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Advances in Real-Time GNSS Monitoring of Earthquakes and Volcanoes in Indonesia

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Abstract: Indonesia is among the most tectonically and volcanically active regions worldwide, where frequent earthquakes, volcanic eruptions, and long-term surface deformation pose serious risks to population centers and critical infrastructure. Reliable real-time geodetic monitoring is therefore essential for hazard assessment, early warning, and disaster mitigation. This study presents the status and recent advances in GNSS-based real-time geohazard monitoring in Indonesia, with an emphasis on precise point positioning with ambiguity resolution (PPP-AR) implemented through the GSeisRT real-time engine. GSeisRT processes 1 Hz multi-GNSS observations and generates low-latency regional satellite clock and phase bias products, enabling stable and high-precision real-time displacement monitoring. GSeisRT has been deployed within the nationwide Ina-CORS network operated by the BIG and supports continuous monitoring of earthquakes, volcanic deformation, land subsidence, and active faults. Several recent seismic events, including the 2023 Banda Sea Mw 7.1 earthquake and subsequent Mw 5.8-6.6 events, were successfully captured in real time. The derived coseismic displacements and peak ground displacements (PGDs) allow rapid earthquake magnitude determination that agrees well with estimates published by the United States Geological Survey (USGS). Performance comparisons with existing real-time PPP systems demonstrate that GSeisRT provides improved robustness and continuity, effectively suppressing spurious position jumps caused by incorrect ambiguity resolution. Additional developments, including the integration of GNSS with collocated accelerometer data and the availability of global 1 Hz real-time satellite products, further enhance short-period deformation monitoring and seismic response capability. Although challenges remain due to sparse station spacing and communication limitations in remote areas, the results confirm that advanced re-al-time GNSS technologies provide a reliable and scalable foundation for strengthening geohazard early warning and resilience in Indonesia.

Keywords: real-time; precise point positioning; ambiguity resolution; geohazard monitoring; earthquake early warning

1. Introduction

Indonesia is one of the most tectonically active regions globally, situated at the convergence of the Indo-Australian, Eurasian, Pacific, and Philippine Sea plates. This complex tectonic setting results in

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frequent earthquakes, tsunamis, volcanic eruptions, and land subsidence, which together pose significant threats to human safety and socio-economic stability. Major events such as the 2004 Sumatra Andaman earthquake and tsunami, the 2006 Yogyakarta earthquake, and the 2018 Palu super shear rupture highlight the catastrophic potential of geohazards in Indonesia (Bao et al., 2019; Lay et al., 2005; Socquet et al., 2019).

In addition, long term deformation processes including crustal strain accumulation, volcanic unrest, and coastal subsidence affect cities like Jakarta, Semarang, and coastal plains, confirming the urgency of advanced monitoring systems (Abidin et al., 2008, 2011; Chaussard et al., 2013; Susilo et al., 2023). These geohazards have repeatedly resulted in casualties, damage to residential and public infrastructure, and the displacement of affected communities, creating substantial social and economic burdens. These consequences highlight the importance of establishing reliable, high-resolution monitoring systems to support early warning, risk mitigation, and effective disaster management.

Global Navigation Satellite Systems (GNSS) play a critical role in geohazard science by enabling continuous, high-rate three-dimensional displacement detection with centimeter to millimeter precision. GNSS observations are invaluable for capturing interseismic strain, coseismic rupture, post seismic relaxation, and volcanic inflation/deflation cycles (Crowell et al., 2013; Geng et al., 2025; Hardy et al., 2025; Kreemer et al., 2006). In real-time seismic monitoring, earthquake waveforms often contain rich low-frequency signals. Traditional seismographs may suffer saturation when determining the magnitude of an earthquake, while GNSS displacements can directly calculate the Peak Ground Displacement (PGD), enabling rapid and precise magnitude estimation without saturation problems. Reflecting on the 2011 Tohoku-Oki earthquake, the early warning issued after the onset of the Mw 9.0 Tohoku-Oki earthquake significantly underestimated its magnitude, saturating, 120 seconds after the earthquake began, at Mw 8.1 because at that time only seismometer for earthquake monitoring operationalization (Wright et al., 2012).

A major innovation in GNSS processing is Precise Point Positioning (PPP), which delivers high-precision results using a single receiver with precise satellite orbit and clock data (Zumberge et al., 1997; Kouba & Héroux, 2001). Enhancements such as integer ambiguity resolution (Collins et al., 2008; Geng et al., 2010; Laurichesse et al., 2009) and real-time corrections have improved PPP’s operational utility. PPP with ambiguity resolution (PPP-AR) enables near-instantaneous estimation of coseismic deformations, making it a cornerstone in GNSS based earthquake and tsunami early warning systems (Geng et al., 2025; Wright et al., 2012).

Recent advances include the development of GSeisRT, a multi-GNSS PPP-AR engine developed for real-time seismic monitoring. GSeisRT supports rapid coseismic displacement estimation and source modeling, significantly enhancing the timeliness and effectiveness of early warning systems (Geng et al., 2025). Similar real-time GNSS systems have been implemented internationally, in Japan (Kawamoto et al., 2017; Ohta et al., 2012; Kawamoto et al., 2016) and the United States (Murray et al., 2023) underscoring a global shift toward integrating GNSS into operational geohazard responses. The Deutsches GeoForschungsZentrum (GFZ) has likewise developed the Real-Time Positioning and Monitoring (RTPM), a real-time PPP framework that provides high-rate and low-latency displacement estimates for rapid earthquake detection and early warning and has been applied in regional monitoring networks in Europe and Indonesia (Jiang et al., 2022).

In Indonesia, GNSS infrastructure has expanded significantly over the past two decades. Indonesia Continuously Operating Reference Station (Ina-CORS) network managed by the BIG provides foundational data for tectonic and volcanic studies (Bayoumi et al., 2024; Subarya et al., 2006). Ina-CORS network enabled key discoveries such as the super shear dynamics of the 2018 Palu earthquake (Bao et al., 2019; Socquet et al., 2019) and support ongoing monitoring of subsidence and tectonic deformation in urban areas (Abidin et al., 2008; Susilo et al., 2023).

