S & M 4083

Technological Advancement Strategies for Global Navigation Satellite Systems Central Station Systems: Enhancing Reliability and Responding to Emerging Demands in the Korean Context

JaeKang Lee[1*] and WooSaeng Kim[2]

[1]Department of Civil Engineering, Dong-A University
[2]DANVI Centre, University-Industry Cooperation Foundation, Dong-A University,
37 Nakdong-Daero 550beon-gil Saha-gu 49315, Busan, Korea

(Received June 2, 2025; accepted June 16, 2025)

Keywords: GNSS, delay minimization, connection stability, service path separation, restorable network redundancy design

The proposed methodology outlines a framework for the implementation of a user-customized service structure and a real-time, high-reliability correction data-provision system, leveraging advancements in central global navigation satellite systems (GNSSs). The proposed structure encompasses a variety of functions, including MountPoint-based user customization, protection level (P_L)-based reliability value provision, multisensor fusion, automatic fault response, and predictive resource allocation. The objective of its design is to satisfy the performance requirements of high-speed, high-precision application fields, including autonomous driving and urban air mobility. In this study, our primary objective is to minimize delays and ensure connection stability through high-frequency transmissions at frequencies greater than 1 Hz, the automatic separation of service paths, and the incorporation of restorable network redundancy design. We posit the hypothesis that GNSSs may evolve to encompass spatial-information-based services across various industries, thereby expanding beyond their traditional role in simple positioning infrastructure. Moreover, the implementation of institutional enhancements, such as certification standards, the delegation of operational authority, and the establishment of quality standards, in parallel with the proposed system, has the potential to serve as the foundation for substantial innovation in national GNSS services.

1. Introduction

The demand for high-precision satellite positioning technology is increasing rapidly worldwide. Global navigation satellite systems (GNSSs) are considered to be a fundamental component of future industrial infrastructure, with potential applications in domains such as autonomous driving, urban air mobility (UAM), precision agriculture, digital twins, and smart

*Corresponding author: e-mail: jaekanglee@dau.ac.kr
https://doi.org/10.18494/SAM5767

construction. Consequently, there is an increasing demand for service systems that provide real-time capabilities, ensure precision, and maintain reliability.[1–3]

In Korea, a network comprising approximately 90 GNSS reference stations has been established around the National Geographic Information Institute (NGII), and precision positioning services based on real-time location correction information (RTK, PPP, etc.) are being provided. However, the current system is still operated as a single structure centered on the public sector, and improvement is needed in various areas, including the expansion of the private sector use, service interruption responses, and user customization.[4,5]

The technical foundations for the advancement of GNSS are currently under active proposal, both domestically and internationally. The field of domestic studies encompasses a range of research areas, including the structural analysis of RTK and PPP technologies for high-precision positioning,[6,7] the design of MountPoint-based user authentication systems,[8] the development of the G-Nut/Anubis tool and the utilization of TEQC (Translate/Edit/Quality Check) for quality analysis,[9,10] and studies on the application of GNSS technology for structural monitoring.[11] Additionally, a multitude of technologies related to automated fault response and reference point stability diagnosis have been proposed,[12,13] and studies on the development of fault detection systems for user interface design and real-time applications are underway.[14,15] Research conducted in technological powerhouse has led to the proposal of advanced technologies, including the standardization of correction data formats based on RTCM 3.x and server-side rendering (SSR),[16,17] real-time PPP, URTK, and integrity-based positioning systems,[18–20] the quantification of reliability based on the protection level (P_L),[21,22] and continuous positioning technology based on GNSS/inertial navigation system (INS)/light detection and ranging.[23–25] Furthermore, the verification and commercialization of additional positioning structures are underway. These structures are based on sensor fusion and operate in environments where satellite signals are obscured. Additionally, cycle slip detection techniques that utilize multiple frequencies are being developed.[26–28] Finally, the precision correction structures based on low-Earth-orbit satellites are also being verified and commercialized.[29,30] These technologies are directly connected to precision positioning in urban environments, continuous navigation for mobile objects, and the enhancement of real-time service stability.

The structure for enhancing the stability and utilization of GNSS services can be classified into three categories, as follows. (a) MountPoint design, which is centered on users and the authority distribution system. It is imperative to consider users' accuracy requirements, service utilization patterns, and industry characteristics to furnish real-time customized data, as this is crucial to the perceived quality of actual services.[31–33] (b) Provision of reliability indicators to ensure GNSS integrity. Beyond the realm of basic positional accuracy, the quantification and provision of the reliability of the received correction data in real time are regarded as indispensable requirements in the domains of industrial safety and aviation.[34–36] (c) A prediction-based resource allocation and automatic recovery system. A server structure based on clusters, anomaly detection based on connection history, and real-time fault recovery systems are all essential elements for ensuring actual service continuity.[15,37]

In the Republic of Korea, the private sector has expressed a marked interest in the advancement of these technologies, underscoring the need for such development. To enhance the correction data-provision system, NGII conducted a survey of the technical and policy requirements for each service from broadcasters [Middle East Broadcasting Center (MBC)] and the three major telecom companies [South Korea Telecom, Korea Telecom (KT), and LGU+]. The survey results indicated that GNSS services require advancement for private real-time applications that will extend beyond the provision of accuracy. These applications will include "availability at all times", "minimization of delay", and "clarification of fault recovery time". This finding indicates that the prevailing NGII system, which was developed with a primary focus on geodesy and surveying, exhibited constraints in fulfilling the requirement for real-time continuous services. The absence of an emergency alert system in the event of faults, delays in system recovery, and the lack of a user group-based alert system are structural constraints on the expansion of private services. The GNSS correction data service currently provided by NGII is primarily operated using the virtual reference station (VRS) RTK and FTP RTK methods. The service is designed with a structure focused on stability for precision surveying. VRS RTK is a method that provides correction data by generating a virtual reference point near the user's location, while FTP RTK is a method that transmits correction data at regular intervals. This configuration is engineered to guarantee that, in the event of a malfunction at select reference stations, the network's overall performance remains largely uncompromised. Nevertheless, the system is subject to constraints with regard to real-time performance, user-customized alert configurations, and fault prediction and recovery mechanisms. Furthermore, an analysis of service-specific requirements identified positioning accuracy, data delay, and user scale as pivotal factors. Group 1 (e.g., autonomous driving) necessitated centimeter-level accuracy and the prevention of data loss as essential conditions. Conversely, Groups 3–5 can tolerate meter-level accuracy; however, the overall system design necessitates a structure capable of addressing these diverse demands separately. This necessity is intrinsically linked to the requirement for advanced technologies, including MountPoint-based user group separation, real-time predictive resource allocation, and automatic fault detection and recovery. This technological foundation serves as the foundational basis for this study. The extant literature has examined individual components of GNSS advancement technology, including high-precision RTK technology,(38) cycle slip correction,(39,40) multisensor fusion,(30,41) and user authentication structures(42) in isolation. However, there is a paucity of research that systematically integrates these components and applies them to actual service structures. Furthermore, studies that integrate the technical advancement of GNSS services with the development of legislative and institutional frameworks are even more limited.

In this paper, we present an integrated technical strategy for the advancement of the GNSS central system of NGII in Korea, taking into comprehensive account these technological trends and institutional foundations. Specifically, we present the system design and basis incorporating elements such as real-time service continuity, the provision of integrity indicators, user-customized access structures, industry-specific MountPoint differentiation, GNSS/INS fusion-based redundancy, predictive resource control, and user authentication-linked structures. We also examine the relevance of the advanced structure in the context of demonstration scenarios, such as autonomous driving and UAM. Concurrently, we explore the potential enhancements to the legal and institutional framework. These explorations culminate in the proposal of a strategy that integrates technological advancement with policy, fostering a comprehensive and synergistic approach to innovation.

2. Summary of Key Technical Requirements and Demonstration Basis for GNSS System Advancement

In this section, we offer a concise overview of the technical prerequisites necessary for the enhancement of the GNSS central system of NGII. Pursuant to the findings of the empirical analysis delineated in the report,[4] the prevailing operational limitations of the system and the technical requirements to supplement them are classified into four categories.

2.1 Necessity to reorganize user-centered operational systems

The GNSS central system provides real-time location correction data to users across various fields. However, a detailed operational system based on each user's access history and service usage patterns is still lacking.

According to a report[4,5] in Korea, the average number of daily users over the past three years is estimated at approximately 16000 (3-year average). This estimation is based on the systems that constitute the GNSS correction data-provision framework (GNSMART, GNSS Integration Center). The annual number of GNSMART users demonstrated an abrupt increase from approximately 153851 in 2020 to 992368 (Table 1). This phenomenon can be attributed to the substantial surge in user demand that ensued subsequent to the amendment of the Public Survey Work Regulations in 2018. The aforementioned amendment led to the integration of the GNSMART system in public surveys.

Furthermore, users of the GNSS Integration Center exhibit diversification across use formats, including RTCM 2.x, 3.1, 3.2, and BINEX. As illustrated in Table 2, there was a more than 50% increase in the number of RTCM 3.2 users in 2022 compared with the previous year. This

Table 1
Daily user statistics by system over the past three years.

Label	PIVOT	GNSMART	Data integration center	Total	Daily average
2020	1246928	153851	5664001 (from March)	6886723	18868
2021	1159743	992368 (to November)	3981284	6133395	16804
2022	880183	—	3714779	4594962	12589

Table 2
Number of users by MountPoint format at the GNSS Integration Data Center.

Year	RTCM 2.x	RTCM 3.1	RTCM 3.2	BINEX[1]
2020. 3–12	1049063	2362050	2224037	28851
2021	432877	2277709	1258282	12416
2022	430663	1468096	1809308	6712

[1]BINEX: Binary exchange

development can be attributed to significant advancements in receiver technology and the increasing demand for multi-GNSS correction signals. Consequently, it is imperative that system response strategies are also refined to reflect the diversification of user environments and technology levels. This trend is consistent with the user group strategy and the precision and correction cycle requirements by industry. Table 3 presents the requirements according to the user group.

To illustrate, autonomous driving necessitates centimeter-level high precision and high-speed correction data at frequencies greater than 1 Hz. Conversely, the agricultural sector favors correction data at relatively lower frequencies. The heterogeneity of demand necessitates user classification based on MountPoint, the control of access paths, and the provision of differentiated services based on authority. Similar discussions have been presented in GNSS user interface design studies.[17]

In summary, a user-centered operational system surpasses mere classification, thereby enhancing the quality and stability of real-time correction data, improving the efficiency of resource allocation, and establishing a foundation for the expansion of private sector applications. The system is then connected to the specific system design in Sect. 3.

2.2 Necessity of automated fault response and redundancy systems

The GNSS central system is regarded as a national key infrastructure, the purpose of which is to provide high-precision correction data. It is therefore vital that this system operates continuously and without interruption. Nevertheless, the report[4,5] indicates that the prevailing system continues to depend on manual responses in the event of faults and that significant servers are deficient in adequate redundancy or automatic recovery systems.

