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Comparative Analysis of Results from Differences in Synthetic Aperture Radar (SAR) Satellite Data Resolution and Analysis Tools

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In this study, commercial (GAMMA) and free [Stanford method for persistent scatterers (StaMPS)] analysis tools, along with synthetic aperture radar (SAR) data of different resolutions, were compared using the interferometry synthetic aperture radar (InSAR) technique to monitor ground displacement at an environmental infrastructure facility site in southeastern Korea. Persistent scatterer interferometry SAR (PSInSAR) analysis was performed using SAR data from Sentinel-1, a representative satellite operating at the C-band frequency, and TanDEM-X, which provides X-band frequency data. The two tools showed similar trends, with root mean squared deviation values of 1–4 mm in areas containing artificial structures. However, differences emerged depending on data resolution and properties in areas with low signal interference, such as large and flat environmental infrastructure sites. The TanDEM-X high-resolution X-band data exhibited a higher reliability than the Sentinel-1 data, confirming their suitability for displacement detection in facilities such as waste landfills. Furthermore, because the StaMPS software has limitations in selecting persistent scatterers, the GAMMA-based results were more stable. These findings highlight the need to simultaneously employ high-resolution SAR data and highly reliable analysis tools for accurate surface displacement monitoring in vulnerable areas, such as waste landfills, and demonstrate the applicability and limitations of SAR-based displacement monitoring in similar environments.

1. Introduction

Satellites have increasingly been applied in various fields, with many new satellites launched into Earth orbit annually, continuously increasing their numbers. Specifically, they serve diverse

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purposes such as providing global positioning services and using synthetic aperture radar (SAR) technology for imaging and monitoring terrestrial sites. As the number of satellites with SAR capabilities has increased, more diverse studies have been utilizing the technique for various applications, including the analysis of ground displacement in urban areas,[(1)] the analysis of the differential settlement of long-span bridge piers,[(2)] and the analysis of impacts of tunnel excavation on buildings.[(3)]

Various techniques exist for observing ground or structural displacement through SAR data, but the interferometry SAR (InSAR) technique is the most commonly applied. The InSAR technique utilizes complex data, obtains phase-difference information from more than two SAR image datasets, extracts high-resolution images, and confirms change detection. The technique has been studied in numerous countries across diverse fields such as volcanic activity detection, Antarctic glacier monitoring, ground subsidence, and surface change analysis.[(4)] Tu *et al.*[(5)] analyzed landslide deformation at China's Three Gorges Dam reservoir using the DInSAR technique with overlapped Sentinel-1 SAR data and suggested a highly efficient method for monitoring by analyzing the hydrological mechanisms of landslides. Another study utilized the persistent scatterer InSAR (PSInSAR) analysis technique and an integrated multi-criteria decision-making framework based on a geographical information system to comprehensively assess ground deformation and subsidence risks and social vulnerability along high-speed railway sections to identify vulnerable sections and suggest measures for maintenance-decision making.[(6)] In another study, the characteristics of ground cracks and deformation in Beijing, China, were analyzed using the small baseline subset (SBAS)-InSAR technique and prevention measures were proposed.[(7)]

Although numerous studies have been conducted, no comparative analysis of the differences among the various programs used for interpretation and the different satellite SAR datasets has yet been conducted. In this study, we examined how to utilize SAR satellite data to efficiently monitor environmental infrastructure facilities for a long-term period. We employed SAR data from two satellites and leveraged the PS-InSAR technique to observe ground displacement. We also conducted a comparative analysis of the time-series ground displacement observation results to confirm differences between commercial (GAMMA) and free (StaMPS) analysis tools. StaMPS is a PS-InSAR processing algorithm developed by Stanford University,[(8)] and the GAMMA software is a SAR image processing software developed by GAMMA Remote Sensing. We compared analysis results on the basis of differences in the analysis tools and resolutions of the SAR data, evaluating their applicability for monitoring ground displacement at waste landfill sites. In addition, we selected a landfill facility—an extensive open area—as the study site, providing a region more suitable for time-series analysis compared with those used in previous studies.

2. Target Site and Analysis Methods

2.1 Target site

We analyzed ground displacement at a waste landfill site, which is an environmental infrastructure facility, in Pohang City in southeastern Korea, and its surrounding areas. Figure 1 shows a Google Earth image of the target site.

Fig. 1. (Color online) Target site and location of the targeted landfill facility (red dot).

2.2 Utilization of SAR data and digital surface model construction methods

2.2.1 SAR data

We utilized the following SAR data: SAR data from the Sentinel-1 satellite operated by the European Space Agency (ESA)(9) and SAR data from the TanDEM-X satellite operated by the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt; DLR).(10)

Sentinel-1 consists of two satellites (Sentinel-1A/1B) with a C-band SAR operating at a center frequency of 5.4 GHz; these two satellites fly in the same orbit with a 180° phase difference and observe the Earth's surface on a 12-day cycle. However, acquiring data after December 23, 2021 was impossible because of a power-supply failure on Sentinel-1B; thus, we utilized only 19 SAR data images from the Sentinel-1A satellite, which covered the target site from October 10, 2023 to October 4, 2024. The spatial resolutions of the SAR data used were 2.4 m in the range direction and 13.9 m in the azimuth direction.

The TanDEM-X satellite has an X-band SAR at a center frequency of 9.65 GHz and is the twin satellite of TerraSAR-X, which is equipped with the same SAR. Both satellites have an 11-day temporal resolution and are effective at acquiring high-resolution SAR data owing to their use of high-frequency microwaves. We obtained a total of seven TanDEM-X SAR data images at 11-day intervals from September 1 to November 6, 2024, in the upward trajectory of the satellite, which were observed in StripMap mode with a VV polarized wave. The spatial resolutions of the TanDEM-X SAR SLC data were 1.4 m in the range direction and 2.2 m in the azimuth direction.

Figures 2 and 3 show examples of the Sentinel-1 and TanDEM-X SAR data; notably, Sentinel-1 and TanDEM-X observed wider areas than indicated in the figures. As shown in Figs.

