Robust Clutter Suppression and Radial Velocity Estimation for High-Resolution Wide-Swath SAR-GMTI

Zhenning Zhang 1,2, Weidong Yu 1,2,*, Mingjie Zheng 2, Liangbo Zhao 3 and Zi-Xuan Zhou 1,2,

1 Department of Space Microwave Remote Sensing System, Aerospace Information Research Institute, Chinese Academy of Sciences, Beijing 100094, China; zhangzhenning17@mails.ucas.ac.cn (Z.Z.); zhouzixuan17@mails.ucas.ac.cn (Z.-X.Z.)
2 School of Electronics, Electrical and Communication Engineering, University of Chinese Academy of Sciences, Beijing 100049, China; zhengmj@mail.ie.ac.cn
3 Institute of Remote Sensing Satellite, CAST, Beijing 100094, China; zhao_lb@hitwh.edu.cn
* Correspondence: ywd@mail.ie.ac.cn

Abstract: Moving targets are usually smeared and imaged at incorrect positions in synthetic aperture radar (SAR) images due to the target motions during the illumination time. Moreover, a moving target will cause multiple artifacts in the reconstructed image since pulse repetition frequency (PRF) operated in high-resolution wide-swath (HRWS) SAR is very low. In order to reliably indicate moving targets, a robust cancellation algorithm is derived in this paper for clutter suppression in multichannel HRWS SAR, which is free by velocity searching and covariance matrix estimation of clutter plus noise. The proposed multilayer channel-cancellation combined with the deramp processing is designed to sequentially suppress the seriously aliased clutter in HRWS SAR. Experimental results show that the proposed algorithm is efficient and robust in tough situations, and have a superior detection ability in weak targets and low-velocity targets. In addition, the radial velocity estimation algorithm combined with the channel cancellation is exploited to relocate moving targets. The effectiveness of the proposed algorithms is validated by actual spaceborne SAR data acquired by a coordination experiment with two controllable vehicles.

Keywords: deramp; high-resolution wide-swath (HRWS); ground moving target indication (GMTI); multilayer channel-cancellation; radial velocity; synthetic aperture radar (SAR)

1. Introduction

Synthetic aperture radar (SAR) is a powerful remote sensing technique that is capable of providing high-resolution images independent of sunlight illumination and has intensively been investigated for both civil and military applications [1–8]. In recent years, multichannel SAR has attracted more and more attention for their abilities of providing high-resolution wide-swath (HRWS) images [9–13] and ground moving target indication (GMTI) [14–18]. Multiple antennas placed along the azimuth direction has been presented to effectively deal with the conflict between high resolution and low pulse repetition frequency (PRF), which has been encountered in HRWS SAR imaging. Moreover, the spatial degrees of freedom in azimuth can also be utilized to suppress the background clutter, indicating a great potential of GMTI capability.

However, achieving GMTI in HRWS SAR systems faces some serious issues. First, there is an additional Doppler shift of the moving target compared with that of the stationary scene, causing the moving target to be dislocated, and the spectrum reconstruction cannot be performed correctly without a priori knowledge of the accurate motion parameters [11,19–22]. Therefore, a moving target will produce multiple artifacts in a reconstructed SAR image, covering stationary targets and misleading the interpretation. The classical along-track interferometry (ATI) [23,24] have been widely used in motion parameter estimation, which implements the conjugate multiplication of two spatially co-registered
channels with high computational efficiency. However, it cannot be applied into under-sampled SAR data. An algorithm to estimate the motion parameters based on compressed sensing is proposed in [25], which theoretically works well for the data with low PRF, but suffers from heavy computational load and high requirements of signal-to-noise ratio (SNR), especially for spaceborne HRWS systems. The matched reconstruction filter bank is proposed in [21] to estimate the radial velocity as well, which in fact is also a searching and iteration operation, and it demands heavy computational load. Besides, the modified cross-correlation coefficient (MCCC) method specializes in motion parameter estimation in HRWS SAR systems, but it cannot deal with moving targets in an azimuth cell [26].

Second, it should be noted that the velocity estimation algorithms discussed above assume that the clutter has been suppressed. However, the clutter suppression is crucial when the moving target is submerged in a strong stationary scene, especially in the HRWS SAR systems with spectrum ambiguities. Displaced-phase-center antenna (DPCA) [27,28] implements the cancellation of two spatially co-registered channels to suppress clutter efficiently. Space-time adaptive processing (STAP) is developed for multichannel radar systems, which involves adaptively adjusting the space-time filter response in attempt at maximizing the output signal-to-clutter ratio (SCR) of the moving target [29–31]. Besides, the clutter suppression based on Kalman filtering [32], the iterative adaptive approach [33], and RELAX method [34] are developed for multichannel SAR-GMTI. Nevertheless, the conventional GMTI techniques above cannot achieve clutter suppression under the circumstance of the Doppler ambiguities caused by low PRF in HRWS SAR systems, and the STAP has a high computational requirement and needs a large amount of target-free homogeneous secondary data, which is hardly available in practice. Therefore, some modified algorithms such as extended DPCA (EDPCA) and Deramp-STAP are particularly exploited for HRWS SAR [35–37], which are also searching operations for the motion parameters to maximize the output SCR, leading to an unacceptable increase in computational load. In addition, the performance of these algorithms is greatly reduced, and the number of degrees of freedom required increases significantly when the sparsity of moving targets is not satisfied, and the signals of the moving targets are mixed into the estimation of the clutter covariance matrix [38,39].

Different from the current principle of adjustment of the space-time filter in the radial velocity searching, the multilayer channel-cancellation based on deramp processing [18,37,40] is proposed in this paper for HRWS SAR clutter suppression in tough situations [18,37,40], which is free by velocity searching and the target-free secondary data. First, the deramp processing is used to compress the Doppler bandwidth for both stationary and moving targets simultaneously by a phase multiplication in the azimuth time domain. The target signal can be converted into a monochromatic signal, and the artifacts can be removed. Moreover, multiple channels can be spatially co-registered by phase compensation based on the deramped frequency, providing a prerequisite of achieving the clutter suppression by channel cancellation. However, the deramping moves the deramped frequency of some monochromatic signals beyond the PRF limits, resulting in aliasing [40,41]. Furthermore, the low PRF in HRWS SAR systems causes the aliasing effects to be much more serious than that in usual stripmap SAR, and the subaperture method cannot address this issue [40–42]. Under theoretical derivations and analyses, the properties of clutter can be illustrated by the aliasing coefficient, which is defined to describe the aliasing time in this paper. Then, the multilayer channel-cancellation is developed for suppressing the aliased clutter sequentially, and each layer of cancellation can suppress the clutter with the specific aliasing coefficient according to the designed strategy of signal usage of multiple channels. All the aliased clutter can be suppressed when the required layer of channel cancellation is performed and moving targets will be retained in the final result. Experimental results show that the proposed algorithm has an excellent performance in tough situations in HRWS SAR-GMTI, and has a better detection ability in low-velocity targets and weak targets. Moreover, the proposed algorithm only takes several iterations of the Hadamard
product and subtraction of the signal matrices, and no velocity searching is required, which makes it more efficient than the adaptive processing.

After clutter suppression, the radial velocity estimation is the next key stage of GMTI. Since the moving target signals are different from the original signals after the multilayer channel-cancellation, the conventional radial velocity estimation algorithms may be unavailable. Therefore, we propose the radial velocity estimation algorithm combined with the channel cancellation. The moving target cannot be suppressed by multilayer channel-cancellation because its residual phase is affected by the radial velocity. Consequently, the basic principle is to find the correct residual phase of a moving target through one-dimensional searching in the azimuth-frequency domain, and the moving target can be suppressed well by channel cancellation after right compensation.

An experiment with controllable vehicles was successfully carried out to acquire the actual SAR data in October 2019 by Gaofen-3, which is developed by the Aerospace Information Research Institute, Chinese Academy of Sciences. Studies and processing results with the data are used to verify the effectiveness of the proposed algorithms.

The rest of this paper is organized as follows. In Section 2, the signal model of a moving target in multichannel HRWS SAR is introduced. The multilayer channel-cancellation algorithm based on the deramp processing is proposed in Section 3, and the requirements on system design are also included in this section. The radial velocity estimation algorithm is described in Section 4. In Section 5, simulation and actual SAR data processing results are provided to validate the effectiveness of the proposed algorithms. The concluding remarks are presented in Section 6.

2. Signal Model for Multichannel SAR-GMTI

Figure 1 illustrates the 3-D geometry of an \( N \)-channel HRWS SAR system \((N = 4)\) with a moving target in the observing scene. The platform moves with velocity \( V \) along the \( y \)-direction at altitude \( h \). Suppose the first channel is the reference channel. The reference channel transmits a signal, and the echoes are received by all channels. The azimuth length from the \( n \)th channel to the reference channel is denoted by \( d_n \), where \( n = 1, \ldots, N \). During the data collection of SAR systems, it is assumed that the moving target moves with a constant velocity \((v_t)\), including the cross-track velocity \((v_r)\) and along-track velocity \((v_a)\).

The instantaneous slant range between a moving target in the scene center and the \( n \)th channel is expressed as

\[
R_n(t_a) = \sqrt{(R_0 + v_r t_a)^2 + [(V - v_a) t_a + d_n]^2}
\approx R_0 + v_r t_a + \frac{[(V - v_a) t_a + d_n]^2}{2R_0}
\]

where \( t_a \) is the azimuth time (slow time), \( R_0 \) represents the nearest slant range. Then, the slant range of the moving target \((R_0, X)\) with azimuth position \( X \) can be expressed by \( R_n(t_a - t_c) \), where \( t_c \) represents the absolute zero Doppler time (the beam center crossing time) of the target, and satisfies \( t_c = X/(V - v_a) \). The round-trip instantaneous slant range of the moving target received at the reference and \( n \)th channel can be expressed as \( 2R_{\text{ref}}(t_a - t_c) \) and \( R_{\text{ref}}(t_a - t_c) + R_n(t_a - t_c) \), respectively.
The multichannel geometry of the radar echoes can be converted into multiple independent ones with a self-transmitted and self-received antenna by a constant phase compensation because the slant range is much longer than the along-track baseline. Therefore, each channel is assumed to be located at its effective phase center (EPC) [43]. After the EPC processing, the radar echo of the \( n \)th channel can be expressed as

\[
s_n(t_r, t_a) = s_{ref}(t_r, t + d_n/2V) \exp\{j\Delta\phi_{e,n}\}
\]  \hspace{1cm} (2)

where \( t_r \) is the range time (fast time), and \( \Delta\phi_{e,n} \) represents the channel mismatch in phase between the \( n \)th and the reference channel [44]. Since we take extra steps for channel calibration, the mismatches in phase and amplitude are not considered in this paper.

