

Improved deformation monitoring technology considering the penetration variation of L-band SAR signals

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Abstract

The influence of soil moisture change on interference phase information is fully taken into account for accurate deformation monitoring in this research. Especially the effects have more prominent contribution to L-band SAR data. In order to obtain high-precision surface deformation information over agricultural area, the interference phase component caused by soil moisture change should be considered, and the optimal processing of interference phase information is achieved. The reliable interference phase information characterizing the surface deformation details is obtained, thus the natural surface deformation information with high precision can be achieved. Firstly, the penetration depth of different band SAR for agricultural soil was analyzed and simulated. And the sensitivity between penetration depth variation and different band SAR signals were discussed. The fact of soil moisture changes for interferometric phase contribution is confirmed, which provided the foundation for reliable deformation monitoring considering the soil moisture variation effects, especially for L-band SAR data. The periodic irrigation for the wheat fields will induce soil moisture variation, which may result in the penetration depth change for radar electromagnetic wave. Therefore, the phase component was derived by the variation of soil moisture over the wheat fields. Multi-temporal Lutan-1 SAR data were acquired over ShanDong agricultural plain in China. The obvious 'deformation details' induced by the soil moisture change were acquired over the agricultural area, which demonstrated the effect of soil moisture variation for interference phase. Therefore, the accurate deformation details over agricultural area can be obtained by the combination of soil moisture information.

1. Introduction

Synthetic Aperture Radar (SAR) has been widely used for soil moisture retrieval based on the sensitivity between soil moisture and radar backscatter (Zhang et al., 2020). The interferometric synthetic aperture radar (InSAR) is a significant technology for deformation monitoring due to the characteristics of interferometric phase and deformation (Gabriel et al., 1989), which has been widely applied for subsidence monitoring, geological disaster investigation and monitoring, urban safety monitoring and so on. Lutan-1 SAR constellation are the first group L-band SAR satellites of China. These two satellites have two formations for deformation monitoring and survey and mapping, which have been used for different quantitative applications (Zhang et al., 2024, 2025; Ji et al., 2023). For deformation monitoring and soil moisture retrieval, SAR observations including backscatter and phase are employed for different application scenes (Rabus et al., 2010; Zwieback et al., 2015). However, the combination of both observations for deformation monitoring or soil moisture retrieval is still rarely used. In addition, a series of phase components in interferometric phase information have significant effects on deformation monitoring accuracy, including orbital error phase, DEM error phase, atmospheric delay phase and ionospheric delay phase. Therefore, in order to obtain reliable and accurate information of surface deformation, it is necessary to effectively remove phase components that are irrelevant to surface deformation characteristics. That is, whether the reliable ground deformation information can be extracted from the interference phase directly depends on the compensation degree of other components in the interference phase. The interference phase caused by soil moisture change have a direct impact on

deformation monitoring, especially for high precision deformation monitoring of agricultural area, the interference phase corresponding to soil moisture change should be considered in deformation monitoring research and application. The orbital error phase, DEM error phase, atmospheric delay phase and ionospheric delay phase have been extensively studied and discussed. However, the interference phase caused by natural surface soil water change has not been studied. Therefore, it is of great significance to study the deformation monitoring method that takes soil water change into account for the high precision deformation monitoring of natural surface.

For agricultural area deformation monitoring, due to the difference in the penetration ability of electromagnetic wave in soil with different humidity, natural surface soil moisture changes directly contribute to the interference phase. Therefore, to obtain high-precision deformation information of natural surface, it is necessary to effectively remove the phase components generated by soil moisture changes. The developed scheme first analyzes the characteristics of electromagnetic wave penetration depth on soil moisture change, so as to construct the interference phase component model caused by soil moisture. Thus, the corresponding interference phase component induced by soil moisture change can be extracted and the phase irrelevant to the surface deformation can be eliminated in the interference phase. In particular, the phase component caused by soil moisture change and ionospheric delay phase component are effectively removed to obtain reliable interference phase information characterizing surface deformation characteristics, so as to realize high-precision deformation monitoring of natural surface.

