SURFACE HEIGHT CHANGE ESTIMATION METHOD USING BAND-DIVIDED COHERENCE FUNCTION WITH FULL POLARIMETRIC SAR IMAGES

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ABSTRACT

Synthetic aperture radar (SAR) is one of the most powerful tools for microwave imaging issue, being applicable to terrain surface measurement regardless of the weather conditions. Recently, the coherent change detection (CCD) method has been widely developed aiming at surface change detection by comparing the plural complex SAR images with the same scanning orbit. However, in the case of a general damage assessment by an earthquake or a mudslide, it requires not only a change detection but also a height change quantity of changed surface. To address with this issue, this paper proposes a novel height change estimation method with a CCD model based on the Pauli decomposition of fully polarimetric band-divided SAR images. The experimental results, assuming the 1/100 scale down model of the X-band SAR system in anechoic chamber, show that the proposed method achieves more accurate height change estimation, compared with those obtained by the method using single polarimetric data.

Index Terms— Synthetic aperture radar(SAR), Fully polarimetric analysis, Coherent change detection(CCD), Height change estimation

1. INTRODUCTION

Synthetic aperture radar (SAR) is one of the most useful tools for microwave remote sensing system, that is able to estimate the structure of terrain surface without regard to lighting or weather conditions. As a notable feature of SAR image, we can obtain a complex-valued image, the phase information of which can include information on the height or structural features of targets. In focusing on such feature of SAR image, a coherent change detection (CCD) technique has been widely developed to detect slight surface changes by assessing coherency of the two SAR images [1]. However, the traditional CCD techniques were designated to detect surface change, and so fail to address height change measurements. Such information of height change is needed to judge if a road is suitable for motor vehicle use following a disaster. As a height measuring method based on the phase interferometry of plural SAR images, the interferometric SAR (InSAR) based methods have been developed [2]. However, the InSAR often suffers from inaccuracy caused by difficulty caused by phase unwrapping problem, and is not capable of detecting change. As a solution for this problem, we have already proposed a method of estimating height change with a CCD model[3], namely, it employs multiple band-divided SAR images and their coherence functions with phases. To accurately reconstruct the height change, this method focuses on the phase characteristic for each center frequency and resolves the ambiguity by employing a multiple non-linear regression scheme. However, this method is oriented to the single polarimetric case, and should be appropriately extended to the full polarimetric case to enhance the height change estimation accuracy. Thus, this paper proposes a novel height change estimation method with a CCD model based on the Pauli decomposition of full polarimetric SAR images. The experimental data acquired in an anechoic chamber, assuming the 1/100 scaledown model of X-band SAR system, demonstrate that our proposed method significantly upgrades the accuracy for the height change estimation compared with those obtained by the single polarimetric based analysis.

2. SYSTEM MODEL

Figure 1 shows the observation geometry. The target is assumed to have a rough surface around on the $z = 0$ plane. Monostatic radar is used to correct a set of scans along the x axis line, located on the straight line at $y = 0$, $z = \mathrm{z}_0$. The off-nadir angle is denoted by θ. Each antenna receives the complex-valued reflection signal $S\left(x; f\right)$ at each frequency f, where the frequency is swept for a finite range. The height of the target surface is changed as $\Delta z_{\mathrm{true}}(x, y)$ along the z axis between the 1st and 2nd observations. The two linear polarizations are assumed to be vertical (denoted by V) and horizontal (denoted by H) with respect to the transmitting and receiving antennas. Then, fully polarimetric data characterized by VV, VH, HV, and HH are obtained. Here, it assumes the reciprocity as $\mathrm{HV} = \mathrm{VH}$. The polarimetric SAR complex image, focused on the $z = 0$ plane at the p th observation, is defined as $S_p^{ij}\left(x, y\right)$, where the superscripts i and j denote H or V, and p denotes 1 or 2. Then, a scattering vector $\boldsymbol{X}_p$ is

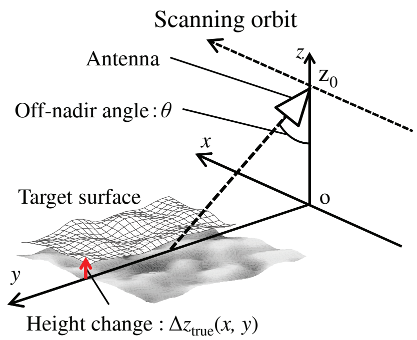

Fig. 1. Observation geometry.

