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Correction of Coordinate Discontinuities Caused by GPS Antenna Replacements

Dusik Kim[1], Kwan-Dong Park[1†], Jihye Won[2]

[1]Department of Geoinformatic Engineering, Inha University, 100 Inha-ro, Nam-gu, Incheon 402-751, Korea
[2]Jipyong Space Inc., #39-307, 100 Inha-ro, Nam-gu, Incheon 402-751, Korea

ABSTRACT

Antennas at permanent GPS stations operated by the former Ministry of Government Administration and Home Affairs (MOGAHA) in Korea were replaced in years 2008 and 2009, and these changes caused abrupt discontinuities in precise coordinate time series. In this study, an algorithm that eliminates those breaks was developed based on 15-year-long coordinate time series for the purpose of creating clean and continuous coordinate time series. The newly developed algorithm to correct for sudden jumps and dips in the GPS time series due to the antenna change was designed to consider all the linear and annual signals observed before and after the event. The accuracy of the new algorithm was confirmed to be at the Root Mean Square Error (RMSE) level of 2.3-2.6 mm. The new algorithm was also found to be capable of reflect site-specific characteristics at each station.

Keywords: GPS, time series, discontinuity, common mode signal

1. INTRODUCTION

The results of crustal movement research using GPS can be used as basic data for the evaluation of seismic safety. The 2011 Tohoku-oki earthquake induced co-seismic displacement in the crust of the Korean Peninsula. In the GPS precise coordinate time series after the earthquake, post-seismic displacement by the Tohoku-oki earthquake is observed in addition to the displacement by the movement of the Amur Plate that has been observed since before the earthquake. To analyze the post-seismic displacement observed in the Korean Peninsula, the horizontal velocity that has acted on the Korean Peninsula since before the earthquake needs to be eliminated. And the pre-seismic horizontal velocity of the Korean Peninsula must be calculated by using long-term coordinate time series. Among the GPS permanent stations in Korea, long-term coordinate time series can be obtained from the stations operated by the National Geographic Information Institute (NGII), the former Ministry of Government Administration and Home Affairs (MOGAHA), and the Korea Astronomy and Space Science Institute (KASI). Among them, the stations operated by the MOGAHA have been integrated and operated by the NGII due to the reorganization of the government organizations in 2008 (NGII 2007). Using the observation data of these stations, about 15-year coordinate time series data can be obtained, and crustal movement analysis can be performed based on this.

With the modernization of GPS and the beginning of the GLONASS service, GPS permanent station operating institutions in many countries around the world have replaced the receiver and antenna of existing GPS permanent stations with equipment that can collect observation data in a new frequency band, since the mid-2000s. The MOGAHA in Korea has operated a total of 30 stations since 2000. The observation had started using the Trimble Microcentered L1/L2 (TRM33429.00+GP) model, and the antenna was replaced with the Trimble Zephyr GNSS Geodetic II (TRM55971.00) model between 2008 and 2009. However, the position of the antenna phase center after the replacement was different from the existing

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†**Corresponding Author**
E-mail: kdpark@inha.ac.kr
Tel: +82-32-860-7604 Fax: +82-32-863-1506

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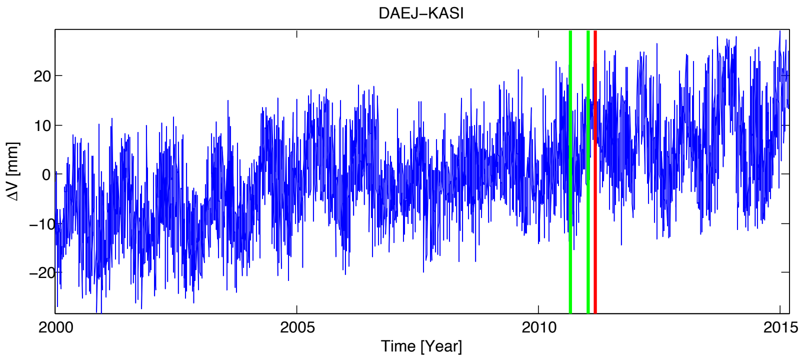

