Vibration Target Imaging Based on the DPCA Technique in Dual-channel SAR

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Abstract. This paper studies the vibration target imaging methods in dual-channel synthetic aperture radar (SAR). Firstly, the echo model of vibration target has been established in dual-channel SAR. According to the analysis of the echo characteristics, an imaging method in original signal domain has been proposed to make vibration target refocused in SAR images. In the meanwhile, due to the problem that when there are static targets in the range cell of vibration targets, the imaging method in original signal domain can’t focus on these two kinds of targets at the same time, another vibration target imaging method based on the displaced phase center antenna (DPCA) technique has been presented as a solution. The validity of the two imaging methods has been verified by simulation, which also points out that compared with the imaging method in original signal domain, the imaging method in DPCA signal domain has better anti-noise performance.

Introduction

Micro-motion is defined as small movement of target’s body or any part beyond translation, such as rotation, vibration and non-constant acceleration [1]. Vibration generally with small amplitude and high frequency (such as the engine vibration of tanks and military vehicles) is a common style of micro-motion. Unlike uniform motion, vibration would bring complicated non-linear phase histories to synthetic aperture radar (SAR) echo, and thus drive some special SAR image features apart from defocusing or displacement. In order to obtain the focused SAR image of vibration target for further study in image interpretation and object identification, the refocused imaging method of vibration target would be discussed in this paper.

The existing literatures [2, 3, 4] on the research of vibration target mainly focused on vibration causing ghost image to SAR imaging in single-channel SAR/ground moving target indication (SAR/GMTI). Furthermore, the existing literatures mainly focused on the separation and estimation of vibration signals, but little of them researched the vibration target imaging method. Based on the various advantages of multi-channel SAR/GMTI, especially dual-channel system, such as the Environment Canada's CV580 SAR, the Canadian RADARSAT-2 satellite, and the German TerraSAR-X satellite [5, 6], which has been applied widely due to the relatively easier to being used and the small space usage of the antenna, we will use the dual-channel SAR system for the research of vibration target imaging algorithms in this paper.

First of all, the echo model of vibration target in dual-channel SAR has been established. Then, two different imaging algorithms in original signal domain and in displaced phase center antenna (DPCA) signal domain respectively, have been presented to make vibration target refocused in SAR images, and at the same time support the SAR image interpretation and target identification. And finally, the validity of the algorithms mentioned in this paper has been approved by simulation and the advantage of dual-channel SAR system has been further highlighted by comparing the two imaging algorithms.
Model of the Received Echo

Consider the dual-channel side-looking SAR geometry, and use transceiver separation operating mode. As in Fig. 1, assume that the fore antenna sends and receives signals at the same time, while the aft antenna only receives signals. The two antennas locations are denoted by ‘X’s, and separated by distance $2d$. Based on the equivalent phase center principle, the system can be regarded as two antennas (the fore antenna and the virtual antenna) partitioned by $d$ sending and receiving signals independently. Suppose a point target $P$ is vibrating along an axis. $P_{nc}$ is the vibration center, $A$ is the amplitude, $\omega$ is the frequency, and $\phi_0$ is the initial phase. $v_A$ is the radar velocity, $T$ is the pulse repetition interval (PRI), $T_a$ is the coherent processing interval (CPI), $t$ is the slow time, and other symbols used below are illustrated in Fig. 1. Assume that $d = mV_T(m=1,2,3\ldots)$, which means that the two channel echoes can be registered completely. After that, the two radars observe the same scene at regular intervals ($d/V_a$), thus the difference between the two radar echoes presents the change in the scene.

Hence we can obtain the range between the fore antenna and the target at $t$

$$R_1(t) = \sqrt{(V_T t - X_{nc})^2 + Y_{nc}^2 + H^2} + A \cos(\omega t + \phi_0)$$

(1)

where the effective vibration amplitude $A_e \equiv A_0 \left[ \cos \beta_1 \cos \beta_n \cos(\alpha_1 + \alpha_n) - \sin \beta \sin \beta_n \right]$. 