GNSS is also integral to volcanic hazard assessment. Continuous GNSS observations at volcanoes such as Merapi, Sinabung, and Agung reveal deformation patterns linked to magma movement (Hotta et al., 2016; Surono et al., 2012; Syahbana et al., 2019).

This paper demonstrates how advanced GNSS method especially PPP-AR and real time platforms such as GSeisRT advance both scientific understanding and operational preparedness in Indonesia's tectonically and volcanically active environment. The remainder of this paper is organized as follows. Section 2 outlines the PPP-AR methodology and the real-time processing framework of GSeisRT. Section 3 describes the Indonesian GNSS infrastructure and associated real-time data streams. Section 4 presents key results from earthquake and volcanic deformation monitoring. Section 5 discusses system performance, including comparisons with the GFZ Real-Time Positioning and Monitoring (RTPM) system, the integration of hybrid GNSS accelerometer approaches, and the global 1 Hz real-time product service capability of GSeisRT. Section 6 concludes the paper and highlights future directions for GNSS-based geohazard monitoring.

2. Method and GSeisRT

GNSS PPP-AR implemented within the GSeisRT (Geng et al., 2025) framework combines several complementary technical advances that together make it a uniquely powerful solution for real-time, high-precision deformation monitoring by operating on 1 Hz multi-GNSS carrier-phase and pseudorange streams and leveraging a geographically distributed regional reference network. Specifically, GSeisRT is based on the ionosphere-free combination observables. The classical observation equation is given by:

$$\begin{cases} \lambda_q \varphi_{i,q}^j = \rho_i^j + c\left(t_i - t^j\right) + m_i^j T_i - g_q^2 I_i^j + \lambda_q N_{i,q}^j \\ P_{i,q}^j = \rho_i^j + c\left(t_i - t^j\right) + m_i^j T_i + g_q^2 I_i^j \end{cases} \tag{1}$$

where i represents the receiver and j represents the satellite. $\varphi_{i,q}^j$ and $P_{i,q}^j$ are the carrier-phase and pseudorange observations of frequency f_q, and λ_q $(q = 1, 2 \cdots)$ is the wavelength of the corresponding signal. ρ_i^j is the geometric distance from satellite j to receiver i. c is the speed of light in vacuum. t_i and t^j are the receiver and satellite clock errors, respectively. m_i^j is the mapping function to project zenith tropospheric delay T_i onto the line-of-sight direction. $g_q = \frac{f_1}{f_q}$ is a scaling factor for the ionospheric delay I_i^j. $N_{i,q}^j$ is the ambiguity. Note that hardware delays, multipath effects, and other unmodeled errors are not explicitly included in the Equation (1). The dual-frequency ionosphere-free combination used in GSeisRT server and client end is:

$$\begin{cases} L_{i,IF}^j = \frac{g_2^2}{g_2^2 - 1} \lambda_1 \varphi_{i,1}^j - \frac{1}{g_2^2 - 1} \lambda_2 \varphi_{i,2}^j = \rho_i^j + c(t_i - t^j) + m_i^j T_i + \lambda_1 N_{i,IF}^j \\ P_{i,IF}^j = \frac{g_2^2}{g_2^2 - 1} P_{i,1}^j - \frac{1}{g_2^2 - 1} P_{i,2}^j = \rho_i^j + c(t_i - t^j) + m_i^j T_i \end{cases} \tag{2}$$

where ‘IF’ denotes the ionosphere-free combination. Based on these, GSeisRT produces high-rate satellite clock estimates via inter-epoch differenced carrier-phase processing and epoch-wise fractional cycle biases (FCBs), which enable practical integer ambiguity resolution in real time and thus convert inherently noisy float PPP outputs into stable, integer-fixed kinematic positions with dramatically lower short-period noise and faster time to first fix compared with conventional global State Space Representation (SSR) PPP. After obtaining the real-time surface displacement of the station, the moment magnitude can be calculated by:

$$\begin{cases} PGD = \max\left(\sqrt{[E(t)^2 + N(t)^2 + U(t)^2]}\right) \\ \log(PGD) = A + B \cdot M_w + C \cdot M_w \cdot \log(R) \end{cases} \tag{3}$$

where t denotes the epoch, $E(t)$, $N(t)$ and $U(t)$ represent the real-time displacements in the East, North and Up components, respectively. PGD is the peak ground displacement. A, B and C are the regression coefficients, R is the distance between the station and the epicenter (in km). M_w is the moment magnitude.

Operationally, GSeisRT’s regional SSR design reduces product latency (mean regional SSR latency reported ~6 s versus ~20 s for global SSRs in the study) and avoids the need for long horizon prediction of clocks/biases, which when required introduces inconsistencies with observations and degrades short period precision; the low latency and tightly coupled server/client streaming substantially improve real time performance for time critical applications such as seismic and transient deformation monitoring. Empirical results from continental deployments demonstrate robust improvements: multi-GNSS PPP-AR under GSeisRT reduces horizontal Root Mean Square (RMS) by tens of percent and vertical RMS materially as well (examples show horizontal RMS reductions of roughly 30–70% at test stations), and median time to first fixs (TTFF) are shortened to the order of minutes (mean TTFF reported ~11.1 min in the Network of the Americas experiment) depending on satellite visibility and network coverage (Geng et al., 2025).