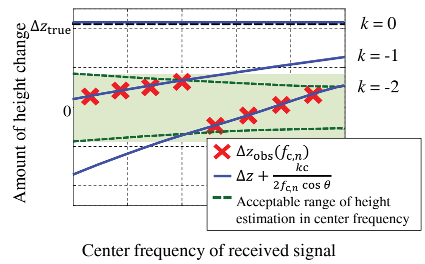

Fig. 2. Fitting approach for height change estimation with multiple frequency bands.

defined as

$$\boldsymbol{X}_p\left(x,y\right)=\left[\ S_p^{\mathrm{HH}}\left(x,y\right),\sqrt{2}S_p^{\mathrm{HV}}\left(x,y\right),S_p^{\mathrm{VV}}\left(x,y\right)\ \right]^{\mathrm{T}} \tag{1}$$

The normal coherence function $\gamma\left(x,y\right)$ between the complex SAR images $S_1^{ij}(x',y')$ and $S_2^{ij}(x',y')$ is defined as [1]

$$\begin{aligned}\gamma^{ij}(x,y) &= \\ &\frac{\iint_{\Omega(x,y)} S_1^{ij}\left(x'-x,y'-y\right) S_1^{ij}\left(x'-x,y'-y\right)^* \mathrm{d}x'\mathrm{d}y'}{\sqrt{\iint_{\Omega(x,y)}\left|S_1^{ij}\left(x'-x,y'-y\right)\right|^2\mathrm{d}x'\mathrm{d}y'}} \\ &\times\frac{1}{\sqrt{\iint_{\Omega(x,y)}\left|S_2^{ij}\left(x'-x,y'-y\right)\right|^2\mathrm{d}x'\mathrm{d}y'}},\end{aligned} \tag{2}$$

where * denotes a complex conjugate and $\Omega(x,y)$ denotes the size of the correlation. Obviously, $0\leq\left|\gamma^{ij}\left(x,y\right)\right|\leq 1$ holds.

3. CONVENTIONAL METHOD

As one approach for height change estimation using CCD model, this section introduces the method which employs the multiply band-divided SAR images and their coherence functions [3]. To avoid the ambiguity error of height change estimation, this method focuses on the frequency characteristic of the multiple phases obtained by the multiple coherence functions. First, the multiple band-divided data are generated from received signal, which has the same frequency band and different center frequency denoted as $f_{\mathrm{c},n}\ (n=1,2,\cdots,N)$, where N is the total number of the divided frequency bands. Second, the SAR images of each observation are generated for each frequency band as $S_p(x,y;f_{\mathrm{c},n})$, where $p=1,2$ denotes the observation number. Third, the coherence functions between $S_1(x,y;f_{\mathrm{c},n})$ and $S_2(x,y;f_{\mathrm{c},n})$ are calculated for each frequency band using Eq.(2). Using the phase of the coherence functions, the amount of height change $\Delta z_{\mathrm{obs}}(x,y;f_{\mathrm{c},n})$ are calculated as

$$\Delta z_{\mathrm{obs}}(x,y;f_{\mathrm{c},n})=-\frac{\mathrm{c}}{4\pi f_{\mathrm{c},n}\cos\theta}\psi(x,y;f_{\mathrm{c},n}), \tag{3}$$