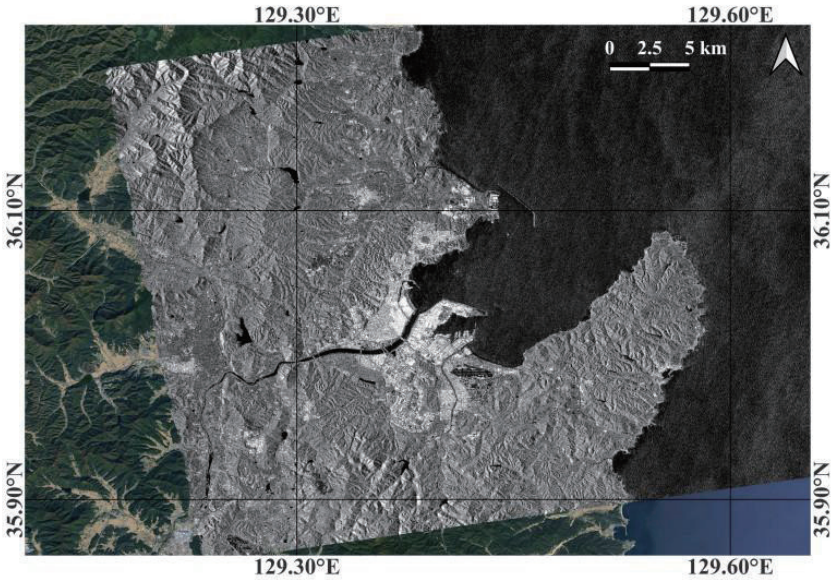

Fig. 2. (Color online) Sentinel-1 SAR data (September 22, 2024).

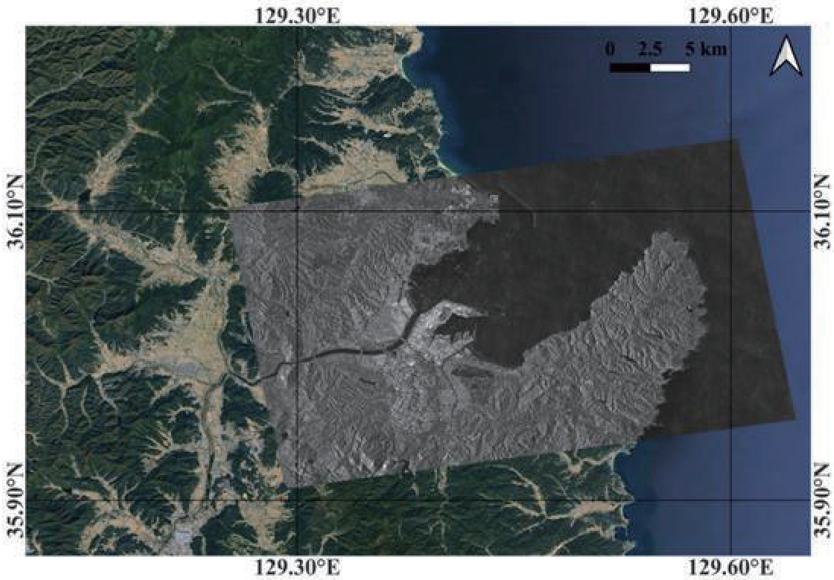

Fig. 3. (Color online) TanDEM-X SAR data (September 23, 2024).

2 and 3, we subset the images of the target environmental infrastructure facility site to improve data-processing efficiency.

Accurate co-registration between SAR datasets and the removal of the topographic phase in interferometric SAR processing must be carried out before applying the InSAR technique for calculating surface displacement. SAR image co-registration is the process of aligning the slave image to the master image with subpixel geometric and phase accuracy. Inter-image offsets are estimated using coherence-based or intensity cross-correlation methods, and the resulting co-registration matrix is applied to align all SAR pixels to the same ground position. Accurate co-registration is essential for ensuring interferometric phase quality and, consequently, for improving the reliability of displacement measurements. In this study, we employed the Copernicus GLO-30 Digital Elevation Model (DEM) for co-registration between SAR images and the removal of the topographic phase in interferometric SAR processing. Figure 4 shows the Copernicus GLO-30 DEM of the target site.

2.3 Surface displacement observation techniques

We applied the DInSAR and time-series InSAR techniques to Sentinel-1 and TanDEM-X SAR data to compare and analyze surface displacement observation results for the landfill and surrounding areas. To implement the time-series InSAR technique, we chose the PSInSAR technique,[11] which enables displacement detection with precision at the several-millimeter level (Fig. 5). PS, which shows a strong but stable back scattering signal within an SAR data pixel, has the advantage of high spatial resolution; it can observe displacement at the resolution of

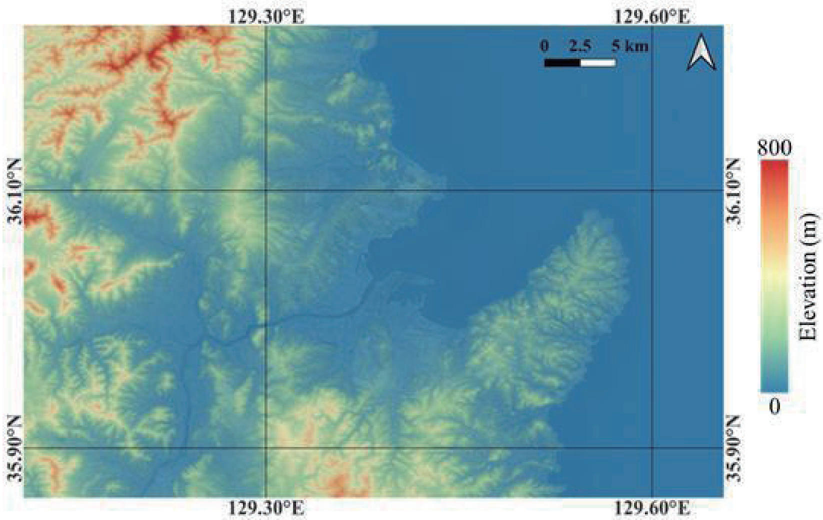

Fig. 4. (Color online) Copernicus GLO-30 DEM of the target site.

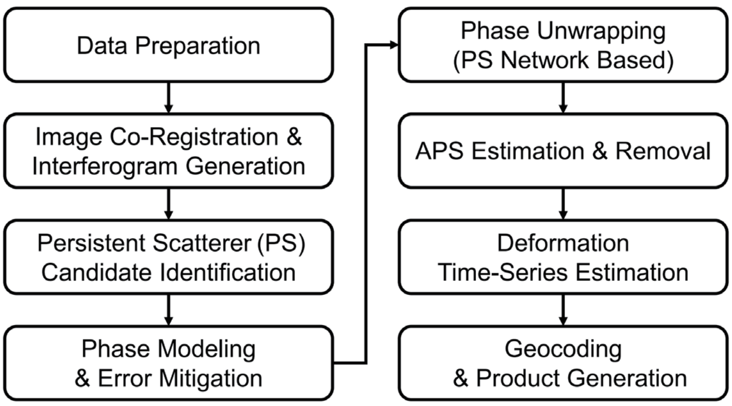

Fig. 5. PS-InSAR workflow for ground subsidence monitoring.

