JPNT 14(4), 353-363 (2025)
https://doi.org/10.11003/JPNT.2025.14.4.353

JPNT Journal of Positioning, Navigation, and Timing

Investigating Ground Station Deployment Strategies to Improve Quality of Orbit Determination of Regional Navigation Satellite System

Kyoung-Min Roh†, Gimin Kim, Eunseo Park
Space Navigation and Geodesy Center, Korea Astronomy and Space Science Institute, Daejeon 34055, South Korea

ABSTRACT

Regional navigation satellite systems (RNSS) consist of geosynchronous orbit for servicing positioning, navigation and timing regionally. This presents a challenging environment for precise orbit determination (OD) as their regional ground networks provide limited line-of-sight diversity and weaken the observation geometry. To address these limitations, this study focuses on Japan's Quasi-Zenith Satellite System (QZSS) as a representative RNSS and evaluates two practical improvement strategies: (i) augmenting the processing with GPS observations, and (ii) expanding the ground tracking network. Three network configurations are tested—an 11-station regional network (R11), a denser 20-station regional network (R20), and a 20-station global network (G20)—under both QZSS-only processing (J) and joint QZSS+GPS (GJ) processing. Orbit and clock solutions are evaluated against the product from the Multi-GNSS Experiment Project (MGEX) of the International GNSS Service (IGS) as a reference. Using R11-J (which is the most probable scenario and exhibits the largest QZSS 3D RMS in our scenarios) as the baseline, including GPS reduces the QZSS 3D RMS by about 70% and shows a clear geometric benefit. Without GPS, R20-J outperforms G20-J, which indicates that for RNSS the number of usable observations from a denser regional network dominates the advantage of global distribution. When GPS is incorporated, the overall optimum shifts to G20-GJ: adding GPS raises QZSS OD to the level achieved by R20-GJ, while the GPS orbits are substantially more accurate—the mean (over days) of the daily-median 3D RMS of GPS reaches ~6.7 cm, compared with ~23.1 cm under R20-GJ. The station-deployment choice is tightly coupled to the processing strategy. If stand-alone independence is required, densifying the regional network to ~20 stations is a more effective option; if GPS augmentation is acceptable, a globally distributed 20-station network is recommended for maximum overall performance.

Keywords: orbit determination, RNSS, multi-GNSS

1. INTRODUCTION

The main goal of Global Navigation Satellite Systems (GNSS) is to provide a positioning, navigation, and timing (PNT) service. GNSS are thus critical infrastructure for sectors including transportation, defense and communication. The service area of the navigation system is now being expanded up to the Moon (Bhamidipati et al. 2021). As societal dependence grows, exclusive reliance on the U.S. GPS has raised concerns and motivated sovereign GNSS initiatives. While GLONASS modernization has slowed, Galileo of the European Union and BeiDou of China have rapidly reached full operational capability. Japan's QZSS and India's NavIC provide regional services referred to as Regional Navigation Satellite Systems (RNSS) (Montenbruck et al. 2017, Akiyama & Montenbruck 2025). Consequently, more than 100 navigation satellites are currently observable (GSA 2020). South Korea launched its own RNSS, the Korean Positioning System program, in 2022 (Choi et al. 2020).

The accuracies of a satellite's orbit and its' onboard clock are key parameters that determine the overall performance of navigation satellite systems. Since orbit determination of

Received Sep 26, 2025 Revised Oct 19, 2025 Accepted Nov 01, 2025

†Corresponding Author E-mail: kmroh@kasi.re.kr

Creative Commons Attribution Non-Commercial License (https://creativecommons.org/licenses/by-nc/4.0/) which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

Copyright © The Institute of Positioning, Navigation, and Timing

http://www.ipnt.or.kr Print ISSN: 2288-8187 Online ISSN: 2289-0866

navigation satellites relies on one-way range measurements between satellites and ground stations, having more satellites and tracking stations increases the number of independent range geometries, which in turn improves the accuracy of both orbit and clock solutions. Unlike global constellations in medium altitude Earth Orbit (MEO), regional systems deliver service over limited areas using Geostationary Earth Orbit (GEO) and Inclined Geosynchronous Orbit (IGSO) synchronized with the Earth's rotation. Since ranging-based navigation benefits from more satellites and more tracking stations, the observation geometry for GEO/IGSO is weak: long ranges and limited time-varying viewing geometry hinder precise orbit determination (Montenbruck et al. 2017, Kawate et al. 2023, Akiyama & Montenbruck 2025). Japan's MADOCA tool shows that QZSS's orbit solutions achieve about 10 cm and 80 cm median daily RMS for IGSO and GEO from 88 ground stations, respectively (Kawate et al. 2023). Li et al. (2020) presented comparison results of orbit determination solutions between MGEX products and showed good agreement in a range of 10~50 cm for IGSO. However, the mean difference of the along-track of GEO satellite between products is about 250 cm due to low measurement sensitivity. In the case of MEO such as GPS, the level of orbit accuracy is about a few cm.

Numerous studies to improve orbit determination accuracy through additional measurements such as two-way time and frequency transfer or augmenting low Earth orbit constellation have been reported (Tang et al. 2016, Chen et al. 2022a, Ge et al. 2022, Li et al. 2024). Nevertheless, adding more satellites and ground stations is the most direct way to obtain more accurate orbital position. However, for RNSS this approach is difficult because satellites in RNSS are deployed in limited areas in the sky when they are seen from the surface of the rotating Earth. Another challenge is the cost for service providers. Expanding the ground monitoring network—often requiring overseas deployments—incurs substantial installation and operations-and-maintenance costs and makes sustained international cooperation indispensable. Accordingly, maximizing orbit determination performance under constrained resources is essential. Two common mitigation strategies are (i) incorporating other GNSS systems (typically GPS) and (ii) expanding the ground network as effectively as possible.

