Rotor blades blockage modulation suppression algorithm for helicopter-borne SAR

Wei Gao | Xiaoming Li | Zheng Liu | Ziqiang Meng | Xiaodong Han | Lei Ran

1National Laboratory of Radar Signal Processing, Xidian University, Xi’an, China
2Leihua Electronic Technology Research Institute, Aviation Industry Corporation of China, Wuxi, China
Correspondence
Zheng Liu, National Laboratory of Radar Signal Processing, Xidian University, Xi’an 710071, China.
Email: ls@xidian.edu.cn
Funding information
China Postdoctoral Science Foundation, Grant/ Award Number: 2018M642249

Abstract
There exists periodic modulation problem in radar echoes due to the main rotor blades periodic blockage in helicopter-borne fire-control radar which is mounted atop the main rotor mast of the helicopter. Such modulation echo induces a set of ghosts in synthetic aperture radar (SAR) image, further resulting in a poor performance of subsequent tracking and striking. To address this problem, this article proposes a method on rotor blades blockage modulation suppression for helicopter-borne SAR. By decomposing the blocked echo into the form of Fourier series in the azimuth direction, a reference function could be constructed to suppress the modulation directly by adopting an iterative approximation strategy. This method effectively avoids the complex blocked data recovery methods, and thus can be used to suppress various kinds of periodic modulation components without requiring certain distribution models. Both simulated and real-measured data are processed to demonstrate the effectiveness of the proposed algorithm.

1 | INTRODUCTION

Benefiting from great potential for detection and identification of ground targets, synthetic aperture radar (SAR) could be widely used in many platforms especially in the military field [1, 2]. With the ability of low altitude flight, vertical take-off and fast reaction, helicopter is an manoeuvrable platform for SAR imaging in army aviation detection. It can flexibly move in any direction, thus expending SAR imaging scope. As a host platform, the helicopter presents some challenges for high-resolution SAR imaging [3–5]. Currently, most research in helicopter SAR imaging focus on the platform vibration [6–9]. Some mathematical models of the platform vibration are established. Analyses of the error induced by helicopter platform vibration have been accordingly presented as well as its compensation to achieve a focussed image.

However, there exists another serious problem on the helicopter platform which should be solved besides the vibration one. For the armed helicopter, the radar is always mounted atop the main rotor mast to take advantage of terrain masking. This would cause echo signals which are blocked periodically along the azimuth time by the rotor blades rotation [10, 11]. When echo signals come in through the rotor blades, an electromagnetic shadowing effect is created as shown in Figure 1. As a result, periodic modulation occurs in radar echo signal, which can be described by three parameters: duration, periodicity and attenuation depth [12]. If not suppressed, such modulation will lead to serious ghost images in SAR imagery.

Currently, there are few studies directly concerning SAR imaging of the periodically blocked signal. Instead, many works mainly focus on SAR images from random incomplete data, including compressive sensing (CS) [13–16] and gapped-data amplitude and phase estimation (GAPES) [17, 18]. CS can be applied for the reconstruction of SAR images from data with random missing samples. One of the key aspects for the successful application of CS is that signal must satisfy the restricted isometry property (RIP) [19, 20]. Unfortunately, the periodically blocked signal does not conform to RIP. Reference [21] devises extensions of GAPES to scenarios with periodically gapped data for spectrum estimation and SAR imaging. However, the periodically gapped amplitude and phase estimation (PG–APES) method cannot be applied to practical SAR imaging as there are several practical issues to be studied further, including motion compensation and range migration compensation. In the absence of effective measurement for the periodically blocked signal compensation, one of the main
problems for the armed helicopter-borne SAR platform is the impact of the main rotor blades blockage on the imaging. Unfortunately, there are no appropriate solutions to this problem in the existing literature until now.

