Ground moving target-detection and focusing imaging under strong noise background

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Abstract: This study proposes a detection algorithm for a three-channel SAR system with weak ground moving target (GMT)-detection and focusing imaging under strong noise background. First, the authors use DPCA cancellation technology to eliminate ground clutter signals. By accumulating the DPCA signal amplitude in the azimuth direction and setting a suitable threshold, they realise GMT detection under strong noise background. After extracting the target range cell DPCA signal, they use the interference processing method to estimate the real-azimuth position of GMT. Then, they perform fractional Fourier transform processing on the extracted DPCA signal. Through the two-dimensional search of the peak point on the (u, v) plane of the parameter, the Doppler parameters and velocity estimation of the GMT are obtained. Finally, the azimuth-matching filter is modified to achieve focusing imaging. Simulation results show that the detection probability of GMT is >95% when SNR ≥ −27 dB. When SNR = −27 dB, the authors can achieve fairly accurate parameter estimation of GMT and ideal focusing imaging.

1 Introduction

Synthetic aperture radar (SAR) is capable of high-resolution imaging for large ground scenes with no dependency on time and weather [1]. However, conventional SAR cannot detect them when there are moving targets on the ground. Since the relative motion between the ground moving target (GMT) and SAR is non-cooperative [2], the imaging result of GMT will be shifted and broadened [3].

Currently, the demand for ground remote-sensing is kept increasing. Military and civil fields such as ground vehicle traffic control, marine ship target monitoring, and battlefield mobile target surveillance are inseparable from the GMT detection technology. As a result, scholars have proposed some multi-channel SAR/GMTI techniques [4–6], which have overcome the bottleneck that conventional SAR cannot detect GMT and have GMT-detection capabilities. Literature [7] proposes the use of GMT shadow feature information to improve GMT detection performance. However, the detection results are mostly obtained under an ideal environment or in a low-noise background thus unreliable. The previously proposed methods may fail to achieve ideal detection performance under strong noise background (such as noise interference background). In recent years, some scholars have introduced the fractional Fourier transform (FrFT) into the SAR system [8–10] to obtain GMT parameters due to FrFT’s excellent chip signal-focusing performance. However, the premise of this method is that the GMT has been detected. In addition, it is necessary to modify the azimuth-matched filter [11] to achieve ideal azimuth focusing. Therefore, a critical precondition for parameter estimation and focusing imaging of weak GMT under the background of strong noise is to obtain the ideal detection performance for GMT. Based on the above background, this paper proposes a method for accumulating the DPCA signal amplitude along the azimuth of the original data and setting a suitable threshold for the detection of weak GMT under strong noise background and improves the GMT detection probability. After that, we use interference and FrFT processing to estimate the parameters of the detected GMT. Finally, the azimuth-matching filter is modified with the result of the parameter estimation, and focusing imaging of weak GMT under strong noise background is realised.

The remainder of this paper is organised as follows. Section 2 presents the signal model of GMT receiving echo. Section 3 proposes GMT-detection algorithm. Then, the algorithms of GMT parameter estimation and focusing imaging are given in Section 4. Section 5 presents some simulation results and discussions to validate the proposed algorithms for GMT detection, parameters estimating, and focusing imaging under strong noise background. Finally, conclusions are drawn in Section 6.

2 Model of the received echo

2.1 Radar-target geometry

As shown in Fig. 1, we suppose the multi-channel SAR platform moves at a constant velocity \( v \) in the direction of the x-axis with a height of \( H \) and a number of channels of 3. Each aperture along the track at intervals \( d \) is equally spaced and meets \( d/2 = v \times mT \) (here \( m \) is a suitable integer, \( T \) is the pulse repetition period). The second aperture launch signal, and the first, second, and third apertures at the same time receive the signal. The length of the synthetic aperture is \( L \), the synthetic aperture time is \( T_L = L/v \). When the slow time \( t_s = 0 \), the distance between GMT and aperture 2 is \( R_0 = \sqrt{x_0^2 + y_0^2 + H^2} \). The coordinates of the uniform motion target \( P \) at \( t_s \) are \( (x_0 + v t_s, y_0 + v t_s, 0) \), \( v_x \) and \( v_y \) are azimuth and range velocity of \( P \), respectively. Hence, the distance from the GMT to apertures 1, 2, and 3 \( R_{1}(t_s), R_{2}(t_s), \) and \( R_{3}(t_s) \) can be given by

