Performance Simulation of the Future Korean eLoran System

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BIOGRAPHY

Joon Hyo Rhee is an M.S./Ph.D. student in the School of Integrated Technology, Yonsei University, Korea. He received his B.S. degree in electrical and electronic engineering from Yonsei University in 2012. His current research focuses on complementary navigation systems such as eLoran and intelligent unmanned systems. Mr. Rhee is a recipient of the Graduate Fellowship from the IT Consilience Creative Program supported by the Ministry of Science, ICT and Future Planning (MSIP), Korea.

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ABSTRACT

During the 16 days' GPS jamming attack from North Korea in 2012, it was reported that 1,016 airplanes and 254 ships in South Korea could not receive GPS signals. As a complementary positioning, navigation and timing system to GPS, the South Korean government recently decided to deploy an eLoran system which is a high-power terrestrial radionavigation system. As an effort toward eLoran in Korea, initial performance simulation results of the future Korean eLoran system are presented in this paper. The eLoran performance simulation tool of this paper is able to accommodate environment variables of Korea and visualize expected navigation accuracy of the eLoran system given arbitrary transmitter locations and transmission powers. In addition to the simulation results, the current status and future plans for deploying eLoran in Korea

are also presented.

I. INTRODUCTION

eLoran is a ground-based high power navigation system that uses low frequency (100 Hz) radio waves. In contrast to the satellite-based navigation systems such as Global Positioning System (GPS) of the United States, eLoran is robust to signal jamming because of its very high transmission power. GPS is used in diverse fields and now it is deeply entrenched in our daily lives. However, the more the society relies on GPS, the higher the risk of the service interruption due to unintentional interference or intentional jamming. Carroll [1] mentioned the vulnerability of GPS and Narins *et al.* [2] insisted the necessity of a robust alternative position, navigation, and timing system.

In South Korea, there was a series of actual jamming attacks from North Korea. During August 23-26 in 2010, jamming signals were broadcast from Gaesong area, which is about 8 km north from the Military Demarcation Line (MDL) between South Korea and North Korea. According to the Central Radio Management Office of South Korea, this jamming attack affected 181 cell towers, 15 planes, and 1 battle ship in South Korea. One year later, another jamming attack occurred for 11 days. At that time, 145 cell towers, 106 airplanes and 10 ships in South Korea had difficulty in receiving GPS signals. In 2012, jamming attacks continued for 16 days and 1,016 airplanes and 254 ships were affected. After experiencing these jamming attacks, South Korea has decided to deploy an eLoran system as a complementary Position, Navigation, and Timing (PNT) system to GPS [3].

In this paper, the Korean eLoran program is briefly introduced in Section II. After presenting the performance simulation tool for Korea in Section III, example eLoran accuracy plots over Korea are generated by the simulation tool in Section IV. Conclusions are given in Section V.

II. CURRENT LORAN-C INFRASTRUCTURE AND FUTURE ELORAN SYSTEM IN KOREA

Korea is in the coverage of the Korea Loran-C chain with GRI 9930, which contains five stations in the northeast Asia as shown in Figure 1. Two stations are in Pohang and Gwangju, Korea, other two stations are in Nijima and Gesashi, Japan, and the last one is in Ussuriysk, Russia. The master station is the Pohang station in Korea and the control station is in Daejeon, Korea. This Loran-C chain is still operating, but it is not widely utilized due to its relatively low navigation performance comparing to Global Navigation Satellite Systems (GNSS) such as GPS. Since Japan plans to discontinue its Loran-C operation by the end of 2014, this Korea Loran-C chain may not stably provide the legacy Loran-C service from 2015.