In this article, we present the demonstration of the ghost images on the armed helicopter-borne SAR. Our objective is to develop an efficient rotor blades blockage modulation suppression algorithm for the helicopter-borne SAR. This article draws on the thought that the periodically blocked signal could be decomposed into a set of Fourier series components [22]. After range pulse compression and motion compensation with respect to the scene centre, SAR echoes are expanded into the Fourier series along the azimuth direction. Then, the focussed ghost image is achieved by range and azimuth resampling procedures, whereas the azimuth interpolation is in a manner just the combination of the range cell migration (RCM) linearization and the keystone transform (KT) [23]. After the blocked echo focussing, the range bins which contain the clearest information about the modulation echo are identified and extracted [24, 25]. Subsequently, an approximate modulation function is estimated by adopting an iterative approximation strategy to estimate the coefficient of each decomposed harmonic component one by one. Finally, the acquired approximate function is used to remove the modulation echo in each range bin.

The rest of this article is organized as follows. Section 2 briefly introduces a helicopter-borne SAR signal model mounted atop the main rotor mast, and periodically blocked echo focussing on such platform is also described. Section 3 derives the theory of the rotor blades blockage modulation suppression algorithm based on the iterative approximation and describes the procedure of the proposed algorithm. In Section 4, the application results of the proposed algorithm to simulated and real-measured data are presented. Finally, Section 5 draws the conclusions.

2 SIGNAL MODEL AND PERIODICALLY BLOCKED ECHO FOCUSING OF HELICOPTER-BORNE SAR

2.1 Signal model

The geometry of the helicopter-borne fire-control SAR imaging is described in Figure 2. The helicopter flies along the axis OX with speed v. Let τ represent the slow time. The coordinate of the reference point is \((0, y_0, z_0)\) when \(t = 0\). \(\theta\) and \(\varphi\) are the instantaneous squint angle and the incidence angle, respectively. Denote \(\varphi_0\) as the reference incidence angle. \(R_i(t)\) is the distance between the radar phase centre and the scene centre (Point O), which determines the instantaneous coordinate \((x_i, y_i, z_i)\) of the radar phase centre. \(R_i(t)\) is the instantaneous distance between the radar phase centre and the generic stationary target \(P\) located on \((x_0, y_0, 0)\). We use the linear frequency modulated (LFM) signal as the transmitted signal. Accordingly, the unblocked echo signal is

\[
S(t, \tau) = \text{rect}\left(\frac{t}{T_a}\right) \text{rect}\left(\frac{\tau - 2R_i(t)/c}{T_p}\right) \\
\times \exp[j\pi k(\tau - 2R_i(t)/c)^2] \exp\left(-j\frac{4\pi f}{c} R_i(t)\right)
\]  

where \(\text{rect}(\cdot)\) denotes the rectangular window function, \(\tau\) is the fast time, \(c\) is the speed of electromagnetic wave propagation, \(f_c\) is the radar centre frequency, \(k\) is the chirp rate, \(T_a\) is the synthetic aperture time, and \(T_p\) is the pulse duration.

Let the rate of the helicopter blade rotation be \(\gamma\) revolutions per second. If there are \(N_R\) blades, the period of modulation function \(p(\theta)\) by rotor blades blockage is \(T_c = 1/(\gamma N_R)\). Then, the blocked echo signal can be expressed as

\[
S_c(t, \tau) = S(t, \tau)p(t)
\]

2.2 Periodically blocked echo focussing

Herein, the polar format algorithm (PFA) is adopted during imaging processing. To proceed with this algorithm, we should firstly convert the radar echoes to the range-frequency domain.
Then, after matched filtering and motion compensation with respect to the scene centre, ignoring the non-essential terms of transmitted pulse envelop and azimuth antenna pattern, the two-dimensional (2-D) signal is described as

\[ S_p(t, f_z) = \exp \left( j \frac{4\pi(f_z + f_{\tau})}{c} \Delta R(t) \right) p(t) \]  

where \( f_z \) denotes the range frequency, \( \Delta R(t) \) is RCM in the PFA, which can be approximated by

\[ \Delta R(t) = R_s(t) - R_i(t) \approx X_t \cos \phi \sin \theta + Y_t \cos \phi \cos \theta \]  