\[
R_{0}(t_s) = \sqrt{[x_0 + d - (v - v_x)t_s] + [y_0 + v_y t_s]^2 + H^2} \\
\approx R_{0}(t_s) - \frac{d(v - v_x)}{R_0} t_s + \frac{d^2 + 2d v_x}{2R_0} \\
R_{1}(t_s) = \sqrt{[x_0 - (v - v_x)t_s]^2 + [y_0 + v_y t_s]^2 + H^2} \\
\approx R_0 + \frac{(v - v_x)^2 + v_y^2}{2R_0} + \frac{y_0 v_x - x_0(v - v_x)}{R_0} t_s \\
R_{3}(t_s) = \sqrt{[x_0 - d - (v - v_x)t_s] + [y_0 + v_y t_s]^2 + H^2} \\
\approx R_{0}(t_s) + \frac{d(v - v_x)}{R_0} t_s + \frac{d^2 - 2d v_x}{2R_0} \\
\]
Fig. 1 Radar-target geometry

### 2.2 Model of the range-compressed echo

Suppose the transmitted pulse is

\[ s(t, t_a) = \text{rect}_r(t) \cdot \exp\left[j2\pi f_0 t + \mu \xi(t)/2 \right] \]

(2)

where \( \text{rect}_r(\cdot) \) is a rectangular window function with time width \( T_P \) and \( t_a \) is fast time, \( T_P \) is the pulse width, \( f_0 \) is the centre frequency, and \( \mu \) is the chirp rate.

The propagation distance from the \( P \) reflection signal to the three apertures is \( R_{a}(t_a) = R_c(t_a) + R_{\tau}(t_a) \), and \( R_{c}(t_a) = R_{c0}(t_a) + R_{\tau0}(t_a) \), respectively. The baseband form of the echoes of the moving target received by the apertures 1, 2, and 3 is

\[
\begin{align*}
\hat{s}_1(t, t_a) &= \text{rect}_r(t) \cdot \exp\left[ j\lambda_0 \mu(t - t_a) + \lambda_0 \xi(t)/c \right] \exp\left[ -j2\pi R_{c0}(t_a)/c \right] \\
\hat{s}_2(t, t_a) &= \text{rect}_r(t) \cdot \exp\left[ j\lambda_0 \mu(t - t_a) + \lambda_0 \xi(t)/c \right] \exp\left[ -j2\pi R_{c0}(t_a)/c \right] \\
\hat{s}_3(t, t_a) &= \text{rect}_r(t) \cdot \exp\left[ j\lambda_0 \mu(t - t_a) + \lambda_0 \xi(t)/c \right] \exp\left[ -j2\pi R_{c0}(t_a)/c \right]
\end{align*}
\]

(3)

where \( c \) is the speed of light, \( \lambda \) is the wavelength of center frequency.

In the fast time domain, after range compress and range migration correction, the arrival time of the target echo to the three apertures can be approximated as \( t_3 \approx t_2 \approx t_1 \approx t_r = 2R_c/c \) because of \( R_{c}(t_a), R_{\tau}(t_a), R_{\tau0}(t_a) \gg d \). Then, \( R_c = \sqrt{x^2 + y^2} \) is the distance from \( P \) to the track. After the result is normalised, the signal expression is

