

Article

A GNSS-R InSAR Method for Deformation Monitoring Based on BeiDou Dual-Frequency Signal Fusion

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Abstract

Global Navigation Satellite System Reflectometry Interferometric Synthetic Aperture Radar (GNSS-R InSAR) offers all-weather, all-day observation capabilities and high temporal resolution, enabling elevation deformation monitoring with a single satellite. However, in hazardous regions, such as tailings dam slopes, measuring the deformation of a greater number of target points is essential for a more accurate assessment of geological hazard risks. Since navigation satellite signals are not originally designed for imaging purposes, their inherent narrow bandwidths result in low spatial resolution and limited target recognition capabilities, rendering them inadequate for such scenarios. To address these limitations, this paper investigates a GNSS-R InSAR deformation measurement architecture utilizing dual-frequency BeiDou-3 (BDS-3) signal fusion. Specifically, a coherent spectrum fusion method is introduced to effectively expand the signal bandwidth, thereby significantly enhancing range resolution and target identification capabilities. Building upon this, deformation measurements are conducted to achieve more refined and detailed monitoring.

Keywords: global navigation satellite system reflectometry (GNSS-R); interferometric synthetic aperture radar (InSAR); fusion imaging; range resolution; deformation monitoring

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1. Introduction

Global Navigation Satellite System Reflectometry Interferometric Synthetic Aperture Radar (GNSS-R InSAR), operating as a bistatic SAR system utilizing satellite signals as transmitters, has emerged as a highly promising technology due to its abundant signal sources, short revisit periods, and cost-effectiveness [1]. The application of this technology to continuous surface displacement measurement has become a major current research

focus, playing an irreplaceable role in disaster mitigation and ensuring the structural integrity of major engineering projects in mountainous regions.

In recent years, GNSS-R InSAR technology has gradually become a vital research direction in the field of surface deformation monitoring. To advance this technology, specific methodologies have been sequentially investigated. As early as 2005, Zeng et al. established a generalized ambiguity function model, laying the theoretical foundation for resolution analysis in bistatic SAR systems [2]. In 2013, Liu et al. demonstrated coherent change detection (CCD) using passive bistatic SAR (BSAR), proving the feasibility of acquiring high-coherence differential phase maps [3]. In 2015, Ma et al. investigated passive GNSS-based SAR resolution improvement using joint Galileo E5 signals [4]. Simultaneously, Zeng et al. developed a novel subsidence monitoring technique based on space-surface bistatic differential interferometry, extending the application of GNSS transmitters in deformation retrieval [5]. In 2018, Liu et al. systematically proposed a 3-D deformation retrieval algorithm based on multi-angle GNSS-R observations, verifying its centimeter-level accuracy [6]. In 2020, Wu et al. demonstrated that optimizing satellite combinations in multi-satellite fusion enhances imaging resolution and interferometric geometric dilution of precision (GDOP) [7]. In 2021, Mao et al. proposed an azimuth split-spectrum interferometry approach to estimate and compensate for ionospheric phase delays, resolving phase inconsistency issues [8]. In 2022, Wang et al. optimized data acquisition to balance accuracy and efficiency for 3-D deformation retrieval [9]. In 2023, Cui et al. improved GNSS-R footprint resolution using a novel joint bandwidth method [10], while Wang et al. simultaneously proposed a multi-angle image aggregation algorithm to resolve varying scattering registration dilemmas [11]. In 2024, Wang et al. designed an adaptive elevation ramp fitting algorithm to enhance processing quality [12]. Concurrently, Liu et al. developed an adaptive fake permanent scatterer removal algorithm to improve the reliability of PS selection [13] and further constructed 3-D deformation fields based on spatial and temporal continuity, expanding GNSS-InBSAR capabilities to continuous regional monitoring [14]. More recently, in 2025, Yu et al. introduced a satellite selection algorithm for GNSS-R InSAR, effectively optimizing the geometric distribution of satellites to further improve elevation deformation monitoring precision [15]. Also in 2025, He et al. proposed an accurate method for global ionospheric total electron content (TEC) estimation using multi-GNSS observations, thereby enhancing the reliability of GNSS data processing [16]. Concurrently, Sun et al. developed a 3-D grid-based resilient pseudorange error prediction model for adaptive navigation in challenging environments [17]. Furthermore, in 2026, Liu et al. formulated a three-step data acquisition optimization algorithm, which successfully facilitated hourly 3-D deformation field construction based on GNSS-InBSAR [18].

However, existing GNSS-R InSAR techniques suffer from narrow signal bandwidths and low imaging resolutions. To address these challenges, this paper introduces the coherent synthesis method for BeiDou-3 (BDS-3) B2a and B2b signals [19], aiming to expand the signal bandwidth and improve range resolution, thereby identifying more target points. Building upon this, deformation measurements are performed to enhance the accuracy of deformation inversion. The remainder of this paper is organized as follows: Section 2 provides an overview of the dual-frequency fusion method and the interferometric phase model; Section 3 presents the simulation results for both imaging and deformation inversion; and Section 4 concludes the paper. It should be noted that this study focuses exclusively on exploring the theoretical feasibility of the dual-frequency fusion imaging method for improving deformation monitoring precision through idealized simulations.

