Wideswath synthetic aperture radar ground moving targets indication with low data rate based on compressed sensing

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Abstract: Wideswath synthetic aperture radar/ground moving targets indication (SAR/GMTI) system increases severely data transmission and storage load. To mitigate this problem, a wideswath GMTI method based on compressed sensing (CS) is proposed. In this method, CS is utilised to process each SAR data sampled sparsely in the azimuth direction for multiple aperture systems after conventional range compression. Then the wavelet transform matrix is used to construct the sparse matrix. Each SAR image is unambiguously achieved by solving $l_1$ norm optimisation problem in the azimuth. The clutter rejection is performed for all spatial SAR images and then moving targets can be well detected. In this way, the data rate together with storage load is reduced, and then the wideswath GMTI can be efficiently realised. Results of real measured and simulated SAR data processing demonstrate the effectiveness of the CS-based wideswath GMTI.

1 Introduction

Synthetic aperture radar (SAR) has become a very important tool for high-resolution mapping in many civilian and military applications. To meet the increasing requirement, the SAR community is presently researching the imaging and identification of moving targets. It is highly desirable to detect, relocate and image moving targets in SAR imagery. In real scenarios, the slowly or fast moving targets are obscured by stationary clutter. An effective solution is to filter the target echoes from static background by using the displaced phase centre antenna [1] or its extension which is space-time adaptive processing with multiple along-track apertures [2].

Traditional SAR data sampling approach must satisfy Nyquist sampling rate to obtain the unambiguous SAR image. For wideswath surveillance SAR/ground moving targets indication (GMTI) systems, especially for wideswath sea surveillance radar, the large amount of raw data increase severely system transmission and storage load because of the fact that the sampled data are restricted by Nyquist sampling rate. When the pulse repetition frequency (PRF) is lower than the Doppler bandwidth, the SAR imaging will be ambiguous by conventional imaging algorithms. For multiple apertures SAR/GMTI system, the ambiguous SAR images lead to the difficulty for clutter suppression, and then degrade the moving targets detection performance greatly. Compressed sensing (CS) developed in recent years gives an important theory support to solve this ambiguous problem, which indicates that an unknown sparse signal can be exactly recovered from a very limited number of measurements with high probability by solving $l_1$ norm optimisation problem without ambiguity [3–6]. At present, in the fields of radar signal processing, CS has recently attracted more and more attention. Some literatures on CS applications in radar have been published [7–13]. An ISAR imaging method based on CS has been proposed with very limited available amount of pulses [8]. In [11], CS is used to perform SAR imaging and produce the unambiguous SAR image.

In the proposed method, the received signal is randomly and sparsely sampled or subaperture sampled to reduce the data rate in the azimuth direction after conventional range compression. For the SAR image in real scenarios, the backscattering field of surveillance area is usually not sparse, and the characteristic of stationary clutter and moving targets are unknown. All of these factors will influence the image recovery for multiple aperture GMTI system. To mitigate this problem, we use the wavelet transform to construct the sparse matrix. Then each SAR image for spatial channels can be effectively achieved by the $l_1$ norm optimisation [7]. After obtaining all recovered SAR images, we joint spatial multiple images and perform clutter suppression. The data rate is reduced without image ambiguity in the azimuth. By using the CS-based GMTI technique, the SAR images for spatial multiple apertures can be unambiguously recovered with lower PRF and wider range swath. Therefore the proposed CS-based GMTI approach can provide large area and wideswath surveillance GMTI for airborne or spaceborne radar.

The remainder of this paper is organised as follows. In Section 2, we review the basic properties of the moving target echo and introduce the signal model. In Section 3, the CS-based SAR imaging and GMTI algorithm is
described. We first present the randomly sampling mode in the azimuth for SAR, and then develop subaperture processing mode in the azimuth. In the last subsection, we give the wideswath GMTI mode, following a brief real measured and simulated data processing. Conclusions are drawn in Section 4.

2 Signal modelling

The geometry relationship between the flying platform and moving target is shown in Fig. 1. In this figure, $v_a$ and $v_c$ denote the along- and cross-track velocities (projection on the imaging plane). $a_a$ and $a_c$ are the along- and cross-track accelerations, whereas $t_m$ is the slow time in azimuth. $R_B$ and $R(t_m)$ are the nearest and instantaneous slant range between the platform and target, respectively. $d$ is the distance between two spatial channels and $v$ is the platform velocity.