\[
\begin{align*}
\hat{s}_s(t, t_a) &= (1 - |\xi|/T_P) \cdot \sin\left[ j\lambda_0 \mu(t - t_a) + \lambda_0 \xi(t)/c \right] \exp\left[ -j2\pi R_{c0}(t_a)/c \right] \\
\hat{s}_s(t, t_a) &= (1 - |\xi|/T_P) \cdot \sin\left[ j\lambda_0 \mu(t - t_a) + \lambda_0 \xi(t)/c \right] \exp\left[ -j2\pi R_{c0}(t_a)/c \right] \\
\hat{s}_s(t, t_a) &= (1 - |\xi|/T_P) \cdot \sin\left[ j\lambda_0 \mu(t - t_a) + \lambda_0 \xi(t)/c \right] \exp\left[ -j2\pi R_{c0}(t_a)/c \right]
\end{align*}
\]

(4)

where \( t_r = t_a - t_r \).

### 3 GMT detection

Ground clutter echo needs to be suppressed before detection of GMT. DPCA is an effective technique for suppressing ground clutter echo [12]. Before channel cancellation, the phase difference generated by the arrangement of aperture must be compensated. The phase compensation function is \( C = \exp\left[ -j2\pi d/(2R_c) \right] \), then make a time match i.e. the channel signal is shifted by \( m \) pulses in the slow time domain, and then the cancellation processing is performed. The expression of the DPCA signal after channel cancellation is

\[
\begin{align*}
\hat{s}_s(t, t_a) &= s_s(t, t_a) : C - s_s(t, t_a + mT) \\
&= A_0 \cdot \exp\left[ -j\frac{2\pi R_{c0}(t_a)}{c} \right] \cdot \left[ 1 - \exp\left[ -j\frac{2\pi y_{\text{d}}}{4R_c} \right] \right] \\
&= A_0 \cdot \exp\left[ -j\frac{2\pi R_{c0}(t_a)}{c} \right] \cdot \left[ 1 - \exp\left[ -j\frac{2\pi y_{\text{d}}}{4R_c} \right] \right]
\end{align*}
\]

(5)

where \( A_0 = (1 - |\xi|/T_P) \cdot \sin\left[ j\lambda_0 \mu(t - t_a) + \lambda_0 \xi(t)/c \right] \).

It can be seen from (5) that since the range velocity of the stationary object is 0, the output values of \( \hat{s}_s(t, t_a) \) and \( \hat{s}_s(t, t_a) \) are 0, so the static ground clutter is suppressed due to channel cancellation. Since the range velocity of GMT is generally not 0, its echo energy is retained.

It is worth pointing out that ground clutter can generally be better cancelled, but noise cannot be eliminated. In order to improve the detection probability under the strong noise background, we use the method of accumulating the DPCA signal amplitude in the azimuth direction since the DPCA signal of GMT in the raw data domain can be exhibited as a straight line in the
azimuth direction, resulting in the accumulation of GMT energy, and the range cell containing the GMT will show a peak which can improve the signal-to-noise ratio (SNR). The sketch map of cumulative DPCA signal along the azimuth is shown in Fig. 2. A threshold is set when the peak value exceeds the threshold; we assume that the range cell has a GMT, and the detection of the GMT and the estimation of the range position are completed. Threshold Th is set to
\[ Th = l \times s + M, \quad l \in \mathbb{R}^+ \] (6)
where \( s \) is the standard deviations of local data, \( M \) is average of the data. When a high detection probability is required, the value of \( l \) should be smaller, but it leads to an increase in false alarm probability simultaneously. Generally, the value of \( l \) is between 1 and 4.

4 Parameter estimation and focusing imaging of GMT

4.1 Parameter estimation

After the GMT detection is completed, the DPCA signal \( s_o(t_1, t_2) \) and \( s_o(t_1, t_2) \) of the corresponding range cell is extracted and the following parameters are estimated:

1. Azimuth position estimation

   The azimuth position of the GMT can be obtained by interfering with the signals \( s_o(t_1, t_2) \) and \( s_o(t_1, t_2) \). Before the interference processing, we need to compensate the time-varying phase difference in \( s_o(t_1, t_2) \) due to the spatial arrangement of the apertures, and the phase difference compensation function is
   \[ C(t_o) = \exp[j2\pi dv_i t_o/\lambda R_0] \]. After the phase compensation for \( s_o(t_1, t_2) \), combined with (1) and (5), we can obtain (see (7)).

