J-GMS Sentinel-1 Based Ground Deformation Monitoring across Japan for Infrastructure Risk Assessment

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Abstract: This paper outlines the Japan Ground Motions Service (J-GMS), designed to analyze ground deformation across Japan comprehensively. Leveraging Sentinel-1 satellite data, the service delivers time-series of ground deformations in the satellite's line-of-sight (LOS) direction, with a final spatial resolution of ~30x30 m. The dataset covers January 2016 to May 2025, featuring descending passes at 12-day intervals and occasional ascending data, subject to availability. Ground deformation data is regionally classified using polygon IDs based on Copernicus DEM. The framework employs advanced Interferometric Synthetic Aperture Radar (InSAR) techniques, specifically the Small Baseline Subset (SBAS) approach, to produce interferograms for effective monitoring of surface deformation over natural terrains. Ground movements are relative observations within each frame, and residual tropospheric noise is mitigated using ERA5 atmospheric data from ECMWF. The regional ground deformation results from J-GMS are crucial for evaluating infrastructure safety, tracking natural hazards such as landslides, and examining environmental effects like groundwater extraction. GNSS data was utilized for validation in selected areas, with plans to enhance outputs through GNSS-calibrated results in the future. The service's frequent revisit schedule and weather-independent data make it a valuable asset for geophysical and environmental studies.

Keywords: InSAR, Subsidence, Infrastructure, planning, hazard management

1. Introduction

Monitoring surface deformation is essential for understanding geodynamic processes, evaluating the structural integrity of built environments, and identifying geophysical hazards such as fault displacement, volcanic inflation, and landslide-induced slope instability. In Japan, where seismic and volcanic activity is frequent due to its complex tectonic setting, traditional monitoring methods such as GNSS, leveling surveys, and ground-based sensors, have been widely used. However, these point-based techniques are limited in spatial coverage, costly to maintain, and offer low temporal resolution, making them inefficient for large-scale, continuous observation. To address these limitations, this study introduces the Japan Ground Motions Service (J-GMS), an integrated platform that utilizes satellite-based remote sensing to systematically monitor surface displacement across the country. Leveraging InSAR technology, J-GMS provides millimeter-scale precision over wide areas, enabling early detection of subsidence, uplift, and slope instability near infrastructure facilities. This capability supports proactive maintenance, post-disaster assessment, and long-term infrastructure resilience.

Recent advancements in InSAR technology have greatly improved its effectiveness for long-term, high-precision ground deformation monitoring, supporting applications such as structural health monitoring and landslide detection (Bell et al. 2008; Bischoff et al. 2020; Luo et al. 2022; Macchiarulo et al. 2022; Yu et al. 2022; Jiang et al. 2024; Cheng et al, 2025). The increasing availability of multi-temporal SAR datasets enables millimeter-level accuracy over wide areas. Advances in atmospheric delay correction, particularly through integration with GNSS data, have improved measurement reliability and enabled scalable, near-real-time deformation analysis (Lu et al. 2024; Yang et al. 2024). These improvements make InSAR a robust tool for infrastructure risk assessment, allowing early detection of subsidence, uplift, and slope instability near critical assets such as bridges, dams, and urban developments.

2. Methodology

J-GMS leverages Sentinel-1 Synthetic Aperture Radar (SAR) data to generate time-series ground deformation maps with a spatial resolution of approximately 30 × 30 meters. The service covers the period from January 2016 to May 2025, ongoing analysis, utilizing descending orbit data at 12-day intervals, supplemented by ascending data when available. J-GMS primarily uses Sentinel-1 SAR imagery (https://search.asf.alaska.edu/) to measure ground deformation along the satellite's line-of-sight (LOS) direction. It employs the Small Baseline Subset (SBAS) technique (Berardino et al. 2002; Fornaro et al. 2009), a well-established method in Interferometric Synthetic Aperture Radar (InSAR) analysis, generating the interferograms with minimal temporal and spatial decorrelation and making it suitable for long-term monitoring over natural terrains. EZ-InSAR, a user-friendly open-source toolbox with a graphical interface (Hrysiewicz et al. 2023), was used for the analysis. It integrates ISCE (Rosen et al. 2012) and MintPy (Yunjun et al. 2019), two powerful tools for InSAR data processing and time-series analysis. To reduce decorrelation, image pairs were selected within 48 days and less than 200 meters of baseline separation. A Goldstein filter strength of 0.2 was applied to suppress noise and enhance phase quality. Pixels with temporal coherence ≥ 0.4 were retained for time-series analysis, while outliers with spatial coherence < 0.2 were masked during phase unwrapping. To mitigate residual tropospheric noise, the framework integrates ERA5 atmospheric reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF). This correction enhances the reliability of deformation measurements, especially in regions with variable weather conditions.

