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Modeling & Simulation Software Design for Coverage Analysis of Multiple Radio Positioning Integration System

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ABSTRACT

Since the Global Navigation Satellite System (GNSS) may not provide navigation information due to external interferences, many countries have plans to prepare a backup system for this situation. One of the possible GNSS backup systems is a multiple radio positioning integration system in combination with the terrestrial radio navigation system. Before constructing such a GNSS backup system, M&S software is needed to analyze if the system satisfies the performance the required navigation performance. This study presents requirements of M&S software for coverage analysis of the navigation system, and proposes an M&S software design scheme on the basis of the requirements. The M&S software is implemented, and coverage analysis is performed to verify the validity of the proposed design scheme.

Keywords: coverage analysis, M&S software, gap filling, terrestrial radio navigation system, integrated navigation system

1. INTRODUCTION

The Global Navigation Satellite System (GNSS), which is an important infrastructure providing navigation information globally, is used in various areas including surveying, time synchronization, weapon system, and communication. However, the GNSS may be disabled by external interferences such as jamming and spoofing, since the received signal strength is very weak (Jeong et al. 2012). To prepare against the GNSS failure, many countries have plans of backup systems based on terrestrial radio navigation systems. The U.S. has a backup system plan which is the NextGen Implementation Plan announced by the Federal Aviation Administration (Eldredge et al. 2010, Lo et al. 2010, FAA 2014). Similarly, Sweden has the Swedish Radio Navigation Plan announced by the Swedish Maritime Administration (SMA 2009). Germany has a plan similar to that of the U.S., which is the Single European Sky ATM Research (Lo et al. 2015). The U.K is carrying out a GNSS backup system on the basis of enhanced Long range navigation (eLoran), which is currently under initial operation (Inside GNSS 2014).

Before applying these GNSS backup systems to the actual environment, a performance evaluation should be required. It should be considered if the required navigation performance is satisfied in the area where the navigation system is operated, and, if not, reducing the gap should be taken into consideration, through a deployment of additional signal sources and/or other methods (Kim 2012a, b).

This study provides results of the M&S software design for the deployment of signal sources of the radio navigation system and the coverage analysis. Through the M&S software, the dilution of precision (DOP) distribution and the coverage are shown and deployment of new signal

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sources to extend the coverage as well as change of the DOP distribution and the coverage of the new signal sources is also verified.

2. COVERAGE ANLYSIS AND GAP FILLING

2.1 Coverage Analysis

Coverage analysis is a process of identifying the areas where a given performance is satisfied on the basis of the suggested deployment of ground station. In case of aircraft, the International Civil Aviation Organization provides the Total System Error (TSE) as an index for the require navigation performance for each flight stages, as shown in Eq. (1):

$$TSE = \sqrt{PDE^2 + FTE^2 + NSE^2} \qquad (1)$$

In Eq. (1), the TSE, defines how much an aircraft is deviated from the planned course. The Path Definition Error (PDE) is the error between the planned course and the defined error, and includes variables reflecting the navigation database error, calculation error, and display error. The Flight Technical Error (FTE) refers to the error caused by pilot's ability or automatic pilot system. The Navigation System Error (NSE) refers to the error between the true position of the aircraft and the estimated position of the navigation system. The PDE generally has a fixed value of 0.25 NM, while the FTE has fixed values according to the flight stages and the required navigation performance, as shown in Table 1. Therefore, the coverage analysis analyzes change of the NSE according to the distribution of the navigation signal sources in the target region (PBN Korea 2014a, b).

For the coverage analysis to the deployment of the navigation signal source, the DOP corresponding to the NSE of the target navigation system should be obtained. The DOP, representing the effect of the navigation system measurement error on the navigation result, is calculated from the measurement matrix of the navigation equation.

Table 1. FTE value at each flight stage (PBN Korea 2014b).

Flight stage	Required navigation performance	FTE (95%)
En route	RNAV 5.0	2.5 NM
	RNP 4.0	2.0 NM
	RNAV 1.0	0.5 NM
	RNP 1.0	0.5 NM
Terminal	RNAV 2.0	1.0 NM
	RNAV 1.0	0.5 NM
	RNP 1.0	0.5 NM
Final approach	RNP APCH	0.25 NM
Missed approach	RNP APCH	0.5 NM

After calculating the DOP corresponding to the NSE of the target navigation system in the target region, the DOP is multiplied by the navigation system measurement error to calculate the estimated error at a certain position. If the estimated performance satisfies a desired vale, the position is included in the coverage (Kim 2012a, b). In the case of a unit navigation system, the performance is estimated from multiplication of the DOP and the navigation system measurement error. However, in the case of an integration of multiple navigation systems, weighting values are given to calculate the weighted DOP, since the errors of the unit navigation systems are different. The estimated performance is calculated and the coverage is determined in the target region on the basis of the weighted DOP (Won et al. 2012).