According to (7), the interference phase \( \Delta \phi \) can be obtained by interference processing of \( s_o(t_1, t_2) \) and \( s_o(t_1, t_2) \). The expression of \( \Delta \phi \) is
\[ \Delta \phi = \text{arg}[s_o(t_1, t_2) \cdot s_o(t_1, t_2)] = -\frac{2\pi}{\lambda} \left( \frac{d^2/2 - 2xd_{\theta}}{2R_0} \right) \] (8)

Therefore, the azimuthal position of the GMT can be estimated as
\[ \hat{x}_o = \frac{R_0}{2\pi d} \Delta \phi + \frac{d}{4} \] (9)

In (9), \( \Delta \phi \) is an estimate of the interference phase without ambiguity or after the resolution of ambiguity.

2. Velocity estimation

   Observing (7), we find that \( s_o(t_1, t_2) \) and \( s_o(t_1, t_2) \) are chirp signals, which can be written as (ignoring amplitude information)
   \[ x(t_o) = \exp[j2\pi f_o t_o + \mu_o t_o/2] \] (10)

   where the expressions of the centre frequency \( f_o \) and the chirp rate \( \mu_o \) are
   \[ \begin{align*}
   f_o &= -\frac{2(v_y - v_x v_y)}{\lambda R_o} = \frac{2v_x v_y}{\lambda R_o} - \frac{2v_x v_y - v_y v_x}{\lambda R_o} \\
   \mu_o &= -\frac{2(v - v_y)^2 + v_y^2}{\lambda R_o}
   \end{align*} \] (11)

If we can estimate \( f_o \) and \( \mu_o \) in the chirp signal \( x(t_o) \), we can get the velocity estimate from (11). Since FrFT has very good focus and estimation performance on chirp signals, FrFT will be used to estimate \( f_o \) and \( \mu_o \). The specific method is to scan \( x(t_o) \) using the rotation angle \( \alpha \), and find the FrFT of the signal to form a two-dimensional distribution of the signal energy in the \((x, u)\) plane, and perform a two-dimensional search of the peak point in this plane [8]. It is possible to obtain the estimated center frequency and chirp rate as \( f_o = \text{imag} \alpha \) and \( \mu_o = -\text{cot} \alpha \), respectively. Then according to (11), we can get the velocity estimates \( \hat{v}_x \) and \( \hat{v}_y \), respectively. Since the static ground clutter is highly cancelled, the detected signal \( x(t_o) \) has high signal-clutter ratio and, therefore, will have better estimation results.
4.2 Focusing imaging

It can be known from (11) that the centre frequency $f_a$ and the chirp rate $\mu_a$ of GMT echo signal are not the same as those of the stationary target. If the azimuth compress is performed, the azimuth matching filter $h_{at}(t_a) = \exp(j2\pi v^2 t_a^2/\lambda R_0)$ of the stationary target is still used, and the GMT imaging will be azimuth position shifted and broadened. Therefore, correct focusing on GMT requires a modified azimuth matching filter. According to the results from Section 4.1, the corrected azimuth matching filter is

$$h^*(t_a) = \exp(-j\pi \mu^\circ t_a^2) \quad (12)$$

Carry out azimuth compress by using the filter $h^*(t_a)$ and move the focus image to the true azimuth position $x^\circ$ to complete the focusing imaging. Detection, parameter estimation and focusing imaging of GMT flow chart is shown in Fig. 3.

