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Operational Deformation Monitoring of the Hong Kong–Zhuhai–Macao Bridge with Multi-Orbit LuTan-1 SAR Satellites

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ABSTRACT:

This study evaluates the operational capability of the Chinese LuTan-1 (LT-1) L-band SAR constellation for monitoring the Hong Kong–Zhuhai–Macao Bridge (HZMB), a representative sea-crossing bridge under a complex subtropical marine climate. Leveraging the advantages of L-band SAR—including strong resistance to decorrelation and a spatial resolution of up to 3 meters—we applied the Small Baseline Subset (SBAS) technique to 47 ascending and descending orbital images. To the best of our knowledge, this represents one of the first comprehensive deformation studies of the HZMB using the LT-1 constellation. A key aspect of our methodology is the cross-validation between multi-orbit datasets, which confirmed both the reliability of the measurements and the complementary distribution of coherent points due to SAR imaging geometry. The results indicate overall structural stability of the HZMB, with the maximum deformation localized at the Jianghai Navigation Bridge, showing a Line-of-Sight (LOS) displacement rate of –4.3 mm/yr. In contrast, the two artificial islands exhibited minor deformation, with LOS rates not exceeding –3.0 mm/yr. These findings validate LT-1 as a powerful and reliable tool for the operational health monitoring of large-scale coastal infrastructure.

1. INTRODUCTION

Structural health monitoring of sea-crossing bridges is essential to ensure their long-term safety and operational stability. The complex marine environment, characterized by typhoons, salt spray erosion, and heavy traffic loads, can induce structural deformation and material degradation, making precise deformation monitoring a critical safeguard. As a landmark mega-project commissioned in 2018, the Hong Kong-Zhuhai-Macao Bridge (HZMB)[1] connects Hong Kong, Zhuhai, and Macao with a total length of approximately 55 kilometers, representing one of the most complex and longest cross-sea bridges globally. Its immense scale and intricate design further amplify the challenges in detecting and assessing potential structural changes. Owing to its scale and strategic significance, the HZMB requires advanced, reliable and extensive monitoring technology.

Traditional geodetic methods, including total stations, levelling, Global Navigation Satellite System (GNSS)[2] and BeiDou Navigation Satellite System (BDS)[3], provide accurate point-based measurements but offer sparse spatial coverage. This makes it difficult and costly to obtain a complete deformation field for large-scale infrastructures like the HZMB[4]. As a powerful alternative, Interferometric Synthetic Aperture Radar (InSAR)[5] has emerged as a remote sensing technique capable of providing extensive, high-precision surface deformation measurements[6]. However, conventional InSAR is often limited by temporal decorrelation and atmospheric effects in dynamic coastal environments. To overcome these limitations, advanced time-series InSAR algorithms, particularly the Small Baseline Subset (SBAS) technique, have been developed. SBAS excels at monitoring slow, cumulative deformation by analysing multiple SAR acquisitions over time, making it exceptionally suitable for tracking the long-term stability of engineering structures.

Launched in 2022, China's LuTan-1 (LT-1) [7] is an L-band satellite constellation dedicated to deformation monitoring[8]. Its long-wavelength radar provides strong penetration through dense vegetation. The system operates in a pursuit monostatic formation, enabling a 4-day revisit interval and 28-day nationwide coverage[9]. This robust acquisition strategy, combined with a high-resolution 3 m imaging mode, effectively mitigates data decorrelation in persistently cloudy and rainy regions. Consequently, LT-1 yields a highly reliable data stream suitable for monitoring large-scale infrastructures like the HZMB.

This study leverages the capabilities of LT-1 by applying the SBAS technique of our LandSAR software[10] to a multi-orbit datasets. We aim to quantify the deformation rates and patterns of the bridge to evaluate its stability, and verify the capability of the LT-1 satellites[11] for critical infrastructure monitoring, using the agreement between ascending and descending[12] results as a key metric of reliability.

2. DATASETS AND METHODS

2.1 Study area

The HZMB, a world-class sea-crossing project, is situated in the Pearl River Estuary. This region's south subtropical marine monsoon climate, characterized by abundant rainfall and persistent cloud cover[13], presents a primary challenge for continuous, high-precision monitoring. Further complexities arise from the local geotechnical conditions, as the bridge foundation rests on soft, complex Quaternary marine and alluvial deposits[14]. Additionally, the structure is exposed to significant wind loads, which induce vibrations and collectively demand robust structural health monitoring[15].