As illustrated in Table 4, 19 faults were identified in GNSMART, comprising 10 MountPoint RTCM32 connection faults, four license recognition faults, two satellite signal processing errors, two reference station disconnections, and one port conflict fault.

Table 3
Classification of requirements according to the user group.

User group	Requirements
1	- Centimeter-level positioning error during customer use - Service with high-operational stability - Service with low-data delay where errors may pose safety risks - Support for alternative functions, such as alerts and service suspension in the event of errors, and use of other similar solutions
2	- Centimeter-level positioning error during customer use - Service with functions that can ensure sufficient customer safety even if errors occur
3	- Meter-level positioning error during customer use - Service that can be replaced by an equivalent or inferior self-owned solution in the event of an error
4	- Meter-level positioning error during customer use - Service that can be used additionally in the event of an error (optional)
5	- Meter-level positioning error during customer use - Service unrelated to safety - Small-scale service used in local areas for development and test verification

Table 4
2022 Central system fault report (detailed).

Date and time of fault	System	Fault symptoms	Measures taken	Remarks
2022/1/8 (Sat)	GNSMART	Disconnection of all reference points	Restored after rebooting	
2022/1/8 (Sat)	Integration center	User connection failure	Restored after rebooting	
2022/1/14 (Fri)	PIVOT	MountPoint RTCM31 fault	Restored after adjusting database capacity	Automatic capacity adjustment set
2022/1/26 (Wed)	GNSMART	MountPoint RTCM32 fault	Restored after rebooting	
2022/1/27 (Thu)	GNSMART	MountPoint RTCM32 fault	Restored after rebooting	Auto-restart set at 06:00, 07:00, 08:00
2022/4/5 (Tue)	GNSMART	License recognition fault	Restored after rebooting	
2022/4/13 (Wed)	GNSMART	Disconnection of all reference points	Restored after rebooting	
2022/5/2 (Mon)	GNSMART	License recognition fault	Restored after rebooting	
2022/5/4 (Wed)	GNSMART	MountPoint RTCM32 fault	Restored after rebooting	
2022/5/6 (Fri)	GNSMART	MountPoint RTCM32 fault	Restored after rebooting	Auto-restart set at 02:00, 05:00, 07:00, 22:00
2022/5/20 (Fri)	GNSMART	MountPoint RTCM32 fault	Restored after rebooting	Auto-restart set at 14:30
2022/6/8 (Wed)	GNSMART	MountPoint RTCM32 fault	Restored after rebooting	Fault occurred around 14:00
2022/6/14 (Tue)	GNSMART	MountPoint RTCM32 fault	Restored after rebooting	Fault occurred around 14:00
2022/6/15 (Wed)	GNSMART	MountPoint RTCM32 fault	Restored after rebooting	Fault occurred around 14:00
2022/7/9 (Sat)	GNSMART	Port 2101 conflict fault	Restored after changing port settings	
2022/7/10 (Sun)	GNSMART	MountPoint RTCM32 fault	Restored after rebooting	
2022/7/18 (Mon)	GNSMART	MountPoint RTCM32 fault	Restored after rebooting	
2022/9/12 (Mon)	GNSMART	License recognition fault	Restored after rebooting	
2022/10/20 (Thu)	GNSMART	Satellite signal processing error	Restored after rebooting	Fault occurred around 07:00–08:00
2022/10/21 (Fri)	GNSMART	Satellite signal processing error	Restored after rebooting	
2022/11/8 (Tue)	GNSMART	License recognition fault	Restored after rebooting	

In the VRS3Net system, a service interruption due to log accumulation was observed. It has been reported that the GNSS Integration Center has encountered fault cases that have been attributed to user access errors. In the case of satellite reference points, several emergency faults occurred over the past 3 years owing to communication failures and receiver malfunctions (see Table 5).

Table 5
GNSS central system fault and downtime statistics.

Facility category	System interruption	Virtual reference station (VRS)3Net		GNSMART		GNSS Integration Data Centre	
		Number of faults	Downtime	Number of faults	Downtime	Number of faults	Downtime
System	Emergency fault	6	3420 min (2.38 d)	32	3645 min (2.53 d)	3	280 min (0.19 d)
	Preventive maintenance	9	4680 min (3.25 d)	10	12600 min (8.75 d)	3	2100 min (1.46 d)
Support equipment	Emergency fault	7	1060 min (0.74 d)	6	970 min (0.67 d)	6	970 min (0.67 d)
	Preventive maintenance	9	3330 min (2.31 d)	9	3240 min (2.25 d)	10	3240 min (2.25 d)

It is therefore observed that the operating systems, databases, and system configuration structures of each system are outdated or no longer supported for security reasons. It is recommended that upgrades to Windows Server 2022 and SQL Server 2022 be implemented. Furthermore, in the case of the GNSMART system, as settings are stored in text files, there is a potential risk of faults caused by operator error. Despite the fact that the modular control center system (MCCS) facilitates automatic switching, a limitation has been identified owing to discrepancies in the specifications of the active and standby servers, thereby hindering optimal functionality. These structural vulnerabilities underscore the necessity for the implementation of a cluster-based automatic switching structure. The satellite reference point network service utilized by NGII is employed to ascertain the precise position of the rover station through the utilization of the VRS method. This method involves the generation of a virtual reference point, as if observed from an arbitrary location in proximity to the rover. This method is also capable of performing RTK with the nearest reference station in conjunction with the FKP method. The FKP method generates correction parameters for each plane within the network and transmits them to the rover to correct distance-based RTK errors. This enables a more precise positioning of the rover station. Notwithstanding the fact that certain observatories neglect to submit data, this does not constitute a significant challenge when it comes to rectifying the identified errors. However, no automatic recovery system has been developed for precision real-time services, such as autonomous vehicles and drone logistics services, nor is there a system that can urgently respond by distinguishing between the user groups mentioned in Sect. 3.1. The subsequent discourse on system design strategies in Sect. 3 is predicated on this premise.

2.3 Necessity for a quality diagnostic system to ensure timeliness and completeness

The quality of GNSS-based correction data is determined by two factors: timeliness and completeness. In this study, we analyzed the reception rate of the RTCM 3.2 format reference points, the results of which are summarized below in Table 6.

The majority of reference stations exhibited a reception rate greater than 98%; however, in the case of Changwon (alloy test), the rate was 95.76%, suggesting a potential data loss of more than 1000 s/d.

Table 6
Data acquisition rates according to location for the RTCM 3.2 format.

Satellite reference point wired communication environment					Satellite reference point wireless communication environment				
	Local (Observatory central system)	Remote	NTRIP* (Wired)	NTRIP (Wireless)		Local (Observatory central system)	Remote	NTRIP (Wired)	NTRIP (Wireless)
Paju (NetR9-NGII**)	100.00	99.66	99.85	99.68	Paju (NetR9 test)	99.59	98.45	99.04	98.53
Changwon (Alloy-NGII)	99.97	99.66	99.64	99.7	Changwon (alloy test)	99.59	95.76	96.71	96.46
Changnyeong (GR50)	99.4	98.67	99.44	99.47	Yangju (GR50)	99.34	99.35	99.00	99.18
Overall average	**99.79**	**99.33**	**99.64**	**99.62**	**Overall average**	**99.51**	**97.85**	**98.25**	**98.06**

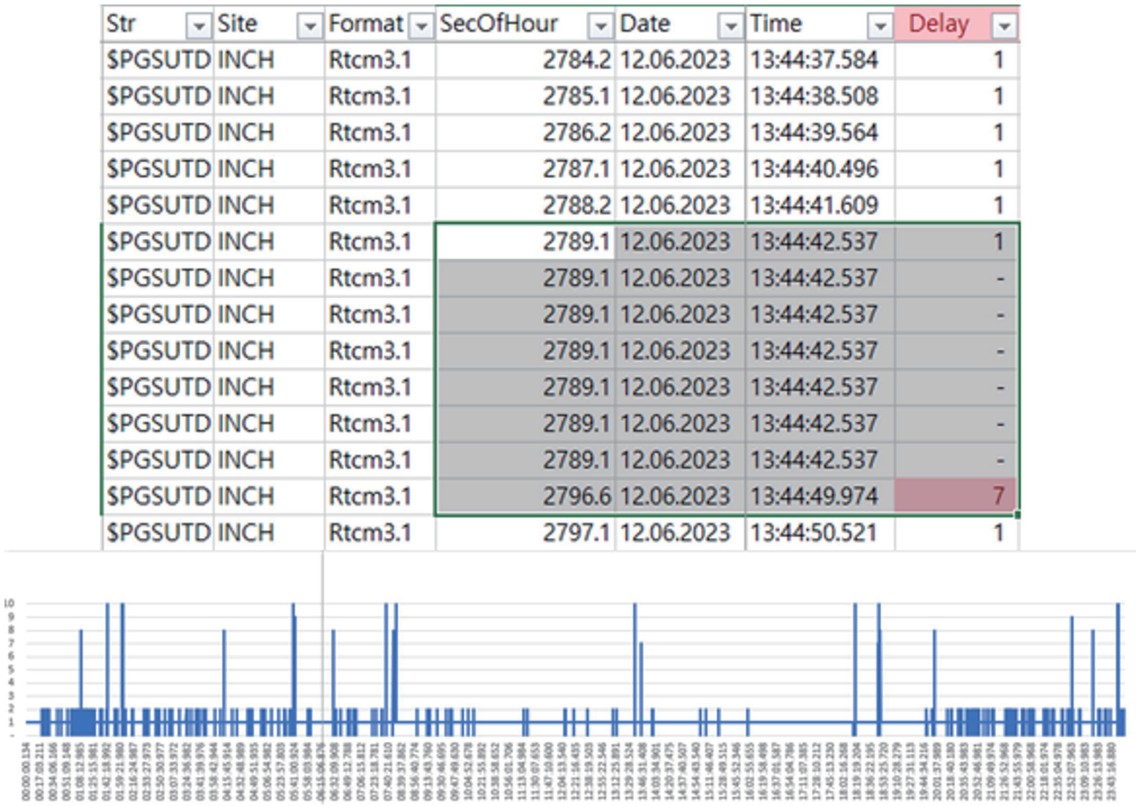
*NTRIP: Networked transport of RTCM via internet protocol
**NGII: National GeographicInformation Institute

In this study, data loss and data age were analyzed using receiver independent exchange (RINEX) files and RTCM reception logs. The 1-s-interval RINEX files, recorded on an hourly basis, were analyzed using TEQC to ascertain the presence of communication interruptions. RTCM reception logs were analyzed using the GNSS Surfer to evaluate data age and data loss. As illustrated in Fig. 1, 30 cases were observed, with a reception delay of 2910 s recorded at the Incheon (INCH) reference point. This suggests that the delay was not attributable to a communication network failure, but rather, it was due to processing issues within the internal NTRIP Caster system. This case demonstrates how an abnormal condition can remain undetected for an extended period owing to the absence of a real-time quality diagnostic system.