2.2 Gap Filling

The gap filling is a process determining positions of additional deployment of navigation signal sources to have a maximum coverage when the coverage is not sufficient and extension is required (Kim 2012a, b).

First, in the coverage analysis result, the areas where the navigation signals are not reached and the required navigation performance is not satisfied are defined as the gap. Positions of the additionally deployed navigation signal sources are determined in the gap. The coverage analysis is performed again to the original navigation signal sources and the additionally deployed navigation signal sources to calculate the coverage area. The newly calculated areas of the coverage are compared. The position of the additionally deployed navigation signal source is a result of the gap filling when the area of the coverage is maximum.

3. REQUIREMENT OF COVERAGE ANALYSIS M&S SOFTWARE

As mentioned previously, the coverage analysis depending on the spatial deployment of the navigation signal sources of the multiple radio navigation systems is a process of identifying the coverage in the target region and determining the positions of the additionally deployed navigation signal sources to extend the coverage satisfying the required navigation performance. The following points should be considered when designing M&S software for the coverage analysis:

1) The M&S software should enable to input parameters

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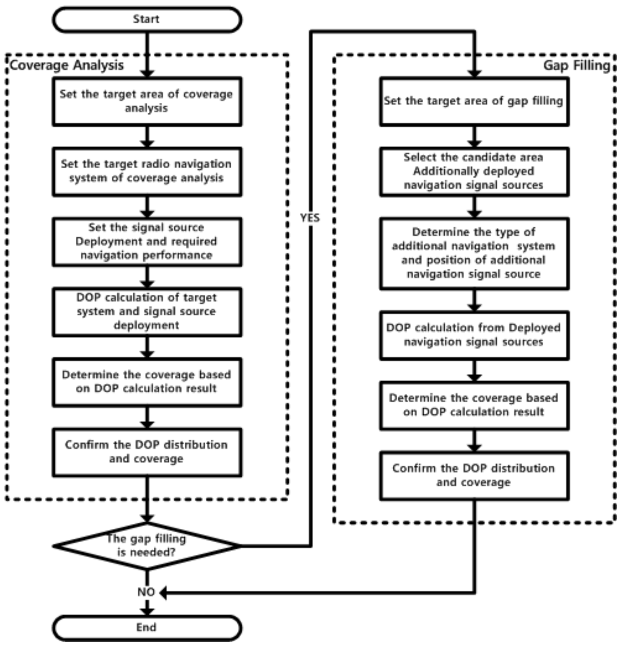

Fig. 1. Multi-GNSS signals in frequency space.

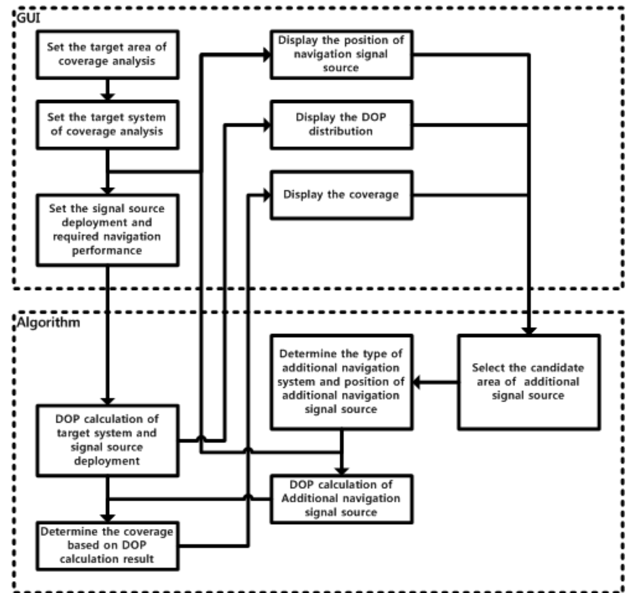

Fig. 2. Coverage analysis M&S software design concept.

needed for the coverage analysis, including the types of navigation signal sources, the deployment of the navigation signal sources, the required navigation performance, and the target region.

2) The M&S software should enable to provide the coverage analysis results according to the deployment of the navigation signal sources.
3) The M&S software should enable to calculate and verify the types and position of new navigation signal sources to carry out the gap filling.
4) The M&S software should enable to compare coverages for various deployments of navigation signal sources.

Fig. 1 shows the coverage analysis and the gap filling process. Fig. 2 shows the design concept reflecting the requirements of the coverage analysis M&S software.

4. DESIGN OF COVERAGE ANALYSIS M&S SOFTWARE

This section presents the design technique for the coverage analysis M&S software reflecting requirements presented in Section 3. The coverage analysis M&S software should enable users to input the parameters in Table 2, and output the results in the items in Table 3. The coverage analysis M&S software consists of the graphic user interface (GUI) part, the coverage analysis part, and the gap filling

Table 2. Inputs for coverage analysis.