In this study a technical analysis is carried out to address two core questions. First, in a RNSS system, what performance gains can be expected if GPS measurements are included in the data processing. Including GPS is thus an option for regional systems such as QZSS and KPS that are designed to interoperate with GPS. Second, when the decision on GPS augmentation is left open, the key question is which network-expansion strategy proves more effective: regional densification or a globally distributed network? Several scenarios that vary GPS inclusion and the spatial distribution of the tracking network (regional vs. global) are designed and then evaluated using real QZSS and GPS data from IGS's tracking network. The resulting orbit accuracies are calculated by comparing with a reference product released by International GNSS Service (IGS). We also analyze relative performance to provide a technical basis for identifying a practical strategy.

2. DATA PROCESSING SCENARIO

2.1 Scenarios Configuration

Scenarios in this study are focused on actual operation of a RNSS. Therefore, the baseline of the scenario consists of several satellites in geosynchronous orbit and about 10 oversea ground stations. The real data of QZSS would be the best option to test the reliability of the proposed scenarios. The variations of the base scenario are then configured, and the resulting orbit determination performance is compared with the base scenario. The initially proposed distribution of KPS's monitoring stations is one domestic and 10 overseas tracking stations over the Asia-Pacific region (Choi et al. 2020).

Coprocessing the GPS signal with QZSS is the key variation from the base scenario in this study. For QZSS and KPS, which declare interoperability and compatibility with GPS, a possible option is to consider incorporating GPS into their orbit determination processing. Increasing measurements by increasing the number of satellites would be a cost-effective and promising option. However, from an operator's point of view, using additional measurements not included in its management could decrease the independence and completeness of the RNSS. Unlike a system operator, there are already many efforts in scientific and commercial areas to service improved orbit solutions achieved through multi-navigation satellites (Montenbruck et al. 2017, Li et al. 2019, Chen et al. 2023, Kawate et al. 2023).

Based on these considerations, the following scenarios listed in Table 1 are selected. The number of tracking stations (20) is chosen based on the cases of GPS and QZSS. While GPS now has about 20 ground stations, QZSS had about 15 regional stations at the time of starting four satellites. However, QZSS has more than 30 global tracking stations for coprocessing QZSS and GPS (Kugi 2018, Numata 2023). One consideration that should be noted here is that we evaluated the scenarios using real data from QZSS. The constellation QZSS therefore consists of one GEO and

Table 1. Test scenarios.

Scenario	Satellite system	Number of ground station	Distribution of ground station
R11_J	QZSS	11	Asia-Pacific Region
R11_GJ	QZSS + GPS	11	Asia-Pacific Region
R20_J	QZSS	20	Asia-Pacific Region
R20_GJ	QZSS+GPS	20	Asia-Pacific Region
G20_J	QZSS	20	Global
G20_GJ	QZSS+GPS	20	Globa

three IGSO satellites, which is still less than the designed constellation (QZSS 2025) at the time of this test, namely, from day of year (DOY) 30 to 49 in 2024.

During the test period, the ground stations worked normally, but one of the QZSS satellites was not processed for seven days among the total 20 days, because of maneuvering or malfunction. The test configuration and period were not changed since the effect of the number of satellites in RNSS can be investigated through real-data processing. The first letter in the scenario denotes the distribution type of ground station, i.e., (R)egional and (G) lobal, and the following number is the number of ground stations. The last one or two letters after the underscore refer to the constellation; namely, J is QZSS and G is GPS.

From the scenarios in Table 1, the following aspects can be investigated through comparison of the results. First, it is important to determine whether incorporating GPS into orbit determination is advantageous even for a small, regionally confined monitoring network. Second, when more ground stations are available, the global distribution could be a better strategy over a regional distribution or vice versa. This analysis is particularly valuable to assess the improvement of QZSS orbit quality by use of a dense regional distribution as compared to adding GPS signals from a globally distributed network. Namely, when the inclusion of GPS has not yet been determined, the study can help decide, as the monitoring network is expanded, whether broader global coverage is preferable to increased station density within the region.

Fig. 1 shows the distribution of R11, R20, and G20 using different symbols. The networks R20 and G20 include stations in R11 to assess the effect of additional stations to the base network globally or regionally. The stations in this study are selected from IGS MGEX stations that provide QZSS (Montenbruck et al. 2017).

2.2 Data Processing

The orbit determination process in this study is tuned for actual operational situations and real observation from ground stations belonging to the IGS network. While there are several options to optimize the orbit determination results besides the number of ground stations and their distribution, we retain the same options for all scenarios such as arc-length and sampling interval. Orbit determination in this study is performed using Positioning and Navigation Data Analyst (PANDA) software (Choi et al. 2020, Chen et al. 2022b), which is based on a batch-based processing strategy. The detailed features of PANDA can be found in the article by Li et al. (2019). Observation data downloaded from the IGS Global Data Center are used. Since real data are used in this study, the physical models for QZSS and GPS such as phase center offset (PCO), phase center variation (PCV), and mass are taken from the files provided by IGS, namely, the ANTEX file (https://igs.org/wg/antenna/) and IGS satellite meta file https://igs.org/wg/antenna/). The force and observation models applied in the data processing are summarized in Table 2. The processing configuration is optimized for a RNSS that has a limited number of ground stations, such as by loosening the residual editing constraint.

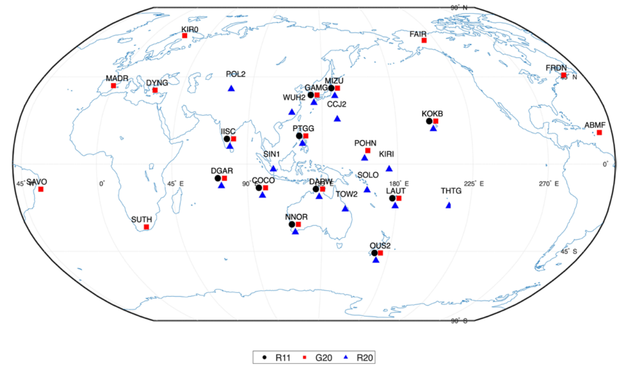


Fig. 1. Distribution of ground stations for R11, G20, and R20.