Assume that a linear frequency modulation waveform is transmitted from the reference channel. In addition, the scattering point model is adopted, and the complex reflection coefficient of points is assumed to be 1 in this paper. After range compression, the \( n \)th channel echo signal of the moving target, which is transformed into the range-frequency domain can be obtained as

\[
s_{n,mov}(f_r, t_a) = W_r(f_r)W_a(t_a - t_c)  
\cdot \exp\left\{-\frac{4\pi}{c}(f_c + f_r) \left[ R_0 + v_r(t_a - t_c) + \frac{[(V - v_a)(t_a - t_c) + d_n/2]^2}{2R_0} \right]\right\}
\]  \hspace{1cm} (3)

where \( f_r \) and \( f_c \) represent the range frequency and carrier frequency, respectively, \( c \) is the light speed, and \( W_r(\cdot) \) and \( W_a(\cdot) \) denote the range-frequency and azimuth-time window functions. Since the PRF in HRWS SAR systems is lower than the Doppler bandwidth,
the moving target signal after transforming into the azimuth-frequency domain can be expressed as

\[ S_{n,\text{mov}}(f_r, f_a) = \sum_{i=-N/2}^{i=N-1} W_r(f_r) \exp\{j\Phi_1(f_r)\} \exp\{-j2\pi(f_a + i\text{PRF})t_c\} \]

\[ \cdot W_{az}\left(f_a + \frac{2(f_c + f_r)}{c}\left(v_r - \frac{(V - v_a)^2 t_c + (V - v_a)d_n/2}{R_0}\right) + i\text{PRF}\right) \]

\[ \cdot \exp\left\{j\pi\frac{cR_0(f_a + i\text{PRF})}{2(V - v_a)^2(f_c + f_r)}\right\} \exp\left\{-j2\pi(f_a + i\text{PRF})\frac{d_n}{2V}\right\} \]

where

\[ \Phi_1(f_r) = \frac{4\pi}{c} (f_c + f_r) \left\{ R_0 + v_rt_c + \frac{(V - v_a)t_c - d_n/2}{2R_0}\right\} \]

\( N \) denotes the number of channels and Doppler ambiguity, \( f_a \) is the azimuth frequency, and \( W_{az}(\cdot) \) represents the azimuth-frequency window function.

From Equation (4), we can find that the signal of a moving target has a nonzero Doppler centroid in a SAR system with zero squint angle, which satisfies \( f_{dc} = -2(f_c + f_r)v_r/c \) with the cross-track velocity, hereinafter referred to as radial velocity. Then, the moving target signal cannot be reconstructed correctly without the known radial velocity, and the multiple artifacts will be produced, leading to the wrong interpretation of SAR images. Besides, the intractable issue is that the moving target signals cannot be extracted from the clutter before imaging and reconstructed separately even if the motion parameters are obtained. Consequently, the clutter suppression is the first essential processing stage.

### 3. Background Clutter Suppression

To address the issues discussed in Section 2, we propose a robust and innovative algorithm based on the deramp processing and multilayer channel-cancellation that can effectively suppress the background clutter in HRWS SAR systems without radial velocity searching.

#### 3.1. Deramp Processing

The azimuth deramp processing from the spectral analysis (SPECAN) fast SAR imaging [40,45,46] is utilized to remove the artifacts of stationary and moving targets caused by the low PRF in multichannel HRWS SAR systems, without a priori knowledge of the accurate motion parameters [37,40]. The Doppler bandwidth of a linear frequency modulation (FM) signal in \( n \)th channel can be compressed by a phase multiplication in the azimuth-time domain, and the deramp function can be expressed as

\[ S_{\text{deramp},n}(f_r, t_a) = \exp\left\{j\frac{4\pi}{c} (f_c + f_r) \frac{(V - v_a)t_a + d_n/2}{2R_0}\right\} \].

The frequency and time characteristics of a stationary target are shown in Figure 2a. The signals are ambiguous because of the low PRF. The deramp function is shown in Figure 2b, whose frequency rate is equal to the negative of targets. With this choice of frequency rate, the deramp processing can convert the target signal into a monochromatic signal, which is shown in Figure 2c. From Equation (5), it seems that \( v_n \) and \( R_0 \) of a specific moving target are needed, which is not available at this stage of processing. Fortunately, they will not affect the azimuth deramping and range cell migration (RCM) correction, which is analyzed in [18]. After multiplying Equation (5) to Equation (3), and performing the azimuth Fourier transform, the moving target signal of \( n \)th channel can be described as
\[ S_{n,\text{mov}}(f_r, f_a) = W_r(f_r) \exp\{-2\pi f_a t_c\} W_a \left( \frac{f_a + 2(f_c + f_r)}{c} - \frac{V - v_a}{v_r} \right) \frac{2}{R_0} \cdot \exp\left\{-j2\pi f_a t_c\right\} \]

\[ \cdot \exp\left\{-j \frac{4\pi(f_c + f_r)}{c} \left[ R_0 - v_t t_c + \frac{(V - v_a) t_c}{2R_0} \right] \right\} \]

where \( W_a(\cdot) \) represents the Fourier transform of \( w_a(\cdot) \).

\[ S_{n,\text{sta}}(f_r, f_a) = W_r(f_r) \frac{V^2 t_c}{2R_0} \exp\{-j2\pi f_a t_c\} \]

\[ \cdot \exp\{-j \Phi_2(f_r)\} \exp\left\{j \frac{4\pi(f_c + f_r)}{c} \frac{V t_c d_n}{2R_0} \right\} \]

where

\[ \Phi_2(f_r) = \frac{4\pi(f_c + f_r)}{c} \left( R_0 + \frac{(V t_c)^2}{2R_0} \right). \]

**Figure 2.** Frequency and time characteristics of a stationary target before and after the deramp processing in a multichannel HRWS SAR system, (a) the signals before the deramping, (b) the deramp function for the HRWS SAR, (c) the monochromatic signal after the deramping.

Figure 2c describes the target signals in the deramped frequency domain. It should be noted that the Doppler bandwidth of stationary and moving targets can be compressed, whereby the target signal is converted into a monochromatic signal (i.e., a sine wave) with the deramped frequency proportional to the position of the signal in the input array. Both moving and stationary targets are coarsely focused in the azimuth-frequency domain after the deramp processing, and the artifacts can be removed.

### 3.2. Multilayer Channel-Cancellation

It is well known that the DPCA algorithm applied into dual-channel SAR-GMTI is very efficient, using the cancellation operation of two spatially co-registered channels to achieve the clutter suppression [27,28]. However, the application of channel cancellation in multichannel deramped signals faces several essential issues, which are conducted in this section by thorough analyses and derivations.

In order to achieve clutter cancellation after the deramp processing, the spatial channel co-registration requires further compensation. The signal of a stationary target in the \( n \)th channel is utilized to analyze the phase compensation after the deramp processing, which is expressed as

\[ S_{n,\text{sta}}(f_r, f_a) = W_r(f_r) \frac{V^2 t_c}{2R_0} \exp\{-j2\pi f_a t_c\} \]

\[ \cdot \exp\{-j \Phi_2(f_r)\} \exp\left\{j \frac{4\pi(f_c + f_r)}{c} \frac{V t_c d_n}{2R_0} \right\} \]

where

\[ \Phi_2(f_r) = \frac{4\pi(f_c + f_r)}{c} \left( R_0 + \frac{(V t_c)^2}{2R_0} \right). \]
From $W_{\alpha}(\cdot)$, the azimuth envelope of a stationary target between channels is aligned. The last exponential term in Equation (7) is the difference between channels, which should be correctly compensated to achieve the spatial channel co-registration, and the term is defined as the residual phase in this paper. The actual antenna spacing $d_n$ can be easily obtained from the SAR system. In addition, we can see that the zero Doppler time $t_c$ of the specific target is related to the deramped frequency where the monochromatic signal is focused, which is shown in Figure 2c. The deramped frequency of a stationary target is defined as $f_{sta}$. Therefore, the $t_c$ can be acquired by

$$t_c = \frac{f_{sta}}{K_a} = \frac{2(f_c + f_r)}{c} \frac{V^2 t_c}{K_a R_0}$$

(8)

where $K_a$ represents the azimuth frequency rate of stationary targets. Then, the residual phase of the specific target in the $n$th channel can be expressed as

$$\Delta \Phi_n(t_c) = -\frac{4\pi(f_c + f_r)}{c} \frac{V t_c d_n}{2R_0}$$

(9)