Items	Parameters	Unit
Target region	Northern boundary of coverage analysis	degree (dms)
	Eastern boundary of coverage analysis	degree (dms)
	Western boundary of coverage analysis	degree (dms)
	Southern boundary of coverage analysis	degree (dms)
Required navigation performance	Type	NM
	Performance index	-
Navigation signal source	Navigation signal source ID	-
	Navigation signal source type	-
	Navigation signal source latitude	degree (dms)
	Navigation signal source longitude	degree (dms)
	Navigation signal source altitude	meter
Additional navigation signal source	Navigation signal source type	-
	Navigation signal source latitude	degree (dms)
	Navigation signal source longitude	degree (dms)
	Navigation signal source altitude	meter

Table 3. M&S software outputs.

Items	Information	Unit
Required navigation performance	Type of performance	NM
	Performance goal index	-
Deployment of navigation signal sources	Navigation signal source ID	-
	Navigation signal source type	-
	Navigation signal source latitude	degree (dms)
	Navigation signal source longitude	degree (dms)
	Navigation signal source altitude	meter
Additional navigation signal sources	Navigation signal source type	-
	Navigation signal source latitude	degree (dms)
	Navigation signal source longitude	degree (dms)
	Navigation signal source altitude	meter
Coverage	DOP distribution in the target region	-
	Coverage in the target region	-

part.

4.1 GUI Part

The GUI part receives from a user the types of navigation signal sources, the positions of the navigation signal sources, and the required navigation performance which are the targets of the coverage analysis. The GUI displays the positions of the navigation signal sources, the DOP distribution according to the deployment of the navigation signal sources, and the coverage according to the required navigation performance.

4.2 Coverage Analysis Part

The coverage analysis part calculates the coverage in the target region by using the input parameters from the GUI part. The coverage analysis part transfers the required navigation performance, which is input from the GUI part, to the coverage analysis algorithm, and transfers the positions of the deployed navigation signal sources of the navigation system selected by the GUI part. On the basis of the transferred required navigation performance and the navigation signal source positions, DOP distribution in the target region is calculated, and coverage is determined from the DOP distribution. The calculated DOP distribution and coverage are transferred to the GUI part to be output as the coverage analysis results.

4.3 Gap Filling Part

The gap filling part determines position of the additional navigation signal source which maximize the coverage in the target region.

Suppose that the result of the coverage analysis is given in Fig. 3. Mark 0 means that the region satisfies the required navigation performance, i.e., it is in the coverage. Mark 1 means that the region is not in the coverage. Outside the coverage, mark 1 means that signals from the navigation stations are not reached. Inside the coverage, mark 1 means that the required navigation performance is not satisfied in the region.

It is assumed that additional signal source would be deployed in the mark 1 regions inside the coverage, mark 1 boundary regions surrounding the coverage or some designated regions.

In order to extract the mark 1 regions inside the coverage and the mark 1 boundary regions, the coverage analysis result is passed through a dilate filter given in Fig. 4.

The procedure of the filtering is shown in Fig. 5. Before describing the procedure, some additional values should be defined. The (0, j) (j = 1, …, 13) element, the (i, 0) (i = 1, …, 12) element, the (13, j) (j = 1, …, 13) element and the (i, 14) (i = 1, …, 12) element are all set to be 1. (Gonzalez et el. 2009).

If the value of the (i, j) (i = 1, …, 12, j = 1, …, 13) element in Fig. 3 satisfies the following 5 conditions, the value of (i, j) (i = 1, …, 12, j = 1, …, 13) element of the output of the dilate filter is 1. Otherwise the output is 0. Output of the dilate filter for the result in Fig. 3 is given Fig. 6.

(0,0) (0,14)

1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	0	0	0	0	1	1	1
1	1	1	1	0	0	0	1	1	0	1	1	1
1	1	1	1	0	0	0	1	1	0	1	1	1
1	1	1	1	1	0	0	0	0	0	1	1	1
1	1	1	1	1	1	0	0	0	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1

(13,0) (13,14)

Fig. 3. Result of coverage analysis.

0	1	0
1	1	1
0	1	0

Fig. 4. Dilate filter.

- The value of the (i, j) element of the coverage analysis result is equal to the value of the (2, 2) element of the dilate filter.
- The value of the (i-1, j) element of the coverage analysis result is equal to the value of the (1, 2) element of the dilate filter.
- The value of the (i, j-1) element of the coverage analysis result is equal to the value of the (2, 1) element of the dilate filter.
- The value of the (i, j+1) element of the coverage analysis result is equal to the value of the (2, 3) element of the dilate filter.
- The value of the (i+1, j) element of the coverage analysis result is equal to the value of the (3, 2) element of the dilate filter.

By subtracting values in Fig. 6 from those in Fig. 3, the result in Fig. 7 can be obtained. Mark 1 in Fig. 7 denotes a candidate region for additional signal source.

