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# Multistatic ground-based differential interferometric MIMO radar for 3D deformation measurement

Cheng HU, Yunkai DENG* & Weiming TIAN

*School of Information and Electronics, Beijing Institute of Technology, Beijing* 100081*, China*

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Deformation measurement is crucial for forecasting landslide hazards of natural and engineered slopes. Ground-based differential interferometric radar (GB-DInRad) uses phase differential interferometric technology for surface deformation measurements and offers the advantages of all-day, all-weather, and noncontact measurements. However, this technique can only measure one-dimensional (1D) deformations along a radar-target line of sight (LOS). For conventional scanning GB-DInRad, its measurement speed is limited by the mechanical movement of antennas. Complicated environmental disturbances also severely affect the measurement accuracy.

This study introduces a novel multistatic ground-based multiple-input multiple-output (GB-MIMO) radar for three-dimensional (3D) deformation measurements. This technique offers fast image acquisition and high measurement accuracy (Figure 1(a)). The proposed GB-MIMO radar based on the MIMO technique was employed for 3D deformation measurements for the first time worldwide in GB-DInRad applications [1].

*System overview.* The GB-MIMO radar adopts the MIMO electronic scanning technology for a high azimuth resolution. It uses 16 transmitting antennas that constitute two dense transmitting subarrays and 32 receiving antennas that constitute one sparse receiving array (Figure 1(b)). An equivalent large aperture with 512 azimuth samples and a length of 2.37 m can be synthesized. Its azimuth resolution is 3.78 mrad, and the range resolution can reach 0.15 m. Generic ground-based synthetic aperture radar (GB-SAR) systems achieve a large aperture based on the mechanical movement of antennas along a linear track or using a rotational arm, whereas the GB-MIMO radar adopts a multi-antenna structure. The GB-MIMO radar offers the advantages of faster image acquisition and better repeat-pass ability than the GB-SAR system. The image acquisition rate can be increased considerably, i.e., from minutes to seconds, using the MIMO electronic scanning technology instead of the mechanical scanning synthetic aperture technology [2].

Using the advanced electronic scanning imaging technology, the GB-MIMO radar offers typical advantages of miniaturization, portability, and rapid measurements compared with the conventional GB-DInRad systems. The proposed GB-MIMO radar can satisfy the needs of the rapid monitoring of landslide disasters and emergency monitoring. This radar has been successfully applied in the fields of mining, railways, electricity, dams, landslide monitoring, etc.

*Novel techniques.* (1) Array error calibration. Owing to the multiantenna structure of the proposed GB-MIMO radar, its imaging quality is severely affected by array errors, including the interchannel and position errors of all transmitting and receiving antennas. To address the image defocusing problem caused by the array errors, a calibration method for a wideband GB-MIMO radar based on multiple prominent targets is proposed. Using four transponders as the imaging targets, the radar image calibrated using the calibration method can achieve the peak sidelobe ratio of −12.99 dB, and the grating lobe can be reduced to be approximately −40 dB [3, 4].

(2) Dynamic permanent scatterer (PS) selection. The interferometric phase is the most crucial element for determining the deformation measurement accuracy. Pixels with a low phase quality in an interferogram are unsuitable for phase analysis. A suitable method for identifying high-quality pixels is essential for interferometric measurements. A dynamic PS selection method with an adaptive threshold adjustment for long-term and real-time monitoring is proposed. The numbers and quality of PS in different interferometric groups can be highly stable, thereby laying a solid foundation for high-accuracy deformation measurements [5].

(3) Complicated atmospheric phase (AP) compensation. The AP is a major error source that affects the measurement accuracy of the GB-DInRad. For the compensation of the complicated AP caused by time-varying weather, a grid partition (GP) method based on the path integral model is adopted. By uniformly dividing one two-dimensional map into sufficient small grids, the constrained linear least-squares problem is solved using a two-step process to compensate for the AP. For time-series interferograms, the statistical results of the compensated maps obtained using different methods prove that the GP method can achieve optimal compensation effects. The experimental result proves that the measurement accuracy of 1D deformations can be

* Corresponding author (email: yunkai_bit@foxmail.com)