The signal after the residual phase compensation is expressed as

$$S_{n,sta}^\prime(f_r, f_a) = S_{n,sta}(f_r, f_a) \exp\{j\Delta \Phi_n(t_c)\}$$

$$= W_r(f_r) \exp\{-j2\pi f_a t_c\} \exp\{-j\Phi_2(f_r)\} W_{\alpha} \left( f_a - \frac{2(f_c + f_r)}{c} \frac{V^2 t_c}{R_0} \right)$$

$$= S_{m,sta}^\prime(f_r, f_a) \exp\{j\Delta \Phi_m(t_c)\}$$

$$= S_{m,sta}^\prime(f_r, f_a).$$

From Equation (10), it is clear that the residual phase between the $n$th channel and $m$th channel is compensated, and the spatial co-registration is achieved. Therefore, the clutter can be suppressed by the channel cancellation in the deramped frequency domain. However, the deramped frequency of a moving target is affected by its zero Doppler time and radial velocity from Equation (6), which can be expressed as

$$f_{mov} = \frac{2(f_c + f_r)}{c} \frac{(V - v_a)^2 t_c}{R_0} - \frac{2(f_c + f_r)}{c} \frac{V r}{R_0}$$

$$= K'_d t_c - \frac{2(f_c + f_r)}{c} \frac{V r}{R_0}$$

(11)

where $K'_d$ represents the azimuth frequency rate of the moving target. Then, the zero Doppler time of the moving target is obtained as $t_{mov} = f_{mov} / K'_d$, and the signal after the residual phase compensation can be expressed as

$$S_{n,mov}^\prime(f_r, f_a) = S_{n,mov}(f_r, f_a) \exp\{j\Delta \Phi_n(t_{mov})\}$$

$$= W_r(f_r) \exp\{-j2\pi f_a t_c\} \exp\left\{ \frac{4\pi(f_c + f_r)}{c} \frac{V (t_c - t_{mov}) d_n}{2R_0} \right\}$$

$$\cdot W_{\alpha} \left( f_a + \frac{2(f_c + f_r)}{c} \frac{V r}{R_0} - \frac{2(f_c + f_r)}{c} \frac{(V - v_a)^2 t_c}{R_0} \right)$$

$$\cdot \exp\left\{ -j \frac{4\pi(f_c + f_r)}{c} \left( R_0 + v_r t_c + \frac{(V - v_a)^2 t_c}{2R_0} \right) \right\}. \quad (12)$$

From Equation (12), the last exponential term related to the channel spacing cannot be removed, so the moving target will be retained in the final result after the cancellation. Based on the above analyses, the basic conclusion we can draw is that clutter suppression can be achieved by the channel cancellation in the deramped frequency domain for HRWS SAR-GMTI. Nevertheless, the channel cancellation with deramp processing is not ideal, as
discussed in the aforementioned content, and it cannot be directly applied into multichannel HRWS SAR-GMTI. The crucial issue is aliasing effects caused by the deramp processing and the low PRF, and it will be more serious in HRWS SAR than that in usual stripmap SAR. In this part, we analyse the aliasing effects in detail and give an innovative solution to address this serious issue.

From Equations (6) and (7), one can conclude that the absolute deramped frequency of a target is determined by its zero Doppler time, which is proportional to the distance from the azimuth center. Therefore, the deramped frequency of some targets in a whole synthetic aperture time will be beyond the PRF limits, which is illustrated by Figure 3. Figure 3a describes the frequency and time characteristics of multiple stationary targets in a synthetic aperture time in multichannel HRWS SAR. The deramp function is shown in Figure 3b, and the compression result after the deramping is shown in Figure 3c. The deramp function multiplication moves the deramped frequency of some targets beyond the PRF limits (the dashed lines), resulting in serious aliasing, and the solid lines are the monochromatic signals with aliased deramped frequency. The subaperture technique [40–42] cannot address this issue.

Figure 3. Frequency and time characteristics of multiple stationary targets in a whole illumination time, before and after the deramp processing in a multichannel HRWS SAR system, (a) the signals of 9 targets before the deramping, (b) the deramp function, (c) the aliased signals of 9 targets after the deramping.

Consequently, the deramped frequency that we can observe and obtain is the fractional PRF part of the deramped frequency. We use a prime to distinguish it from the absolute deramped frequency, namely \( f'_{\text{sta}} \), and the aliasing number is unknown, which is shown...
in Figure 3. Then, the residual phase compensation which is dependent on $t_c$ cannot be implemented correctly, resulting in failure of the spatial co-registration and channel cancellation.

Moreover, the PRF of a multichannel HRWS SAR system is much lower than the Doppler bandwidth, so the aliasing effects are much more serious than that in the stripmap SAR. After the deramping, targets that in the edges of the observed scene will be aliased for multiple times in the azimuth-frequency domain, which is illustrated in Figure 3c, i.e.,

$$S_{\text{n,sta}}(f_r, f_a) = W_t(f_r)W_a\left(f_a - \left(\frac{2(f_c + f_r)}{c} V_t'_{c} + A \cdot \frac{\text{PRF}}{2}\right)\right)$$

$$\cdot \exp\{-j\Phi_2(f_r)\} \exp\{-j2\pi f_a t_c\} \exp\left\{j\frac{4\pi(f_c + f_r) V_{t'd_n}}{c} \right\} \cdot \exp\{-\frac{j\Phi_2(f_r)}{2}\}$$

(13)

where $A = \lfloor 2K_a t_c / \text{PRF} \rfloor$ is defined as the aliasing coefficient, which can be positive or negative, and $\lfloor \cdot \rfloor$ is the floor function. $t'_c$ is baseband zero Doppler time of the target, which is obtained by

$$t'_c = t_c - A \cdot \text{PRF} / K_a.$$  

Figure 4 shows the aliasing effects after the deramp processing with 10 stationary targets in an $N$-channel HRWS SAR system ($N = 5$), and the PRF is about one-fifth of the Doppler bandwidth. We can see that the largest aliasing coefficient is 4. all the targets (green points) are focused in the same azimuth cell in the visible frequency domain, and so are the red targets. The targets with the aliasing coefficient $A = \pm 4$ are aliased for four times, and the fifth layer of the channel cancellation is needed to suppress them. With the non-aliased targets, the required layer of the channel cancellation is equal to the Doppler ambiguity.

However, the deramped frequency of a target that we can obtain directly after the deramping is always $f'_{\text{sta}}$, which is shown in Figure 3c, and the baseband zero Doppler time can be obtained by

$$t'_c = \frac{f'_{\text{sta}}}{K_a}.$$  

(14)

The residual phase compensation for the first layer of channel cancellation is defined as

$$\Delta \varphi_{n,1}(t'_c) = -\frac{4\pi(f_c + f_r) V_{t'd_n}}{c} \cdot \frac{2R_0}{\text{PRF}}.$$  

(15)
The residual phase of the targets, which is not aliased \((A = 0\) clutter) can be correctly compensated, and it can be suppressed by the first layer of channel cancellation. \([-\text{PRF}/2, \text{PRF}/2]\) is free by the \(A = 0\) clutter, but the other aliased targets are still retained. Then, the data without \(A = 0\) clutter of multiple channels is performed the second layer of channel cancellation to suppress the stationary targets with the aliasing of \(A = -1\) in \([-\text{PRF}, -\text{PRF}/2]\) (the blue area) and with the aliasing of \(A = 1\) in \([\text{PRF}/2, \text{PRF}]\) (the red area), which is shown in Figure 4. Two key points need to be considered carefully for the implementation of the second layer of channel cancellation, which is elaborated as follows:

First, clutter with aliasing coefficients (different signs and same modulus) must be processed separately. The absolute deramped frequency for the second layer residual phase can be obtained by \(f_{\text{sta,z,1}} = f'_{\text{sta}} \pm \text{PRF}\), which can be found in Figure 3c.

The absolute zero Doppler time of the aliased clutter with \(A = 1\) in Figure 4 (the red area in the range of channel cancellation II) can be obtained as

\[
t_{c,1} = \frac{f_{\text{sta},1}}{\text{PRF}} = t'_c + T_a
\]

where \(T_a\) is the illumination time. The absolute zero Doppler time of aliased clutter with \(A = -1\) in Figure 4 (the blue area in the range of channel cancellation II) is \(t_{c,-1} = t'_c - T_a\). Then, the absolute zero Doppler time of the second layer of channel cancellation is \(t_{c,\pm1} = t'_c \pm T_a\). Then, the residual phase for the second layer of channel cancellation is

\[
\Delta \Psi_{n,2}(t_{c,\pm1}) = -\frac{4\pi (f_c + f_r) V t_{c,\pm1} d_m}{c} \frac{1}{2R_0}.
\]

Second, the previous residual phase compensation will affect the subsequent cancellation, so the elimination of \(\Delta \Psi_{n,1}(t'_c)\) must be carried out on the data, which is processed by the first channel cancellation, before the second layer of channel cancellation. Consequently, the second layer of residual phase is \(-\Delta \Psi_{n,1}(t'_c) + \Delta \Psi_{n,2}(t_{c,\pm1})\).

The signal of the first layer of cancellation between the \(m\)th channel and \(m\)th channel is assumed to be \(S''_{n-m}(f_r, f_a)\), which is derived as

\[
S''_{n-m,\text{sta}}(f_r, f_a) = S'_{n,\text{sta}}(f_r, f_a) - S'_{m,\text{sta}}(f_r, f_a)
\]

\[
= \mathcal{W}_n(f_r) \exp \left\{-j \Phi_2(f_r) \exp \left\{-j 2\pi f_a t_c \right\} \right\}
\times \left\{\exp \left\{\frac{4\pi (f_c + f_r)}{c} \frac{V (t_c - t'_c) d_m}{2 R_0}\right\} - \exp \left\{\frac{4\pi (f_c + f_r)}{c} \frac{V (t_c - t'_c) d_m}{2 R_0}\right\}\right\}.
\]

The clutter with \(A = \pm 1\) cannot be suppressed by channel cancellation due to the obtained zero Doppler time. The second phase term is \(\exp \left\{j [-\Delta \Psi_{n,1}(t'_c) + \Delta \Psi_{m,2}(t_{c,\pm1})] \right\}\), and the signal after the second residual phase compensation can be obtained as

\[
S''_{n-m,\text{sta}}(f_r, f_a) = \mathcal{W}_n(f_r) \mathcal{W}_m(f_r) \exp \left\{j [-\Delta \Psi_{n,1}(t'_c) + \Delta \Psi_{m,2}(t_{c,\pm1})] \right\}
\]

\[
= S'_{n-m,\text{sta}}(f_r, f_a) \exp \left\{\frac{-4\pi (f_c - f_r)}{c} \frac{V (t_c + t'_c) d_m}{2 R_0}\right\}
\times \exp \left\{-j \Phi_2(f_r) \exp \left\{\frac{4\pi (f_c + f_r)}{c} \frac{V (t_c, \pm1 - t'_c) (d_n - d_m)}{2 R_0}\right\}\right\}.
\]