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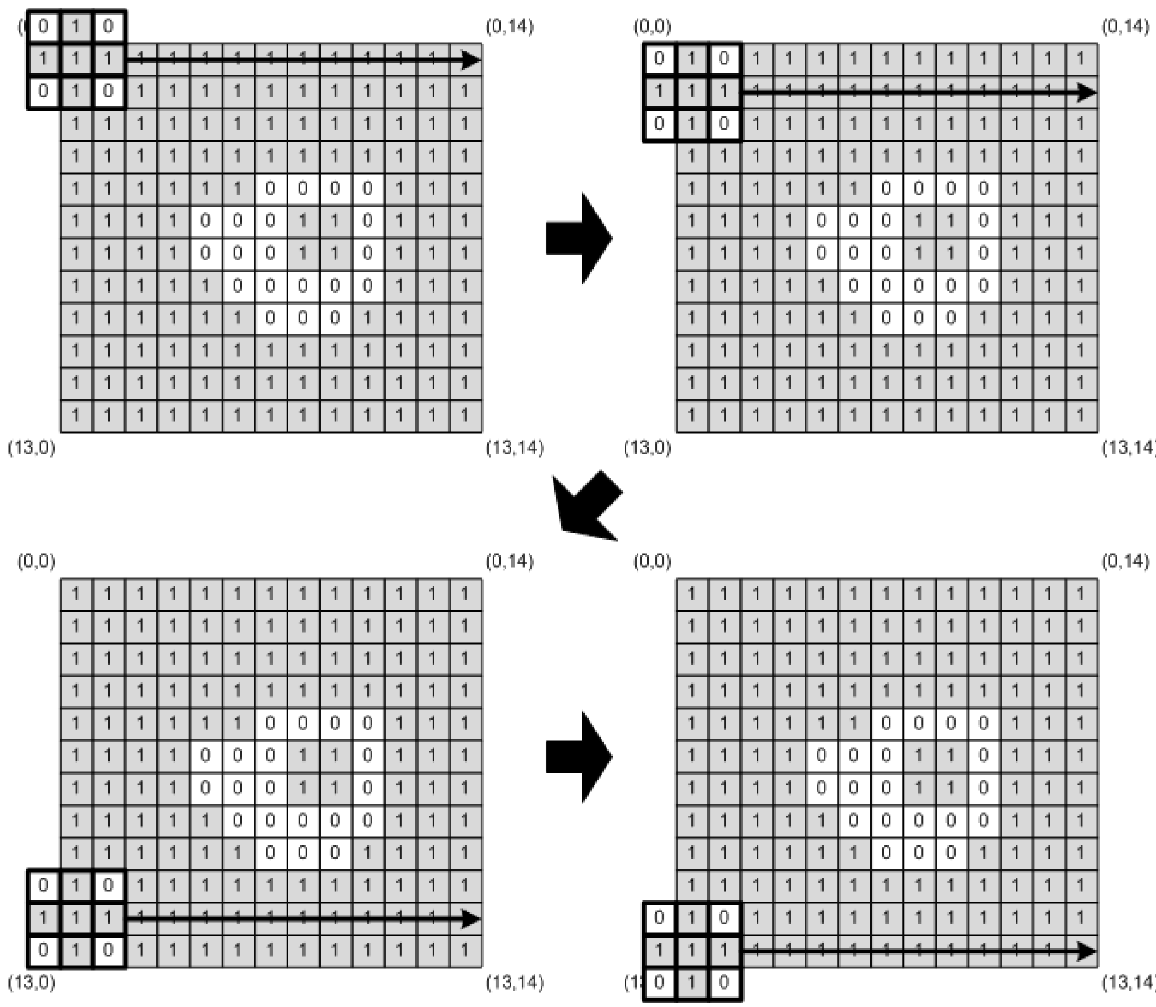

Fig. 5. Procedure of dilate filtering.

Designated regions for additional signal source deployment are supposed to be mark 1 region in Fig. 8. Due to some topographical reasons, it is assumed that it is possible to locate the signal sources only the mark 1 regions in Fig. 9.

As assumed previously, additional navigation signal source would be deployed in mark 1 regions in Fig. 7 or Fig. 8. However topographically, it is possible to locate the signal source only the mark 1 regions in Fig. 9. Finally candidate regions for deployment of additional navigation signal source are obtained as mark 1 regions in Fig. 10.

After deploying a new navigation signal source in a mark 1 area in Fig. 10, coverage analysis is performed for the new deployment of the navigation signal sources. This operation is repeated for all the mark 1 regions in Fig. 10. For the all cases, area of the coverages are obtained and compared. When the coverage area is maximum, the candidate region is determined to be the location of new deployment of navigation signal source. This location is the final result

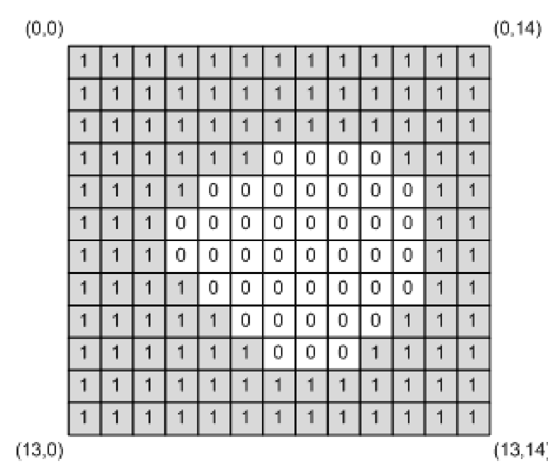

Fig. 6. Output of dilate filer for the result of coverage analysis.

of the gap filling. Weighting values can be used to the significance of the signal source in the calculation. This gap filling result is transferred to the GUI part.