Since QZSS and GPS satellites transmit several common frequencies for compatibility including L1, L2, and L5, GPS Time (GPST) is used as a reference time system. The observation equations for dual-frequency observation can be expressed as follows (Choi et al. 2020),

$$P_1^{[GJ]} = \rho + c \cdot \left(dt_R + B_R^{[G]} - dt^S\right) + I_1 + T + \varepsilon_{P1} \quad (1)$$

$$P_2^{[GJ]} = \rho + c \cdot \left(dt_R + B_R^{[G]} - dt^S\right) + \frac{f_1^2}{f_2^2} I_1 + T + \varepsilon_{P2} \quad (2)$$

$$L_1^{[GJ]} = \rho + c \cdot \left(dt_R + B_R^{[G]} - dt^S\right) - I_1 + T + \lambda_1 N_1 + \varepsilon_{L1} \quad (3)$$

$$L_2^{[GJ]} = \rho + c \cdot \left(dt_R + B_R^{[G]} - dt^S\right) - \frac{f_1^2}{f_2^2} I_1 + T + \lambda_2 N_2 + \varepsilon_{L2} \quad (4)$$

where P and L represent the code and carrier phase measurements, respectively. The superscript G or J indicates the constellation system, and the subscripts 1 and 2 denote the frequency band. The range, ρ, includes antenna phase center offsets and phase center variation of the satellite and the receiver, the relativistic correction, and tidal effects as well as

Table 2. Lists of the applied force and observation model.

Item	Models/Method
Force model	
Earth gravity	EIGEN-G (12x12)
Solid Earth tide, Pole tide	IERS Conventions 2010 (Petit & Luzum 2010, Roh & Choi 2014)
Ocean tide	EOT11a (10x10) (Savcenko et al. 2012)
N-Body	JPL DE405
Relativistic perturbation	IERS Conventions 2010 (Petit & Luzum 2010, Roh & Choi 2014)
Solar radiation pressure	ECOM2 (Prange et al. 2020)
Earth orientation	IERS C04
Attitude model	Eclips.f (Kouba 2009, Montenbruck et al. 2015)
Observation model	
Observations	Undifferenced ionospheric free linear combination
Signal	L1/L2
Elevation cutoff	7 degree
Sampling rate	300s
Arc length	24 hours
Reference frame	igs20
Satellite PCO/PCV	igs14.atx
Receiver PCO/PCV	igs14.atx
Satellite metadata	igs_satellite_metadata.snx
Tropospheric delay	Saastamoinen with GMF (Boehm et al. 2006) , estimated zenith wet delay
Station position	igs combination solution

the geometrical distance between the satellite and the ground receiver. The parameter c denotes the speed of light in vacuum. The satellite and the receiver clocks errors, denoted as dt^S and dt_R, are estimated as white noise. The ionospheric and tropospheric delay are represented by $I_{1,2}$ and T, respectively; N is the integer ambiguity; and the code and carrier-phase observation noise, ε_P and ε_L, follow zero-mean Gaussian distributions with standard deviations of 1.0 m and 0.005 m, respectively. Lastly, when GPS measurements are included, the intersystem bias, $B_R^{[G]}$, is added into the equation. In the data processing, the observations are weighted as elevation angle. The frequencies f_1 and f_2 correspond to the L1 and L2 signals, respectively, and λ_1 and λ_2 are their wavelengths. Since the orbit determination in this study is based on real observation, the PCO values and PCV patterns are applied to both satellites and ground receivers using the antenna phase center correction model provided by IGS.

We set parameters to be estimated including the satellite's position and velocity, the satellite's clock error, the receiver's clock error, and the zenith wet delay due to the troposphere. The determined orbital position and clock error are evaluated using the product provided by the IGS MGEX project that uses highly densified globally distributed ground stations (Montenbruck et al. 2017, Steigenberger et al. 2023). The orbit and clock product of MGEX covers most of the navigation satellites and the orbital accuracy is believed to be at the level of a few cm for MEO satellites and several decimeters for IGSO.

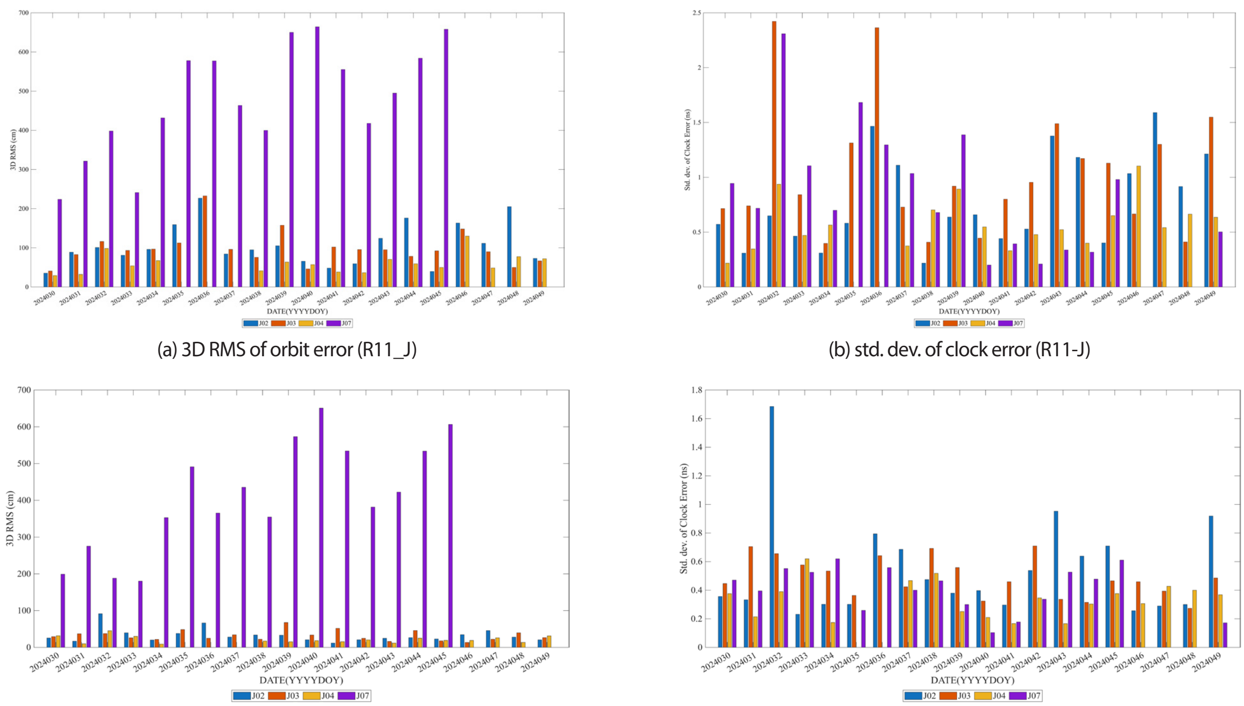
The performance of the navigation system is expressed as Signal-In-Space Range Error (SISRE). Because GNSS positioning relies on one-way range observation, SISRE is highly correlated with radial component error rather than along and cross track errors. Satellite clock error also projects predominantly into the radial component error. As the aim of this study is to analyze orbit determination performance, the 3-dimensional position errors are compared as well as the decomposed radial component and the satellite clock error.