Ground deformation data is organized by polygon IDs matching the size and layout of the Copernicus DEM to facilitate localized analysis and support integration with other geospatial datasets. More than 200 polygons have been generated across Japan. Analyses have already been completed for regions including Tokyo, Nagoya, Sendai, and Fukuoka, while evaluations for the remaining areas are currently underway, as illustrated in Fig. 1. The ground movement data is measured relative to each radar frame, meaning it shows how the surface shifts within each observed area. To improve accuracy, the system removes atmospheric interference (tropospheric noise) using weather data from the ERA5 dataset provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysisv5 (Hersbach et al. 2022). InSAR displacement velocities were validated against GNSS data to confirm measurement accuracy and support future development of GNSS-calibrated deformation products.

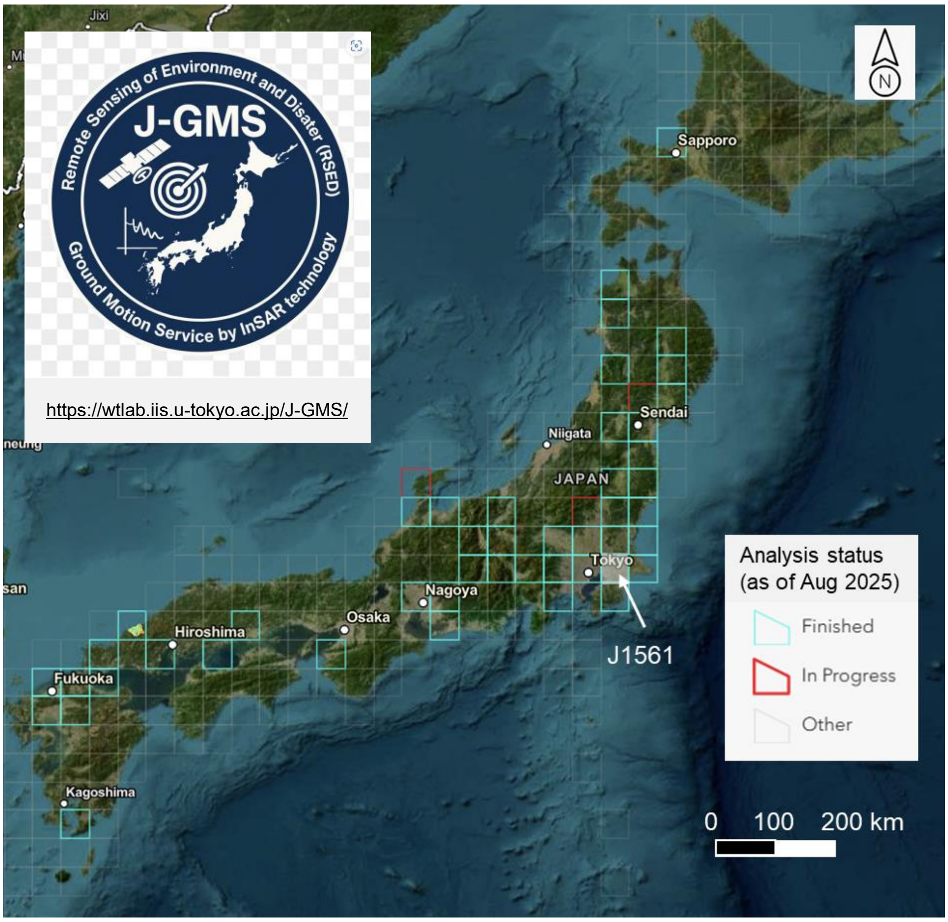

Figure 1: J-GMS analysis overview (as of August 2025).

GNSS data, processed by the Nevada Geodetic Laboratory using the IGS20 reference frame (Blewitt et al. 2018), were utilized to verify displacement rates derived from InSAR. The selection of GNSS stations was based on their closeness to key areas, the availability of data, and the consistency of their time series. The GNSS measurements in the east, north, and vertical directions were projected into satellite LOS displacement to align with the radar geometry of Sentinel-1 SAR data using radar geometry equation (Wright et al. 2004).

