Novel MIMO-SAR system applied for high-speed and high-accuracy deformation measurement

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Abstract: As a novel system, multiple-input multiple-output synthetic aperture radar (MIMO-SAR) has achieved rapid development in the past years. Based on the MIMO technique, multiple transmitting and receiving antennas could be utilised to compose a specific geometrical structure and acquire a large aperture. The MIMO-SAR system can be utilised to take deformation measurement to scenes with high deformation rate and can avoid the problems of phase errors caused by the antennas’ vibration on the rail. This study introduces the basic principle of the MIMO technique and the key problems in the system design. Experimental datasets are acquired with the MIMO-SAR and GB-SAR (ground-based SAR) systems simultaneously to validate the high-speed and high-accuracy performance of the MIMO-SAR system.

Moreover, the system costs can be reduced much without the high-precision rail, which benefits the large-scale commercial popularising.

The paper presents a novel MIMO-SAR system applied for high-speed and high-accuracy deformation measurement. The paper is organised as follows. The basic principle of the MIMO-SAR system is firstly introduced. Then some key problems in the system design are briefly introduced. Lastly, the experimental datasets are utilised to validate the high-speed and high-accuracy measurement ability of the MIMO-SAR system.

1 Introduction

As one of the most destructive natural events, landslide hazard has caused severe threats to human lives and properties. Surface deformation is one of the prominent phenomena associated with geological hazards. Therefore, detection and measurement of the accompanying surface deformation is important for landslide hazard monitoring. Over the past few decades, ground-based synthetic aperture radar (GB-SAR) technique has been widely applied to monitor surface deformation of the natural and engineered structures, with the advantages of all-day, all-weather, far-range measurement and large coverage [1].

The large aperture of the GB-SAR system is typically synthesised by the mechanical moving of the antennas along a high-precision track [2]. In order to realise high-accuracy deformation measurement, the rail needs to be kept highly stable while the antennas move along the rail. Therefore, the moving speed of the antennas could not be too fast, which causes the scanning period of the GB-SAR system to be about several minutes. Therefore, the GB-SAR system is mainly utilised to take deformation measurement to scenes with low deformation rate. To increase the acquisition speed of the radar images, the rail length can be shortened. However, the rail length determines the upper limit of the synthesised aperture. A short rail causes the decrease of the azimuth resolution of the GB-SAR system.

As a novel system applied for high accuracy and high-speed deformation measurement, multiple-input multiple-output SAR (MIMO-SAR) has achieved rapid development in the past years [3]. Based on the MIMO technique, multiple transmitting and receiving antennas could be utilised to compose a specific structure and acquire a large synthesised aperture. In the imaging period of the MIMO-SAR system, the transmitting antennas can transmit the signals at the same or different time, and the receiving antennas can receive the echo signals at the same time. Therefore, the monitoring scene can be scanned fast with the MIMO-SAR system, and the images acquisition interval can be reduced to several seconds contrast with that of the GB-SAR system. The MIMO-SAR system can be utilised to take deformation measurement to scenes with high deformation rate [4]. Without adopting the metal rail to synthesise a large aperture, the MIMO-SAR system can avoid the problems of phase errors caused by the antennas’ vibration on the rail or the altitude instability of the rail [5].

2 System design

2.1 Basic principle

The MIMO-SAR system utilises multiple transmitting and receiving antennas to compose a specific geometrical structure and acquire a large aperture. Fig. 1 shows a simplified MIMO array. The transmitting and receiving arrays include three transmitting antennas T1−T8 and eight receiving antennas R1−R8, respectively. The orientations of both arrays are parallel and the height difference is H. The total length of the receiving array is L and the space interval between the neighbouring receiving antennas is d. The space interval between the neighbouring transmitting antennas is L/6. Under the condition of far field, the equivalent phase centre between each transmitting antenna and each receiving antenna can be regarded as the geometrical centre of their connection. For example, the phase centre between the transmitting antenna T1 and the receiving antenna R1 is A1, and the phase centre between T1 and R2 is A2. Therefore, when T1 transmits signals and each receiving antenna R1−R8 receives signals consecutively, the equivalent phase centres vary from A1 to A8. According to the geometrical structure of the MIMO array, the space interval between neighbouring phase centres is the same and d/2. In a similar way, when the transmitting antennas T2 and T8 work separately and each receiving antennas work consecutively, the phase centres vary from B1 to B8 and C1 to C8. Moreover, the space interval between neighbouring phase centres is still d/2.

