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Generation of speckle-reduced phase images from three complex parts for synthetic aperture radar interferometry

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Interferometric synthetic aperture radar (InSAR) has applications in many fields. However, decorrelation speckle noise hinders the wider application of InSAR. In this letter, we propose an innovative method termed contoured correlation interferometry to generate speckle-noise-reduced phase images. This method only needs three part images of the two complex images instead of four for the conventional method, which is a significant advantage if processing synthetic aperture radar images on satellites. It proves an efficient tool that reduces speckle noise while preserving the phase derived, which is one of most difficult problems in InSAR data processing. The proposed method can serve as an alternative to generate better InSAR interferograms, whose physical meaning is clearer. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2185250]

Interferometric synthetic aperture radar (InSAR) imaging is one of the most important success stories of remote sensing. Compared to traditional optical remote sensing techniques, InSAR needs shorter signal processing time and can achieve a high resolution in height determination, with an accuracy of less than a wavelength.[1] InSAR is based on an interferogram generated from two SAR complex images of the same area but acquired from slightly different look angles from one or a repeat pass. The interferograms output by standard InSAR methods are full of speckle noise, i.e., decorrelation phase noise, which implies that the interferograms are of low signal to noise ratio.

There is plenty of research on speckle noise suppression and phase unwrapping for InSAR images. Neither standard procedures nor totally satisfactory solutions have been worked out until now. Most of the noise filtering algorithms suppresses speckle noise at the expense of blurring the phase.[2–4] In order to overcome the blurring effect in fringe patterns, low-pass filters with fringe tangential directional windows or, even better, fringe contoured windows, have been developed.[5–8] A filtering algorithm with a similar idea of fringe directional windows has been successfully applied for InSAR phase image processing.[9]

We propose an innovative method termed "contoured correlation interferometry" (CCI) to generate speckle-noise-reduced phase images for InSAR image processing. We perform correlations with fringe-contoured windows among two real parts and one imaginary part, and vice versa, of the two complex InSAR images. The most important advantage of the CCI method is that the phase images generated are nearly speckle-noise free while the blurring effect is reduced to a minimum due to contoured correlation. Another important advantage is that the CCI method only needs any three parts of the two complex images instead of four for the conventional conjugate multiplication method. Saving one image transmission from four is a significant advantage if processing SAR images on satellites, a recent tendency for InSAR.

For InSAR, two complex images of the same scene are obtained by one-pass or repeat-pass SAR imaging:

$$\begin{aligned} V_1(r,x) &= A_1 e^{i\phi_1} \\ &= A_1 \cos\phi_1 + iA_1 \sin\phi_1 \\ &= A_1 \cos(\phi_{1c}+u_1) + iA_1 \sin(\phi_{1c}+u_1) \end{aligned}$$

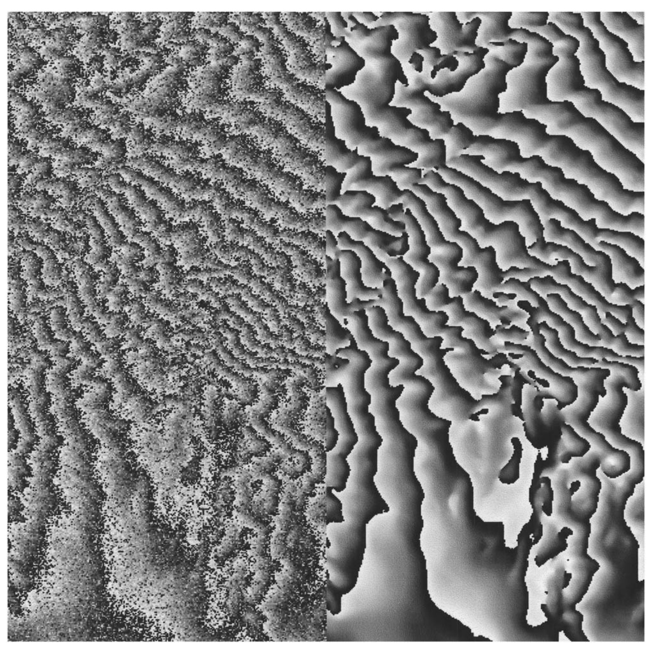

FIG. 1. The left and right parts present the phase images for InSAR data derived by the conventional method and our method with adaptive window sizes, respectively.

