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Architecture Design for Maritime Centimeter-Level GNSS Augmentation Service and Initial Experimental Results on Testbed Network

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ABSTRACT

In this paper, we overview the system development status of the national maritime precise point positioning–real-time kinematic (PPP-RTK) service in Korea, also known as the Precise POsitioning and INTegrity monitoring (POINT) system. The development of the POINT service began in 2020, and the open service is scheduled to start in 2025. The architecture of the POINT system is composed of three provider-side facilities—a reference station, monitoring station, and central control station—and one user-side receiver platform. Here, we propose the detailed functionality of each component considering unidirectional broadcasting of augmentation data. To meet the centimeter-level user positioning accuracy in maritime coverage, new reference stations were installed. Each reference station operates with a dual receiver and dual antenna to reduce the risk of malfunctioning, which can deteriorate the availability of the POINT service. The initial experimental results of a testbed from corrections generated from the testbed network, including newly installed reference stations, are presented. The results show that the horizontal and vertical accuracies satisfy 2.63 cm and 5.77 cm, respectively. For the purpose of (near) real-time broadcasting of POINT correction data, we designed a correction message format including satellite orbit, satellite clock, satellite signal bias, ionospheric delay, tropospheric delay, and coordinate transformation parameters. The (near) real-time experimental setup utilizing (near) real-time processing of testbed network data and the designed message format are proposed for future testing and verification of the system.

Keywords: GNSS augmentation, SSR, PPP-RTK, GNSS reference station

1. INTRODUCTION

Since the early 2000s, various users in the marine environment have claimed a need for centimeter-level precise positioning. In this context, the International Maritime Organization (IMO) published resolution A.915(22), which described the requirement of the horizontal and vertical absolute accuracies to both be under 10 cm for automatic docking, cargo handling, construction, and dredging (IMO 2001). In the Republic of Korea, a new positioning service for maritime users is in development with support from the Ministry of Oceans and Fisheries to satisfy the requirements of positioning accuracy. The ground-based centimeter-level maritime precise Positioning, Navigation, and Timing (PNT) augmentation service called Precise POsitioning and INTegrity monitoring (POINT) will provide a state-space-represented (SSR) global navigation satellite system (GNSS) augmentation message to users at maximum 100 km from the coastline. The correction and integrity information mainly relies on the reference station (RS) and monitoring station infrastructure of the National Maritime PNT office (NMPNT), which is currently used for Differential GNSS (DGNSS) service.

Recently, the SSR GNSS correction has been rapidly developed and widely used in various correction/

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augmentation systems (Kee et al. 1991, 2013, Kouba & Heroux 2001). In contrast to the Real-Time Kinematic (RTK) method, which uses observation-space-represented (OSR) correction (Takac & Zelzer 2008), SSR correction distinguishes the GNSS error from the measurement domain into state variables, such as satellite orbit, satellite clock, ionosphere delay, and tropospheric delay, according to their characteristics. The traditional Precise Point Positioning (PPP) technique widely uses the SSR corrections of satellite orbit and clock. To improve the decimeter-level accuracy and long convergence time, PPP added with phase bias (called PPP-Ambiguity Resolution or PPP-AR) was suggested (Ge et al. 2008), which enabled ambiguity resolution after combining an ionosphere-free combination. The PPP-RTK technique (Wübbena et al. 2005), which includes ionosphere and tropospheric corrections, as well as phase bias, was also introduced. PPP-RTK can reduce the convergence time of PPP-AR by interpolating spatial corrections in small- or medium-scale networks.

Numerous services using PPP, PPP-AR, and PPP-RTK technologies are in operation by governments, proprietors, and organizations. The Quasi-Zenith Satellite System with Centimeter-Level Augmentation Service (QZSS CLAS) is an open nationwide PPP-RTK service for Japan (Cabinet Office 2022). CLAS has been operational since November 2018 and provides correction and integrity messages in Compact-SSR format (Hirokawa et al. 2016). The High Accuracy Service (HAS) of the European satellite navigation system, Galileo, is scheduled to provide open PPP correction through the Galileo E6-B signal and by terrestrial means (Martini et al. 2022). Galileo HAS will provide PPP corrections including satellite orbit, clock, and biases for global users in service level 1 (SL1) and atmospheric correction for European users in service level 2 (SL2).