SingleLook Complex (SLC) data. Furthermore, given that this study investigates displacement across a broad area, this method was employed owing to its advantage in more effectively addressing various sources of error, including vegetation and seasonal effects, when analyzing overall displacement trends. PSInSAR performs InSAR by setting one of the multiple SAR datasets obtained in a time series as the reference data, and all other data as the secondary data. The reference data are selected by considering the perpendicular baseline distance to secondary data. The selection is generally made by deriving a perpendicular baseline distance with a small mean and variance. In this study, we selected the Sentinel-1 SAR data from May 1, 2024 (Fig. 6) and the TanDEM-X SAR data from September 23, 2024 (Fig. 7) as the reference data to perform PSInSAR.

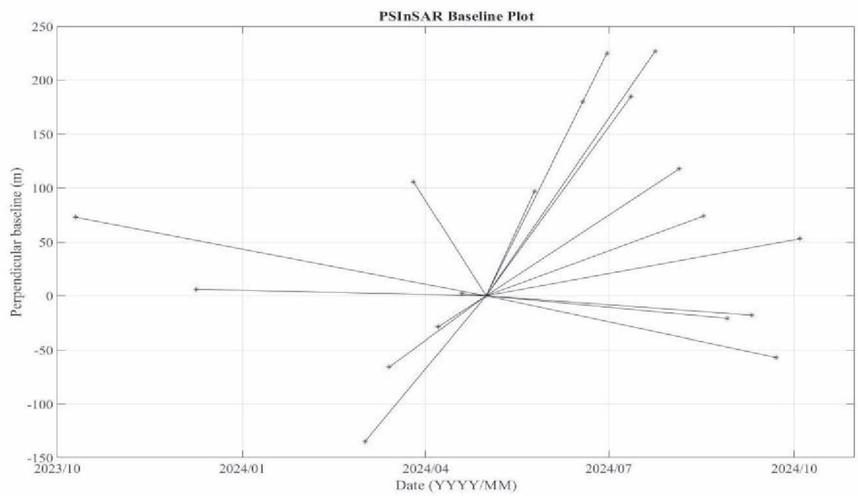

Fig. 6. Spatiotemporal baseline distance network of Sentinel-1 SAR interferometric pairs for PSInSAR implementation.

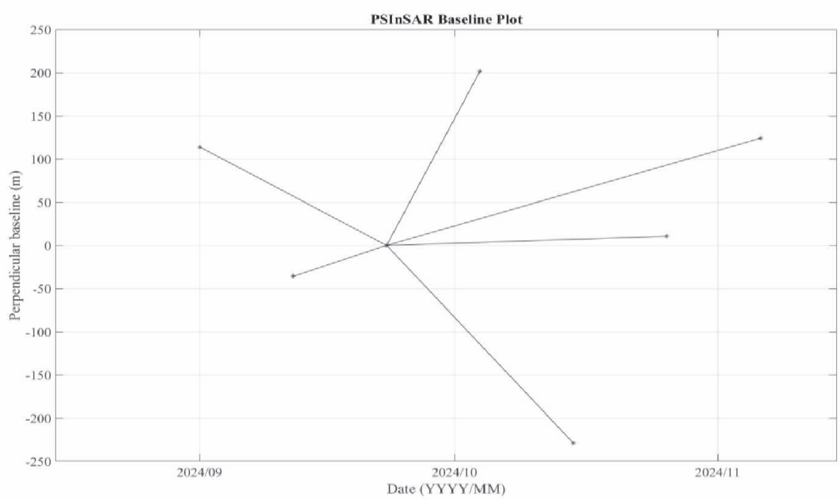

Fig. 7. Spatiotemporal baseline distance network of TanDEM-X SAR interferometric pairs for PSInSAR implementation.

3. Analysis Results

3.1 Comparative analysis of PSInSAR results based on the Sentinel-1 SAR data

We selected six points around the target waste landfill site to analyze and compare the time-series surface displacement outcomes in accordance with the two types of analysis tools and evaluated their mutual reliability. Figure 8 indicates six points at which a comparative analysis of displacement was performed using the satellite data of the target site and the StaMPS-based displacement velocity map. The six analysis points were selected as positions within the area of interest exhibiting relatively distinct differences in time-series displacement and displacement velocity compared with surrounding areas.

3.1.1 Point 1

Point 1 corresponds to the western part of the Pohang Sports Complex in Daedo-dong, Nam-gu, Pohang, South Korea (Fig. 9). The time-series displacement over one year, calculated using the two analysis tools, exhibited a root mean squared deviation (*RMSD*) of 3.3 mm with a very similar trend, with linear displacement velocity showing a small difference within 1 mm/yr. The PS in the western part of the Pohang Sports Complex has moved closer to the radar observation direction since mid-2024; however, this may partly reflect errors in the InSAR observations.

3.1.2 Point 2

Figure 10 shows the PSInSAR displacement velocity results from StaMPS and GAMMA software around the PS in Point 2 (Pohang Indoor Shooting Range, Yongheung-dong, Buk-gu, Pohang) and the time-series displacement calculated using each analysis tool. The *RMSD* between the time-series displacements from the two analysis tools was 3.85 mm, confirming a highly similar trend in displacement changes. The displacement trend in the Pohang Indoor

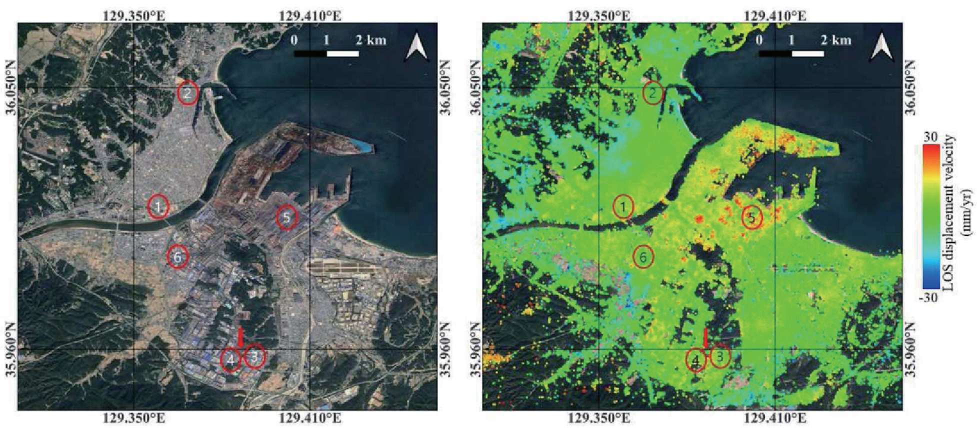

Fig. 8. (Color online) Satellite images and time-series displacement analysis results of six points subject to comparative analysis (Sentinel-1 data).