3. Results and Discussion

This section presents an example result for the J1561 polygon, which encompasses the Chiba region. The descending LOS displacement velocity data indicates a range of ground deformation patterns across the region, with values approximately spanning from −60 mm/year to +30 mm/year (Fig. 2). Most areas show stable ground conditions, with velocities generally within ±5.0 mm/year. Displacements from GPS stations I014 and I018 (retrieved from Nevada Geodesy, MAGNET + Global GPS Network Map, indicated by blue dots in Fig. 2) were projected into the satellite LOS direction to compare with InSAR data. The resulting RMSE values confirm good agreement, validating the InSAR measurements (Fig. 3). While localized GPS deformation may differ slightly from InSAR observations, descending RMSE shows higher accuracy (Fig. 3b & 3d), likely due to more favourable geometry and reduced atmospheric effects. Overall, the displacement trends are consistent across datasets.

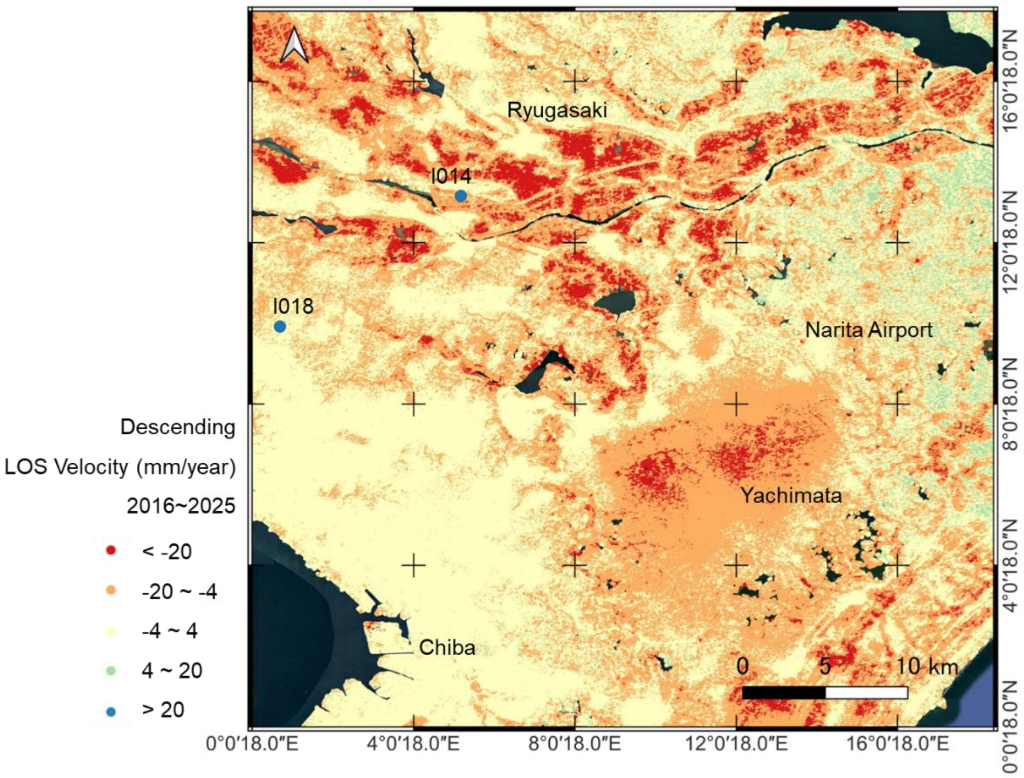

Figure 2: Time-series LOS displacement plot in descending orbit over Chiba area.