PPP/PPP-RTK corrections are mostly transferred to users in a unidirectional way, and the corrections are usually applied to the user by a similar algorithm. However, the SSR message format describing how the correction data is sent to the user is not globally standardized, with the exception of satellite orbit and clock message, until today. The Radio Technical Commission for Maritime Services (RTCM) defined the RTCM 3 format in the RTCM Special Committee 104 (SC-104). PPP/PPP-RTK is standardized in RTCM SC-104 as RTCM SSR (RTCM SC-104 2022).

In this paper, we introduce the initial architectural design of the POINT system and its development status. In Chapter 2, the architecture of the POINT system is proposed in detail after representing the overall specifications and requirements of POINT service. In Chapter 3, the installation procedure of a new RS network and initial operating results are described.

Table 1. POINT performance requirements.

Index	Requirement
Horizontal accuracy (95%)	5 cm
Vertical accuracy (95%)	10 cm
Alert limit	25 cm
Integrity risk	10^{-5}
Time to alarm	10 s
Availability	99.8%
Continuity	99.97%

In Chapter 4, we present the experimental setup and results from a testbed network. In Chapter 5, the POINT message format is defined to (near) real-time broadcast correction data. After briefly introducing the ongoing real-time implementations on the testbed network, the future plan in development of the POINT system is described in Chapter 6.

2. ARCHITECTURE OF POINT SYSTEM

2.1 Overview of POINT Service

POINT service is a PPP-RTK service for marine users who are located within 100 km from the coastline of the Republic of Korea. Table 1 shows the performance requirements of the POINT system. The system will provide the corrections primarily based on Global Positioning System (GPS) dual frequency (L1 and L2) codes and carrier phase observables. User positioning accuracy depends on not only the accuracy of POINT correction but also the user environment, such as the receiver multipath and geometry of correctable satellites. Users who want to achieve full accuracy from the service can apply ambiguity resolution after applying the SSR correction.

To achieve the performance requirement in the static environment described in Table 1, the POINT system should provide accurate and precise correction continuously and monitor the uncertainty and fault of the correction. As a result, the aggregation of each piece of equipment in the RS or monitoring station is critical to switch to the alternative flawlessly.

2.2 Architecture of POINT System

The architecture of the POINT system is divided into two segments—the service segment and user segment (Park et al. 2021). The RS, central control station (CCS), and integrity monitoring station (IM) are the three main module blocks in the service segment whereas the user segment includes the receiver platform (RP). Fig. 1 shows the overall block diagram of the POINT system. The RS and IM in POINT form a continuously operating reference stations (CORS) network that receives GNSS signals from GNSS satellites,

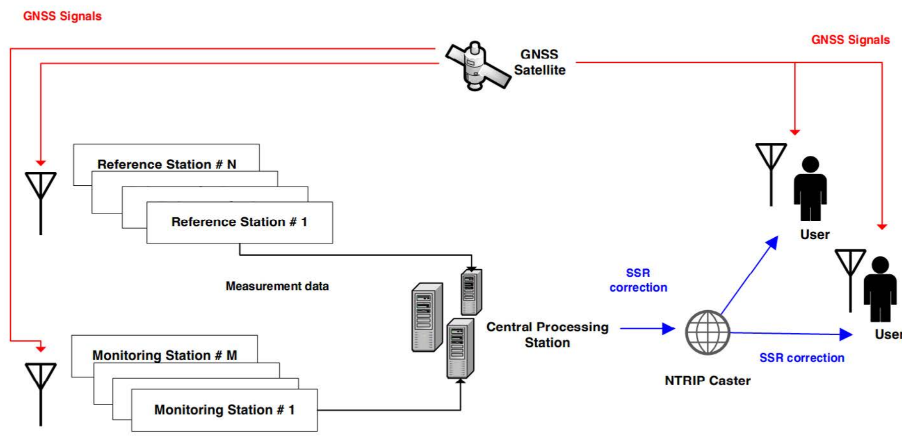

Fig. 1. Overall block diagram of POINT system.