The practical strengths of this approach stem from three interrelated pillars. First, multi-GNSS redundancy increases satellite counts and geometry, accelerating convergence and stabilizing ambiguity resolution when Beidou/Galileo/GLONASS signals are available alongside GPS. Second, epoch wise Uncalibrated Phase Delays (UPD) estimation from a sufficiently large, distributed reference network (empirically ∼10 well-placed stations for stable UPD estimation) transforms non integer PPP ambiguities into integer candidates that modern integer search methods can reliably resolve. Third, high-rate satellite clock generation using inter epoch differencing allows 1 Hz clock products to be delivered without the multi hour initialization inherent to undifferenced network analysis, enabling the real time exploitation of carrier phase precision as soon as satellites rise with respect to the regional network.

At the system level, GSeisRT's architecture server side producing regional SSR's and client side running independent real time PPP/PPP-AR per station scales to continental networks while keeping each client lightweight and resilient to local data issues; the design also intentionally avoids regional orbit estimation (relying instead on International GNSS Service (IGS) ultra-rapid orbits) to isolate server responsibilities and exploit reliable orbit products while focusing compute resources on clocks and phase biases. Together, these choices yield a practical, fieldable real time engine that has demonstrably captured coseismic and transient displacements in operational networks.

In short, GNSS PPP-AR with GSeisRT offers a balanced combination of algorithmic rigor, engineering pragmatism (regional low latency SSR streaming, 1 Hz clock products, use of established orbit streams), and operational safeguards (ambiguity-float fallback, conservative fix validation, empirical station count requirements) that together make it especially well-suited for high cadence deformation monitoring where both short period sensitivity and real-time availability are essential.

Fig. 1 shows the deployment of GSeisRT platform in the CORS network of Indonesia. Before its deployment, GNSS based earthquake monitoring using PRIDE PPP-AR (Geng et al., 2019). It should be noted that both PRIDE PPP-AR and GSeisRT are software platforms independently developed by the PRIDE group at Wuhan University. PRIDE PPP-AR employs a least-squares framework and is primarily applied to post-processing precise geoscientific research. Conversely, GSeisRT utilizes a Square Root Information Filter (SRIF) framework, making it more suitable for real-time precise positioning services. In the following text, "PRIDE GSeisRT" and "GSeisRT" refer to the same platform. Main difference between PRIDE PPP-AR and GSeisRT lies in their processing approaches, for earthquake and volcano monitoring, GSeisRT is more suitable. GSeisRT supports the real-time determination of 1Hz global/regional precise satellite products, including satellite clock and phase biases, by synchronously collecting GNSS observation streams worldwide, or within a regional GNSS network, and updating necessary external IGS product.

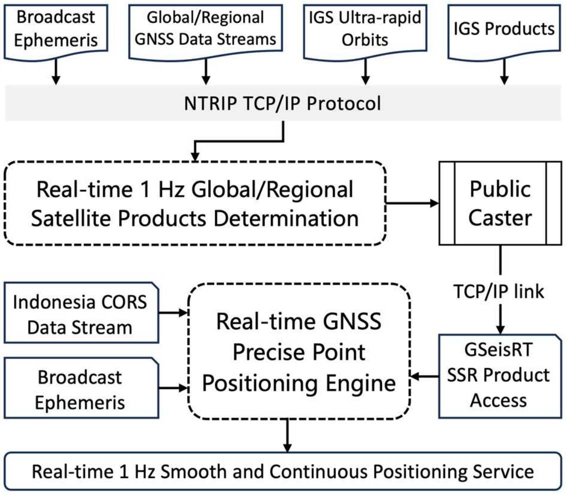


Fig. 1 GSeisRT deployment in Ina-CORS network

The estimated products are then broadcasted to global/regional users, including those in Indonesia, through an NTRIP Caster running on a public server to provide real-time positioning services. For the GSeisRT client deployed in the Indonesian CORS network, after accessing the real-time observation stream of the Ina-CORS network, the client also needs to access the necessary real-time SSR stream and broadcast ephemeris. Through the PPP engine and the soft constraint of fixed ambiguities, GSeisRT client can provide continuous and smooth real-time displacement output, serving real-time geological disaster monitoring and early warning in the Indonesian region.

3. Network and Data

As of 2025, BIG managed 476 CORS station named Ina-CORS (Indonesia Continuously Operating Reference Station) nationwide in real-time (Fig. 2). Ina-CORS data communication utilizes multiple transmission media, including optical fiber–based networks, GPRS cellular communication, and satellite-based links, to ensure reliable and continuous data delivery under varying geographic, infrastructural, and operational conditions, particularly in remote and hazard-prone regions. Initially Ina-CORS was used only for surveying and mapping, but recently Ina-CORS also utilized for geohazard monitoring such as earthquake, volcano, and land subsidence. The detailed configuration information of GSeisRT for the real-time data processing of Ina-CORS is listed in Table 1.

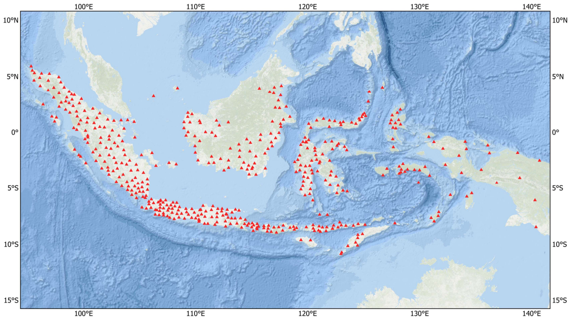
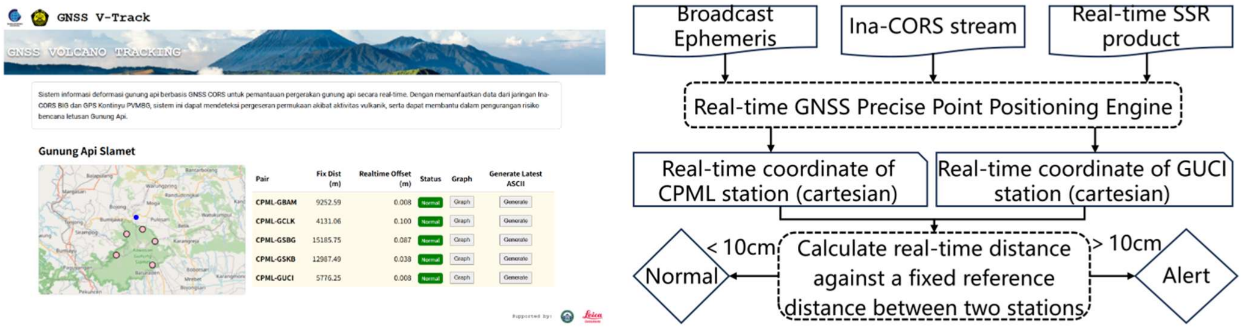