(0,0) (0,14)

0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	1	1	1	1	0	0	0
0	0	0	0	1	1	0	0	0	0	1	0	0
0	0	0	1	0	0	0	1	1	0	1	0	0
0	0	0	1	0	0	0	1	1	0	1	0	0
0	0	0	0	1	0	0	0	0	0	1	0	0
0	0	0	0	0	1	0	0	0	1	0	0	0
0	0	0	0	0	0	1	1	1	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0

(13,0) (13,14)

Fig. 7. Extracted candidate region for additional signal source.

(0,0) (0,14)

0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	1	1	0	0	0	0	0	0	0	0
0	1	1	1	1	0	0	0	0	0	0	0	0
0	1	1	1	1	0	0	0	0	0	0	0	0
0	0	1	1	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0

(13,0) (13,14)

Fig. 8. Designated region for additional signal source deployment.

(0,0) (0,14)

0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	1	1	0	0	0	0
0	0	0	0	0	0	1	1	1	0	0	0	0
0	0	0	1	1	1	1	1	0	0	0	0	0
0	0	1	1	1	1	1	1	0	0	0	0	0
0	0	1	1	1	1	1	1	0	0	0	0	0
0	0	0	0	0	1	1	1	1	1	0	0	0
0	0	0	0	0	0	0	1	1	1	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0

(13,0) (13,14)

Fig. 9. Regions where a navigation signal sources can be located.

(0,0) (0,14)

0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	1	1	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	1	1	0	0	1	0	0	0	0	0
0	0	1	1	1	0	0	1	0	0	0	0	0
0	0	1	1	1	0	0	0	0	0	0	0	0
0	0	0	0	0	1	0	0	0	1	0	0	0
0	0	0	0	0	0	0	1	1	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0

(13,0) (13,14)

Fig. 10. Candidates for the arrangement of additional navigation signal sources.

5. IMPLEMENTATION AND PERFORMANCE EVALUATION OF COVERAGE ANALYSIS M&S SOFTWARE

The design technique for the coverage analysis M&S software presented in Section 4 was implemented for Distance Measuring Equipment (DME), Long-Range Navigation-C (Loran-C), eLoran, and DME/eLoran Multiple Radio Positioning Integration System, and the performance evaluation was carried out.

5.1 Implementation of Coverage Analysis M&S Software

Figs. 11 and 12 show the GUI of the coverage analysis M&S software implemented for the multiple radio positioning integration system.

5.2 Coverage Analysis and Gap Filling of Unit Navigation System

To verify the design concept mentioned above, coverage analysis and gap filling were performed for the DME, Loran-C, and eLoran systems.

In the case of the DME system, the required navigation performance was set to be RNP 0.3, and the coverage analysis was performed by selecting 5 out of 50 DME signal sources located in Korea. Fig. 13 shows the coverage when the DME signal sources located at Gimhae, Songtan, Jeju, Muan, and Wonju were selected. Fig. 14 shows the coverage when the DME signal sources located at Gimhae, Gangneung, Muan, Yeosu, and Ulsan were selected. Figs. 13 and 14 show that the coverage change to the geometrical deployment of the five navigation signal sources.

Among the coverage analysis results, gap filling was

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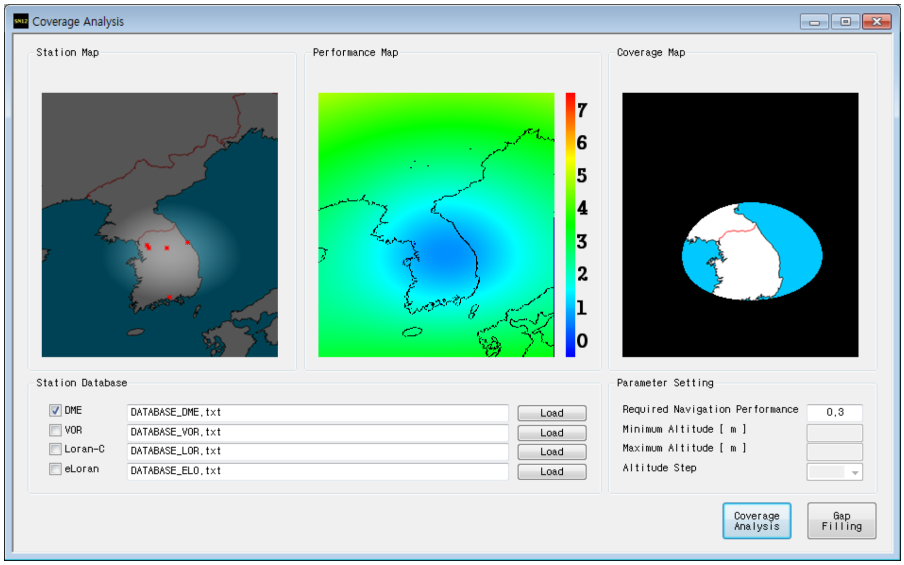

Fig. 11. Coverage analysis GUI.