Consider that the transmitted signal

$$p(t) = \text{rect} \left( \frac{t}{T_0} \right) \exp \left( j \frac{\pi \Delta B t^2}{T_0} \right)$$

where $t$ is the fast time, $T_0$ is the pulse duration time, $\Delta B$ is the bandwidth of the transmitted signal, $\text{rect} (\cdot)$ is the rectangular function. For the sideloooking radar with zero squint angle, the received signal of the moving target after down conversion and range compression can be expressed as

$$s(t, t_m) = \sigma_s G w(t_m) \text{sinc} \left( \Delta B \left( t - \frac{2R(t_m)}{c} \right) \right) \times \exp \left( -j \frac{4\pi R(t_m)}{\lambda} \right)$$

where $\sigma_s$ is the complex reflectivity of the target, $G$ is the range compression gain, $w(t_m)$ is the azimuth windowing function [14], $c$ is the speed of light and $\lambda$ is the wavelength. In the above formula, the slow time satisfies

$$t_m \in \{ t_1, t_2, \ldots, t_i, \ldots, t_M \} = \frac{t_1 + t_M}{2}$$

The slant range of moving target for the second spatial channel $R_2(t_m)$ can be expressed as (see (5))

$$R_2(t_m) = \sqrt{\left( v_{f_m} - v_{a_m} - \frac{1}{2} a_{a_m} t_m^2 \right)^2 + \left( R_B - v_{c_m} - \frac{1}{2} a_{c_m} t_m^2 \right)^2}$$

where $M$ denotes the number of transmitted pulses. The instantaneous slant range of moving target for the first spatial channel $R_1(t_m)$ is given by [14, 15]

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The slant range of moving target for the second spatial channel $R_2(t_m)$ can be expressed as (see (5))

For stationary clutter, there is only quadratic phase term and no linear phase term. However, for a moving target, it is seen that both linear and quadratic terms exist and along-track velocity together with cross-track acceleration appears in the quadratic coefficient.

3 SAR imaging algorithm and GMTI based on CS

Fig. 2 shows the transmitted and received reflected echoes for conventional SAR. where $\theta_s$ denotes the squint angle. For stationary clutter, range migration is not considered in this paper for convenience. We assume that no more than $N_0$ scattering centres can be distinguished in the synthetic aperture time $T_0$, the signal after range compression received by the first channel can be written as

$$s(t, t_m) = \sum_{i=1}^{N_0} B \sigma_i \text{sinc} \left( \Delta B \left( t - \frac{2R_B}{c} \right) \right) \exp \left( -j \frac{4\pi R_B}{\lambda} \right)$$

$$w_a(t_m - t_c) \exp \left( j 2\pi f_{dc} (t_m - t_c) \right) + j \pi R_B (t_m - t_c)^2$$

$$(6)$$

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![Fig. 1 Slant-range history geometry of the moving target](image1)

![Fig. 2 Transmit and receive pulses for conventional SAR in the azimuth](image2)
where \( f_{dc} \) and \( t_c \) are the Doppler centroid frequency and Doppler centroid time of the stationary scattering centre, respectively. \( \gamma_{m}(R_B) \) is the corresponding Doppler chirp rate. For the moving target, we have \( f_{dc} = 2v_c/\lambda \) and \( \gamma_{m}(R_B) = -2(\nu - v_c)^2/aR_B \). For a given range bin data, (6) can be rewritten as

\[
s(t_m) = \sum_{i=1}^{N_a} s_i w_a(t_m - \nu^{(i)}_a) \times \exp\left(i2\pi f_{dc}^{(i)}(t_m - \nu^{(i)}_c) + j\pi \gamma^{(i)}_m(R_B)(t_m - \nu^{(i)}_c)^2\right)
\]

(7)

where 
\[
s_i = B \sigma_i \text{sinc}\left(\Delta B \left(t - \frac{2R_c}{c}\right)\right) \exp\left(-\frac{4\pi}{\lambda} R_B\right).
\]

According to (7), the measurement matrix of the stationary clutter is constructed as (see (8))

The measurement matrix is constructed by the transmitted signal and it captures the contribution to the received signal of a point target. The column vectors are the samples of the transmitted signal waveform which consists of a chirp signal. Since the autocorrelation of the chirp signal is relatively low, the orthogonality of the column of measurement matrix has been verified in [16]. It can be well observed that the measurement matrix is almost the identity and satisfies the restricted isometric property (RIP) [16].