Fig. 2 Distribution of 476 Ina-CORS stations covering the entire territory of Indonesia

Table 1 Data processing by GSeisRT

Items	Descriptions
Observations	Dual-frequency pseudorange and carrier-phase
GNSS & Frequency	GPS L1/L2, BDS B1I/B3I, GLONASS G1/G2, Galileo E1/E5a
Sampling rate	1 s
Cut-off angle	10°
Code OSBs	Chinese Academy of Sciences (http://ftp.gipp.org.cn)
Antenna phase center	igs20.atx
Tidal displacements	Solid earth tides, pole tides and ocean tidal loading
Troposphere delays	Saastamoinen for a priori delays and global mapping function
Satellite orbits	Ultra-rapid products of Wuhan University (ftp://igs.gnsswhu.cn)
Qaulity control	TurboEdit and DIA method

In addition to earthquake monitoring, GNSS has become a critical component in the surveillance of active volcanoes. Volcanic systems frequently undergo deformation caused by magma migration, pressurization, or structural failure within the edifice. GNSS networks installed around volcanoes provide continuous measurements of three-dimensional surface displacement, allowing to identify inflation, deflation, uplift, or lateral movement associated with magmatic activity.



Sistem informasi deformasi gunung api berbasis GNSS CORS untuk pemantauan pergerakan gunung api secara real-time. Dengan memanfaatkan data dari jaringan Ina-CORS BIG dan GPS Kontinyu PVMBG, sistem ini dapat mendeteksi pergeseran permukaan akibat aktivitas vulkanik, serta dapat membantu dalam pengurangan risiko bencana letusan Gunung Api.

Gunung Api Slamet

Pair	Fix Dist (m)	Realtime Offset (m)	Status	Graph	Generate Latest ASCII
CPML-GBAM	9252.59	0.008	Normal	Graph	Generate
CPML-GCLK	4131.06	0.100	Normal	Graph	Generate
CPML-GSBG	15185.75	0.087	Normal	Graph	Generate
CPML-GSKB	12987.49	0.038	Normal	Graph	Generate
CPML-GUCI	5776.25	0.008	Normal	Graph	Generate

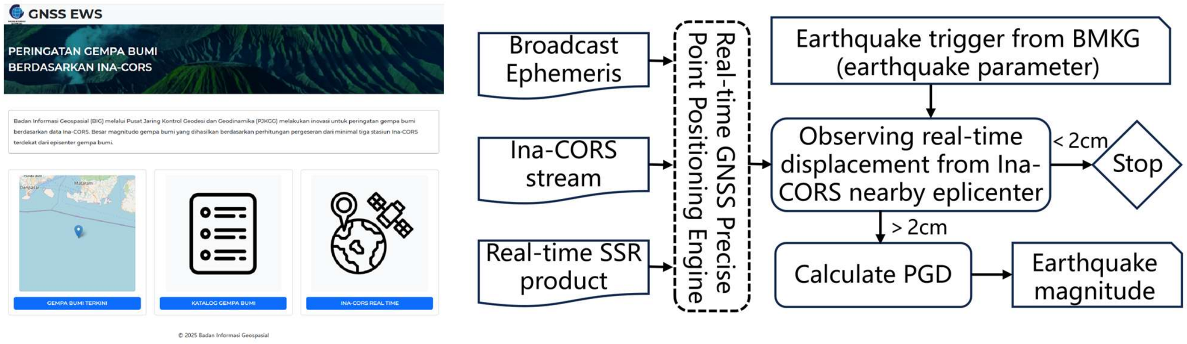
Fig. 3 GNSS-based Volcano Tracking (GNSS V-Track) framework for real-time volcanic deformation monitoring. The operational web interface is available at http://36.92.41.75:8300/volcano/Slamet.

The system named GNSS Volcano Tracking (GNSS V-Track), a GNSS based volcanic deformation information system, provides real time monitoring of volcanic movements. Utilizing data from the Ina-CORS network and CVGHM's GNSS network, the system can detect surface shifts caused by volcanic activity and assist in reducing the risk of volcanic eruptions (Fig. 3).

4. Results

GNSS technology has emerged as a highly effective geodetic tool for detecting crustal deformation with high spatial and temporal precision. GNSS enables continuous and real-time monitoring of ground movements by measuring subtle changes in station coordinates relative to a global reference frame. In tectonically active regions such as Indonesia, where the interaction of multiple major plates generates high seismic and volcanic activity, GNSS provides essential observations for understanding the dynamics of the Earth's surface. The dense deployment of GNSS networks across the country reflects its strategic role in regional geodynamic research.

For earthquake monitoring, GNSS stations continuously record crustal motions that accumulate stress along active fault systems. These measurements allow stakeholders to quantify inter-seismic strain accumulation, detect co-seismic deformation immediately after an event, and analyze post-seismic relaxation processes. This information is vital for seismic hazard assessment and for strengthening disaster risk reduction strategies.



Badan Informasi Geospasial (BIG) melalui Pusat Jaring Kontrol Geodesi dan Geodinamika (PJKGG) melakukan inovasi untuk peringatan gempa bumi berdasarkan data Ina-CORS. Besar magnitudo gempa bumi yang dihasilkan berdasarkan perhitungan pergeseran dari minimal tiga stasiun Ina-CORS terdekat dari episenter gempa bumi.