2. Methodology

This section introduces a high-resolution GNSS-R InSAR deformation monitoring method based on BeiDou dual-frequency signal fusion imaging [19]. First, the signal fusion process is analyzed. Second, a dual-baseline differential interferometric phase model is established to achieve elevation deformation inversion.

2.1. Dual-Frequency Signal Fusion

According to the range resolution calculation Equation (1), the range resolution is inversely proportional to the bandwidth.

$$\rho_r = \frac{0.586 \cdot c}{2B \cos(\beta/2) \cos \alpha} \quad (1)$$

where c is the speed of light, B represents the signal bandwidth. Constant 0.586 accounts for the main-lobe broadening effect introduced by the Kaiser window. β is the bistatic angle formed by the transmitter, the target, and the receiver, α is the projection angle between the bistatic bisector and the imaging plane. As shown in Table 1, the single-frequency range resolution is limited by the 10.23 MHz effective bandwidth of the BDS-3 B2a and B2b signals. However, given their narrow center frequency spacing of 30.69 MHz and shared spaceborne atomic clock, the B2a and B2b signals can be jointly reconstructed in the frequency domain.

Table 1. Signal parameters.

Parameter	Value
Carrier frequency	1176.45 MHz(B2a)
	1207.14 MHz(B2b)
Signal bandwidth	10.23 MHz

After acquiring the BDS-3 B2a and B2b signals and completing the direct-reflected signal synchronization and sub-code stripping, this paper constructs the reference signal S_d based on the tracking results of the direct signal, as follows:

$$S_d(\tau, u) = C[\tau - \tau_d(u)] \cdot \exp(j2\pi f_d(u)\tau - j2\pi f_c \tau_d(u)) \quad (2)$$

where τ is the range time, u is the azimuth time, C is the coarse acquisition (C/A) code, τ_d is the direct signal delay, f_c is the carrier frequency, f_d is the Doppler frequency.

By performing frequency-domain complex conjugate multiplication, the reference signal is correlated with the reflected signal, and the final range compression result S_r is obtained as follows:

$$S_r(\tau, u) = \sigma P_{CA} \{ \tau - [\tau_r(u) - \tau_d(u)] \} \cdot \exp \{ -j2\pi f_c [\tau_r(u) - \tau_d(u)] \} \quad (3)$$

where σ is the backscattering coefficient, P_{CA} is the cross-correlation result, τ_r is the reflected signal delay.

Prior to range compression, down-converting the signals to the baseband causes spectrum aliasing. To resolve this issue, a frequency shift operation based on interferometric phase consistency is adopted in this paper [19]. The negative frequency shift factor $K_{low}(\tau)$ designed for B2a and the positive one $K_{high}(\tau)$ for B2b are respectively as follows:

$$K_{low}(\tau) = \exp(-j2\pi \cdot \Delta f \cdot \tau) \quad (4)$$

$$K_{high}(\tau) = \exp(+j2\pi \cdot \Delta f \cdot \tau) \quad (5)$$

where Δf is the frequency shift amount. Consequently, the frequency-shifted results of the two signals are expressed as [19]:

$$\begin{aligned} S_{r_B2a_shift}(\tau, u) &= S_r(\tau, u) \cdot K_{low}(\tau) \\ &= \sigma P_{CA} \left\{ \tau - [\tau_r(u) - \tau_d(u)] \right\} \\ &\quad \cdot \exp \left\{ -j2\pi (f_{c_B2a} + \Delta f) [\tau_r(u) - \tau_d(u)] \right\} \\ &\quad \cdot \exp \left\{ -j2\pi \cdot \Delta f \cdot [\tau - (\tau_r(u) - \tau_d(u))] \right\} \end{aligned} \quad (6)$$

$$\begin{aligned} S_{r_B2b_shift}(\tau, u) &= S_r(\tau, u) \cdot K_{high}(\tau) \\ &= \sigma P_{CA} \left\{ \tau - [\tau_r(u) - \tau_d(u)] \right\} \\ &\quad \cdot \exp \left\{ -j2\pi (f_{c_B2b} - \Delta f) [\tau_r(u) - \tau_d(u)] \right\} \\ &\quad \cdot \exp \left\{ +j2\pi \cdot \Delta f \cdot [\tau - (\tau_r(u) - \tau_d(u))] \right\} \end{aligned} \quad (7)$$

where f_{c_B2a} is the carrier frequency of the B2a signal, f_{c_B2b} is the carrier frequency of the B2b signal, $S_{r_B2a_shift}$ is the frequency-shifted result of the B2a signal, $S_{r_B2b_shift}$ is the frequency-shifted result of the B2b signal.