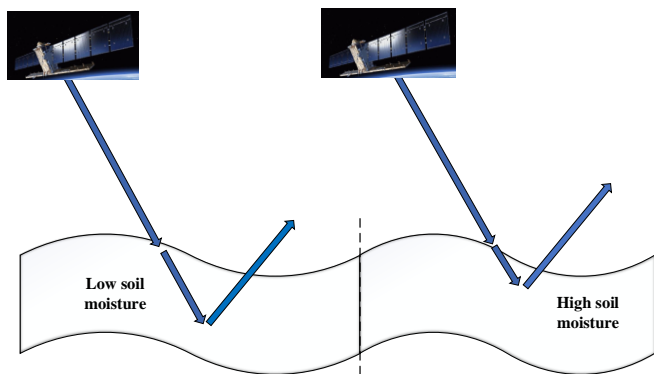


Figure 1. Variation of electromagnetic wave penetration depth for natural surface with different soil moisture

2. Study area and datasets

The study area is located on the Shandong Plain, which is mainly the agricultural area. The summer corn and winter wheat are the dominated crops over the study area, shown as Figure 2.

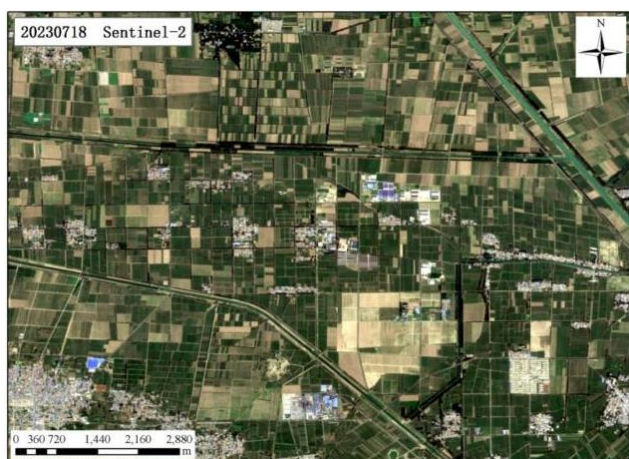


Figure 2. Study area of Shandong Plain

The LuTan-1 satellites data with Stripmap1 imaging mode from July 19, 2023 to January 7, 2024 in Shandong Plain area were selected for experiment. These two L-band SAR satellites have two formations for survey and mapping and deformation monitoring, respectively. For deformation monitoring, the monostatic formation was operated, and two satellites operate in a common reference orbit with 180 degree phase difference, shown as Figure 3. The revisit cycle of two satellites can be improved from 8 days to 4 days, which obtain the high coherence for interferometric applications. In addition, the accurate orbit tube control within 350 meters provides the high spatial coherence for quantitative applications.

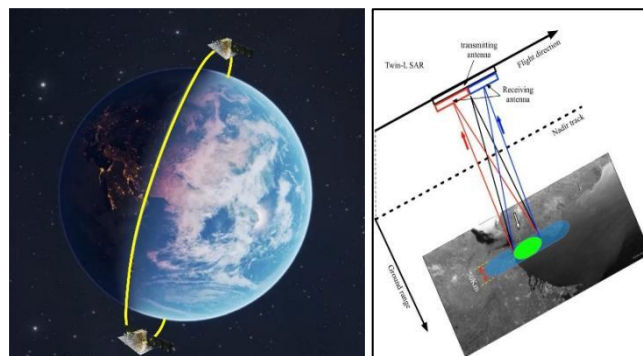


Figure 3. Lutan-1 SAR satellites and imaging mode

Six interference pairs were obtained according to the conditions that the temporal baseline was no more than 32 days and the vertical baseline was no more than 700 meters, and differential interference processing was carried out respectively. The deformation information was obtained by time series differential interference.

3. Methodology

The penetration depth of electromagnetic wave can be characterized as a functional relationship with several parameters including radar frequency, soil composition and soil moisture content, thus SAR penetration depth P with different radar frequencies can be obtained through soil parameters, which is specifically expressed as:

$$P = \frac{\lambda \sqrt{\epsilon'}}{2\pi \epsilon''} \quad (1)$$

$$\epsilon' = f(m_v, S, C), \quad \epsilon'' = g(m_v, S, C) \quad (2)$$

In which, ϵ' and ϵ'' are the real and imaginary parts of soil dielectric constant, expressed as a function of soil moisture content m_v , soil clay content C and sand content S . m_v is the soil moisture content, unit cm^3/cm^3 , S and C indicates the sand and clay content in soil, respectively. P is the penetration depth of electromagnetic wave, λ is the radar wavelength.