where $\psi(x,y;f_{\mathrm{c},n})$ denotes the phase of coherence function for n th frequency band. To resolve the ambiguity of height change estimation, the optimum amount of height change $\hat{\Delta}z(x,y)$ is calculated as

$$\begin{aligned}\hat{\Delta}z(x,y) = \mathop{\arg\min}_{|\Delta z|\leq\Delta z_{\max}} \sum_{n=1}^{N} \min_{k\in\mathbf{Z}} \Bigg| \Delta z_{\mathrm{obs}}(x,y;f_{\mathrm{c},n}) \\ -\left(\Delta z+\frac{k\mathrm{c}}{2f_{\mathrm{c},n}\cos\theta}\right)\Bigg|^2,\end{aligned} \tag{4}$$

where $\Delta z_{\max}$ denotes the investigating range of height estimation, which is set to sufficiently large value. Figure 2 shows the fitting approach of Eq.(4). In this figure, the investigating index Δz correctly fit into the actual value Δz_{true} because the curved line is completely adjusting to $\Delta z_{\mathrm{obs}}(f_{\mathrm{c},n})$. While the band-divided data is not completely independent for each other, this method can enhance the robustness to the phase fluctuation by employing the multiple frequency data points. Since this method is oriented to the single polarimetric case, there is a possibility to enhance its accuracy by introducing full polarimetric data.

4. PROPOSED METHOD

This section introduces the principle and methodology of the proposed method, which exploits the full polarimetric data combination. First, a received signal for each polarimetric combination is divided into multiple band in the frequency domain, as similar to the method introduced in Sec. 3. Second, the full polarimetric SAR images of p th observation are generated for each frequency band as $S_p^{ij}(x,y;f_{\mathrm{c},n})$, where the subscripts i and j denote H or V, respectively. Then, the Pauli scattering vector is generated from each band divided polarimetric SAR images as

$$\boldsymbol{k}_p(x,y;f_{\mathrm{c},n})=$$

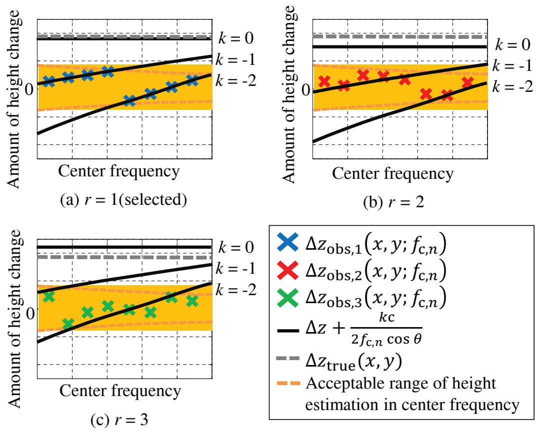

Fig. 3. Fitting approach for height change estimation with each Pauli component.

$$\frac{1}{\sqrt{2}}\begin{bmatrix} S_p^{\mathrm{HH}}(x, y; f_{\mathrm{c},n}) + S_p^{\mathrm{VV}}(x, y; f_{\mathrm{c},n}) \\ S_p^{\mathrm{HH}}(x, y; f_{\mathrm{c},n}) - S_p^{\mathrm{VV}}(x, y; f_{\mathrm{c},n}) \\ 2S_p^{\mathrm{HV}}(x, y; f_{\mathrm{c},n}) \end{bmatrix}, \tag{5}$$

where the 1st, 2nd and 3rd rows of the Pauli vector $\boldsymbol{k}_p(x, y; f_{\mathrm{c},n})$ are regarded as the surface, double and volume scattering components, respectively. Here, a spatial gap due to ray over effect caused between $\boldsymbol{k}_1(x, y; f_{\mathrm{c},n})$ and $\boldsymbol{k}_2(x, y; f_{\mathrm{c},n})$ is compensated for each SAR image by evaluating local cross-correlation function between 1th and 2nd observed SAR images. Third, the height change $\Delta z_{\mathrm{obs},r}(x, y; f_{\mathrm{c},n})$ is calculated as

