DEVELOPMENT OF THE KOREAN eLORAN TESTBED AND ANALYSIS OF ITS EXPECTED POSITIONING ACCURACY

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SUMMARY

Due to the vulnerability of global navigation satellite systems to radio frequency interference, South Korea has decided to deploy the eLoran system. A research and development project to develop an eLoran testbed by 2020 is currently in progress. For the eLoran testbed, a new eLoran transmitter is planned to be installed in Gyodong and two differential correction stations are expected to be installed in Incheon and Pyeongtaek. In this paper, we briefly introduce the current status of the Korean eLoran testbed project. Then, the expected accuracy performance is presented by simulations and experiments. The software simulations compare two cases: a Korean transmitters-only case and a Far East Radio Navigation Service (FERNS) chain case. Because the new eLoran transmitter is not yet deployed, its positioning accuracy cannot be directly measured. Thus, we used the multichain Loran-C positioning algorithm to obtain the expected performance of the eLoran "all-in-view" positioning. The measured performance with five FERNS transmitters and the multichain positioning algorithm for a static user in Incheon was 14.0 m (95%), which satisfies the accuracy requirement of the Korean eLoran testbed project.

RESUME

A cause de la vulnérabilité des systèmes mondiaux de navigation par satellites la Corée du Sud a décidé de déployer le système eLoran. Un projet d'élaboration d'un banc essai à l'horizon 2020 est actuellement en cours. Pour ce banc d'essai un nouvel émetteur eLoran est prévu à Gyodong et deux stations de corrections différentielles vont être installées à Incheon et Pyeongtaek. Dans ce rapport, nous présentons brièvement l'état actuel du projet de banc d'essai eLoran coréen, puis les résultats attendus en précision, au moyen de simulations et d'expérimentations. Le logiciel de simulation compare deux cas : le cas des émetteurs coréens uniquement, et le cas de la chaine du service de radionavigation d'Extrême Orient (FERNS). Parce que le nouvel émetteur eLoran n'est pas encore en service, la précision de la position ne peut pas être mesurée directement. Donc nous avons utilisé l'algorithme de positionnement Loran-C multi chaine pour obtenir le résultat espéré du positionnement « tout-en-un » du eLoran. Le résultat mesuré avec cinq émetteurs FERNS et l'algorithme de positionnement multi chaine pour un utilisateur statique à Incheon est de 14,0 m (95%), ce qui satisfait aux exigences de précision du banc d'essai eLoran coréen.

CONTENTS

1. INTRODUCTION

The Long Range Navigation (Loran) system is a radionavigation system based on high power signals broadcast from terrestrial transmitters. It has been used mainly as a navigation system in maritime areas, but its use has greatly diminished due to the development of global navigation satellite systems (GNSSs) that provide much better navigation performance. However, GNSSs have the disadvantage of being vulnerable to intentional or unintentional jamming [1, 2], and the need of a complementary navigation system that can compensate for the vulnerabilities of GNSSs arises [3].

As the enhanced Loran (eLoran) system has been actively tested and it has been demonstrated that eLoran can provide approximately 10 m positioning accuracy at sea [4], eLoran is recognized as one of the most appropriate complementary navigation systems to GNSSs, especially for maritime users. South Korea, already operating its Loran-C system, plans to upgrade its existing Loran-C system to an eLoran system [5]. The existing Pohang and Gwangju Loran-C transmitters will be time-synchronized to coordinated universal time (UTC) and a new eLoran transmitter will be installed in Gyodong. (The original plan was to install a new transmitter in Ganghwa but the location is now changed to Gyodong.) Two differential correction stations (also known as DLoran stations) are to be deployed in Incheon and Pyeongtaek for additional secondary factor (ASF) corrections that are required to improve positioning accuracy.