Fig. 1. Vertical time series of DAEJ.

position, and thus discontinuities occur in the coordinate time series at the time of the antenna replacement. In particular, the vertical coordinate time series showed larger discontinuities compared to the horizontal direction. The NGII recognized this phenomenon, and started to provide vertical offset correction value along with notified coordinates in the 2010 notified results (NGII 2010). However, the NGII didn't notified the method of offset correction calculation. Thus, reliability of this correction value cannot be examined. In addition, the discontinuities are still remain in the corrected coordinate time series. Therefore, for accurate correction of coordinate time series, a new algorithm needs to be developed and applied.

Discontinuities in coordinate time series due to antenna replacement were also found in the antenna replacement case of Germany in 2008. In this case, the offset of the vertical coordinate time series was larger, similar to the case of Korea. Wanninger (2009) mentioned that a slight position change during antenna replacement could have a large effect on multipath signals, and the change in the multipath effect was the major cause of the discontinuities in coordinate time series before and after the antenna replacement. Also, Wanninger (2009) pointed out that the discontinuities in coordinate time series from antenna replacement could occur due to the difference in the multipath signal sensitivity between the antennas before and after the replacement, and could also occur due to the use of a radomes and antennas with no calibration information.

As a technique for correcting the discontinuities in vertical time series for the stations of the MOGAHA, Jung & Lee (2012) suggested a method in which vertical time series correction is calculated based on the difference in the average coordinate time series of 28 days before and after the antenna replacement. As mentioned above, comparison of the short-term averages of the coordinate time series during a certain period before and after antenna replacement can be used for offset calculation. However, some stations have a gap in the observation data during this period, and thus error could occur in the case of these stations. In addition, using only this method, inherent crustal displacement trends of stations that have occurred before antenna replacement cannot be reflected; thus an algorithm that can resolve this needs to be developed.

In this study, a method that calculates coordinate time series correction by combining a linear trend and a common mode signal (CMS) was devised to correct the discontinuities from antenna replacement that occur in the coordinate time series of the MOGAHA stations for the purpose of post-seismic displacement analysis using the precise coordinate time series of GPS permanent stations. For the analysis, precise coordinate time series from 2000 to March 10, 2015 were calculated using GIPSY-OASIS II (GPS Inferred Positioning System-Orbit Analysis and Simulation Software, hereinafter GIPSY) (Webb & Zumberge 1993). After the development of an algorithm, the performance of the algorithm was examined by performing a simulation for stations with no discontinuities in coordinate time series; and using this algorithm, coordinate time series corrections were calculated for 27 stations among the stations of the MOGAHA.

2. DISCONTINUITIES IN COORDINATE TIME SERIES FOR THE MOGAHA STATIONS

Fig. 1 shows the vertical coordinate time series of the Daejeon (DAEJ) operated by the KASI. In Fig. 1, the blue line represents the daily coordinate time series generated by the GIPSY data processing, and the green and red lines represent the times for the antenna replacement and the occurrence of the Tohoku-oki Earthquake, respectively. The vertical time series generally showed signals with an annual cycle as shown in Fig. 1, and each station showed a specific linear trend. Also, when the phase center of an existing

