Radar remote sensing for archaeology in Hangu Frontier Pass in Xin’an, China

A H Jiang\textsuperscript{1,2}, F L Chen\textsuperscript{2,3}, P P Tang\textsuperscript{2,3}, G L Liu\textsuperscript{1}, W K Liu\textsuperscript{1}, H C Wang\textsuperscript{4}, X Lu\textsuperscript{4} and X L Zhao\textsuperscript{5}

\textsuperscript{1} Geomatics College, Shangdong University of Science and Technology, Qingdao 266590, China; \\
\textsuperscript{2} Key Laboratory of Digital Earth Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, No. 9 Dengzhuang South Road, Haidian District, Beijing 100094, China; \\
\textsuperscript{3} International Centre on Space Technologies for Natural and Cultural Heritage under the Auspices of UNESCO; \\
\textsuperscript{4} Institute of conservation and management of Xin’an Hangu Pass (Han Dynasty), Cultural relic bureau of Xin’an County, Luoyang, 471800, China; \\
\textsuperscript{5} Institute of cultural relics and archaeology of Zhengzhou city, Zhengzhou, 450052, China.

E-mail: jiang.ai.hui@163.com

Abstract. As a non-invasive tool, remote sensing can be applied to archaeology taking the advantage of large scale covering, in-time acquisition, high spatial-temporal resolution and etc. In archaeological research, optical approaches have been widely used. However, the capability of Synthetic Aperture Radar (SAR) for archaeological detection has not been fully exploded so far. In this study, we chose Hangu Frontier Pass of Han Dynasty located in Henan Province as the experimental site (included into the cluster of Silk Roads World Heritage sites). An exploratory study to detect the historical remains was conducted. Firstly, TanDEM-X SAR data were applied to generate high resolution DEM of Hangu Frontier Pass; and then the relationship between the pass and derived ridge lines was analyzed. Second, the temporal-averaged amplitude SAR images highlighted archaeological traces owing to the depressed speckle noise. For instance, the processing of 20-scene PALSAR data (spanning from 2007 to 2011) enabled us to detect unknown archaeological features. Finally, the heritage remains detected by SAR data were verified by Ground Penetrating Radar (GPR) prospecting, implying the potential of the space-to-ground radar remote sensing for archaeological applications.
1. Introduction
Remote sensing was applied in archaeology almost since the beginning of aerial photography owing to the synoptic observation of large-scale landscapes. This technology together with the geophysical prospection have been indispensable tools for the investigation of ancient cities and surrounding landscapes without causing a loss of archaeological evidence. Moreover, it is beneficial for the schedule of archaeological excavations [1, 2].

Nowadays, Synthetic Aperture Radar (SAR) systems have not been widely used in archaeological prospection. This is mainly due to the rather complex nature of SAR data processing. However, the advantages of SAR remote sensing for archaeology are obvious. First, SAR systems are capable of acquiring data in all-weather, all-day conditions. Second, digital surface models with a high height accuracy can be generated by using interferometric SAR, and in turn the terrain data can be used for the ortho-rectification of SAR images as well as very high-resolution (VHR) optical data [2, 3].

Up to now, there are several studies have been undertaken to assess the potential of satellite SAR data [3, 4, 5]. Archaeological investigations conducted by SAR data have moved forward to another stage focusing on archaeological detection and monitoring by developing technologies related to the polarimetric enhancement, backscattering change detection, motion detection and diagnosis. The second-generation spaceborne SAR data, represented by multi-band, polarization as well as high-resolution, e.g., ALOS PALSAR-2, TerraSAR/TanDEM-X and Cosmo-SkyMed, are favorable in archaeology. For instance, the X-band COSMO-SkyMed data have been used for the detection of archaeological marks in diverse environmental conditions [6].

2. Experimental site and data
2.1. Experimental Site
Hangu Frontier Pass of Han Dynasty, in Xin’an County of Henan Province, China, was built in the Western Han Dynasty (114 B.C.). Hangu Frontier Pass is the gate as well as one of most important defences of Xi’an that was the capital of Western Han. When Luoyang was chosen as the capital in Eastern Han Dynasty, the Pass was even more important and nominated as the head of Eight Great Passes. After that, as a military pass, it held a responsible position until Sui and Tang Dynasties. It was also the first-round pass of the Silk Road Corridor. The pass was not only a military fortress but also the monument that had witnessed the prosperity of the Silk Trade. As a heritage site of "Silk Road Routine", it was listed as a World Heritage Site in 2014. History records that the Hangu Frontier Pass of Han Dynasty stretched from Yellow River to Luohe River, with a dimension of approximately 60 kilometers (Figure 1). The storehouse of Hangu Frontier Pass of Han Dynasty was excavated in 1998, and the core section in Xin’an was excavated in 2012. However, most sections of Hangu Frontier Pass are still unknown, in particular the lost ruin of San-kuan Pass (the southern end of Hangu Frontier Pass).
2.2. Data

Satellite SAR data have played an important role in archaeological prospecting. As an active survey method by transmitting microwave frequency signatures, SAR has several advantages such as all-weather and all-day acquisitions [7]. Three categories of microwave remote sensing data were acquired, including X-band TanDEM, L-band PALSAR-1 satellite images as well as GPR prospecting data from the field.