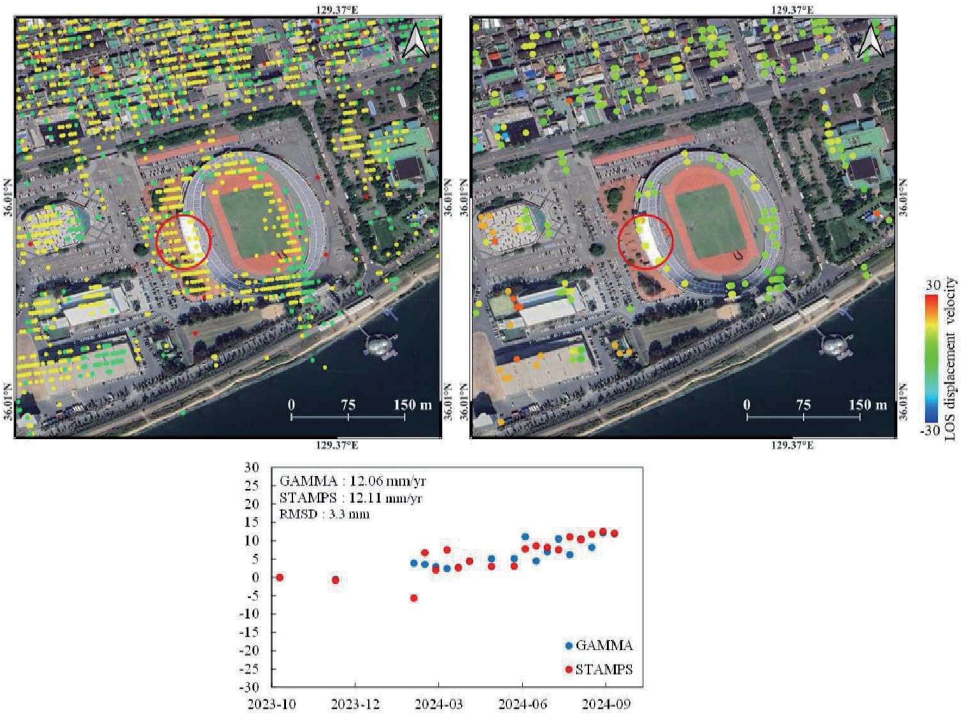

Fig. 9. (Color online) GAMMA (top left) and StaMPS (top right) results for the PS in Point 1.

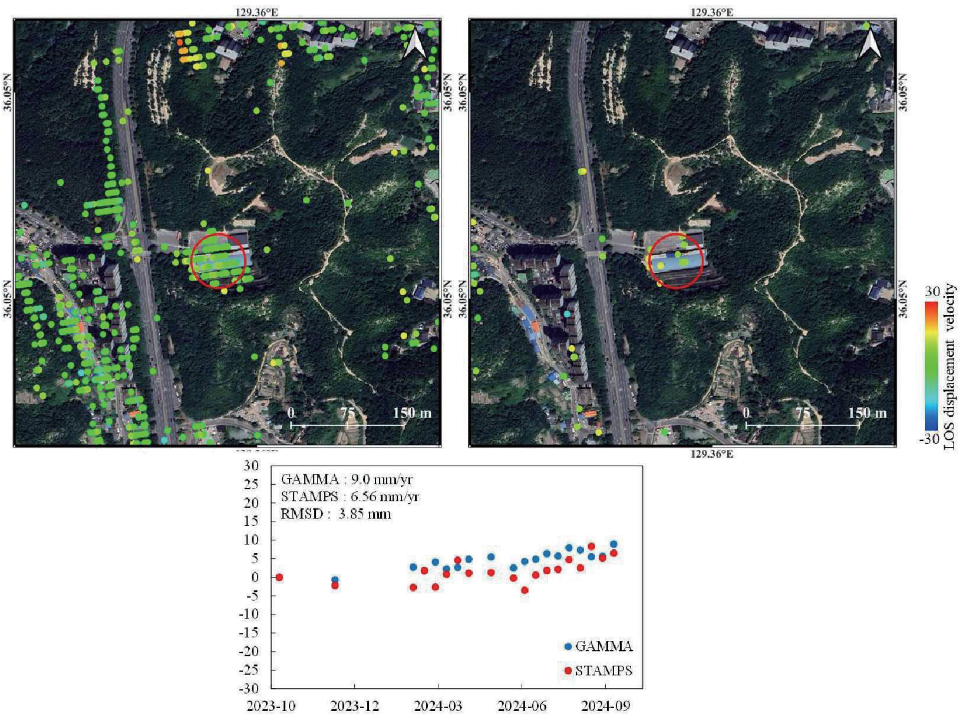

Fig. 10. (Color online) GAMMA (top left) and StaMPS (top right) results for the PS in Point 2.

Shooting Range was similar to that in the Pohang Sports Complex. The increase in displacement toward the radar direction after summer likely reflects the thermal expansion property of the structures. Nevertheless, the small magnitude of the displacement itself indicates a stable state.

3.1.3 Points 3 and 4

Point 3 corresponds to a building near the waste landfill (Daesong-myeon, Nam-gu, Pohang City), specifically Fairwind Plant 2 (Fig. 11), and Point 4 corresponds to the material storage yard at the No. 2 Product Yard of the Hyundai Steel Plant located south of the landfill (Fig. 12). The displacement results from different analysis tools at these two scatterers show *RMSD*s of 2.98 mm for Point 3 and 2.27 mm for Point 4, confirming a similar trend. For the factory building, displacement increased to some extent after the summer of 2024, as with the PS in Points 1 and 2. The large magnitude of displacement found at the PS in Point 4 was attributed to the increased quantity of cumulative materials. Although a large displacement was found, the two analysis tools yielded very similar displacements.

3.1.4 Point 5

Point 5 is one of the structures at POSCO Pohang Steelworks (Fig. 13). The two analysis tools yielded similar trends in displacement changes but showed an *RMSD* of 3.86 mm, with a large displacement velocity difference of more than 7 mm/yr. This result may partially reflect errors