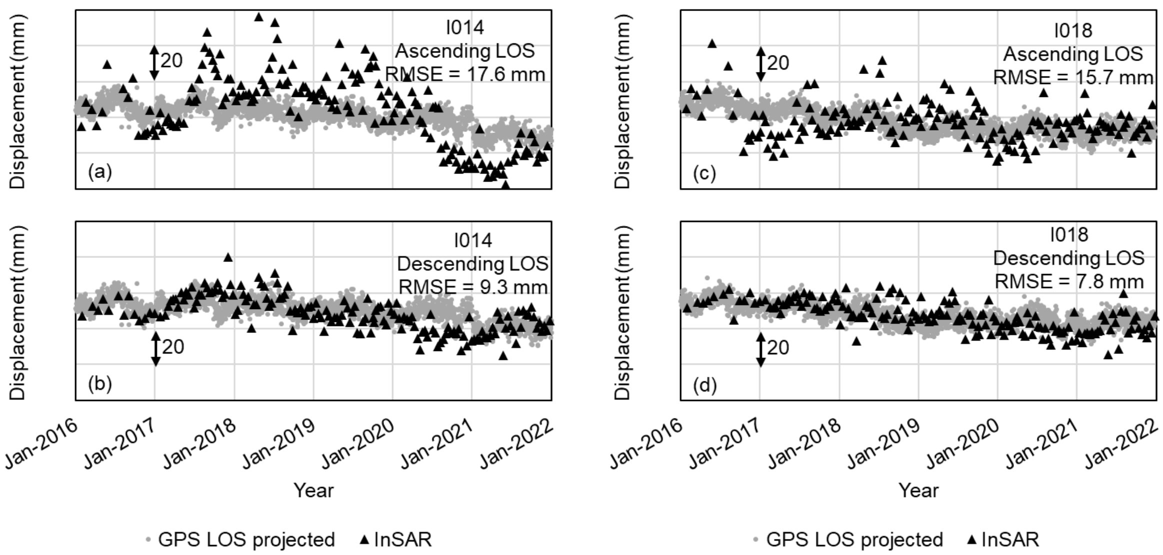

Figure 3: Comparison of GPS LOS-projected and InSAR time series of displacement at sites I014 and I018, (a,c) results from ascending data, and (b,d) results from descending data.

In some parts of Ryugasaki especially in southern riverbank, the J-GMS system detected a significant downward trend in the descending LOS direction, around -35 mm/year (Fig. 4). This continuous displacement observed from 2016 to 2025 indicates a chronic geotechnical issue rather than a temporary event, likely driven by groundwater extraction and soil compaction, warranting further investigation. A similar downward trend, around -15 mm/year, was also observed in the Yachimata area (Fig. 4).

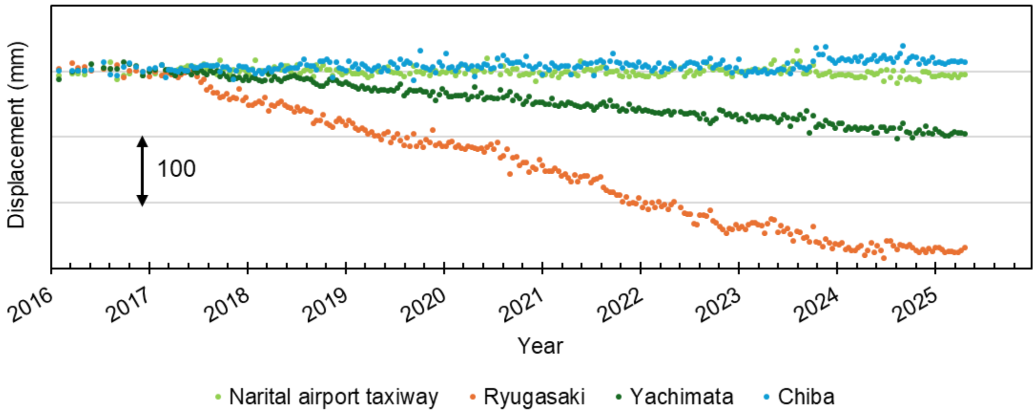

Figure 4: Time-series of LOS displacement plot in descending orbit.

Such changes in ground elevation can alter local topography, thereby exacerbating hydrological vulnerability to flooding during extreme precipitation events or typhoons. InSAR-derived displacement velocity can be spatially correlated with infrastructure geodatabases, demographic density distributions, and subsurface geological models to facilitate multi-criteria risk assessment of infrastructure in post-processing analysis.

4. Conclusions

Japan's aging infrastructure, combined with frequent natural hazards and limited human resources, underscores the need for such technologies. A significant proportion of bridges, tunnels, and underground utilities have exceeded their design life, elevating the risk of structural failure. Recurrent seismic events, typhoons, and flooding further stress these assets, while incidents such as sinkholes reveal critical weaknesses in subterranean networks. To address infrastructure risks, national initiatives are adopting advanced technologies for early detection and efficient asset management. InSAR plays a key role by providing millimeter-scale ground deformation monitoring over large areas through phase analysis of radar images.