2.2.1. TanDEM-X. TanDEM-X is a SAR system which allows not only an independent operation from TSX-1 in mono-static mode but also supports synchronized operations [8]. The main objective of the TanDEM-X mission is to generate a high resolution global DEM by SAR interferometry (InSAR). The TanDEM CoSSC datasets for the DEM generation were listed in Table 1. In addition, the SRTM DEM (1 arc-second) of Hangu Frontier Pass has been used as the complementary data for the generation of TanDEM-X DEM.

| Date            | Pol./Path | Pixel size   | Angle of Incidence | Baseline(perp) | Height of Ambiguity |
|-----------------|-----------|--------------|--------------------|----------------|---------------------|
| 08 January 2014 | HH/Desc   | 2.26 × 2.03m | 37.1°              | 112.9          | 52.6m               |

2.2.2. PALSAR. L-band ALOS PALSAR-1 data applied in this study were acquired with two modes, including the fine-beam dual-polarization (HH and HV) and the single-polarization (HH). In total, 20 scenes of PALSAR-1 were collected. There are 9 scenes acquired in single-polarization with the pixel spacing of 4.68m and 3.15m in range and azimuth direction, respectively, and the other 11 scenes acquired in dual-polarization with the pixel spacing of 9.37m and 3.15m in range and azimuth direction, respectively (see Table 2).

| No. | Acquisition(Day Month Year) | Pol. | No. | Acquisition(Day Month Year) | Pol. |
|-----|------------------------------|------|-----|------------------------------|------|
| 1   | 03 January 2007              | HH   | 11  | 23 February 2009             | HH   |
2.2.3 Ground-Penetrating Radar. There are several geophysical methods that can be used for the detection of archaeological features under beneath. One of them is the Ground-Penetrating Radar (GPR). When thousands of radar reflections are measured as antennas moving along transects within a grid, a three-dimensional imagery related to physical properties of soils, sediments and feature changes can be derived [1,9]. In this study, a sub-area with the occurrence of outer-south city-wall is measured by the GPR prospecting, as marked by a green rectangle in Figure 2.

3. Data processing

3.1. TanDEM-X Data Processing
TanDEM-X is the first mission which provides interferometric data in bistatic mode. There is a standard InSAR procedure for the interferometric processing of both monostatic and bistatic data [10]. The whole process for the high resolution DEM generation was done using the SARscape software. Figure 3 provides the flowchart adopted for the TanDEM-X DEM generation. The co-registration procedure was not needed for the co-registered CoSSC image pairs. Then the ridge lines were extracted using terrain analysis tools in ArcGIS software by utilizing TanDEM-X DEM data.
3.2. PALSAR Data Processing

The pixel-based image analysis and interpretation is generally prevailing in archaeological applications. Consequently, when multi-temporal SAR data were available, co-registration was an essential preprocessing step not only significant for the enhancement of features (e.g. temporal averaging) but also for the implementation of the change detection. The co-registration of PALSAR-1 data was conducted by using GAMMA software tools. In this procedure, it is generally preferable to register the lower-resolution image (dual-polarization data) into the higher-resolution image (single-polarization data) to preserve the spatial details. The following $1 \times 3$ multi-looking (looks in range and azimuth, respectively) generated amplitude SAR products with a pixel spacing of $4.7m \times 9.4m$. In order to enhance the spatial anomalies, a temporal stacking technique was applied. In such a way, the emerging wall-remains become more evident that was beneficial for the identification of archaeological traces using SAR images.

3.3. GPR Data Processing

For the selected sub-area (highlighted by the green rectangle in Figure 2), 15 GPR profiles were carried out using the RIS K2-Fastwave (K2FW). Taking the occurrence of buried remains as well as the penetration capability of radar signals, 100MHz antenna with the monostatic type was applied. The spatial dimension of the sub-area is $60m \times 30m$. A 2m step-size was selected for the next profile in the data acquisition. The GRED software has been used to process the data. Image filtering and the antenna gain correction were jointly used for the signal enhancement, including the processing steps.
of background removal, vertical bandpass filter, linear gain and smoothed gain.

4. Results and analysis

4.1. Topography Analysis

Ridge line is the boundary of terrain changes; therefore, it is an effective factor for the analysis of topography. Generally, there is a close relationship between the occurrence of ancient passes and the direction of ridge lines. Owing to the high-resolution of DEM data (with a relative height accuracy of 2m), the primary and thin ridge lines were all extracted (see Figure 4). Considering the collapse phenomenon, the identification of ram-earthed outer walls (extending from the core zone to the Yellow River or to the San-kuan Pass) by ridge lines was challenging. Nonetheless, the spatial correlation could be observed, such as the direction of several outer-wall sections followed the trend of ridge lines, particularly for the section as marked by the green rectangle in Figure 4.