We begin the analysis by considering the Fourier series representation of generic periodic signal. The periodic signal \( p(t) \) can be represented with a Fourier series corresponding to a sum of harmonically related complex exponential signal, and the complex exponentials with frequencies that are integer multiples of the fundamental frequency \( (f_p = 1/T_c) \) associated with \( p(t) \). Hence, \( p(t) \) can be expressed in the Fourier series form as

\[ p(t) = \sum_{n=-\infty}^{+\infty} C_n \exp(j2\pi nf_p t) \]  

where \( C_n \) is the Fourier series coefficient. By substituting Equations (4) and (5) into Equation (3), the blocked echo signal can be rewritten in the following form:

\[ S_p(t, f_z) = \sum_{n=-\infty}^{+\infty} C_n \exp(j2\pi nf_p t) \times \exp \left( j \frac{4\pi(f_z + f_{\tau})}{c} \left( X_t \cos \phi \sin \theta + Y_t \cos \phi \cos \theta \right) \right) \]  

In order to eliminate the variation of range information with azimuth time \( t \) and simultaneously align the resampled data to enable the subsequent azimuth resampling, the range frequency should be scaled as

\[ f_{\tau} = f_z(\delta_r - 1) + f'_{\tau} \]  

where the scaling factor \( \delta_r \) can be given by

\[ \delta_r = \frac{\cos \phi \sin \theta}{\cos \phi \cos \theta} \]  

Substituting Equations (7) and (8) into Equation (6), we have the resampled range data

\[ S_R(t, f'_z) = S_p(t, f_z(\delta_r - 1) + f'_{\tau}) \]

\[ = \sum_{n=-\infty}^{+\infty} C_n \exp \left( j2\pi nf_p' t \right) \times \exp \left( j \frac{4\pi(f_z + f'_{\tau})}{c} \cos \phi_0(X_t \tan \theta + Y_i) \right) \]  

The term \( \tan \theta \) in Equation (9) is a function of \( t \). Let us define \( t = 0 \) when \( \theta = 0 \). Then \( \tan \theta \) can be rewritten as

\[ \tan \theta = \frac{\omega t}{\gamma_c} = \Omega t \]  

where

\[ \Omega = \frac{\omega}{\gamma_c} \]  

By substituting Equation (10) into Equation (9), we obtain

\[ S_R(t, f'_z) = \sum_{n=-\infty}^{+\infty} C_n \exp \left( j2\pi nf_p' t \right) \times \exp \left( j \frac{4\pi(f_z + f'_{\tau})}{c} \cos \phi_0(X_t \Omega t + Y_i) \right) \]  

After this procedure, it can be assumed that the radar travels ideally in parallel with axis \( OX \) at a constant speed \( \nu \), that is, RCM linearization. We define

\[ t = \frac{f_z}{f_z + f'_{\tau}} \]  

Substituting Equation (13) into Equation (12) and using \( KT \), we have the resampled azimuth data as

\[ S_{KT}(t', f'_z) = S_R \left( \frac{f_z}{f_z + f_{\tau}}', f'_{\tau} \right) \]

\[ = \sum_{n=-\infty}^{+\infty} C_n \exp \left( j2\pi nf_p' t' \right) \exp \left( j \frac{4\pi}{c} \cos \phi_0 \left( X_t \Omega t' + Y_{\Omega t'} \right) \right) \]

After the azimuth resampling procedure, the cross-product quadratic phase term of \( t \) and \( f_z \) is eliminated. The signal in Equation (14) can be converted into a focussed target response via 2-D Fourier transform, which can be expressed as the product of two sinc functions:
\[ F[S_{KT}(\tau', f')] = \sum_{n=-\infty}^{\infty} C_n \exp\left(\frac{4\pi}{\lambda} \cos \phi_0 Y_t \right) \sin\left(\frac{\tau - 2 \cos \phi_0 Y_t}{c} \right) \times \sin\left( f_z - \frac{2 \cos \phi_0 \Omega}{\lambda} X_t - nf_p \right) \]

where \( F[\cdot] \) denotes the 2-D Fourier transform, \( \tau \) is the range time, \( f_z \) is the Doppler frequency. We define

\[ a = \frac{2 \cos \phi_0 \Omega}{\lambda} X_t \]  
(16)

and

\[ b = \frac{2 \cos \phi_0 Y_t}{c} \]  
(17)