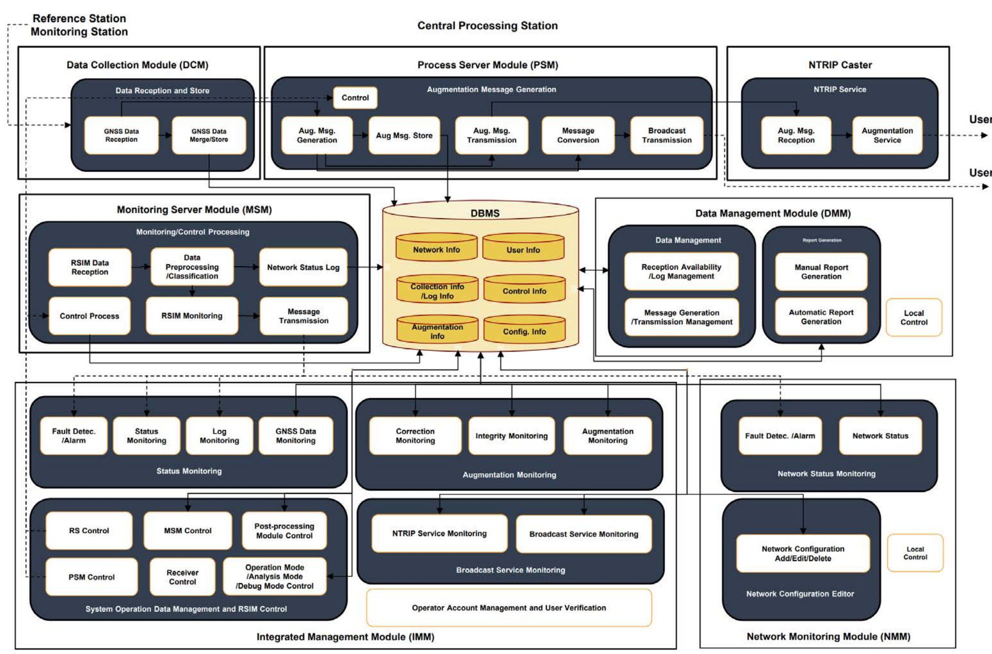

Fig. 2. POINT CCS architecture.

and consequently, the CCS receives raw data directly from the RS and IM. The CCS merges all navigation message data and re-arranges the code and carrier phase observables. After pre-processing and applying a priori models, the CCS estimates PPP-RTK corrections based on the precise coordinates of the RS. Simultaneously, PPP-RTK correction data are tested and verified in the IM measurement data. The SSR correction message is generated from the correction data through the designed POINT message format, and the binary message is transferred by the Network Transport of RTCM via Internet Protocol (NTRIP) caster. Once RP access receives the SSR correction message with the NTRIP client in addition to the GNSS signals, the user can correct the GNSS raw measurement with SSR correction data parsed from the correction message.

The RS block is composed of GNSS signal reception, environment, and operations/control parts. The GNSS receiver and GNSS antenna are included in the GNSS signal reception part, and the receiver clock can be replaced with an atomic clock, if necessary. The IM block is also composed of GNSS signal reception, environment, and operations/control parts. In most cases, IM stations are operated and controlled by the CCS; however, IM stations can operate in a local operation mode independent from the CCS.

The CCS accounts for most system functions to manage data, generate corrections, monitor integrity, and transmit correction messages. Fig. 2 shows the modules in the CCS and their interactions. The process server module (PSM)

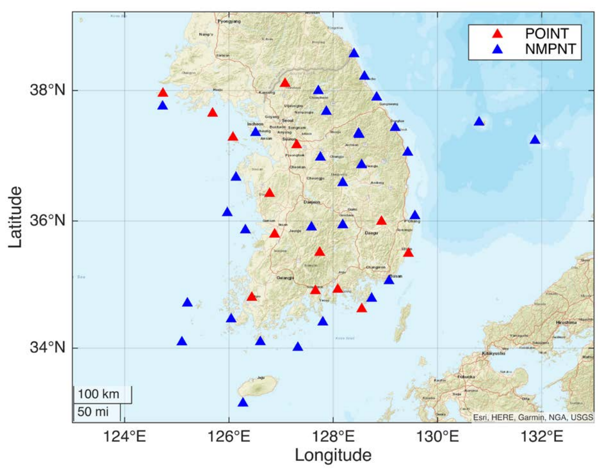

Fig. 3. Locations of POINT CORS network including NMPNT RSs, IMs (blue triangles), and newly installed POINT RSs (red triangles).

generates augmentation data from the data collection module (DCM) and converts the augmentation data into POINT message format. To store continuously fed raw data, correction data, status, and logs of each module, a database management system (DBMS) and data management module (DMM) are implemented.

