Optimized Development of Seismic Networks through High-Rate GNSS Observations

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ABSTRACT

While seismic monitoring networks play a fundamental role in earthquake observation, their development shall not be restricted to increasing the number of recording stations. In contrast, network enhancement has to take into account the scientific objectives, seismic hazard levels, available resources, and operational feasibility. High-Rate GNSS (HR-GNSS) technology provides an important advantage over traditional seismic instruments due to its ability to record three-dimensional ground displacements directly, without saturation during strong shaking, and with no need for baseline correction. These capabilities turn HR-GNSS into one of the most promising complements of seismic measurements, at least for surface-wave analysis and crustal velocity modeling. In tectonically active regions like Iran, where multiple seismic sources converge with densely populated areas, an optimized seismic–geodetic network is of paramount importance. This research proposes a goal-oriented and cost-effective framework for upgrading existing GNSS stations into high-rate operation instead of expanding the network size. By integrating HR-GNSS along with seismic observations, especially within the Zagros and Alborz tectonic zones, the monitoring system will achieve enhanced azimuthal coverage, improved near-field displacement detection, and a unified broadband dataset enabling advanced seismic studies and geodynamic modeling. Results will show that scientifically optimized and economically feasible HR-GNSS integration may significantly enhance the nation's earthquake monitoring capability and add much value to crustal structure understanding in tectonically active regions.

Keywords: High-Rate GNSS, Seismic Networks, Earthquake Monitoring, Surface Waves, Network Development.

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1. INTRODUCTION

Earthquake observation and geophysical research are basically based on precision, density, and configuration of the monitoring networks. Traditional seismic instruments represented by broadband seismometers and accelerometers have been the dominant earthquake monitoring tools for decades. However, large events demonstrate their crucial limitations. Seismometers may saturate under strong ground motion, and accelerometers require double integration to get displacement, which might introduce long-period drifts and a cumulative error (Bock et al., 2011). These limitations reveal the need for complementary datasets that will help improve the completeness and reliability of earthquake observations.

Recent advances in satellite-based geodesy have introduced High-Rate Global Navigation Satellite System (HR-GNSS) technology as a transformative tool in seismic–geodetic studies (Bilich et al., 2008). At 1 sampling rates, HR-GNSS directly records three-dimensional ground displacements without the need for either integration or baseline correction. Unlike seismometers, during strong ground shaking and major earthquakes, these HR-GNSS stations do not become saturated and capture both static offsets and long-period motion (Geng et al. 2013; Melgar and Bock, 2013). When combined with seismic data, HR-GNSS fills the low-frequency gap and produces broadband displacement waveforms that span the full spectrum of earthquake motion (Crowell et al., 2013; Dahmen et al., 2020).

The successful application of HR-GNSS has already been demonstrated internationally. The GEONET network of over 2000 stations in Japan, for example, contributed greatly to earthquake studies during large earthquake such as the 2011 Tohoku-Oki earthquake (Mw 9.0) through its real-time displacement records for slip inversion and tsunami modeling (Ohta et al., 2012). Similarly, following the 2023 Kahramanmaraş earthquake in Turkey, HR-GNSS observations of the TUSAGA-Aktif network allowed an accurate characterization of near-field deformation (Melgar et al., 2023). These examples illustrate the fact that cost-effective and scientifically valuable approaches to developing the capability for earthquake monitoring can be realized by upgrading existing GNSS stations to high-rate mode.

Iran, located within the Alpine–Himalayan collision belt, is one of the most tectonically active regions worldwide (Mahmoodabadi, 2019). Therefore, this region benefits from well-established seismological and geodetic monitoring systems, including the Iranian Seismological Center (IRSC), the International Institute of Earthquake Engineering and Seismology (IIEES), and the National Cartographic Center (NCC).