Therefore, when three transmitting antennas and eight receiving antennas are utilised to compose a specific structure as shown in Fig. 1, the MIMO array can be regarded as a linear array including...
24 phase centres with the same space interval. If the space interval is small enough to satisfy Nyquist criterion, the high resolution can be realised with the MIMO array based on the digital beam forming technique. Therefore, if $M$ transmitting antennas and $N$ receiving antennas are utilised to compose a MIMO array with a specific geometrical structure, an equivalent linear array with $MN$ phase centres can be acquired.

2.2 Key problems

Based on the basic principle introduced above, several key problems should be paid attention in the MIMO-SAR system design [7].

2.2.1 Accuracy: When taking deformation measurement with the differential interferometry technique in the radar applications, the measurement accuracy is closely related with the carrier frequency. In general, to achieve measurement accuracy of the sub-millimeter level, the radar system should work in the X- or Ku-band.

2.2.2 Resolution: The resolution contents include the range resolution and the azimuth resolution. The range resolution depends on the bandwidth of the transmitted signal. The azimuth resolution depends on the length of the synthesised aperture.

2.2.3 Costs and size: MIMO-SAR system is composed with multiple transmitting and receiving antennas. The antenna number directly affects the system costs. In general, the transmitting antenna is more expensive than the receiving antenna. Therefore, the number of the transmitting and receiving antennas should be properly selected to satisfy the system demand and control the system costs.

3 Experimental datasets

3.1 Radar systems

Fig. 2a shows the photo of the MIMO-SAR system independently developed by the Beijing Institute of Technology. The radar system utilises 16 transmitting antennas to constitute one sparse transmitting array and 32 receiving antennas to constitute two dense receiving arrays. An equivalent large aperture with 512 sampling intervals can be synthesised.

To better make contrast with the MIMO-SAR system, a GB-SAR system developed by the Beijing Institute of Technology is also utilised to take experiments. Fig. 2b shows the photo of the MIMO-SAR system. The transmitting and receiving antennas move along the long metal rail to synthesise a large aperture. To keep highly stable of the rail in the monitoring period, the GB-SAR system should be installed on a fixed platform, such as the cement platform or concrete road.

The MIMO-SAR system has a light weight and can be installed on a tripod. On one hand, with a tripod as the radar platform, the MIMO-SAR system has no strict requirement for monitoring locations and can be flexibly installed. On the other hand, with a fixed platform, the altitude instability of the GB-SAR rail can be kept stable. However, the antennas’ vibration on the rail cannot be avoided when moving along the rail. Therefore, the MIMO-SAR system can avoid phase errors caused by the antennas’ vibration or the altitude instability of the rail contrast with the GB-SAR system.

The parameters of the MIMO-SAR and GB-SAR systems are shown in Table 1. The radar systems both work at Ku-band. The transmitted signal is frequency-modulated continuous wave and the range resolution is obtained with de-ramping compression technique [8].

3.2 Experimental scene

To validate the high-speed and high-accuracy measurement ability of the MIMO-SAR system, a monitoring experiment was taken to an open-pit iron mine located in Qian’an City, Hebei Province, China. Fig. 3 shows the photo of the experimental scene. The diameter of the open-pit mine is ~600 m and meets the environment demand for radar monitoring. The open-pit mine is a typical side slope and beneficial for deformation measurement.

In the experimental period, the MIMO-SAR and GB-SAR systems were put at different positions and kept monitoring at the same time. Although the MIMO-SAR images could be acquired fast with the image interval <1 min, the image acquisition intervals of both systems were set to be the same 3 min to better validate the rail stability of the MIMO-SAR system. Experimental datasets of ~1.5 h from 15 July 2017 13:00 to 14:30 were selected to take analysis. The number of SAR images acquired with the two systems during the period was both 30.