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$$= a_1 + b_1 i, \quad (1)$$

$$V_2(r,x) = A_1 e^{i\phi_2} = A_2 \cos(\phi_{2c} + u_2) + iA_2 \sin(\phi_{2c} + u_2) = a_2 + b_2 i, \quad (2)$$

where r and x represent the range direction and the azimuth direction coordinate, A_1 and A_2 are the amplitudes of the complex data, and ϕ_1 and ϕ_2 are response wave phases of the two antennas with random speckle noise. ϕ_1 and ϕ_2 include two parts: one is the propagation induced phase term ϕ_{1c} and ϕ_{2c} proportional to the range and the other is an uncertain phase or scattering phase term, u_1 and u_2, corresponding to random speckle, i.e., $\phi_1 = \phi_{1c} + u_1$, $\phi_2 = \phi_{2c} + u_2$.[10] The phase difference, $\Delta\phi_c = \phi_{1c} - \phi_{2c}$, is proportional to the height of the ground surface we are interested in. $\Delta u = u_1 - u_2$ corresponds mainly to the decorrelation random speckle phase term. In the conventional method, the phase difference between ϕ_1 and ϕ_2 is derived by a conjugate multiplication of the two images and an arctan function[10]

$$\phi_1 - \phi_2 = (\phi_{1c} - \phi_{2c}) + (u_1 - u_2) = \Delta\phi_c + \Delta u = \arctan\left\{ \frac{\mathrm{Im}[V_1(r,x) \cdot V_2^*(r,x)]}{\mathrm{Re}[V_1(r,x) \cdot V_2^*(r,x)]} \right\} = \arctan\left(\frac{a_2 b_1 - a_1 b_2}{a_1 a_2 + b_1 b_2} \right). \quad (3)$$

Equation (3) shows that the conventional method based on complex conjugate multiplication computes the phase images including Δu, the decorrelation speckle noise, from an four complex components of the two complex images.

In this letter, we propose a method based on CCI which works as follows: First, we correlate the real part of the first complex image and the imaginary part of the second image within fringe-contoured windows for each pixel, resulting in a mostly speckle-free sine fringe image. Then, another correlation is performed between the two real parts or the two imaginary parts of the two complex images, resulting again in a mostly speckle-free cosine fringe image. Finally, the phase image is generated by means of the arctan function for the ratio of the sine and the cosine images.

The standard correlation formula that measures the similarity between functions f_1 and f_2 is defined as follows:

$$C(r,x) = \frac{\langle (f_1 - \langle f_1 \rangle_{m\times n})(f_2 - \langle f_2 \rangle_{m\times n}) \rangle_{m\times n}}{[\langle (f_1 - \langle f_1 \rangle_{m\times n})^2 \rangle_{m\times n}]^{1/2} [\langle (f_2 - \langle f_2 \rangle_{m\times n})^2 \rangle_{m\times n}]^{1/2}}, \quad (4)$$

$\langle f_1 \rangle$ and $\langle f_2 \rangle$ are the average values of f_1 and f_2 within the windows with size $m \times n$, respectively. There are different types of correlation formulae according to different applications.

We use the simplest correlation, the direct cross correlation between the real and the imaginary parts of the two complex images as follows, while other correlation formulae result in the same solution:

$$\langle a_1 a_2 \rangle_{m\times n} = \langle A_1 \cos(\phi_{1c} + u_1) \cdot A_2 \cos(\phi_{2c} + u_2) \rangle_{m\times n} = \left\langle \tfrac{1}{2} A_1 A_2 \cdot [\cos(\phi_{1c} + \phi_{2c} + u_1 + u_2) + \cos(\phi_{1c} - \phi_{2c} + u_1 - u_2)] \right\rangle_{m\times n} \quad (5)$$

with u_1 and u_2 both random speckle variables. According to speckle statistic theory,[11] for a window with size $m \times n$ large enough holds for a random variable u_i

$$\langle \cos u_i \rangle_{m\times n} = \langle \sin u_i \rangle_{m\times n} = 0 \quad (i = 1,2). \quad (6)$$

Since u_1 and u_2 are random speckle variables, it follows that

$$\langle \cos(\phi_{1c} + \phi_{2c} + u_1 + u_2) \rangle_{m\times n} = \langle \sin(\phi_{1c} + \phi_{2c} + u_1 + u_2) \rangle_{m\times n} = 0. \quad (7)$$