The main structure of the bridge spans approximately 29.6km, comprising a 22.9km-long bridge section and a 6.7km

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immersed tube tunnel. From east to west, the HZMB successively crosses the Qingzhou, Jianghai and Jiuzhou navigation spans, each served by its cable-stayed bridge[16]. Since the deformation magnitude of cable-stayed bridge is very small, the monitoring method must be millimetre level credible. Only sub-millimetre accuracy measurements such as total station level, PPP-RTK, InSAR time-series can distinguish this long-term trend, otherwise it will be overwhelmed by errors.

This study focuses on the bridge section, a representative large-span steel structure renowned for its high structural stability. The extensive use of steel materials makes it an ideal subject for L-band SAR due to its strong signal reflection and stability. According to the measured case, the average spacing of bridge deck BDS PPP-RTK[17] monitoring is about one point every few hundred metres. Although the HZMB was equipped with an embedded BDS at commissioning, the sparse point-wise arrangement cannot capture spatially continuous settlement gradients along the bridge. InSAR technology therefore provides the indispensable, full-bridge measurement density needed to detect unexpected local deformation and to validate the bridge-wide stability assumed in the original design[18].

2.2 Datasets and Methods

This study utilizes a total of 47 LT-1[19] acquisitions with a 3-metre-resolution, including 23 from ascending orbits and 24 from descending orbits. The datasets cover the period from July 2023 to July 2025 for ascending orbits and to August 2025 for descending orbits, with detailed data parameters and acquisition times provided in Table 1 and Table 2, respectively. All data were processed using LandSAR software version 1.5.2 [20], developed by the Land Satellite Remote Sensing Application Center, Ministry of Natural Resources.

The SBAS[21] technique was employed to process the LT-1[22] datasets, leveraging its capability to derive deformation time series from multi-temporal SAR acquisitions. Interferometric pairs were selected and SLC data extracted, followed by interferograms generation and difference under 1000-m perpendicular and 776-day temporal baseline constraints. Precise orbit data removed orbital errors, and an 11-m resolution ZY-3 DEM removed the topographic phase component. Coherent points were selected based on amplitude stability to construct a Delaunay network for the observation model. Arc model parameters were solved via global network adjustment, followed by spatial filtering of phase vectors. Finally, phase unwrapping retrieved the absolute phase, from which nonlinear deformation components were extracted and integrated into the final time series.

Table 1. Data parameters

Parameter	**Contents**	
Orbit direction	Ascending	Descending
Band	L	
Wavelength (cm)	23.8cm	
Polarization	HH	
Azimuth/Range pixel spacing	1.42m/1.67m	1.57m/1.67m
Acquisition time	July 2023-July 2025	July 2023-August 2025
Number of data	23	24

Table 2. Acquisition date

Ascending		Descending	
20230701	20240703	20230701	20240719
20230802	20240731	20230818	20240913
20230830	20240828	20230915	20241011
20230927	20240925	20231013	20241206
20231122	20241023	20231208	20250103
20231220	20241218	20240105	20250228
20240117	20250115	20240202	20250328
20240214	20250312	20240301	20250425
20240313	20250409	20240329	20250523
20240410	20250507	20240426	20250620
20240508	20250702	20240524	20250718
20240605		20240621	20250815

Both ascending and descending datasets were processed independently through dedicated workflows. Key steps included the generation of interferograms network with small baselines to optimize coherence over the bridge structure, and the subsequent inversion to obtain line-of-sight (LOS) deformation velocity maps and time series.

A central aspect of our methodology was the cross-validation of results between the multi-orbit results. This step was designed to qualitatively and quantitatively assess the consistency of the deformation patterns from ascending and descending observations. The strong agreement between these geometrically independent measurements underscores the reliability of both the LT-1 data and the subsequent stability assessment of the HZMB.

3. RESULTS AND DISCUSSION

3.1 The SBAS Results

Surface deformation maps derived from ascending and descending LT-1 data are presented in Fig. 1 and Fig. 2, with SBAS results accurately overlaid on a ZY-3 optical base map. A key finding consistently identified in both datasets is the localization of the maximum deformation signal at the Jianghai Navigation Bridge in the central section of the HZMB. As the descending track provided limited coverage of the easternmost Qingzhou Bridge, the deformation analysis of the main bridge focuses primarily on the Jianghai and Jiuzhou navigation spans. Zoomed-in views of these sections (Fig. 3 and Fig. 4) reveal a displacement rate of -4.3 mm/yr at location (a), independently detected by both orbits for robust cross-validation.