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Fig. 4 GNSS-based earthquake early warning (EWS) framework implemented by the Geospatial Information Agency of Indonesia. The real-time GNSS displacement visualization and earthquake information are available at http://36.92.41.75.

GNSS Earthquake Warning System (GNSS EWS) developed by BIG (Fig. 4) has successful story for earthquake event that capable captured by the system. When Banda Sea earthquake M7.1 (Fig. 5) happened on 8th November 2023, the system captured displacement from three nearby stations from the epicenter, although distance from epicenter was more than 250 km. After displacement was captured, next process was calculating Peak Ground Displacement (PGD) and finally became earthquake magnitude.

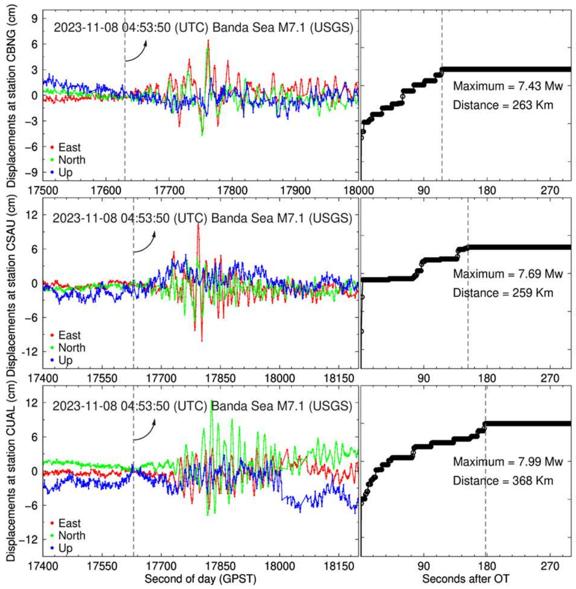

Fig. 5 Banda Sea M7.1 earthquake on 8th November 2023.

The system captured many earthquakes event that are M6.4 Bawean earthquake on 22nd March 2024, M5.8 Poso earthquake on 16th August 2025, and M6.6 Sinabang earthquake on 27th November 2025 (all magnitude parameters from USGS).

Fig. 6-8 shows several seismic events captured by GSeisRT during its deployment in Indonesia, namely the M6.4 Bawean earthquake on March 22, 2024, the M5.8 Poso earthquake on August 16, 2025, and the M6.6 Sinabang earthquake on November 27, 2025. We calculated the distances from these stations to the epicenters using the epicenter locations released by the United States Geological Survey (USGS) and further extracted the peak ground displacements (PGD) from the real-time displacements of the stations to calculate the magnitudes of the earthquakes. The left-hand side of Fig. 6-8 shows the coseismic displacements in the East, North, and Up components of these GNSS stations after the earthquakes, with the vertical dashed lines in the left figure indicating the origin time of the earthquakes, and the vertical dashed lines in the right figure indicating the time when the peak ground displacements were finally determined. From these figures, GSeisRT can accurately and quickly obtain the permanent ground displacements, and the estimated magnitudes are relatively close to the standard magnitudes released by the USGS.

Unfortunately, several earthquakes were recorded by only a single station, which is insufficient for reliable estimation of the final earthquake magnitude. At least displacement observations from three stations are required to derive a robust final earthquake magnitude. That problem came from Ina-CORS sparse network, the nationwide density of network is 70 km. From Tsuji et al. (2018) the recommendation of ideal density network is 20 km – 25 km for geohazard monitoring. Table 2 shows the earthquake magnitude comparison between USGS and this study, for M6.4 Bawean earthquake, the final magnitude calculated by averaging method.

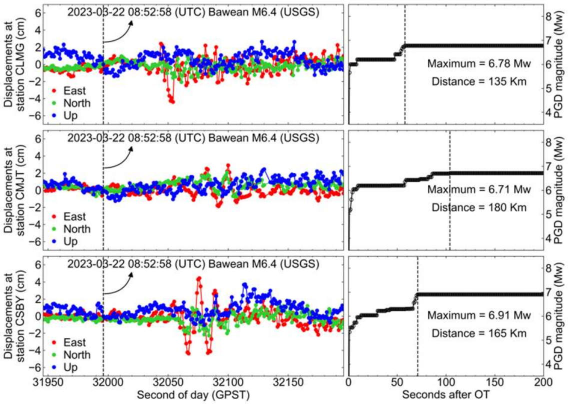

Fig. 6 M6.4 Bawean earthquake on 22 nd March 2024.

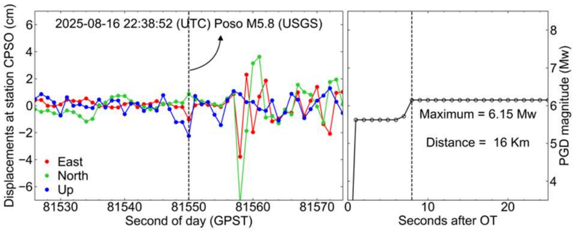

Fig. 7 M5.8 Poso earthquake on 16th August 2025.

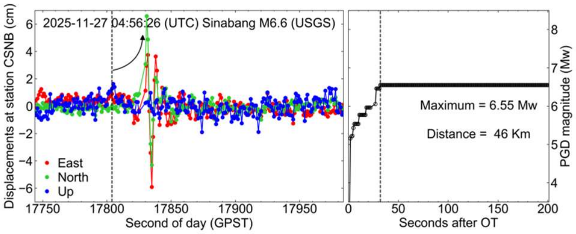

Fig. 8 M6.6 Sinabang earthquake on 27th November 2025.

Table 2 Comparison of earthquake magnitude.