$$\Delta z_{\mathrm{obs},r}(x, y; f_{\mathrm{c},n}) = -\frac{\mathrm{c}}{4\pi f_{\mathrm{c},n}\cos\theta}\psi_r(x, y; f_{\mathrm{c},n}), \tag{6}$$

where $\psi_r(x, y; f_{\mathrm{c},n})$ denotes the phase of coherence function between the r th component of $\boldsymbol{k}_1(x, y; f_{\mathrm{c},n})$ and $\boldsymbol{k}_2(x, y; f_{\mathrm{c},n})$. To suppress the ambiguity error caused by phase lapping, this method also determines the height change using the following evaluation function as;

$$\hat{\Delta} z_{\mathrm{pro}}(x, y) = \underset{|\Delta z| \leq \Delta z_{\max}, r}{\arg\min} \sum_{n=1}^{N} \min_{k \in \mathbf{Z}} \left| \Delta z_{\mathrm{obs},r}(x, y; f_{\mathrm{c},n}) - \left(\Delta z + \frac{k\mathrm{c}}{2 f_{\mathrm{c},n}\cos\theta}\right)\right|^2, \tag{7}$$

where $\Delta z_{\max}$ denotes the range of height estimation. This is natural extension from that used in single polarimetric analysis. Figure 3 shows the fitting approach of each Pauli component expressed in Eq.(7) in the case that a surface scattering is dominant, namely, the 1st Pauli component is predicted to be highest in all components. Since the SNR of the 1st Pauli scattering component also becomes higher than others, there are less fluctuation in observed data points in case (a). Then Δz of case (a) fits into the actual value $\Delta z_{\mathrm{true}}(x, y)$. In other words, the proposed method can select the optimal estimation for height change by considering the dominant scattering phenomena.

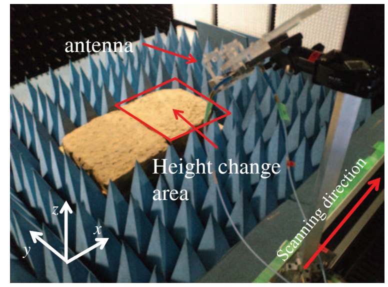

Fig. 4. Experimental setup.

5. PERFORMANCE EVALUATION WITH EXPERIMENTAL DATA

This section introduces the experimental validation of our proposed method. Here, we assume a 1/100 th scale model of X-band radar system for the observation geometry and spatial resolution, except for the center frequency. Figure 4 shows the setup of the experiment. The set of transmitting and receiving antennas is scanned for the range -800 mm$\leq x \leq$ 800 mm, where $y = 0$ mm and $z_0 = 900$ mm holds. The minimum and maximum frequencies are $f_{\min}$ = 26 GHz and $f_{\max}$ = 40 GHz, respectively. The off-nadir angle is 50.0 degree. Two targets made of clay are neighbored along the x-axis, assumed for simulating the terrain surface. The width, depth and thickness of each clay target are 400 mm, 500 mm and 100 mm, respectively. The number of divided frequency bands N is 7, where each bandwidth of the received signal is 8 GHz and the interval of the center frequency is 1 GHz. The theoretical range resolutions before and after the band dividing are 14.0mm and 24.5mm, respectively. The theoretical azimuth resolution is around 12.5mm in any case. One clay target located $x \geq 0$ is uniformly lifted as $\Delta z_{\mathrm{true}}(x, y) = 20$ mm after the first observation. The white Gaussian components are added to the received signal in the frequency domain for simulating lower SNR situations. The SNRs of HH, HV and VV polarization are 27 dB, 12 dB and 28 dB, respectively. On the other hand, the SNRs of 1st, 2nd and 3rd component of Pauli vector are 31 dB, 20dB and 12 dB, respectively. Fig. 5(a) shows the actual spatial distribution of height change. Figs. 5(b) and (c) show the height change estimation results using only VV polarization and the proposed method, respectively. There is a significant improvement for height change estimation accuracy by introducing the full polarimetric data with Pauli decomposition. For quantitative analysis for height change estimation, the probability of ambiguity resolution is introduced as the ratio of the number of

