JPNT 4(2), 79-85 (2015)
http://dx.doi.org/10.11003/JPNT.2015.4.2.079

JPNT Journal of Positioning, Navigation, and Timing

Development of a Virtual Reference Station-based Correction Generation Technique Using Enhanced Inverse Distance Weighting

Hyunu Tae[1†], Hye-In Kim[2], Kwan-Dong Park[1]

[1]Department of Geoinformatic Engineering, Inha University, Incheon 402-751, Korea
[2]Jipyong Space Inc., Incheon 402-751, Korea

ABSTRACT

Existing Differential GPS (DGPS) pseudorange correction (PRC) generation techniques based on a virtual reference station cannot effectively assign a weighting factor if the baseline distance between a user and a reference station is not long enough. In this study, a virtual reference station DGPS PRC generation technique was developed based on an enhanced inverse distance weighting method using an exponential function that can maximize a small baseline distance difference due to the dense arrangement of DGPS reference stations in South Korea, and its positioning performance was validated. For the performance verification, the performance of the model developed in this study (EIDW) was compared with those of typical inverse distance weighting (IDW), first- and second-order multiple linear regression analyses (Planar 1 and 2), the model of Abousalem (1996) (Ab_EXP), and the model of Kim (2013) (Kim_EXP). The model developed in the present study had a horizontal accuracy of 53 cm, and the positioning based on the second-order multiple linear regression analysis that showed the highest positioning accuracy among the existing models had a horizontal accuracy of 51 cm, indicating that they have similar levels of performance. Also, when positioning was performed using five reference stations, the horizontal accuracy of the developed model improved by 8 ~ 42% compared to those of the existing models. In particular, the bias was improved by up to 27 cm.

Keywords: satellite navigation correction system, virtual reference station, positioning accuracy, inverse distance weighting

1. INTRODUCTION

Among Global Positioning System (GPS) positioning methods, the accuracy of GPS-only positioning using code pseudorange is several meters to dozens of meters. However, if positioning is performed based on a Differential GPS (DGPS) method, the accuracy can be improved to approximately 1 meter. DGPS is a technique that corrects the GPS error at a user position by receiving the pseudorange correction for each satellite observed at a specific time from a reference station. To perform DGPS positioning, reference station infra that generates and transmits DGPS correction is required. In Korea, a total of 32 maritime reference stations, maritime integrity monitoring stations, and inland reference stations have been established all over the country at 50 ~ 100 km intervals by the DGNSS Central Office of the Ministry of Oceans and Fisheries as of 2015, and they provide DGPS correction. In the case of single reference station-based DGPS positioning that is generally used, DGPS correction is received from one reference station. Accordingly, if the positions of a reference station and a user are close, the effect of the common error factor becomes large, and the DGPS positioning accuracy is improved. On the other hand, if the positions of a reference station and a user are distant, the effect of the common error factor becomes small, and the DGPS positioning accuracy deteriorates. To resolve this, many reference stations could be additionally installed, but it is inefficient because installation of a reference station requires a lot of

Received Apr 21, 2015 **Revised** May 15, 2015 **Accepted** May 18, 2015
†**Corresponding Author**
E-mail: hyunwoo313@nate.com
Tel: +82-32-873-4305 Fax: +82-2-6455-4305

http://www.gnss.or.kr Print ISSN: 2288-8187 Online ISSN: 2289-0866

cost.

Multiple reference station-based DGPS positioning is a method that generates new correction at a user position based on the error correction of a number of reference stations through interpolation. When a reference station is far from a user, multiple reference station-based DGPS positioning could minimize the effect of baseline distance compared to single reference station-based DGPS positioning, and thus it has high accuracy. However, multiple reference station-based DGPS uses data from many reference stations, and the processing speed deteriorates as the number of used reference stations increases, which limits the actual application. Therefore, a technique that can minimize the number of used reference stations and can secure high positioning accuracy is needed.