Assume that the other signals after the first layer of channel cancellation are obtained by the \(m\) th and \(k\) th channel. The signal after the second layer of residual phase compensation with \(\exp \left\{j [-\Delta \Psi_{m,1}(t'_c) + \Delta \Psi_{k,2}(t_{c,\pm1})] \right\}\) is obtained as
Remote Sens. 2022, 14, 1555

which means that adjacent channels are used for multilayer cancellations. It is a simple and practical strategy, which makes the residual phase of each channel to be obtained as:

\[
S_{m-k, \text{sta}}''(f_r, f_a) = S'_{m-k, \text{sta}}(f_r, f_a) \exp \left\{ j \left[ -\Delta \varphi_{m,1}(t'_c) + \Delta \varphi_{m,2}(t_{c,\pm 1}) \right] \right\}
\]

\[
= S'_{m-k, \text{sta}}(f_r, f_a) \exp \left\{ -j \frac{4\pi (f_c - f_r)}{c} V(t_{c,\pm 1} - t'_c) d_k \right\}
\]

\[
= W_r(f_r) W_a \left( f_a - \left( \frac{2(f_c + f_r)}{c} \frac{V^2 t'_c}{R_0} + A \frac{\text{PRF}}{2} \right) \right) \exp \left\{ -j 2\pi f_a t_c \right\}
\]

\[
\cdot \exp \left\{ -j \Phi_2(f_r) \right\} \cdot \exp \left\{ -j \frac{4\pi (f_c + f_r)}{c} V(t_{c,\pm 1} - t'_c)(d_m - d_k) \right\}.
\]

We can see that the difference between the signals with the second layer of residual phase compensation in Equations (19) and (20) is the last exponential term. To achieve the second layer of channel cancellation between \(S''_{n-m, \text{sta}}(f_r, f_a)\) and \(S''_{m-k, \text{sta}}(f_r, f_a)\), the condition can be described as

\[
d_n - d_m = d_m - d_k.
\]

Equation (21) is the signal usage strategy of multiple channels that must be satisfied before the implementation of multilayer channel-cancellation. The time interval between multilayer cancellation is a constant to obtain

\[
S''_{n-m, \text{sta}}(f_r, f_a) - S''_{m-k, \text{sta}}(f_r, f_a) = 0.
\]

The stationary targets with \(A = -1\) in \([-\text{PRF}, -\text{PRF}/2]\) and \(A = 1\) in \([\text{PRF}/2, \text{PRF}]\) can be suppressed by the second layer of channel cancellation. Now, \([-\text{PRF}, \text{PRF}]\) is free by the \(A = 0\), \(A = \pm 1\) clutter. The third layer of residual phase compensation is described as \(\exp\{ j(-\Delta \varphi_{m,2}(t_{c,\pm 1}) + \Delta \varphi_{m,3}(t_{c,\pm 2})) \}\). Keeping to the signal usage strategy of multiple channels according to Equation (21), the clutter with \(A = \pm 2\) can be effectively suppressed. Five layers of channel cancellation are required to suppress all the aliased and non-aliased clutter in the HRWS SAR system, and the clutter-free frequency range is \([-5\text{PRF}/2, 5\text{PRF}/2]\).

3.3. Implementation

Based on the aforementioned content, residual phase compensation for different channel-cancellation is essential for the proposed algorithm. In the \(n\)th channel, the \(m\)th layer of residual phase compensation is illustrated in Figure 5. Based on Equation (17), the residual phase is obtained by \(t_{c,\pm(m-1)} = t'_c \pm (m-1)T_{d} \). The sign before \(T_{d}\) can be determined from Figure 4. Since the clutter is aliased and spread over the whole image, the compensation of the residual phase is performed separately for each line of pixels, which is shown in Figure 5. The azimuth frequency of each line of pixels in the SAR image is used as the basis for obtaining the absolute Doppler time \(t_{c,\pm(m-1)}\). In addition, considering that the position of the deramped spectrum of a target may not be in the center of an azimuth cell, interpolation processing is an effective approach to obtain the precise deramped frequency, which will increase the computational load.

In order for fast implementation to occur, we design an optimization structure on the proposed algorithm. The signal usage strategy that we develop for the multilayer channel-cancellation in this paper is

\[
d_n - d_m = d_m - d_k = d,
\]

which means that adjacent channels are used for multilayer cancellations. It is a simple and practical strategy, which makes the residual phase of each channel to be obtained as:
\[
\Delta \phi_1 \left( t', c \right) = -\frac{4\pi (f_c + f_r)}{c} \frac{V t'_c d}{2R_0},
\]
\[
\Delta \phi_2 \left( t_{c, \pm 1} \right) = -\frac{4\pi (f_c + f_r)}{c} \frac{V t'_{c, \pm 1} d}{2R_0},
\]
\[
\Delta \phi_n \left( t_{c, \pm (n-1)} \right) = -\frac{4\pi (f_c + f_r)}{c} \frac{V t'_{c, \pm (n-1)} d}{2R_0},
\]
(24)

Figure 5. The implementation of the \( m \)th residual phase compensation for the \( n \)th channel.

From Equation (24), the residual phase for each channel is free of channel spacing \( d_n \). Then, all channels are grouped in pairs, and the residual phase compensation for a certain layer of channel cancellation is the same. Meanwhile, the residual phase of a same azimuth cell is consistent since the target signals are focused in the deramped frequency domain. Therefore, one-dimensional residual phase acquisition and compensation is performed in the actual SAR data processing, which can simplify the complexity of the proposed algorithm. The optimized processing structure of the proposed algorithm is shown in Figure 6. Stationary targets with a different aliasing coefficient is described by different colored dots, and moving target are represented by red dots. It is clear that stationary targets can be suppressed sequentially, and each layer of cancellation can suppress the clutter with specific aliasing coefficient.

3.4. Requirements on System Design

As analyzed in Section 3.2, the required layer of channel cancellation on a multichannel HRWS SAR system to suppress the aliased and non-aliased stationary targets is \( N \). Nevertheless, the maximum layer of channel cancellation that can be implemented is \( N - 1 \) for an \( N \)-channel SAR system. This is why there are 6 channels in Figure 6, although the maximum aliasing coefficient of the clutter is 4. Five layers of channel cancellation are required for suppressing all the aliased stationary targets.

To achieve the expected performance of the multilayer channel-cancellation, a constraint on the multichannel HRWS SAR system design to provide enough channel-cancellation layers is addressed in this subsection. Azimuth sampling ratio is defined to describe the relationship between the Doppler bandwidth and PRF, which is

\[
F_a = \frac{\text{PRF}}{B_{\text{dop}}},
\]
where $B_{dop}$ represents the Doppler bandwidth. Therefore, the PRF of an $N$-channel HRWS SAR, which satisfies

$$F_a \cdot (N - 1) > 1 \Rightarrow PRF > \frac{1}{N - 1} \cdot B_{dop},$$

(26)

guarantees that the Doppler ambiguity of a $N$-channel HRWS SAR system is $N - 1$. Therefore, the first solution to overcome the limitation is to adjust the system PRF, reducing the required layer of channel cancellation. $N - 1$ layers of channel cancellation can suppress the aliased clutter. The second solution is to use a redundant channel to satisfy the required layer of channel cancellation, which is illustrated in Figure 6. The resulting issue is an increase in system complexity.

Figure 6. According to Equation (21), signal usage strategy that we designed for the multilayer channel-cancellation in this paper for fast implementation with nine stationary targets and two moving targets in an HRWS SAR system.

In a spaceborne multichannel SAR system, the relation between the operating PRF and Doppler bandwidth is $N \cdot PRF \approx 1.3 \cdot B_{dop}$. Accordingly, a SAR with a large number of channels (at least 6 channels) has the ability to satisfy Equation (26) easily without any changes in system. Otherwise, increasing the PRF is an effective and cheap way for the proposed algorithm to suppress the aliased clutter in a SAR system with a small number of channels.

4. Radial Velocity Estimation

The clutter suppression is the first processing stage of GMTI. For better recognition and interpretation of SAR images, the next key issue that should be addressed is motion parameter estimation for relocating and imaging moving targets.
4.1. Basic Principle

Since signal properties of moving targets are changed after the multilayer channel-cancellation, the conventional estimation methods of the radial velocity fail. In this section, we develop an estimation algorithm of the radial velocity combined with the proposed channel cancellation. According to the analyses of the clutter suppression in Section 3.2, the essential of a moving target cannot be suppressed by the channel cancellation is that its zero Doppler time $t_{mov}$ obtained by the deramped frequency $f_{mov}$ is affected by the radial velocity, which is illustrated in Equation (11).