5 Experiment results

Experiments are carried out below to verify the validity of the proposed method for GMT detection and focusing imaging under strong noise background. The main experimental parameters of the multi-channel SAR system are shown in Table 1. Assume that there are two static targets and a moving target in the scene and their reflection coefficient is 1. The two stationary target coordinates are $(0, 10000, 0)(m)$ and $(-20, 10050, 0)(m)$, respectively. The uniform motion target coordinates are $(20, 9950, 0)(m)$ when $t_a = 0$, and its range velocity and azimuth velocity are 2 m/s and 6 m/s, respectively. In the simulation experiment, the background noise obeys a Gaussian distribution, and the number of the samplings in range direction and azimuth direction is 2769 and 1697, respectively.

5.1 Simulation of GMT detection

Fig. 4 shows the detection result when the background noise is not considered. From the figure, we can see that in each channel range compress grayscale, static targets, and the GMT are all presented as straight lines in the azimuth direction (Fig. 4a), but only the GMT component remains after offset by DPCA (Fig. 4b), and by accumulating in the azimuth direction, a peak is generated in the range position of the GMT (Fig. 4c), which is the same as analysed in Section 3.

Fig. 5 shows the detection result of an experiment when $SNR = -27dB$, and the threshold is set to $Th = 3\sigma + M$. From the figure we can see that, due to the noise, it is difficult to detect the GMT from the result after offset by DPCA (Fig. 5a), and by using the method mentioned before to make accumulation in the azimuth direction, we find that only in the 1345th range cell does the amplitude exceed the threshold (Fig. 5b). Therefore, there must be a GMT in this range cell, which is consistent with the actual situation.

Table 1  Multi-channel SAR experimental parameters

| SAR parameter                  | Value |
|-------------------------------|-------|
| center frequency, GHz         | 10    |
| pulse width, μs                | 20    |
| range bandwidth, MHz          | 100   |
| azimuth bandwidth, Hz         | 400   |
| number of channels             | 3     |
| pulse repetition period, Hz    | 480   |
| synthetic aperture length, m  | 300   |
| loader velocity, m/s           | 200   |
| flight altitude, m             | 6000  |
| antenna spacing, m            | 0.83  |
In order to analyze the detection performance, 600 times of Monte–Carlo experiments have been done under different SNR. The detection performance curve is shown in Fig. 6. It can be seen from Fig. 6 that the detection probability of GMT by this method is better than 95%.

**5.2 Simulation of GMT parameter estimation**

When SNR = −27dB, \(s_{21}(t_r, t_a)\) and \(s_{32}(t_r, t_a)\) of the range cell where the detected GMT is located are extracted to perform interference processing, and the interference phases of all sampling points are averaged to obtain the estimated value as \(\Delta \phi = 0.3819\) rad. According to (9), the estimated azimuth position is \(x_0 = 21.97\) m.

The FrFT process is performed on \(s_{21}(t_r, t_a)\) and the result is shown in Fig. 7. Using the peak search method, the \(p\)-values and \(u\)-values corresponding to the peaks are obtained, and then they are brought into \(\hat{\mu}_a = -\cot(\hat{p} \cdot \pi/2)\) and \(\hat{f}_a = \csc(\hat{p} \cdot \pi/2)\). After correcting the scale effect caused by the difference between the time domain and the frequency domain dimension, the estimated values of the chirp rate and the center frequency can be \(-253.11\) Hz/s and \(-80.47\) Hz, respectively. According to (11), the estimated velocity are \(v_x = 5.65\) m/s and \(v_y = 2.01\) m/s, respectively, which is consistent with the theoretical value.

**5.3 Simulation of GMT focusing imaging**

If the azimuth matched filter \(h(t_a) = \exp\left[i2\pi v_x t_a/(\lambda R_0)\right]\) is used for azimuth compress, the imaging result is shown in Fig. 8. It can be seen that the GMT image has a widening and azimuth position shift (Fig. 8a) and the GMT image is relatively blurred (Fig. 8b).