In this paper, first we introduce the eLoran development status in Korea. Several sites were investigated to determine the location for the new eLoran transmitter, with the Gyodong location being finally selected. Two DLoran station locations were also selected after monitoring the quality of received signals at several alternative sites. The expected positioning accuracy after deployment of the new Gyodong transmitter and DLoran stations was simulated with the help of the General Lighthouse Authorities of the UK and Ireland (GLA). Finally, the expected eLoran "all-in-view" positioning accuracy was evaluated based on the current Loran-C signal measurements. For this purpose, we used our multichain Loran-C positioning algorithm that is expected to provide similar positioning accuracy to the eLoran "all-in-view" positioning method.

2. STATUS OF THE KOREAN eLORAN TESTBED PROJECT

2.1. REQUIRED PERFORMANCE OF THE KOREAN eLORAN TESTBED

The Korean eLoran testbed project is led by the Korea Research Institute of Ships and Ocean Engineering (KRISO), which is joined by several organizations, including Yonsei University, to form the KRISO Consortium. The required performance of the Korean eLoran testbed, as defined in the request for proposal (RFP), is to ensure the positioning accuracy to 20 m (95%) within a 30 km range from a DLoran station, time synchronization to UTC within 50 ns, and the eLoran data channel (LDC) to provide necessary data including temporal ASF corrections to users as summarized in Table 1.

Positioning accuracy	Timing accuracy	eLoran data channel modulation
< 20m	< 50 ns (rms)	Eurofix or 9th pulse

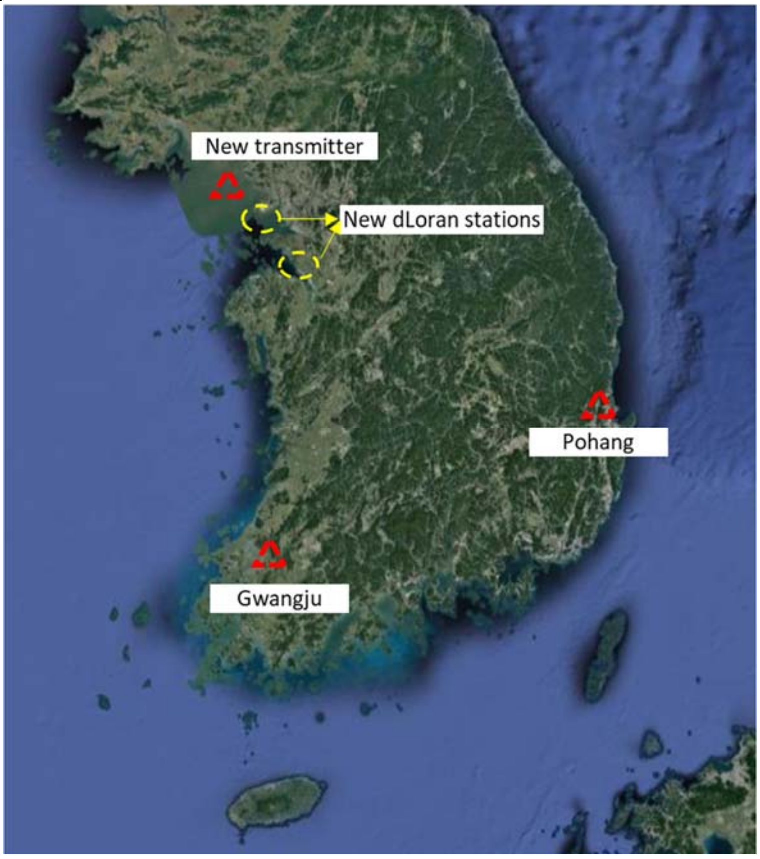
Table 1 - Required performance of the Korean eLoran testbed

2.2. IMPLEMENTATION OF eLORAN INFRASTRUCTURES

2.2.1. SITE SELECTION FOR THE NEW ELORAN TRANSMITTER

The eLoran system calculates a user's 2D position based on signals from at least three transmitters that are time-synchronized to UTC. In order to utilize the existing Loran-C transmitters as a part of the Korean eLoran testbed, the Pohang and Gwangju transmitters need to be time-synchronized to UTC. In addition, installation of a new eLoran transmitter is required because South Korea wants to provide the eLoran service even when the transmitters of nearby countries are unavailable. To maximize the performance of the eLoran testbed, several candidate sites for the new eLoran transmitter installation were evaluated. After considering many practical restrictions, Gyodong was recently selected as the transmitter site (Image 1).

