as real moving targets. From Fig. 3d, after three-channel CSI processing, the located azimuth position of deceptive moving targets seems to be consistent with the setting azimuth position. To further analyze the effectiveness of the proposed jamming method,
the estimated interferometric phase, radial velocity, and located position of each deceptive moving target are present in Table 3. Contrasted Table 2 with Table 3, the estimated interferometric phase, radial velocity, and located position of the deceptive moving targets 3, 5, and 6 are coincident with the setting value, while the estimated values of 1, 2, 7, and 8 exist a litter error, which will reduce the fidelity of deceptive moving target to some extent. In fact, because the azimuth intervals between deceptive moving target and jammers are different, especially when the deceptive moving target does not locate in the middle of the jammers, it is difficult to ensure that the complex scattering coefficients ratio of deceptive moving target is the same with the setting value, which will lead to the interferometric phase does not equal to the desired interferometric phase. However, deceptive moving target generated by the novel deceptive jamming against multi-channel SAR-GMTI based on two jammers is still more controllable than deceptive moving target generated by a single jammer.

**Table 3** Estimated interferometric phase, radial velocity and located position of real and deceptive targets

| Deceptive moving target | Estimated interferometric phase, rad | Estimated radial velocity, m/s | Located position, m   |
|-------------------------|-------------------------------------|-------------------------------|-----------------------|
| 1                       | 1.655                               | −1.976                        | (−48.8, 9970)         |
| 2                       | 1.296                               | −1.547                        | (−22.4, 9990)         |
| 3                       | 0.8347                              | −0.996                        | (0.36, 10,010)        |
| 4                       | 0.4151                              | −0.496                        | (10.23, 10,030)       |
| 5                       | −0.4283                             | 0.511                         | (20.56, 10,030)       |
| 6                       | −0.8387                             | 1.001                         | (30.06, 10,010)       |
| 7                       | −1.307                              | 1.56                          | (53.03, 9990)         |
| 8                       | −1.714                              | 2.046                         | (82.3, 9970)          |
5 Conclusion

Aimed at the problem that the radial velocity and located azimuth position of the deceptive moving target generated by single jammer are not controllable in multi-channel SAR, this paper studies a novel deceptive jamming against multi-channel SAR-GMTI based on two jammers. In this method, the deceptive moving target at arbitrary location is composed by the jamming signals of both the two jammers, and the interferometric phase of the deceptive moving target is the function of the complex scattering coefficient ratio of modulated jamming templates in the two jammers. Simulation results of the controllable deceptive moving targets are provided to validate the proposed algorithm.

In the paper, we just point out the interferometric phase of deceptive moving target is decided by the complex scattering coefficient ratio of modulated jamming templates in the two jammers. However, how to choose the complex scattering coefficient ratio according to the interferometric phase of deceptive moving target is still unknown. In the next stage, we will focus determination method of the complex scattering coefficient ratio and develop the integrity flow of deceptive jamming against multi-channel SAR-GMTI based on two jammers.

6 References

[1] Cerutti-Maori, D., Sikaneta, I., Gierull, C.H.: ‘Optimum SAR/GMTI processing and its application to the radar satellite RADARSAT-2 for traffic monitoring’, IEEE Trans. Geosci. Remote Sens., 2012, 50, (10), pp. 3868–3881

[2] Entzminger, J.N., Fowler, C.A., Kenneally, W.J.: ‘Joint STARS and GMTI: past present and future’, IEEE Trans. Aero. Electron. Syst., 1999, 35, (2), pp. 748–761

[3] Lin, C.C., Huang, P.M., Li, Y.: ‘Research progressing in multichannel SAR-GMTI’, Telecommun. Eng., 2017, 57, (1), pp. 118–126

[4] Huang, L., Dong, C.X., Shen, Z.B., et al.: ‘The influence of rebound jamming on SAR GMTI’, IEEE Geosci. Remote Sens. Lett., 2015, 12, (2), pp. 399–403

[5] Zhou, Y., Bi, D.P., Fang, M.X., et al.: ‘A smart area shading jamming method for SAR-GMTI’, Mod. Rad., 2016, 38, (6), pp. 79–83

[6] Zhou, Y., Bi, D.P., Fang, M.X., et al.: ‘Intermittent sampling repeater shading jamming method based on motion modulation for SAR-GMTI’, J. Radars, 2017, 6, (4), pp. 359–367

[7] Li, W., Liang, D.N., Dong, Z.: ‘SAR jamming technique based on deceptive moving target’, J. Remote Sens., 2006, 10, (1), pp. 71–75

[8] Lv, B., Feng, Q., Zhang, X.F., et al.: ‘A study on deceptive moving target jamming technique against SAR’, Mod. Rad., 2008, 30, (6), pp. 102–104

[9] Xu, S.K., Li, Y.N., Fu, Y.W.: ‘A study on SAR jamming technique based on deceptive moving target’, Mod. Rad., 2008, 30, (7), pp. 94–98

[10] Wu, X.F., Liang, J.X., Wang, X.S., et al.: ‘Modulation jamming method of active false uniformly-accelerating targets against SAR-GMTI’, J. Astronaut., 2012, 33, (6), pp. 761–768

[11] Wu, X.F., Liang, J.X., Wang, X.S., et al.: ‘Modulation jamming method of high-vivid false uniformly-moving targets against SAR-GMTI’, J. Astronaut., 2012, 33, (10), pp. 1472–1479

[12] Sun, G.C., Xing, M.D., Xia, X.G., et al.: ‘Robust ground moving-target imaging using Deramp–Keystone processing’, IEEE Trans. Geosci. Remote Sens., 2013, 51, (2), pp. 966–982

[13] Gierull, C.H., Sikaneta, I., Cerutti-Maori, D.: ‘Two-step detector for RADARSAT-2’s experimental GMTI mode’, IEEE Trans. Geosci. Remote Sens., 2013, 51, (1), pp. 436–454

[14] Zhang, X.J.: ‘Study on SAR/GMTI technology for multi-phase center receive system’ (Nanjing University of Aeronautics and Astronautics, Nanjing, 2009)

[15] Zhou, Z.G.: ‘Study on key techniques of SAR-GMTI for multi-channel radar system’ (Xidian University, Xi’an, 2009)

[16] Zhang, J.K., Dai, D.H., Qi, Z.F., et al.: ‘Characteristic of deceptive moving target generated by single jammer in multi-channel SAR-GMTI’, ACES-China 2017, Suzhou, China, August 2017, pp. 1–4

[17] Zhang, J.K., Xing, S.Q., Dai, D.H., et al.: ‘Three-dimensional deceptive scene generation against single-pass InSAR based on coherent transponders’, IET Radar Sonar Navig., 2016, 10, (3), pp. 477–487