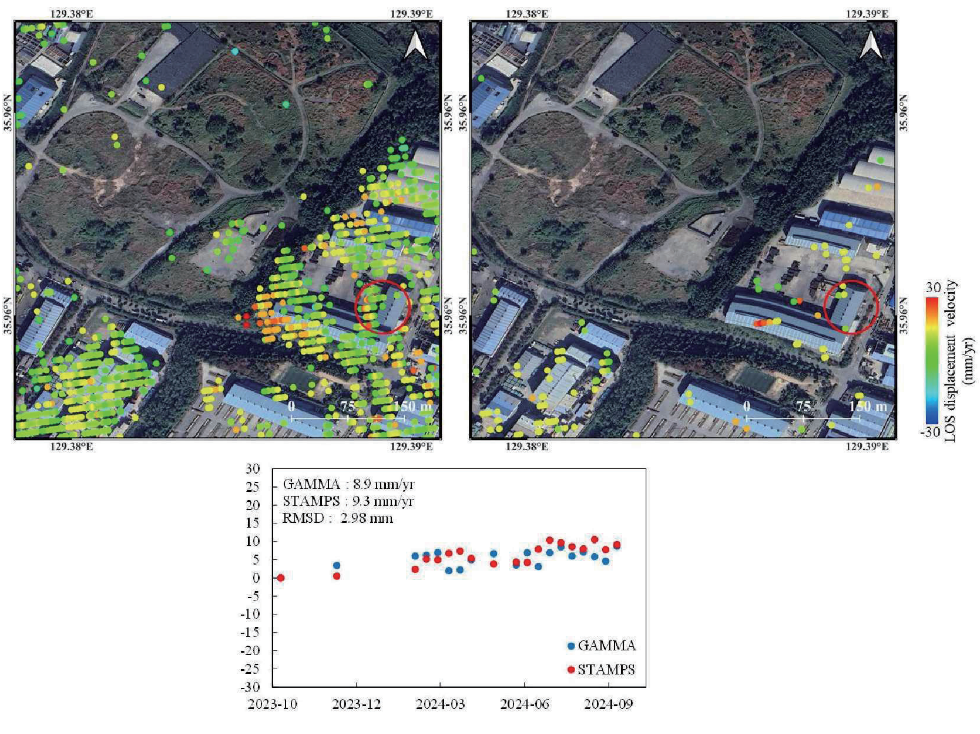

Fig. 11. (Color online) GAMMA (top left) and StaMPS (top right) results for the PS in Point 3.

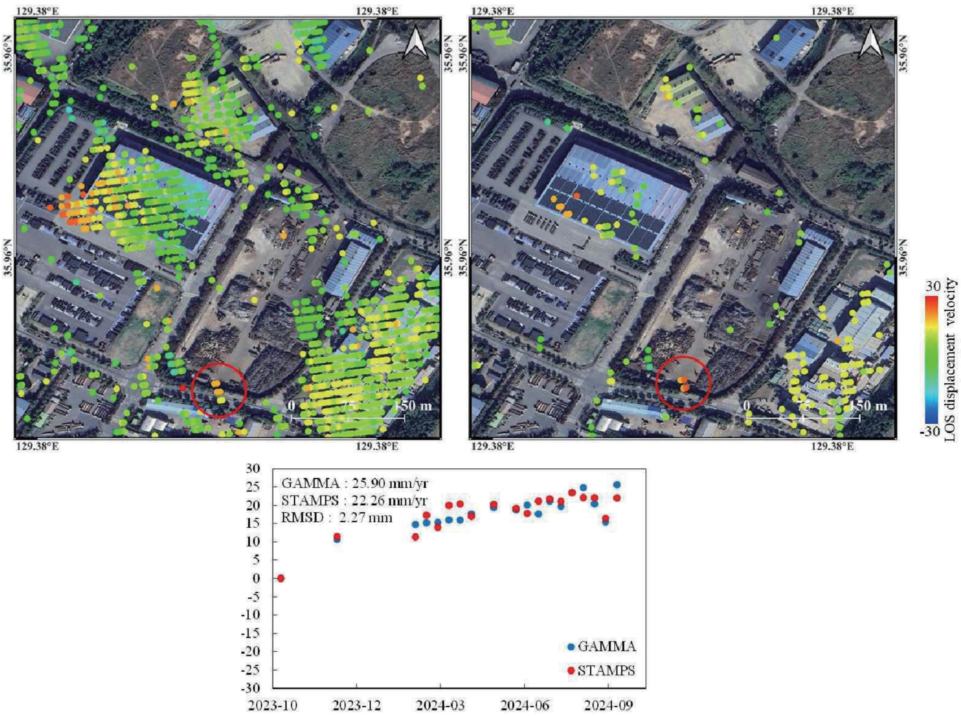

Fig. 12. (Color online) GAMMA (top left) and StaMPS (top right) results for the PS in Point 4.

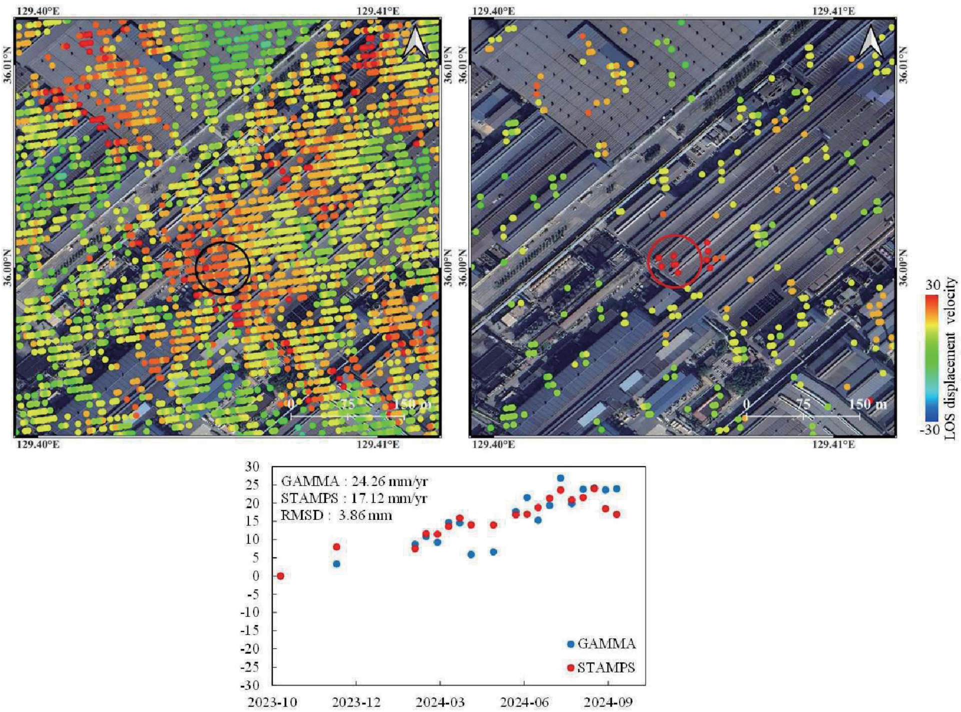

Fig. 13. (Color online) GAMMA (top left) and StaMPS (top right) results for the PS in Point 5.

in the PSInSAR implementation, considering that steelworks involve possible structural modifications and movements, resulting in large changes in scatterer characteristics.

3.1.5 Point 6

Point 6 corresponds to a building structure in Daesong-myeon, Nam-gu, Pohang, which is in close proximity to the Chilseongcheon Stream. Figure 14 indicates the displacement velocity and time-series displacement obtained by each analysis tool for this PS. Both analysis tools yielded displacements with an *RMSD* of 3.27 mm at Point 6. The PS in Point 6 indicated displacement away from the radar observation direction in both analysis results, with a velocity exceeding 1.6 cm/yr based on the StaMPS observation criteria, indicating a relatively high rate. If this displacement was vertical, the PS in the corresponding point would subside at a rate exceeding 1.6 cm per year. Considering the nearby Chilseongcheon Stream, this result suggests that the ground characteristics may be relatively weak, making subsidence possible. Thus, this site can be considered as an area requiring continuous monitoring.