Table 2. Newly installed POINT reference stations.

Environment category	Station name		Site location	Receiver	Antenna
	Primary	Secondary			
Maritime	BKRD	BKR2	Baengnyeongdo	Leica GR50	Leica AR20
	GWYN	GWY2	Gwangyang		
	MOKP	MOK2	Mokpo		
	SACN	SAC2	Sacheon		
	SMMD	SMM2	Somaemuldo		
	SNMD	SNM2	Seonmido		
	ULGI	ULG2	Ulsan		
	YNPD	YNP2	Yeonpyeongdo		
Land	CHYN	CHY2	Cheongyang	Leica GR50	Leica AR20
	GMJE	GMJ2	Gimje		
	HMYN	HMY2	Hamyang		
	YNCH	YNC2	Yeongcheon		
	YNCN	YNC2	Yeoncheon		
	YNGN	YNG2	Yongin		

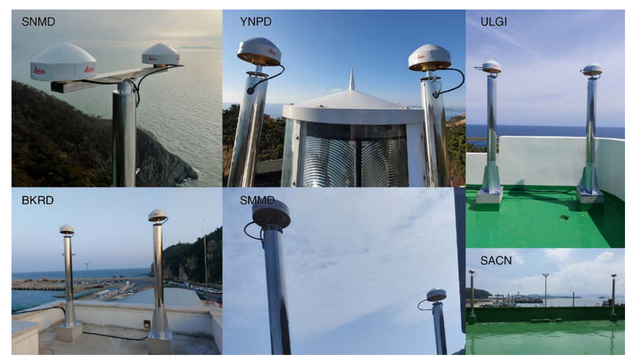

Fig. 4. Installed GNSS antennas at POINT reference stations: SNMD (top left), YNPD (top middle), ULGI (top right), BKRD (bottom left), SMMD (bottom middle), and SACN (bottom right).

3. INSTALLATION OF POINT REFERENCE STATIONS

3.1 Locations for POINT RSs

The RS block of the POINT system is fundamental input for the user to achieve centimeter-level accuracy. The POINT network inherits the DGNSS infrastructure of NMPNT RSs and IMs. The NMPNT operates 30 stations: 20 marine stations and 10 in-land stations. In 2022, the marine stations are located on islands or near coast regions.

To maximize the coverage and improve the accuracy of the POINT system, the need install more RSs was raised by the preliminary research on the performance prediction. Lee et al. (2020) analyzed the NMPNT network using a performance index related with Interpolative Dilution of Precision (IDOP) and suggested candidate locations of extra RSs that can broaden the coverage of precise positioning. Based on this research, we selected 14 locations for new RSs. Fig. 3 shows the location of the completed POINT network, including NMPNT RSs and IMs with newly installed POINT RSs.

3.2 Installation of POINT RSs

New POINT RSs were installed among candidate locations after evaluating the signal availability, multipath, and cycle slip index of each site. The evaluation was conducted based on a threshold of availability of 99%, multipath of 0.3 m (both for L1 and L2), and cycle slip rate (CSR) index of 1.0. The CSR index was computed by the ratio of the number of cycle slips to the number of observations × 1000 (Jeon et al. 2021). Table 2 lists the 14 newly installed POINT RSs. Each RS operates with a dual receiver and dual antenna to reduce the risk of malfunctioning, which can deteriorate the availability of POINT service. In each RS, two Leica GR50 receivers are installed. These receivers are independently connected with two Leica AR20 antennas with radomes. Fig. 4 shows the newly installed antennas from the representative POINT RSs. A rackmount case that is capable of temperature and humidity control is installed at each site to sustain stable operation of the receiver and server. An uninterruptible power supply (UPS) unit is also equipped inside rackmount case to prevent power shortages or blackouts at the site location. The data from the two receivers in an RS are transferred to the CCS through an ethernet connection, as well as periodically stored on a file transfer protocol (FTP) server in the RS. The two receivers in an RS can be remotely

Table 3. Quality analysis results of POINT RSs.