To ensure the fused signal phase accurately reflects the geometric configuration, the following condition must be met:

$$f_{c_B2a} + \Delta f = f_{c_B2b} - \Delta f \quad (8)$$

That is [19]:

$$\Delta f = \frac{f_{c_B2b} - f_{c_B2a}}{2} = 15.345 \text{ MHz} \quad (9)$$

Finally, the signals undergo coherent fusion, extending the synthesized bandwidth to 51.15 MHz. The range compression result is expressed as [19]:

$$\begin{aligned} S_{r_syn} &= S_{r_B2a_shift}(\tau, u) + S_{r_B2b_shift}(\tau, u) \\ &= \sigma P_{CA} \left\{ \tau - [\tau_r(u) - \tau_d(u)] \right\} \\ &\quad \cdot 2 \cos \left[2\pi \Delta f (\tau - [\tau_r(u) - \tau_d(u)]) \right] \\ &\quad \cdot \exp \left\{ -j2\pi f_{syn} [\tau_r(u) - \tau_d(u)] \right\} \end{aligned} \quad (10)$$

where $f_{syn} = \frac{f_{c_B2a} + f_{c_B2b}}{2}$. The power spectral density of the synthesized signal is illustrated in Figure 1a. At this stage, the spectrum of the synthesized signal exhibits a prominent double-peak characteristic with a wide spectral gap in the middle, rendering it unsuitable for direct imaging. Therefore, a filter is designed based on the reference signal to perform spectrum shaping on the synthesized double-peak spectrum [19], molding the main lobe of the composite signal into a rectangular amplitude spectrum as shown in Figure 1b, thereby obtaining a sinc waveform in the time domain.

The filter expression is given by:

$$H(f) = \frac{1}{|S_{ref}(f)|}, f \in B_{eff} \quad (11)$$

where $|S_{ref}(f)|$ is the magnitude of the reference signal spectrum, B_{eff} is the main-lobe bandwidth of the signal. Regarding the computational cost, the proposed dual-frequency fusion process involves time-frequency domain transformations via Fast Fourier Transform (FFT) and Inverse FFT (IFFT), alongside frequency-domain element-wise operations such as frequency shifting and spectrum shaping. While the element-wise operations only require a linear computational complexity of $O(N)$, the FFT/IFFT procedures dictate the upper bound of the processing load. Consequently, the overall computational complexity is strictly maintained at the $O(N \log N)$ level, ensuring that the method is highly efficient for practical implementation.

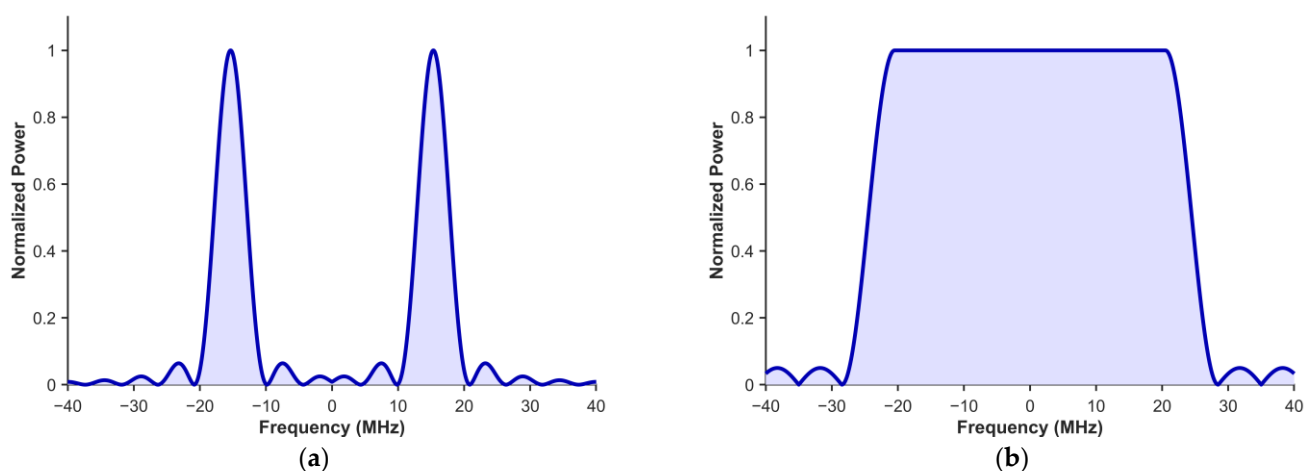


Figure 1. (a) Power spectral density of the synthesized signal; (b) Rectangular amplitude spectrum.

2.2. Interferometric Phase Model

Based on a single satellite, the typical bistatic configuration for GNSS-R InSAR elevation deformation retrieval is illustrated in Figure 2.