The J1561 polygon case study highlights J-GMS's robustness and adaptability for subsidence monitoring, aiding infrastructure management and urban planning. GNSS-based validation and atmospheric corrections enhance the precision and reliability of the displacement data, as evidenced by the acceptable RMSE between the InSAR and GNSS datasets. Additional regional results are accessible via this web interface (J-GMS).

J-GMS effectively identified long-term subsidence hotspots, with persistent ground deformation posing increased flood risks due to altered topography. Integrating InSAR displacement data with infrastructure, demographic, and geological datasets enables comprehensive risk assessment to support resilient urban planning. Future system enhancements will include GNSS calibration across all regions and machine learning for automated anomaly detection. Multi-geometry radar integration will further allow decomposition of vertical and horizontal displacement components, improving monitoring precision.

References

Bell J. W, et al, 2008. Permanent scatterer InSAR reveals seasonal and long-term aquifer-system response to groundwater pumping and artificial recharge, *Water Resour Res*, 44.

Berardino, P., Fornaro, G., Lanari, R. and E. Sansosti, 2002. A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms. *IEEE Trans. Geosci. Rem. Sens*, 40, 2375-2383.

Bischoff, C. A. et al, 2020. Nationwide deformation monitoring with SqueeSAR® using Sentinel-1 data, *Proc. IAHS*, 382, 31–37.

Blewitt, G., W. C. Hammond, and C. Kreemer, 2018. Harnessing the GPS data explosion for interdisciplinary science, *Eos,* 99, https://doi.org/10.1029/2018EO104623.

Cheng, Y. et al, 2025. Applications and Advancements of Spaceborne InSAR in Landslide Monitoring and Susceptibility Mapping: A Systematic Review, *Remote Sensing*, 17(6), 999.

Fornaro, G., Reale, D. and F. Serafino, 2009. Four-dimensional SAR imaging for height estimation and monitoring of single and double scatterers. IEEE Trans, *Geosci. Remote Sens*, 47, 224-237.

Hersbach, H. et al, 2022. The ERA5 global reanalysis. *Q J R Meteorol Soc*, 146, 1999-2049.

Hrysiewicz, A., Wang, X. and E. P. Holohan, 2023. EZ-InSAR: An easy-to-use open-source toolbox for mapping ground surface deformation using satellite interferometric synthetic aperture radar, *Earth Sci Inform*, 16, 1929-1945.

Jiang, L., Shao, Y., Zhou, Z., Ma, P., and T. Wang, 2024. A review of intelligent InSAR data processing: Recent advancements, challenges and prospects, *Acta Geodaetica et Cartographica Sinica*, 53(6), 1037–1056.

Lu, J. et al, 2024. A Method by using predefined windows to improve the InSAR atmospheric correction model based on GNSS ZTD and its horizontal delay gradient, *International Journal of Remote Sensing*, 45(18), 6495–6520.

Luo, Q., Li, J. and Y. Zhang, 2022. Monitoring subsidence over the planned Jakarta-Bandung (Indonesia) high-speed railway using Sentinel-1 multi-temporal InSAR data, *Remote Sens,* **14,** 4138.

Macchiarulo, V., Milillo, P., Blenkinsopp, C. and G. Giardina, 2022. Monitoring deformations of infrastructure networks: A fully automated GIS integration and analysis of InSAR time-series, *Struct. Health Monit*, 21(4), 1849-1878.

Rosen, P. A., Gurrola, E., Sacco, G. F. and H. Zebker, 2012. The InSAR scientific computing environment. *Proc. EUSAR 2012; 9th Eur. Conf. Synthetic Aperture Radar,* 730-733.

Wright T. J., Parsons B.E., and Z. Lu, 2004. Toward mapping surface deformation in three dimensions using InSAR. *Geophys Res Lett,* 31: L01607.

Yan, H., Dai, W., and W. Xu, 2024. A method for correcting InSAR interferogram errors using GNSS data and the K-means algorithm, *Earth Planets Space*, 76, 51.

Yu, C., Junshi, X., Chen, Y., and C. Bingqian, 2022. Editorial: InSAR crustal deformation monitoring, modeling and error analysis, *Frontiers in Environmental Science*, 10.

Yunjun, Z., Fattahi, H. & F. Amelung, 2019. Small baseline InSAR time series analysis: Unwrapping error correction and noise reduction, *Comput. Geosci*, 133, 104331.