4 Experimental results

4.1 System comparisons

To validate the imaging performance of the MIMO-SAR system, a mature GB-SAR system is utilised to make contrast in the experiment, as shown below.
4.1.1 SAR imaging: Both systems can realise SAR imaging with two-dimensional high resolution. In general, the back-projection algorithm is taken to realise imaging. Figs. 4a and 4b show the MIMO-SAR and GB-SAR imaging results in the polar coordinates, respectively. Different pixels' colours represent the scattering properties of corresponding regions of the open-pit mine. Since the beam widths of the transmitted signal in the vertical direction are both $\pi/4$ and the radar systems were located right above the pit and directly opposite the monitoring area, the bottom of the pit could not be illuminated. Considering that the synthesised aperture lengths and the bandwidths of both systems are almost the same, the resolutions and amplitudes of the imaging results are intuitively similar. The imaging ability of the MIMO-SAR system is rather good.

4.1.2 PS selection: The SAR images are usually utilised to take deformation analysis based on the pixels' phase information. However, limited by the thermal noise and atmospheric disturbances etc., not all the pixels in a phase interferogram can be utilised. Some pixels with high phase quality are usually selected and the permanent scatter (PS) method is mostly adopted [9]. The PS method estimates the pixels' phase stability with the amplitude dispersion (ADI) estimator. By setting a proper ADI threshold, pixels with ADI lower than the threshold can be selected as reliable pixels.

Figs. 5a and 5b show the PS selection results of the MIMO-SAR and GB-SAR systems with the same ADI threshold 0.15 and with all the 30 images acquired, respectively. Although both systems were put at different positions, the PS numbers and distributions are similar. Since the selected PS are the pixels whose amplitude and phase information are stable in the monitoring period, that means the MIMO-SAR images are highly correlated and can be utilised to take deformation analysis with the differential interferometry technique.

4.1.3 Differential interferometry: When taking differential interferometry to the 30 MIMO-SAR images, the first image is taken as the master image and other images are taken as slave images. Fig. 6a shows the phase interferogram formed by the 1st and 30th MIMO-SAR images. It can be noted that the interferogram is wrapped and the wrapped phase is located $[-\pi, \pi)$ which presents periodical variation along the range direction. The wrapped interferogram is mainly caused by the atmospheric disturbances. Fig. 6b shows the interferogram formed by the 1st

| Table 1 | Parameters of the MIMO-SAR and GB-SAR systems |
|---------|-----------------------------------------------|
| **MIMO-SAR system** | **Value** | **Parameters** | **Value** |
| carrier frequency | 16.2 GHz | sampling rate | 25 MHz |
| wavelength | 0.018 m | range resolution | 0.375 m |
| bandwidth | 400 MHz | synthetic aperture | 1.138 m |
| angle resolution | 0.466° | detection range | 30–3000 m |
| **GB-SAR system** | | | |
| carrier frequency | 16.2 GHz | sampling rate | 25 MHz |
| wavelength | 0.018 m | range resolution | 0.375 m |
| bandwidth | 400 MHz | synthetic aperture | 1.2 m |
| angle resolution | 0.442° | detection range | 30–3000 m |

Fig. 3 Photo of the monitoring scene

Fig. 4 Imaging results of (a) MIMO-SAR, (b) GB-SAR

Fig. 5 PS selection results of (a) MIMO-SAR, (b) GB-SAR
and 30th GB-SAR images. The unit of the colour bars in the two figures is both radian.

The temporal baselines of the two phase interferograms are 1.5 h and the systems were set to acquire SAR images almost at the same time in the monitoring period, which means that the atmospheric phases in the two interferograms should be rather close. However, the phase variation trends present large differences, and the phase quality of the GB-SAR interferogram is much worse, which is mainly caused by the antennas' vibration. The comparison results can effectively validate that the MIMO-SAR system has a better repeat-track interferometry performance than the GB-SAR system.