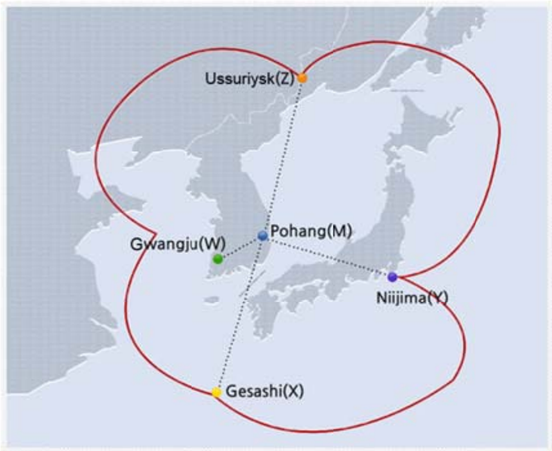

Figure 1 Locations of transmitters of the Korea Loran-C chain (from DGNSS Central Office, Korea)

As Seo and Kim [3] announced based on the eLoran design development and construction documents [4] prepared by ANSE Technologies, the South Korean government recently decided to deploy an eLoran system which can provide much better navigation performance than the legacy Loran-C system. The initial plan locates the five transmitters as in Figure 2. Two existing Loran-C stations in Pohang and Gwangju planned to be upgraded to eLoran stations, and additional three stations planed to be built in Jeju, Ganghwa, and Ulleung. In addition, 43 differential eLoran stations planned to be deployed over the country to provide a nationwide 20 m accuracy coverage. Currently, as of February 2014, there are on-going discussions to change this initial architecture of the Korean eLoran system, but the final decision is not yet made.

Figure 2 Initial plan of the transmitters locations of the future Korean eLoran system ([4], Figure 3 of [3])

III. ELORAN PERFORMANCE SIMULATION TOOL FOR KOREA

This paper presents an eLoran performance simulation tool for Korea, which can estimate the navigation performance such as accuracy of the future Korean eLoran system. This simulation tool development is based on the previous study of Lo *et al.* [5], which simulated the eLoran performance over the conterminous United States (CONUS).

In this section, the process of simulating eLoran accuracy is explained. In order to estimate eLoran accuracy, it is necessary to estimate the Signal-to-Noise Ratio (SNR) of received signals. In Section III-A, the received signal strength is calculated with the consideration of signal attenuation due to the effective ground conductivity. Then, the atmospheric noise estimation over Korea is discussed in Section III-B. Using the estimated received signal strength and atmospheric noise, the SNR is calculated in Section III-C. Lastly, the accuracy of the future Korean eLoran system is predicted in Section III-D based on the obtained SNR.

A. Received Signal Strength Simulation

Generally, the amount of signal attenuation is related to the distance that the radio wave travels. Signal strength decreases logarithmically when the propagation distance of the signal increases, but the distance is not the only factor that affects the signal attenuation. The character of ground along the traveling path of a signal induces additional signal attenuation to the signal strength. This effect due to the character of ground is evaluated numerically and represented as an effective ground conductivity. As discussed in [6], the equation showing the relationship between a received signal strength and an attenuation factor is,

$$\mathrm{PL}(r)[\mathrm{dB}] = \mathrm{PL}(r_0) - 10n\log\left(\frac{r}{r_0}\right) + ea$$

$\mathrm{PL}(r)$ is the signal power loss at a distance r, r_0 is a reference distance, n is a propagation path loss coefficient, and ea is an extra attenuation due to the effective ground conductivity. Thus, the signal attenuation is a function of the effective ground conductivity. Figure 3 shows the signal attenuation patterns for different effective ground conductivities. The signal strength decreases more rapidly along the terrain with a lower effective conductivity. Since the effective ground conductivity of sea water is 4 S/m, which is much higher than the one of land, the attenuation over the sea surface is significantly smaller than the one over the land surface. The effective ground conductivity data from the ITU [7] are used to simulate the received signal strengths over Korea in this paper.