In this study, domestic and foreign research trends for existing virtual correction generation methods that had been devised for multiple reference station-based DGPS positioning were introduced, and representative algorithms were implemented. Also, by supplementing the disadvantages of these methods, a model that can secure high DGPS positioning accuracy using a minimum number of reference stations was developed. To evaluate the positioning accuracy of the developed model, the horizontal RMS error and bias were compared with those of the existing techniques. The implemented algorithms were the inverse distance weighting that is widely used for the generation of DGPS virtual correction, the first- and second-order multiple linear regression analyses suggested by Kim & Park (2011), the exponential function-based virtual correction generation technique suggested by Abousalem (1996), and the exponential function-based virtual correction generation technique suggested by Kim (2013).

2. EXISTING CORRECTION GENERATION TECHNIQUES BASED ON A VIRTUAL REFERENCE STATION

Virtual reference station-based DGPS positioning methods can be broadly classified into a position domain method, a state-space domain method, and a measurement domain method (Abousalem 1996). In the position domain method, a user performs single reference station-based positioning for each reference station using the correction received from many DGPS reference stations, and the calculated position information is corrected using a weighted mean. The position domain method has a simple processing procedure, but the accuracy is lower than those of the other methods.

In the state-space domain method, a user position is corrected by modeling the error at the user position for each error factor through analyzing the factor for causing the error of the GPS observation data received from a reference station. This method produces the most accurate result among the three methods, but the amount of calculation is large and the procedure is complicated.

In the measurement domain method, a user position is calculated by generating virtual correction at the user position using the correction received from many reference stations and by applying this to positioning. This method does not require a large amount of computation, and can obtain a certain level of positioning accuracy. In this study, virtual reference station correction generation algorithms developed in Korea and in foreign countries that correspond to the measurement domain method were implemented.

2.1 Inverse Distance Weighting (IDW)

In the inverse distance weighting method, the reciprocal of the baseline distance between a reference station and a user is assigned as a weighting factor, where a small weighting factor is assigned to a reference station with a long baseline distance from a user and a large weighting factor is assigned to a reference station with a short baseline distance from a user (Bae 2003). Fig. 1 shows the generation of the virtual correction of a rover station from a number of reference stations based on inverse distance weighting.

The method for generating new correction at a user position based on inverse distance weighting is expressed in Eq. (1). In Eq. (1), δ^l is the pseudorange correction of the l-th satellite at the user position generated through inverse distance weighting, and $\delta\rho_j^l$ is the pseudorange correction

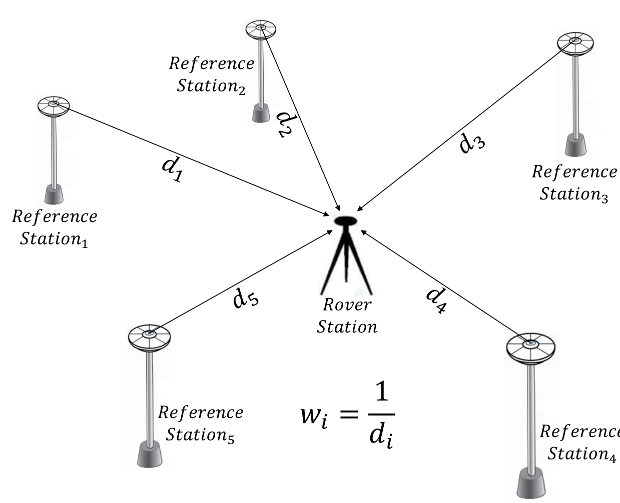


Fig. 1. Generation of virtual correction based on inverse distance weighting.

http://dx.doi.org/10.11003/JPNT.2015.4.2.079

of the l-th satellite at the j-th reference station. d_j is the baseline distance between the user and the j-th reference station among a number of reference stations, and a weighting factor depending on the distance is established by taking the reciprocal of this ($\frac{1}{d_j}$). In the equation, k is the number of reference stations used for the generation of correction.