Substituting Eq. (7) into Eq. (5) yields

$$\langle a_1 a_2 \rangle_{m\times n} = \left\langle \tfrac{1}{2} A_1 A_2 \cdot \cos(\Delta\phi_c + \Delta u) \right]_{m\times n} = \tfrac{1}{2} \langle A_1 A_2 \rangle_{m\times n} \cdot \langle \cos \Delta\phi_c \cos \Delta u - \sin \Delta\phi_c \sin \Delta u \rangle_{m\times n}. \quad (8)$$

Since the two complex parts of Eqs. (1) and (2) are acquired from nearby positions, they are subject to a very similar random phase, inducing speckle noise that is strongly correlated. The subtraction of u_1 and u_2, Δu, thus results in a small difference that on average is narrowly distributed around zero, whereas the values of u_i in Eq. (6) evenly range over the whole interval $[0 - 2\pi]$. If we again assume that the window size is not too small, the following is true:

$$\langle \sin \Delta u \rangle_{m\times n} = 0, \quad \langle \cos \Delta u \rangle_{m\times n} 0. \quad (9)$$

Letting $\Delta\phi_c$ be constant inside windows and substituting Eq. (9) into Eq. (8) yields

$$\langle a_1 a_2 \rangle_{m\times n} = \tfrac{1}{2} \langle A_1 A_2 \rangle_{m\times n} \cdot [\cos \Delta\phi_c \langle \cos \Delta u \rangle_{m\times n} - \sin \Delta\phi_c \langle \sin \Delta u \rangle_{m\times n}] = \tfrac{1}{2} \langle A_1 A_2 \rangle_{m\times n} \cdot \cos \Delta\phi_c \langle \cos \Delta u \rangle_{m\times n}. \quad (10)$$

In the same way we obtain

$$\langle a_1 b_2 \rangle_{m\times n} = -\tfrac{1}{2} \langle A_1 A_2 \rangle_{m\times n} \cdot \sin \Delta\phi_c \langle \cos \Delta u \rangle_{m\times n}. \quad (11)$$

Dividing Eq. (11) by Eq. (10) yields

$$\frac{\langle -a_1 b_2 \rangle_{m\times n}}{\langle a_1 a_2 \rangle_{m\times n}} = \frac{\sin \Delta\phi_c \langle \cos \Delta u \rangle_{m\times n}}{\cos \Delta\phi_c \langle \cos \Delta u \rangle_{m\times n}} = \frac{\sin \Delta\phi_c}{\cos \Delta\phi_c}. \quad (12)$$

Thus, the final solution of phase image, $\Delta\phi_c$, the interferogram, is determined by

$$\Delta\phi_c = \arctan\left(\frac{\langle -a_1 b_2 \rangle_{m\times n}}{\langle a_1 a_2 \rangle_{m\times n}} \right) = \arctan\left(\frac{\sin \Delta\phi_c}{\cos \Delta\phi_c} \right). \quad (13)$$

Equation (13) indicates that the pure phase distribution of $\Delta\phi_c$derived by the method is the same as that of the conjugate multiplication method of Eq. (3), but the random decorrelation speckle noise, Δu, is cancelled out. The same solution can be derived from three arbitrary groupings of a_1, b_1, a_2, b_2 by the same principle.

From the above deduction, it can be concluded that provided windows on which the phase $\Delta\phi_c$ is constant, i.e., fringes are given and the window sizes are large enough to make assumptions of Eqs. (6) and (9) valid, the pure phase solution of Eq. (13) can be obtained without random decor-