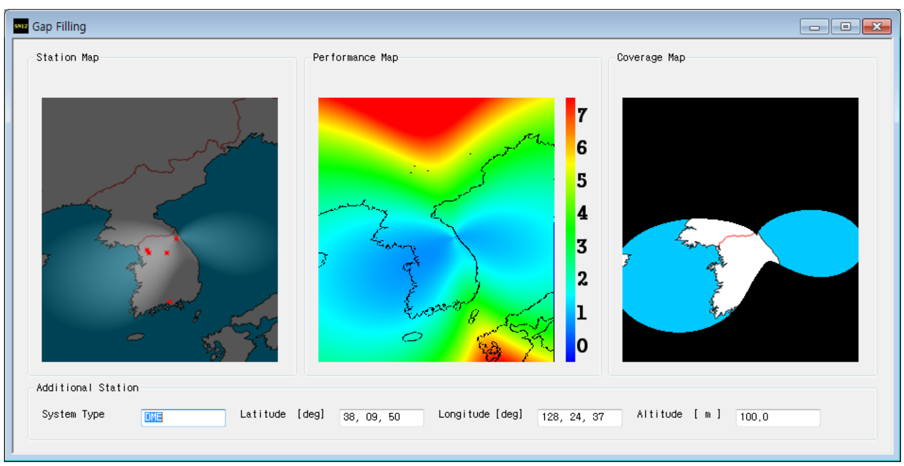

Fig. 12. Gap filling GUI.

performed for the DME signal sources located at Gimhae, Songtan, Jeju, Muan, and Wonju. The result is shown in Fig. 15. The position of the additional navigation signal source to extend the coverage is lat. N 38°12′34.74″, long. E 128°29′48.8″.

In the case of the Loran-C system, the required navigation performance was set to be RNP 0.3 as the DME system. The coverage analysis was performed for all the Loran-C signal sources included in the Loran-C Korea Chain, which are the sources at Pohang, Gwangju, Niijima, Gesashi, and Ussuriisk. Even though the signal sources located at Niijima and Gesashi have been stopped since February 1, 2014, and February 1 (National Maritime PNT Office 2013), 2015, respectively, they were used for the performance analysis to verify the proposed method in this study. Fig. 16 shows the coverage analysis result for RNP 0.3. Fig. 17 shows the result of the gap filling for the Loran-C system. The position of the additional navigation signal source to extend the coverage of the Loran-C system is lat. N 38°7′5.50″, long. E 127°24′56.3″.

In the case of the eLoran system, the required navigation performance was set to be RNP 0.3 as the DME and Loran-C systems. The coverage analysis was performed for five navigation signal sources located at Ganghwa, Ulleung, Jeju, Pohang, and Gwangju. Fig. 18 shows the result of the coverage analysis of the eLoran system. The standard deviation of the navigation measurement error of the eLoran was set to be 10 m which is smaller than that of the DME system or Loran-C system. Thus, the result shows that the coverage is much wider. As shown in Fig. 18, when the required navigation performance is RNP 0.3, all the target region satisfies the required navigation performance, and

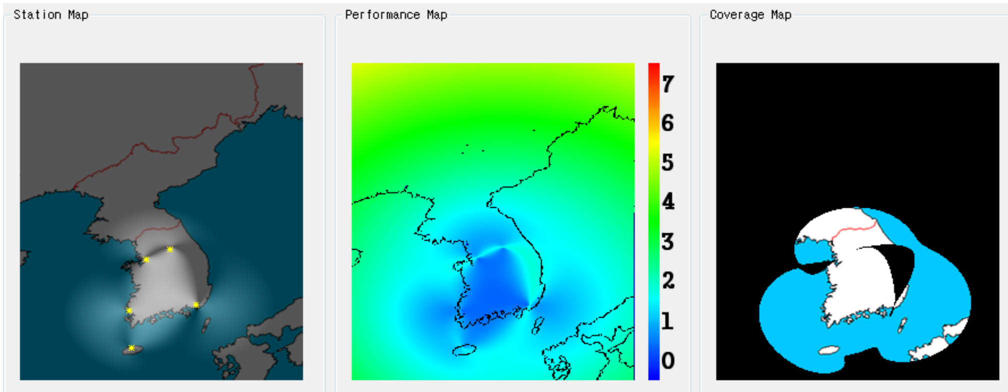

Fig. 13. DME coverage analysis result (1).