Equation (15) can be further expressed using Equations (16) and (17) as

\[ S_F(f_z, \tau) = F[S_{KT}(\tau', f')] = \exp\left(-\frac{4\pi}{\lambda} \cos \phi_0 Y_t \right) \times \left\{ C_n \sin\left(f_z - a\right) \cdot \sin\left(\tau - b\right) + \sum_{|n| \geq 1} C_n \sin\left(f_z - a - nf_p\right) \sin\left(\tau - b\right) \right\} \]  
(18)

The first term of brace in Equation (18) stands for the Fourier spectrum of a target by definition in the azimuth Doppler domain, and the second term of brace accounts for the azimuth Doppler domain characteristics of the harmonics, which is corresponding to integer multiples of the modulation frequency \( f_p \). From Equation (18), we can see that the azimuth Doppler domain consists of multiple harmonics with an octave relationship, which also indicates that the target is repeated with the interval \( f_p \) in the azimuth Doppler domain. It implies that the periodic modulation of rotor blades blockage will lead to a set of ghost images in the SAR image.

3 ROTOR BLADES BLOCKAGE MODULATION SUPPRESSION ALGORITHM

This section describes the proposed iterative method to remove rotor blades blockage modulation in detail. After imaging by PFA, the signal can reasonably be decomposed into one basic signal with different amplitudes and frequency shifts in the azimuth Doppler domain. By extracting amplitude and frequency shift from each decomposed harmonic component, the reference function \( \hat{p}(t) \) can be constructed to suppress such modulation. It is an iterative approximation technique that estimates the coefficient of the decomposed harmonic components one by one. When the residual harmonic components become smaller than a certain limit, the loop is ended and the approximate modulation echo function is selected. Such an iterative approximation process exploits the periodic modulation echo information contained in the azimuth frequency, which is independent of the SAR scene content. Its basic premise is that all image range bins share the same underlying modulation echo function along the azimuth time. Finally, the demodulation signal can be expressed as

\[ \hat{S}_F(f_z, \tau) = F[S_{KT}(\tau', f')] \hat{p}(t) \]  
(19)

The flowchart of the proposed iterative approximation method is shown in Figure 3, which can be detailed as follows.

Step (1) Range bin selection. Select a subset of the range bins which contain the clearest information about the modulation echo. The selection approach is based on the following two criterions: (i) The modulation components of strong reflecting scatterer are measured most accurately and further consequently result in the best extraction. These range bins contribute significantly to the iterative approximation algorithm and should be selected. (ii) Some range bins that have a lot of scatterers should be excluded. In this case, each scatterer contains periodic modulation components obviously and there is no good dominant scatterer to extract the periodic modulation component from the range bin.

Step (2) Extraction of the azimuth profile. For all selected range bins, the azimuth cell with the strongest response is circularly shifted to the image centre, so that the frequency offset in the corresponding Doppler domain introduced by the azimuth position of the strongest response can be removed.

![Flowchart of iterative approximation method](Figure 3)
Then, a consistent estimation of the azimuth profile vector $s_\theta$ can be obtained by calculating the mean value along the range bins.

Step (3) Initial value set. The initial iteration index is set as $i = 0$, and the initial reference function value is $H_0(t) = 1$.

Step (4) Isolation of the dominant scatterer. Isolate the response of the dominant scatterer in the centre region of $s_\theta$; Taking into account the modulation echo period, the isolation window should be selected such that it is less than $f_m$. On filling the azimuth bins inside the isolation window with zeros, the windowed azimuth profile $s_{\theta w}$ consisting of periodic modulation components can be obtained.

Step (5) Calculation of the reference function. Find the maximum complex value $A_i$ and its position $X_i$ from $s_{\theta w}$, $A_i = \max(s_{\theta w})$, and calculate its normalized azimuth frequency $F_i = (X_i - M/2)/M$, where $M$ is the total number of azimuth bins. If $|A_i| < a$ (the pre-set threshold $a$), or $i > K$ (the preset maximum iteration number $K$), end the iteration process, and go to Step 7; otherwise, calculate the reference function $H_i(t) = A_i \exp(\jmath 2\pi F_it) + 1$.