$$\delta\rho^{l} = \frac{\sum_{j=1}^{k} \delta\rho_j^{l} \frac{1}{d_j}}{\sum_{j=1}^{k} \frac{1}{d_j}} \quad (1)$$

2.2 Multiple Linear Regression Analysis

The conceptual diagram of the multiple linear regression analysis method (Kim & Park 2011) can be expressed as shown in Fig. 2. In this method, a linear function that minimizes the sum of squares of residuals is made and fitted. Fig. 2 shows the generation of correction at a virtual reference station using first-order multiple linear regression analysis. A planar function is generated using the correction of multiple reference stations, and the planar position for the latitude and longitude of a virtual reference station is calculated based on new correction. The correction for first-order multiple linear regression analysis is expressed as Eq. (2) along with the coordinates and coefficients of each reference station, and the coefficients are estimated by mathematizing the sum of squares of residuals as shown in Eq. (3). In Eq. (2), $\delta\rho^{1}$ is the pseudorange correction of the -th satellite at the user position calculated through the first-order multiple linear regression analysis; and in Eq. (3), $\delta\rho_j^{1}$ is the pseudorange correction of the l-th satellite generated at the j-th reference station. $\Delta\phi_j$ and $\Delta\lambda_j$ represent the differences between the average latitude/longitude

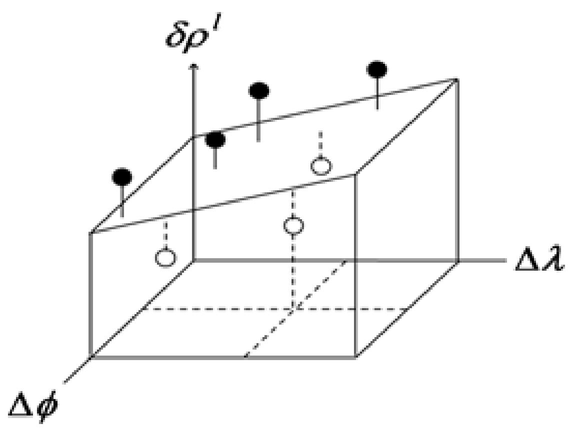


Fig. 2. Conceptual diagram of first-order multiple linear regression analysis (Kim & Park 2011).

coordinates of the used reference stations (ϕ_0 and λ_0) and the latitude/longitude of the j-th reference station. k is the number of reference stations used for the generation of correction, and a_0, a_1, a_2 are the coefficients that minimize the sum of squares of residuals, S_r.

$$\delta\rho_l = a_0 + a_1\Delta\phi + a_2\Delta\lambda \quad (2)$$

$$S_r = \sum_{j=1}^{k}\left(\delta\rho_l^{j} - a_0 - a_1\Delta\phi - a_2\Delta\lambda\right)^2 \quad (3)$$

The equations of second-order multiple linear regression analysis are expressed as Eqs. (4) and (5), and the procedure of correction generation is identical to that of first-order multiple linear regression analysis. For first-order multiple linear regression analysis, the number of unknowns to be obtained is 3, and thus it requires data from at least three reference stations; while for second-order multiple linear regression analysis, the number of unknowns to be obtained is 6, and thus it requires data from at least six reference stations.

$$\delta\rho_l = a_0 + a_1\Delta\phi + a_2\Delta\lambda + a_3\Delta\phi^2 + a_4\Delta\lambda^2 + a_5\Delta\phi\Delta\lambda \quad (4)$$

$$S_r = \sum_{j=1}^{k}\left(\delta\rho_l^{j} - a_0 - a_1\Delta\phi - a_2\Delta\lambda - a_3\Delta\phi^2 - a_4\Delta\lambda^2 - a_5\Delta\phi\Delta\lambda\right)^2 \quad (5)$$