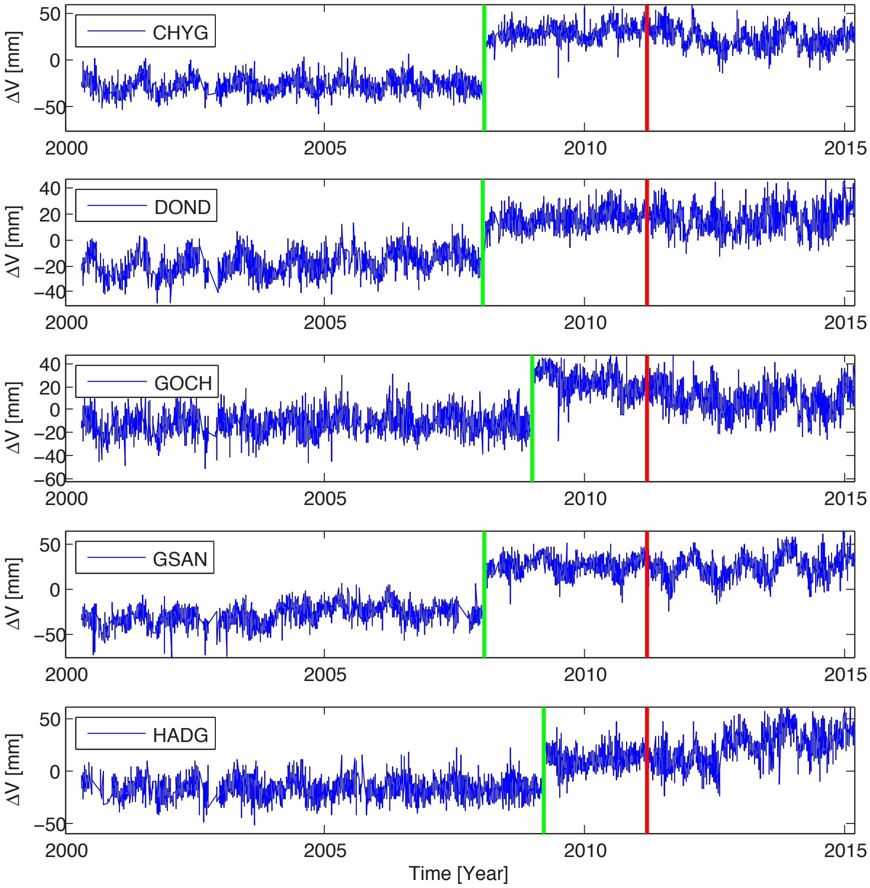

Fig. 2. Discontinuities in vertical time series of MOGAHA sites.

antenna was considered during antenna replacement, discontinuities in time series due to the antenna replacement did not occur as in the DAEJ. However, for the MOGAHA stations, discontinuities in coordinate time series were found after the antenna replacement as shown in Fig. 2.

Fig. 2 shows the examples of the discontinuities in vertical coordinate time series for the MOGAHA stations. For all the stations operated by the MOGAHA including the examples shown in Fig. 2, similar discontinuities in coordinate time series were observed. These discontinuities in vertical time series had a size of about 30~50 mm depending on the station. The comparison of the antenna specifications before and after the replacement showed that when the Antenna Reference Point (ARP) position is identical to that before the antenna replacement, the position of the antenna phase center rises by 22.5 mm (NGS 2014). However, the vertical position displacements for Dongducheon (DOND) and Cheongyang (CHYG) notified by the NGII were 38.0 mm and 57.0 mm, respectively. The comparison of the photographs before and after the antenna replacement showed that the ARP position after the replacement was located at the end of the screw of the structure, while the antenna ARP position before the replacement was located at different vertical positions depending on the station (Fig. 3).


Before DOND Antenna Change
After DOND Antenna Change
Before CHYG Antenna Change
After CHYG Antenna Change

Fig. 3. Different ARP locations of each site.

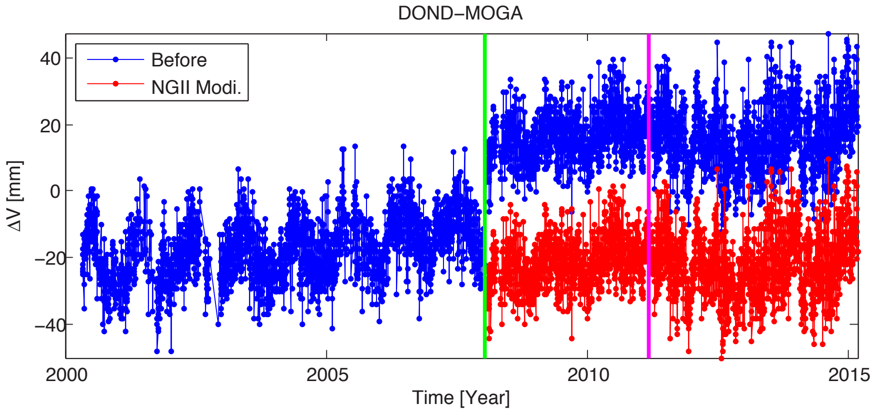

Fig. 4. Corrected time series by using height corrections from NGII.

