博士論文（要約）

Distortion and Its Reduction in Synthetic Aperture Radar Interferogram
（合成開口レーダー干渉画像における歪みとその解消に関する研究）

平成 25 年 12 月 2 日提出

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Synthetic Aperture Radar (SAR) has been widely used for airborne and spaceborne radar observation which can only carry small antenna. Though the resolution of SAR image is lower than the optical observation, it can remotely observe phase and polarization information, while the optical one can only observe intensity. From SAR image, we can acquire various information of the observation area. For example, its amplitude and polarization images show the condition of crops, deforestation and effect of disaster.

Interferometric SAR (InSAR) uses two or more images taken from different places and / or at different times. Their phase differences are geometrically the same as the topography of the observation area. In particular, we need two complex-valued SAR data obtained by observing identical place, named "master" and "slave." An interferogram is a result of multiplication of the master and the conjugated slave. The height information is periodically "wrapped" in phase value of the interferogram. InSAR is widely applicable. If there is an earthquake between two observations, we can see the landscape deformation and it is called Differential InSAR (DInSAR). If we can use polarization data, we can observe the change of vegetation, Polarimetric InSAR (PolInSAR). For any application, accurate interferogram is necessary.

Phase unwrapping process is required to generate DEM from interferogram. As the interferogram corresponds to real landscape, its phase map has to be a conservative field. However, an unwrapping process is disturbed seriously by Singular Points (SPs), the non-zero rotational points existing in the phase map.

Many papers reported two origins of the SP generation. One is the landscape roughness. In this case, SPs are the evidence of the steep slope, and the SPs should exist there. The other is the low signal to noise ratio (SNR) in low coherence areas of the ground. To remove the latter SPs and create an accurate DEM, various filtering and unwrapping methods have been proposed.

In this thesis, we aim to generate more accurate SAR interferogram for landscape observation. Here, we made a hypothesis that there is a local distortion between master and slave, the third origin of SPs. That is, the slight difference in the observation orbit between the master and the slave causes the change of dominant scatterer, resulting in local phase distortion in the interferogram. There are several reflectors in one pixel of the SAR image and the brightest dominant scatterer will be recognized by the satellite. The dominant scatterer can be different in the two observations with slightly different sight angle, and different observation time resulting in local phase distortion in the interferogram. Local distortion makes small difference in the phase value, but exists all over the interferogram. On the other hand, SPs from low coherency exist in large scale and cliffs exist only in the specific area.

We firstly present the experimental results in anechoic chamber which simulates the generation of local distortion. Slight difference of incidence angle causes the change of dominant scatterer. This change is predictable as long as the scatterers and radar positions are accurately estimated. However, spaceborne SAR has several meter orbit error and in general, we do not know the scatterers' position on the ground. In short, local distortion between master and slave is unavoidable.

Next, we propose the local sub-pixel scale co-registration method for master and slave. We propose a sub-pixel co-registration method which employs the SP number and the amplitude-implied phase gradient as the evaluation criterion (the SFS-SPEC method). Usually the co-registration is realized by maximizing the amplitude cross-correlation of the maps in macro scale, while by maximizing the complex-amplitude correlation in micro scale. The correlations require an averaging process over a certain area for sufficient reduction of included noise. However, a wide-area averaging degrades the locality in the matching required to eliminate the distortion. This trade-off brings a limitation in the co-registration performance. Our proposed SFS-SPEC method uses the number of SPs in the interferogram. SP indicates the existence of local distortion between master and slave in our hypothesis. We move master and slave only around the SP and if the SP disappears, we regard the master and slave best co-registered. If there are multiple candidates of direction and amount of movement, we propose to use shape-from-shading technique for evaluation. From amplitude information, we can estimate the phase gradient roughly. We can evaluate the results of co-registration by use of this estimated phase gradient.

One of the drawbacks of the SFS-SPEC method is that it uses the phase gradient in order to evaluate the co-registration result though the interferogram generally contains large phase ambiguity. The phase gradient in the original interferogram is rough. To solve this problem, we propose the use of an interferogram generated with a large-number multilook as the reference in the evaluation process. This reference interferogram is used in the evaluation process to avoid the phase noise of which effect is large in the small-number multilook interferogram. That is, we calculate the phase difference between the co-registered pixel value and the pixel value of the reference interferogram. Without the distortion, no SP is expected through an appropriate co-registration of non-aliasing master and slave maps. Experimental results showed that the proposed method solve 90percent of SPs and increased 2dB in the SNR.

In the last chapter, we present the results of research on statistical approach for filtering methods of SAR Interferogram. Spacial distortion between master and slave appears as the rotational point (Singular Point: SP) in the interferogram. The removal of spacial distortion can be done in the co-registration process, but it is also possible to treat phase information of the interferogram with filters and reduce the effect of the distortion. In this case, filters for interferogram must be compatible with phase information, though in general, ordinal image filters only deal with absolute value, amplitude information.

Recently a new filtering method based on complex-valued Markov random field (CMRF) model has been introduced. Its dynamics can be reduced to a simple and fast complex-valued correlation learning process, the CMRF filter.

This complex-valued correlation learning is compatible with complex-amplitude information of SAR interferogram. Once the CMRF filter finds a SP, it estimates the phase values of four pixels which generate the SP. The CMRF filter uses the complex-valued correlation between those four pixels and their neighbor N pixels.

A complex number is represented by two real numbers. Thus, if the CMRF filter consists of N inputs and 4 outputs, we feed real 2N as input values and receive 8 as output values. In this sense, the N complex-valued correlation learning is similar to a 2N real-imaginary double-dimensional correlation learning. If the real-imaginary double-dimensional Markov random field (RI-MRF) filter can estimate correct phase values as same as the CMRF, it has possibility to calculate faster than the CMRF because it does not need to calculate complex number. At the same time, other image filters which can only compatible with amplitude are also be able to apply by separating complex-amplitude image into real and imaginary images.

Here, we analyze the bases of their processing dynamics and experimentally compare the filtering accuracy of the CMRF (complex N-inputs 4-outputs) and RI-MRF (real 2N-inputs 8-outputs) filters. It is found that the RI-MRF filter creates interferogram presenting inappropriate anisotropy in the phase values whereas the CMRF filter generates accurate interferogram.

Two other traditional famous filters, the Goldstein-Werner filter and the Lee filter for comparison. The Goldstein-Werner filter calculates the interferogram in frequency domain. They firstly cut the original interferogram into small patches. Then, they apply FFT to those cut out interferogram patches and apply two-dimensional Gaussian shaped filter for smoother. That is, this Goldstein-Werner filter works as low-pass filter in Fourier domain. The Lee filter reduces the noise level by use of local noise level estimator and directionally dependent windows. First, they calculate the noise level from coherence estimation to decide the strength of mean filter. At the same time, they find the direction of the slope so that the mean filter the mean filter will be applied to contour direction of the slope. Experimental results showed those conventional filters are compatible for the phase, but they erase the phase fringe.

As written above, we proposed the idea of local distortion and solved with co-registration and filtering methods. Experimental results showed that the proposed method can generate more accurate SAR interferogram than conventional methods.