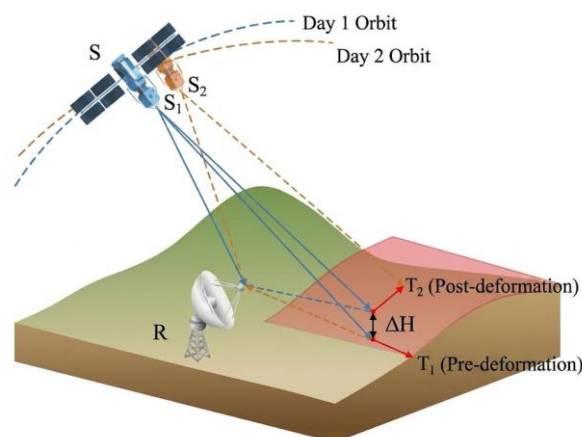


Figure 2. Bistatic configuration for GNSS-R InSAR elevation deformation retrieval.

For a given target point $\mathbf{T}$, assuming it is projected onto point $\mathbf{Q}$ within the imaging plane after the focusing process, the phase of the k -th SAR image is expressed as [20–23]:

$$\varphi_k(\mathbf{Q}) = \frac{2\pi}{\lambda_{syn}} (|\mathbf{S}_k - \mathbf{Q}| + |\mathbf{R} - \mathbf{Q}| - |\mathbf{S}_k - \mathbf{T}_k| - |\mathbf{R} - \mathbf{T}_k|) + \varphi_{k_atm}(\mathbf{Q}) + \varphi_{k_channel}(\mathbf{Q}) + \varphi_{k_noise}(\mathbf{Q}) \quad (12)$$

where $\mathbf{S}_k$ represents the equivalent satellite position within the synthetic aperture time of the k -th image, $\mathbf{R}$ denotes the position of the receiver, $\lambda_{syn} = \frac{c}{f_{syn}}$ is the wavelength of the synthesized signal, $\varphi_{k_atm}(\mathbf{Q})$ represents the atmospheric phase, $\varphi_{k_channel}(\mathbf{Q})$ is the phase difference between the reflection and direct channels of the receiver, $\varphi_{k_noise}(\mathbf{Q})$ is the noise phase. It should be noted that since the receiver processes both the direct and reflected signals using a shared local oscillator, the oscillator drift manifests as a common-mode error, which is effectively canceled out during the complex conjugate multiplication for range compression.

Through the analysis of the repeat-pass characteristics of the navigation satellite constellation, interferometric processing utilizing SAR images from adjacent days demonstrates exceptionally superior temporal and spatial baseline performance. The ultra-short temporal baseline effectively suppresses temporal decorrelation induced by variations in surface scattering characteristics and minimizes uncorrelated atmospheric delays. Concurrently, the highly stable repeat orbit trajectories maintain a strictly constrained spatial baseline, substantially reducing spatial decorrelation and effectively mitigating topographic phase errors. Therefore, precisely co-registered SAR images from adjacent days are selected to form interferometric pairs via complex conjugate multiplication, and the resulting ideal interferometric phase can be expressed as follows [20–23]:

$$\begin{aligned} \Delta\varphi_k(\mathbf{Q}) &= \varphi_{k+1}(\mathbf{Q}) - \varphi_k(\mathbf{Q}) \\ &= \frac{2\pi}{\lambda_{syn}} (|\mathbf{S}_{k+1} - \mathbf{Q}| - |\mathbf{S}_{k+1} - \mathbf{T}_{k+1}| - |\mathbf{R} - \mathbf{T}_{k+1}|) \\ &\quad - \frac{2\pi}{\lambda_{syn}} (|\mathbf{S}_k - \mathbf{Q}| - |\mathbf{S}_k - \mathbf{T}_k| - |\mathbf{R} - \mathbf{T}_k|) \\ &\quad + \Delta\varphi_{k_atm}(\mathbf{Q}) + \Delta\varphi_{k_channel}(\mathbf{Q}) + \Delta\varphi_{k_noise}(\mathbf{Q}) \end{aligned} \quad (13)$$

When the distance between the receiver position and the target point is much greater than the target deformation, the interferometric phase can be approximated as follows [23,24]:

$$\begin{aligned} \Delta\varphi_k(\mathbf{Q}) &= \varphi_{k+1}(\mathbf{Q}) - \varphi_k(\mathbf{Q}) \\ &\approx \frac{2\pi}{\lambda_{syn}} (\mathbf{S}_{k+1} - \mathbf{S}_k)^T \left(\frac{\mathbf{S}_k - \mathbf{Q}}{|\mathbf{S}_k - \mathbf{Q}|} - \frac{\mathbf{S}_k - \mathbf{T}_k}{|\mathbf{S}_k - \mathbf{T}_k|} \right) \\ &\quad + \frac{2\pi}{\lambda_{syn}} (\mathbf{T}_{k+1} - \mathbf{T}_k)^T \left(\frac{\mathbf{S}_k - \mathbf{T}_k}{|\mathbf{S}_k - \mathbf{T}_k|} + \frac{\mathbf{R} - \mathbf{T}_k}{|\mathbf{R} - \mathbf{T}_k|} \right) \\ &\quad + \Delta\varphi_{k_atm}(\mathbf{Q}) + \Delta\varphi_{k_channel}(\mathbf{Q}) + \Delta\varphi_{k_noise}(\mathbf{Q}) \end{aligned} \quad (14)$$