2.3 Virtual Correction Generation Models Based on an Exponential Function

Abousalem (1996) and Kim (2013) suggested virtual correction generation techniques based on an exponential function. In existing inverse distance weighting, the reciprocal of distance was used as a weighting factor. Unlike this, Ablousalem devised a weighting factor shown in Eq. (6). W^j is the weighting factor for the j-th reference station, and d^j is the baseline distance between the user and the j-th reference station. Kim devised a weighting factor shown in Eq. (7). In the equation, d_{max} and d_{min} represent the longest and shortest baseline distances, respectively, among the baseline distances between the user and the reference stations. Also, the coefficient w_{dj}, which varies depending on the d_{max} – d_{min} value, was empirically established, and a model that had been optimized for the environment in Korea was suggested.

$$w^j = \exp\left(-\frac{d^j \times 2}{400}\right) \quad (6)$$

$$w^j = \exp\left(-\frac{d^j \times w_{d_j}}{d_{max} - d_{min}}\right) \quad (7)$$

3. ENHANCED CORRECTION GENERATION TECHNIQUE BASED ON A VIRTUAL REFERENCE STATION

The baseline distance between a reference station and a user has a large effect on DGPS positioning accuracy. As the baseline distance increases, the common error of the reference station and the user decreases, and the accuracy deteriorates. In foreign countries, DGPS reference stations are generally arranged at 300 ~ 1,000 km intervals; while in Korea, DGPS reference stations are arranged at 50 ~ 100 km intervals which is relatively dense. Therefore, when a weighting factor is assigned based on inverse distance weighting similar to foreign countries, the effect is not large because the baseline distance difference between reference stations is not large. This problem can be resolved by effectively assigning a weighting factor through maximizing a small baseline distance difference. In this study, a new model was developed using an exponential function that can maximize a small difference in values.

The developed model regenerates DGPS correction at a user position based on inverse distance weighting using the error correction provided from a number of reference stations. The developed model can be expressed as Eqs. (8) and (9). In Eq. (8), w_{dj} is the coefficient that varies depending on the baseline distance between the user and the j-th reference station, d_j is the baseline distance between the user and the -th reference station, and avg (d) is the average baseline distance between the user and all the reference stations. By raising the reciprocal of distance to the power of w_{dj}, a new weighting factor shown in Eq. (9) is generated. w_j is the weighting factor for the j-th reference station correction.

$$w_{d_j} = \exp\left(\frac{d_j}{avg(d)}\right) \tag{8}$$

$$w_j = \left(\frac{1}{d_j}\right)^{w_{d_j}} \tag{9}$$

In the existing inverse distance weighting, simple reciprocal of distance is used as a weighting factor; while in the developed model, the reciprocal of distance is raised to the power of w_{dj} (i.e., an exponential function-type coefficient), which increases the difference in the weighting factor depending on the distance. As the baseline increases, the coefficient w_{dj} basically increases in the form of an exponential function. However, the average baseline distance between a user and multiple reference stations (avg (d)) is considered, and this prevents the coefficient w_{dj} from increasing exponentially.

For example, when the correction of a reference station with a long baseline distance from a user and the correction of a reference station with a short baseline distance are used to generate new correction at the user position, the reference station with a baseline distance that is longer than average has a relatively large w_{dj} value than the reference station with a short baseline distance, based on Eq. (8). As a result, the exponent for the reciprocal of distance ($\frac{1}{d_j}$) is larger in Eq. (9), and thus the weighting factor for the reference station with a long baseline distance (w_j) becomes small. On the other hand, the reference station with a short baseline distance has a value that is smaller than average, and thus w_{dj} becomes relatively small. As a result, the weighting factor for the reference station with a short baseline distance (w_j) becomes larger than that for the reference station with a long baseline distance. Thus, correction that is close to the actual amount of error at the user position is generated by preferentially reflecting the correction of the reference station with a short baseline distance, and more accurate positioning results could be obtained based on this.