 

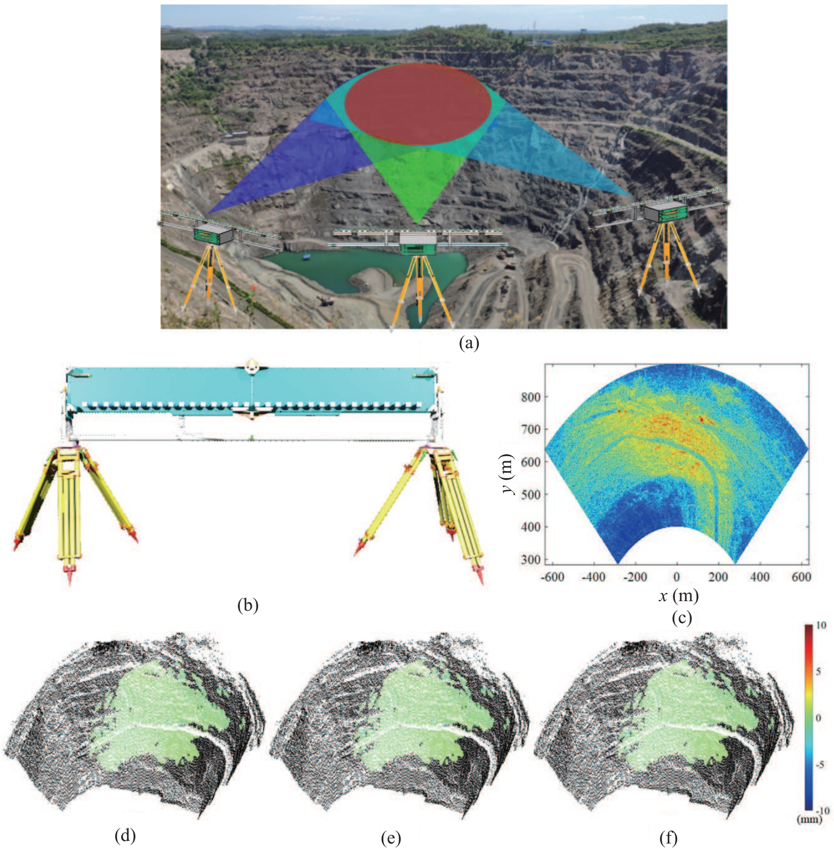


**Figure 1** (Color online) (a) Measurement geometry of a 3D deformation; (b) GB-MIMO radar; (c) radar image; (d) deformation along the $x$-axis; (e) deformation along the $y$-axis; (f) deformation along the $z$-axis.

increased from 0.1 to 0.05 mm [6, 7].

(4) Optimal geometric design. When multiple GB-MIMO radars are used collectively to resolve 3D deformations, the resolving accuracy is closely related to the measurement geometry constructed by these radars. Theoretical analysis proves that for a single target, the optimal geometry can be obtained when the unit measurement vectors of these radars construct a specific pyramid. For a 3D scene, the optimal geometry can equal a collection of numerous targets. The optimal accuracy problem can be converted into a minimization problem of an objective function with a boundary constraint and solved using a genetic algorithm [8].

(5) 3D deformation measurement. The 3D deformation measurement is conducive to identifying deformation features and landslide warnings. To realize 3D deformation measurements, the first domestic multistatic system based on three GB-MIMO radars is developed. The key problems in multistatic measurements, including multistatic image registration and 3D deformation inversion, are solved. The experimental results prove that the measurement accuracy of the 3D deformations based on the use of a displaceable corner reflector as the imaging target can reach the millimeter level, affording its first realization worldwide in GB-DInRad applications [1].

*Applications.* Three GB-MIMO radars were used collectively to measure an open-pit mine (N40°06′44′′, E118°36′23′′) from different aspects; the mine is located in Qian'an, Hebei Province, China. Figure 1(c) shows the radar image, where the road features and slopes are obvious. With three groups of 1D deformations along three LOS directions, the 3D deformations along three orthogonal directions can be measured (Figures 1(d)–(f)). No obvious deformations are detected during the short monitoring period of 1 day.

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