Step (6) Updating the azimuth profile. Transform $s_\theta$ into the time domain $s_t = \text{IFFT}(s_\theta)$, where IFFT denotes the inverse fast Fourier transform, and calculate $s_\theta = s_t/H_i$ to remove the harmonic component $A_i$. Perform $s_\theta = \text{FFT}(s_\theta)$, where FFT denotes the fast Fourier transform. Set $i = i + 1$, and go to Step 4).

Step (7) Suppression of the modulation echo. Calculate the final temporal approximate modulation echo function $\hat{p}(t) = \prod_{i=0}^{K} H_i(t)$, and transform the input SAR image data to azimuth-time domain, then use $\hat{p}(t)$ to remove the modulation echo of each range bin in Equation (19).

Through above steps, the proposed method can eliminate the periodic modulation components one by one.

4 | EXPERIMENTAL RESULTS

Here, some experimental results based on both simulated and measured data are presented to demonstrate the effectiveness and validity of our proposed method.

4.1 | Simulated data experiment

Table 1 lists the relevant parameters associated with the simulation. The flight geometry and target distribution are shown in Figure 4. There are three stationary point targets denoted with $P$, $P_1$, and $P_2$ which are arranged in the same azimuth line with equal intervals of 15 m. The signal-to-noise ratio (SNR) is 10 dB.

Parameters of modulation function generated by rotor blades blockage are set as follows: modulation period is 50 ms, duration is 10 ms and attenuation depth is 10 dB. The characteristic of modulation function is shown in Figure 5, where the blue solid line is the original modulation function and the red dashed curve is the estimated modulation function. On comparison, the estimation result is mostly consistent with the original one, which verifies the effectiveness of the proposed method.

Figure 6a is the imaging result obtained by applying PFA. It is obvious that each target is duplicated along the azimuth

| TABLE 1 Simulation parameters |
|--------------------------------|
| Parameters                  | Value |
| Carrier frequency           | 35 GHz |
| Pulse repetition frequency  | 1000 Hz |
| Signal bandwidth            | 300 MHz |
| Sampling frequency          | 360 MHz |
| Plane velocity              | 55 m/s |
| Range resolution            | 0.5 m  |
| Azimuth resolution          | 0.5 m  |
| Slant range                 | 20 km  |
| Height                      | 1 km   |

FIGURE 4 Flight geometry and target distribution

FIGURE 5 Modulation characteristic
For comparison, Figure 6b shows the imaging result processed with the proposed method. It is clear that the proposed method eliminates the influence of rotor blades blockage accurately and suppresses ghost targets effectively. To assess the suppression performance of our method, Figure 7 gives the results on the near look at the azimuth profile of target P. Figure 7a is the extracted azimuth profile of imaging result obtained by applying PFA. It is obvious that the modulation echo is periodic, and the value of peak side lobe ratio (PSLR) is about −6.78 dB. Figure 7b depicts the demodulation result of the azimuth profile with the proposed method, from which, it can be seen that the modulation echo is significantly removed, and the value of PSLR is about −19.67 dB.

Figure 8 compares the image performance of the proposed method under different noise conditions. We note that the proposed method is able to produce an acceptable result when the SNR is higher than −10 dB. If SNR is lower than −10 dB, the approximate modulation function suffers obviously because of the existence of noise. As a consequence, the ghost targets cannot be removed.

4.2 Real data experiment

The real data were collected by a Ka-band helicopter-borne fire-control radar system, where the radar is mounted atop the main rotor mast of the helicopter.

Figure 9 is the raw data matrix of the helicopter-borne fire-control radar echo. It is obvious that the raw data is periodically modulated in the azimuth time domain. The SAR image obtained by applying PFA is shown in Figure 10 whose resolution is 1 × 1 m. As aforementioned, the SAR image consists of a set
of ghost images, which are periodically repeated along the azimuth direction. And the regions of the white rectangle are indistinguishable due to the modulation echo from the strong scatters.