The two parts of the approximation result can be denoted as follows [23,24], respectively:

$$\varphi_{DEM}(\mathbf{Q}) = \frac{2\pi}{\lambda_{syn}} (\mathbf{S}_{k+1} - \mathbf{S}_k)^T \left(\frac{\mathbf{S}_k - \mathbf{Q}}{|\mathbf{S}_k - \mathbf{Q}|} - \frac{\mathbf{S}_k - \mathbf{T}_k}{|\mathbf{S}_k - \mathbf{T}_k|} \right) \quad (15)$$

$$\varphi_{def}(\mathbf{Q}) = \frac{2\pi}{\lambda_{syn}} (\mathbf{T}_{k+1} - \mathbf{T}_k)^T \left(\frac{\mathbf{S}_k - \mathbf{T}_k}{|\mathbf{S}_k - \mathbf{T}_k|} + \frac{\mathbf{R} - \mathbf{T}_k}{|\mathbf{R} - \mathbf{T}_k|} \right) \quad (16)$$

where $\varphi_{DEM}(\mathbf{Q})$ is the topographic phase, which is closely related to the spatial baseline, $\varphi_{def}(\mathbf{Q})$ is the deformation phase of the target point, induced by the displacement of the target.

Specifically, the total phase obtained through interferometric processing inherently comprises the topographic phase, the deformation phase, and other residual error phases. First, the topographic phase of the target is compensated according to Equation (15). To achieve higher-precision deformation retrieval results, it is necessary to acquire accurate Digital Elevation Model (DEM) data of the current scene for high-precision compensation of the topographic phase. It should be noted that a DEM elevation error propagates into the deformation retrieval as a residual topographic phase error. This error is directly proportional to the DEM elevation error and the spatial baseline. Because the space baseline of repeat-pass in GNSS-based InSAR is much larger than that of the traditional system, high-precision DEM data with sub-meter accuracy (e.g., acquired via LiDAR) are strictly required to accurately compensate for the topological phase and ensure millimeter-level deformation accuracy [24]. For the monitoring of deployed strong point targets, more precise position information can be acquired via RTK. Then we compensate for the inter-channel phase errors and atmospheric phase errors according to the method in Reference [24]. Additionally, the impact of target motion is considered negligible due to the quasi-static nature of the monitored targets within the integration time. Subsequently, the spatial positions of the satellite at the center of the synthetic aperture, the receiver, and the target point (whose elevation coordinate must be iteratively updated using the retrieved deformation value from the previous epoch in time-series interferometry) are uniformly converted into the local East-North-Up (ENU) coordinate system. Finally, by incorporating the equivalent wavelength of the synthesized signal and the specific bistatic observation geometry, Equation (16) is inverted to precisely retrieve the elevation deformation of the target.

3. Results

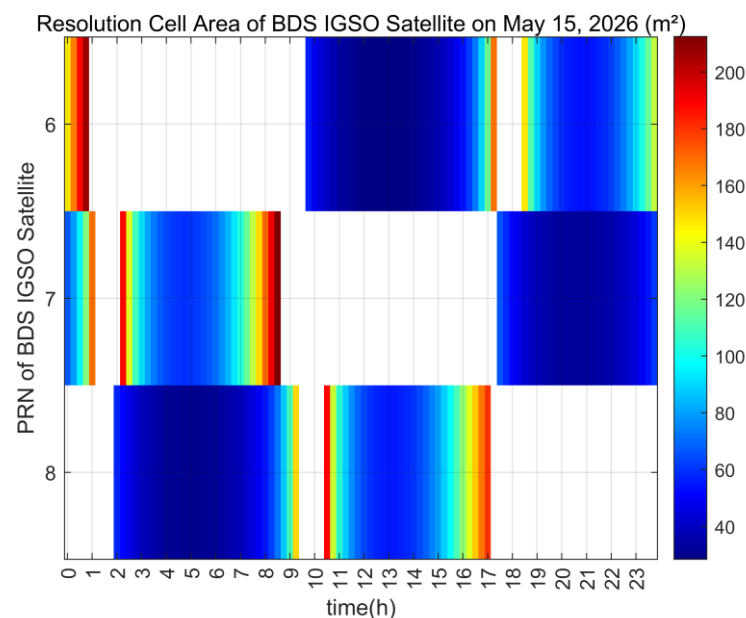
3.1. Single-Target Imaging Simulation

To validate the aforementioned method, a point-target imaging simulation based on a repeat-pass bistatic configuration is conducted, with the imaging simulation parameters detailed in Table 2.