These networks have provided valuable observations for earthquake detection and long-term crustal deformation analysis. However, their independent operation means that seismic and geodetic measurements are often analyzed separately, which may limit the ability to fully characterize earthquake source processes and ground-motion behavior especially during major events (Houlié et al., 2011).

Integrating HR-GNSS observations with existing seismic datasets can enhance both systems by providing complementary information in the low-frequency and high-frequency domains (Dahmen et al., 2020). This integration does not reflect any deficiency in the existing networks but instead is a scientific opportunity to combine their merits and establish a hybrid seismic–geodetic framework that can enhance real-time monitoring capability and enrich geophysical research.

This paper aims to propose a scientifically optimized and economically efficient framework for incorporating HR-GNSS observations into the earthquake monitoring system of Iran. Without increasing the number of stations, the proposed methodology focuses on upgrading existing GNSS sites to higher sampling rates to exploit the current infrastructure and consequently reduce the installation costs. The study particularly examines the Zagros and Alborz tectonic zones two of Iran’s most seismically active regions and identifies candidate stations for HR operation based on network geometry, seismic relevance, and proximity to existing seismic arrays.

2. METHODOLOGY

This paper proposes a methodological framework that enhances the earthquake monitoring capability not by expanding the spatial coverage of the network, but rather through upgrading the existing GNSS stations to high-rate configurations. Different from the traditional approaches relying only on seismometers and accelerometers, this strategy seeks a hybrid seismic-geodetic observation system using infrastructures that already exist across Iran. Most GNSS receivers are technically capable of 1 Hz sampling but currently operate at 15–30 second intervals. Therefore, high-rate reconfiguration can be achieved with limited cost, avoiding the need for new installations.

Iran already benefits from valuable seismic networks operated by IRSC and IIEES, together with a geodetic GNSS network managed by NCC. Although these systems function independently, their combined scientific potential has not yet been fully utilized. The locations of a number of NCC stations are within short distances from seismic stations, naturally providing opportunities for co-location and hybrid monitoring. Instead of establishing new stations, upgrading these sites to HR-GNSS enables the recording of displacement, velocity, and acceleration simultaneously, thereby improving the scientific return of the existing infrastructure without additional installations.

3.1 Station Selection Criteria

Four scientific and operational considerations formed the basis for the identification of GNSS stations suitable for HR upgrading:

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Proximity to seismic stations allows co-located or near-co-located monitoring, which facilitates waveform integration and improves both phase alignment and frequency-content comparison between datasets. Recordings from HR-GNSS and seismic sensors can be compared directly in both the time and frequency domains when they operate within close spatial distance. This ensures increased reliability of hybrid ground-motion analysis by allowing high-frequency seismic signals to complement low-frequency GNSS displacements. Previous works have underpinned that co-location significantly enhances dataset coherence, reduces timing uncertainties, and strengthens the capability of monitoring systems to capture near-field deformation during major earthquakes. (Crowell et al., 2013; Melgar and Bock, 2013; Psimoulis, 2014). Therefore, co-location is a fundamental criterion in selecting GNSS stations for high-rate operation and plays a central role in developing an integrated seismic–geodetic monitoring framework. Second, tectonic significance is a key parameter. locations near active faults or high-strain regions offer greater geophysical value and stronger potential for HR observation. Third, network geometry was considered to see whether a GNSS station would reduce azimuthal gaps or enhance station distribution in the seismic network. The fourth was cost efficiency. stations that require minimal infrastructure modifications to become operational are preferred in line with the principle of optimizing existing resources.

Through this assessment, several candidate stations were identified in the Alborz and Zagros regions, which were later evaluated in detail through case studies.