Figure 11a is the extracted azimuth profile after imaging processing. It can be seen that the modulation echo is periodic, and the PSLR is about −7.97 dB. Figure 11b shows the result processed with the proposed method. The modulation echo is suppressed obviously, and the value of PSLR is about −18.49 dB. Figure 12 shows the SAR image result by using the proposed method, from which ghost images are apparently eliminated. It clearly indicates that the modulation echo effect is effectively suppressed. The modulation echo function estimated by the proposed method is shown as Figure 13. In addition, image contrast (IC) and image entropy (IE) are used herein to measure the image focussing quality [26–28]. As reported in Table 2, the images of two local scenes A and B generated by the proposed method show the larger IC value
**FIGURE 10** SAR image obtained by applying PFA

**FIGURE 11** Azimuth profile extracted from SAR image. (a) Processing with the conventional PFA method, (b) Processing with the proposed method

**FIGURE 12** SAR image after modulation suppression with the proposed iterative approximation method
FIGURE 13 Estimated modulation characteristic

| TABLE 2 | IC and IE of two local scenes |
|---------|-------------------------------|
|         | IC | IE |
|         | A  | B  | A   | B   |
| By PFA  | 1.7303 | 1.2766 | 8.4078 | 9.1618 |
| Proposed method | 1.9380 | 1.4939 | 7.9661 | 8.5809 |

and the smaller IE value than the focussed results obtained by applying PFA, which further proves the previous analysis.

5 | CONCLUSIONS

To address the periodic modulation problem in radar echoes due to the main rotor blades periodic blockage, this article develops a rotor blades blockage modulation suppression algorithm for helicopter-borne SAR imaging. First, a theoretical model of the periodic modulation echo for the helicopter platform is described, which is identical in each range bin. Based on the fact that the periodic modulation signal could be decomposed into a set of Fourier series components, the blocked echo is focussed on the azimuth Doppler domain by applying PFA. Then, by adopting the iterative approximation strategy, the reference function is constructed to suppress the modulation echo in each range bin. And finally, SAR image without ghosts could be obtained. Not requiring modulation function to be of certain distribution models, the iterative approximation algorithm can be used to suppress kinds of periodic modulation components. In addition, the realization of helicopter-borne radar rotor blades blockage modulation suppression could improve its imaging focus performance significantly in this field. Experimental results on both simulated and real-measured data have confirmed the effectiveness of the presented algorithm.

ACKNOWLEDGEMENTS

This work was supported by the China Postdoctoral Science Foundation under grant 2018M642249.