Earthquake events	USGS (M)	This Study (M)
Bawean earthquake	6.4	6.8
Poso earthquake	5.8	6.1
Sinabang earthquake	6.6	6.5

In addition, BIG collaborate with CVGHM from Geological Agency of Indonesia to monitor Slamet Volcano in Central Java with GNSS network. BIG and CVGHM not only collaborate for volcanic activity, but also collaborate to monitor two active faults, that are Cimandiri active fault and Opak active fault.

Five GNSS network on volcano body integrated with the BIG GNSS real time processing system, that are GBAM, GCLK, GSBG, GSKB, and GUCI. Those stations provide real time positions relative to BIG station, namely CPML. The idea is to monitor real time distance offset from CPML to those stations near volcano body. If there is offset larger than 10 cm, the system will transmit alert messages for stakeholders.

5. Discussion

5.1 Validation with GFZ's Real-Time PPP

Real-time kinematic displacements are essential for rapid seismic response, but usually compromised by deficiencies in real-time quality control, resulting in losses in position precision and reliability. Specifically, real-time PPP-AR struggles to maintain continuously correct ambiguity resolution, and incorrectly fixed ambiguities introduce false jump signals in the position domain, perhaps undermining the earthquake magnitude estimation. We have deployed the Real-Time Positioning and Monitoring (RTPM) system from GFZ (Jiang et al., 2022) and the PRIDE GSeisRT software from the GNSS Research Center at Wuhan University (Geng et al., 2025) in the InaCORS network to monitor surface displacements in real time. Taking the M6.1 earthquake that occurred in Modisi, North Sulawesi, Indonesia on February 25th, 2025, as an example, Fig. 9 shows the real-time GNSS displacements at the CALO station processed by RTPM and PRIDE GSeisRT during the earthquake. The data can be accessed from https://srgi.big.go.id/visual_gnss/list_quake. For the position time series from RTPM, due to unstable ambiguity resolution, jumps of 3-4 centimeters occurred repeatedly in the East, North and Up components, misleading false seismic signal recognition which could potentially invalidate the magnitude estimation. In contrast, GSeisRT, with its built-in robust positioning mode (Zhang et al., 2025), provided continuous and stable displacement during the earthquake, effectively avoiding false seismic signals.

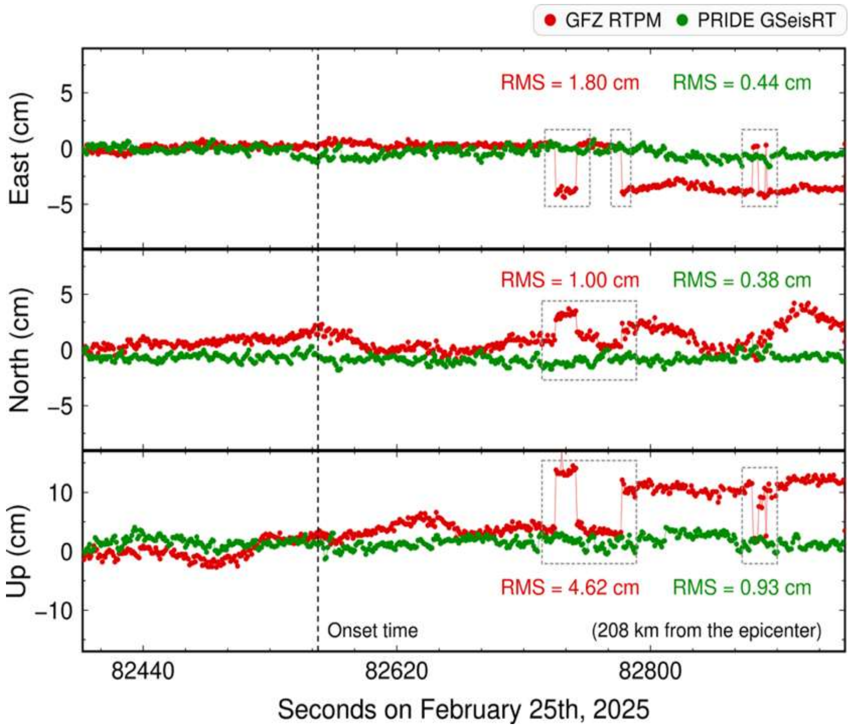

Fig. 9 Real-time GNSS displacements recorded at the CALO station by RTPM and PRIDE GSeisRT during the M6.1 Modisi earthquake in Indonesia on February 25th, 2025. RMS errors are plotted on the top of each panel in different colors. The horizontal axis represents the seconds of day, while the vertical axes represent displacements in the East, North, and Up components, respectively. Red and green lines denote RTPM and GSeisRT solutions, respectively.

5.2 Potential to Integrate Collocated Accelerometer Data

The GSeisRT client supports deployment of embedded instruments (*i.e.*, GNSS accelerometer), and it fuses with the high-frequency accelerometer data inside the instrument, thereby providing higher sampling rates and more precise displacement outputs. This further enhances the capabilities of real-time seismic monitoring and response. In the future, the Indonesian region also plans to deploy more GNSS, and accelerometer co-located stations to enhance the performance of the real-time disaster monitoring system. Currently, one GNSS accelerometer has been deployed in Valparaíso, Chile, for continuous seismic monitoring. Constrained by the noise of GNSS ranging signals, the quality of real-time satellite products, and data processing uncertainties, GNSS-only displacements exhibit random short-term fluctuations in the position series. However, the incorporation of accelerometer data can provide a direct complement to short-term positioning performance. Therefore, it can be seen from Fig. 10 that the fusion displacement has better short-term positioning noise than GNSS-only displacement, and the position sequence is also smoother, which is beneficial to improving the performance of real-time seismic monitoring. Furthermore, Fig. 11 presents the power spectral densities corresponding to the two real-time surface displacements. Since the GNSS-only displacements are sampled at 1 s, their power spectral density curves are limited to 0.5 Hz, failing to capture higher-frequency displacement signals. Additionally, the noise power levels off beyond approximately 0.05 Hz, restricting its ability to resolve signals at higher frequencies. In contrast, the high-frequency GNSS/accelerometer fused displacement offers a broader frequency band coverage compared to the 1 Hz GNSS-only displacement and exhibits lower noise in the high-frequency range, enhancing the capability to capture rich seismic signals. In the future, GNSS accelerometer will also be deployed in the Indonesian region to provide real-time disaster monitoring services.