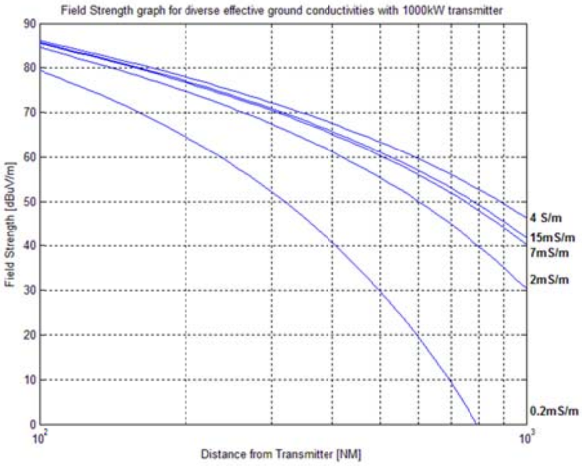

Figure 3 Signal strength attenuation for various effective ground conductivities

B. Atmospheric Noise Estimation

The research about the atmospheric noise and its influence on radio wave communications has been performed by the International Telecommunication Union (ITU). (Refer to Boyce [8] for details.) The ITU has collected the atmospheric noise data named as F_a since 1956 when it was CCIR, the predecessor of ITU, and it organized the data as a form of a document [9]. Because the atmospheric noise is a stochastically distributed variable, not a specific value, the data contains only the medium value of a certain percentage condition (90%). Therefore the value on the document has to be converted into the value with the desired condition. Next formula is used to change the 90% F_a value on the document to the F_a with required P% [8].

$$F_{a,P} = F_{am} + D_u \cdot \frac{\text{norminv}(P/100\,,0,1)}{\text{norminv}(90/100\,,0,1)}$$

F_{am} is the medium F_a value of the distribution represented by the data from the ITU document, and D_u is the upper decile of the distribution. With this $F_{a,P}$, the atmospheric noise E_n for a certain percentage P%, is calculated by the following formula.

$$E_n[\text{dB}(\mu V/m)] = F_{a,P} + 20\log f_{MHz} + 10\log b - 95.5$$

f_{MHz} is the frequency of radio wave and b is the bandwidth of radio wave. The detailed process of induction of this equation is included in [8]. The obtained atmospheric data varies with the season and the time slot of a day. For instance, Figure 4 shows an example output from our software with the condition of a winter season and 21:00 ~ 22:00 time slot.

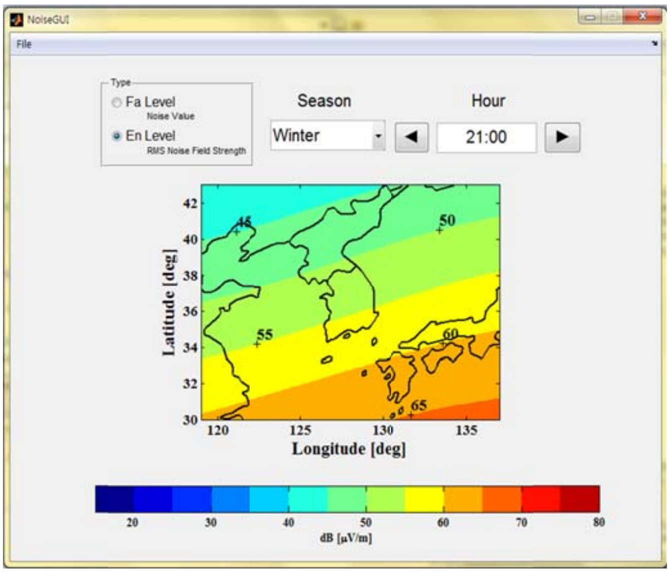

Figure 4 Example output of the atmospheric noise over Korea

C. SNR Calculation

Most of the atmospheric noise is due to the lightning and it has a peak at 10 kHz and bandwidth between 1 kHz and 20 MHz [8]. Since the eLoran signal is a 100 kHz radio wave and it is within the bandwidth of the lightning, the atmospheric noise becomes the main source of the noise for the eLoran receiver. Therefore, the SNR of received eLoran signals can be estimated as a ratio between the received signal strength and atmospheric noise. The received signal strength of eLoran signal is simulated in Section III-A, and the atmospheric noise over Korea is obtained in Section III-B. Thus, the ratio between those two results becomes SNR.