The above equation was differentiated to obtain the sensitivity of penetration depth of electromagnetic wave with different bands to soil moisture variation.

$$P' = \lambda / 2\pi (\sqrt{\epsilon'} / \epsilon'')' \quad (3)$$

Thus, the sensitivity between the penetration depth of radar electromagnetic wave and soil moisture change directly depends on the radar wavelength λ , that is, the longer the radar wavelength, the higher the sensitivity for soil moisture variation. Therefore, compared with the X-band and C-band SAR signal, the change of electromagnetic wave penetration depth of L-band SAR signal is more significantly affected by the change of soil moisture. In other words, L-band SAR data was applied to monitor natural land surface deformation information, it is necessary to consider the interference phase component caused by surface soil moisture change.

Through the formula (1), the penetration depth of SAR signals with different frequency to natural land surface with different soil components and soil moisture content can be obtained. And it can be concluded that soil moisture change will induce electromagnetic

wave penetration depth variation, thus making corresponding contributions to the interferometric phase ϕ_s .

$$\phi_s = (P_2 - P_1) \frac{4\pi}{\lambda} \quad (4)$$

In which, P_1 and P_2 are the corresponding electromagnetic wave penetration depth with different soil moisture content, respectively.

Using multi-temporal SAR data as inputs, the interferometric phase information is obtained through registration, resampling, filtering and interference processing. The interferometric phase includes terrain phase, deformation phase, soil moisture change induced phase, orbit error phase, atmosphere phase and ionospheric phase components, as shown in the formula:

$$\phi_{int} = \phi_{def} + \phi_s + \phi_{orb} + \phi_{top} + \phi_{atm} + \phi_{ion} \quad (5)$$

In which, ϕ_{int} is the interferometric phase, ϕ_{top} is the terrain phase, ϕ_{def} is the deformation phase, ϕ_{orb} is the orbit error phase, ϕ_{atm} is the atmosphere phase, ϕ_{ion} is the ionospheric phase. Compared with the traditional expression formula of interferometric phase, the above formula mainly increases the interferometric phase component ϕ_s , which represents the interferometric phase caused by soil moisture change. It is also the phase component information that is not fully considered in traditional InSAR technique. For natural surface deformation monitoring, this component has a direct impact on high-precision surface deformation monitoring. Therefore, the developed scheme focuses on solving the influence of interferometric phase caused by soil moisture change on deformation monitoring, so as to obtain high-precision and reliable deformation details of natural land surface.

By eliminating the interferometric phase components that are irrelevant to the deformation characteristics, including the phase caused by soil moisture change, the atmospheric delay phase and the ionospheric delay phase, the interferometric phase information representing the deformation characteristics is obtained.

$$\phi_{def} = \phi_{int} - \phi_s - \phi_{atm} - \phi_{ion} \quad (6)$$

Therefore, the reliable and accurate deformation details can be obtained by using the optimized interferometric phase characterizing the natural land deformation characteristics.

4. Experimental results

4.1 SAR signal penetration variation analysis

Based on the relationship between the penetration depth of electromagnetic waves and parameters such as radar wavelength, soil dielectric constant and soil texture, the penetration capabilities of X-band, C-band and L-band SAR signals in the agricultural experimental area were respectively simulated and analyzed.

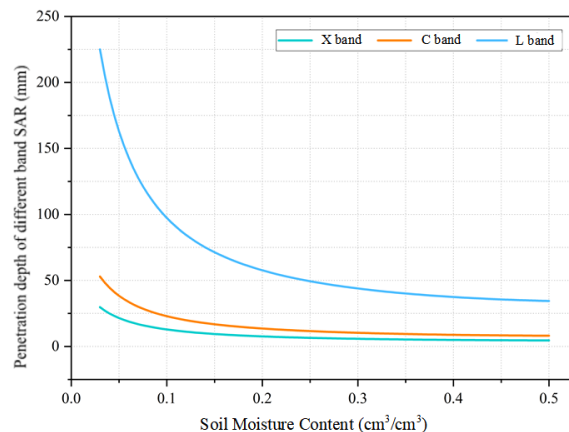


Figure 4. Penetration ability analysis of X, C and L band SAR signal for agricultural area.