ORCID

Wei Gao https://orcid.org/0000-0003-0704-1836

REFERENCES

1. Carrara, W.G., Goodman, R.S., Majewski, R.M.: Spotlight Synthetic Aperture Radar: Signal Processing Algorithms. Artech House, Norwood, MA (1995)
2. Jokowatz, C.V., et al.: Spotlight-Mode Synthetic Aperture Radar: A Signal Processing Approach. Kluwer Academic, Boston, MA (1996)
3. Barclay, M.W., Williams, N.K.: High resolution SAR/ISAR imaging from a helicopter platform, vol., Radar 97, Edinburgh, UK pp. 109–113 (Oct. 1997)
4. Pearson, J.T., Goodall, R.M., Lyndon, I.: Active control of helicopter vibration. Comput. Control Eng. J. 5(6), 277–284 (1994)
5. Axelsson, S., Nelande, A.: SAR-MTI from helicopters. In: Proc. IGARSS '03, France, Toulouse, pp. 4242–4245 (Jul. 2003)
6. Zhang, Y., et al.: High-frequency vibration compensation of helicopter-borne THz-SAR [correspondence]. IEEE Trans. Aerosp. Electron. Syst. 52(3), 1460–1466 (2016)
7. Gao, Y., et al.: Paired echo suppression algorithm in helicopter-borne SAR imaging. IET Radar, Sonar Navig. 11(11), 1605–1612 (2017)
8. Marechal, N.: High frequency phase errors in SAR imagery and implications for autofocus Proc. IGARSS, Lincoln, NE, USA, vol. 96, pp. 1233–1240 (May 1996)
9. Li, H., et al.: Improved back-projection algorithm on small time bandwidth product SAR imaging. IEEE Geosci. Remote Sensing Lett. 7, 8–15 (2010)
10. Kadar, I.: An analysis of helicopter rotor modulation interference. IEEE Trans. Aerosp. Electron. Syst. AES-9(3), 434–441 (1973)
11. Fines, P., Christofylaki, E., Agliani, H.A.: Bandwidth efficient techniques for helicopter links via satellite. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, London, UK pp. 348–352 (Sept. 2013)
12. Yoon, S.-H., Kim, B., Kim, Y.-S.: Helicopter classification using time-frequency analysis. Electron. Lett. 36(22), 1871–1872 (2000)
13. Alonso, M.T., Lopez-Dekker, P., Mallorqui, J.J.: A novel strategy for radar imaging based on compressive sensing. IEEE Trans. Geosci. Remote Sens. 48(12), 4285–4295 (2010)
14. Potter, L.C., et al.: Sparsity and compressed sensing in radar imaging. Proc. IEEE. 98(6), 1086–1102 (2010)
15. Tomel, S., et al.: Compressive sensing-based inverse synthetic radar imaging from incomplete data. IET Radar, Sonar Navig. 10(2), 386–397 (2016)
16. Yang, J., et al.: Segmented reconstruction for compressed sensing SAR imaging. IEEE Trans. Geosci. Remote Sensing. 51(7), 4214–4225 (2013)
17. Larsson, E.G., et al.: High-resolution SAR imaging with angular diversity. IEEE Trans. Aerosp. Electron. Syst. 37(4), 1359–1372 (2001)
18. Larsson, E.G., Stoica, P., Jian Li, J.: Amplitude spectrum estimation for two-dimensional gapped data. IEEE Trans. Signal Process. 50(6), 1343–1354 (2002)
19. Candés, E.J.: The restricted isometry property and its implications for compressed sensing. Compt. Rendus Math. 346(9), 589–592 (2008)
20. Candes, E.J., Tao, T.: Near-optimal signal recovery from random projections: universal encoding strategies? IEEE Trans. Inform. Theory. 52(12), 5406–5425 (2006)
21. Larsson, E.G., Jian Li, J.: Spectral analysis of periodically gapped data. IEEE Trans. Aerosp. Electron. Syst. 39(3), 1089–1097 (2003)
22. Oppenheim, A.V., Schafer, R.W.: Discrete-Time Signal Processing, 3rd ed Upper Saddle River, NJ 2010. Prentice Hall (1989)
23. Zhu, D., et al.: Far-field limit of PFA for SAR moving target imaging. IEEE Trans. Aerosp. Electron. Syst. 46(2), 917–929 (2010)
24. Van Rossum, W.L., Otten, M.P.G., Van Bree, R.J.P.: Extended PGA for range migration algorithms. IEEE Trans. Aerosp. Electron. Syst. 42(2), 478–488 (2006)
25. Zhu, D., et al.: Multi-subaperture PGA for SAR autofocus. IEEE Trans. Aerosp. Electron. Syst. 49(1), 468–488 (2013)
26. Li, N., et al.: Autofocus correction of residual RCM for VHR SAR sensors with light-small aircraft. IEEE Trans. Geosci. Remote Sensing. 55(1), 441–452 (2017)

27. Bertizzi, F., Corsini, G.: Autofocusing of inverse synthetic aperture radar images using contrast optimization. IEEE Trans. Aerosp. Electron. Syst. 32(3), 1185–1191 (1996)

28. Wang, J., Liu, X.: SAR minimum-entropy autofocus using an adaptive-order polynomial model. IEEE Geosci. Remote Sensing Lett. 3(4), 512–516 (2006)

**How to cite this article:** Gao W, Li X, Liu Z, Meng Z, Han X, Ran L. Rotor blades blockage modulation suppression algorithm for helicopter-borne SAR. *IET Signal Process*. 2021;15:281–290. [https://doi.org/10.1049/sil2.12032](https://doi.org/10.1049/sil2.12032)