When comparing satellite clock solutions with a reference product, clock-datum alignment must be handled, since all satellite and receiver clock errors in the system are constrained to the reference clock in the master station. In our processing, we tightly constrain one satellite clock rather than fix the reference clock on a ground receiver because the master-station time scale for QZSS/GPS is not available in these scenarios. Here, clock solutions are aligned with the MGEX product by setting the reference clock as the mean value of clock differences. Therefore, the standard deviation of the clock difference is used as a performance parameter across scenarios.

3. STRATEGICAL QUESTIONS

3.1 Effect of GPS Inclusion in Small Network (R11)

First, orbit determination is performed for the base scenario with 11 regionally distributed ground stations. The achieved orbit and clock errors are then compared with the MGEX product from the GFZ analysis center (Montenbruck et al. 2017). For the scenarios R11_J and R11_GJ, the 3-dimensional position error of four QZSS satellites and the standard deviation of satellite clock error differences from the reference product are depicted in Figs. 2 and 3, respectively. As can be seen from Figs. 2 and 3,



(a) 3D RMS of orbit error (R11_J) (b) std. dev. of clock error (R11-J)

(c) 3D RMS of orbit error (R11_GJ) (d) std. dev. of clock error (R11-GJ)

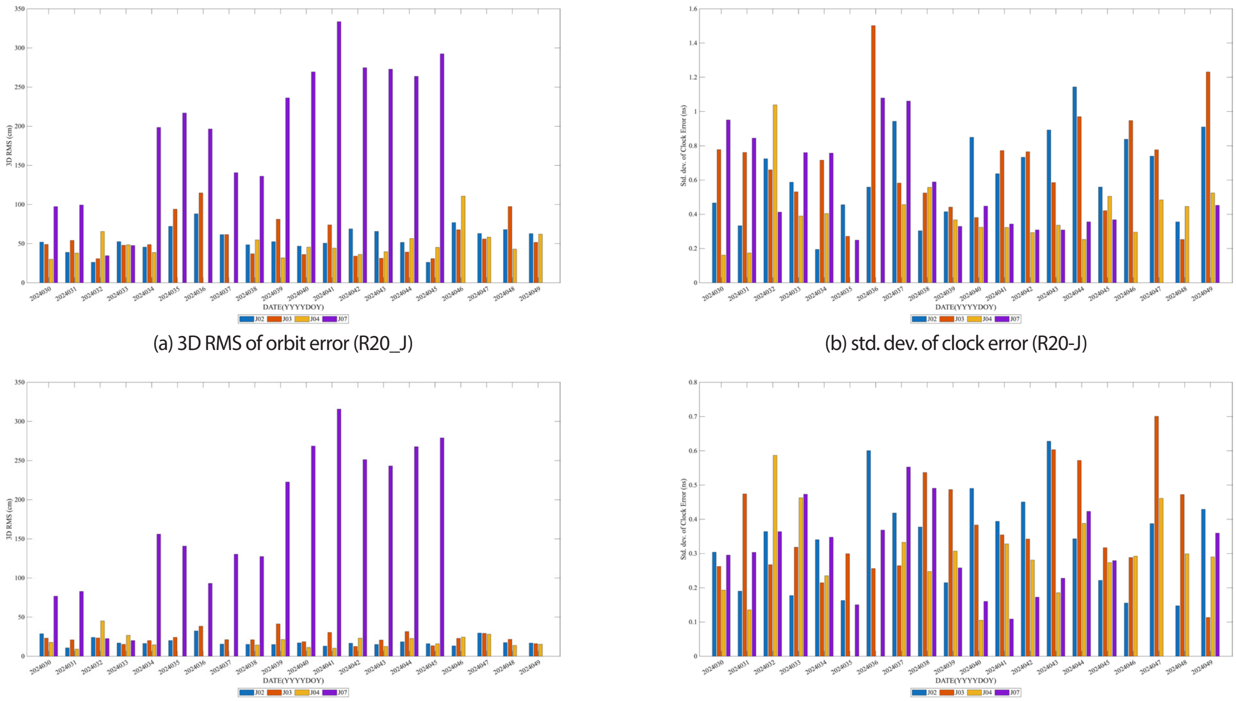
Fig. 2. 3D RMS orbit error and standard deviation of clock error for Scenarios R11-J and R11-GJ.

Table 3. Orbit and clock error determination result from R11-J and R11-GJ.

	PRN	3D RMS (cm)	Radial (cm)	Along (cm)	Cross (cm)	std. Clk. (ns)
R11-J	J07	478.7	30.3	476.9	36.1	0.9
	J02	107.0	45.9	86.4	52.1	0.8
	J03	98.4	44.8	75.4	48.4	1.0
	J04	60.4	32.8	43.3	32.1	0.6
	Mean of daily median	101.5	40.2	82.2	43.3	0.9
R11-GJ	J07	409	12.8	408.5	14.2	0.4
	J02	32.5	21.3	19.5	15.4	0.5
	J03	32	17.1	21.2	16.9	0.5
	J04	21.1	10.8	15.7	11.3	0.3
	Mean of daily median	33.5	14.9	23.6	13.6	0.4

PRN J04 (yellow) from DOY 35 to 37 and PRN J07 (purple) from DOY46 to 49 are excluded due to outage of the satellite (PS-QZSS-005 2025). It should be noted that some analysis centers provide the solution for that satellite, even if the outage is notified by the operator. In this study, we remove those satellites from the analysis to remove unreliable solutions. Table 3 summarizes the mean 3D RMS, the decomposed position errors, and the standard deviations of clock errors in two scenarios. The along-track error for PRN J07 is significantly larger than other QZSS satellites because J07 is a geostationary orbit, the determination of which in the along-track direction is challenging due to low measurement sensitivity and poor geometry. Nevertheless, radial directional accuracy is the most dominant factor to determine the positioning quality since satellite navigation systems are based on range measurement. Improving the OD accuracy of GEO is one of the challenging tasks in the GNSS community (Kawate et al. 2023).