Figure 4 shows the penetration capabilities of X-band, C-band and L-band SAR signals for agricultural soil. For relatively dry soil ($m_v < 0.10 \text{ cm}^3/\text{cm}^3$), SAR signals exhibit strong penetration capabilities on the agricultural soil, especially the L-band SAR signal can reach decimeter or even meter-level penetration depth. However, as the soil moisture content increases, the penetration depths of X-band, C-band and L-band SAR signals on the soil show a decreasing trend. When the soil moisture content reaches a moderate level ($m_v > 0.15 \text{ cm}^3/\text{cm}^3$), the penetration depth of X-band and C-band SAR signals into the agricultural experimental area are relatively close. As the soil moisture content increases, the penetration depths of X-band and C-band SAR signals gradually tend to be consistent. That is, the changes in the penetration depths of X-band and C-band SAR signals with respect to soil moisture variation have a relatively weak response sensitivity. Especially for agricultural areas, the soil moisture content is usually maintained at a medium level or above (the average soil moisture content in the experimental area is approximately $0.15 \text{ cm}^3/\text{cm}^3$). Therefore, for C-band and X-band SAR data, as the soil moisture changes, the corresponding electromagnetic wave penetration depth changes (InSAR phase information) are relatively small. That is to say, the interferometric phase information is not sensitive to soil moisture changes. Thus the penetration depth variation can be ignored for deformation monitoring by using the X-band or C-band SAR data. On the contrary, the L-band SAR corresponds to a longer wavelength and has a stronger penetration ability for the soil with different humidity in the experimental area. At the same time, as the soil moisture content changes, the penetration depth of the electromagnetic wave changes significantly.

To further evaluate the sensitivity of different wavelength electromagnetic wave penetration depth to the response of soil moisture changes, the derivative processing was carried out on the relationship between electromagnetic wave penetration depth and soil moisture changes, that is, the curvature analysis was conducted on the soil penetration depth change curve to obtain the sensitivity of different wavelength SAR data interferometric phase information to soil moisture changes. The results are shown in Figure 5. For C-band and X-band SAR data, due to their relatively weak response to soil moisture changes in electromagnetic wave penetration ability, the interferometric phase information has a lower sensitivity to soil moisture changes. L-band SAR, with its stronger penetration ability, the sensitivity of electromagnetic wave penetration depth to soil moisture change is high. Therefore, the

penetration depth component should be considered for agricultural area deformation monitoring using the L-band SAR data.

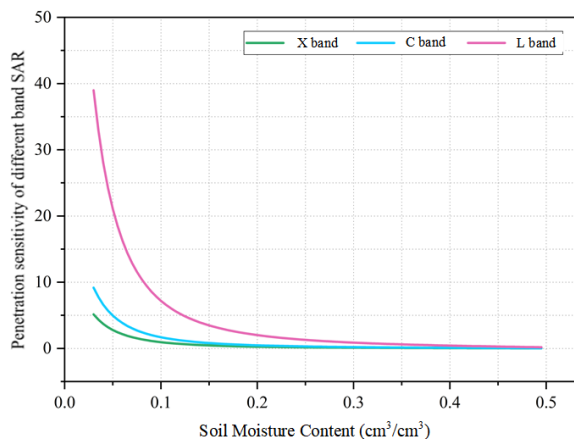


Figure 5. Sensitivity analysis of X, C and L band SAR signal for soil moisture variation.

4.2 Experimental analysis based on multi-temporal Lutan-1 SAR data

Based on the developed technical scheme, the multi-temporal Lutan-1 SAR data was applied for deformation monitoring over Shandong agricultural plain. The optical data over the study area from 16 September 2023 to 4 January 2024 was shown as follows.