4.2. Temporal Stacking

The processing of PALSAR imagery was aimed at the enhancement of features linked to the occurrence of frontiers. For the test site selected (marked by green rectangle in Figure 5), the capability of multi-temporal PALSAR imagery in identifying spatial anomalies of emerging remains was assessed. The comparison of temporal-stacked imagery and the single-acquisition imagery was illustrated in Figure 5. A more remarkable visualization of the latter demonstrated that multi-temporal stacking provides a better performance for the detection of archaeological traces due to the suppressed speckle noise in SAR data. Furthermore, one significant feature high-probably linked

![Figure 5. Comparison between Single-date and Multi-temporal SAR data](image)
to the stretching of Hangu Frontier Pass was identified in the temporal-averaged imagery (Figure 6), as marked by red polylines. According to the historical document, this archaeological trace was coincidence with the trend of Hangu Frontier Pass approaching to the Yellow River.

4.3. GPR Prospection

GPR profiles of the investigated area show reflections that could be associated with the occurrence of buried ancient walls. Figure 7 showed the vertical profile of L4 with a 60m length in T direction. The penetration depth of radar signatures is approximately 5m. This profile pointed out reflection anomalies with a depth of 3.5m, which could be related to the south outer-wall of the ancient city. Moreover, several other hyperbolas were also visible in the L4 profile caused by the reflection from the stones and broken tiles buried.

5. Summary

In this study, data jointly from satellite SAR images and GPR prospecting have been analyzed in order to assess their capability in detecting archaeological remains in Hangu Frontier Pass of Han Dynasty. The spatial correlation of ridge lines with the occurrence of outer walls was rather preliminary and thus further investigations were required. Temporal-stacking of PALSAR-1 imagery enabled us to
detect unknown archaeological remains. Finally, buried archaeological remains, particularly the south outer wall, were detected by the profile of the GPR prospecting. Consequently, it is feasible and the time to develop a methodology framework of radar remote sensing in archaeology by integration the space and ground observations.

Acknowledgements
This work was supported by funding from Hundred Talents Program of the Chinese Academy of Sciences (CAS) (Y5YR0300QM), CAS-TWAS Centre of Excellence on Space Technology for Disaster Mitigation “Joint Program on Space Technology for Disaster Mitigation in Asia”, and Scientific Research Foundation Project for the Talents of Shandong University of Science and Technology (2014RCJJ047).

References
[1] Balz T, Liao M, Caspari G, Fu B, Rosenbauer R and Erasmi S 2015 Analyzing TerraSAR-X Staring Spotlight Mode Data for Archaeological Prospections in the Altai Mountains IEEE 5th APSAR 528-532
[2] Rowlands A and Sarris A 2007 Detection of exposed and subsurface archaeological remains using multi-sensor remote sensing J. Arc. Sci. 34(5) 795-803
[3] Linck R, Busche T, Buckreuss S, Fassbinder J W E and Seren S 2013 Possibilities of Archaeological Prospection by High-resolution X-band Satellite Radar - a Case Study from Syria Arc. Pro. 20(2) 97-108
[4] Chen F, Lasaponara R and Masini N 2015 An overview of satellite synthetic aperture radar remote sensing in archaeology: From site detection to monitoring J. Cul. Her.
[5] Chen F, Masini N, Yang R, Milillo P, Feng D and Lasaponara R 2014 A Space View of Radar Archaeological Marks: First Applications of COSMO-SkyMed X-Band Data Rem. Sen. 7(1) 24-50
[6] Moreira A, Krieger G, Hajnsek I, Hounam D, Werner M, Rieger S and Settelmeyer E 2004 TanDEM-X A TerraSAR-X add-on Satellite for Single-pass SAR Interferometry IEEE IGARSS 2 1000-1003
[7] Gruber A, Wessel B, Huber M, Breunig M, Wagenbrenner S and Roth A 2012 Quality Assessment of First TanDEM-X DEMs for Different Terrain Types EUSAR. 9th Eur. Conf. 101-104
[8] Krieger G, Fiedler H, Hajnsek I, Eineder M, Werner M and Moreira A 2005 TanDEM-X Mission Concept and Performance Analysis IEEE Int. Geo. Rem. Sen. Sym. 7 4890-4893
[9] De Reu J, Bourgeois J, De Smedt P, Zwertvaegher A, Antrop M, Bats M and Crombé P 2011 Measuring the relative topographic position of archaeological sites in the landscape, a case study on the Bronze Age barrows in northwest Belgium J. Arc. Sci. 38(12) 3435-3446.
[10] Pandit A Ramsankaran R and Rao Y S 2014 Generation and validation of the interferometric SAR DEMs from TanDEM-X data for Gangotri and Hamtah Glaciers of Indian Himalayas Pro. Tech. 16 793-805.