The overall orbit quality is analyzed by the mean daily median value of 3D RMS because the median is robust to outliers and fair for day weighing. By incorporating GPS observations into the processing, the median of 3D RMS and the standard deviation of the clock error improve about 67% (101.5 cm to 33.5 cm) and 51% (0.9 ns to 0.6 ns), respectively. The decomposed directional components exhibit improvements of similar magnitude. These results demonstrate a clear benefit to including GPS measurements in the OD processing, even with a regionally distributed ground network of about ten stations. This network cannot cover the whole arc of the GPS orbit within the arclength (24 hours) and the average number of observations per satellite is approximately 900 for GPS, which is about one-third of



(a) 3D RMS of orbit error (R20_J)

(b) std. dev. of clock error (R20-J)

(c) 3D RMS of orbit error (R20_GJ)

(d) std. dev. of clock error (R20-GJ)

Fig. 3. 3D RMS orbit error and standard deviation of clock error for Scenarios R20-J and R20-GJ.

that of QZSS. Despite these limitations, the data processing change from QZSS only to GPS+QZSS yields a large jump in measurement redundancy and sky coverage and resultantly causes this improvement.

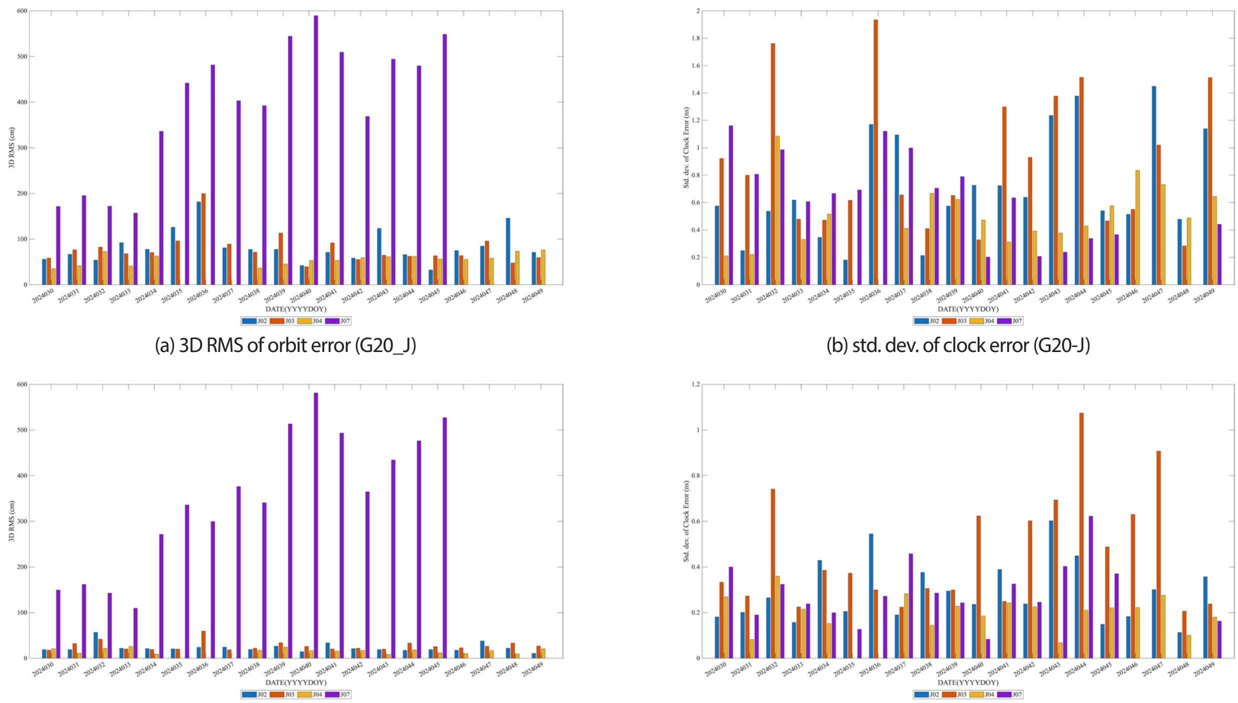
Lastly, only three satellites were available on seven of 20 days and therefore it is worthwhile to assess differences between the three-satellite and four-satellite cases. The median of 3D RMS for the four satellites case is improved by about 10% from that of the three satellite case, i.e., from 96.1 cm to 85.9 cm. These improvements are mostly achieved in radial and cross track components, i.e., 30% and 32%, respectively. Because of large errors in the along-track component, the resulting improvement is limited to about 10%.

3.2 Expansion of Ground Stations

Since the number of observations is a key factor for estimating precise orbital position, having enough well-distributed stations is one of main approaches to improve orbit and clock solution. It is therefore natural for service providers to seek to expand their ground network geometrically or densify the network, even though it could be very difficult to install and maintain ground stations in a foreign country. Because of these practical difficulties, any expansion of ground station should be based on a comprehensive analysis – specifically, in terms of determining whether a global but sparse or regional but dense network configuration is more effective.

In practice, expanding the network coverage is related to the question of whether GPS can be incorporated into the OD processing. A globally distributed network enables longer orbital-arc and is expected to be particularly beneficial for improving GPS OD quality. However, incorporating GPS into the processing is not a simple decision as it can compromise the system's independency, especially for the open service. To evaluate these trade-offs, two configurations are tested: R20, representing a denser regional network, and G20, a globally distributed network. If maintaining independence is the top priority, R20 would be the preferred option. On the other hand, if future policy allows GPS augmentation, the relative advantages of R20 and G20 must be reevaluated in terms of OD quality for both GPS and QZSS, ensuring that the chosen configuration remains robust against potential policy changes.