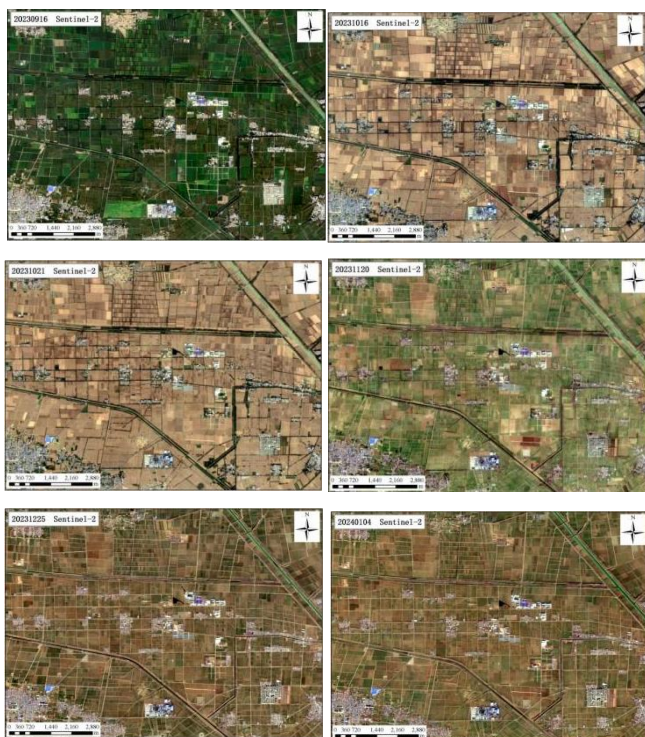
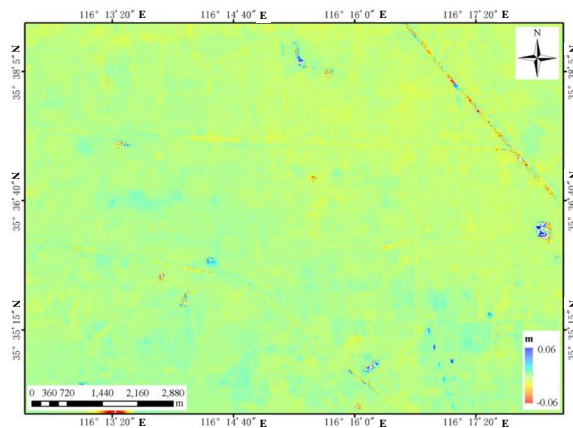


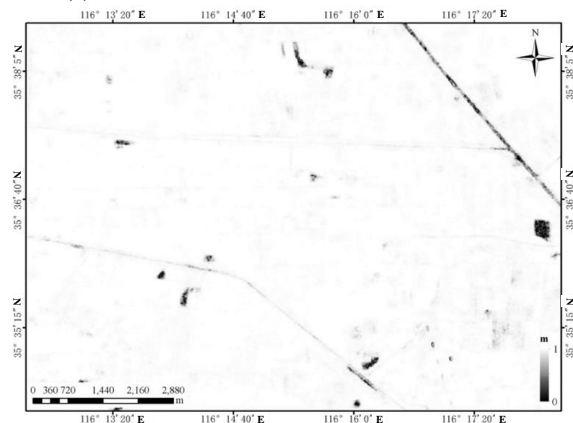
Figure 6. Multi-temporal optical data over the study area.

The Lutan-1 SAR data acquired on winter was applied for analysis and discussion. From 12 November to 10 December 2023, the study area show high coherence characteristics with an average coherence coefficient of 0.93, shown as Figure 7 (b). There is no obvious deformation details in the result of differential

interferometry during this period, shown as Figure 7 (a). Compared with the optical images in 20 November and 25 December 2023, it can be found that there was no obvious change in the agricultural area during this period. The agricultural area was covered by winter wheat with a low degree of surface coverage. The winter wheat entered the overwintering period after emergence, during which its growth basically stopped. Agricultural irrigation was not carried out in the farmland during this period, and the differential interference results showed no obvious information.