D. Accuracy Simulation

In order to simulate accuracy of the eLoran system, the error standard deviation of position measurements is required. The standard deviation can be obtained by the following formula.

$$\sigma_i^2 = J^2 + (\sigma_{256}^2 \cdot \frac{256}{T_{avg} \cdot pps_i}) \times 10^{-\frac{SNR_i}{10}}$$

J is the jitter of a transmitter, σ_{256} is a reference standard deviation of 256 pulses, T_{avg} is the integration time in seconds, pps_i is the number of pulses per second transmitted from the i^{th} transmitter, and SNR_i is the SNR of the signal transmitted from the i^{th} transmitter that we obtained in Section III-C. Weight matrix W is a diagonal matrix which is composed of the error standard deviation for each station.

$$W = \begin{bmatrix} \sigma_1^2 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \sigma_N^2 \end{bmatrix}^{-1}$$

Then the position error matrix can be calculated by the following equation.

$$\begin{bmatrix} \sigma_x^2 & 0 & 0 \\ 0 & \sigma_y^2 & 0 \\ 0 & 0 & \sigma_t^2 \end{bmatrix} = (G^T W G)^{-1}$$

G is a geometry matrix which contains cosine and sine values of azimuth of each station. Then horizontal 95% accuracy is calculated by the following formula.

$$\text{Accuracy} = 2\sqrt{\sum_i K_i \sigma_i^2} = 2\sqrt{\sigma_x^2 + \sigma_y^2}$$

The horizontal accuracy of the planned Korean eLoran system is simulated through this series of calculations. The accuracy simulation is performed with various conditions and example results are shown in Figure 5. Note that Figure 5 represents repeatable accuracies which do not consider temporal and spatial variations of Additional Secondary Factor (ASF). The accuracy from this simulation assumes ASF errors are mostly mitigated by differential eLoran stations and ASF maps.