4. EVALUATION OF THE ACCURACY OF THE DEVELOPED MODEL

In this study, virtual correction at a rover station was generated using a DGPS reference station network in Korea based on the existing correction generation models introduced in Chapter 2 and the new weighting factor model proposed in Chapter 3. First, the positioning accuracy of the model developed in this study was compared with that of the second-order multiple linear regression analysis (Kim & Park 2011) which has the highest accuracy among the existing algorithms. The positioning accuracy of the developed model was also compared with those of the first-order multiple linear regression analysis, the inverse distance weighting, the model of Abousalem (1996), and the model of Kim (2013), which have lower positioning accuracy than the second-order multiple linear regression analysis but can generate correction using only five reference stations. For the implemented algorithms, the second-order multiple linear regression analysis was expressed as Planar 2, the first-order multiple linear regression analysis as Planar 1, the inverse distance weighting as IDW, the model of Abousalem (1996) as Ab_EXP, the model of Kim (2013) as Kim_EXP, and the model developed in the present study as enhanced inverse distance weighting (EIDW).

As described earlier, to generate correction using Planar 2, more than six reference stations are required. In this study, to maximize the positioning accuracy of Planar 2 and EIDW, the positioning accuracies were compared using all

http://dx.doi.org/10.11003/JPNT.2015.4.2.079

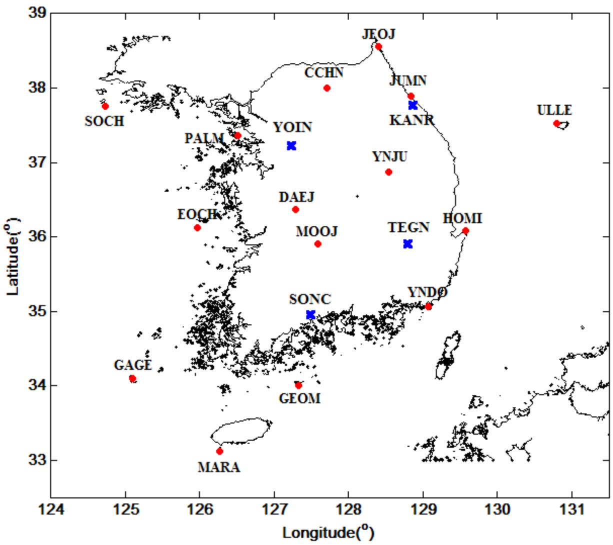


Fig. 3. Positions of the reference stations (●) and rover stations (✖) used for the DGPS positioning based on Planar 2 and EIDW.

the 15 reference stations that had stably provided correction at the time of the positioning among the DGPS reference stations operated by the Ministry of Oceans and Fisheries. Fig. 3 shows the positions of the 15 reference stations used for the generation of correction. To judge whether stable positioning accuracy is secured at an arbitrary location in Korea, the Gangneung (KANR), Daegu (TEGN), Suncheon (SONC), and Yongin (YOIN) permanent stations operated by the National Geographic Information Institute were selected as the rover stations as shown in Fig. 3. The correction that had been generated at the 15 reference stations for about 4 hours and 30 minutes (from 22:40, December 20 to 02:17, December 21, 2014) was obtained, and virtual reference station-based DGPS positioning was performed by generating correction at the rover stations using Planar 2 and EIDW. For the GPS observation data, the Receiver Independent Exchange Format (RINEX) observation data of each rover station provided by the National Geographic Information Institute were used. The coordinates of the rover stations were calculated based on least squares estimation using the RINEX observation data, and the horizontal RMS error and bias were calculated using the notified coordinates provided by the National Geographic Information Institute as true values.