The importance of ensuring timeliness and completeness in determining the perceived quality for users cannot be overstated, particularly in the context of precision application services such as autonomous driving, UAM, and drones. This is a prerequisite for implementing a private service model based on SLA contracts, and it leads to the discussion on the quality-based certification system design in Sect. 3.

2.4 Core technical requirements for providing highly reliable positioning information

GNSS correction data is a fundamental component of infrastructure for high-precision location-based application services, including autonomous driving, smart cities, and UAM. In the context of these application areas, it is imperative to not only provide precise location information but also quantitatively evaluate the “level of reliability” of this information. The concept recently emphasized for this purpose is P_L.(15) As illustrated in Fig. 3–34 of the report,(5) Trimble’s method of calculating P_L is presented visually, and the numerical range within which the correction information lies at a specific confidence level when provided to users is expressed. This configuration functions as a foundational element for the real-time transmission of reliability and the establishment of a service quality assurance system based on SLA. As demonstrated by Zumberge *et al.*,(20) a case study that verified the reliability of PPP-based correction was presented. Furthermore, the P_L concept was emphasized by Rizos,(21)



Str	Site	Format	SecOfHour	Date	Time	Delay
$PGSUTD	INCH	Rtcm3.1	2784.2	12.06.2023	13:44:37.584	1
$PGSUTD	INCH	Rtcm3.1	2785.1	12.06.2023	13:44:38.508	1
$PGSUTD	INCH	Rtcm3.1	2786.2	12.06.2023	13:44:39.564	1
$PGSUTD	INCH	Rtcm3.1	2787.1	12.06.2023	13:44:40.496	1
$PGSUTD	INCH	Rtcm3.1	2788.2	12.06.2023	13:44:41.609	1
$PGSUTD	INCH	Rtcm3.1	2789.1	12.06.2023	13:44:42.537	1
$PGSUTD	INCH	Rtcm3.1	2789.1	12.06.2023	13:44:42.537	-
$PGSUTD	INCH	Rtcm3.1	2789.1	12.06.2023	13:44:42.537	-
$PGSUTD	INCH	Rtcm3.1	2789.1	12.06.2023	13:44:42.537	-
$PGSUTD	INCH	Rtcm3.1	2789.1	12.06.2023	13:44:42.537	-
$PGSUTD	INCH	Rtcm3.1	2789.1	12.06.2023	13:44:42.537	-
$PGSUTD	INCH	Rtcm3.1	2789.1	12.06.2023	13:44:42.537	-
$PGSUTD	INCH	Rtcm3.1	2796.6	12.06.2023	13:44:49.974	7
$PGSUTD	INCH	Rtcm3.1	2797.1	12.06.2023	13:44:50.521	1

Fig. 1. (Color online) Status of missing Radio Technical Commission for Maritime Services (RTCM) record data at Incheon confirmed using the GNSS Surfer.

Yang and Xu,[22] and others as a key element for ensuring integrity. Yang and Xu[22] demonstrated an enhancement in reliability through a robust estimation-based RAIM technique, indicating the potential for advancement in current integrity provision models. In addition, to guarantee high-reliability correction, there is a necessity for sophisticated correction for various GNSS error factors, including ionospheric delay, multipath, and orbital error. Technologies such as GNSS/INS fusion-based multisensor optimization and hybrid models such as BeiDou satellite-based augmentation systems (BDSBAS), PPP, and RTK are necessary for this purpose.[24,25] As illustrated in the report, these related hybrid correction scenarios and methods for ensuring GNSS service stability include predictive evaluations assuming applications in UAM and urban navigation environments. A certification system based on reliability figures provides the institutional foundation for GNSS industry services intended to be integrated with public infrastructure. The GNSS advancement strategy outlined in the report represents a significant departure from the status quo.

3. Design and Implementation Strategy for GNSS System Advancement

In this section, we will discuss the detailed design and implementation strategies for advancing the GNSS central system based on the key technical requirements presented in Sect. 2. The proposal sets out an integrated approach that addresses the limitations of the current system and the latest technology trends. These include the design of automatic recovery systems, user-centered authority management structures, high-precision and high-reliability correction data provision, and technical frameworks suitable for responding to future demands.

3.1 User-centered system design strategy

Despite the possibility of divergent service-specific requirements across investigating institutions, user groups can be classified according to the following five indicators: the accuracy of location data, the presence or absence of service delays, the availability of substitute functions in cases of service failure, the presence of stability control functions, and user scale.

With regard to Group 1, the provision of centimeter-level high-precision location data is imperative, the service must be stable, and data delays must be absent. It is imperative that the system is equipped with alert functions, with the capacity to suspend service in the event of an error and to switch to an alternative service, given the direct impact that errors may have on safety.

Group 2 also requires centimeter-level positioning accuracy; however, the system is based on the premise that user safety can be ensured through its own stability control functions even in the event of errors occurring.

Groups 3 and 4 deviate from the aforementioned group classifications in that their required positioning accuracy values are at the meter level, and the groups are distinguished on the basis of whether an equivalent or alternative solution can be used in the event of a fault. Finally, Group 5 is comparatively unassociated with stability and serves to test and develop small-scale users in a localized manner. The following user group-based service is hereby proposed in Table 7.

Among the indicators employed to differentiate between user groups, “provision of substitution function in case of service error” and “stability control function” are elements that can be addressed at the terminal or service software level as opposed to by the GNSS correction data-provision system. Consequently, they exhibit minimal direct relevance to the correction system. Conversely, “accuracy of location data”, “presence of service delay”, and “user scale” are highly relevant to the GNSS correction data-provision system.

Table 7
Example of user group classification.

Group	Accuracy of location data	Service delay	Service error substitution function	Stability control function	User scale
1	Cm	Low	Service suspension or substitution with similar solution	Service suspension or substitution with similar solution	Irrelevant
2	Cm	↕	Service continuity	Safety control	Irrelevant
3	M		Substitution with own solution	Substitution with own solution	Irrelevant
4	M		Optional supplementary service	Optional supplementary service	Irrelevant
5	M	Irrelevant	Operates regardless	Operates regardless	Small-scale, specific region

*Definition of Irrelevant: "Not required at system level" or "Not critical for GNSS correction system"

The accuracy of location data is directly linked to the positioning performance of the correction system, and the presence of service delay depends on the stability and continuity of correction data provision. The user scale is also closely related to the number of concurrent users that the correction data system is capable of accommodating. Should a system for distinguishing user groups be introduced, analogous to the system proposed in this study, the emergency fault response system of NGII's GNSS correction data service can be enhanced to be more systematic and user-customized. First, as the required positioning accuracy and service stability standards become clearer to the user group, appropriate response levels and notification methods can be applied differently in the event of a fault. For instance, Group 1 users – those requiring high-precision location data and high stability – can benefit from real-time fault notifications and alternative service guidance, which are automatically provided, thus minimizing risks due to service interruptions. Conversely, for Groups 4 and 5 users with low-stability requirements, optional notifications or periodic status updates can be sufficient. This differentiated fault response system has been demonstrated to be more efficient than the conventional unified text alert method and can also contribute to enhancing users' trust in the service. Moreover, the group-based system enables the operating agency to assign priorities to recovery targets and allocate resources on the basis of the type and frequency of faults.

Table 8 provides a comparative overview of the legacy NGII MountPoint configuration and the proposed access authority separation structure. Key improvements include group-specific session control, customized fault response, and format differentiation for enhanced flexibility and reliability.

3.2 Prediction analysis and autonomous response structure based on connection history

To ensure the real-time capability and continuity of GNSS services, a prediction analysis and autonomous response system is required, the said system being based on user connection history and network status. In the report [4,5], the authors propose a structure that includes functions for prefault detection and automatic switching, which form the foundation for implementing an uninterrupted system.

Table 8
MountPoint-based access control comparison.

Feature	Description	Legacy NGII system	Proposed system	Benefit
Session control	Control over number of active users	Not supported	Supported	Dynamic load balancing
User group separation	MountPoint linked to user type	Not applied	Applied	Customized service provisioning
Fault alert customization	Alerts by user criticality	Unified alerts	Differentiated by group	Risk mitigation
Authority differentiation	Access by authentication	Basic login	Per-MountPoint roles	Security and SLA-based management
Transmission format separation	RTCM, BINEX, SSR handling	Mixed output	Session-linked separation	Reduced latency

Figure 2 illustrates the operational logic of the proposed prediction and response system, effectively serving as a simplified flowchart of the algorithmic structure. It visualizes the connection status analysis, anomaly detection based on transmission logs, and the automated switching mechanism triggered by abnormal data gaps or delays.

The fault response system is composed of static triggers and dynamic prediction methods. Static triggers are characterized by their immediate transition to redundant servers, a process that is contingent upon well-defined criteria. These criteria may include factors such as reception failure, response delay, and an increase in data loss rate. In contrast, dynamic prediction methods employ log-based analysis to predetect abnormal patterns, thereby facilitating proactive measures. As illustrated in Fig. 2, the report presents a visual representation of the methodology for assessing data loss at all GNSS sites.

The prediction system is predicated on numerical indicators, including connection frequency, response time, and transmission delay, as documented in server logs. The system analyzes these in time series to detect deviations from normal ranges in real time and dynamically adjusts detection sensitivity through an internal threshold adjustment algorithm. This functions as a self-operating structure that goes beyond simple notifications and performs server switching before faults occur. Furthermore, to prevent data loss in the event of a system fault, each server is equipped with real-time log backup and state snapshot storage functions. A function has also been incorporated to facilitate the regeneration and transmission of correction data, which is derived from recoverable data points, in the event of data loss. This ensures the completeness and timeliness of the data.

The validity of this design is substantiated by the empirical findings derived from a thorough analysis of the reception log. As demonstrated in Fig. 1, for instance, Incheon Station encountered a protracted RTCM delay – the intricacies of which are elaborated upon in Sect. 3.4.