Station name	Availability (%)	MP1 (m)	MP2 (m)	C/S index
SNMD	98.45	0.39	0.40	0.72
YNCN	99.97	0.19	0.20	0.56
YNPD	99.98	0.15	0.16	0.37
YNGN	99.86	0.32	0.37	0.60
CHYN	99.95	0.24	0.26	0.61

controlled from the CCS when a change of configuration or a reset of real-time stream is needed. Installation of RSs was completed in October, 2022.

Long-term evaluation of the performance in the POINT RSs was conducted with the TEQC program (Estey & Meertens 1999). Table 3 shows the average quality index of initially installed RSs. The statistics are averaged from daily values from January 2022 to June 2022. In Table 3, the SNMD station shows lower availability and multipath than other stations. The lack of the availability and multipath condition is considered to be originated from the unexpected obstacle of the lighthouse building and limitations in the island's steep topography. Although there are limitations in using the SNMD station to generate POINT correction, the station is included, as the location of the station is critical to improve coverage in the West Sea. To mitigate higher code multipath, a testing algorithm based on a sidereal filter is ongoing.

4. TESTBED EXPERIMENTAL SETUP AND RESULT

4.1 Testbed Experimental Setup

The testbed experiment was conducted at the north-west region of objective service coverage. Fig. 5 shows the testbed POINT network and user position for this experiment. The seven RSs (four NMPNT stations and three new POINT stations) were used to generate SSR corrections. The list of stations and the experimental setup are described in Table 4.

In the server side, we collected 1 Hz of GPS measurement data from each RS as well as GPS navigation messages in RINEX format. Using the collected data as inputs, we processed the measurement data via a processing server module in the CCS to generate SSR correction.

In the user side, we also collected 1 Hz of GPS measurement data from the user station in RINEX format. The a priori position for the user was estimated by single point positioning without correction. Ionospheric and tropospheric delay in the user approximate position were computed by bilinear interpolation from station-wise ionospheric and tropospheric correction.

We estimated the user position along with receiver clock,

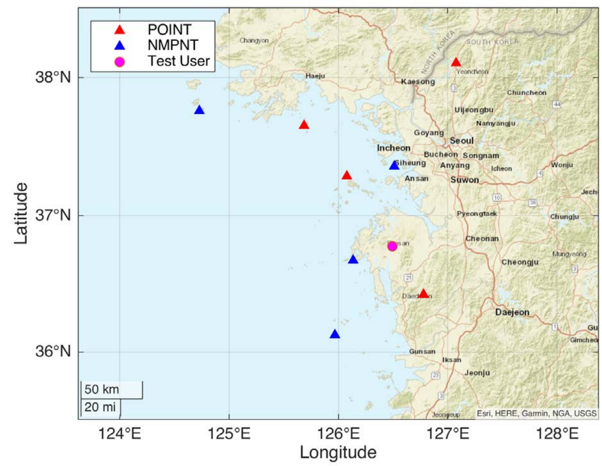

Fig. 5. Location of testbed network RSs used to generate POINT corrections (in blue and red triangles) and test user location (in a magenta circle).

Table 4. Testbed experiment setup.

Index	Description
Reference stations	(NMPNT) ANHN, EOCH, PALM, SOCH (POINT) CHYN, SNMD, YNCN
Experiment time	1 sec
Measurement interval	Every 3 hours
GNSS constellation	GPS only
Receiver	Trimble NETR9
Antenna	TRM59800.00 SCIS

receiver hardware bias, and ambiguity per each frequency after applying POINT SSR correction. After the acquisition of a float solution, we performed full ambiguity resolution from the float solution using least-squares ambiguity decorrelation adjustment (LAMBDA) (Teunissen et al. 1997) to fix ambiguity into the integer domain in every epoch. Integer least squares with fixed failure-rate ratio test and partial ambiguity resolution are used to fix ambiguity. The final integer-fixed position was logged into output format after the ratio test. The user-side Kalman filter was re-initialized every 3 hours to check epoch-dependent differences in convergence and avoid possible saturation of the filter.