Owing to the fact that target motion parameters are unknown and the Doppler centroid of clutter is zero for the sidelaooking radar with zero squint angle \( \theta_0 \), \( s_0(t_m) = i\chi(t) \) can be set as (see (9))

\[
\gamma_{m}(R_B) = -\frac{\left(2-v_c^2\right)}{\lambda(R_B)}.
\]

where \( \gamma_{m}(R_B) = -\left(2-v_c^2\right)\lambda(R_B) \), \( T_1 \) is the full synthetic aperture time, \( \Delta t = 1/\Delta f_c \) (\( \Delta f_c \) is the Doppler bandwidth with full sampling data), \( N \geq (T_0 + T_1)/\Delta t \) and \( M \) is usually far less than \( N \). Let \( s = [s(t_1), s(t_2), \ldots, s(t_M)] \) and \( \rho = [\rho_1, \rho_2, \ldots, \rho_{M-1}, \rho_M] \), then (7) can be written in a simplified form as

\[
s_{M \times 1} = \Phi_{M \times N} \rho_{N \times 1}
\]

(10)

where \( s_{M \times 1} \) is the received data for a given range bin after range compression, \( \rho_{N \times 1} \) is the complex image for a range bin and \( \Phi_{M \times N} \) is the measurement matrix which is associated with the sampling mode. Equation (10) is an ill-conditional question with infinite solutions. However, according to the RIP [3, 4], if every set of sensing matrix columns with cardinality less than the sparsity of signal is satisfied, the measurement matrix satisfies the RIP principle, the sparse vector \( x_{N \times 1} \) can be recovered by the \( l_1 \) norm optimisation. Then the solution to (10) can be achieved by [13]

\[
\min \|x\|_{l_1} \quad \text{s.t.} \quad s = Ax = \Phi \Psi x
\]

(11)

In the presence of noise, (11) is transformed as

\[
\min \|x\|_{l_1} \quad \text{s.t.} \quad \|s - Ax\|_{l_2} \leq \varepsilon
\]

(12)

where \( \varepsilon \) is determined by the level of noise energy. According to the Lagrange multiplier method, the optimisation problem (12) can be rewritten as

\[
x = \arg \min \left\{ \|x\|_{l_1} + \lambda \|s - Ax\|_{l_2} \right\}
\]

(13)

where \( \lambda \) is also determined by the noise energy. The sparse vector can be retrieved by the optimisation problem (13) and the recovered complex image of the scene for a given range cell can be formulated as

\[
\rho_{N \times 1} = \Psi_{N \times N} x
\]

(14)

If all range cells data after range compression are operated by (14), the whole SAR imaging of the scene can be achieved. In practical applications, when the reflectivity of the scene cannot satisfy the sparse condition in the space domain, we should make great effort to seek the suitable sparse matrix in other transformation domains. If the coefficients of stationary clutter satisfy \( \rho_{N \times 1} = \Psi_{N \times N} x_{N \times 1} \), which indicates that the coefficient is sparse under the basis matrix \( \Psi_{N \times N} \), we can also exactly obtain the SAR image by CS. It is confirmed that the ground coefficients have lower information potentially [17]. That means the information can be sparsely represented in certain transformed domain to make the CS available in SAR, although these scatters are not distributed dispersely. It is well known that the magnitude of the SAR image contains speckle noise. In addition, the phase of the image can also be modelled as uniform white noise. Owing to the noise-like properties, we can use the joint magnitude and phase wavelet representation method to sparsely represent the complex-valued SAR image. We can also adopt other sparse matrices to represent the SAR images, such as discrete cosine transform (DCT), which is suitable for the textures with periodic property in the SAR magnitude image. If the scene can be represented as a combination of some shapes such as points, lines and so on, then a more efficient sparse matrix can be constructed by collecting all possible positions of the fundamental elements in the sparse representation matrix.

It is known that wavelet has a good local property in space/frequency domain. Since the widely application and the sparse decomposition property, the processing based on wavelet has been replaced the DCT or

\[
\Phi = \left[ s_0(t_m + N/2 - \Delta t), \ldots, s_0(t_m + N/2), s_0(t_m + N/2 + \Delta t), \ldots, s_0(t_m + N - \Delta t) \right]_{M \times N}
\]

(8)

\[
s_0(t_m - i\Delta t) = \begin{cases} 
\exp\left[i\pi \gamma_{m}(R_B)(t_m - i\Delta t)^2\right] & |t_m - i\Delta t| \leq \frac{T_1}{2} \\
0 & |t_m - i\Delta t| > \frac{T_1}{2}
\end{cases}, \quad i \in \left\{ -\frac{N}{2} + 1, \ldots, 0, \ldots, \frac{N}{2} \right\}
\]