Similarly, the range between the equivalent virtual antenna and the target at $t$ is

$$R_2(t) = \sqrt{(-d + V_T t - X_{nc})^2 + Y_{nc}^2 + H^2} + A \cos(\omega t + \phi_0).$$

(2)

The registered form of (2) can be expressed as

$$R_{2 \text{ reg.}}(t) = R_2(t + mT)$$

$$= \sqrt{(V_T t - X_{nc})^2 + Y_{nc}^2 + H^2} + A_0 \cos(\omega (t + mT) + \phi_0).$$

(3)

Suppose that radar transmits linear frequency modulation signal (LFM), with carrier wavelength $\lambda$. After demodulation and range compression, the registered base-band azimuth echoes of the two channels are respectively

$$s_1(t) = A_e \exp \left[ -j \frac{4\pi R_1(t)}{\lambda} \right] \text{rect} \left( \frac{t}{T_a} \right)$$

(4)

$$s_2(t) = A_e \exp \left[ -j \frac{4\pi R_{2 \text{ reg.}}(t)}{\lambda} \right] \text{rect} \left( \frac{t}{T_a} \right)$$

(5)

where the constant $A_0$ is determined by both the scattering coefficient of the target and the antenna radiation pattern.
Vibration Target Imaging

Since the vibration target energy dispersed in multiple azimuth cells, ghost image would appear in the SAR image when static target imaging method was used. In order to obtain the focused SAR image of vibration target for further study in image interpretation and object identification, the refocused imaging method of vibration target would be discussed in this section.

Usually, for moving target imaging in SAR/GMTI, we produce regular SAR image first, and then refocused image for the moving target which appears as fuzzy or dislocated in the regular SAR image. And thirdly, by adding the refocused image to the static SAR image, we can finally get all the image information in the whole observed scene. This method would not be useful, however, when there’s static target in the range cell of moving target. Because if the new azimuth matched filter is used to refocus for the moving target, defocusing would appear in the existing focused static target image and then influence the image interpretation of moving target. According to literature [7], dual-channel SAR based on DPCA technique has good advantage in static clutter suppression. Assume that if moving target focused image can be realized in the DPCA signal domain, and then the problem mentioned before would be solved. In conclusion, vibration target imaging method should be studied in both original signal domain and DPCA signal domain separately.

Imaging in the Original Signal Domain

The essential reason for vibration target focused image can’t be obtained by using static target matched filtering function in the processing the vibration target SAR echo is that vibration would causes the modulation to SAR azimuth echo. Therefore, if multiplying compensating factor can be done before azimuth compression to make the azimuth echo in vibration target and static target the same signal form, and then vibration target focused SAR image can be obtained by using static target azimuth matched filtering function for azimuth compression. According to Eq. (1) and Eq. (4), the form of this compensating factor would be

\[ h_1(t) = \exp \left[ j \frac{4\pi}{\lambda} A_e \cos (\omega t + \phi_0) \right]. \]  

(6)

This equation shows that the compensating factor is related with parameters \( \lambda, A_e, \omega \), and \( \phi_0 \), which \( \lambda \) is the radar intrinsic parameter that is already known, the estimated value of \( A_e, \omega \), and \( \phi_0 \) can be calculated by the method mentioned in literature [7]. Therefore Eq. (6) can be realized.

![Flow chart of vibration target imaging in original signal domain.](image)

In Figure 2, an algorithm flow chart of vibration target SAR imaging based on original channel echo has been given, which \( H_r(f_r) \), \( H_a(f_a) \) represent the matched filtering function of the range and azimuth direction which are necessary for static target imaging, respectively. Here assume the distance curve driven by radar translation can be ignored. Since common vibration target with small amplitude in centimeter-level (even smaller), which is far smaller than SAR range resolution and would not cause any additional range cell migration (RCM), the range migration modification module can also been ignored in this figure.

Imaging in the DPCA Signal Domain

DPCA [15,16] is a common technique of clutter suppression for SAR/GMTI. Essentially, DPCA is...
the difference of the complex SAR data from two (co-registered) channels. From Eq. (1), Eq. (3), Eq. (4), Eq. (5), we can get the vibration target azimuth echo signal after range compression and DPCA clutter suppression as

\[
DPCA(t) = \sin \left[ \frac{2\pi}{\lambda} (R_{2,\text{reg}}(t) - R_{1}(t)) \right] \cdot \exp \left[ -j \frac{2\pi}{\lambda} (R_{1}(t) + R_{2,\text{reg}}(t)) \right]
\]

\[
= \sin \left[ -\frac{4\pi}{\lambda} A_v \sin \left( \frac{\omega \cdot d}{2V_a} \right) \sin \left( \omega_0 t + \frac{\omega \cdot d}{2V_a} + \phi_0 \right) \right]
\]

\[\cdot \exp \left[ -j \frac{4\pi}{\lambda} A_v \cos \left( \frac{\omega \cdot d}{2V_a} \right) \cos \left( \omega_0 t + \frac{\omega \cdot d}{2V_a} + \phi_0 \right) \right]
\]

\[\cdot \exp \left[ -j \frac{4\pi}{\lambda} \sqrt{V_a t - X_a} + Y_a^2 + H^2 \right]
\]