4.2 MIMO-SAR validation

When taking deformation analysis to the MIMO-SAR images, the detailed processing steps include phase unwrapping, atmospheric compensation and deformation measurement, other than the above steps of SAR imaging, PS selection and differential interferometry [10]. Considering that the MIMO-SAR and GB-SAR systems were put at different positions, the deformations were along different line-of-sight directions. Therefore, no effective comparisons could be made with the deformation measurement results. Experimental results below are utilised to validate the high-accuracy measurement ability of the MIMO-SAR system.

4.2.1 Phase unwrapping:

The phase unwrapping procedures include two-dimensional spatial unwrapping and one-dimensional temporal unwrapping. In the spatial domain, the minimum cost flow algorithm in the irregular grids can be adopted. In the temporal domain, the Kalman filtering or Euler unwrapping can be adopted. Fig. 7 shows the phase unwrapping result of the phase interferogram shown in Fig. 6a. The unwrapping result presents obviously linear variation trend along the range direction.

4.2.2 Atmospheric compensation:

The atmospheric phase should be well compensated to correctly take deformation measurement [11]. By building a proper atmospheric model, such as first-order linear model or multiple-regression model, the atmospheric parameters can be estimated iteratively and utilised to take atmospheric compensation. Fig. 8 shows the atmospheric compensation result. It can be noted that most of the pixels' unwrapped phase is about zero radian and the atmospheric phase has been well compensated.

4.2.3 Deformation measurement:

With the above processing steps, the deformation information is linearly related with the compensated phase as shown in Fig. 8 and can be directly acquired. Fig. 9a shows the cumulative deformation map during the monitoring period. The unit of the colour bar is mm. The maximum deformation value is ~2 mm, which locates in the upper part of the open-pit mine and corresponds to a soil slope. The negative sign represents the direction close to the radar. Considering that the soil slope was covered by dense vegetation in the experimental period, some small errors of the measurement results were unavoidable. Fig. 9b shows the measurement curves of three representative pixels selected from the monitoring scene. Pixels A and B locate in the mine slope and C locates in the soil slope. It can

![Fig. 6 Phase interferogram formed by the 1st and 30th SAR images of (a) MIMO-SAR, (b) GB-SAR](image)

![Fig. 7 Phase unwrapping result](image)

![Fig. 8 Atmospheric compensation result](image)

![Fig. 9 Deformation measurement results (a) Cumulative deformation map, (b) Measurement curves of three representative pixels](image)
be noted that in the monitoring period ∼1.5 h, no obvious deformations of the open-pit mine were measured. The open-pit mine was not under construction in the experiment period and it is a stable slope with low deformation rate. Therefore, no obvious deformations should be measured in several hours. The measurement results with the MIMO-SAR system are credible.

5 Conclusion

The paper presents a novel MIMO-SAR system applied for high-speed and high-accuracy deformation measurement. Based on the MIMO technique, multiple transmitting and receiving antennas could be utilised to compose a specific structure and acquire a large synthesised aperture. On one hand, the monitoring scene can be scanned fast with the MIMO-SAR system, and the images acquisition interval can be reduced to several seconds contrast with that of the GB-SAR system. The MIMO-SAR system can be utilised to take deformation measurement to scenes with high deformation rate. On the other hand, without adopting the metal rail to synthesise a large aperture, the MIMO-SAR system can avoid the problems of phase errors caused by the antennas' vibration on the rail or the altitude instability of the rail. Moreover, the system costs can be reduced much without the high-precision rail.

The paper introduces in detail the basic principle of the MIMO technique with a simplified MIMO array and the key problems in the system design. Based on the experimental datasets, the paper introduces the processing steps to realise high-accuracy deformation measurement, including MIMO-SAR imaging, PS selection and differential interferometry, et al. Comparisons of the imaging results indicate that the MIMO-SAR system has a better repeat-track interferometry performance than the GB-SAR system. Moreover, deformation measurement results are utilised to validate the high-accuracy deformation measurement ability of the novel MIMO-SAR system.

6 Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grant nos. 61427802, 61601031, 61625103, 31727901), Chang Jiang Scholars Programme (Grant no. T2012122), and 111 Project of China (Grant no. B14010).

7 References

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