The distribution of coherent points exhibits a systematic complementary pattern between the two orbits, a direct consequence of SAR side-looking geometry. This imaging configuration causes structures perpendicular to the radar's Line-of-Sight (LOS) to experience geometric distortions such as layover and shadowing, which degrade coherence. Accordingly, the western facets of bridge segments show higher coherent point density in ascending results, while the eastern facets are better covered in descending results.

Furthermore, results from both orbits confirm the overall stability of the two artificial islands. The SBAS results for the western and eastern islands are shown in Fig. 5 and Fig. 6 respectively. Detected deformation is negligible, with maximum LOS displacement rates not exceeding -3.0 mm/yr. These values fall within the expected range of measurement uncertainty and therefore hold no engineering significance for the islands' structural integrity.

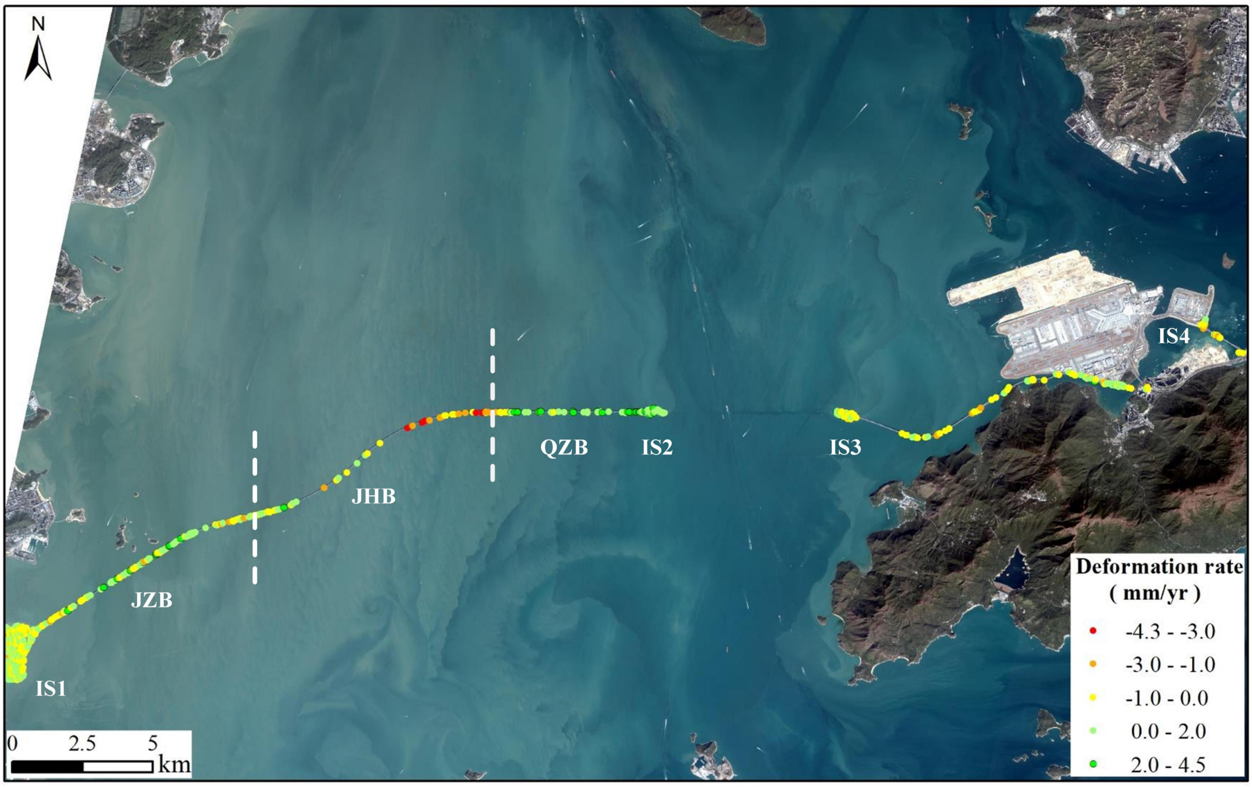

Figure 1. The SBAS results of the HZMB from the LT-1 ascending orbit overlaid on a ZY-3 optical image.