Image 1 - Selected sites for a new eLoran transmitter and two DLoran stations



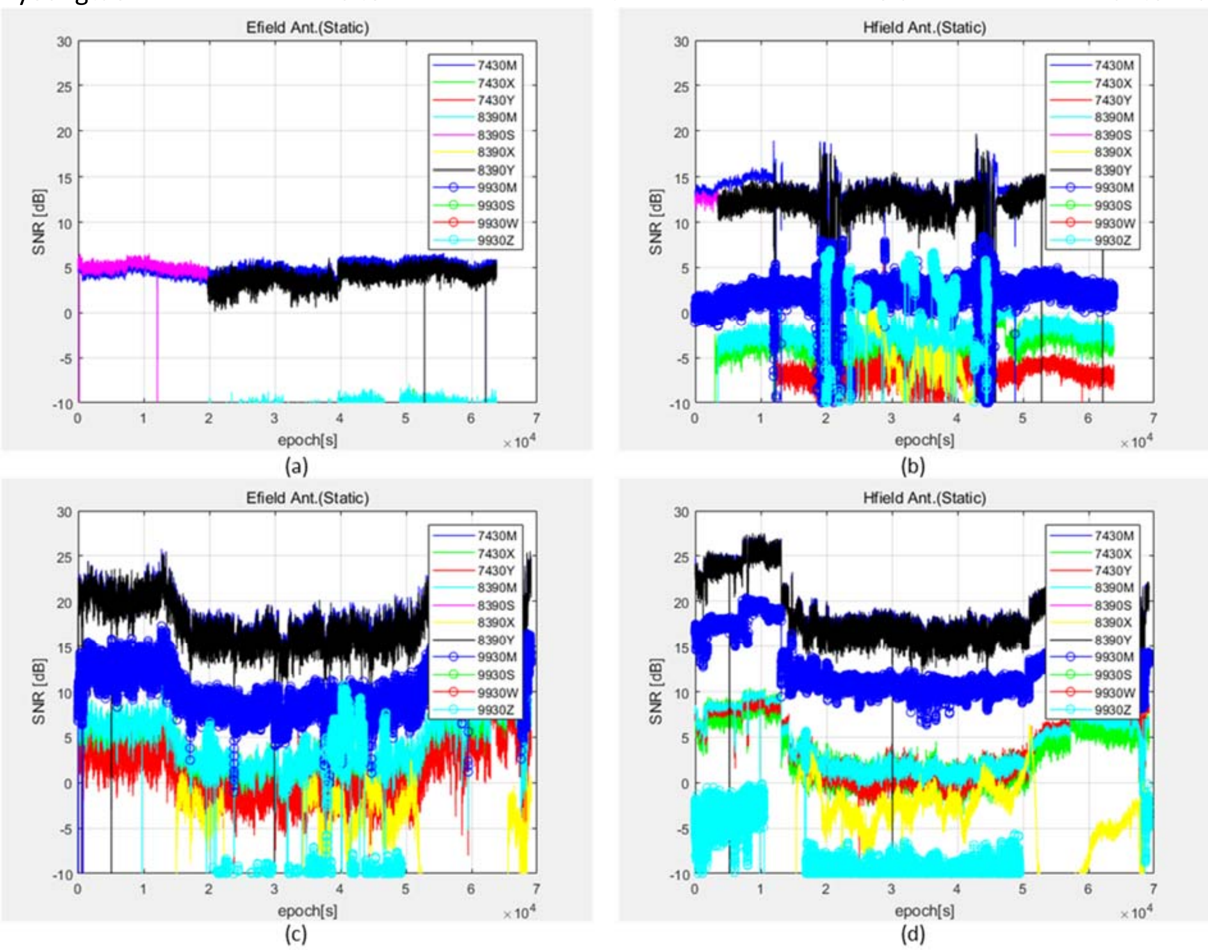
2.2.2. SITE SELECTION FOR DLORAN STATIONS