3.2 Data Processing

Once operational, HR-GNSS stations can be processed using the Precise Point Positioning (PPP) technique with IGS satellite products, and raw displacement time series can be filtered using low-pass Butterworth filters to remove high-frequency noise (Geng et al., 2013). Meanwhile, seismic data will undergo instrumental response correction and band-pass filtering to retrieve velocity or displacement waveforms. In those co-location sites where both GNSS and seismic datasets are available, synchronization can be done by cross-correlating waveform peaks, which is followed by frequency-domain merging that produces broadband displacement waveforms covering the full spectrum of earthquake ground motion. Overall, this methodology promotes a science-oriented and economically efficient strategy for developing a hybrid seismic–geodetic network in Iran. By focusing on strategic location upgrading of existing GNSS stations, this approach promotes network geometry, high-frequency sampling, compatibility with seismic observations, broadband displacement analysis, and surface-wave tomography. It leverages international experiences and addresses the geological context of Iran without a need to increase the number of stations. Accordingly, the proposed innovation ensures full utilization of the capacity of current infrastructure, providing a realistic pathway toward high-resolution earthquake monitoring and improved seismic hazard assessment.

3. CASE STUDY: APPLICATION TO IRAN'S ACTIVE REGIONS

The proposed methodology was applied to the real spatial distribution of Iran's existing geodetic and seismic observation networks. Iran's tectonic framework, shaped by the ongoing convergence of the Arabian and Eurasian plates, consists of multiple deformation provinces most notably the Zagros and Alborz regions. These are regions with high seismic potential and complex fault interactions that provide an ideal environment for studying the feasibility and scientific value of upgrading existing GNSS stations to high-rate operation.

The main purpose of this case study is to determine where HR-GNSS enhancement would provide the greatest impact regarding earthquake monitoring and geodynamic research. Three selection criteria were chosen in order to accomplish the purpose:
(1) Proximity to active regions, where the likelihood of significant co-seismic displacement is highest;
(2) Availability of nearby seismic stations enabling co-location or near co-location and supporting synchronized hybrid observation;
(3) Contribution to network geometry, mainly by reducing the azimuthal and spatial gaps in the current monitoring system, thus increasing station coverage and source parameter resolution.
The following case study presents how these tectonic and operational constraints, combined, allow HR-GNSS upgrades to strengthen the observational capability in existing networks and fill key gaps in the Iranian monitoring infrastructure. Results are given in the next sections, along with the selected candidate stations.

3.1 The Zagros Region

The Zagros Mountains represent one of the most seismically active and structurally complex regions in the Middle East, accommodating a major portion of the ongoing convergence between the Arabian plate and central Iran (Agard, 2011). This fold and thrust belt are characterized by distributed deformation, thick sedimentary sequences, and a history of large and destructive earthquakes such as the 2017 Mw 7.3 Ezgeleh event (Nissen et al., 2019) and the 2014 Mw 6.2 Murmuri (Rezapour 2018) earthquake. Given the structural segmentation of the belt and the strong lateral variations in crustal properties, the Zagros region provides an ideal natural laboratory for high-rate geodetic monitoring and integrated seismo-geodetic analysis.

Within this tectonic setting, the GNSS station KHRM is the most promising candidate for high-rate upgrade, as it is exceptionally close to the IRSC seismic station KMR, at a distance of about 1.3 km. This short separation creates a near-co-located configuration, which is extremely valuable for combining low-frequency GNSS displacement measurements with high-frequency seismic waveform data. Over these distances, the two sensors effectively sample the same ground motion field, enabling a number of key advantages: broadband reconstruction of displacement time series, improved phase alignment, and more reliable estimation of permanent and dynamic deformation. The KHRM–KMR pair offers a unique opportunity to observe near-field co-seismic offsets, long-period surface waves, and high-frequency body-wave arrivals in a unified framework.

Beyond the KHRM–KMR pair, several GNSS stations across the Zagros enhance the monitoring capability of the region even though they may not be strictly co-located with seismic instruments. Of these, LALI represents a key site because of its location within the central part of the Zagros fold and thrust belt, which is characterized by intense deformation and structural complexity with recurring seismicity related to several interacting thrust faults (Vernant et al., 2004). Although the nearest seismic stations lie at distances greater than a few kilometers, LALI's tectonic location and stable geodetic performance make it a valuable candidate for HR operation. Upgrading LALI would significantly improve azimuthal coverage around the central Zagros deformation zone, support surface-wave dispersion studies, and contribute to more accurate inversion of crustal velocity structure particularly in areas where sedimentary thickness and rock properties vary sharply across short distances (Movaghari et al., 2019).