Based on the broadcast ephemeris and simulation parameters, the resolution cell areas of the BeiDou-3 navigation satellites within the imaging scenario on 15 May 2026, are calculated, as depicted in Figure 3. The resolution cell area characterizes the minimum physical region on the ground that the radar system can effectively distinguish, serving as a core metric for evaluating spatial resolution; a smaller value indicates higher imaging precision. Subsequently, guided by this metric, the BDS IGSO satellite C6 during the period from 12:30 to 12:32 is selected. With the receiver positioned at the origin of the East-North-Up (ENU) coordinate system and oriented due east, the target point is deployed 300 m due east of the receiver. Under this specific geometry, an imaging simulation spanning 120 s is performed. It should be noted that the effects of the troposphere and ionosphere are not considered in the simulated data.

Table 2. Simulation parameters.

Parameter	Value
Carrier frequency	1176.45 MHz (B2a) 1207.14 MHz (B2b)
Ranging code bandwidth	10.23 MHz
Receiver position	(39.9769°, 116.3435°, 110 m)
Synthetic aperture time	120 s
Intermediate frequency	15.55 MHz (B2a) 15.86 MHz (B2b)
Sampling frequency	62 MHz
Target position	(300 m, 0, −110 m)
Imaging plane	250 m ≤ x ≤ 350 m −50 m ≤ y ≤ 50 m

**Figure 3.** Resolution cell area for BeiDou-3 navigation satellites on 15 May 2026.

The single-target imaging simulation results are presented in Figure 4. Although both the single-frequency B2a signal and the fused signal accurately focus at their theoretical locations, significant differences are observed in their range profiles. As illustrated in Figure 4c, the single-frequency B2a signal exhibits a noticeably broader main lobe. In contrast, Figure 4d demonstrates that the main lobe width of the fused signal is significantly narrowed. Based on Equation (1), the range resolution of the single-frequency B2a signal is 16.2 m, whereas the fused signal improves this resolution to 8.2 m. While the theoretical ideal range resolution is approximately 2.93 m, the reported 8.2 m represents the ground range resolution. This practical value comprehensively incorporates both the main-lobe broadening effect from the applied Kaiser window and the geometric widening caused by the specific bistatic angle and projection angle within the simulated scene.