4.2 Testbed Experimental Results

The positioning error is evaluated with respect to the post-processed daily precise position of the user receiver in the IGb14 coordinate frame. The post-processing process was conducted using Bernese software (Dach et al. 2015) with data from International GNSS Service (IGS) stations. Fig. 6 shows the positioning errors in the east, north, and up directions. The float solution (in blue color) shows initial convergence at every direction in 3 hours. The ambiguity fixed solution (in orange) shows improved error and convergence time compared with that of the float solution.

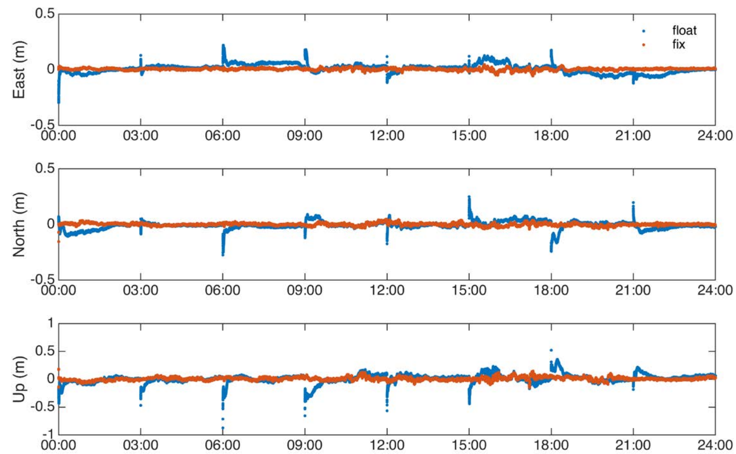

Fig. 6. Positioning results with POINT correction generated from testbed network.

Table 5. Test site experiment results.

Time	Horizontal error (RMS / 95th percentile) (cm)	Vertical error (95%) (RMS / 95th percentile) (cm)	Fix rate (%)	Convergence time (s)
00:00 – 03:00	1.48 / 2.77	2.69 / 5.48	99.96	5
03:00 – 06:00	1.14 / 1.92	2.43 / 4.69	100.00	1
06:00 – 09:00	1.24 / 2.00	2.38 / 4.24	99.87	3
09:00 – 12:00	1.90 / 3.28	3.40 / 7.66	100.00	1
12:00 – 15:00	1.43 / 2.73	2.26 / 4.56	99.91	3
15:00 – 18:00	2.20 / 3.98	4.85 / 9.40	100.00	1
18:00 – 21:00	1.60 / 2.90	3.46 / 6.07	100.00	1
21:00 – 24:00	0.90 / 1.43	1.73 / 4.07	99.86	2
Average	1.49 / 2.63	2.90 / 5.77	99.95	2.13

Table 6. Sub-message type of POINT message format.

Sub type number	Sub type name	Description
1	Satellite orbit correction	
2	Satellite clock correction	
3	Satellite orbit/clock correction	
4	Satellite signal bias	Code bias and phase bias
5	Ionospheric delay correction	Slant TEC grid
6	Tropospheric delay correction	ZHD and ZWD grid
7	Integrity information	
8	CRS transformation parameter	15 parameters
9	GPS PRN mask	
10-15	Reserved	

Table 5 shows the horizontal and vertical errors that were computed at each 3-hour interval. The average of the 95th percentiles of the 3-hour horizontal errors resulted in 2.63 cm, while that of the vertical errors resulted in 5.77 cm. The convergence time in Table 6 is computed by the first time to fix phase ambiguity. The average of convergence times was 2.13 s.

5. DESIGN OF POINT MESSAGE FORMAT

The POINT message format partially follows the RTCM 10403.3 with Amendment 3 SSR standards. As the RTCM SSR format has not yet been completed, corrections, other than orbit and clock parameters, were designed in an in-house format. However, the POINT message format will fully follow the RTCM SSR format when the RTCM SSR standard is completely published from RTCM SC104.

The POINT correction message format follows the fundamental structure of the current RTCM message format. Fig. 7 shows the structure of the POINT message. Sub-message types (SMTs) are defined within the data message field (as shown in Table 6). Ionospheric delay (SMT 5) and tropospheric delay (SMT6) are provided in 32 grid points, mostly with inter-grid spacing of 1°. The Coordinate Reference System (CRS) transformation parameters are composed of one epoch parameter, seven Helmert transformation parameters, and their rates to transform POINT CRS to national geodetic CRS.