(7)

Therefore, if static target azimuth matched filtering function would be used to get the vibration target focused SAR image, before azimuth compression, the signal above should multiply the compensating factor given as below

\[
h_\text{a}(t) = \sin^{-1} \left[ -\frac{4\pi}{\lambda} A_v \sin \left( \frac{\omega \cdot d}{2V_a} \right) \sin \left( \omega_0 t + \frac{\omega \cdot d}{2V_a} + \phi_0 \right) \right]
\]

\[\cdot \exp \left[ j \frac{4\pi}{\lambda} A_v \cos \left( \frac{\omega \cdot d}{2V_a} \right) \cos \left( \omega_0 t + \frac{\omega \cdot d}{2V_a} + \phi_0 \right) \right]
\]

(8)

The imaging method flow chart mentioned before shows in Figure 3. Please note that, the DPCA signal here refers to the subtracting result between the two channel echoes after registration (before range compression).

![Flow chart of vibration target imaging in the DPCA signal domain.](image)

**Simulation**

Assume that there are four static targets in a scene and a vibration target seated in the center of the scene. The size of the scene is 300m (range direction)×400m (azimuth direction). The simulation parameters are: \( \lambda = 0.1 \text{m} \), \( B = 150 \text{MHz} \), \( V_a = 400 \text{m/s} \), \( T = 2 \text{ms} \), \( T_s = 0.625 \text{s} \), \( d = V_a T = 0.8 \text{m} \), \( A_v = 0.01 \text{m} \), \( \omega = 2\pi \times 10 \text{rad/s} \), \( \phi_0 = 45^\circ \), \( \alpha_0 = \pi/2 \), \( \beta_0 = 0 \), \( \alpha_i = \pi/2 \), \( \beta_i = 0 \), the range resolution \( \rho_r = 1 \text{m} \), the azimuth resolution \( \rho_a = 1 \text{m} \), the scattering strength of all targets are considered as the same 1, and the number of the samples in range direction and in azimuth direction is 1024, 512 respectively.

Figure 4 are the results of regular SAR imaging. Figure 5 shows the refocused imaging result by using original signal imaging method. Unlike the result in Figure 4, the energy of the focused ghost image has been focused on the main lobe well, and the refocused image of vibration target has been realized, thus the validity of the algorithms mentioned before also has been approved. Figure 6 shows the SAR imaging result of the DPCA signal after clutter suppression in two channels by using DPCA signal imaging method. From this figure we can get that in DPCA signal domain, static target has
been restrained, vibration target image has been located in the real position, and the energy of target has focused on the main lobe, thus the validity of the algorithms mentioned before also has been approved. In the meanwhile, comparing with Figure 6 (b) and Figure 5 (b), we can get that the imaging peak of the former is nearly twice that of the latter. As a result, the conclusion that imaging method in DPCA signal domain has better anti-noise performance than that in original signal domain can be easily derived.

Figure 4. Regular SAR imaging result.

Figure 5. Compensation imaging result in original signal domain.

Figure 6. Compensation imaging result in DPCA signal domain.

A static target has been imported in the range cell of vibration target for repeating the experiment in order to further compare the two imaging algorithms. Figure 7 shows the compensation imaging result in original signal domain. From this figure we can get that focused image for the static target can’t be realized currently, and the dispensed energy influence the image interpretation of the vibration target. However, the static clutter has been restrained effectively by using the imaging method in DPCA signal domain instead, and the same imaging result has been obtained as Figure 6.
Summary

Vibration target imaging method has been discussed based on dual-channel SAR system in this paper. First of all, the echo model of vibration target in dual-channel SAR has been established. In addition, through the analysis of the echo characteristics, a vibration imaging method in original signal domain has been presented in order to obtain the focused SAR image in the whole observed scene. Furthermore, based on the highly effective feature of clutter suppression in DPCA technique, another vibration target imaging method in DPCA signal domain has been presented and used as a solution for the problem that when there are static targets in the range cell of vibration targets, the two kinds of targets can’t be focused at the same time by using the imaging method in original signal domain. In the end, the validity of the two imaging algorithms has been approved by simulation. In the meanwhile, it has been pointed out that the imaging method in DPCA signal domain has better anti-noise performance than that in original signal domain.

References