The GNSS station AHWZ, situated in the southern Zagros and near the foreland basin of Khuzestan, provides another high-value candidate for HR enhancement. This region is known for its thick sedimentary deposits, large-amplitude long-period ground motion, and the potential for moderate-to-strong earthquakes associated with blind thrusting and basement-involved structures (Hessami, 2001). HR-GNSS observations from AHWZ would thus be essential for analyzing large-scale deformation, constraining the amplitude of long-period surface waves, and extending the frequency range of broadband ground-motion recordings. Furthermore, AHWZ improves the spatial distribution of geodetic instrumentation in the southern Zagros, contributing to a more balanced observational network capable of characterizing rupture processes across the entire belt.

In addition to KHRM, LALI, and AHWZ, the station ALVN plays an important complementary role. Located between the seismically active regions of Lorestan, Ilam, and Kermanshah, ALVN occupies a key position in a tectonically transitional zone where the geometry of the seismic network reveals clear azimuthal gaps. Although ALVN is not located as close to seismic sensors, its placement within a structurally important corridor makes it scientifically valuable for improving the regional response to major earthquakes. HR-GNSS observations from ALVN would help fill the observational gap between the northwestern and central Zagros, enabling a more complete picture of strain distribution, surface-wave propagation paths, and crustal heterogeneity. This is especially relevant for future large events, given the historical occurrence of major earthquakes along the Main Zagros Reverse Fault and its subsidiary structures.

Taken together, KHRM, LALI, AHWZ, and ALVN form a scientifically robust and strategically distributed subset of GNSS stations that are well suited for HR operation in the Zagros region (Figure 1). KHRM provides the essential near-co-located seismo-geodetic pair, LALI strengthens coverage across the central fold and thrust belt, AHWZ enhances monitoring of long-period deformation in the foreland basin, and ALVN fills a critical azimuthal gap in the northern–central transition zone. Upgrading these stations would substantially improve the ability to capture broadband ground motion, constrain co-seismic and post-seismic slip models, and refine regional velocity structures. In doing so, they would enhance Iran's capacity for earthquake monitoring and hazard assessment in one of its most tectonically active regions.

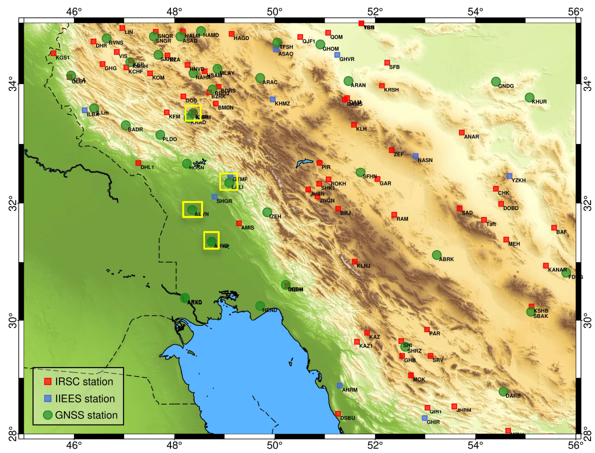

Figure 1: Distribution of GNSS (green), IRSC seismic (red), and IIEES stations (blue) across the Zagros fold-and-thrust belt. The GNSS stations highlighted in yellow are identified as the most suitable candidates for high-rate operation due to their tectonic significance, co-location potential with seismic stations, and contribution to reducing azimuthal and spatial gaps in the current monitoring system.