Table 1 summarizes the DGPS positioning results when the correction was generated by Planar 2 and EIDW, respectively, using data from the 15 reference stations. Planar 2 had a horizontal RMS error of 50 ~ 52 cm at each rover station, which showed a small deviation, and EIDW had a horizontal RMS error of 47 ~ 60 cm. The average horizontal RMS error of Planar 2 was 51 cm, and that of

Table 1. Analysis of the errors of the virtual reference station-based DGPS positioning using Planar 2 and EIDW (m).

	Planar 2			EIDW		
	RMSE	Bias		RMSE	Bias	
	H	N-S	E-W	H	N-S	E-W
KANR	0.50	0.04	0.17	0.52	-0.01	0.15
YOIN	0.50	0.15	0.19	0.60	0.08	0.35
TEGN	0.51	-0.02	0.23	0.47	0.03	0.06
SONC	0.52	0.03	0.25	0.53	-0.03	0.26
AVG.	0.51	0.06	0.21	0.53	0.04	0.21

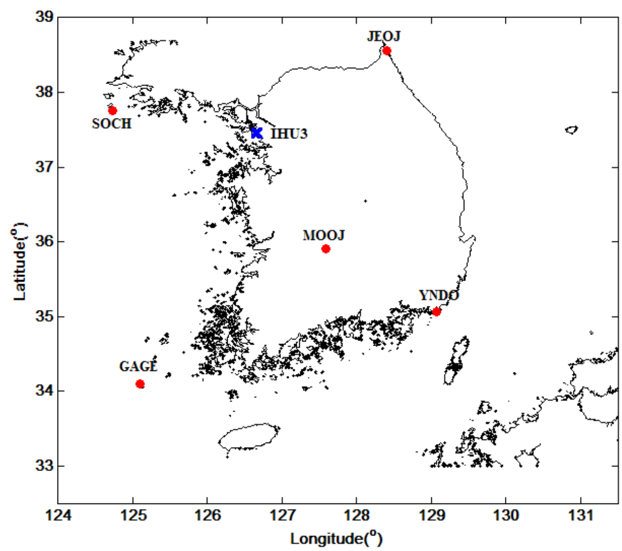


Fig. 4. Positions of the reference stations (●) and rover station (✖) used for the DGPS positioning based on Planar 1, IDW, Ab_EXP, Kim_EXP, and EIDW.

EIDW was 53 cm, indicating that the two models had similar horizontal positioning performances. In the case of the bias, the performances of Planar 2 and EIDW were not significantly different. For the north-south bias, the bias of EIDW was improved by 2 cm on average; and for the east-west bias, the average values were identical. The average of the biases in Table 1 was calculated by converting the biases of each rover station into absolute values. The analysis showed that the positioning performance of EIDW developed in this study was similar to that of Planar 2.

The Planar 2 algorithm requires at least six reference stations, while the other algorithms described in Chapter 2 and EIDW can generate correction using less than six reference stations. A minimum of two reference stations can be used; but when the number of reference stations is small, the geometric arrangement of reference stations relative to a rover station is inefficient, which deteriorates the positioning accuracy. Therefore, in this study, positioning was performed by generating correction using only five reference stations so that minimum performance could be guaranteed while obtaining efficient geometric arrangement. The

Table 2. Analysis of the errors of the virtual reference station-based DGPS positioning at IHU3 depending on the type of algorithm (m).

	RMSE	Bias	
	H	N-S	E-W
Planar 1	0.60	0.47	-0.19
IDW	0.52	0.37	-0.17
Ab_EXP	0.50	0.35	-0.17
Kim_EXP	0.38	0.22	-0.08
EIDW	0.35	0.20	0.03