3.2 Comparative analysis of PSInSAR results based on TanDEM-X SAR data

We selected one scatterer near the waste landfill and two scatterers in an area with numerous buildings to compare time-series surface displacement results derived from TanDEM-X SAR time-series data. We analyzed time-series displacement using the two analysis tools for these

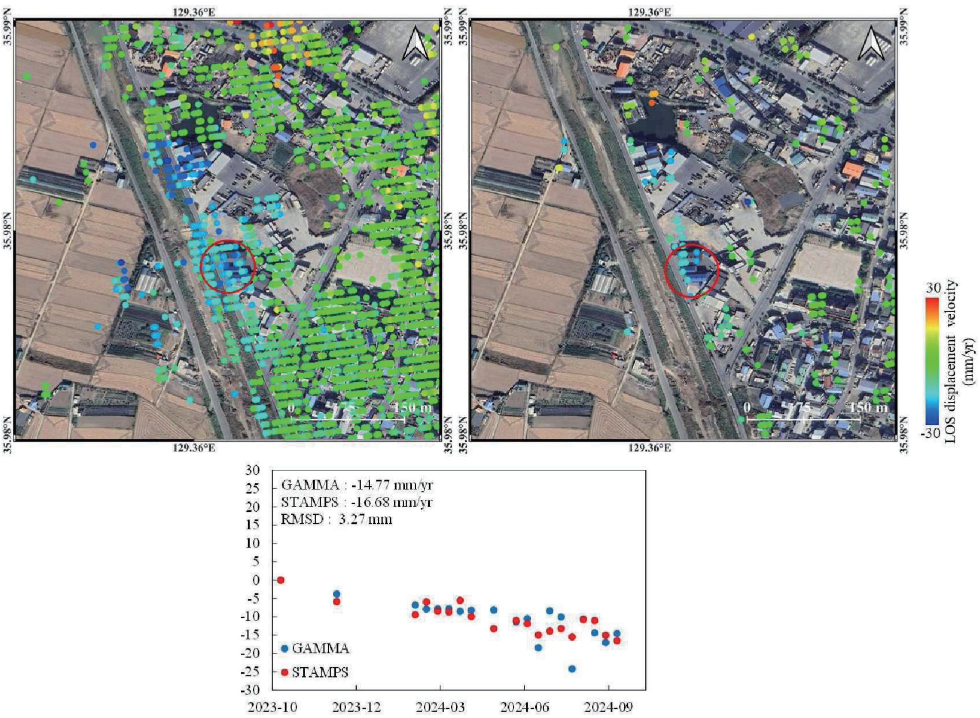

Fig. 14. (Color online) GAMMA (top left) and StaMPS (top right) results for the PS in Point 6.

points. Figure 15 shows the satellite imagery of the areas of interest and the three points at which displacements were analyzed and compared on the StaMPS-based displacement velocity map over the TanDEM-X SAR time-series imagery. As with the Sentinel-1 SAR analysis, we selected surrounding areas and points showing differences in time-series displacement and displacement velocity within the areas of interest.

3.2.1 Point 1

Figure 16 shows the PSInSAR displacement velocity results from StaMPS and GAMMA software, along with the time-series displacement calculated using each analysis tool for Point 1. The red arrow indicates the location of the analysis target, the landfill facility. Point 1, where time-series displacement was detected, corresponds to a building near the waste landfill site in Daesong-myeon, Nam-gu, Pohang. The GAMMA software-based result indicated a displacement velocity of −0.32 cm/yr away from the radar observation direction, whereas the StaMPS-based time-series displacement velocity was 0.05 cm/yr, indicating a displacement closer to the radar observation direction. However, both analysis tools calculated the time-series displacement as approximately 0.2 cm, which implies that the building corresponding to Site 1 was analyzed to be highly stable, despite its proximity to the landfill.

3.2.2 Point 2

Point 2 corresponds to a building in Ocheon-eup, Nam-gu, Pohang City. Figure 17 shows the PSInSAR displacement velocity results from StaMPS and GAMMA software for this site, as well as the time-series displacement calculated using each analysis tool. In StaMPS, the displacement velocity was found to be closer to the radar observation direction, whereas in the GAMMA software, the displacement velocity was found in the direction away from the radar observation. However, similar to Point 1, the time-series displacement fluctuated within

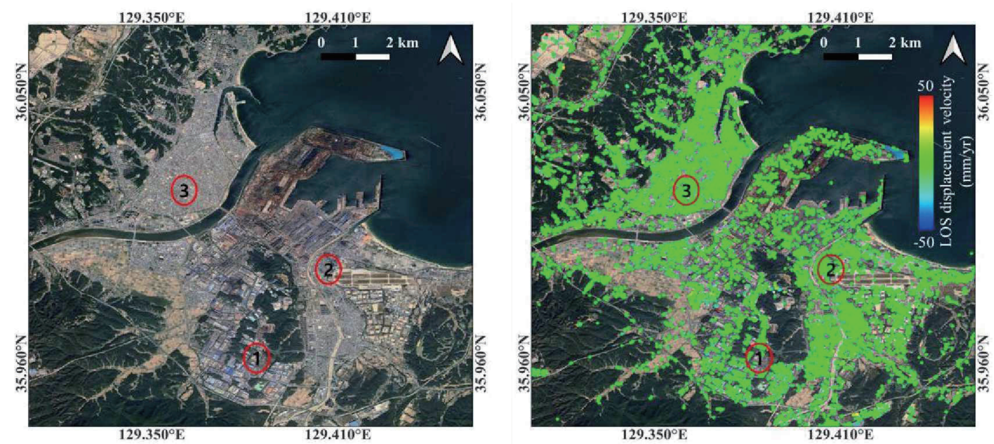

Fig. 15. (Color online) Satellite imagery of three points subject to comparative analysis and time-series displacement analysis results (TanDEM-X Data).