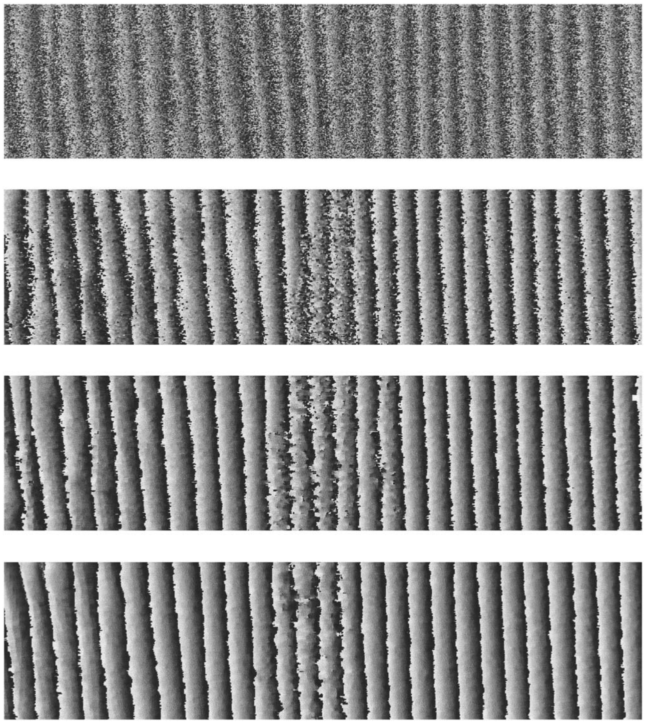

FIG. 2. (a), (b), (c), (d) Phase images derived by our method of Eq. (13) but with square windows with window sizes of 1×1, 3×3, 5×5, and 7×7 pixels, respectively, for the same area as Fig. 1.

relation speckle noise. In reality, this will always be only approximately valid. Practically, we first determine windows of equal phase located along the fringes, which we term "contoured windows." The contoured windows can be derived for each pixel by Yu's contoured window methods[7,8,12,13] from the cosine (sine) fringes generated by Eqs. (8) and (13) using a square window.

The basic procedure to determine fringe-contoured windows works as follows:

(1) Apply a two-dimensional planar least square fit to a local square window and define the zero directional derivative direction of the fitted plane as the local fringe direction.

(2) Repeat Step 1 for every pixel to derive the local fringe orientation map (FOM). The FOM is low pass filtered. Since normally the fringe direction changes slowly, we can derive high quality FOM in most cases.

(3) Based on the derived FOM, the contoured windows are determined along the local fringe tangential directions.

For verification, we processed repeat-pass. The left part of Fig. 1 depicts a phase image derived by the conventional conjugate multiplication of Eq. (3), showing clearly high-density and high-amplitude speckle noise. The right part of Fig. 1 presents the phase image generated by our method with a contoured window. It demonstrates that the phase image is basically speckle noise free and very smooth. The phase fringes are 2π modular nearly ideally distributed without the low signal to noise ratio shown in the left part. Figures 2(a)–2(d) present the phase images derived by our method of Eq. (13), but with square windows with window sizes of 1×1, 3×3, 5×5, and 7×7 pixels, respectively. Figure 2(a) with window size 1×1 pixel shows a much higher noise, because without averaging the random terms of $(\phi_{1c}+\phi_{2c}+u_1+u_2)$ do not cancel out in Eq. (5). Figures 2(b)–2(d) demonstrate that even with square windows our method can provide good quality phase images, yet with some blurring. These phase results or their cosine (sine) fringes derived by Eqs. (10) and (11) provide good quality fringe orientation information to determine our fringe contoured windows.

The conventional multiplication method utilizes the full four images of the two complex InSAR images to generate the phase image, whereas the proposed method utilizes three images, two real parts and one imaginary part, and vice versa, to generate the phase image. In the case of imaging in the satellite, with our method only three parts, instead of four, have to be transmitted to the ground. This is an advantage for saving transmission power from SAR satellites. The important information of one part image, however, is lost this way. It could be used to improve the signal to noise ratio if data transfer problems are not of first concern.

Furthermore, the method produces phase images of high quality barely without random decorrelation speckle noise that plagues conventional methods. This is true even in those areas where the phase resulting from the conventional method is incomplete and noisy. This demonstrates that the method can yield phase images of high quality and improve considerably InSAR results for low quality InSAR data with poor coherence, if the fringe directions are estimated correctly and the derived contoured windows approximate the fringes. Since the speckle noise suppression is performed on the contoured windows, the precise phase information is provided and preserved and the blurring effect of the noise suppression is reduced to the minimum. Phase images can also be derived with a square window by our method. The phase image thus obtained, however, shows some distortion and blurring (cf. Fig. 2).

The correlation of the proposed method measures the phase similarity on contoured windows of equal phase between the two complex images. The obtained coefficients of the similarity form the phase images, $\Delta\phi_c$, with the phase results mostly free of the speckle noise. The method offers an alternative way with a clearer physical meaning to produce InSAR interferograms, which is also a distinct advantage over the conventional method. The method and its procedure are, therefore, an innovation for InSAR data processing and might replace the conventional method of conjugate multiplication. Further research will be directed toward the determination of adaptive fringe-contoured windows and optimal window sizes.

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