According to the photographs before and after the antenna replacement, we found that the ARP position became lower than that before the antenna replacement in most of MOGAHA sites. Therefore, the discontinuities in vertical time series with a size of more than 50 mm are thought to be complex results, rather than simply due to the difference in the physical heights of the antennas, similar to the case of Germany presented in Wanninger (2009). In particular, the non-standard radome and the steel plate at the bottom of the antenna used by all the stations of the MOGAHA had also caused problems in Japan (Hatanaka et al. 2001). Thus, for the occurrence of discontinuities in coordinate time series in Korea, the effect of multipath signals due to the structure of the station is also thought to be the major cause.

Fig. 4 shows the corrected vertical time series by using correction information which the NGII notified. The blue dot represents the original coordinate time series, and the red dot represents the corrected vertical time series. Based on the examination of the long-term changes in the coordinate time series shown in Fig. 4, it is thought that coordinate time series that is consistent with the past linear trend could not be obtained when this correction was applied. The comparison of about 30 days before and after the antenna replacement in Fig. 4 indicated that the corrected coordinate time series for the 30 days before and after the replacement showed similar values. Therefore, it is thought that the vertical position displacement calculated by the NGII would be a result based on the comparison of short-term coordinate time series. However, this correction method could not reflect the crustal displacement characteristics that had been observed in the station before the antenna replacement, as shown in Fig. 4.

3. CORRECTION ALGORITHM FOR THE DISCONTINUITIES IN COORDINATE TIME SERIES DUE TO ANTENNA REPLACEMENT

3.1 Common Mode Signal

In precise positioning using GIPSY, the coordinate estimation results of GPS permanent stations are affected by common errors such as the signal delay in the atmosphere and the satellite orbit error. These common errors are defined by a common mode signal (Wdowinski et al. 1997, Park et al. 1999). A common mode signal can be calculated using the coordinate time series of stations as follows. First, velocities for each station are determined by obtaining a linear trend from each coordinate time series. Then, the residual for each coordinate time series ($\epsilon_s(d)$) can be expressed as Eq. (1).

$$\epsilon_s(d) = O_s(d) - C_s(d) \tag{1}$$

where $O_s(d)$ and $C_s(d)$ are the observed coordinates and estimated coordinates of the station S for the date d, respectively. In other words, $O_s(d)$ is the coordinate time series value of the station s for the date d, and $C_s(d)$ is the linear trend value of the station s for the date d. Then, the common mode signal $\epsilon(d)$ for each date can be calculated by averaging the residuals obtained from n sites.

$$\epsilon(d) = \frac{\sum_{s=1}^{n} \epsilon_s(d)}{n} \tag{2}$$

where $\epsilon(d)$ is the average residual for the date d. In other words, the common mode signal is a signal that reflects the signal shape of the residual that is observed in all the stations used for the calculation. In particular, when the distance between stations is within 100 km, the common

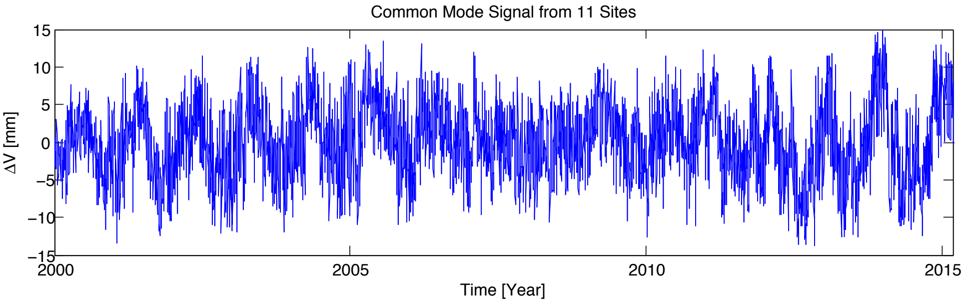

Fig. 5. Calculated common mode signal from 11 sites.