The RTCM reception test configuration presented in Table 9 was designed to track and record missing data by the receiver, thereby indirectly supporting the effectiveness of the system

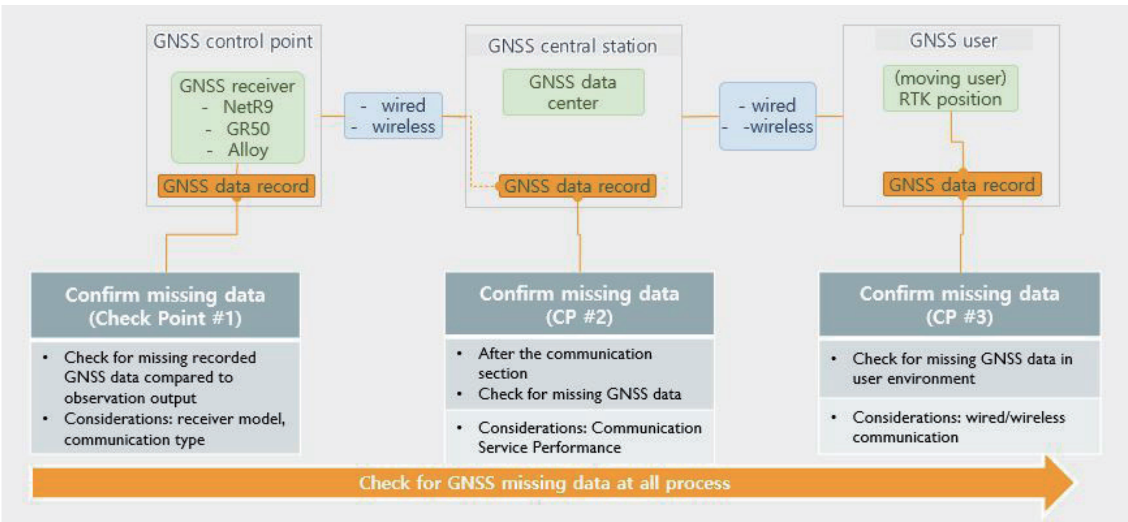
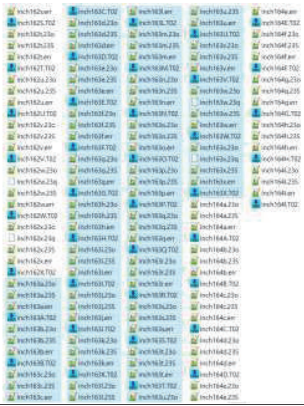
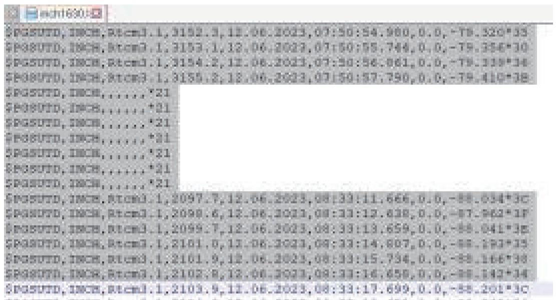


Fig. 2. (Color online) Data loss confirmation for GNSS data acquisition rate analysis.

Table 9
(Color online) Time-synchronized generation records of RINEX and RTCM reception logs for confirming correction data loss.

Hourly RINEX (VRS3Net records)	RTCM reception log records (GNSS Surfer records)
	

```
$PGSUTD,INCH,Rtcm3.1,3152.3,12.06.2023,07:50:54.980,0.0,-79.320*33
$PGSUTD,INCH,Rtcm3.1,3153.1,12.06.2023,07:50:55.746,0.0,-79.356*30
$PGSUTD,INCH,Rtcm3.1,3154.2,12.06.2023,07:50:56.861,0.0,-79.339*34
$PGSUTD,INCH,Rtcm3.1,3155.2,12.06.2023,07:50:57.790,0.0,-79.410*38
$PGSUTD,INCH,,,,,,*21
$PGSUTD,INCH,,,,,,*21
$PGSUTD,INCH,,,,,,*21
$PGSUTD,INCH,,,,,,*21
$PGSUTD,INCH,,,,,,*21
$PGSUTD,INCH,,,,,,*21
$PGSUTD,INCH,,,,,,*21
$PGSUTD,INCH,Rtcm3.1,2097.7,12.06.2023,08:33:11.666,0.0,-88.034*3C
$PGSUTD,INCH,Rtcm3.1,2098.6,12.06.2023,08:33:12.638,0.0,-87.962*1F
$PGSUTD,INCH,Rtcm3.1,2099.7,12.06.2023,08:33:13.659,0.0,-88.041*3E
$PGSUTD,INCH,Rtcm3.1,2101.0,12.06.2023,08:33:14.807,0.0,-88.193*35
$PGSUTD,INCH,Rtcm3.1,2101.9,12.06.2023,08:33:15.734,0.0,-88.166*38
$PGSUTD,INCH,Rtcm3.1,2102.8,12.06.2023,08:33:16.658,0.0,-88.142*34
$PGSUTD,INCH,Rtcm3.1,2103.9,12.06.2023,08:33:17.699,0.0,-88.201*3C
```

Time (UTC)	Hourly RINEX (VRS3Net records)	RTCM Reception Log (GNSS Surfer records)
2024-04-01 0:00	File created (OK)	Continuous reception (OK)
2024-04-01 1:00	File created (OK)	Data gap detected (3.2%)
2024-04-01 2:00	File missing	RTCM disconnected
2024-04-01 3:00	File created (OK)	Recovery – switched to backup
2024-04-01 4:00	File created (OK)	Continuous reception (OK)

fault detection and recovery algorithm. The continuity of user experience is also a factor that is taken into account during the process of switching systems. It has been established that correction data format, transmission cycle, and MountPoint information are synchronized between servers. Furthermore, it has been determined that user session information is shared, thereby enabling the client to continue using the service without reconnecting even when switching to a backup server in the event of a fault. Switch logs are reported to administrators in real time and subsequently included in automatic diagnostic reports. Whilst the prevailing system relied on manual recovery and a solitary server, the proposed structure automates the entire process of detection, switching, recovery and reporting. This ensures both real-time performance and stability. The scope of redundancy is subdivided by core components such as the correction data generator, transmitter, and authentication system. Accordingly, single points of failure can be eliminated through status replication and integrity verification functions. This is pivotal in ensuring the stability and quality of GNSS services. The subsequent section provides a detailed exposition on the conceptualization of a high-reliability correction data and redundancy structure for the dissemination of alerts to users.

3.3 Design of high-reliability correction data provision and redundancy structure

To deliver precise GNSS services, it is essential to ensure not only location accuracy but also the reliability and continuity of service. Despite the fact that the current RTCM-based transmission system provides correction data in real time, it does not quantify the reliability of the information, which complicates the ability to respond to risks in application areas.

Figures 3 and 4 provide a synopsis of the flow related to the reference station network, correction data generator, and transmitter, presenting an integrated structure that includes correction data quality diagnosis and reliability (P_L) calculation functions. Figure 4 illustrates the current Active-Standby redundancy system deployed at the NGII GNSS Central Station. This architecture is designed to ensure service continuity in the event of a failure, rather than load balancing, and includes automatic synchronization and failover between systems. The GNSS correction service infrastructure consists of separate subsystems—RTS1 for VRS RTK, RTS2 for FKP RTK, and an integrated GNSS service system—each physically isolated but switchable through a network interface. These systems are directly connected to GNSS reference stations and maintain operational continuity even if one subsystem fails.

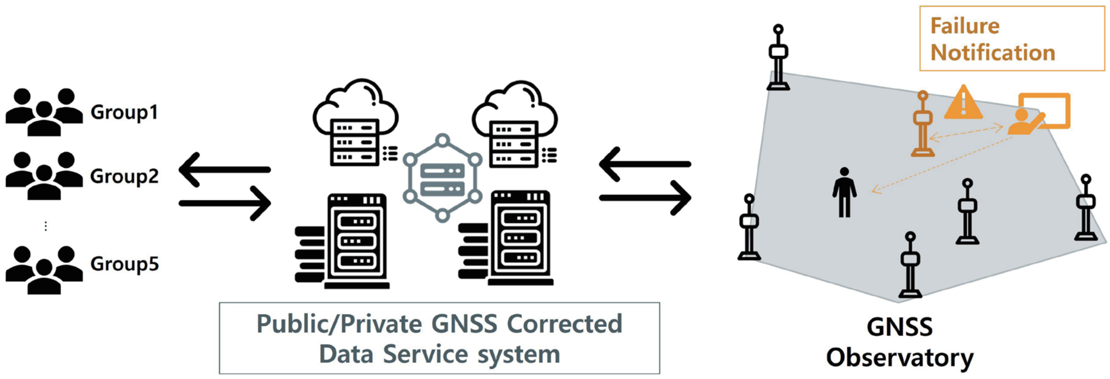


Fig. 3. (Color online) Conceptual diagram of improvement for NGII's GNSS correction data system.

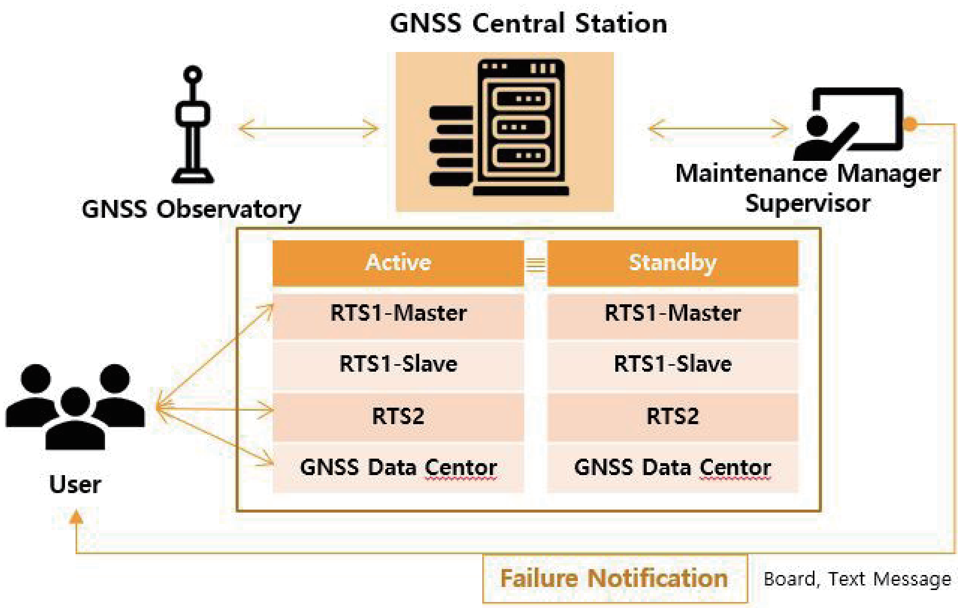


Fig. 4. (Color online) Current configuration of NGII’s GNSS correction data system.

Figure 3 proposes a multilayered redundancy framework that integrates physical and virtual cloud infrastructure to support stable and uninterrupted real-time GNSS services. To enhance reliability, it recommends redundant configurations for receivers, power supply, and communication systems, including dual network paths (e.g., wired/wireless or multi-carrier setups). Additionally, it suggests geographically distributing core systems and establishing dedicated teams to support increasing private-sector demands and reduce the risks of centralized operation.

In comparison with the legacy architecture, the proposed system is capable of supporting significantly more concurrent sessions without compromising the timeliness of correction data. The system incorporates a functionality that enables the obstruction of transmission or the dissemination of warnings in instances where stipulated quality standards are not fulfilled. Furthermore, the system processes transmission cycles and traffic in a discrete manner, utilizing various formats, including RTK, PPP, and SSR. Furthermore, the system under scrutiny here analyzes a plethora of fault cases, namely, those from GNSMART and VRS3Net systems, including, by way of illustration only, NTRIP errors, license recognition failures, and RTCM interruptions. The system then proposes a redundancy structure that applies an MCCS-based active-standby automatic recovery system.