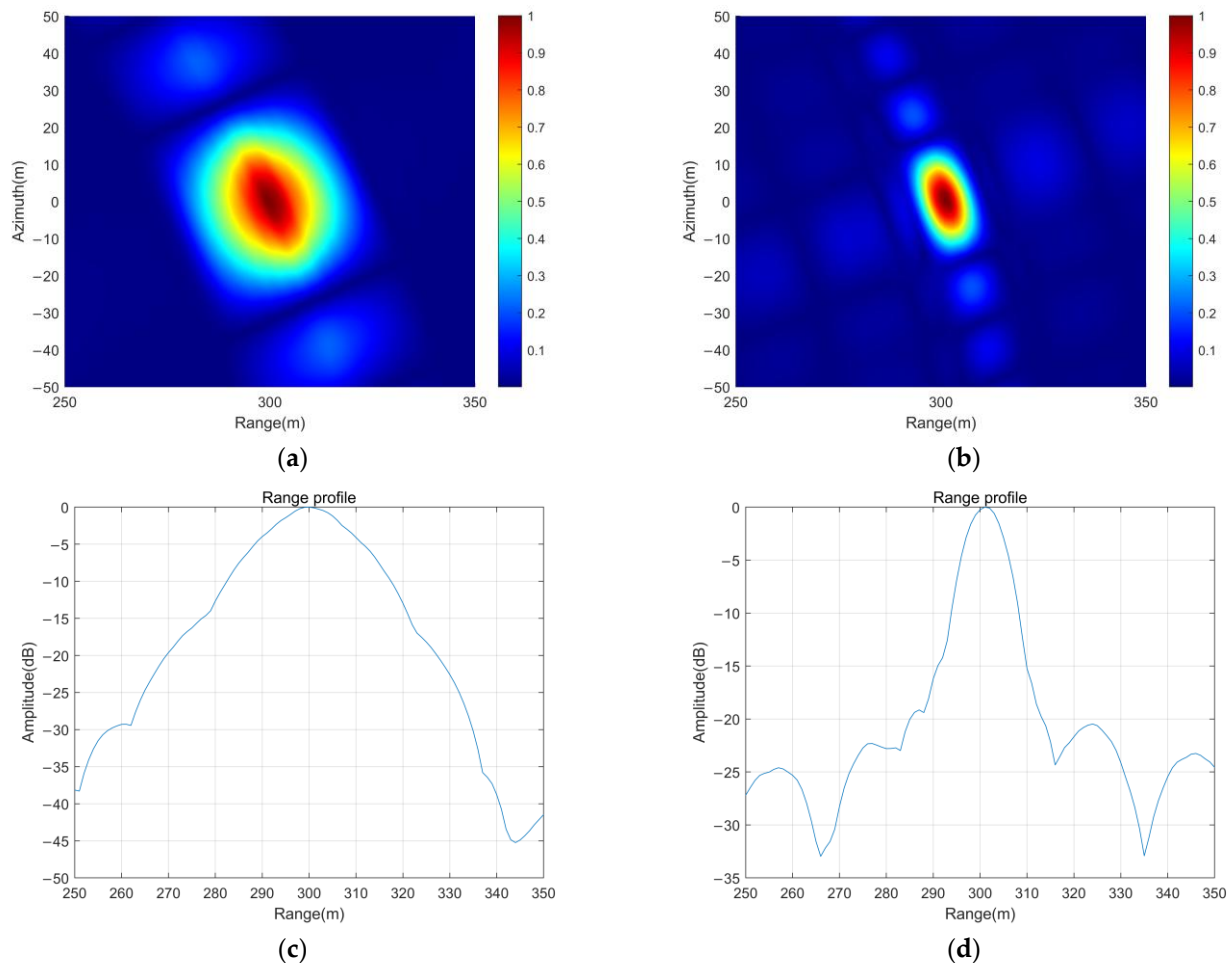


Figure 4. Single-target imaging simulation results. (a) Magnitude of the simulated single-frequency B2a signal; (b) Magnitude of the simulated fused signal; (c) Range profile of the simulated single-frequency B2a signal; (d) Range profile of the simulated fused signal.

3.2. Multi-Target Imaging Simulation

To further validate the target resolvability and visually demonstrate the resolution enhancement achieved by dual-frequency fusion, a multi-target imaging simulation is conducted.

A total of eight point targets are deployed in the simulation scene, divided into four groups. The two targets within each group are spaced 10 m apart in the range direction. As shown in Figure 5a, due to the limited range resolution of the single-frequency B2a signal, it fails to resolve these two targets, causing them to merge into a single blurred target in the image. In contrast, as illustrated in Figure 5b, the fused signal, benefiting from its improved resolution, successfully distinguishes the two targets, forming two clear and sharp main lobes. While the simulation visually demonstrates resolvability at a 10 m spacing, the theoretical minimum resolvable distance between targets is strictly bounded by the system's ground range resolution of 8.2 m. Any targets positioned closer than this physical limit will inevitably experience main-lobe overlap, rendering them unresolvable.

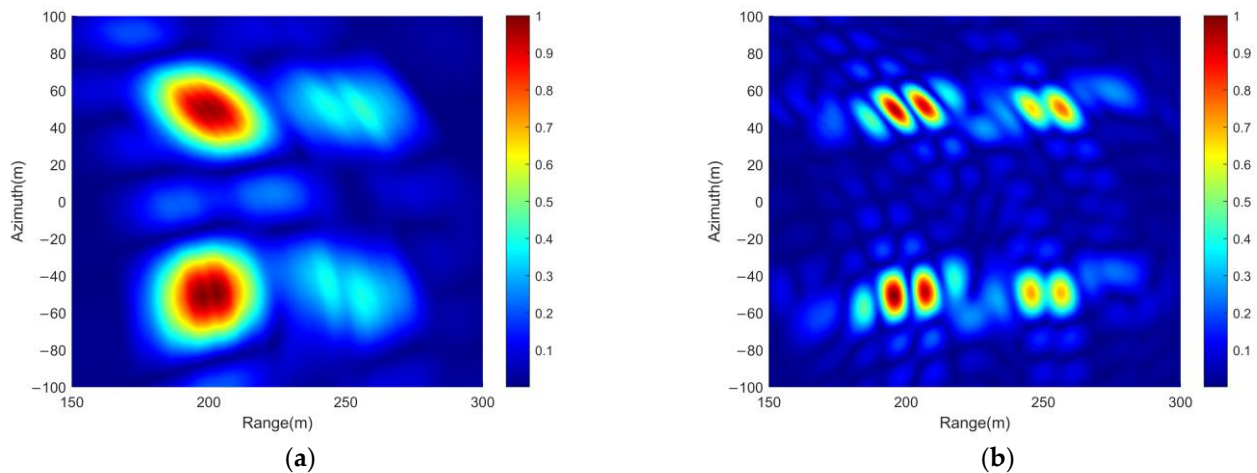


Figure 5. Multi-target imaging simulation results. (a) SAR image of the single-frequency B2a signal; (b) SAR image of the dual-frequency fused signal.