The ASF is the largest source of error for Loran and it needs to be compensated by ASF maps and differential corrections. ASF maps to compensate for spatial ASF variations are generated by an ASF survey [6, 7] and stored in user receivers [8]. The DLoran stations generate differential corrections that compensate for temporal ASF variations. We tested received Loran signal qualities at several candidate sites for DLoran stations. The RFP of the Korean eLoran testbed project specifies the test areas as Incheon harbour and Pyeongtaek harbour. Thus, we selected two DLoran sites based on the measured signal quality, which can cover these two harbours. The coordinates of the selected sites are given in Table 2. Image 2 presents the signal-to-noise ratios (SNRs) observed during a one-day campaign at each DLoran site. The 9930M in Image 2 is the Pohang transmitter and the 9930W is the Gwangju transmitter.

Site	Coordinates
Incheon Regional Office of Oceans and Fisheries / Incheon	Latitude : 37° 26′ 56.7″ N Longitude: 126° 35′ 42.1″ E
Loran-C monitoring station / Pyeongtaek	Latitude : 36° 59′ 56.3″ N Longitude: 126° 47′ 44.2″ E

Table 2 - Coordinates of the selected sites for DLoran stations

Image 2 - Observed signal to noise ratios (SNRs) during one day at the (a) Incheon site with E-field antenna, (b) Incheon site with H-field antenna, (c) Pyeongtaek site with E-field antenna, and (d) Pyeongtaek site with H-field antenna



3. POSITIONING ACCURACY SIMULATION OF THE KOREAN eLORAN TESTBED

3.1. eLORAN POSITIONING ACCURACY SIMULATION WITH ONLY KOREAN TRANSMITTERS

Assuming that a new eLoran transmitter is installed in Gyodong and only three Korean transmitters are used, the positioning accuracy was simulated with the help of GLA; results are shown in Image 3. Note that the accuracy contours in Image 3 represent the repeatable accuracy that assumes complete ASF compensation everywhere. Thus, it is the best-case ideal accuracy.

Image 3 - Repeatable accuracy simulation with three Korean transmitters marked in red triangles (Figure used with permission from [13]).

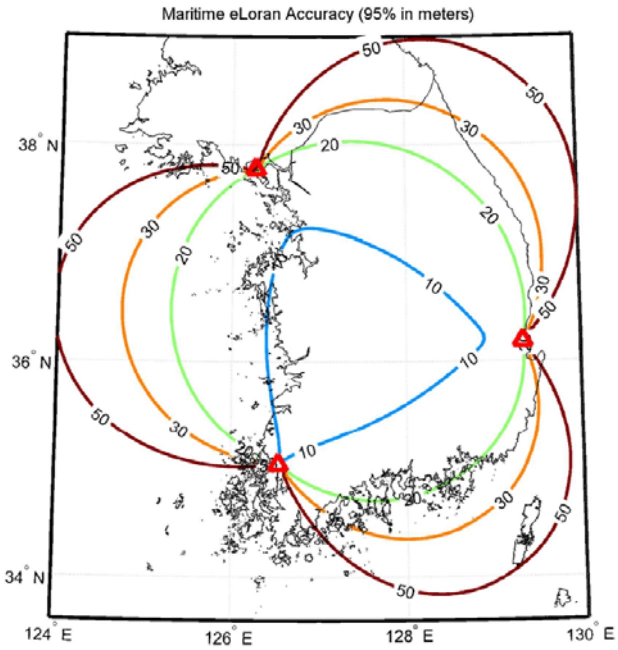
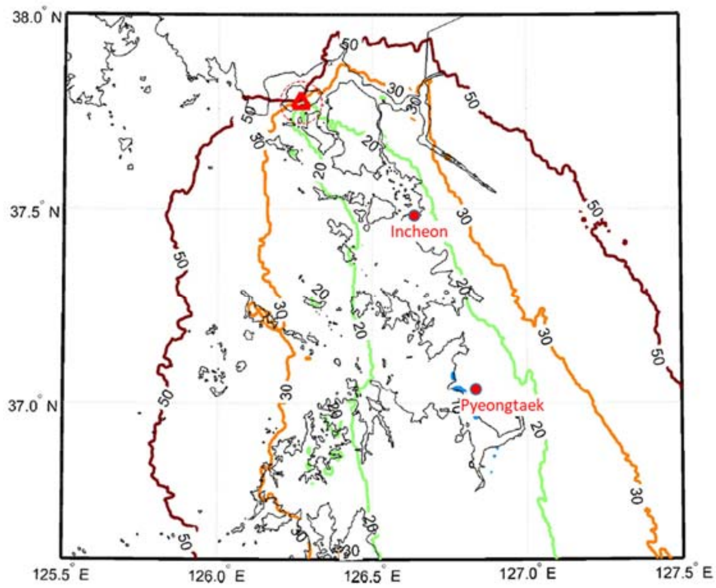