The necessity of a real-time fault alert system is emphasized. In contrast to the conventional manual bulletin board notice method, a novel structure is hereby proposed. This structure incorporates automatic alerts and alternative data transmission in the event of reference station faults, communication disruptions or reception delays. As demonstrated in Fig. 1, the Incheon reference station exhibited a 2910-second RTCM reception delay, attributable to NTRIP Caster processing issues, despite the absence of network failure. This case demonstrates the critical necessity for a real-time quality diagnostic and automated fault response system. Moreover, in this study, we put forward four options for the decentralized operation of the GNSS central system.

- Option 1 aims to maintain the existing NGII system while additionally establishing a dedicated private system for decentralized operation. This approach facilitates the stable operation of both public and private services without necessitating alterations to the system structure or maintenance framework. Furthermore, it ensures the continuity of service with a standby system for private use in the event of a fault. Nevertheless, the preliminary investment costs (including the establishment of a dedicated team, the securing of space, and the construction of the system) are substantial.
- Option 2 is intended to achieve the logical separation and operation of the existing system for private and public use, as well as private use only. Notwithstanding the fact that this option is associated with lower initial construction costs and facilitates systematic operation, it may prove challenging to immediately transition to the public system in the event of a fault in the private system.
- Option 3 aims to add a standby system to the current system for the purpose of decentralized support of private services. This option would achieve a similar level of stability to that offered by Option 1. However, it would require the establishment of a monitoring and automatic switching system between systems. Furthermore, it would entail significant space and cost burdens for decentralized operation.

- Option 4 is predicated on the principle of decentralization, which is to be achieved by the separation of the active and standby systems for public and private use. This option is distinguished by its economic efficiency, enabling the prompt remediation of power or communication failures while leveraging the existing system infrastructure. However, there may be a paucity of specialized personnel and a dedicated management system to respond to increasing private demands.

Following a comprehensive comparison and analysis of the four options, it was determined that Options 1 and 4 were the most cost-effective (see Table 10). Option 1, in particular, facilitates the establishment of redundancy in the event of a problem in the private system, whilst also enabling the efficient creation of a dedicated system to support new private sector businesses. The GNSS Integration Data Center is the foundation of this method, necessitating collaboration among five institutions: the NGII, the National Maritime Positioning, Navigation, and Timing Office, the Space Weather Center, the Meteorological Satellite Center, and the Korea Astronomy and Space Science Institute. Private services may be initiated from NGII reference stations and gradually expanded; it is imperative to construct an ecosystem that encourages private company participation and supports specialized services through a "public–private cooperation system for discovering and supporting new location-based businesses".

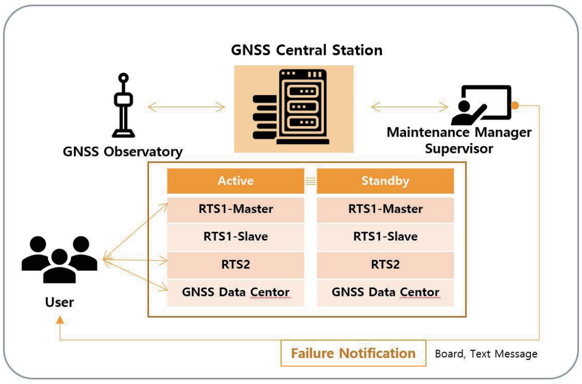
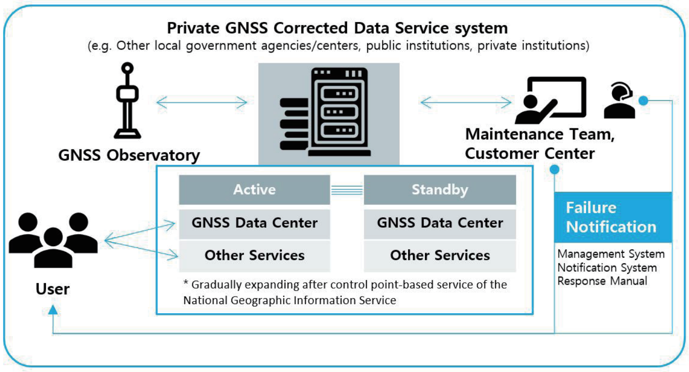
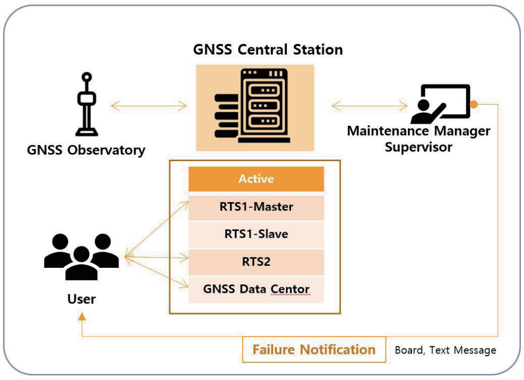
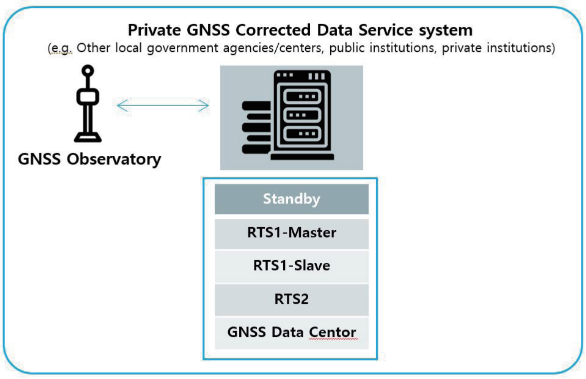
4. Strategy for Addressing Future Demand and Securing an Institutional Foundation for High-precision GNSS Services

In this section, we provide a synopsis of the anticipated outcomes and future relevance of the GNSS system advancement strategies previously outlined, when implemented in practical operations. In particular, it details the specific ripple effects across various aspects, including system performance improvements, enhanced user experience, and applicability by industry, explaining the feasibility of the proposal.

4.1 Advancement of real-time correction data systems to meet the autonomous driving and UAM demands

The future direction of high-precision GNSS correction data systems should reflect the demand for next-generation transport modes, such as autonomous vehicles and UAM.[43] According to the Korea Institute of Science & Technology Evaluation and Planning,[44] it is anticipated that the number of autonomous vehicles will increase from 600000 in 2025 to 21 million in 2035. These vehicles are designed to facilitate cooperative autonomous driving, underpinned by cooperative intelligent transport systems (C-ITS) at levels LV3–LV4. This objective necessitates the integration of advanced core technologies, including high-definition maps, precision global positioning systems, long-term evolution (LTE)/5G, and wireless access in vehicular environments/dedicated short-range communications. Consequently, GNSS correction data from NGII must undergo technical review for integration with C-ITS, and interdepartmental cooperation is essential.

Table 10
(Color online) Proposal for design improvement of NGII's GNSS correction data system.

<table>
<tr><th>Category</th><th>Public + private system</th><th>Private system</th></tr>
<tr><td rowspan="2">Option1</td><td>Public+Private</td><td>
</td></tr>
<tr><td>Private</td><td>
</td></tr>
<tr><td rowspan="2">Option 4</td><td>Public+Private</td><td>
</td></tr>
<tr><td>Private</td><td>
</td></tr>
</table>

It is the considered opinion of experts in the field of autonomous driving that stable autonomous driving is contingent upon horizontal precision within the range of 20–30 cm. The survey results from this project indicate that autonomous vehicles utilize various sensors, with GNSS serving as a complementary tool. Concurrently, agricultural machinery such as rice transplanters, tractors, and combines have recently adopted auto-steering functions. In Korea, machines with this function are required to meet certain certification standards to be sold (Fig. 5).

Note that the deviation from the target path should not exceed 70 mm. To comply with this requirement, the majority of manufacturers incorporate high-precision GNSS devices into their machinery.

Moreover, the Ministry of Land, Infrastructure and Transport stipulates the utilization of GNSS-based navigation systems in its K-UAM Operational Concept,[45] employing a hybrid structure that incorporates SBAS during flight paths and differential GNSS during landing approaches. UAM aircraft operate at altitudes ranging from 300 to 600 m, where terrestrial communication systems such as LTE/5G experience limited coverage. This necessitates the parallel utilization of alternative transmission media, including satellite communications and broadcast networks, to ensure seamless connectivity. As evidenced by the cases of autonomous vehicles, unmanned aerial vehicles, and agricultural machinery, there is a high demand for high-precision location information. This has led to active attempts to overcome the limitations of accuracy and availability through the fusion of other sensors centered on GNSS.

Despite the necessity for corrected data to be delivered in real time, signal loss frequently occurs owing to transmission media interruptions or environmental disturbances. Consequently, technologies such as PPP-RTK, which facilitate one-way communication, are gaining popularity in the mass market. These technologies offer the advantage of fast convergence times, high accuracy, and small message sizes, and are already applied in commercial systems such as Trimble's real-time extended, Hexagon's Terrastar-X, and U-blox's PointPerfect.

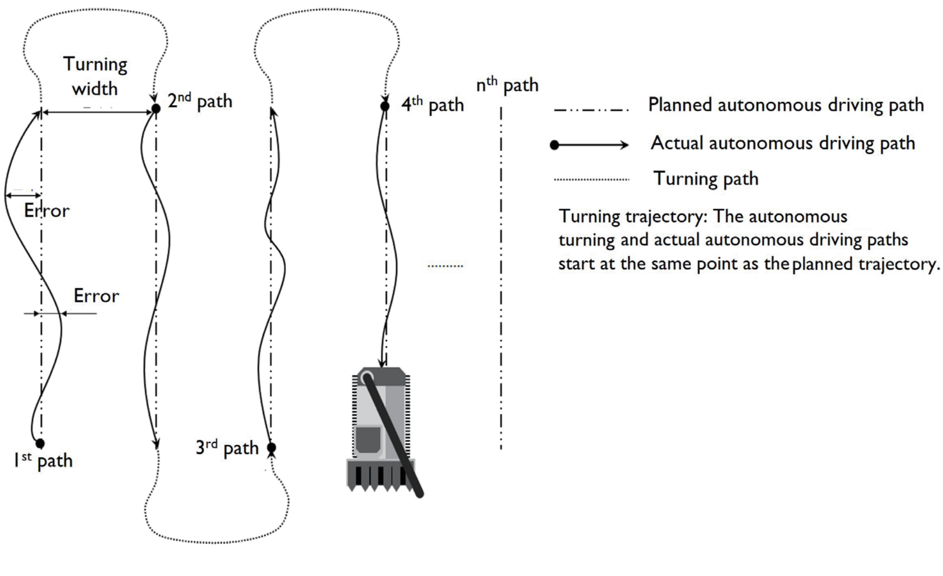


Fig. 5. Agricultural machinery testing standards.