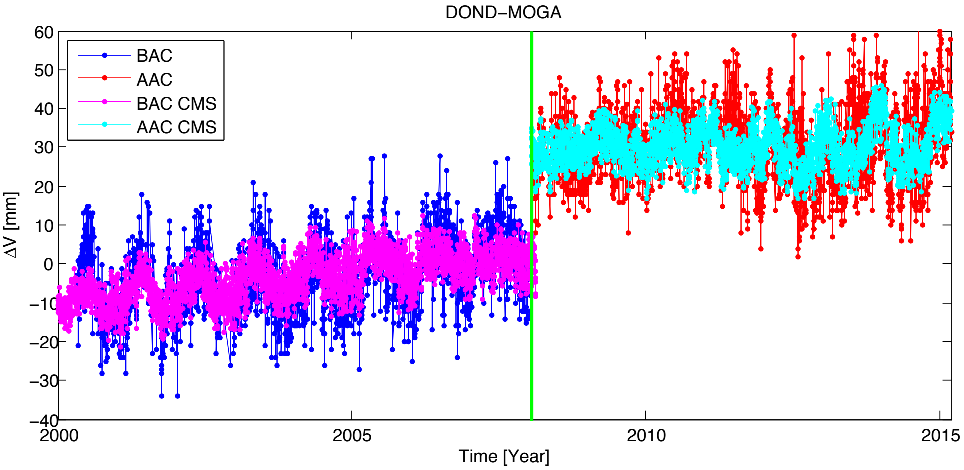

Fig. 6. Before vertical time series correction (DOND).

errors of the stations are almost identical, and thus it has been widely used as a technique that can eliminate the common errors of a local observation network in the analysis of coordinate time series, crustal displacement, etc. Also, the common mode signal includes a periodic signal shape that is identically observed in a local observation network, and thus can be used as a signal that substitutes a gap in coordinate time series.

3.2 Calculation Method for the Coordinate Time Series Discontinuity Correction

To generate a common mode signal for the vertical coordinate time series, the coordinate time series of 11 stations were used: six stations of the NGII (CHJU, CNJU, JINJ, JUNJ, KANR and KWNJ) and five stations of the KASI (DAEJ, JEJU, MKPO, SKCH and SKMA) excluding the stations of the MOGAHA. Fig. 5 shows the common mode signal calculation results for the entire data processing period. As described earlier, the common mode signal in Fig. 5 shows a distinct annual cycle.

In this study, for the calculation of vertical time series correction, the vertical coordinate time series obtained from each station were classified into before and after the antenna replacement, and the linear trend for each period was calculated. By adding the common mode signal for the corresponding period to the calculated linear trends before and after the antenna replacement, two signals to be used for the determination of coordinate time series correction were generated.

Figs. 6~8 show the examples of the calculation process and results for the vertical time series correction at the DOND station. In the figures, the blue and red dots represent the original time series before and after the antenna replacement, respectively (Vertical time series Before and After Antenna Change); and the magenta and cyan dots represent the combined results of the linear trend and the common mode signal for each time series, respectively. In this regard, to compare the values in the same period, the common mode signal part before the antenna replacement (BAC CMS, Before Antenna Change CMS) was additionally calculated up to a certain period after the antenna replacement. In the examples shown in Figs. 6 and 7, the comparison interval was selected to be