(a) Differential interference deformation results

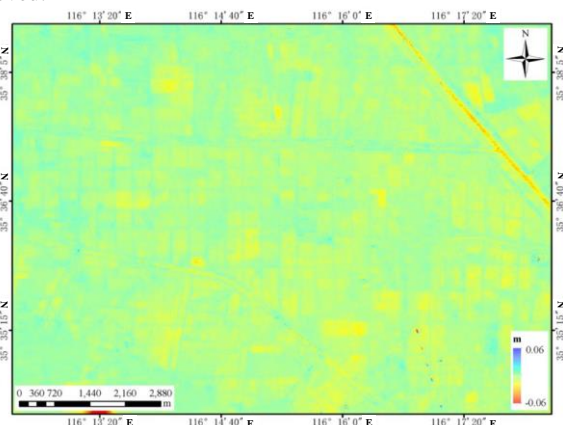


(b) Coherence coefficient

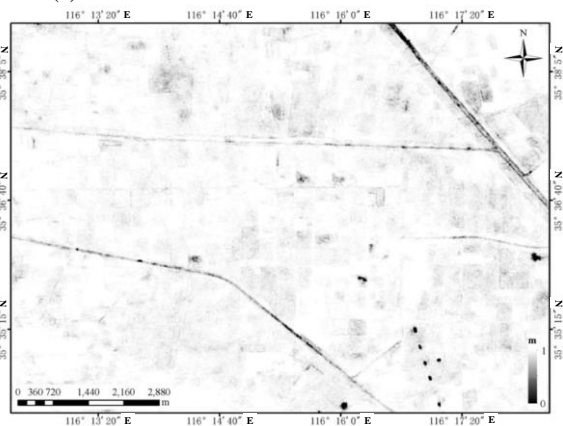
Figure 7. Differential interference deformation results and coherence over the study area from 12 November to 10 December 2023.

In addition, the Lutan-1 SAR data acquired on 10 December 2023 and 7 January 2024 were applied for further analysis and discussions. The overall deformation of the differential interference results is small, in which there are obvious 'deformation' signals in the cultivated land, shown as Figure 8 (a). The 'deformation' area is consistent with the contour of the cultivated land, majority deformation magnitude of the 'deformation' area is within 2 cm to 4 cm, and the coherence coefficient is high over the cultivated area with an average value of 0.87, shown as Figure 8 (b). Comparing with the optical images in 25 December 2023 and 4 January 2024, it can be found that there is no obvious change in the cultivated land during this period, and sparse winter wheat covered over the agricultural area. Considering that the local winter wheat is irrigated from late November to early December, the soil moisture changes significantly during this period.

According to the above analysis, the imaging time of the main image is December 10, which is close to the overwintering water pouring time, the soil moisture content is high after the water pouring, and the penetration ability of SAR signal is poor. The imaging time of the secondary image is far from the irrigation time, and the soil moisture content decreases obviously. At this time, the penetration ability of SAR signal is better, and the electromagnetic wave penetrates to a certain depth below the soil surface. The Lutan-1 data acquired on the two stages were used for interferometric applications. Due to the difference in the propagation path of electromagnetic wave caused by the significant change of soil moisture, the result of differential interference showed obvious 'subsidence deformation', and the deformation area was highly consistent with the contour of cultivated land. This result was mainly induced by the agriculture irrigation carried out in separate plots. The experiment indicated that obvious interferometric phase can be induced by soil moisture variation, which is an error factor for reliable deformation monitoring over natural land surface. The monitoring results of Shandong agricultural area are consistent with actual agricultural activities, which provide an important support for reliable deformation monitoring over agricultural area. In order to obtain the accurate and reliable deformation results over agricultural area, the soil moisture variation effects for interferometric phase should be fully considered. The soil moisture variation induced interferometric phase should be removed from the InSAR observations, thus to obtain the accurate interferometric phase information characterizing the surface deformation details. Finally, the natural land surface deformation information with high precision can be achieved.



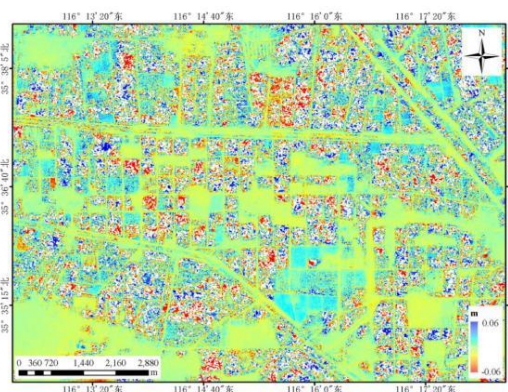
(a) Differential interference deformation results



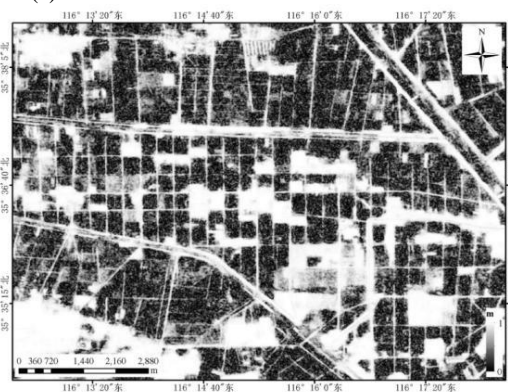
(b) Coherence coefficient

Figure 8. Differential interference deformation results and coherence over the study area from 10 December 2023 to 7 January 2024.