The estimated parameter \(\hat{\mu}_a = -253.11\) Hz/s are brought into (12), and the reference function of azimuth matching is modified, then the azimuth compress is carried out, and then the focus image is moved to \(x_0 = 21.97\) m, the result is shown in Fig. 9. It can be seen that the GMT achieves good focus and returns to the true azimuth position (Fig. 9a), and the GMT image is very clear.
This shows that when SNR = − 27dB, the method can clear focusing imaging of GMT and proves the correctness and effectiveness of the proposed method for GMT focusing imaging under strong noise background.

6 Conclusion
This paper mainly studies the method of weak GMT detection, parameter estimation and focusing imaging under strong noise background. Experiment results show that the detection probability of the GMT is higher than 95% when SNR ≥ − 27dB. When SNR = − 27dB, we can achieve fairly accurate parameter estimation and ideal focusing imaging of GMT. After correcting the azimuth matching filter, a well-focused GMT image can be obtained after azimuth compress. The research in this paper is of great significance to the monitoring of weak GMT in the background of strong noise interference.

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8 References
[1] Cumming, I., Wong, F.: 'Digital processing of synthetic aperture radar data: algorithms and implementation' (Artech House, Boston, MA, USA, 2009)
[2] Liu, B., Yin, K., Li, Y., et al.: ‘An improvement in multichannel SAR-GMTI detection in heterogeneous environments’, IEEE Trans. Geosci. Remote Sens., 2014, 42, pp. 810–827
[3] Li, Z., Wu, J., Yi, Q., et al.: ‘Bistatic forward-looking SAR ground moving target detection an imaging’, IEEE Trans. Aerosp. Electron. Syst., 2015, 51, pp. 1000–1016
[4] Kei, S., Kazuhiko, Y., Masayoshi, T., et al.: ‘Image-based target detection and radial velocity estimation methods for multichannel SAR-GMTI’, IEEE Trans. Geosci. Remote Sens., 2017, 55, pp. 1325–1338
[5] Eduardo, M., Stefan, B., Marc, J., et al.: ‘Multichannel SAR-GMTI in maritime scenarios with F-SAR and TerraSAR-X sensors’, IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens., 2015, 8, pp. 5052–5067
[6] Zhang, X., Liao, G., Zhu, S., et al.: ‘Geometry-information-aided efficient motion parameter estimation for moving-target imaging and location’, IEEE Trans. Geosci. Remote Sens., 2015, 12, pp. 155–159
[7] Xu, H., Huang, Z., Tian, M., et al.: ‘An extended moving target detection approach for high-resolution multichannel SAR-GMTI systems based on enhanced shadow-aided detection’, IEEE Trans. Geosci. Remote Sens., 2018, 56, pp. 715–729
[8] Chen, S., Zhang, S., Zhao, H., et al.: ‘A New chirp scaling algorithm for highly squinted missile-borne SAR based on FrFT’, IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens., 2015, 8, pp. 3977–3987
[9] Sun, G., Xing, M., Xia, X., et al.: ‘A unified focusing algorithm for several modes of SAR based on FrFT’, IEEE Trans. Geosci. Remote Sens., 2013, 51, pp. 3139–3155
[10] Zhang, X., Liu, B., Lv, Z., et al.: ‘Efficient radon fractional Fourier transform for efficient motion parameters estimation in SAR-GMTI system’, IEEE Int. Geoscience and Remote Sensing Symp. (IGARSS), Bejing, People’s Republic of China, July 2016, pp. 1392–1405
[11] Zhang, S., Xing, M., Xia, X.: ‘Robust clutter suppression and moving target imaging approach for multichannel in azimuth high-resolution and wide-swath synthetic aperture radar’, IEEE Trans. Geosci. Remote Sens., 2015, 53, pp. 687–709
[12] Huang, Z., Xu, J., Peng, S., et al.: ‘A new channel balancing algorithm in image domain for multichannel SAR-GMTI system’. IET Int. Radar Conf., Hangzhou, People’s Republic of China, October 2015, pp. 1–5