Different number of channels in SAR systems causes different signal expression forms after the required layer of cancellations, which makes the form complicated and impractical to derive. Therefore, minimizing the power of a moving target after the channel cancellation through residual phase searching is the basic principle of our radial velocity estimation algorithm, which can be written by

$$\min_{f_a} |\Delta S_{m,n}(f_r,f_a)|$$

with

$$\Delta S_{m,n}(f_r,f_a) = S^*_m,\text{mov}(f_r,f_a) - S^*_{n,mov}(f_r,f_a),$$

$$S^*_{m,mov}(f_r,f_a) = S_{m,mov}(f_r,f_a) \exp\left\{j\frac{2\pi(f_c + f_r)}{c} Vd_m \cdot \Delta F(f_a) \right\},$$

$$S^*_{n,mov}(f_r,f_a) = S_{n,mov}(f_r,f_a) \exp\left\{j\frac{2\pi(f_c + f_r)}{c} Vd_n \cdot \Delta F(f_a) \right\}$$

where $\Delta F(f_a)$ is defined as a step function of $f_a$. $\Delta F(f_a)/K'_a$ is the zero Doppler time searching for the moving target. When the correct residual phase is found and compensated, the moving target signals in the $m$th and $n$th channel can be expressed by

$$S^*_{m,mov}(f_r,f_a) = W_r(f_r) \exp\{-j2\pi f_at\} W_a\left(f_a + \frac{2(f_c + f_r)}{c} v_r - \frac{2(f_c + f_r)(V - v_a)^2 t_c}{R_0} \right)$$

$$\cdot \exp\left\{-j\frac{4\pi(f_c + f_r)}{c} \left(\frac{R_0 - v_rt_c + \frac{(V - v_a)t_r}{2R_0}}{2R_0} \right)^2 \right\}$$

$$= S^*_{n,mov}(f_r,f_a).$$

Then, the deramped frequency of the moving target can be obtained as

$$f_{mov} = -\frac{2(f_c + f_r)}{c} v_r + \frac{2(f_c + f_r)(V - v_a)^2 f_a}{R_0K'_a}$$

where $f_a$ represents the azimuth frequency corresponding to the minimum value of (27). The radial velocity can be obtained as

$$v_r = \frac{(V - v_a)^2 f_a}{R_0K'_a} - \frac{c f_{mov}}{2(f_c + f_r)}.$$  

It is important to note that Equation (33) is suitable for moving targets with small radial velocities. However, the deramped frequency caused by $t_c$ and $v_r$ may exceed the PRF/2, resulting in the incorrect acquisition of $f_{mov}$. To address this issue, our solution is to eliminate the part of deramped frequency caused by $t_c$ through a phase multiplication with $f_a$, which is expressed by
\[ \Delta S_{m,n}(f_r, f_a) = \Delta S_{m,n}(f_r, f_a) \exp \left\{ \frac{j 4\pi (f_c + f_r) (V - v_a)^2 f_a}{c R_0 K_a'} \right\} \]
\[ = W_r(f_r) \exp \left\{ j2\pi f_a t_c \right\} W_a \left( f_a + \frac{2(f_c + f_r)}{c} v_r \right) \cdot \exp \left\{ -j \frac{4\pi (f_c + f_r)}{c} \left( R_0 - v_r t_c + \frac{(V - v_a) t_c^2}{2R_0} \right) \right\}. \]

Now, the deramped frequency of Equation (34) is purely caused by the radial velocity, which can be obtained by \(-c f_{mov} / 2(f_c + f_r)\). Furthermore, the proposed algorithm has a good performance when moving targets are in the same range or azimuth cell since they are coarsely focused and can be extracted and processed separately.

Nevertheless, it is evident that the radial velocity estimation of moving targets needs two channels for cancellation. As discussed before, a redundant channel is needed to achieve the required layer of cancellation, and the final clutter suppression result contains only one set of data, which is shown in Figure 6. Therefore, another redundant channel is required to implement the channel cancellation for estimating the radial velocities of moving targets.

4.2. Radial Velocity Estimation Ambiguity and Maximum Unambiguous Radial Velocity

In this section, we will analyze the estimation ambiguity of the radial velocity. As we discussed before, the basic principle of the velocity estimation is residual phase searching for a moving target. The phase wrapping ambiguity will inevitably occur during the phase searching.

After the deramp processing, the residual phase of a moving target in the nth channel can be further approximated as

\[ \Delta \phi_{mov} = \frac{2\pi (V - v_a) t_c d_n}{\lambda R_0} \] (35)

where \( \lambda \) represents the wavelength. The phase wrapping ambiguity and the zero Doppler time of the moving target can be expressed as

\[ \Delta \phi_{mov} = 2\pi \Rightarrow t_c = \frac{\lambda R_0}{(V - v_a)d_n} \] (36)

The deramped frequency of the moving target is

\[ f_{mov} = \frac{-2(f_c + f_r)}{c} v_r + \frac{2(V - v_a)}{d_n} \] (37)

Therefore, if the search range of the residual phase is too large, the velocity ambiguity will occur in the estimation curve, which is \((V - v_a) / d_n \cdot \lambda\). In addition, the range of the deramped frequency that was purely caused by the radial velocity is \([-\text{PRF}/2, \text{PRF}/2]\) after the transformation in Equation (21), and the maximum unambiguous radial velocity can be easily obtained by \(v_{r,max} = \text{PRF} \cdot c / 4(f_c + f_r)\).

Figure 7 shows the flowchart of clutter suppression and radial velocity estimation for GMTI in an HRWS SAR system with the proposed algorithms. The channel calibration is the first step in the processing framework to balance the multiple channels. Second, the azimuth deramp processing is carried out on the multichannel range-compressed data according to Equation (5). The Doppler bandwidth of both moving and stationary targets are compressed, and the artifacts are removed. The third key step is to develop the signal usage strategy for the multilayer channel-cancellation according to Equation (21), which is essential for the proposed algorithm. Meanwhile, we determine the required layer of channel cancellation for aliased clutter suppression. After that, the proposed multilayer
channel-cancellation can be performed, including the compensation and elimination of the residual phase, channel cancellation. All the aliased clutter can be suppressed when the required layer of channel cancellation is reached. Then, the radial velocities of moving targets can be estimated by the clutter-free data with residual phase searching. Finally, the moving targets that are in their original location can be obtained.

Figure 7. The flowchart of the GMTI in a multichannel HRWS SAR systems with the proposed multilayer channel-cancellation and radial velocity estimation algorithm.

5. Experimental Results

5.1. Simulation Experiments

5.1.1. Point-target Experiments

In this section, we provide a simulation experiment of multiple targets with different aliasing coefficients to verify the correctness of the multilayer channel-cancellation. An $N$-channel HRWS SAR system is simulated ($N = 6$), whose main parameters are tabulated in Table 1. The azimuth sampling ratio is 0.22, and the biggest aliasing coefficient is 4, satisfying the condition of $(N - 1)PRF > B_{dop}$. Therefore, five layers of channel cancellation are required for suppressing all the aliased clutter. A total of 22 targets are generated in the observed scene, and the positions are shown in Figure 8a. A total of 20 stationary targets (black dots) with different aliasing coefficients are distributed in different colored areas. There are two moving targets (red dots) in the observing scene with opposite radial velocities, which are 4 m/s and $-3$ m/s.
Table 1. Main parameters of the simulated HRWS SAR system.

| Parameter             | Value       |
|-----------------------|-------------|
| Carrier frequency     | 5.40 GHz    |
| Platform velocity     | 7560 m/s    |
| Scene center range    | 873,589.97 m|
| Number of channels    | 6           |
| Range bandwidth       | 80 MHz      |
| Range sampling rate   | 100 MHz     |
| Doppler bandwidth     | 3572.4 Hz   |
| PRF                   | 785.9 Hz    |
| Azimuth sampling ratio| 0.22        |
| Receiving antenna length | 3.75 m    |
| Radial velocity of Target I | 4 m/s    |
| Radial velocity of Target II | −3 m/s  |

Figure 8. Target distribution and preliminary experiment results, (a) the distribution of simulated targets with different aliasing coefficients, (b) signals after the deramp processing in azimuth-frequency domain.

Clutter with all theoretical aliasing coefficients of a whole illumination time are included in the simulated scene, and the azimuth range of different aliasing coefficients are corresponded to the colored area in Figure 8a (the right label). The zero Doppler time of the stationary targets with the azimuth position \( X = ±4900 \) m is \( t_c = ±0.6481 \) s, and its deramped frequency is obtained as

\[
 f_{sta} = K_at_c = ±1781 \text{ Hz}.
\]  

(38)

The aliasing coefficients of the targets are \( \lfloor 2f_{sta} / \text{PRF} \rfloor = ±4 \), which needs the fifth layer of channel cancellation to suppress them. The zero Doppler time of the stationary targets with the azimuth position \( X = ±3920 \) m is \( t_c = ±0.5185 \) s, and its deramped frequency is obtained as ±1424.8 Hz. The aliasing coefficients are \( \lfloor 2f_{sta} / \text{PRF} \rfloor = ±3 \), which needs the fourth layer of channel cancellation to suppress them. Similar calculations can also be performed for other targets, which are omitted here.

Figure 8b shows that the Doppler bandwidth of stationary and moving targets in a channel is compressed by the deramp processing, and the artifacts are removed. Clutter with different aliasing coefficients is marked by colored boxes, which correspond to the colored area in Figure 8a, and the moving targets are marked by red ellipses. Then,
the multilayer channel-cancellation is performed after the residual phase compensation. Figure 9a shows that the suppression result of the first layer of channel cancellation, and the stationary targets with aliasing coefficient $A = 0$ are canceled. The moving targets and the other stationary targets with bigger aliasing coefficients are still retained. Figure 9b–e show the suppression results of the remaining channel-cancellation, showing that moving targets remained in the final result with any prior knowledge, and the stationary targets with different aliasing coefficients are suppressed sequentially. Table 2 describes the output SCR, input SCR and improvement factor (IF) [47] of the two moving targets, indicating that the proposed algorithm has an excellent clutter suppression performance in HRWS SAR-GMTI.

Figure 9. The processing results of multilayer channel-cancellation on simulated HRWS SAR data of point-target, which is shown in Figure 8, (a) the first layer of channel cancellation, (b) the second layer of channel cancellation, (c) the third layer of channel cancellation, (d) the forth layer of channel cancellation, (e) the last layer of channel cancellation.