Image 4 represents a more realistic accuracy for the case with two DLoran stations at the Incheon and Pyeongtaek sites. In this case, the ASF spatial decorrelation model is used and ASF is assumed to be completely compensated only within a 30 km range of the DLoran stations. Based on this simulation, the 20-m accuracy requirement at Incheon and Pyeongtaek harbours of the RFP is expected to be satisfied. However, the 10 m International Maritime Organization (IMO) requirement in Table 3 appears to be challenging.

Image 4 - Accuracy simulation with three Korean transmitters and two DLoran stations (Figure used with permission from [13]).



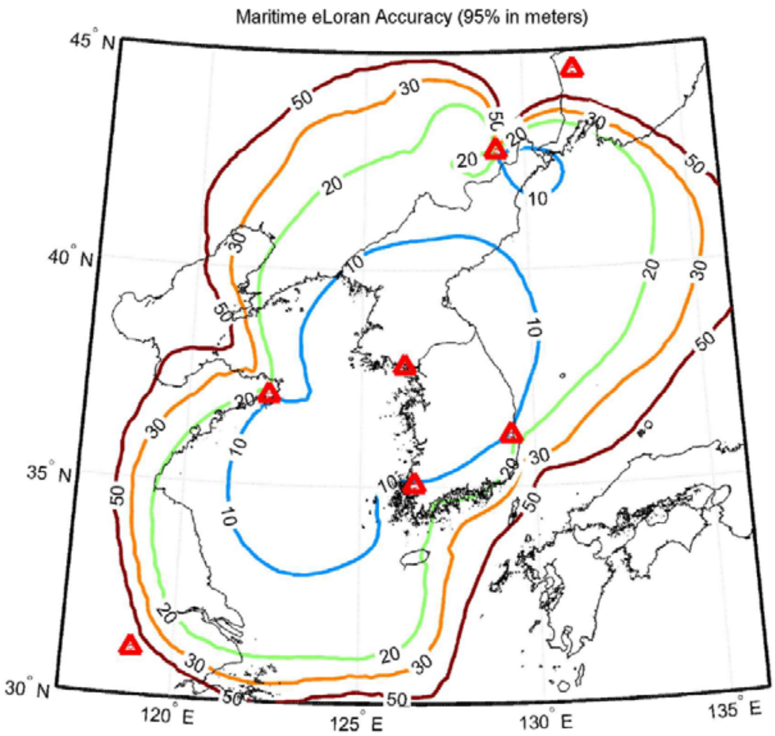
	Accuracy (95%)	Integrity	Availability	Continuity
IMO Res. A.1046(27) & A.915(22) (Harbour entrances, harbour approaches and coastal waters) [9, 10]	10 m	Alert limt (25 m) Time to alarm (10 s) Integrity risk (10^{-5} per 3 h)	99.8% per 30 days	99.97% over 15 min
ILA eLoran Definition (Harbour entrance and approach) [11]	8-20 m	-	-	-
IALA Recommendation R-129 (Port approach) [12]	10 m	Alert limt (25 m) Time to alarm (10 s) Integrity risk (10^{-4} per 3 h)	99% per 30 days	99.97% over 15 min

Table 3 - Required navigation performance

3.2. eLORAN POSITIONING ACCURACY SIMULATION WITH FERNS CHAINS (GRI 7430, GRI 9930)