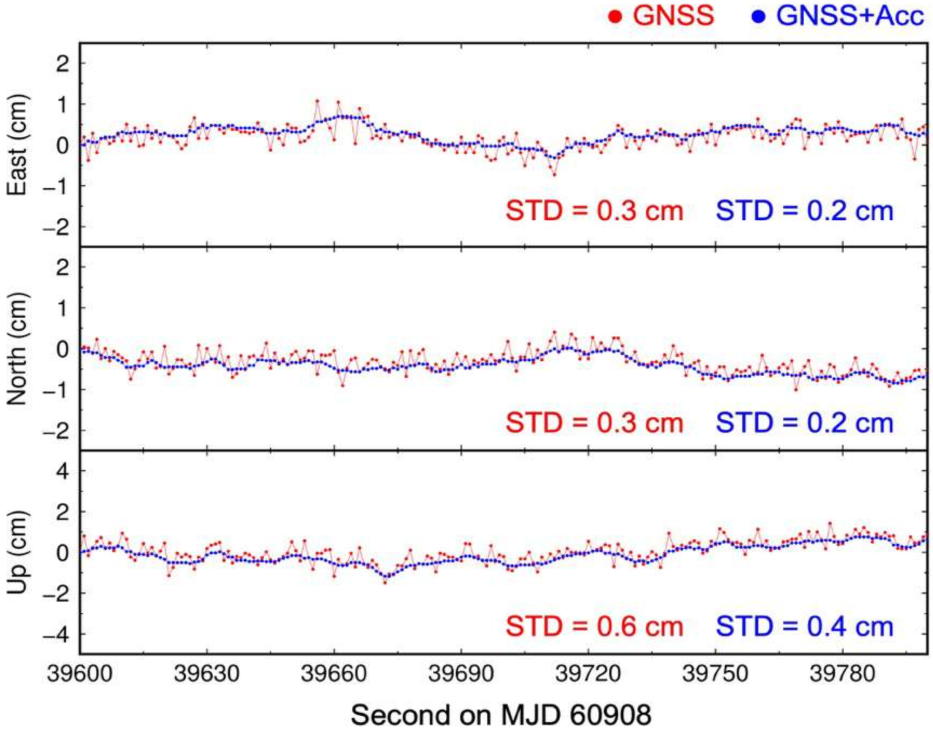

Fig. 10 Real-time surface displacement recorded by the GNSS accelerometer.

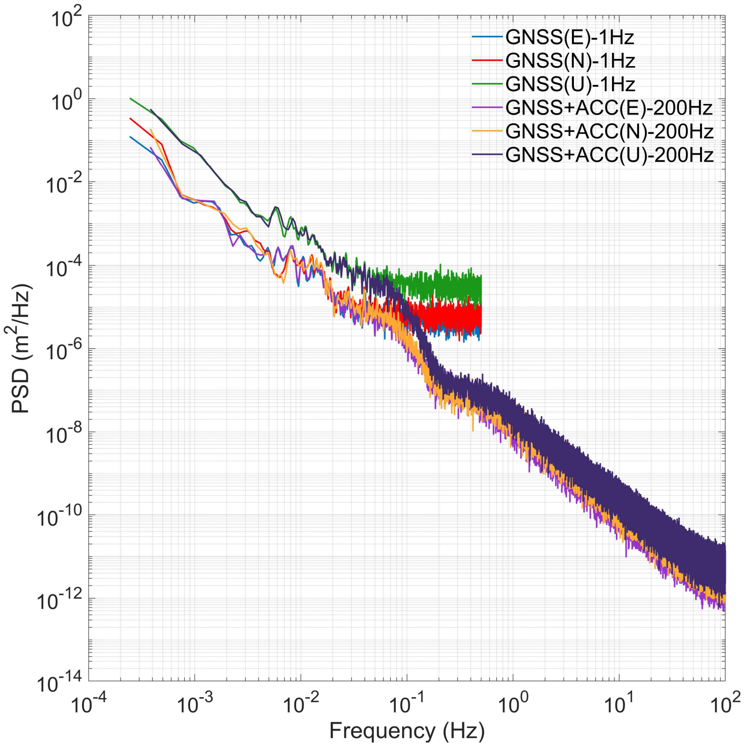

Fig. 11 Power spectral densities of the displacement recorded by the GNSS accelerometer.

5.3 1 Hz Satellite Clocks to Empower GSeisRT in Terms of Positioning Precisions

GSeisRT currently supports 1Hz global multi-constellation real-time product services, which is 5 times the sampling rate of other public IGS real-time services. This can effectively improve the short-term noise level of users' real-time precise positioning. Fig. 12 below shows the positioning results of the BRUX station on MJD 60998 using GSeisRT (green) and traditional IGS real-time products (red). In all three components, the products of GSeisRT can provide more stable and smooth positioning precision, while the position series using traditional IGS real-time products will show an error increase with a 5-second period, affecting its positioning performance. This is mainly because the variation characteristics of satellite clock are complex and difficult to predict. If only real-time products with a 5-second sampling interval are used, the short-term positioning precision will be affected, and in severe cases, it may affect the real-time seismic monitoring performance. Fig. 13 illustrates the power spectral densities of positioning errors derived from GSeisRT SSR and publicly available IGS SSR products. Notably, the IGS SSR reveals a significant noise elevation within the 0.1–1 Hz band, whereas GSeisRT SSR demonstrates more consistent noise characteristics and is superior to the public IGS SSR service throughout the full frequency spectrum. GSeisRT supports 1 Hz global real-time product estimation, effectively improving the short-term stability and precision of real-time positioning.