Table 2. SCR and IF of the simulated moving targets.

| Moving Targets | SCR$_{after}$/dB | SCR$_{before}$/dB | IF/dB  |
|----------------|-----------------|------------------|--------|
| I              | 53.8905         | 0.0091           | 53.8996|
| II             | 51.6615         | 0.0089           | 51.6704|

5.1.2. Simulation Experiments with Real Data

Here, a simulated SAR data set, which has been derived starting from a spaceborne SAR (Gaofen-3) image covering three roads, is utilized to evaluate the effectiveness and performance of the proposed algorithms. The main parameters of this system are listed in Table 3. Since the PRF is bigger than the Doppler bandwidth and the data that belongs to the same channel cannot be used to suppress clutter by cancellation, we subsample the two-channel data to four-channel data, and the azimuth sampling ratio is 0.7. The simulated return from five targets, which are moving along the three roads has been added to the raw data set, which is shown in Figure 10. The velocity parameters of the five moving targets are listed in Table 4.
Table 3. Main parameters of the simulated HRWS SAR system.

| Parameter                  | Value       |
|----------------------------|-------------|
| Carrier frequency          | 5.40 GHz    |
| Platform velocity          | 7539 m/s    |
| Scene center range         | 898,741.06 m|
| Number of channels         | 2           |
| Range bandwidth            | 60 MHz      |
| Range sampling rate        | 66.67 MHz   |
| Doppler bandwidth          | 1781.3 Hz   |
| PRF                        | 2585.58 Hz  |
| Receiving antenna length   | 7.5 m       |

Table 4. Velocities of the simulated moving targets.

| Moving Targets | I     | II    | III   | IV    | V     |
|----------------|-------|-------|-------|-------|-------|
| $v_r$/m/s      | 12.0  | 10.0  | 6.0   | −8.0  | −5.0  |
| $v_a$/m/s      | 5.0   | 5.0   | 5.0   | 5.0   | 5.0   |

Based on Equation (26), two layers of channel cancellation are required to suppress all the aliased clutter in the scene. Figure 11 shows the processing results by the proposed algorithm. Figure 11a shows the deramp processing of a set of subsampled data. It can be seen that moving and stationary targets are coarsely focused, and the artifacts caused by the low PRF are removed. However, it is obvious that the aliasing effect appears in the deramped frequency domain. Figure 11b shows the first layer of channel cancellation result. The strong scatterers in the middle area such as highways are suppressed effectively. These are non-aliased signals ($A = 0$) because the zero Doppler time of these targets is small, which is consistent with the theoretical analysis. Figure 11c shows the second layer (the last layer) of the channel cancellation result, showing that the aliased clutter is suppressed effectively, and the simulated five moving targets are detected by Constant False-Alarm Rate (CFAR). Table 5 shows the input SCR, output SCR and IF of the simulated moving targets before and after the clutter suppression by the multilayer channel-cancellation, which indicates a good performance of the proposed algorithm in HRWS SAR-GMTI.
Figure 11. Processing result of the simulated moving targets in stationary scene in a 4-channel HRWS SAR system, (a) the deramp processing for a set of subsampled data, (b) the first layer of the channel cancellation, (c) the second layer (the last layer) of channel cancellation, (d) estimated results of the radial velocities of the five simulated moving targets.

Table 5. SCR and IF of the simulated moving targets.

| Moving Targets | SCR_{after}/dB | SCR_{before}/dB | IF/dB |
|----------------|----------------|-----------------|-------|
| I              | 35.24          | 9.18            | 26.06 |
| II             | 33.09          | 9.65            | 23.44 |
| III            | 26.73          | 7.37            | 19.36 |
| IV             | 29.00          | 9.01            | 19.99 |
| V              | 24.02          | 8.91            | 15.11 |

The velocity ambiguity of the Gaofen-3 is obtained as 55.81 m/s, and the maximum unambiguous radial velocity is obtained as 17.94 m/s according to the system parameters. Figure 11d shows the estimated results of the radial velocities of the five simulated moving targets through residual phase searching. The power of moving targets can be suppressed by cancellation if about 50 dB, which provides a good performance in indicating the correctness of the residual phase search of a moving target. Furthermore, the estimated radial velocities are very close to the theoretical values in Table 4.

In addition, two sets of experiments were implemented to illustrate that the proposed multilayer channel-cancellation has a better detection ability of the low-SCR targets and low-velocity targets compared to the conventional DPCA. Firstly, the detection of moving targets with low radial velocities is an essential point of the cancellation methods, since the power is greatly reduced by the channel cancellation. Minimum detectable velocity
(MDV) is usually used to evaluate the detection ability of low-velocity targets. Figure 12a shows the power variation of a moving target with different radial velocities and a constant backscatter coefficient before and after the processing of the DPCA and the proposed algorithm with the simulated HRWS SAR data. It can be seen that the proposed multilayer channel-cancellation can effectively reduce the MDV, indicating a better performance in low-velocity moving targets detection.

Secondly, another set of experiments were implemented to evaluate the detection ability of weak moving targets of the proposed algorithm. The radial velocity of the moving target is 8 m/s, which is bigger than the MDV. Figure 12b shows that the power variation of a moving target with different backscatter coefficients before and after the processing of the DPCA and the proposed algorithm. It is clear that the multilayer channel-cancellation also has a better detection ability in dealing with low-SCR targets.

![Figure 12](image-url) **Figure 12.** Experimental results and comparisons, (a) Comparisons of the power variation of a moving target versus radial velocity before and after clutter suppression by the DPCA and the proposed multilayer channel-cancellation, (b) Comparisons of power variation of a moving target (8 m/s) versus input SCR before and after clutter suppression by the DPCA and the multilayer channel-cancellation.

5.2. Experiments with Actual SAR Data

To validate the effectiveness and practicability of the proposed algorithms in tough situations, we successfully carried out a coordination experiment with two controllable vehicles in a complicated scene to acquire the actual SAR data in October 2019 by Gaofen-3 developed by the Aerospace Information Research Institute, Chinese Academy of Sciences, whose main parameters of the Gaofen-3 are tabulated in Table 6. The location that we selected for this experiment is the Jingliang Road, Beijing, China, which is shown in Figure 13a, and the numbers of vehicles and strong scatterers contained on this road. The red solid line represents the track of the Gaofen-3, and the angle with Jingliang Road is 81.6°. The incidence angle at the center of the road is 30.09°.
Figure 13. The actual scene of the coordination experiment with controllable vehicles, (a) the selected location (the Jingliang Road) for this experiment, and (b) the five corner reflectors on the ground near the road, (c,d) the two moving vehicles with corner reflectors.

Table 6. Main parameters of the Gaofen-3 system.

| Parameter               | Value          |
|-------------------------|----------------|
| Carrier frequency       | 5.40 GHz       |
| Platform velocity       | 7560 m/s       |
| Scene center range      | 858,961.53 m   |
| Number of channels      | 2              |
| Range bandwidth         | 60 MHz         |
| Range sampling rate     | 66.67 MHz      |
| Doppler bandwidth       | 1781.34 Hz     |
| PRF                     | 2356.05 Hz     |
| Azimuth sampling ratio  | 1.32           |
| Receiving antenna length| 7.5 m          |
| Ground velocity of vehicle I | 40 km/h       |
| Ground velocity of vehicle II | 56 km/h      |

In order to distinguish our vehicles from others, we placed multiple corner reflectors on them, which is shown in Figure 13c,d. The ground velocities of the two vehicles are 40 km/h and 56 km/h, which can be converted into radial velocities of 5.51 m/s and 7.62 m/s, respectively. The selection of the radial velocities is derived from the actual scene to ensure that no strong scatterers exist at the imaging position where the moving vehicles deviate due to the radial velocities. Besides, there are five corner reflectors on the ground that can be used as indicators and references, which is shown in Figure 13b. Since the PRF operated in the Gaofen-3 system during this experiment is bigger than the Doppler bandwidth, we subsampled the two-channel data to four-channel data, and the azimuth sampling ratio is 0.66. Therefore, two layers channel cancellation are required for suppressing the aliased clutter.

Figure 14 shows the processing results by two types of clutter suppression algorithms: (1) the adaptive processing method, (2) the cancellation methods. The adaptive algorithm contains the Deramp-STAP [37], and the cancellation algorithms contain the conventional DPCA and the proposed multilayer channel-cancellation. Moreover, since the DPCA cannot
be applied to the low-sampled data directly, its processing result comes from original oversampled data. The imaging result of the original SAR data is shown in Figure 14a, corresponding to the selected area marked by a blue rectangle in Figure 13a. The corner reflectors on the ground are marked by a red circle, and the two moving targets are marked by blue rectangles. Figure 14b shows the clutter suppression result by the DPCA in dealing with the two-channel oversampled SAR data. Figure 14c,d show the clutter suppression result by the Deramp-STAP and the proposed multilayer channel-cancellation, respectively. Besides, a moving train entered the observing scene during this experiment, and it is detected by the various algorithms, which are marked by purple rectangles.

**Figure 14.** Experimental results and comparisons, (a) the imaging result from the original SAR data, and selected location of this experiment (the Jingliang Road), the corner reflectors on the ground, which are marked by a red circle, and the two moving vehicles, (b) the conventional DPCA result based on the original SAR data, (c) the clutter suppression result by the Deramp-STAP based on the subsampled data, and (d) the clutter suppression result (after the second layer of channel cancellation) by the proposed algorithm based on the subsampled data.

From Figure 14, the GMTI results are similar, and the certain moving targets, such as our vehicles and the train are detected. However, there are some differences in the strong clutter suppression, the amplitude enhancement of moving targets, computational load, and the azimuth ambiguity suppression. The detailed quantitative analyses and performance comparisons are given below.

In the first analysis, we evaluate the GMTI performance of the algorithms. Figure 15 shows the extractions of vehicles I and II and a general moving vehicle on the Jingliang road. It should be noted that the azimuth resolution of the processing results from the Deramp-STAP and the proposed multilayer channel-cancellation are worse than the DPCA because of the subsample. From the previous discussions in Section 5.1.2, the proposed algorithm can effectively reduce the MDV of an HRWS SAR system, and it can be seen from Figure 15(d1–d3) that the amplitude enhancement of moving targets of the proposed algorithm is better than the conventional DPCA, even the adaptive processing, which is illustrated in detail by the slices in Figure 15(a5,b5,c5). In addition, Figure 16 illustrates the strong clutter suppression ability of the GMTI algorithms. Therefore, the input SCR, output SCR and IF of the two moving vehicles processed by the three algorithms can be obtained, which is shown in Table 7. The power of the corner reflectors on the ground is taken as the
clutter power. One can obtain that the performance of the adaptive processing is seriously degraded since abundant signals of moving targets are mixed in the clutter covariance matrix. It is clear from Table 7 that the proposed algorithm has an excellent performance for HRWS SAR-GMTI, which is not limited by the number of moving targets in the scene.