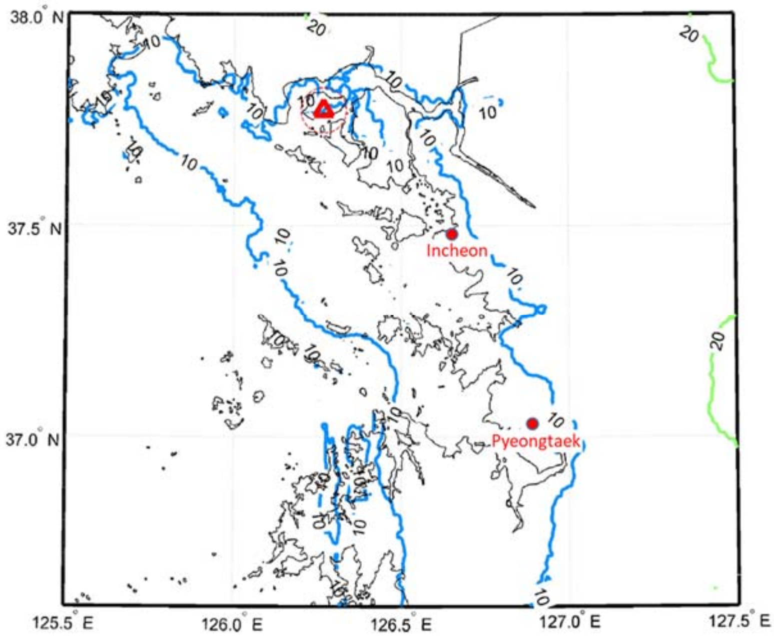
As the number of eLoran transmitters increases, the horizontal dilution of precision (HDOP) usually decreases, and consequently the positioning accuracy improves. In Korea, signals from Chinese and Russian transmitters are also available. These transmitters, including Korean transmitters, are usually called Far East Radio Navigation Service (FERNS) transmitters. The results of the repeatable accuracy simulation using the three Korean, three Chinese, and one Russian transmitters together in the eLoran "all-in-view" mode are shown in Image 5. This simulation with the seven FERNS transmitters demonstrates significant improvement in repeatable accuracy over the case of Image 3 with three Korean transmitters.

Image 5 - Repeatable accuracy simulation with seven FERNS transmitters marked in red triangles (Figure used with permission from [13]).



Similar to Image 4, ASF spatial decorrelation is considered in the more realistic accuracy simulation in Image 6. Image 6 indicates the possibility of satisfying the 10 m IMO accuracy requirement at Incheon and Pyeongtaek harbours. However, during our field test in Incheon, the received signal quality from the Ussuriysk station was not suitable for navigation [14]. Thus, the actual performance of the future Korean eLoran testbed may be worse than the case of Image 6.

Image 6 - Accuracy simulation with seven FERNS transmitters and two DLoran stations (Figure used with permission from [13]).



4. POSITIONING ACCURACY PREDICTION OF THE KOREAN ELORAN TESTBED BASED ON FERNS LORAN-C MEASUREMENTS

4.1. MULTICHAIN LORAN-C POSITIONING ALGORITHM

In addition to the simulation results, we used the multichain Loran-C positioning algorithm that we have previously developed [14] and actual Loran-C measurements in Incheon to predict the positioning accuracy of the future Korean eLoran testbed. The multichain Loran-C positioning algorithm enables all received Loran-C signals to be used for positioning regardless of their Loran chains. Therefore, the accuracy performance of the multichain Loran-C algorithm is expected to be similar to that of the eLoran “all-in-view” positioning algorithm. Note that the conventional Loran-C positioning method cannot simultaneously use transmitted signals from multiple Loran chains.