For each network, orbit and clock error estimations are processed with QZSS only and QZSS+GPS. A total of four cases are evaluated by comparing the basis scenario (R11_J). Through these tests, we can determine the best expansion approach when the data processing strategy is not yet fixed. Expansion of the ground monitoring network and the adoption of multi-GNSS (multi-constellation) processing



(a) 3D RMS of orbit error (G20_J)

(b) std. dev. of clock error (G20-J)

(c) 3D RMS of orbit error (G20_GJ)

(d) std. dev. of clock error (G20-GJ)

Fig. 4. 3D RMS orbit error and standard deviation of clock error for Scenarios G20-J and G20-GJ.

are also closely linked to high-precision services beyond the open service. Japan's SLAS (Sub-meter Level Augmentation Service) (Matsumoto et al. 2019) and Galileo's HAS (High Accuracy Service) provide high-accuracy corrections by leveraging multi-GNSS processing (Naciri et al. 2023). KPS likewise should consider an expanded satellite constellation and ground monitoring network for services such as MLS (Meter-Level Service) and CLS (Centimeter-Level Service) (Choi et al. 2020, KARI 2025).

Fig. 3 and 4 depict bar charts of 3D RMS and the standard deviation of clock error for all four cases, i.e., R20-J, R20-GJ, G20-J, and G20-GJ. As seen in the R11 case, the improvements by co-processing GPS can be seen in both Figs. 3 and 4, i.e., figures (c) and (d) over (a) and (b). Table 4 summarizes the RMS of orbit errors and standard deviation of clock errors per satellite during the test period. For QZSS, the percentage of improvement of the mean of the daily median with respect to the base scenario R11-J is depicted as a heatmap in Fig. 5. The largest improvement is achieved from R20-GJ and the lowest is obtained with G20-J. The improvement of R20-J (41%) compared with G20-J (19%) indicated that the ground station expansion strategy should be to increase the density of the regional network when the RNSS should be a stand-alone system.

If GPS inclusion is an option, we should consider the orbit determination quality of GPS as well. In Table 5, the means of the daily median of all GPS satellites are summarized and their distributions are depicted in Fig. 6 for 3D RMS and clock error as a boxplot. In Fig. 6, the box covers the 25^{th} to 75^{th} percentile of the daily median and the whisker extends to the maximum and minimum values. The red plus symbols denote outliers, which are located outside an area 1.5-fold larger than the interquartile range. In the case of 3D RMS, the resulting means of the daily median from G20-GJ and R20-GJ are 6.7 cm and 23.1 cm, respectively. The average number of observations per GPS satellites in the G20-GJ case is about 1700, which is just slightly larger than that of R20-GJ, i.e., about 1650. The accuracy improvement in G20-GJ therefore can be attributed to its' global distribution providing a longer orbital arc than the case of the regional network. Therefore, we could conclude that G20-GJ is the best strategy when the ephemeris of GPS is part of the service since the improvement difference of 3D RMS of QZSS between R20-GJ and G20-GJ is less than 4%.

4. CONCLUSION

Transmitting precise ephemeris is the core of navigation satellite systems and therefore it is often challenging to determine satellite orbits with limited resources. In particular, regional navigation satellite systems pose a

Table 4. Orbit and clock error determination result from R20-[G]J and G20-[G]J.

	PRN	3D RMS (cm)	Radial (cm)	Along (cm)	Cross (cm)	std. Clk. (ns)
R20-J	J07	194.4	18.5	193.4	19.9	0.6
	J02	55.9	36	35	30.6	0.6
	J03	56.9	29.3	42.9	26.4	0.7
	J04	50	25.5	33.8	29.2	0.4
	Mean of daily median	59.3	27.7	41.9	27.3	0.6
R20-GJ	J07	168.6	7.4	167.6	8.5	0.3
	J02	18.4	13.3	10.2	8.5	0.3
	J03	23.3	15.8	14	11.1	0.4
	J04	19.3	8.7	13.6	10.8	0.3
	Mean of daily median	22.1	11.5	14.2	9.5	0.3
G20-J	J07	392.7	22.8	392.4	25.9	0.6
	J02	83	43.5	58.8	43.4	0.7
	J03	78.5	39	59.9	37.7	0.9
	J04	55.6	29.4	38.9	30.4	0.5
	Mean of daily median	82.2	34.3	60.9	35.0	0.7
G20-GJ	J07	348.6	8	348.3	8.1	0.3
	J02	23.3	12.6	15.1	12.1	0.3
	J03	27.1	18.7	15.9	12.7	0.5
	J04	16.2	6.8	11.4	9.4	0.2
	Mean of daily median	25.9	11.3	16.9	10.2	0.3

Table 5. Mean of daily median for GPS satellites.

Mean of daily median	3D RMS	Radial (cm)	Along (cm)	Cross (cm)	Std. Clk. (ns)
R11_GJ	52.1	20.3	65.4	12.6	2.4
R20_GJ	23.1	9.8	28.0	6.2	1.2
G20_GJ	6.7	3.1	5.4	3.7	0.2

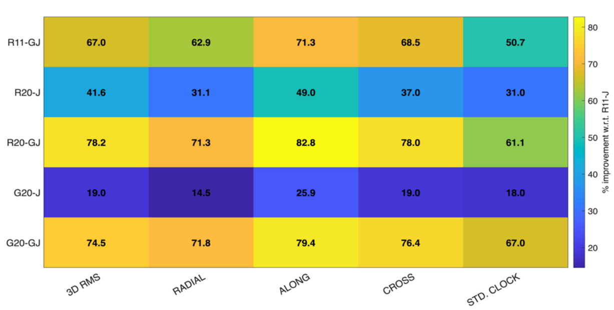


Fig. 5. Relative improvement of the tested scenarios with respect to R11-J.