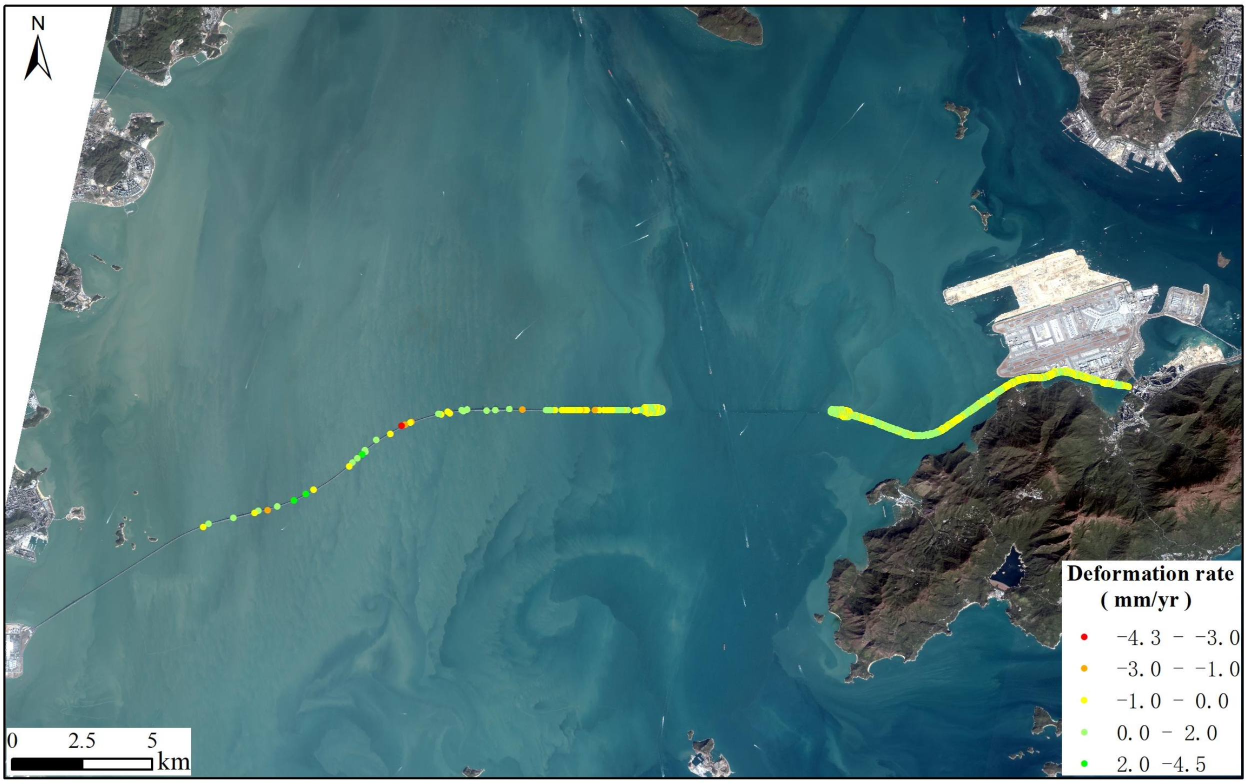

Figure 2. The SBAS results of the HZMB from the LT-1 descending orbit overlaid on a ZY-3 optical image.

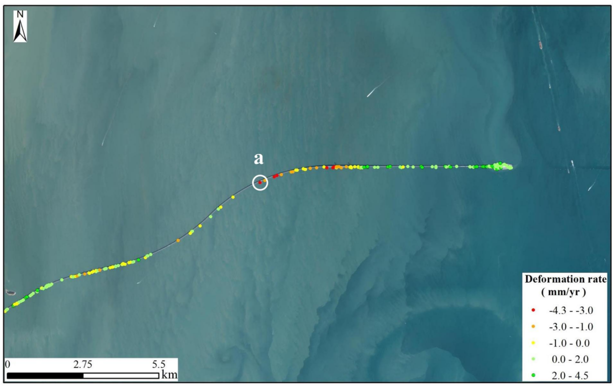

Figure 3. The maximum displacement of the HZMB from the LT-1 ascending orbit overlaid on a ZY-3 optical image.

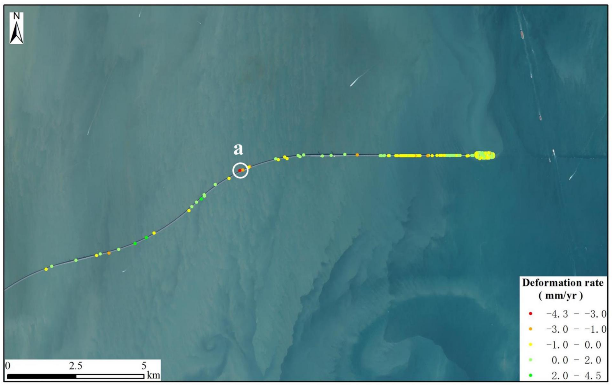

Figure 4. The maximum displacement of the HZMB from the LT-1 descending orbit overlaid on a ZY-3 optical image.