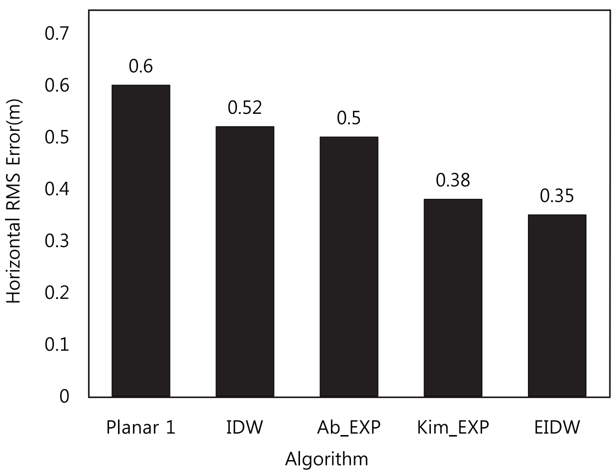


Fig. 5. Horizontal RMS errors of the virtual reference station-based DGPS positioning at IHU3 depending on the type of algorithm.

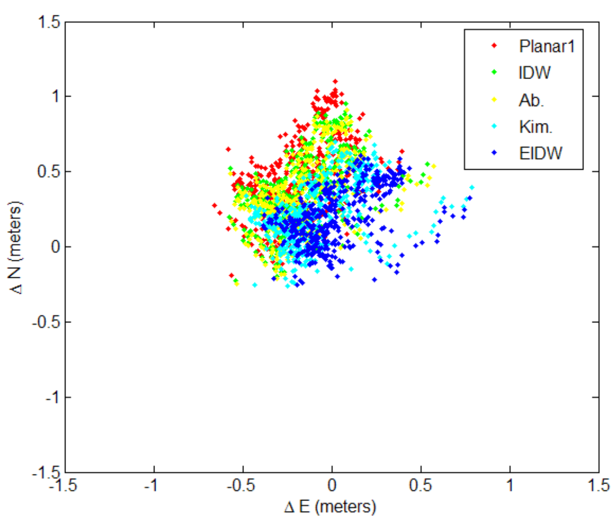


Fig. 6. Horizontal accuracy of the virtual reference station-based DGPS positioning at IHU3 depending on the type of algorithm.

reference stations used in this study were Socheong (SOCH), Jeojin (JEOJ), Muju (MOOJ), Gageo (GAGE), and Yeongdo (YNDO); and they were selected so that a reference station network could be formed based on a minimum number of reference stations, as shown in Fig. 4. The correction that had been generated at each reference station from 22:40, December 20 to 02:17, December 21, 2014 was used, similar to the analysis performed earlier. The rover station used for the verification of positioning accuracy was the IHU3 station located at Building #4, Inha University.

Table 2 and Fig. 5 show the positioning results using the correction generated through Planar 1, IDW, Ab_EXP, Kim_EXP, and EIDW. The results indicated that EIDW showed the highest positioning accuracy. The horizontal RMS error of EIDW decreased by 25 cm compared to that of Planar 1, indicating a higher positioning accuracy. This corresponds to a 42% improvement in the horizontal accuracy. Also, the north-south and east-west biases of EIDW decreased by 27 cm and 16 cm, respectively, compared to those of Planar 1. When EIDW was compared with IDW and Ab_EXP, the horizontal RMS error decreased by 15~17 cm, and the bias also decreased by 15 ~ 17 cm. When EIDW was compared with Kim_EXP, the horizontal RMS error decreased by 3 cm, and the bias was smaller. Therefore, it is thought that EIDW has superior positioning performance compared to the models developed in existing studies.

Fig. 6 shows the horizontal accuracy and bias of the DGPS positioning results using each algorithm. The existing algorithms had lower horizontal accuracies than the developed algorithm, and they were biased toward north and west. EIDW had a smaller bias than the existing algorithms, and thus the results were relatively densely distributed near the measuring point. Based on this, it was found that EIDW could perform positioning at a higher horizontal accuracy and a smaller bias compared to the models of existing studies.