(9)
other coding technology for stationary imaging processing. Some previous work has established that the wavelet transform can sparsely represent natural scene images [18]. Wavelet transform has been widely used in image analysis, noise reduction and data compression in SAR images because of their multiresolution decomposition [19]. In this paper, the sparse decomposition theory based on Daubechies wavelet transform is adopted for the sparse representation of stationary clutter. We use the Daubechies wavelet basis \( w_N \times N \) to construct the sparse matrix, and then we have \( A_M \times N = \Phi_M \times N \times W_M \times N \). According to formulae (6), (7), (8) and (9), we obtain

\[
\rho_i = Br_i\text{sinc} \left( \Delta B \left( t - \frac{2R_B}{c} \right) \right) \exp \left( -\frac{4\pi}{\lambda} R_b \right) \\
\times \exp \left( j\frac{2\pi^2 R_b}{\lambda^2} \right) \\
\]  

(15)

Similarly, the image of the second spatial channel can also be exactly recovered. After clutter suppression, the residue signal is formulated as

\[
z_i = Br_i \left( 1 - \exp \left( j\frac{2\pi}{\lambda} \left( \frac{d}{v} \right) \right) \text{sinc} \left( \Delta B \left( t - \frac{2R_B}{c} \right) \right) \right) \\
\times \exp \left( -\frac{4\pi}{\lambda} R_b \right) \exp \left( j\frac{2\pi^2 R_b}{\lambda^2} \right) \\
\]  

(16)

The residue signal \( z_i \) is nearly zero for stationary clutter, whereas the value is non-zero for moving targets. More details for target signal after the clutter suppression can be found in [14]. If the scattering centres of background stationary clutter and moving targets are sparse, CS can be used to accomplish multi-channel SAR images, and clutter suppression can be achieved by (16). In real scenarios, the coregistration error influences the clutter suppression drastically. The internal clutter motion exists as a result of the long coherent processing interval in SAR mode system. The point spread functions differ from sensors. Therefore the clutter suppression method based on joint pixels processing is appropriate and robust to these deleterious factors [20].

### 3.1 Random sampling mode in the azimuth direction

In this mode, the slow time in the azimuth direction can be formulated as \( t_m \in \{ t_1, t_2, \ldots, t_M, t_M \} \), where \( t_m \) denotes the random sampling time. Different from conventional uniform PRF sampling mode, the pulses in azimuth is randomly transmitted and received, as shown in Fig. 3. For the randomly sampling mode, we adopt CS method to recover the image for each spatial channel, and then coregister all SAR images for all spatial channels. The joint pixel processing method is utilised to suppress stationary clutter [20]. We use multi-channel X band radar data to verify the effectiveness of the randomly sampling GMTI mode and compare the difference between the CS-based GMTI and conventional SAR imaging GMTI. The radar works at X-band with the wavelength 0.033 m and broadside mode. The experimental vehicles are trucks equipped with corner reflectors to achieve a large radar reflectivity. Other parameters are listed in Table 1.

![Random sampling mod](image)

**Table 1** System parameters for gmti experiment

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3.2 Subaperture processing mode in the azimuth direction

For the random sampling mode in the azimuth, the measurement matrix has a good RIP characteristic and then the data rate can be well reduced. However, for the random sampling mode, the engineering implementation becomes difficult and the Doppler parameters are difficult to estimate. The inaccurate Doppler parameters lead to the difficulty for the measurement matrix construction. Therefore in this section, we discuss the subaperture processing mode in the azimuth, as shown in Fig. 6. In this mode, the slow time can be formulated as (see (17))

\[ t_m \in \{ T, 2T, ..., KT, (L + K + 1)T, (L + K + 2)T, ..., (L + 2K)T, ..., \} \]

where \( T \) is the time interval between two pulses, \( K \) is the number of effective subaperture, \( L \) is the number of discarded pulses. The data rate can be reduced by subaperture processing in the azimuth. Similarly, the range compression should be performed by conventional matched filter. Meanwhile, the wavelet basis is used for the sparse matrix and then the reflectivity can be recovered by \( l_1 \) norm optimisation in the azimuth. In this mode, the Doppler parameters can be well estimated for each subaperture by some existing methods. In this way, the measurement matrix can be precisely formed by the estimated parameters and thus improve the quality of SAR imaging. In addition,
the subaperture mode can be easily implemented in available radar system without complex equipment setup.

We also use real measured data to verify the feasibility of the CS-based GMTI for the subaperture mode. Fig. 7a shows the SAR imaging with the data rate 70% and Fig. 7b is the residue after clutter suppression. From this figure, we observe that the moving targets can be well detected. Define the improvement factor (IF) as \( IF = \frac{SCNR_{out}}{SCNR_{in}} \). Fig. 8 shows the IFs comparison of six detected targets by the random sampling mode and subaperture sampling mode. From this figure, it is found that the performance of clutter suppression is slightly better than that in the random sampling mode. This is because of the fact that the measurement matrix constructed by the estimated Doppler parameters is more accurate than that in randomly sampling mode. Therefore the CS-based GMTI for the subaperture processing mode has some robustness. In this experiment, we use the conventional average cross-correlation coefficient approach and map drift methods to estimate the Doppler centroid and Doppler rate, respectively.