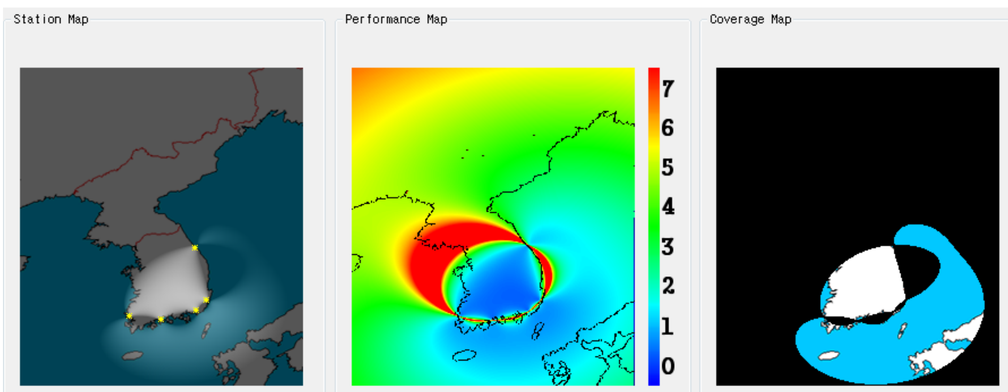

Fig. 14. DME coverage analysis result (2).

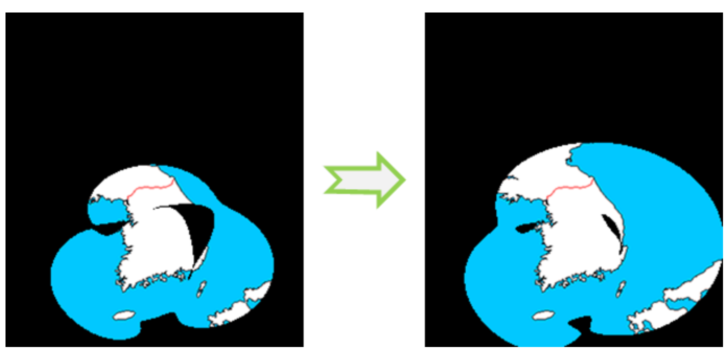

Fig. 15. DME gap filling result.

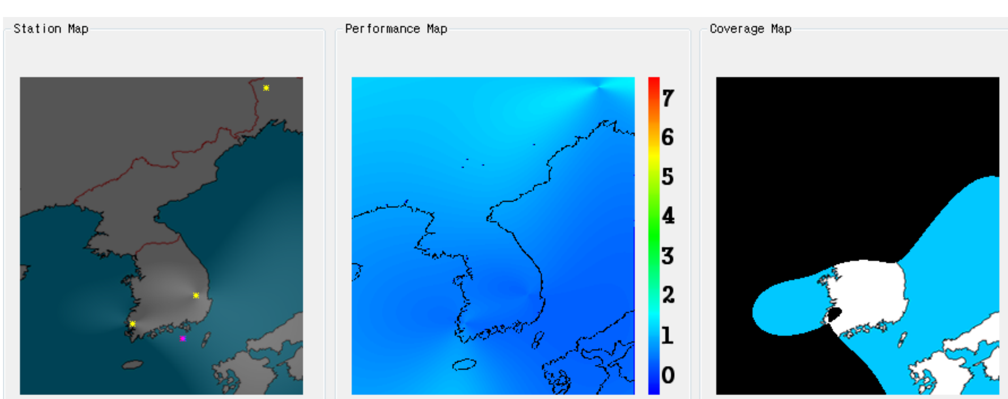

Fig. 16. Loran-C coverage analysis result.

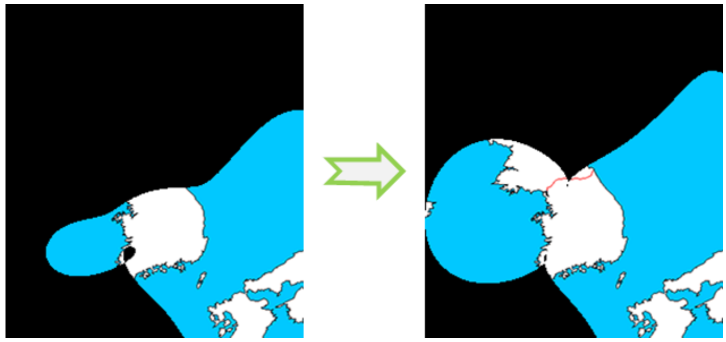

Fig. 17. Loran-C gap filling result.