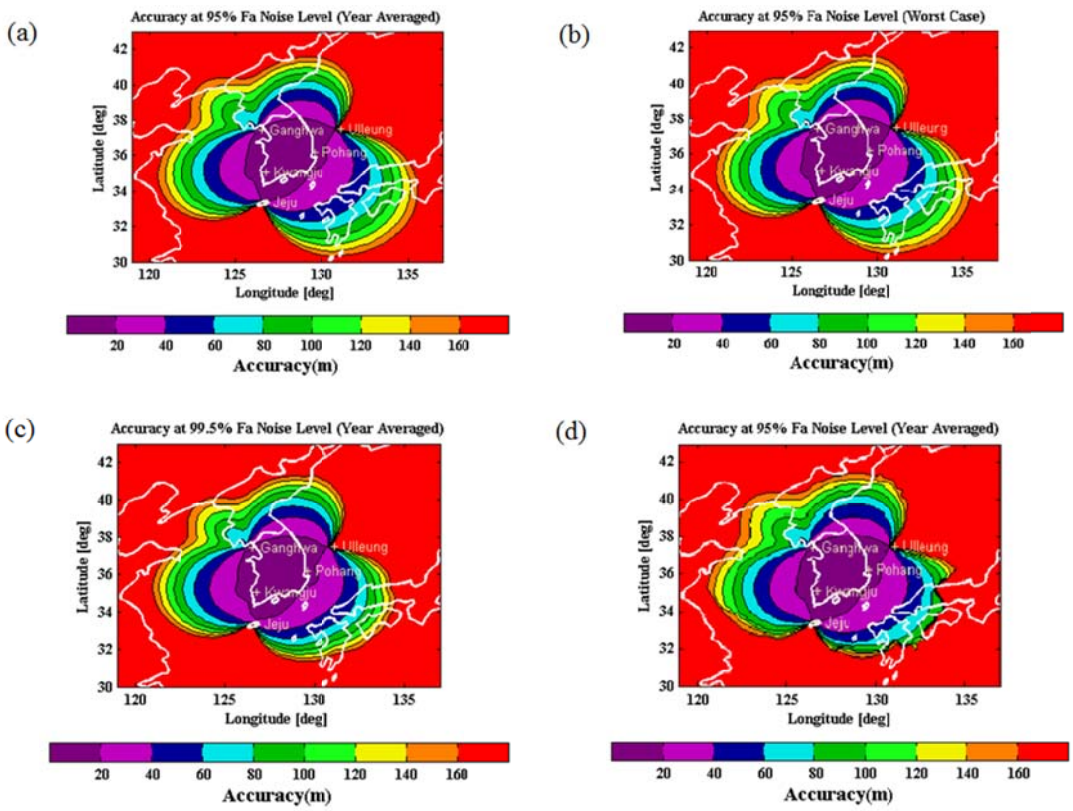

Figure 5 Example accuracy simulation results for various conditions (a) Repeatable accuracy plot for 95% noise level,

year averaged, -15dB of SNR threshold (b) Repeatable accuracy plot for 95% noise level, worst case of a year, -15dB of SNR threshold (c) Repeatable accuracy plot for 99.5% noise level, year averaged, -15dB of SNR threshold (d) Repeatable accuracy plot for 95% noise level, year averaged, -12dB of SNR threshold

IV. SIMULATED ELORAN ACCURACY OVER KOREA

As of February 2014, the locations and powers of the transmitters for the Korean eLoran system are not yet confirmed. There are several proposals for the transmitting powers. Three example cases are presented in Table 1 and the accuracy plot for each case is shown in Figure 6. The first case assumes 1000 kW transmitting powers of the five stations. The second case is a set of reasonable powers without noticeable impact on the coverage. The coverage area in Figure 6(b) is not much smaller than the case 1 in Figure 6(a). In order to expand the coverage, the case 3 uses additional transmitter in Goseong. The expanded area with a 20 m accuracy is shown in Figure 6(c). Again, these accuracy plots in Figure 6 represent ideal accuracy when temporal and spatial ASF errors are mitigated by differential eLoran stations and ASF maps respectively.

Table 1 Three sample cases of transmitting powers for the future Korean eLoran system

	Pohang	**Gwangju**	**Jeju**	**Ganghwa**	**Ulleung**	**Gosung**
Case 1	1000	1000	1000	1000	1000	-
Case 2	150	50	250	250	100	-
Case 3	150	50	250	250	1000	250