Figure 5. The SBAS results of the western artificial island

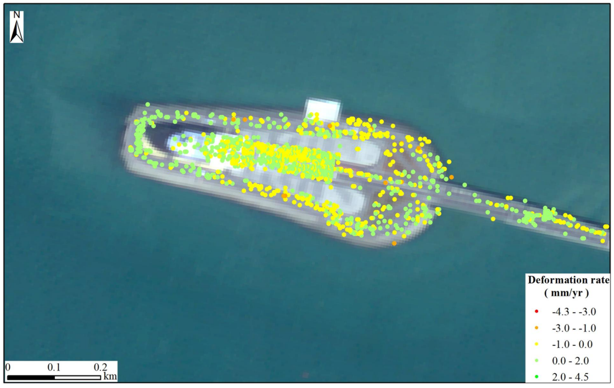

Figure 6. The SBAS results of the eastern artificial island

3.2 Discussion

The deformation patterns obtained from multi-orbit LT-1 data provide critical insights into the structural behavior of the HZMB under long-term service conditions. The concentration of maximum deformation at the Jianghai Navigation Bridge (-4.3 mm/yr) directly corresponds to its structural configuration as a cable-stayed span, which possesses greater flexibility compared to adjacent continuous girder sections. This deformation magnitude represents a slow, cumulative movement that aligns with expected long-term behavior and falls within established safety thresholds for normal operational performance.

The observed deformation likely results from the combined effect of multiple factors. The bridge foundation is situated on compressible Quaternary deposits in the Pearl River Estuary, where regional ground settlement contributes a foundational displacement component. Simultaneously, the structure experiences continuous environmental and operational loads. Persistent wind pressure[23] induces long-term deflection, while daily traffic flow — comprising tens of thousands of vehicles including substantial heavy truck presence — imposes significant cyclic loading. This combination of traffic-induced fatigue and potential material creep effects is particularly pronounced at the central spans, which experience the highest load intensity while exhibiting the greatest structural flexibility.

The reliability of our findings is significantly enhanced by the multi-orbit monitoring strategy. The complementary distribution of coherent points between ascending and descending datasets represents an effective utilization of SAR imaging geometry rather than a data limitation. Through integration of both datasets, we transform this geometric characteristic into an analytical advantage, achieving comprehensive spatial coverage and independent validation of key deformation signals. The consistent identification of primary deformation patterns across independent orbital geometries confirms the operational maturity of the LT-1 system, whose broad coverage and regular acquisition capability effectively address the spatial and temporal limitations of traditional ground-based survey methods.

The deformation gradient derived from our multi-orbit LT-1 data — from the flexible central spans to the stable artificial islands — provides an empirical basis for a system-level performance assessment. Critically, the negligible deformation observed at both artificial islands (with LOS rates not exceeding -3.0 mm/yr) confirms their foundational stability. This minimal displacement, which falls within typical measurement uncertainty ranges for InSAR, validates the geotechnical design and construction quality of these key transition structures. This holistic perspective aligns with advanced structural evaluation paradigms. Specifically, the principle of evaluating a bridge as an integrated system of components with varying functions and vulnerabilities is well-established in other domains, most notably in fragility-based system seismic performance assessment[24]. Our observed deformation patterns effectively constitute a serviceability-level fragility field validation, where the clear differentiation in mechanical response between the flexible superstructure (cable-stayed bridge) and rigid substructure (artificial islands) demonstrates a rational deformation hierarchy under operational loads.

4. CONCLUSION

This study demonstrates that China's LT-1 L-band SAR constellation enables monitoring of millimeter-scale deformations in coastal mega-structures. Through multi-orbit SBAS analysis of the HZMB, we confirmed the overall structural stability of the bridge while identifying the central Jianghai Navigation Bridge as the area of most significant deformation, with a measured rate of -4.3 mm/yr.

The technical characteristics of LT-1 were essential to these results. The L-band wavelength maintained strong coherence in the humid environment of the Pearl River Estuary, while the 3-meter spatial resolution allowed for detailed monitoring of the bridge structure. Furthermore, the SBAS technique applied to multi-orbit data consistently produced coherent results, where the systematic acquisition of both ascending and descending orbits formed the foundation for a robust analysis. The consistent identification of key deformation patterns across independent orbital geometries strengthens the confidence in the observed deformation signals.

In summary, this work establishes LT-1 as a viable tool for critical infrastructure monitoring. The integration of multi-orbit data provides a precise deformation baseline for the HZMB, offering a reference framework for assessing similar major coastal structures.

5. ACKNOWLEDGEMENTS

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