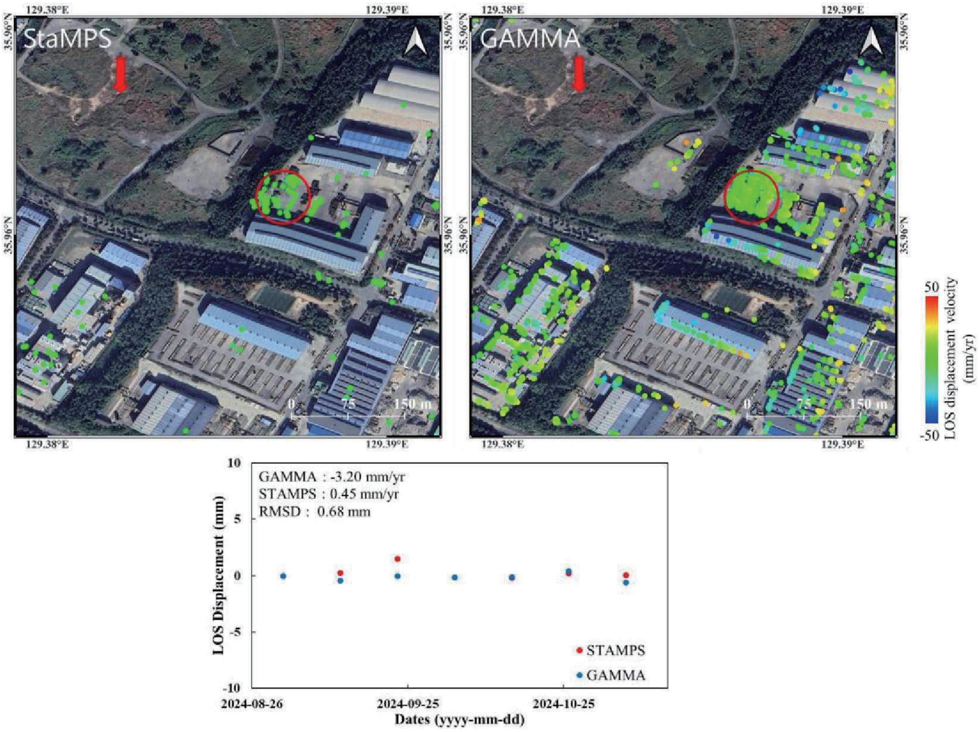

Fig. 16. (Color online) GAMMA and StaMPS results for the PS in Point 1.

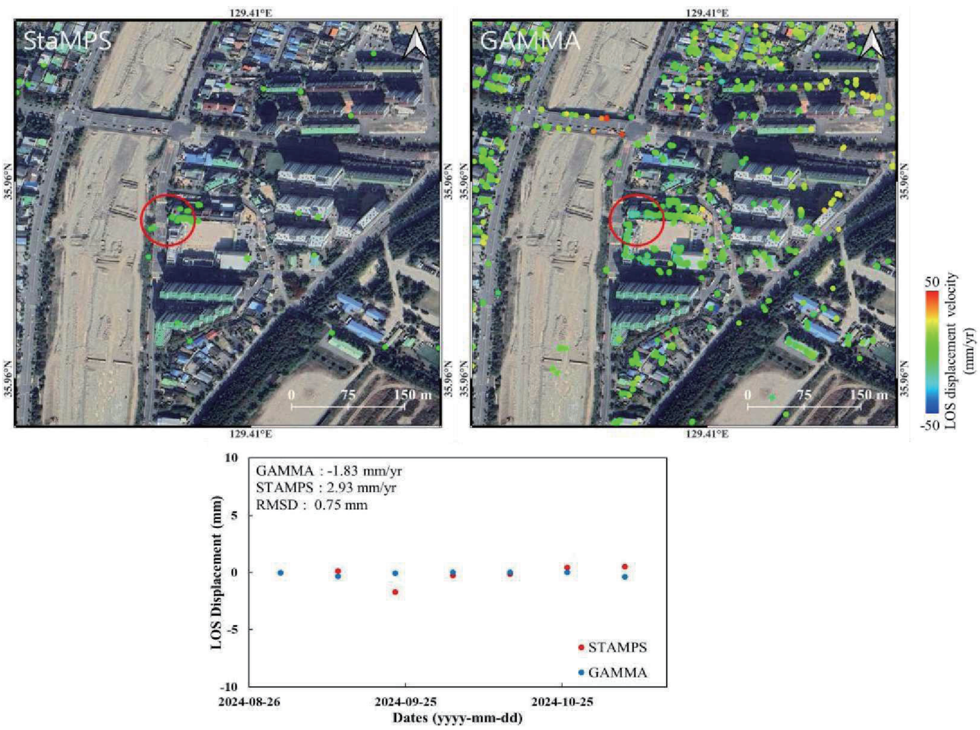

Fig. 17. (Color online) GAMMA and StaMPS results for the PS in Point 2.

approximately 0.2 cm, and the *RMSD* was found to have a small value within 0.08 cm, indicating that it was analyzed as highly stable.

3.2.3 Point 3

Figure 18 illustrates the PS calculated at Daedo Elementary School in Daedo-dong, Nam-gu, Pohang City and indicates the PSInSAR displacement velocity results from StaMPS and GAMMA software as well as the time-series displacement calculated using each analysis tool. The PS in Site 3 is a scatterer found near the landfill site but showed almost no displacement velocity, which is similar to the scatterers in Points 1 and 2. Although very small displacements were found, the *RMSD* between the two analysis tools was 0.03 cm, indicating the most similar displacement pattern among the three PSs. Scatterers in Site 3 were calculated using both StaMPS and GAMMA software at the center of an area with multiple scatterers. As there were numerous stable scatterers around the observation point under both analysis tools, it was assumed that there would be less phase unwrapping noise in the spatial term. Consequently, the results from both analysis tools were analyzed to be similar.

3.3. Comparison of reliability analysis results based on resolution

When determining surface displacement by image radar interferometry, the reliability of the calculated displacement can be analyzed by examining the coherence of the interferogram. Figure 19 shows the differential interferogram and coherence of a 20-m-spatial-resolution map,