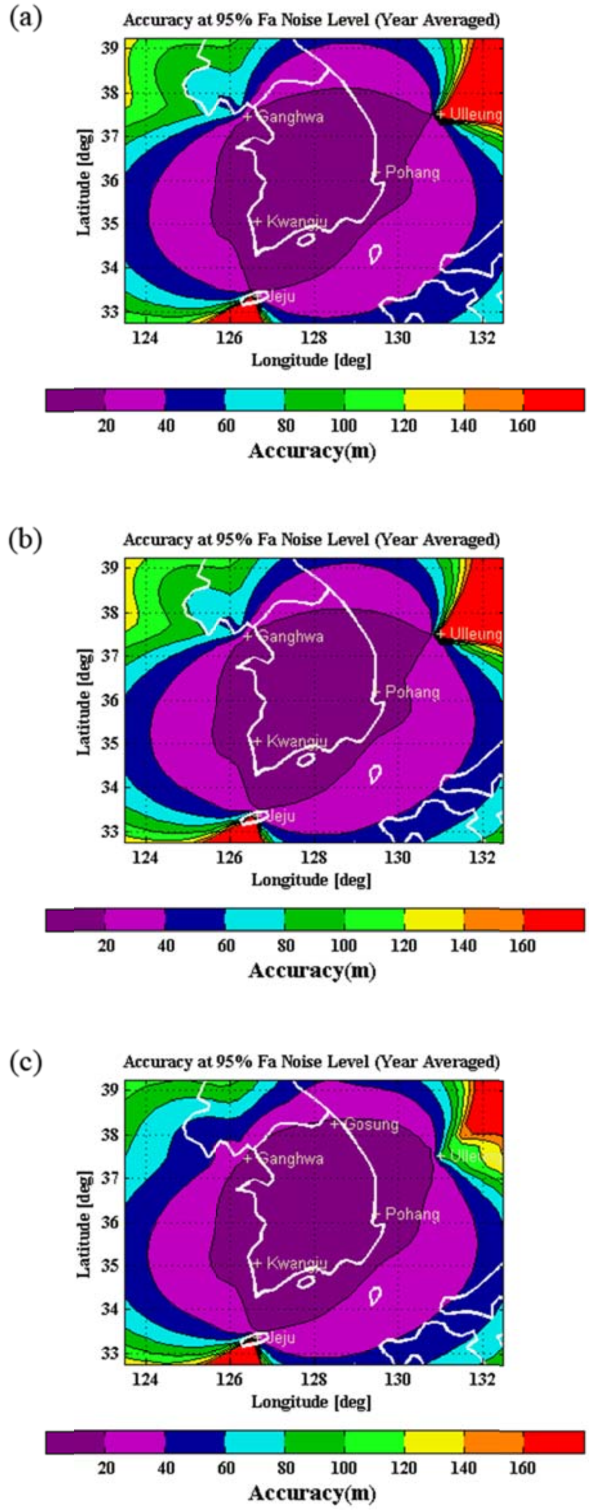

Figure 6 Simulation results for the cases of Table 1 (a) Accuracy plot for the case 1 of Table 1 (b) Accuracy plot for the case 2 of Table 1 (c) Accuracy plot for the case 3 of Table 1

V. CONCLUSIONS

In this paper, an eLoran performance simulation tool for Korea is presented. The simulation tool can calculate the eLoran accuracy based on the SNR estimation, which is the ratio between the received signal strength and the atmospheric noise. This tool can simulate the accuracy performance for various conditions such as transmitting powers, locations of transmitters, an SNR threshold of a receiver, seasons, noise levels, and so forth. Example accuracy results obtained by this tool were presented in this paper. This simulation tool will be further expanded to simulate other navigation performances such as integrity, availability, and continuity.

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REFERENCES

[1] Carroll, J. V., 2003, Vulnerability assessment of the US transportation infrastructure that relies on the Global Positioning System, NAVIGATION: The Journal of Navigation, Vol. 56, Issue 2, pp. 185-193

[2] Narins, M., Eldredge, L., Enge, P.K., Harrison, M., Kenagy, R., Lo, S., 2010, Alternative Position, Navigation, and Timing-The Need for Robust Radionavigation, Royal Institute of Navigation -NAV 10, London, UK.

[3] Seo, J. and Kim, M., 2013, eLoran in Korea - Current Status and Future Plans, Proceedings of the European Navigation Conference 2013, Vienna, Austria

[4] The Ministry of Oceans and Fisheries of Korea, Design Development and Construction Documents for the Korean eLoran System, 2013, Unpublished internal documents by ANSE Technologies

[5] Lo, S. C., Peterson, B. B., Boyce Jr., C.O. L., Enge, P. K., 2008, Loran Coverage Availability Simulation Tool, Proceedings of the Royal Institute of Navigation NAV08 / International Loran Association 37th Annual Meeting

[6] Rhee, J. H. and Seo, J., 2013, eLoran Signal strength and Atmospheric Noise Simulation over Korea, Journal of Korean GNSS Society, Vol. 2, Issue 2, pp. 101-108

[7] International Telecommunication Union – Radiocommunication Sector, 1992, Groundwave Propagation Curves for Frequencies between 10 kHz and 30 MHz, REC.ITU-R P.368-7

[8] Boyce, Jr., C. O. L., 2007, Atmospheric Noise Mitigation for Loran, Ph.D. dissertation, Stanford University

[9] International Telecommunication Union – Radiocommunication Sector, 2009, Radio Noise REC.ITU-R P.372-10