UAM involves numerous aircraft operating in far more complex airspace than passenger aircraft, making it difficult to manage with traditional human-based air-traffic management (ATM) systems. Consequently, countries worldwide are at the forefront of developing unmanned aerial system traffic management systems for ultralight drones and integrating them into Urban ATM (UATM) frameworks. The Ministry of Land, Infrastructure and Transport of the Republic of Korea is developing an integrated traffic management system for UATM and ATM. The stable provision of GNSS correction data is a key component of this system.

From a market perspective, the value of GNSS-based services is predicted to increase from €199 billion in 2021 to €492 billion in 2031. The market for GNSS correction data is forecast to expand at a compound annual growth rate (CAGR) of 7%, from €25 billion in 2021 to €51 billion in 2031. This finding suggests that the primary catalyst for market expansion is the emergence and proliferation of precision positioning-based novel industries.

Conversely, the advancement strategy for the correction data system to meet this future demand can be realized on the basis of the technical design presented in Sect. 3. In particular, the high-reliability correction, data quality diagnosis function, automatic transmission block and fault response system, and active-standby redundancy structure proposed in Sect. 3.1 ensure the continuity and reliability needed for autonomous driving and UAM environments. Furthermore, the prediction-based access analysis and server switching algorithm (Sect. 3.2) enables uninterrupted services even in complex UATM operational environments and can function as a core element of GNSS-based transport infrastructure.

4.2 Advancement strategy for high-precision GNSS correction data-based business models

Private business models centered on high-precision GNSS services are classified into three layers: platforms, providers, and users.

As illustrated in Fig. 6, this industrial structure is represented in a manner that clearly demonstrates the interconnectivity between the technological flow of each layer and the major market players. Within the domain of the platform layer, telecommunications entities (SK, KT, and LGU+) and broadcasting organizations (MBC, Korean Broadcasting System, and Seoul Broadcasting System) are responsible for the collection and processing of reference station correction data. This data is subsequently disseminated in various forms. Note that prominent global chipset companies, such as U-blox, have recently become active participants in this structure. The provider layer is further subdivided into modules, devices, and solutions. Within the module field, U-blox's F9P product serves as a representative example, with companies such as STMicroelectronics, Quectel, and Unicorecomm also engaged in the mass production of compact, high-precision receiver modules, which are subsequently supplied to the market at a competitive price point. Within the high-performance category, there is a high demand for Septentrio's Mosaic. The reliance of Korean companies on imported modules poses a significant challenge to future technological collaboration with specialized domestic companies. In the field of device technology, MBC, Ascen Korea, and PP-Solution are at the forefront of innovation, specializing in the development and distribution of industry-specific receivers. In the

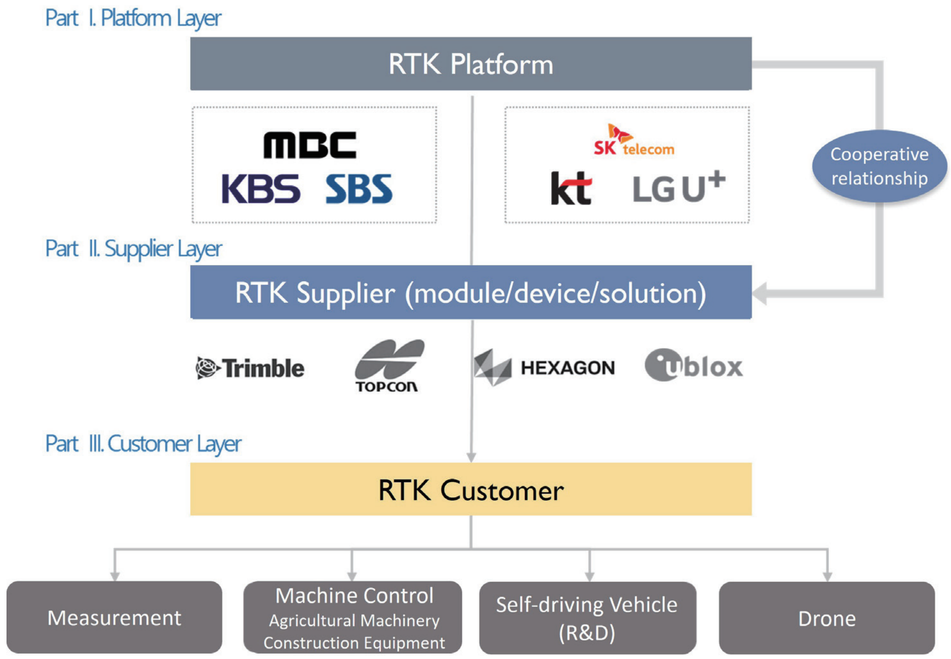


Fig. 6. (Color online) Industrial structure of high-precision GNSS services.

construction and agricultural sectors, there is a discernible and sustained increase in demand for original equipment manufacturer (OEM) board products that incorporate communication modems and GNSS receivers. The service sector is undergoing rapid expansion, with a focus on sensor fusion-based, high-precision positioning software. Companies such as Hexagon, Swift Navigation, and Point One Navigation are developing engines for vehicles and drones. In the user layer, autonomous vehicles, agricultural machinery, and drones are identified as representative mass markets. In the domain of autonomous driving, attaining a lane-level accuracy of less than 50 cm is imperative. The majority of global automotive manufacturers have adopted PPP-RTK-based correction data subscription models. In the domain of agricultural machinery, the prevailing standard is communication reception via NTRIP, largely due to the predominance of older users, for whom automated integrated receivers are the preferred option. The demand for drones is such that there is a requirement for both real-time RTK-based correction receivers and OEM boards. The industrial structure of the United Kingdom is substantiated by empirical evidence from other countries. In the United States (US), Swift Navigation offers Skylark services for US dollars (USD) 29/month (PPP-RTK) and USD 69/month (RTK), with its Starling engine meeting automotive safety integrity level-B safety standards. Point One Navigation offers Polaris services for USD 50/month, utilizing RTCM correction data from 1440 reference stations. Switzerland's U-blox provides the PointPerfect service via the internet and satellite networks, enhancing cost efficiency by employing MQ Telemetry Transport/Secure Position Augmentation for Real Time Navigation-based data compression technology. In Japan, companies such as SoftBank (ichimill), Nippon Telegraph and Telephone, Docomo, and KDDI offer correction data services based on OSR or VRS-RTK at a rate of 2000–3300 Japanese Yen per month. These companies have established integrated business models that include supplying correction data receivers. These international case studies can function as practical benchmarking resources for domestic private businesses, and the advanced system based on the GNSS Integration Data Center and redundancy structure proposed in Sect. 3 can function as a core infrastructure for private models.

4.3 Institutional foundation improvement measures for the establishment of GNSS information systems

At present, with regard to the public operation of GNSS correction data services, the NGII has legally delegated the installation and management of satellite reference stations. However, there is insufficient legal basis for overall operations such as the collection, processing, and transmission of correction data. In contrast, the Ministry of the Interior and Safety and the Ministry of Oceans and Fisheries operate the Address Innovation Platform and Marine Correction System, respectively, through LX and the National Maritime Positioning, Navigation, and Timing Office, based on clear legal grounds such as the “Road Name Address Act” and the “Aids to Navigation Act”.[46]

In accordance with Article 7 of the “Act on the Establishment and Management of Spatial Data” and Article 8 of its Enforcement Decree, satellite reference points are defined as a type of national control point. Furthermore, as outlined in Article 103, the Minister of Land, Infrastructure and Transport is permitted to delegate the authority for the installation and management of satellite reference points to the Director of NGII. However, it should note that the delegation of these responsibilities is restricted to “markers”. Consequently, there is an absence of a legal foundation for tasks such as GNSS data collection, processing, utilization, and correction data transmission.

The “Regulations on the Management of Satellite Reference Points” and “Regulations on the Provision and Management of Spatial Information by the National Geographic Information Institute” aim to supplement this, but owing to the absence of higher-level laws, they have limited legal effectiveness. In accordance with the aforementioned points, it is imperative to establish a provision within the “Act on the Establishment and Management of Spatial Data” to specify the installation and operation of a (tentatively named) “GNSS Information System”. This would provide a legal basis for the correction data operation system based on satellite reference point data.

In the future, Article 103 of the Enforcement Decree should be amended to delegate system operation to the Director of NGII, and maintenance provisions should be revised following the legislative precedent of Article 22 of the Enforcement Decree of the “Aids to Navigation Act”. However, the re-delegation of these responsibilities is not permitted under the current legal framework. Consequently, private sector involvement must be pursued through the provision of outsourced services rather than re-delegation. As illustrated in Table 10 of Appendix, the legal amendments under consideration address current delegation structures and institutional deficiencies.

To support this, it is essential that technical infrastructures such as the active-standby redundancy structure, fault detection, and the automatic recovery system proposed in Sect. 3 are incorporated into laws and enforcement decrees to ensure sustainable operation. In particular, with regard to the expansion of private services, the establishment of subsequent legislation such as the "establishment of public-private cooperation systems" and a "certification system for private correction data providers" should be given due consideration.

5. Conclusions

In this study, we presented a comprehensive advancement strategy for the GNSS central system operated by the NGII of Korea. The proposed strategy integrates four core pillars: technical system enhancement, fault-resilient service architecture, user-centered operation design, and institutional reform. Through this multidimensional approach, we aimed to transform the existing single-structured, public-sector-focused GNSS correction data service into a robust, scalable platform that can support real-time applications in autonomous driving, urban air mobility (UAM), and other industrial domains. The methodology centers on predictive analytics, differentiated user service, and high-reliability correction, each backed by empirical data analysis and fault-case validation.

In response to increasing demands for uninterrupted real-time service, we developed an automatic failover and redundancy structure for GNSS correction data provision. In Sect. 4.3, we highlighted the role of log-based anomaly detection and real-time switching in maintaining continuity during system faults. Figures 1 and 2 illustrate critical RTCM reception delays—most notably, a 2910 s delay observed at the Incheon reference station—and how such cases can be proactively managed using the proposed infrastructure. The corresponding completeness and acquisition performance are quantified in Table 7, underscoring the necessity for automated diagnostic and recovery systems. These elements together form a high-availability GNSS architecture capable of maintaining data quality even under degraded conditions.

In Sects. 4.1 and 4.2, we presented user-group differentiated correction strategies and high-precision service paths aligned with sector-specific demands. The proposed architecture accommodates centimeter-level positioning for safety-critical applications such as autonomous vehicles, while offering scalable correction formats for other sectors. This is further supported by authentication-linked MountPoint separation, session-based resource prioritization, and transmission cycle customization. In Figs. 3 and 4, we compared the legacy and improved system configurations, emphasizing the increased concurrent session handling capacity and multi-format data output. In particular, the revised system supports real-time service adaptation and proactive stability control based on usage context.