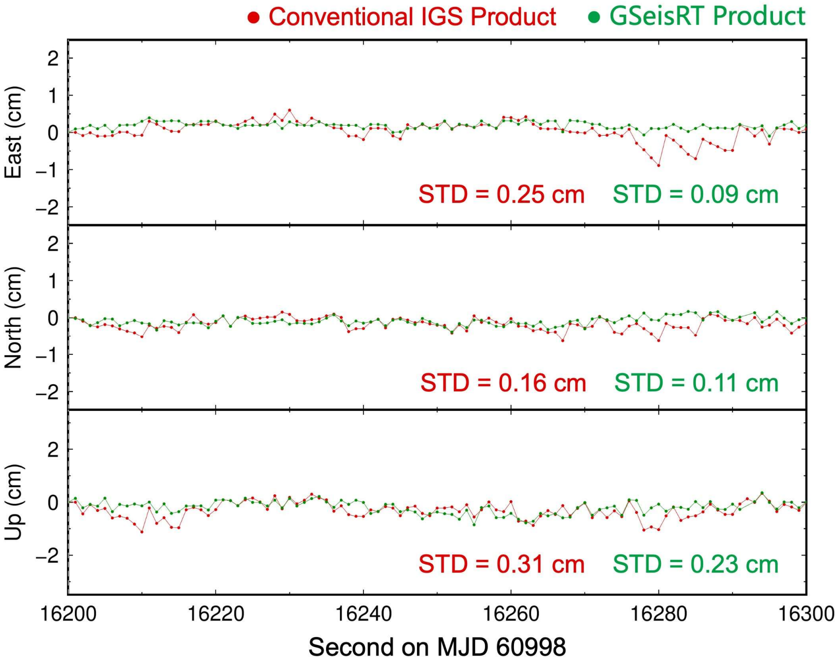

Fig. 12 Positioning errors in GSeisRT and IGS global real-time products.

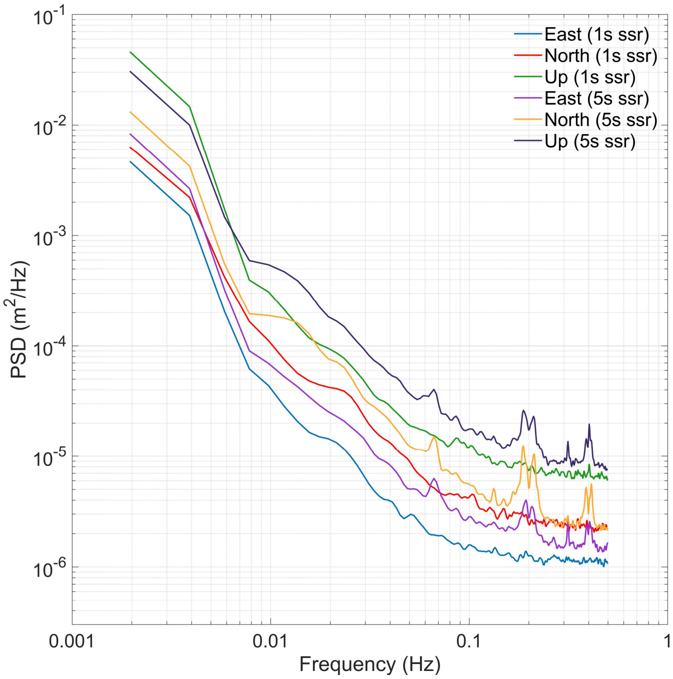

Fig. 13 Power spectral densities of positioning errors in GSeisRT and IGS real-time products.

5.4 Inter-agency collaboration

Inter-agency collaboration can mitigate the sparsity of the Ina-CORS network by establishing formal data sharing agreements, integrating GNSS stations from multiple institutions under Indonesia National Standards of CORS development 7964:2022, and jointly deploying and maintaining stations in priority areas. Shared real-time data infrastructure and coordinated processing frameworks enable efficient use of observations for earthquake and volcanic monitoring, while capacity building and clear governance ensure technical consistency and long-term sustainability, effectively creating a virtual dense GNSS network for geohazard applications.

6. Conclusions

This study highlights the expanding role of GNSS in supporting real-time geohazard monitoring across Indonesia. The integration of advanced PPP-AR techniques within the GSeisRT framework enables high-rate, low-latency displacement measurements that are critical to rapid seismic and volcanic response. Comparative analyses indicate that GSeisRT offers improved stability and robustness over existing real-time systems, while additional capabilities, including GNSS accelerometer fusion and global 1 Hz real-time products, further enhance short-period deformation monitoring. As a result, BIG has officially chosen GSeisRT as the GNSS-based real-time hazard monitoring system for nationwide deployment within the Ina-CORS network.

Persistent challenges remain, particularly the sparse distribution of GNSS stations and limitations in real-time data communication in remote regions. Continued network densification strengthened data infrastructure, and broader interagency integration will be essential for realizing the full potential of GNSS-based monitoring. Overall, the results demonstrate that modern real-time GNSS technologies provide a solid foundation for improving early warning and strengthening geohazard resilience in Indonesia.

Contributions

Muhammad Al Kautsar: conseptualization, writing original draft; Moh. Fifik Syafiudin, Rahmat Triyono, and Priatin Hadi Wijaya: writing review and editing; Oktadi Prayoga, Sulistiyani, Ayu Nur Safi’i, Thomas Hardy and Ajat Sudrajat : data curation; Fanny Zafira Mukti: image creation.

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provide valuable GNSS real-time data to Ina-CORS network.

Data Availability

GNSS high-rate data from BIG and all of earthquake magnitude parameters from USGS.

Conflicts of Interest

The authors declare no conflicts of interest.

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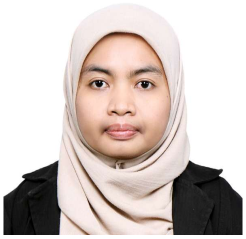

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