4.2. POSITIONING ACCURACY OF A STATIC USER IN INCHEON

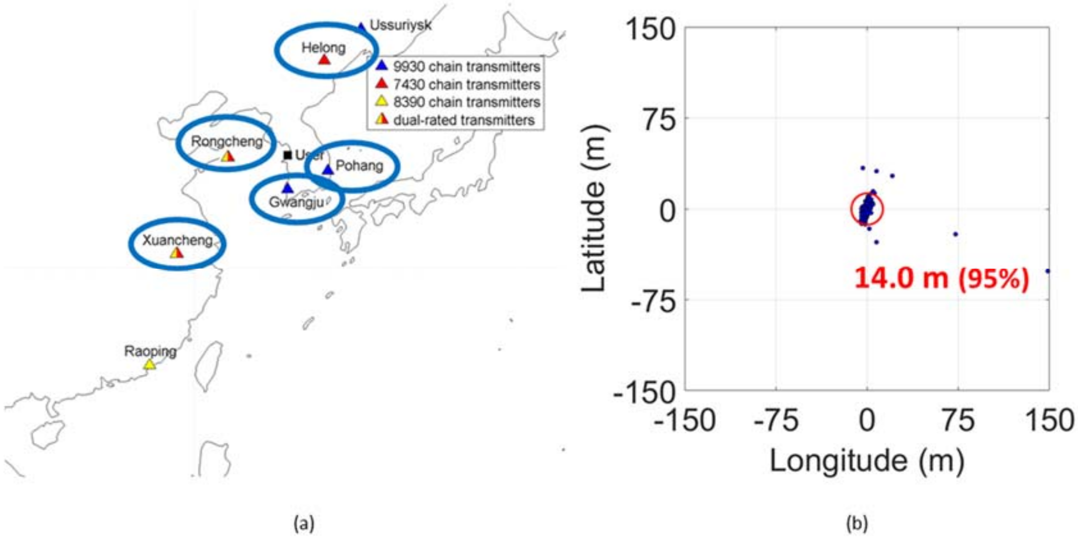
Among the seven FERNS transmitters utilized for the simulations of Images 5 and 6, a new eLoran transmitter in Gyodong is not yet deployed and the Ussuriysk signals recorded in Incheon were not of suitable quality for navigation. Thus, we performed the positioning accuracy evaluation based on the actual measurements from the remaining five FERNS transmitters.

We used the DLoran station at Yonsei University in Incheon to monitor the FERNS Loran-C signals and generate temporal ASF corrections. Table 4 summarizes the observed accuracy performance during a 15 min period. The result of a static user test at the same location as the DLoran station (i.e., zero baseline case) are shown in Table 4. If the baseline distance between a user and the DLoran station increases, the ASF spatial decorrelation also increases and hence the positioning accuracy decreases. HDOP decreases, as expected, as the number of transmitters used for position calculation increases, and thus positioning accuracy improves (Table 4). Once the new eLoran transmitter is deployed, signals from six transmitters would become available in Incheon. Consequently, the positioning accuracy for the same static user is expected to be better than the 14.0 m (Table 4).

Positioning algorithm	Single-chain (7430 chain only)	Multichain (7430 chain + Pohang)	Multichain (7430 chain + Pohang + Gwangju)
HDOP	2.43	1.06	0.95
Positioning accuracy (95%)	23.4 m	15.0 m	14.0 m

Table 4 - HDOP and positioning accuracy comparison according to the number of transmitters utilized in the position calculation.

Image 7 - Multichain Loran positioning results for a static user in Incheon with five FERNS transmitters. (a) Locations of the five transmitters. (b) Position fixes during 15 min.



5. CONCLUSION

South Korea is developing an eLoran testbed to complement the vulnerabilities of GNSS to radio frequency interference. Two existing Loran-C transmitters will be time-synchronized to UTC to be used together with a new eLoran transmitter that is planned to be deployed in Gyodong. In addition, two DLoran stations are to be deployed. After presenting the accuracy simulation results from GLA, we evaluated the expected accuracy performance of the future Korean eLoran testbed based on the actual Loran-C measurements. A static user in Incheon demonstrated a 14.0 m accuracy under the zero baseline condition using the existing five FERNS Loran-C transmitters and the multichain Loran-C positioning algorithm, which is better than the 20 m accuracy requirement of the Korean eLoran testbed.

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