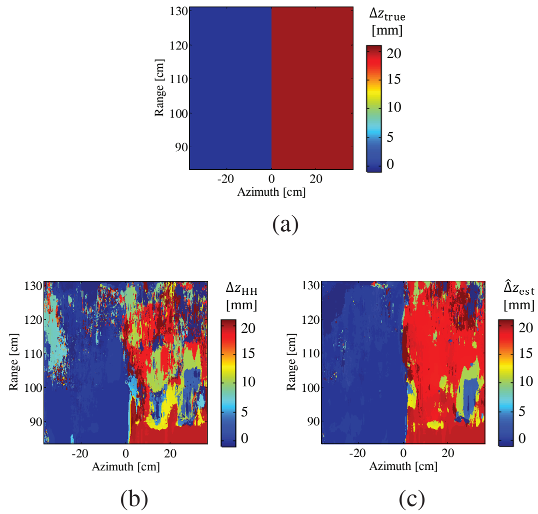

Fig. 5. Distribution of height change ((a): actual, (b): estimated by only S_{VV}, (c): estimated by the proposed method).

pixels satisfying the following equation to the total number of pixels.

$$| \Delta z_{\mathrm{true}}(x, y) - \hat{\Delta} z_{\mathrm{est}}(x, y) | < \frac{\mathrm{c}}{4 f_{\mathrm{c}} \cos\theta}, \tag{8}$$

where $f_{\mathrm{c}} = (f_{\min} + f_{\max})/2$ holds. Figs. 6, 7 and 8 show the probability of ambiguity resolution, the median error and inter quartile range (IQR) of height change estimation versus SNR, respectively. These figures demonstrate that the proposed method obtains more accurate estimation for height change than that obtained by the method using the single polarization data. This is because the proposed method based on Pauli decomposition can select the dominant scattering effect, surface, double-bounce or volume scattering, and eliminates lower SNR components efficiently. Actually, in this case, the 1st component of Eq.(5), the surface scattering component is dominant, and retains the highest SNR compared with other components. However, the proposed method still suffers from large error as in the case (c) in Fig. 5. This is due to the fact that the optimal solution around here does not reach the global optimal. We need to modify the evaluation function or add a regularization term to this evaluation function in future work.

6. CONCLUSIONS

This paper proposed the accurate height change estimation method that employs the phases of the coherence functions obtained from multiple band divided full polarimetric SAR images. The results obtained from the experiment have verified that the proposed method significantly enhances the estimation accuracy of surface height change when compared with each other single polarization cases.

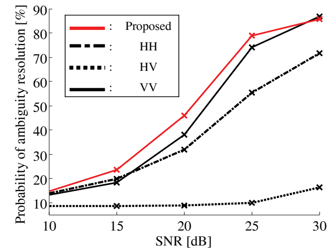

Fig. 6. Probability of ambiguity resolution versus SNR.

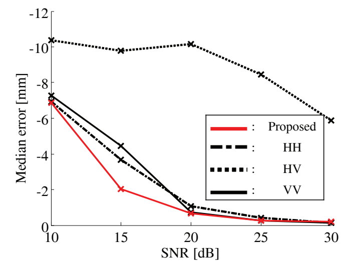

Fig. 7. Median error versus SNR.

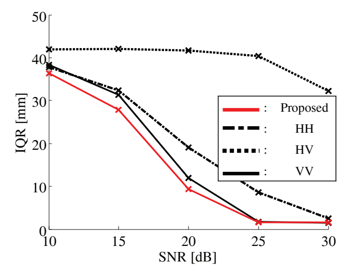

Fig. 8. IQR versus SNR.

7. REFERENCES

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