6. REAL–TIME TESTBED EXPERIMENT

The real-time implementation of raw data collection from the RSs and broadcast of the augmentation message is a key infrastructure providing (near) real-time user positioning. In both cases, NTRIP is used. When the CCS collects data from the RSs and IMs, the DCM in Fig. 2 functions as an NTRIP client. When the CCS broadcasts an augmentation message,

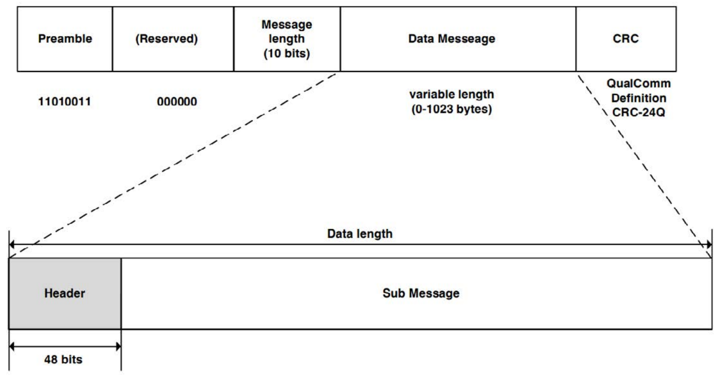

Fig. 7. Structure of POINT SSR message format.

(a) (b)

Fig. 8. Real-time experimental configuration at Daesan port: (a) landscape of testbed port facility; (b) RP.

Fig. 9. Testbed operations room located in KRISO.

each real-time stream of the augmentation message (NTRIP sources) transports to the NTRIP server. The NTRIP caster is capable of receiving correction messages from each NTRIP server and distributing correction messages to multiple NTRIP clients.

A real-time testbed experiment was designed to examine the port environment and verify the real-time implementations. Daesan port, which is one of the major ports in the West Sea of Korea, was chosen as a testbed port (Fig. 8). To describe the user environment, we installed a NovAtel VEXXIS® GNSS-850 antenna on the roof of the test facility. Two types of receivers were used: a Leica GR50 for reference and a NovAtel OEM7720 for testing. The NovAtel receiver was implemented in the RP uniquely designed and developed for a POINT service user. The baseboard of the RP is composed of interfaces, such as RS232, for broadcast signal reception, and a 60-pin board-to-board connector to connect with the GPS module. An ethernet port was also used to connect an LTE or 3G communication modem.

Currently, the real-time experiment of POINT service is ongoing. Fig. 9 shows test operation room in Korea Research Institute of Ships and Ocean engineering (KRISO), which acts as a temporary CCS. In the test operation room, the status of data collection, correction generation, and RTCM message transport is monitored and controlled by the integrated management program. The real-time experiment is planned to be conducted until December, 2022.

Further development for full operation with full coverage based on a nationwide RS network and test broadcasting of POINT correction is scheduled in 2023–2024. In addition to correction data, integrity information, such as uncertainty in correction, system alerts, and ionospheric delay alarms, is currently in development to provide users with risk-free capability.

7. CONCLUSION

In this contribution, we presented the development status of the precise GNSS augmentation service called POINT. A designed architecture for POINT service is proposed, along with an overview of the service. Furthermore, the installation of new RSs, and offline test results with the RSs, are presented.

The offline test results showed 2.63 cm of horizontal error and 5.77 cm of vertical error. Using the designed POINT message format, the real-time implementation has been developed with NTRIP. The real-time experiment is ongoing at Daesan port in Korea. Based on the architecture proposed in this study, the results are expected to provide precise and reliable navigation services in the maritime environment by developing the ground-based centimeter-level maritime PNT system.

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AUTHOR CONTRIBUTIONS

Conceptualization, S.G.P and S.H.P; methodology, G.K.; software, G.K. and T.J.; validation, G.K., T.J. and J.S.; formal analysis, G.K. and T.J.; investigation, G.K.; resources, S.G.P, J.S., T.J, and G.K; data curation, G.K and T.J.; writing—original draft preparation, G.K.; writing—review and editing, S.G.P.; visualization, G.K.; supervision, S.H.P.; project administration, S.G.P; funding acquisition, S.H.P.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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