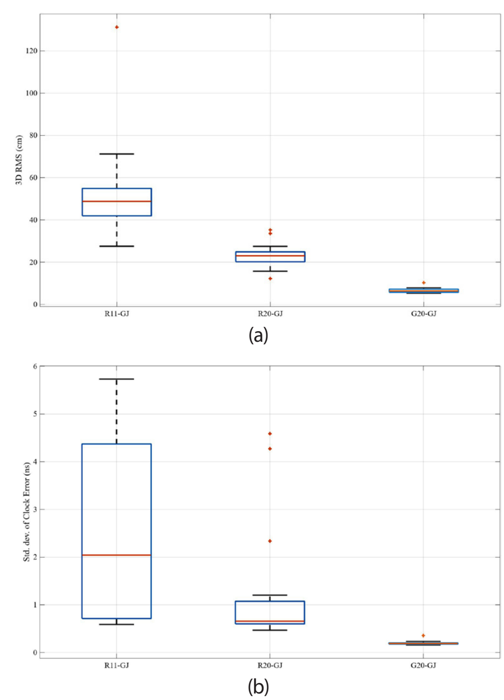


Fig. 6. (a) 3D RMS and (b) Std. Dev. of GPS satellite for the tested ground tracking networks.

particularly challenging environment for precise orbit determination. From the perspective of ground tracking stations, the satellites remain confined over a limited geographic region. This confinement reduces the temporal and azimuth–elevation diversity of the line-of-sight and thereby weakens the observation geometry and impedes accurate orbit determination. To mitigate this, RNSS operations often consider augmenting the processing with measurements from other constellations; however, such inclusion introduces external dependence and thus reduces stand-alone system independence.

In this study, we analyzed which expansion strategy is the most appropriate when the monitoring network is scaled up, depending on whether GPS is included in the processing. We considered three network designs: a regionally distributed 11-station network (R11), a denser regional 20-station network (R20), and a 20-station network expanded to a global distribution (G20). For each network, we evaluated two processing modes—QZSS-only (J) and joint QZSS+GPS (GJ)—and assessed orbit quality against IGS MGEX reference products. Also, the percentage of improvement is calculated with respect to the R11-J case, which is possibly the basis of a RNSS.

When focusing on QZSS orbits alone, the best performance was obtained with R20-GJ. Notably, even without GPS inclusion, the denser R20-J network outperformed the globally distributed G20-J case. This pattern indicates that, for RNSS with near full-arc visibility from regional sites, the number of usable observations is the dominant driver of POD quality; increasing the regional station density directly improves the geometry and reduces orbit error. However, when the GPS orbit quality is considered, the overall optimal choice becomes G20-GJ. Including GPS raises the QZSS's orbit quality to the level achieved by R20-GJ, while the GPS orbits are substantially more accurate: the mean (over days) of the daily-median 3D RMS for GPS reaches 6.7 cm, compared with 23.1 cm under R20-GJ. In other words, joint processing with a globally distributed 20-station network yields the best composite performance when both QZSS and GPS solutions are considered.

These findings have a practical design implication: the station-deployment strategy that yields the best orbit determination performance is tightly coupled to the processing strategy. If preserving stand-alone independence (QZSS-only processing) is a priority, densifying the regional network to 20 stations (R20) is a safer and more effective path than moving to a globally distributed 20-station network. If GPS inclusion is acceptable, a globally distributed 20-station network with joint processing (G20-GJ) provides the highest overall orbit quality. This study thus offers a technical basis for selecting a deployment and processing strategy that maximizes performance under realistic operational constraints.

ACKNOWLEDGMENTS

This research was supported by Core Technology Development for Korea Positioning System funded by the Korea AeroSpace Administration (KASA).

AUTHOR CONTRIBUTIONS

Conceptualization, K.R., G.K., and E.P.; methodology, K.R.; software, K.R. and G.K.; validation, K.R., G.K., and E.P.; formal analysis, K.R.; investigation, K.R., G.K., and E.P.; data curation, K.R., G.K., and E.P.; writing—original draft preparation, K.R..; writing—review and editing, G.K. and E.P.; visualization, K.R.; supervision, K.R.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

REFERENCE

Akiyama, K. & Montenbruck, O. 2025, Along-track orbit error of geostationary GNSS satellites, Advances in Space Research, 75, 6302-6316. https://doi.org/10.1016/j.asr.2025.01.067

Bhamidipati, S., Mina, T., & Gao, G. 2021, Design Considerations of a Lunar Navigation Satellite System with Time-Transfer from Earth-GPS. Proc 34th Int Tech Meet Satell Div Inst Navig (ION GNSS+ 2021), St. Louis, Missouri, Sep 20-24 2021, pp.950-965. https://doi.org/10.33012/2021.18021

Boehm, J., Niell. A., Tregoning, P., & Schuh, H. 2006, Global Mapping Function (GMF): A new empirical mapping function based on numerical weather model data, Geophysical Research Letters, 33. https://doi.org/10.1029/2005gl025546

Chen, G., Guo, J., Geng, T., & Zhao, Q. 2023, Multi-GNSS orbit combination at Wuhan University: strategy and preliminary products, Journal of Geodesy, 97, 41. https://doi.org/10.1007/s00190-023-01732-2

Chen, J., Wang, J., Yu, C., Zhang, Y., & Wang. B. 2022a, Improving BDS broadcast ephemeris accuracy using ground-satellite-link observations. Satellite Navigation 3, 11. https://doi.org/10.1186/s43020-022-00072-4

Chen, X., Ge, M., Hugentobler, U., & Schuh, H. 2022b, A new parallel algorithm for improving the computational efficiency of multi-GNSS precise orbit determination. GPS solutions, 26, 83. https://doi.org/10.1007/s10291-022-01266-8

Choi, B.-K., Roh, K.-M., Ge, H., Ge, M., Joo, J.-M., et al. 2020, Performance Analysis of the Korean Positioning System Using Observation Simulation, Remote Sensing, 12, 3365. https://doi.org/10.3390/rs12203365

Ge, H., Li, B., Jia, S., Nie, L., Wu, T., et al. 2022, LEO Enhanced Global Navigation Satellite System (LeGNSS): progress, opportunities, and challenges, Geo-spatial Information Science, 25, 1–13. https://doi.org/10.1080/10095020.2021.1978277