5. CONCLUSION

In this study, domestic and foreign algorithms developed for multiple reference station-based DGPS positioning were introduced. Also, by supplementing the disadvantages of the introduced algorithms, a model that can secure improved positioning accuracy using a minimum number of reference stations was developed. To verify the performance of the developed model, the positioning accuracy was compared with those of the introduced algorithms. DGPS positioning based on second-order multiple linear regression analysis has high positioning accuracy, but it has the disadvantage of low positioning speed because at least six reference stations are needed to generate correction.

On the other hand, other algorithms developed in Korea and in foreign countries such as first-order multiple linear regression analysis, inverse distance weighting, the model of Abousalem (1996), and the model of Kim (2013) can generate correction using only five reference stations. The model developed in the present study can also generate correction using five reference stations, and correction that has been optimized for a rover station can be generated by improving the inverse distance weighting based on an exponential function.

When the positioning performances of the second-order multiple linear regression analysis and the developed model were compared using 15 reference stations, the horizontal accuracy and bias of the developed model were similar to those of the second-order multiple linear regression analysis. Also, when the positioning accuracies of the first-order multiple linear regression analysis, the inverse distance weighting, the model of Abousalem (1996), the model of Kim (2013), and the model developed in the present study were compared using five reference stations, the horizontal accuracy of the developed model was improved by 42% and the bias decreased by 16 ~ 27 cm compared to those of the first-order multiple linear regression analysis which showed the lowest positioning accuracy among the algorithms introduced in the present study. When the positioning accuracies of the model developed in the present study and the model of Kim (2013) which showed the highest accuracy among the existing techniques were compared, the horizontal accuracy of the model developed in the present study was improved by 8%, and the bias decreased by 2 ~ 5 cm, indicating a superior performance. The developed model has a simple algorithm, and shows outstanding positioning performance using a small number of reference stations. Also, it has higher positioning accuracy and lower bias compared to single reference station-based DGPS positioning or the existing multiple reference station-based DGPS algorithms. Therefore, it is thought that the developed model could be used for the fields requiring high positioning accuracy. In the future, additional analysis of the positioning accuracy that varies depending on the observation environment of a rover station or the geometric arrangement of reference stations when correction is generated using the model developed in this study is needed.

ACKNOWLEDGMENTS

This research was supported by a grant from "Development of GNSS based Transportation Infrastructure Technology" funded by Ministry of Land, Infrastructure and Transport of Korean government.

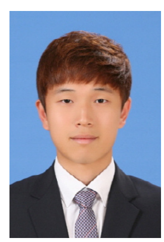
REFERENCES

Abousalem, M. A. 1996, Development and Analysis of Wide Area Differential GPS Algorithms, Ph.D. dissertation, Geomatics Engineering, The University of Calgary

Bae, S. T. 2003, Algorithm development for correction data improvement of DGPS using multi reference station, M.S. Thesis, Hanbat National University

Kim, G. T. 2013, Technology development for improving the positioning accuracy of DGPS service based on the minimum number of reference stations, M.S. Thesis, Inha University

Kim, H. I. & Park, G. D. 2011, A study on the PRC generation algorithms for virtual reference stations using a network of DGNSS reference stations, Journal of the Korean Society of Surveying, Geodesy, Photogrammetry, and Cartography, 29, 221-228. http://dx.doi.org/10.7848/ksgpc.2011.29.3.221



Hyunu Tae received B. S. degrees in geoinformatic engineering from Inha University, Korea in 2015. He is currently working towards M. S. degree on geoinformatic engineering at the same university. His research interests include DGNSS algorithm development.

Hye-In Kim received her Ph. D. degree from the Geoinformatic Engineering at the Inha University, and she is currently working at Research Institute of Jipyong Space Inc. Her research interests include DGNSS/PPP-RTK algorithm development.

Kwan-Dong Park received his Ph. D. degree from the Department of Aerospace Engineering and Engineering Mechanics at the University of Texas at Austin, and ge is currently at Inha University as a professor. His research interests include DGNSS/PPP-RTK algorithm development and GNSS geodesy.