Scenario-based demonstrations in Sect. 4.4 further validated the practical applicability of the proposed structure. As depicted in Figs. 5 and 6, the system is compatible with GNSS-integrated machinery in agriculture, air route control in UAM, and smart-city-based traffic systems. These examples demonstrate that the GNSS infrastructure can transcend traditional geodesy functions and evolve into a key enabler of intelligent mobility, logistics, and urban planning. The integrated control capacity also supports data continuity through communication hybridization, making the system resilient to connectivity gaps and signal obstructions in urban and aerial environments.

Beyond technical advancement, we emphasized the urgency of institutional reform to support sustainable GNSS operations. Current legal provisions under the Spatial Data Act largely focus on reference station infrastructure, without sufficiently addressing data processing, quality control, or private-sector participation. Section 4.5 and Appendix Table provide a structured proposal for legislative amendments, including a new legal definition of GNSS information systems, the delegation of operational authority, and the establishment of a public-private cooperation framework. These institutional enhancements are essential for legalizing correction data certification systems, supporting SLA-based service models, and fostering innovation through regulated private participation.

Despite the comprehensive scope of the proposed strategy, this study has several limitations. First, the architecture and service models were primarily validated through conceptual design and case-based analysis, without full-scale deployment or system-level simulation. Although the log-based fault scenarios and user segmentation frameworks provide strong theoretical support, their performance under operational-scale loads and multi-user concurrency remains to be tested. Second, the study assumes interoperability with existing GNSS hardware and network infrastructure; however, integration challenges—particularly regarding legacy equipment and nonstandard data protocols—may limit immediate scalability. Third, institutional reform proposals are presented at a framework level, lacking real-world stakeholder feedback or legal feasibility assessments. These limitations underscore the need for future studies to pursue empirical validation, pilot implementation, and cross-sector consultation to ensure successful adoption and policy integration.

In summary, the proposed system redefines the GNSS central station as a dynamic, policy-integrated service infrastructure. It combines user-customized correction paths, real-time integrity provision, and fault-resilient design into a cohesive next-generation platform. While we focused on design logic and feasibility analysis, in future research, we should conduct simulation-based validation, cost-benefit evaluations, and scenario-specific implementation studies. Ultimately, the convergence of technological refinement and institutional support can enable Korea's GNSS infrastructure to become a global benchmark in precision positioning services.

Acknowledgments

This study was supported by the Dong-A University research fund.

References

1 P. J. G. Teunissen and O. Montenbruck: Springer Handbook of Global Navigation Satellite Systems. Springer (2017). https://doi.org/10.1007/978-3-319-42928-1
2 R. Dach, U. Hugentobler, P. Fridez, and M. Meindl: Bernese GPS Software Version 5.0. Astronomical Institute, University of Bern (2007).
3 G. Wübbena, M. Schmitz, and A. Bagge: Real-time GNSS Data Transmission Standard RTCM 3.0. IGS Workshop (2006).
4 National Geographic Information Institute: GNSS Central System Automatic Recovery System Design Report (2023).
5 National Geographic Information Institute: Legal and Institutional Improvement Plan for GNSS Services (2023).

6 S. H. Yun: J. Inst. Internet Broadcasting Commun. **17** (2017) 145.
7 J. Kim and Y. Ahn: Struct. Health Monit. **18** (2019) 1234.
8 D. Bartoněk and I. Opatřilová: J. Adv. Inf. Technol. **5** (2014) 15. https://doi.org/10.4304/jait.5.1.15-20
9 L. H. Estey and C. M. Meertens: GPS Solut. **3** (1999) 42. https://doi.org/10.1007/PL00012778
10 P. Vaclavovic and J. Dousa: IAG Proc. IAG 150 Years, Int. Assoc. of Geodesy Symposia (2016). https://doi.org/10.1007/1345_2015_97
11 S. B. Im, S. Hurlebaus, and Y. J. Kang: J. Struct. Eng. **139** (2011) 1653.
12 J. R. Kim: Research Report, Korea Aerospace University (2022).
13 J. G. Park and Y. K. Kwak: J. Navig. **74** (2021) 150.
14 J. Seo and C. Hwang: Spat. Inf. Res. **24** (2016) 291.
15 N. Boguspayev, D. Akhmedov, A. Raskaliyev, A. Kim, and A. Sukhenko: Appl. Sci. **13** (2023) 4819. https://doi.org/10.3390/app13084819
16 R. Ji, X. Jiang, X. Chen, H. Zhu, M. Ge, and F. Neitzel: Geo-Spat. Inf. Sci. **26** (2023) 1. https://doi.org/10.1080/10095020.2023.2189330
17 U. Weinbach, M. Brandl, X. Chen, H. Landau, F. Pastor, N. Reussner, and C. Rodriguez-Solano: ION GNSS+ Proc. 31st Int. Tech. Meet., Inst. Navig. (2018) 1902. https://doi.org/10.33012/2018.15971
18 W. Jiang, X. Zou, and W. M. Tang: Chin. J. Geophys. **55** (2012) 284.
19 X. Zou, M. Ge, W. Tang, C. Shi, and J. Liu: GPS Solut. **17** (2013) 283.
20 J. F. Zumberge, M. B. Heflin, D. C. Jefferson, M. M. Watkins, and F. H. Webb: JGR: Solid Earth **102** (1997) 5005. https://doi.org/10.1029/96JB03860
21 C. Rizos: Principles and Practice of GPS Surveying. School of Geomatic Engineering, University of New South Wales (1996).
22 Y. Yang and J. Xu: Geodesy Geodyn. **7** (2016) 117. https://doi.org/10.1016/j.geog.2016.04.004
23 C. Forster, L. Carlone, F. Dellaert, and D. Scaramuzza: IEEE Trans. Robotics **33** (2016) 1.
24 D. Wisth, M. Camurri, and M. Fallon: IEEE Trans. Robotics **39** (2023) 309.
25 J. N. Wong, D. J. Yoon, A. P. Schoellig, and T. D. Barfoot: IEEE Robotics Autom. Lett. **5** (2020) 5291.
26 X. Xu, Z. Nie, Z. Wang, and Y. Zhang: Sensors **20** (2020) 5756. https://doi.org/10.3390/s20205756
27 J. Wang and D. Huang: Sci. Rep. **14** (2024) 6615. https://doi.org/10.1038/s41598-024-57063-5
28 N. Shen, L. Chen, J. Liu, L. Wang, T. Tao, D. Wu, and R. Chen: Sens. **11** (2019) 1001. https://doi.org/10.3390/rs11091001
29 X. Zuo, X. Jiang, P. Li, J. Wang, M. Ge, and H. Schuh: Satell. Navig. **2** (2021) 28. https://doi.org/10.1186/s43020-021-00060-0
30 J. Xin, D. Wang, and K. Li: Remote Sens. **16** (2023) 4574. https://doi.org/10.3390/rs16234574
31 Y. Xia, S. Pan, Z. Meng, W. Gao, F. Ye, Q. Zhao, and X. Zhao: Remote Sens. **12** (2020) 971. https://doi.org/10.3390/rs12060971
32 S. B. Lee and S. C. Eo: J. Korean Soc. Surv. Geodesy Photogramm. Cartogr. **32** (2014) 213.
33 Y.-J. Lee, K.-H. Jung, and M.-J. Lee: J. Korean Soc. Surv. Geodesy Photogramm. Cartogr. **30** (2012) 199.
34 European GNSS Agency: EGNOS Safety of Life (SoL) Service Definition Document (2020).
35 Japan Cabinet Office: MADOCA-based L6 Service Design and Application (2021).
36 R. Loth et al.: Eng. Proc. **54** (2023) 40. https://doi.org/10.3390/engproc54040040
37 H. Gao, X. Wang, Y. Yao, L. Zhang, Y. Zhao, Z. Li, and S. Fang: Adv. Sp. Res. **75** (2025) 4395.
38 F. Dellaert and M. Kaess: Auton. Robots **43** (2019) 415.
39 S. H. Yun: J. Korea Contents Assoc. **16** (2016) 362.
40 D. Odijk, P. J. Teunissen, and B. Zhang: J. Surv. Eng. **138** (2012) 193.
41 T. Barfoot, C. H. Tong, and S. Sarkka: Robotics: Sci. Syst. (2014).
42 D. J. Yoon, K. Burnett, J. Laconte, Y. Chen, H. Vhavle, and S. Kammel: IEEE/RSJ IROS (2023) 5304.
43 J. N. Wong, D. J. Yoon, A. P. Schoellig, and T. D. Barfoot: IEEE RA-L **5** (2020) 5291.
44 KISTEP: Recent Trends in the Autonomous Vehicle Industry, https://www.kistep.re.kr/gpsIssueView.es?mid=a30101000000&list_no=48676&nPage=8 (Accessed February 22, 2021).
45 Ministry of Land, Infrastructure and Transport: Korean Urban Air Mobility (K-UAM) Operational Concept 1.0 (2022).
46 National Law Information Center: https://www.law.go.kr/LSW/main.html

About the Authors

Jae Kang Lee received his Ph.D. degree from University of Nottingham, UK, in 2015. From 2019 to 2022, he was a senior researcher at the Korea Institute of Civil Engineering and Building Technology (KICT). He is currently an associate professor at Dong-A University. His research interests range from safety policy in civil engineering to software programming in relation to GNSS positioning, UAV photogrammetry, and the application of the big data platform to civil engineering. (jaekanglee@dau.ac.kr)

Woo Saeng Kim received his M.S. degree in Civil and Environmental Engineering (Geotechnical Engineering) from Pusan National University in 2006 and his Ph.D. in Civil Engineering (Geotechnical Engineering) from the same university in 2010. He is currently an associate professor and deputy director of the Construction System Engineering Track at Dong-A University, where he has been working since 2021. His research interests include geotechnical engineering, smart infrastructure safety management systems, and technology commercialization in civil engineering. Dr. Kim has also served on various government and municipal advisory boards, including those of the Ministry of Oceans and Fisheries and the Korea Research Foundation. He has contributed to multiple national R&D program evaluations and currently serves as a member of evaluation and safety advisory committees related to land and maritime civil engineering.

Appendix

Table
Article 7 of the Act on the Establishment and Management of Spatial Data, and Articles 8 and 103 of the Enforcement Decree of the Act on the Establishment and Management of Spatial Data.

