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GBSAR Geocoding Based on Bayes Theorem:

Applications to Slope and Structural Deformation Monitoring

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ABSTRACT

Ground-based synthetic aperture radar (GB-SAR) is pivotal for high-precision deformation monitoring in infrastructure (e.g., dams, bridges) and geological hazards (e.g., landslides). However, near-field 2D-to-3D geocoding challenges persist due to geometric distortions and multi-candidate ambiguities. Traditional orthogonal projection methods, reliant on far-field assumptions, fail in complex scenarios. This study proposes a Bayesian maximum a posteriori framework integrated with Doppler projection and multi-source fusion. By mapping 3D models to synthetic aperture radar coordinates via Doppler projection and incorporating physical priors (e.g., radar incidence angles), the method constructs a joint probabilistic model to screen infeasible scatterers. Experiments achieved sub-millimeter accuracy (root mean square [RMS] <0.8 mm) in deformation mapping and identified structural vibrations (10–25 hertz) with <2% deviation from accelerometer data. The framework mitigates layover and foreshortening artifacts, outperforming conventional methods, and offers robust solutions for infrastructure safety and hazard early warning.

KEYWORDS

Estimation, Doppler Projection, Geocoding, Deformation Monitoring, Vibration Frequency Analysis

INTRODUCTION

Ground-based synthetic aperture radar (GB-SAR) has emerged as a pivotal tool for high-precision deformation monitoring of critical infrastructure (e.g., dams, bridges) and geological hazards (e.g., landslides), owing to its capability for millimeter-level displacement measurement and all-weather operability (Casagli et al., 2016). However, the unique imaging geometry of GB-SAR, characterized by near-field acquisition and slant-range projection, introduces significant challenges in geocoding—translating 2D synthetic aperture radar (SAR) images into unambiguous 3D coordinates (Auer et al., 2017; Xie et al., 2020; Zheng et al., 2024b). Traditional geometric projection methods, such as the orthogonal projection, rely on far-field assumptions or flat terrain approximations, leading to severe

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distortions and ambiguous multi-candidate mappings in complex near-field scenarios, for example, vertical structures like dam facades or steep slopes (Noferini et al., 2007; Z. Wang et al., 2024; Y. Wang et al., 2024; Zhang et al., 2021; Zheng et al., 2024c). This limitation fundamentally stems from the neglect of Doppler-induced azimuthal dependencies and the lack of robust statistical frameworks to resolve overlapping scatterers within a single SAR pixel.

Existing approaches, including Doppler projection that accounts for radar motion effects, partially mitigate geometric errors but still struggle with persistent ambiguities caused by signal overlap and layover effects (Noferini et al., 2007). Moreover, conventional threshold-based candidate point selection lacks physical interpretability, often retaining geometrically infeasible points (e.g., shadowed regions or extreme incidence angles) that degrade monitoring reliability (Halldór & Þorsteinn, 2024; Mondini et al., 2021; Z. Wang et al., 2024; Zhang et al., 2021; Zheng et al., 2022; Zheng et al., 2024a; Zheng et al., 2024d). To address these issues, recent studies have explored multi-source data fusion, yet a systematic integration of physical priors and probabilistic inference remains underexplored in GB-SAR geocoding (Li et al., 2025; Luo et al., 2017; Turner et al., 2015).

In this study, we propose a novel Bayesian maximum a posteriori (MAP) estimation framework coupled with multi-source fusion to achieve high-precision 3D geocoding for GB-SAR (Atzeni et al., 2015; Ghamisi et al., 2019; Sestras et al., 2025; Woods, 2020; Ye et al., 2024). The core innovation lies in the first incorporation of a physics-driven statistical model into GB-SAR data processing, which synergizes Doppler projection with prior knowledge of radar antenna patterns and incidence angles. Specifically, high-resolution 3D terrain models are mapped into the SAR coordinate system via Doppler projection to accurately represent azimuthal dependencies, while Bayesian inference optimizes candidate point selection by evaluating the joint probability of geometric feasibility and signal reflectivity (De-Macedo et al., 2017; Liang et al., 2023; Xiao et al., 2022). This approach effectively filters out physically implausible scatterers (e.g., those in shadow zones or with excessive incidence angles) and resolves ambiguities in vertical structures. Recent advancements in distributed formation control (Yu et al., 2023) and barrier function-based safety methods (Ferraguti et al., 2022) have demonstrated potential in handling multi-agent coordination and safety-critical constraints for remote sensing tasks. Inspired by these developments, our framework integrates physics-driven priors with probabilistic optimization to address near-field ambiguities, bridging a gap in current GB-SAR geocoding research.

Experimental validation encompasses both controlled laboratory simulations and real-world infrastructure monitoring scenarios. In multi-degree-of-freedom structural vibration tests, the proposed method successfully identified vibration frequencies (10–25 hertz [Hz]) with <2% deviation from accelerometer measurements, demonstrating robustness against environmental noise. Furthermore, sub-millimeter-level deformation accuracy (root mean square [RMS] <0.8 mm) was achieved in dam and bridge monitoring, significantly outperforming traditional methods plagued by layover artifacts. These results underscore the framework's potential to enhance the reliability of GB-SAR in safety-critical applications, such as landslide early warning and structural health assessment.

This paper introduces a novel Bayesian MAP framework integrated with Doppler projection. By combining physical priors (radar incidence angle and antenna pattern) with observational data, the framework constructs a joint probability model to enhance reliability and accuracy in 3D coordinate inversion for complex near-field scenarios. A Doppler frequency shift-corrected projection method overcomes limitations of traditional approaches, enabling sub-millimeter deformation resolution (RMS <0.8 mm) in structure monitoring while suppressing shadowing and foreshortening effects. Additionally, a geometry-reflectivity joint probability screening mechanism integrates radar incidence constraints and scattering stability criteria to eliminate non-physical candidate points, resolving ambiguity in multiple scatterers within a single pixel.

The remainder of this paper is organized into three sections: Section 2 details the methodology, including Doppler projection principles and the Bayesian MAP framework. Section 3 presents experimental setups and results. Conclusions are summarized in Section 4.