GSA 2020, GNSS User Technology Report, Issue 3. Publication Office of the EU, Luxembourg

KARI 2025, [Internet], cited 2025 Sep. 1, available from

https://www.kari.re.kr/eng/contents/199
Kawate, K., Igarashi, Y., Yamada, H., Akiyama, K., Okeya, M., et al. 2023, MADOCA: Japanese precise orbit and clock determination tool for GNSS, Advances in Space Research, 71, 3927–3950. https://doi.org/10.1016/j.asr.2023.01.060
Kouba, J. 2009, A simplified yaw-attitude model for eclipsing GPS satellites, GPS Solutions, 13, 1-12. https://doi.org/10.1007/s10291-008-0092-1
Kugi, M. 2018, Status Update on the Quazi-Zenith Satellite System (QZSS), 13th Meeting of the International Committee on GNSS (ICG), Xian China, 4-9 Nov 2018.
Li, K., Tang, C., Zhou, S., Hu, X., & Zhou, X. 2024, High-precision GPS orbit determination by integrating the measurements from regional ground stations and LEO onboard receivers, Satellite Navigation, 5, 27. https://doi.org/10.1186/s43020-024-00147-4
Li, X., Chen, X., Ge, M., & Schuh, H. 2019, Improving multi-GNSS ultra-rapid orbit determination for real-time precise point positioning, Journal of Geodesy, 93, 45-64. https://doi.org/10.1007/s00190-018-1138-y
Li, X., Zhu, Y., Zheng, K., Yuan, Y., Liu, G., et al. 2020, Precise Orbit and Clock Products of Galileo, BDS and QZSS from MGEX Since 2018: Comparison and PPP Validation, Remote Sensing, 12, 1415. https://doi.org/10.3390/rs12091415
Matsumoto, D., Kaneso, T., Urushido, T., & Owada, S. 2019, Evaluation of QZSS SLAS (Sub-meter Level Augmentation Service) Performance, Proceedings ION 2019 Pacific PNT Meeting, 361-366. https://doi.org/10.33012/2019.16811
Montenbruck, O., Schmid, R., Mercier, F., Steigenberger, P., Noll, C., et al. 2015, GNSS satellite geometry and attitude models, Advances in Space Research, 56, 1015-1029. https://doi.org/10.1016/j.asr.2015.06.019
Montenbruck, O., Steigenberger, P., Prange, L., Deng, Z., Zhao, Q., et al. 2017, The Multi-GNSS Experiment (MGEX) of the International GNSS Service (IGS) – Achievements, prospects and challenges, Advances in Space Research, 59, 1671-1697. https://doi.org/10.1016/j.asr.2017.01.011
Naciri, N., Yi, D., Bisnath, S., de Blas, F. J., & Capua, R. 2023, Assessment of Galileo High Accuracy Service (HAS) test signals and preliminary positioning performance, GPS solutions, 27, 73. https://doi.org/10.1007/s10291-023-01410-y
Numata, K. 2023, QZSS System and service Updates, 17th Meeting of the International Committee on GNSS (ICG), Madrid Spain, 15-20 Oct 2023.
Petit, G. & Luzum, B. 2010, IERS Conventions (2010), IERS Conventions Centre, IERS Technical Note No.36
Prange, L., Beutler, G., Dach, R., Arnold, D., Schaer, S., et al. 2020, An empirical solar radiation pressure model for satellites moving in the orbit-normal mode, Advances In Space Research, 65, 235-250. https://doi.org/10.1016/j.asr.2019.07.031
PS-QZSS-005 2025, Quasi-Zenith Satellite System Performance Standard, https://qzss.go.jp/en/technical/download/pdf/ps-is-qzss/ps-qzss-005.pdf
QZSS 2025, [Internet], cited 2025 Sep. 1, available from https://sys.qzss.go.jp/dod/en/index.html.
Roh, K.-M. & Choi, B.-K. 2014, The Effects of the IERS Conventions (2010) on High Precision Orbit Propagation, Journal of Astronomy and Space Science, 31, 41-50. https://doi.org/10.5140/jass.2014.31.1.41
Savcenko, R., Bosch, W., Dettmering, D., & Seitz, F. 2012, EOT11a - Global Empirical Ocean Tide model from multi-mission satellite altimetry, with links to model results dataset, PANGAEA. https://doi.org/10.1594/PANGAEA.834232
Steigenberger, P., Deng, Z., Guo, J., Prange, L., Song, S., et al. 2023, BeiDou-3 orbit and clock quality of the IGS Multi-GNSS Pilot Project, Advances In Space Research, 71, 355-368. https://doi.org/10.1016/j.asr.2022.08.058
Tang, C., Hu, X., Zhou, S., Guo, R., He, F., et al. 2016, Improvement of orbit determination accuracy for Beidou Navigation Satellite System with Two-way Satellite Time Frequency Transfer, Advances In Space Research, 58, 1390-1400. https://doi.org/10.1016/j.asr.2016.06.007

Kyoung-Min Roh received his B.S., M.S., and Ph.D. in astronomy and space sciences from Yonsei University, Rep. of Korea, in 1997, 1999, and 2006, respectively. From 2007 to 2008, he worked as a postdoctoral researcher at GFZ German Research Centre for Geosciences. Since 2008, he has been with Korea Astronomy and Space Science Institute as a senior research staff member. He is currently involved in development of Korean Positioning System. His research interests include satellite GNSS data processing, high precision orbit determination, and their applications to space geodesy.

Gimin Kim is a researcher in the Center for Space Navigation and Geodesy of Korea Astronomy and Space Science Institute in Daejeon, Korea. He received his B.S. and M.S. in Astronomy from Yonsei University in 2018 and 2020, respectively. His current research interests cover GNSS satellite orbit

determination, GNSS clock determination, and GNSS PPP-RTK.

Eunseo Park is a researcher in the Center for Space Navigation and Geodesy of Korea Astronomy and Space Science Institute in Daejeon, Korea. He received his Ph.D. in Astronomy from Yonsei University in 2009. His current research interests cover GNSS satellite orbit determination, GNSS clock determination, and SLR satellite orbit determination.