3.2 The Alborz Region

In the Alborz region, two GNSS stations JIRN and ABBR were identified as the most suitable candidates for high-rate upgrading based on their geometric configuration, tectonic context, and proximity to key seismic instruments. The Alborz Mountains constitute one of the most seismically active and structurally complex zones in Iran, accommodating high rates of shortening and distributed deformation between the South Caspian Basin and the central Iranian plateau. This narrow, arcuate mountain belt hosts several major active fault systems including the Mosha–Fasham, Taleqan, Firuzkuh, and North Tehran faults that have produced numerous destructive earthquakes throughout historical and instrumental periods (Vernant et al., 2004).

Within this context, JIRN provides a uniquely valuable opportunity for establishing a near-ideal seismo-geodetic observation site. The station is located at a horizontal distance of only about 1.4 km from the IRSC seismic station JIR1, placing the two instruments effectively in an almost co-located configuration. Such close spacing is extremely rare in regional networks and offers significant scientific advantages. High-rate GNSS observations from JIRN can capture low-frequency and long-period components of ground motion including static offsets, permanent displacements, and large-amplitude surface waves while the co-located seismic instrument records high-frequency body waves, accelerations, and strong-motion signals. When these complementary datasets are integrated, it becomes possible to reconstruct broadband ground-motion waveforms with substantially higher fidelity than achievable by either sensor alone. This broadband capability is critical for rupture process studies, validating strong-motion simulations, and enabling improved hybrid magnitude estimation methods that combine GNSS-derived displacements with seismic waveforms.

The proximity of JIRN to several active structures in the central Alborz enhances its scientific value. The surrounding region has repeatedly produced moderate and large earthquakes, and the combination of HR-GNSS and seismic observations would provide unprecedented insights into the relations between coseismic displacement, fault geometry, and wave propagation in this structurally heterogeneous landscape. Given the complex lithological layering and abrupt variations of crustal thickness characteristic of the Alborz, HR-GNSS recordings from JIRN would also contribute to improved surface-wave dispersion measurements allowing tighter constraints on shear-wave velocity structure.

Complementing JIRN, the GNSS station ABBR occupies a position of strategic importance on the southern margin of the central Alborz, close to the transition between the mountain front and the Tehran–Karaj urban corridor. This is a site of particular importance for various reasons. First, the southern flank of the Alborz hosts a number of major active faults, including segments of the Mosha–Fasham system, the North Tehran fault, and subsidiary structures accommodating distributed deformation and uplift. These give rise to considerable seismic hazard in the capital region, but the current seismic network shows noticeable azimuthal gaps in near-fault coverage, particularly toward the south and southwest. These geometry gaps can be reduced by upgrading ABBR to high-rate mode, improving the ability of the network.

JIRN and ABBR together result in a balanced and scientifically sound pair of GNSS stations for high-rate operation in the Alborz. The co-location synergy of JIRN with local seismic instrumentation offers unparalleled opportunities for precise broadband waveform reconstruction and thorough investigation of near-field ground motion. ABBR fills a significant gap in station position in the southern Alborz, thereby enhancing network geometry, increasing coverage over active fault systems, and providing superior long-period deformation measurements. Upgrading these stations to high-rate sampling would substantially advance the observational capabilities of Iran’s geodetic and seismological monitoring systems in one of the country’s highest-risk tectonic settings.

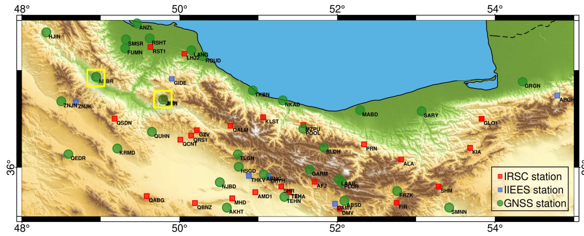

Figure 2: Distribution of GNSS (green), IRSC seismic (red), and IIEES stations (blue) across the Alborz Mountains. The GNSS stations highlighted in yellow are identified as the most suitable candidates for high-rate operation due to their tectonic significance, co-location potential with seismic stations, and contribution to reducing azimuthal and spatial gaps in the current monitoring system.