Furthermore, the Lutan-1 SAR data acquired on 17 September 2023 and 15 October 2023 were applied for further analysis and discussions. The results were shown as Figure 9. Due to the harvesting of crops in this area, significant land surface changes occurred on the agricultural area, resulting in an obvious coherence decrease in the interferograms with an average coherence coefficient of 0.31. Especially for the harvesting area, the coherence coefficient is extremely low. Therefore, there are obvious noise in the interferograms, and the differential interferometric information can not be effectively obtained for most of the agricultural area. For different phenological stages of crops, the applicability of InSAR technique for land deformation monitoring change significant. The agricultural area deformation can be effectively obtained in combination with soil moisture variation contribution during winter.



(a) Differential interference deformation results



(b) Coherence coefficient

Figure 9. Differential interference deformation results and coherence over the study area from 17 September 2023 to 15 October 2023.

5. Conclusions

In order to obtain the reliable deformation information over natural land surface, the phase component induced by soil moisture variation was analyzed and simulated in this research. Furthermore, the theoretical foundation was analyzed and discussed. In addition,

the multi-temporal Lutan-1 SAR data was applied for experiment analysis. The following conclusions were summarized.

1. For natural surface deformation monitoring, such as agricultural area, the phase component induced by soil moisture variation should be considered, especially for L-band SAR data.

2. Obvious 'deformation details' was detected by multi-temporal Lutan-1 SAR data over Shandong agricultural Plain. Due to the irrigation of winter wheat, the interferometric phase information was induced by the soil moisture variation, which is also an error factor for accurate deformation monitoring. In order to obtain the accurate and reliable deformation results over agricultural area, the soil moisture variation effects for interferometric phase should be fully considered.

3. It is promising to obtain the phase component induced by soil moisture variation, thus there is every reason to believe that the reliable and accurate deformation details over agricultural area can be achieved by effectively removing the soil moisture variation effects.

Acknowledgements

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References

Gabriel, A.K., Goldstein, R.M., Zebker, H.A. 1989: Mapping Small Elevation Changes over Large Areas: Differential Radar

Interferometry. *Journal of Geophysical Research: Solid Earth*, 94(B7), 9183-9191.

Ji, Y.N., Zhang, X., Li T., et al., 2023: Mining Subsidence Monitoring Based on Lutan-1 Monostatic and Bistatic Data. *Remote Sensing*, 15, 5668.

Rabus, B., When, H., Nolan, M. 2010: The Importance of Soil Moisture and Soil Structure for InSAR Phase and Backscatter, as Determined by FDTD Modeling. *IEEE Transactions on Geoscience and Remote Sensing*, 48(5): 2421-2429.

Zhang, X., Tang, X.M., Li, T. et al., 2024: Multi-temporal Monitoring for Road Slope Collapse by Means of LUTAN-1 SAR Data and High Resolution Optical Data. *ISPRS TC 1 Mid-term Symposium "Intelligent Sensing and Remote Sensing Application"*, 13-17 May 2024, Changsha.

Zhang, X., Zhao, H., Tang, X.M., et al., 2025: Large Gradient Subsidence Monitoring in Mining Area Based on Lutan-1 SAR Images. *ISPRS Geospatial Week (GSW 2025)*, 6-11 April 2025, Dubai.

Zhang, X., Tang, X.M., Gao, X.M. et al., 2020: Soil Moisture Estimation Based on the AIEM for Bare Agricultural Area. *IGARSS, Virtual Symposium*, 4723-4726.

Zwieback, S., Hensley, S., Hajnsek, I. 2015: Assessment of soil moisture effects on L-band radar interferometry. *Remote Sensing of Environment*, 164, 77–89.