![Figure 15](image)

**Figure 15.** Comparisons of GMTI algorithms in moving target indication, (a1) the moving vehicle I before clutter suppression, (a2–a4) clutter suppression result by the DPCA, the Deramp-STAP and the proposed multilayer channel-cancellation, (a5) the slice of amplitude enhancement of the vehicle I by the three algorithms, (b1) the moving vehicle II before clutter suppression, (b2–b4) clutter suppression result by the DPCA, the Deramp-STAP, and the multilayer channel-cancellation, (b5) the slice of amplitude enhancement of the vehicle II, (c1) a general vehicle on the Jingliang Road, (c2–c4) clutter suppression result by the DPCA, the Deramp-STAP, and the multilayer channel-cancellation, (c5) the slice of amplitude enhancement of the general vehicle.

![Figure 16](image)

**Figure 16.** Comparisons of the suppression performance of strong clutter, (a1) a strong building on the road-side, (a2–a4) the suppression result by the DPCA, the Deramp-STAP and the proposed algorithm, (b1) the corner reflectors that we placed on the road-side, (b2–b4) the suppression result by the DPCA, the Deramp-STAP and the multilayer channel-cancellation.
Table 7. SCR and IF of the detected moving targets before and after clutter suppression through the proposed algorithm and the DPCA.

| Targets   | Algorithm                        | SCR<sub>after</sub>/dB | SCR<sub>before</sub>/dB | IF/dB |
|----------|----------------------------------|------------------------|-------------------------|-------|
| Vehicle I| DPCA                             | 6.83                   | 2.12                    | 4.71  |
|          | Deramp-STAP                       | 10.41                  | 8.29                    | 2.12  |
|          | Multilayer channel-cancellation   | 23.11                  | 20.99                   | 2.12  |
| Vehicle II| DPCA                            | 6.72                   | 7.69                    | 9.45  |
|          | Deramp-STAP                       | 11.08                  | 13.81                   | 2.73  |
|          | Multilayer channel-cancellation   | 25.80                  | 28.53                   | 2.73  |

In the second analysis, we will quantitatively compare the computational load of the proposed algorithm with other SAR-GMTI techniques. This is important to prove not only the effectiveness of the proposed algorithm but also its efficiency. The adaptive technique is optimum processing, which requires radial velocity searching, and the estimation and inverse of the interference covariance matrix, leading to an unacceptable increase in computational load. The proposed algorithm requires a small amount of iterations of matrix subtraction and multiplication, so the computational load is relatively low. Table 8 shows the computational time of the three algorithms with the same computing platform in dealing with the SAR data in Figure 14, indicating that the proposed algorithm is more efficient than the adaptive technique. Moreover, using the structure in Section 3.3 and parallel processing, the computational time of the proposed algorithm can be reduced to 3.77 s.

Table 8. Comparison of computational times of various algorithms and the proposed algorithm.

| Algorithms                        | Computational Times |
|-----------------------------------|---------------------|
| DPCA                              | 1.46 s              |
| Deramp-STAP                       | 103.04 s            |
| Multilayer channel-cancellation   | 13.78 s             |

In the third analysis, as shown in Figure 17a, the azimuth ambiguities (the area marked by green circles in Figure 14 caused by the side lobes of the antenna pattern degrade the quality of SAR images and leads to an increase of the false alarm rate of moving target detection in HRWS SAR systems [48–50]. The DPCA and the adaptive processing cannot address this issue, which are shown in Figure 17b,c. Based on the previous discussions, the aliasing property of the side lobes is similar to the main part of the signal, but with bigger aliasing coefficients. Consequently, use of redundant channels or raising the PRF is a viable way to suppress them. With the relatively high PRF of the experimental data set, the azimuth ambiguities can be removed through the multilayer channel-cancellation, which is illustrated by Figure 17d.

Figure 17. Comparisons of the algorithms in dealing with the azimuth ambiguities, (a) the azimuth ambiguities caused by the side lobes of the antenna pattern, (b–d) the processing result of the azimuth ambiguities by the DPCA, the Deramp-STAP, and the multilayer channel-cancellation.
The velocity ambiguity of the Gaofen-3 system is obtained as 55.81 m/s, and the maximum unambiguous radial velocity is obtained as 16.35 m/s. Figure 18 shows the moving target’s power curve after the channel cancellation with the residual phase searching. The power of the moving target can be suppressed by the cancellation about 70 dB when the residual phase is compensated correctly, which can very well indicate the correctness of the phase searching. The estimation results of radial velocity for the two moving targets are −5.37 m/s and −7.21 m/s, which are very close to the actual values. Furthermore, the retained moving targets are extracted and processed separately since the proposed estimation method is utilized in coarsely focused clutter-free data, indicating that this method is not limited by moving targets in the same azimuth and range cell, and that the computational load is not high.

![Figure 18](image_url)

**Figure 18.** The estimated results of the radial velocities of our moving vehicles by the proposed algorithm.

6. Conclusions

The multilayer channel-cancellation based on deramp processing is proposed in this paper for HRWS SAR clutter suppression in tough situations. The deramp processing is utilized to simultaneously remove the artifacts of stationary and moving targets caused by the low PRF in HRWS SAR. However, it results in serious aliasing effects of compressed spectrum due to the residual phase. The property of aliased clutter can be illuminated by aliasing coefficient, and it can be sequentially suppressed by the proposed multilayer channel-cancellation according to the designed signal usage of channels. The proposed algorithm has a very high computational efficiency because there is no need for clutter-plus-noise covariance matrix estimation and motion parameter search.

Furthermore, we also propose the radial velocity estimation algorithm combined with the multilayer channel-cancellation. Finally, the simulated data and actual SAR data from a coordination experiment with controllable vehicles are utilized to verify the practicability of our proposed algorithms. The processing results show that the proposed algorithm can effectively reduce the MDV and have an excellent performance in clutter suppression at a cost of few iterations in HRWS SAR-GMTI. In addition, the proposed algorithm is not only adapted to the nonuniform sampling case but also to the uniform sample case, which can enormously reduce the complexity of the system.

**Author Contributions:** Conceptualization, Z.Z. and M.Z.; methodology, Z.Z. and M.Z.; software, Z.Z.; validation, Z.Z.; formal analysis, Z.Z. and W.Y.; investigation, Z.Z. and M.Z. and Z.-X.Z.; resources, W.Y. and L.Z.; data curation, L.Z.; writing—original draft preparation, Z.Z.; writing—review and editing, W.Y.; visualization, Z.Z., M.Z. and W.Y.; project administration, W.Y. and M.Z.;
funding acquisition, W.Y. and M.Z. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was supported by the Civil Space Pre-Research Project under Grant D040114.

**Conflicts of Interest:** The authors declare no conflict of interest.

**References**

1. Jakowatz, C.V.; Wahl, D.E.; Eichel, P.H.; Ghiglia, D.C.; Thompson, P.A. Spotlight-Mode Synthetic Aperture Radar: A Signal Processing Approach; Kluwer: Norwell, MA, USA, 1996.

2. Cerutti-Maori, D.; Klare, J.; Brenner, A.R.; Ender, J.H.G. Wide-Area Traffic Monitoring with the SAR/GMTI System PAMIR. *IEEE Trans. Geosci. Remote Sens.* 2008, 46, 3019–3030. [CrossRef]

3. Baumgartner, S.V.; Krieger, G. Fast GMTI Algorithm For Traffic Monitoring Based on a Priori Knowledge. *IEEE Trans. Geosci. Remote Sens.* 2012, 50, 4626–4641. [CrossRef]

4. Gao, G.; Huang, K.; Gao, S.; He, J.; Zhang, X. Ship Detection Based on Oceanic Displaced Phase Center Antenna Technique in Along-Track Interferometric SAR. *IEEE J. Sel. Top. Appl. Earth Observ. Remote Sens.* 2019, 12, 788–802. [CrossRef]

5. Touzi, R. Target Scattering Decomposition in Terms of Roll-Invariant Target Parameters. *IEEE Trans. Geosci. Remote Sens.* 2007, 45, 73–84. [CrossRef]

6. Muhuri, A.; Manickam, S.; Bhattacharya, A. Scattering Mechanism Based Snow Cover Mapping Using RADARSAT-2 C-Band Polariometric SAR Data. *IEEE J. Sel. Top. Appl. Earth Observ. Remote Sens.* 2017, 10, 3213–3224. [CrossRef]

7. Zyl, J.J.v.; Zebker, H.A.; Elachi, C. Imaging radar polarization signatures: Theory and observation. *Radio Sci.* 1987, 22, 529–543.

8. Bhattacharya, A.; Muhuri, A.; De, S.; Manickam, S.; Frey, A.C. Modifying the Yamaguchi Four-Component Decomposition Scattering Powers Using a Stochastic Distance. *IEEE J. Sel. Top. Appl. Earth Observ. Remote Sens.* 2015, 8, 3497–3506. [CrossRef]

9. Gebert, N.; Krieger, G.; Moreira, A. Multichannel Azimuth Processing in ScanSAR and TOPS Mode Operation. *IEEE Trans. Geosci. Remote Sens.* 2010, 48, 2994–3008. [CrossRef]

10. Gebert, N.; Krieger, G.; Moreira, A. Multi-Channel ScanSAR for High-Resolution Ultra-Wide-Swath Imaging. In Proceedings of the 7th European Conference on Synthetic Aperture Radar, Friedrichshafen, Germany, 2–5 June 2008; pp. 1–4.