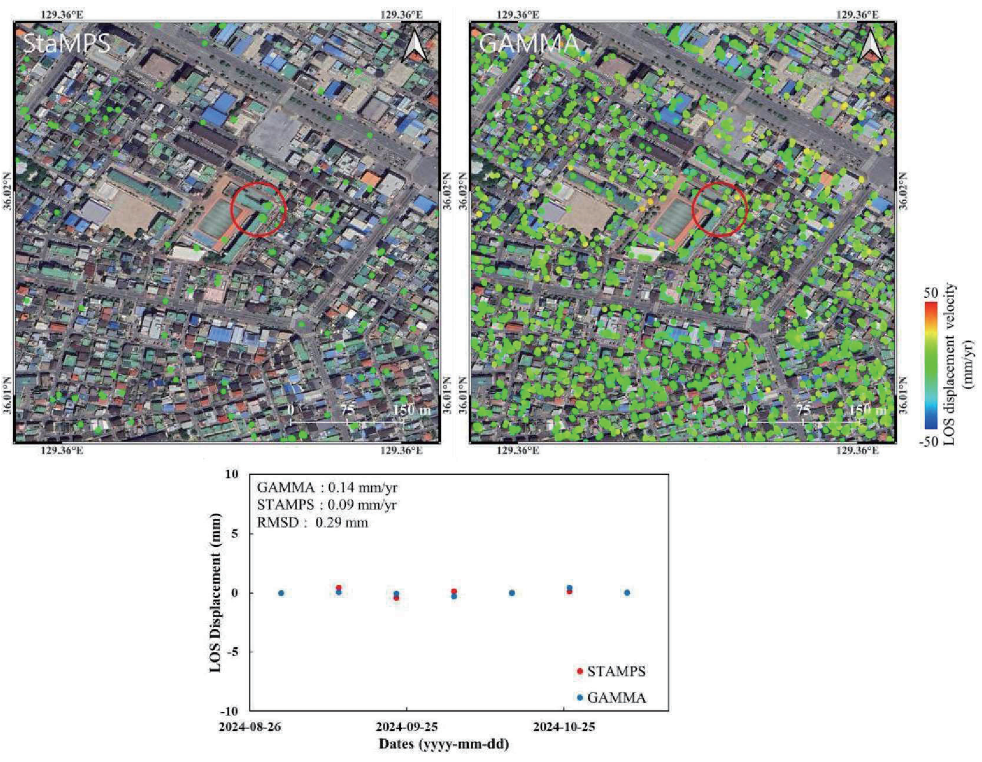

Fig. 18. (Color online) GAMMA and StaMPS results for the PS in Point 3.

which was created using Sentinel-1 SAR data from September 22 and October 4, 2024, for the target area. Except in areas covered by vegetation, high coherence values exceeding 0.5 were predominantly observed, indicating that highly reliable displacement can be obtained from differential interferograms in urban areas. However, low coherence values were observed at the waste landfill, the target site of this study, indicating that the reliability of displacement detected using Sentinel-1 SAR data may be limited and, therefore, a quantitative error assessment of the detected displacement is necessary.

Figure 20 indicates the differential interferogram and coherence of a 3-m-spatial-resolution map, which was created with TanDEM-X SAR data acquired on September 23 and October 4, 2024. Similar to the differential interferogram based on the Sentinel-1 data, the differential interferogram based on TanDEM-X data shows high coherence in urban areas and low coherence in vegetation-covered areas. This result indicates that TanDEM-X differential interferometry can be expected to yield displacements with high reliability in urban areas. As it also has a higher spatial resolution and a shorter microwave wavelength than the Sentinel-1 SAR data, it is assumed that it enables spatially precise displacement observation. Furthermore, it showed a

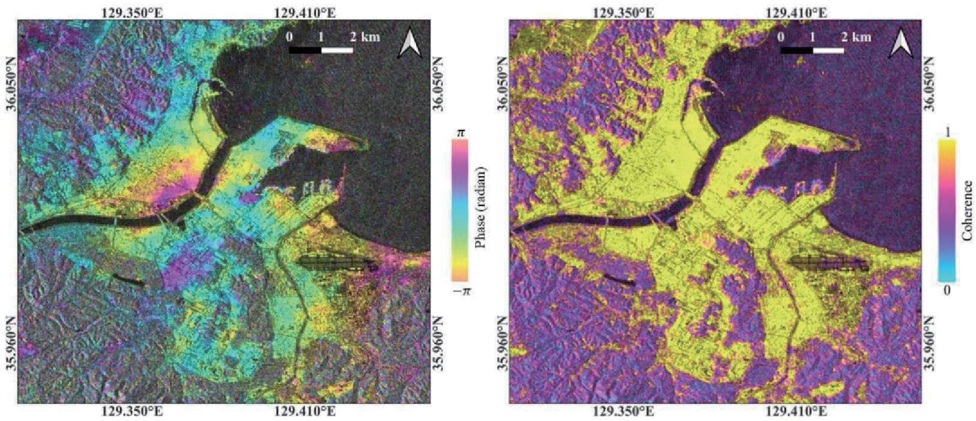

Fig. 19. (Color online) Differential interferogram and coherence analysis results based on Sentinel-1 SAR data.

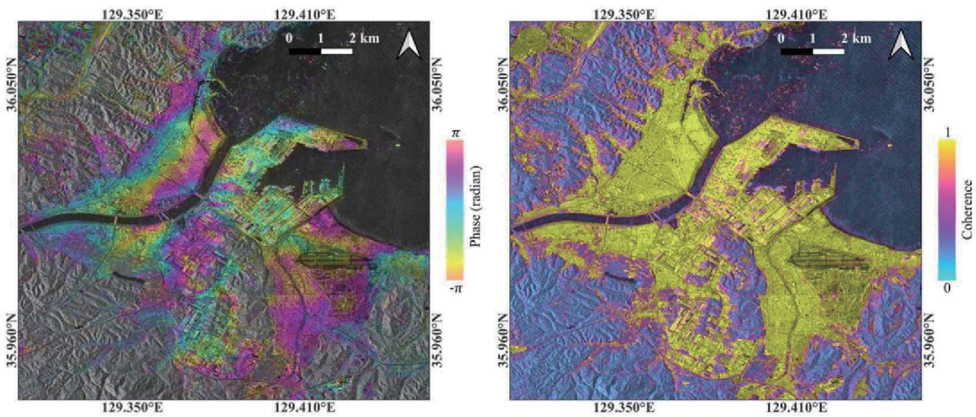

Fig. 20. (Color online) Differential interferogram and coherence analysis results based on TanDEM-X SAR data.

higher coherence than the Sentinel-1 SAR data in the target site, i.e., the waste landfill. Thus, it is assumed that landfill displacement can be reliably detected if high-resolution SAR data such as TanDEM-X or TerraSAR-X data are utilized.

4. Conclusion

The research objects of this study were a waste landfill and its surrounding areas. The Sentinel- 1 C-band and the TanDEM-X X-band SAR data were used to analyze time-series displacements through the PS-InSAR technique based on commercial and free analysis tools. The results are as follows.

1. The PSInSAR technique with SAR satellite data was deemed highly useful for monitoring time-series surface displacement in areas with numerous artificial structures.
2. In the areas encompassing the environmental infrastructure facility site and its surroundings, the relatively high-resolution X-band SAR data exhibited comparatively higher coherence, indicating its potential for more effective application in these regions.
3. In the comparative analysis of results from commercial and free software capable of applying the PSInSAR technique, small deviations were observed: approximately 3 mm for time-series displacements based on the Sentinel-1 SAR data and approximately 1 mm for calculated time-series displacements based on the TanDEM-X SAR data. Thus, this technique was assumed to enable a relatively precise analysis if high-resolution data are used.
4. The free software StaMPS was found to select PSs in areas where a PS is unlikely to exist. Therefore, the PSInSAR-based time-series displacement calculated using the commercial software (GAMMA) was deemed more reliable than the free software StaMPS.
5. In relatively open areas with few artificial structures, such as landfill facilities, further research is required to identify additional man-made objects that can serve as stable scatterers. In addition, further studies are required to ensure the reliability of the interpretation by validating the analyzed results against actual ground displacement measurements.

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