### 3.3 Wideswath GMTI mode

As shown, a good azimuth resolution requires short antenna to illuminate a long synthetic aperture which results in high

![Fig. 7](image1)

**Fig. 7** SAR image based on CS and clutter suppression for subaperture mode with data rate 70%

- a SAR image based on CS for subaperture mode
- b Clutter residue after clutter suppression

<table>
<thead>
<tr>
<th>System parameters</th>
<th>Values</th>
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![Fig. 8](image2)

**Fig. 8** IFs of the detected six targets

![Fig. 9](image3)

**Fig. 9** SAR image based on RD and CS for wideswath GMTI mode

- a SAR image based on RD for wideswath GMTI mode
- b SAR image based on CS for wideswath GMTI mode

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**Table 2** System parameters for simulations

<table>
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<th>System parameters</th>
<th>Values</th>
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Doppler bandwidth. This means that a high PRF is needed to sample the Doppler spectrum. In contrast, a low PRF is favourable to unambiguously image a wide swath ground scene illuminated by a small antenna. The higher the PRF is, the smaller the swath width becomes. The relationship between the maximum imaged swath $W_g$, the system parameters can be expressed by

$$W_g < \frac{c}{2 \sin \varphi \text{PRF}}$$

(18)

where $\varphi$ denotes the incident angle. The above formula gives an upper bound for the swath range width with a predetermined PRF.

Alternative SAR imaging modes makes the trade-off between the range and azimuth directions. The spotlight mode yields a high azimuth resolution, but the coverage is limited, while burst modes such as scanSAR and terrain observation with progressive scan-SAR provide a wide swath but give only a coarse resolution in the azimuth dimension. In burst modes operation, the antenna footprint is continuously switched between subswaths. As a result, the whole width is composed by all subswaths. However, the obtained wideswath is at the cost of a reduced illumination time per subswath and thus the azimuth resolution is relatively coarse. Burst mode GMTI system increases image swath by sensing multiple sub-swaths of coarsened resolution. It can provide wideswath GMTI. In order to increase the range width, the Doppler spectrum will be ambiguous with a low PRF. In this case, the SAR image cannot be well retrieved by conventional SAR imaging algorithms. Therefore for the wideswath GMTI, we use CS-based imaging approach to recover the unambiguous image for multiple spatial channels and the perform clutter suppression with multiple apertures.

We use simulated data experiments to demonstrate the validity and feasibility of the wideswath GMTI based on CS. The simulation parameters are listed in Table 2. Fig. 9 shows the SAR image based on RD algorithm and CS for wideswath GMTI mode, respectively. In the experiment, six static scattering centres and a moving scattering centre with cross-track velocity are simulated in different range and azimuth positions with low PRF. Fig. 9 shows the azimuth image of both scattering centres. It is seen that the moving target image has an azimuth deviation compared with the stationary clutter image. From Fig. 9a, it is seen that the stationary and moving targets are ambiguous in the azimuth direction whereas the image can be unambiguously recovered by CS as shown in Fig. 9b when the PRF is lower than the Doppler bandwidth. Fig. 10a and b give the recovered SAR images for two spatial channels by CS, respectively. Fig. 11 shows the moving target after clutter suppression. It is observed that the target can be well detected.

4 Conclusions

This paper is primarily addressing a new GMTI approach with low data rate based on CS. In the proposed method, the sampled raw SAR data can be reduced significantly in the azimuth direction (such as randomly sampling and subaperture sampling). This means the PRF can be lower than the Doppler width to obtain the wide range swath GMTI. In the proposed CS-based GMTI algorithm, the wavelet basis is utilised to form the sparse matrix. The SAR image can be unambiguously recovered by CS for each spatial channel and then the clutter rejection can be well performed. The effectiveness and practicability of this wideswath GMTI approach are verified by real measured and simulated SAR data. In practical applications, it should
be noted that the platform motion error is inevitable. Further study will be turned to robust wide swath GMTI method based on CS, including CFAR algorithms.

5 Acknowledgment

This work was supported by the National Nature Science Foundation of China (NSFC) under grant nos. 61101249, 61101243 and 60825104, and the Fundamental Research Funds for the Central Universities under grant no. K50510020014 as well as the Programme for Cheung Kong Scholars and Innovative Research Team in University (PCSIRT, IRT0954).

6 References