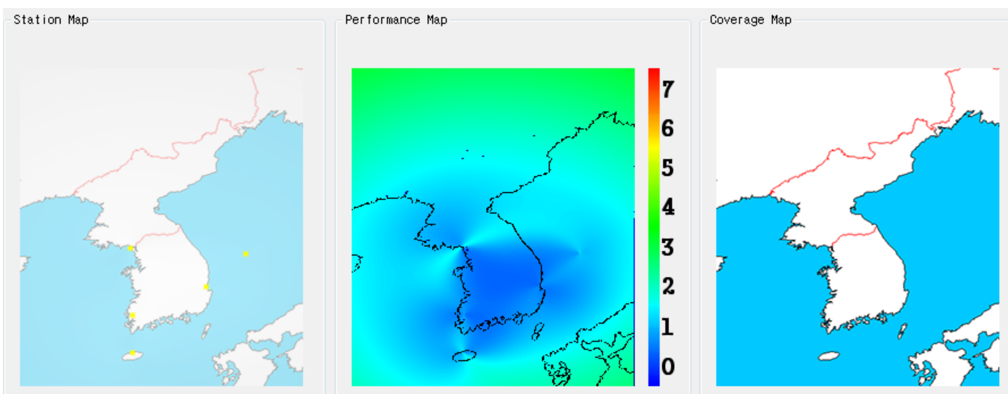

Fig. 18. Coverage analysis result of eLoran-C.

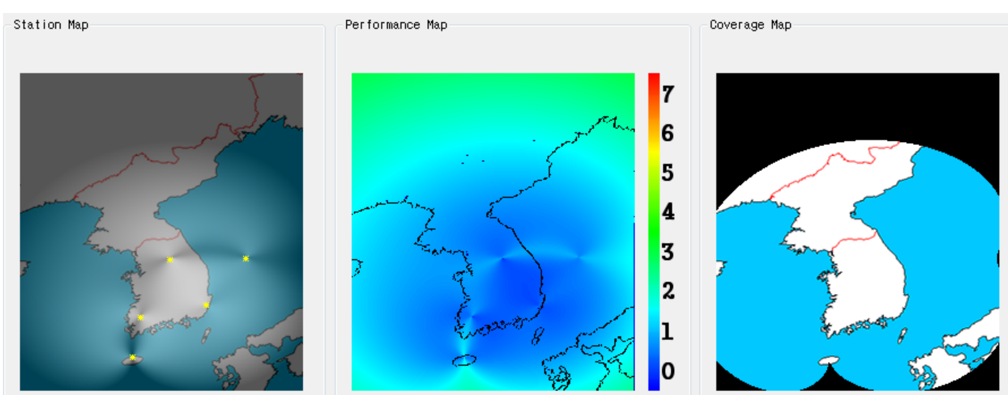

Fig. 19. Coverage analysis result of DME/eLoran.

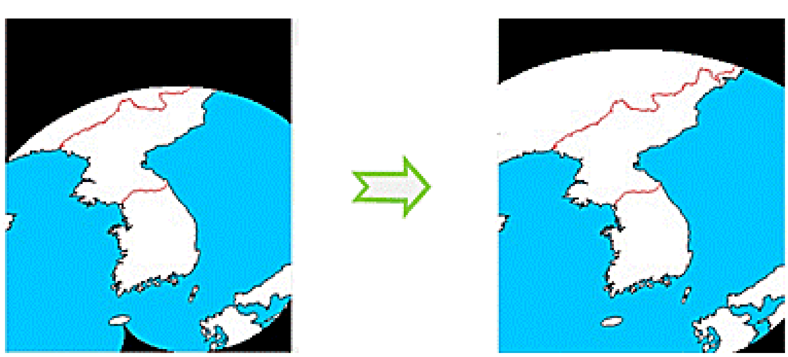

Fig. 20. Gap filling result of DME/eLoran.

thus the gap filling was not performed.

5.3 Coverage Analysis and Gap Filling of Multiple Radio Positioning Integration System

Coverage analysis and gap filling were performed for the DME/eLoran integration system. The required navigation performance of the DME/eLoran integration system was set to be RNP 0.3. The coverage analysis was performed for the DME navigation signal sources located at Gwangju, Wonju, and Ulsan as well as the eLoran navigation signal sources located at Ulleung and Jeju. Fig. 19 shows the result of the coverage analysis for the DME/eLoran integration system, and Fig. 20 shows the result of the gap filling. The position of the additional navigation signal source is lat. N 38°07´05.80″, long. E 127°14´33.2″, and the type of the additional navigation system is the DME system.

6. CONCLUSIONS

In this paper, a design method of the M&S software has been proposed for the coverage analysis according to the deployment of navigation signal sources of the radio navigation system. The requirements of the M&S software have been firstly presented, and then a design method to satisfy the requirements has been proposed. To verify the proposed design method the M&S software has been implemented for the DME, Loran-C, eLoran, and DME/eLoran integration systems, and coverage analysis and gap filling have been performed for the systems. The design method has been verified on the basis of the results.

In the future, change of the coverage will be analyzed to the shading of the navigation signal and height of the vehicle on the M&S software design method proposed in this paper. Coverage and gap filling will be performed for more various kinds of navigation systems. Finally more effective deployment method of navigation signal sources will be derived in order to maximize the coverage.

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