3.3. Interferometric Deformation Retrieval

To validate the effectiveness of applying the spectrum fusion imaging method to BDS-R InSAR repeat-pass interferometric elevation deformation measurement for improving measurement accuracy, six repeat-pass SAR images of a single point target are simulated based on the imaging simulation parameters in Table 2. During the formation of adjacent SAR images, the spatial baseline corresponding to the satellite at the center of the synthetic aperture is set to 0 and did not introduce other relevant environmental error sources. This ideal assumption strictly isolates topographic phase errors and environmental impacts, enabling a pure evaluation of the deformation accuracy improvement brought by the fusion method. The elevation variation of the target relative to its initial position is illustrated in Figure 6. Using the target's projection point $\mathbf{Q}$ in the SAR image for approximation, the target's elevation deformation is accurately retrieved via (16).

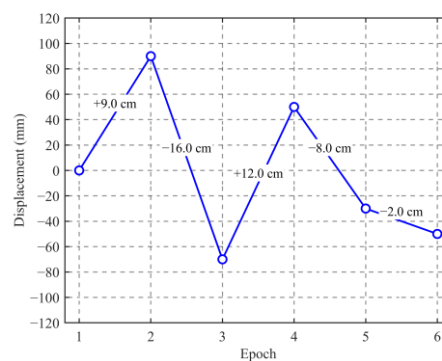


Figure 6. The elevation variation of the target.

The deformation retrieval results for the single-frequency B2a and fused signals are respectively presented in Table 3. Simulation results in a controlled environment demonstrate that the maximum error of the repeat-pass elevation deformation retrieval for the fused signal does not exceed 0.46 mm, with a root-mean-square error (RMSE) of 0.27 mm. These metrics are consistently superior to those of the single-frequency B2a signal, verifying the effectiveness of the signal fusion method in improving range resolution and enhancing deformation retrieval accuracy. The 0.27 mm RMSE represents a theoretical limit achieved under ideal noise-free conditions. Evaluating the algorithm's performance under realistic noise environments will be a critical next step in our future real-world field experiments.

Table 3. Comparison of simulated repeat-pass elevation deformation retrieval results between single-frequency and fused signals.

True Value/mm	Single-Frequency B2a Signal		Fused Signal	
	Measured Value/mm	Error/mm	Measured Value/mm	Error/mm
90	88.79	−1.21	90.32	0.32
−160	−157.87	2.13	−160.46	−0.46
120	118.41	−1.59	120.16	0.16
−80	−79.04	0.96	−79.83	0.17
−20	−19.70	0.30	−20.13	−0.13
RMSE	1.38 mm		0.27 mm	

4. Conclusions

In this paper, a spectrum fusion imaging method is introduced to enhance image resolution, thereby identifying more target points. Based on this, deformation measurement is conducted to achieve more detailed observations, addressing the issues of limited range resolution and reduced deformation inversion accuracy caused by the narrow bandwidth of single GNSS signals.

Simulation results comprehensively demonstrate the superiority of the introduced method in terms of spatial resolution and deformation inversion. This signal fusion strategy successfully expanded the bandwidth to 51.15 MHz, directly improving ground range resolution from 16.2 m to 8.2 m. A closely spaced multi-target simulation further visually confirmed this enhancement by successfully distinguishing four groups of targets 10 m apart, effectively solving the target point aliasing problem. Quantitative analysis of repeat-pass elevation deformation inversion under a controlled simulated environment showed that the maximum error of the fused signals was less than 0.46 mm, with a root-mean-square error (RMSE) of 0.27 mm. These metrics consistently outperform those of single-frequency signals, confirming the effectiveness of this fusion method in improving deformation monitoring accuracy.

Overall, the BeiDou dual-frequency fusion strategy introduced in this paper provides a cost-effective and highly reliable technical solution for deformation monitoring. Specifically, by utilizing existing navigation satellites as opportunity transmitters, this approach avoids the massive capital costs associated with dedicated active radar satellites such as Sentinel-1 or TerraSAR-X. Furthermore, compared to the 6-to-11-day revisit cycles of conventional LEO SARs, the continuous illumination and shorter repeat-pass periods of GNSS constellations ensure higher operational reliability for high-frequency continuous monitoring. Future work will focus on validating the algorithm using actual airborne or spaceborne observation data from high-risk areas, and exploring multi-satellite joint observation geometries. This aims to further enhance three-dimensional deformation inversion capabilities, construct continuous deformation fields, and thereby achieve continuous spatial monitoring.

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Data Availability Statement: The simulation code and parameter configurations used to support the findings of this study have been deposited in a public GitHub repository, which can be accessed at: <https://github.com/xqc-debug/GNSS-R-InSAR-Deformation-Monitoring> (accessed on 30 June 2026).

Conflicts of Interest: Author Xiaochen Zhang was employed by CCCC Highway Consultants Co., Ltd., Beijing, China; author Hongxiang Li was employed by Shanghai Huace Navigation Technology Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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