Act on the Establishment and Management of Spatial Data
Article 7 (Survey Control Points) (1) Survey control points shall be classified according to the following subparagraphs: 1. National Control Points: Survey control points established by the Minister of Land, Infrastructure and Transport at major points across the entire national territory as the basis for surveying to ensure the accuracy and enhance the efficiency of surveying. 2. Public Control Points: Survey control points separately established by a public survey implementer under Article 17(2) based on national control points to conduct public surveys accurately and efficiently. 3. Cadastral Control Points: Survey control points separately established by the Special Metropolitan City Mayor, Metropolitan City Mayor, Special Self-governing City Mayor, Do Governor, or Special Self-governing Province Governor (hereinafter referred to as 'Mayor/Do Governor') or the cadastral competent authority based on national control points, to conduct cadastral surveys accurately and efficiently. (2) Detailed matters concerning the classification of survey control points under paragraph (1) shall be prescribed by Presidential Decree. Article 105 (Delegation, Entrustment, etc. of Authority) (1) Part of the authority of the Minister of Land, Infrastructure and Transport under this Act may be delegated as prescribed by a Presidential Decree, to the head of an agency under his/her jurisdiction, a Mayor/Do Governor, or the cadastral competent authority. (2) Among the authorities of the Minister of Land, Infrastructure and Transport, a Mayor/Do Governor, and the cadastral competent authority under this Act, the authority concerning the duties specified in the following subparagraphs may be entrusted, as prescribed by a Presidential Decree, to the Korea Land and Geospatial Informatix Corporation, the Spatial Information Industry Association under Article 24 of the Spatial Information Industry Promotion Act, or a nonprofit corporation established with the permission of the Minister of Land, Infrastructure and Transport under Article 32 of the Civil Act and equipped with survey-related personnel and equipment prescribed by a Presidential Decree.

1. Deleted
Subparagraph 1-2. Establishment and operation of the integrated management system for surveying business information under Article 10-2.
Subparagraph 1-3. Disclosure of business performance capabilities for surveying service projects by surveyors under Article 10-3, receipt of performance records, etc., and verification of details.
2. Examination regarding the publication of maps, etc., under Article 15(4) Subparagraph 2-2. Examination regarding the publication of precise road maps under Article 15-2.
3. Examination of public survey results under Article 18(3).
4. Deleted.
5. Deleted.
6. Deleted.
7. Deleted.
8. Deleted.
9. Receipt of reports from survey technicians under Article 40, maintenance and management of records, issuance of survey technician career certificates, request for submission of related data to verify reported details and receipt of submitted data, verification of survey technicians' place of work and careers, etc.
10. Deleted.
11. Education and training of cadastral technicians under Article 98.
12. Management of survey control points (limited to cadastral control points) under Article 8(1).
13. Receipt of reports on the status survey of survey control point markers (limited to cadastral control point markers) under Article 8(5).
(3) Executives and employees of the Korea Land and Geospatial Informatix Corporation, Spatial Information Industry Association under Article 24 of the Spatial Information Industry Promotion Act, or a nonprofit corporation engaged in duties entrusted by the Minister of Land, Infrastructure and Transport, a Mayor/Do Governor, or the cadastral competent authority pursuant to paragraph (2) shall be deemed public officials when applying Articles 127 and 129 through 132 of the Criminal Act.

Enforcement Decree of the Act on the Establishment and Management of Spatial Data

Article 8 (Classification of Survey Control Points) (1) Survey control points under Article 7(1) of the Act are classified according to the following
subparagraphs:
1. National Control Points
a. Space Geodetic Control Points: Control points established by linking with Very Long Baseline Interferometry systems worldwide to establish the national geodetic reference system.
b. Satellite Control Points: Control points established based on the Republic of Korea Geodetic Datum Origin to be used as standards for measuring geographic latitude and longitude, rectangular coordinates, and geocentric Cartesian coordinates.
c. Benchmark Points (Levelling Points): Control points established based on the Republic of Korea Vertical Datum Origin to be used as standards for height measurements.
d. Gravity Control Points: Control points established to be used as standards for gravity measurements.
e. Unified Control Points: Control points established based on satellite control points, benchmark points, and gravity control points to be used as standards for measuring geographic latitude and longitude, rectangular coordinates, geocentric Cartesian coordinates, height, and gravity.
f. Triangulation Points: Control points established based on satellite control points and unified control points to be used as standards for measuring geographic latitude and longitude, rectangular coordinates, and geocentric Cartesian coordinates.
g. Geomagnetic Points: Control points established to be used as standards for geomagnetic measurement.
h. Deleted.
i. Deleted
2. Public Control Points
a. Public Triangulation Points: Control points established based on national control points to be used as standards for horizontal positioning in public surveys.
b. Public Benchmark Points (Levelling Points): Control points established based on national control points to be used as standards for height in public surveys.

3. Cadastral Control Points

a. Cadastral Triangulation Points: Control points established based on national control points to be used as standards for horizontal position surveying in cadastral surveys.

c. Cadastral Traverse Points: Control points established based on national control points, cadastral triangulation points, cadastral auxiliary triangulation points, and other cadastral traverse points to be used as standards for horizontal position surveying for land parcels in cadastral surveys.

(2) Each control point under paragraph (1) may be classified by grade as necessary.

Article 103 (Delegation of Authority) (1) The Minister of Land, Infrastructure and Transport delegates the authority specified in the following subparagraphs to the Director General of the National Geographic Information Institute pursuant to Article 105(1) of the Act:

1. Public notice of surveys under Article 4 of the Act.
2. Establishment of the Basic Plan for Surveying under Article 5(1) of the Act and establishment and evaluation of annual implementation plans under paragraph (2) of the same Article.
3. Public notice of the origin under the proviso of Article 6(1)2 of the Act.
4. Installation and management of national control point markers under Article 8(1) of the Act.
5. Receipt of notifications regarding the types and installation locations of national control point markers under Article 8(2) of the Act.
6. Receipt of reports on the status survey of survey control point markers under Article 8(5) of the Act.
7. Status survey of survey control point markers under Article 8(6) of the Act.
8. Provision of data related to maps, etc., under Article 10(2) of the Act.
9. Receipt of notifications on changes in topography and features under Article 11(2) of the Act, receipt of notifications on the commencement of construction work and changes in topography and features under paragraph (3) of the same Article, and request for submission of basic survey data under paragraph (4) of the same Article.
10. Conduct and notification of basic surveys under Article 12 of the Act.
11. Public notice of basic survey results under Article 13(1) of the Act.
12. Request for accuracy verification of basic survey results under Article 13(2) of the Act.
13. Correction of basic survey results under Article 13(3) of the Act.
14. Storage of basic survey results and basic survey records under Article 14(1) of the Act.
15. Receipt and issuance of applications for reproduction or copies of basic survey results or basic survey records under Article 14(2) of the Act.
16. Publication, sale, and distribution of maps, etc., under Article 15(1) of the Act.
17. Designation of base maps under Article 15(3) of the Act.
18. Permission for taking basic survey results out of the country under Article 16(1) of the Act.
19. Receipt of public survey work plans under Article 17(2) of the Act.
20. Request for submission of long-term plans or annual plans under Article 17(3) of the Act.
21. Review of the feasibility of plans and notification of the results under Article 17(4) of the Act.
22. Request for submission of copies of public survey records under Article 18(2) of the Act.
23. Public notice of public survey results under Article 18(4) of the Act.
24. Storage and perusal of public survey results or copies of public survey records under Article 19(1) of the Act.
25. Receipt and issuance of applications for reproduction or copies of public survey results or public survey records under Article 19(2) of the Act.
26. Permission for taking public survey results out of the country under Article 21(1) of the Act.
27. Request for submission of copies of general survey results and general survey records under Article 22(2) of the Act. 27-2. Establishment of work standards for general surveys under Article 22(3) of the Act.
28. Suspension of duties of survey technicians (excluding cadastral technicians) under Article 42(1) of the Act.
29. Registration of surveying business under Article 44(2) of the Act.
30. Issuance of surveying business registration certificates and surveying business registration handbooks under Article 44(3) of the Act.
31. Acceptance of reports on changes in registered matters under Article 44(4) of the Act.
32. Acceptance of reports on succession to the status of a surveyor under Article 46(1) of the Act.
33. Acceptance of reports on temporary closure, permanent closure, etc., of surveying business under Article 48 of the Act.

34. Revocation of registration and suspension of business of surveying business under Article 52(1) of the Act and public announcement of the fact of revocation of registration and suspension of business under paragraph (3) of the same Article.
35. Calculation of standards for the cost of basic surveys and public surveys under Article 55(2) of the Act and consultation with the Minister of Economy and Finance.
36. Public notice of geographical names under Article 91(2) of the Act.
37. Conduct of performance inspections under Article 92(1) of the Act.

Subparagraph 37-2. Fact-finding inspection and corrective orders regarding the performance inspection of surveying instruments by the Korea Land and Geospatial Informatix Corporation under Article 92(5) of the Act.

38. Receipt of notification of the fact of issuance of a performance inspection agent registration certificate under Article 93(2) of the Act.
39. Receipt of notification of the fact of cancellation of registration of a performance inspection agent under Article 96(2) of the Act.
40. Promotion of policies for the development of the surveying system and promotion of cooperation activities with international organizations and between nations under Article 97 of the Act.
41. Education and training for persons engaged in surveying work under Article 98(1) of the Act.

Subparagraph 41-2. Education for performance inspection agents and their employees under Article 98(2) of the Act.

42. Receipt of reports from and investigation of surveyors (excluding cadastral surveyors) under Article 99 of the Act.
43. Hearing regarding the cancellation of registration of surveyors (excluding cadastral surveyors) under Article 100 of the Act.
44. Expropriation or use of land, buildings, trees, and other structures for conducting basic surveys under Article 103(1) of the Act.
45. Performance of surveying work entrusted under Article 104 of the Act. (Note: Based on literal text; context might imply Article 105 of the Act or Article 104 of the Enforcement Decree).
46. Imposition and collection of administrative fines under Article 111(1) (excluding subparagraphs 14 and 15) of the Act.
47. Designation and public notice of public surveys under Article 3.
48. Designation and public notice of digital thematic maps under Article 4 and Attached Table 1, subparagraph 22.
49. Designation and public notice of special exception areas for the origin under Article 6(4).
50. Conduct of field investigations or request for reinvestigation under Article 11(3).
51. Receipt of applications for, designation of, and public announcement regarding the designation of basic survey result verification agencies under Article 14.
52. Public notice of facilities under Article 16(5).

Subparagraph 52-2. Composition and operation of the consultative body under Article 16-2.

53. Joint production of topographic maps with public survey implementers under Article 17(1)1.
54. Receipt of notifications regarding the scale, selling price, etc., of maps under Article 17(3).
55. Public announcement of surveying business registration under Article 35(6).
56. Reissuance of surveying business registration certificates or surveying business registration handbooks under Article 38.
57. Public notice of the standards for the cost of surveys under Article 48(3).
58. Guidance and supervision of survey result examination entrusted agencies designated under Article 104(1).
59. Receipt of applications for, designation of, and public announcement regarding the designation of survey result examination entrusted agencies under paragraphs (1) through (4) of Article 104.
60. Receipt of examination result reports under Article 104(6) and provision of data under paragraph (7) of the same Article.

(2) The Minister of Land, Infrastructure and Transport delegates the authority for fact-finding inspection and corrective orders regarding the performance inspection of surveying instruments by performance inspection agents under Article 92(5) of the Act to Mayors/Do Governors pursuant to Article 105(1) of the Act.