4. DISCUSSION AND CONCLUSION

The results of this study demonstrate that upgrading existing GNSS infrastructure to high-rate operation provides a highly effective pathway for modernizing Iran's national earthquake monitoring capabilities. Instead of increasing the number of monitoring stations, the approach here proposed focuses on the cost-effective enhancement of the existing assets. Several GNSS receivers are already deployed across Iran that support high-rate sampling; hence, substantial improvement of the monitoring performance can be achieved with minimal interventions, which for the most part involve firmware updates, telemetry improvements, and optimized data pipelines, without any construction of new, expensive stations. This makes the proposed strategy economically attractive and operationally feasible for nationwide implementation.

A key outcome of this study is the demonstration that integrating HR-GNSS and seismic observations significantly improves the harmonization of Iran’s geodetic and seismological networks. Historically, these networks have operated largely independently, with GNSS focused on long-term crustal deformation and seismic instruments dedicated to high-frequency waveforms by integrating the two systems strategically, particularly at co-locations and sites within short distances of each other, the networks can complement one another in frequency coverage, spatial resolution, and scientific functionality. This configuration allows simultaneous recording of displacement, velocity, and acceleration, thereby enabling broadband waveform reconstruction. A unified dataset is provided that spans the full range of earthquake-related ground motion.

This integrated framework, when applied across major tectonic belts in Iran, notably the Alborz and Zagros regions, shows great potential to enhance earthquake hazard assessment. These regions accommodate the majority of active deformation and historical large earthquakes of the country. GNSS station upgrades, such as those for JIRN and ABBR in the Alborz and KHRM, LALI, AHWZ, and ALVN in the Zagros, further increase the capability for characterizing near-field co-seismic offsets, resolving long-period surface waves, and constraining fault-rupture processes. The selected sites not only provide valuable HR-GNSS signals but also improve the azimuthal coverage and geometric balance of the national monitoring network, reducing observational gaps in regions where large earthquakes are most likely to occur.

From a scientific perspective, the integration of HR-GNSS and seismic data offers major advantages for understanding earthquake source processes. GNSS delivers stable measurements of long-period and permanent ground motion, while seismic instruments record high-frequency body and surface waves. When these datasets are combined, they yield broadband displacement time series that can be used to refine finite-fault models, surface-wave tomography, and shear-wave velocity structure. This hybrid observational capability is very important in terms of earthquake rupture studies in tectonically complex regions such as Alborz and Zagros with strong lateral heterogeneity and thick sedimentary sequences, which influence the wave-propagation and deformation patterns.

Despite the scientific advantages of HR-GNSS integration, the continuous recording of high-rate data generates a large volume of information that requires appropriate infrastructure for long-term storage and efficient archiving. Hence, it is of paramount importance to establish dedicated data centers with reliable storage capacity and optimized retrieval systems for making the HR-GNSS datasets accessible and preserved. In particular, the necessity for such infrastructure becomes evident for those stations located in seismically active regions with continuous monitoring requirements and whose data rates may rapidly increase during large earthquake events. Developing sustainable data-management strategies will thus be a key component of implementing a nationwide seismic–geodetic network.

Looking ahead, the results of this study provide a practical foundation for nationwide implementation of HR-GNSS technology in Iran. The proposed framework is inherently scalable and can be expanded to other tectonically active areas as additional infrastructure becomes available. Future efforts should be directed toward pilot implementation at selected stations, developing standardized protocols for seismic–geodetic data fusion, and building cooperation between scientific institutions in view of establishing a national data platform dedicated to real-time monitoring. Ultimately, this approach demonstrates that significant improvements in earthquake monitoring can be achieved through intelligent utilization of current infrastructure without the need for expanding the number of stations and offers a strategic pathway toward a robust and future-oriented national monitoring network.

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