11. Gebert, N.; Krieger, G.; Moreira, A. Digital Beamforming on Receive: Techniques and Optimization Strategies for High-Resolution Wide-Swath SAR Imaging. *IEEE Trans. Aerosp. Electron. Syst.* 2009, 45, 564–592. [CrossRef]

12. Cerutti-Maori, D.; Sikaneta, I.; Klare, J.; Gierull, C.H. MIMO SAR Processing for Multichannel High-Resolution Wide-Swath Radars. *IEEE Trans. Geosci. Remote Sens.* 2014, 52, 5034–5055. [CrossRef]

13. Sikaneta, I.; Gierull, C.H.; Cerutti-Maori, D. Optimum Signal Processing for Multichannel SAR: With Application to High-Resolution Wide-Swath Imaging. *IEEE Trans. Geosci. Remote Sens.* 2014, 52, 6095–6109. [CrossRef]

14. Zhang, S.X.; Xing, M.D.; Xia, X.G.; Guo, R.; Liu, Y.Y.; Bao, Z. 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, 687–709. [CrossRef]

15. Yang, D.; Yang, X.; Liao, G.; Zhu, S. Strong Clutter Suppression via RPCA in Multichannel SAR/GMTI System. *IEEE Geosci. Remote Sens. Lett.* 2015, 12, 2237–2241. [CrossRef]

16. Guo, B.; Yu, D.; Xu, L.; Xue, M.; Li, J. Ground Moving Target Indication via Multichannel Airborne SAR. *IEEE Geosci. Remote Sens. Lett.* 2011, 49, 3753–3764. [CrossRef]

17. Suwa, K.; Yamamoto, K.; Tsuichida, M.; Nakamura, S.; Wakayama, T.; Hara, T. Image-Based Target Detection and Radial Velocity Estimation Methods for Multichannel SAR-GMTI. *IEEE Trans. Geosci. Remote Sens.* 2017, 55, 1325–1338. [CrossRef]

18. Sun, G.; Xing, M.; Xia, X.G.; Wu, Y.; Bao, Z. Robust Ground Moving-Target Imaging Using Deramp–Keystone Processing. *IEEE Trans. Geosci. Remote Sens.* 2013, 51, 966–982. [CrossRef]

19. Krieger, G.; Gebert, N.; Moreira, A. Unambiguous SAR signal reconstruction from nonuniform displaced phase center sampling. *IEEE Geosci. Remote Sens. Lett.* 2004, 1, 260–264. [CrossRef]

20. Jungang, Y.; Xiaotao, H.; Tian, J.; Thompson, J.; Zhimin, Z. New Approach for SAR Imaging of Ground Moving Targets Based on a Keystone Transform. *IEEE Geosci. Remote Sens. Lett.* 2011, 8, 829–833. [CrossRef]

21. Baumgartner, S.V.; Krieger, G. Simultaneous High-Resolution Wide-Swath SAR Imaging and Ground Moving Target Indication: Processing Approaches and System Concepts. *IEEE J. Sel. Top. Appl. Earth Observ. Remote Sens.* 2015, 8, 5015–5029. [CrossRef]

22. Cristallini, D.; Pastina, D.; Colone, F.; Lombardo, P. Efficient Detection and Imaging of Moving Targets in SAR Images Based on Chip Scaling. *IEEE Trans. Geosci. Remote Sens.* 2013, 51, 2403–2416. [CrossRef]

23. Gierull, C.H. Ground moving target parameter estimation for two-channel SAR. *Proc. Inst. Elect. Eng.—Radar Sonar Navig.* 2006, 153, 224–233. [CrossRef]

24. Suchandt, S.; Runge, H.; Breit, H.; Steinbrecher, U.; Bals, U. Automatic Extraction of Traffic Flows Using TerraSAR-X Along-Track Interferometry. *IEEE Trans. Geosci. Remote Sens.* 2010, 48, 807–819. [CrossRef]

25. Wu, Q.; Xing, M.; Qiu, C.; Liu, B.; Bao, Z.; Yeo, T.S. Motion Parameter Estimation in the SAR System With Low PRF Sampling. *IEEE Geosci. Remote Sens. Lett.* 2010, 7, 450–454. [CrossRef]

26. Zhang, Z.; Yu, W.; Zheng, M.; Zhou, Z.X. Doppler Centroid Estimation for Ground Moving Target in Multichannel HRWS SAR System. *IEEE Geosci. Remote Sens. Lett.* 2021, 19, 1–5. [CrossRef]
28. Lightstone, L.; Faubert, D.; Rempel, G. Multiple phase centre DPCA for airborne radar. In Proceedings of the 1991 IEEE National Aerospace Conference Digest, Crested Butte, CO, USA, 3–8 February 1991; pp. 1/1–1/28.

29. Klemm, R. Introduction to space-time adaptive processing. *Electron. Commun. Eng. J.* 1999, 11, 5–12. [CrossRef]

30. Ward, J. Space-Time Adaptive Processing for Airborne Radar; Tech. Rep. 1015; MIT Lincoln Lab.: Lexington, MA, USA, 1995.

31. Ender, J.H. Space-time processing for multichannel synthetic aperture radar. *Electron. Commun. Eng. J.* 1999, 11, 29–38. [CrossRef]

32. Yan, H.; Zheng, M.; Wang, R.; Gao, C.; Deng, Y.; Wang, C. Clutter suppression for multichannel wide-area surveillance systems via Kalman filtering. *IET Radar Sonar Navig.* 2013, 7, 246–254. [CrossRef]

33. Yardibi, T.; Li, J.; Stoica, P.; Xue, M.; Bagheroer, A.B. Source Localization and Sensing: A Nonparametric Iterative Adaptive Approach Based on Weighted Least Squares. *IEEE Trans. Aerosp. Electron. Syst.* 2010, 46, 425–443. [CrossRef]

34. Li, J.; Zheng, D.; Stoica, P. Angle and waveform estimation via RELAX. *IEEE Trans. Aerosp. Electron. Syst.* 1997, 33, 1077–1087. [CrossRef]

35. 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, 3868–3881. [CrossRef]

36. Cerutti-Maori, D.; Sikaneta, I. A Generalization of DPCA Processing for Multichannel SAR/GMTI Radars. *IEEE Trans. Geosci. Remote Sens.* 2013, 51, 560–572. [CrossRef]

37. Li, X.; Xing, M.; Xia, X.G.; Sun, G.C.; Liang, Y.; Bao, Z. Simultaneous Stationary Scene Imaging and Ground Moving Target Indication for High-Resolution Wide-Swath SAR System. *IEEE Trans. Geosci. Remote Sens.* 2016, 54, 4224–4239. [CrossRef]

38. Yan, H.; Wang, R.; Li, F.; Deng, Y.; Liu, Y. Ground Moving Target Extraction in a Multichannel Wide-Area Surveillance SAR/GMTI System via the Relaxed PCP. *IEEE Geosci. Remote Sens. Lett.* 2013, 10, 617–621. [CrossRef]

39. Zhang, X.; Liao, G.; Zhu, S.; Yang, D.; Du, W. Efficient Compressed Sensing Method for Moving-Target Imaging by Exploiting the Geometry Information of the Defocused Results. *IEEE Geosci. Remote Sens. Lett.* 2015, 12, 517–521. [CrossRef]

40. Cumming, I.G.; Wong, F.H. *Digital Signal Processing of Synthetic Aperture Radar Data: Algorithms and Implementation*; Artech House: Norwood, MA, USA, 2004.

41. Yang, J.; Sun, G.; Chen, J.; Mao, L.; Xing, M. A Subaperture Imaging Algorithm to Highly Squinted TOPS SAR Based on SPCAN and Deramping. In Proceedings of the 10th EUSAR, Berlin, Germany, 3–5 June 2014; pp. 1–4.

42. Li, N.; Bie, B.; Sun, G.C.; Xing, M.; Bao, Z. A High-Squint TOPS SAR Imaging Algorithm for Maneuvering Platforms Based on Joint Time-Doppler Deramp Without Subaperture. *IEEE Geosci. Remote Sens. Lett.* 2020, 17, 1899–1903. [CrossRef]

43. Gebert, N.; Krieger, G.; Moreira, A. Digital Beamforming for HRWS-SAR Imaging: System Design, Performance and Optimization Strategies. In Proceedings of the IEEE International Symposium on Geoscience and Remote Sensing, Denver, CO, USA, 31 July–4 August 2006; pp. 1836–1839.

44. Feng, J.; Gao, C.; Zhang, Y.; Wang, R. Phase Mismatch Calibration of the Multichannel SAR Based on Azimuth Cross Correlation. *IEEE Geosci. Remote Sens. Lett.* 2013, 10, 903–907. [CrossRef]

45. Moreira, A.; Mittermayer, J.; Scheiber, R. Extended chirp scaling algorithm for air- and spaceborne SAR data processing in stripmap and ScanSAR imaging modes. *IEEE Trans. Geosci. Remote Sens.* 1996, 34, 1123–1136. [CrossRef]

46. Mittermayer, J.; Moreira, A.; Loffeld, O. Spotlight SAR data processing using the frequency scaling algorithm. *IEEE Trans. Geosci. Remote Sens.* 1999, 37, 2198–2214. [CrossRef]

47. Rose, G.; Hoffman, J. Effect of leading edge jitter on MTI improvement factor. In Proceedings of the IEEE International Conference on Radar, Arlington, VA, USA, 7–10 May 1990; pp. 322–328.

48. Li, F.; Johnson, W. Ambiguities in Spaceborne Synthetic Aperture Radar Systems. *IEEE Trans. Aerosp. Electron. Syst.* 1983, AES-19, 389–397. [CrossRef]

49. Moreira, A. Suppressing the azimuth ambiguities in synthetic aperture radar images. *IEEE Trans. Geosci. Remote Sens.* 1993, 31, 885–895. [CrossRef]

50. Avolio, C.; Costantini, M.; Di Martino, G.; Iodice, A.; Macina, F.; Ruello, G.; Riccio, D.; Zavagli, M. A method for the reduction of ship-detection false alarms due to SAR azimuth ambiguity. In Proceedings of the 2014 IEEE Geoscience and Remote Sensing Symposium, Quebec City, QC, Canada, 13–18 July 2014; pp. 3694–3697.