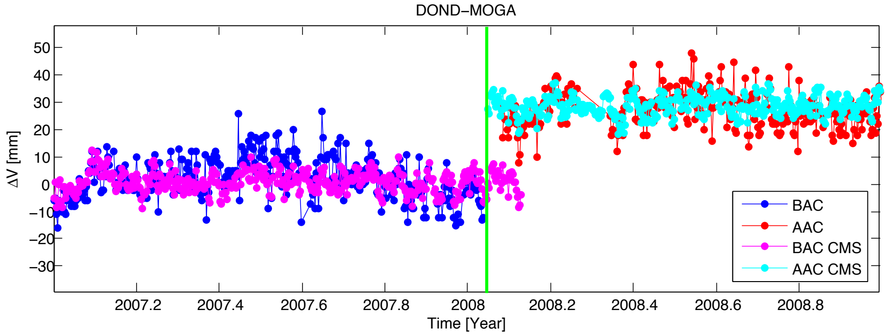

Fig. 7. Process of vertical time series correction (DOND).

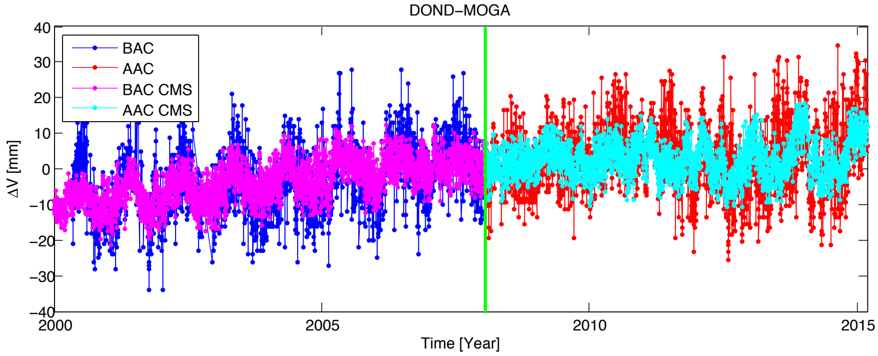

Fig. 8. Result of vertical time series correction (DOND).

30 days. The amount of correction was calculated using the difference in the average values of the BAC CMS, which extended the time series variation characteristics before the antenna replacement to the period after the antenna replacement, and of the common mode signal after the antenna replacement (AAC CMS, After Antenna Change CMS). Figs. 6 and 7 show the examples when the comparison range was selected to be 30 days. When the corrected time series were compared before and after the antenna replacement, the increasing pattern of the time series was consistent with the annual cycle signal, as shown in Fig. 8. Therefore, it is thought that the coordinate time series correction algorithm devised in this study could enable the correction of the discontinuities in coordinate time series considering the signal shapes before and after the antenna replacement.

3.3 Evaluation of the Correction Algorithm for the Discontinuities in Coordinate Time Series

There is no method that can examine the correction accuracy of the vertical time series correction algorithm described earlier. It is because the discontinuities in vertical time series are thought to be a complex result due to the radome and the surrounding environment, rather than a simple result due to the increase in the physical height of the antenna. Thus, the accuracy of the algorithm can be indirectly evaluated by examining if existing time series characteristics are well maintained when the algorithm is arbitrarily applied to coordinate time series with no discontinuities from antenna replacement.

For the algorithm evaluation, simulations were performed for DAEJ and SKCH among the permanent stations of the KASI. In this study, two kinds of algorithms were implemented. In the first algorithm, the average of the BAC CMS estimated for the period after the antenna replacement in Fig. 7 was compared with the average of the AAC for the same period (Algo1). In the second algorithm, the BAC CMS estimated for the period after the antenna replacement using the method identical to that in the previously described algorithm was compared with the average of the AAC CMS for the same period (Algo2). For the comparison of the correction accuracies, the comparison range for the calculation of the average value after the antenna replacement was selected to be 30, 60, and 90 days, respectively. The algorithm was implemented from 2001 to 2014 at 100-day intervals, and the coordinate time series corrections calculated at each given time were compared.

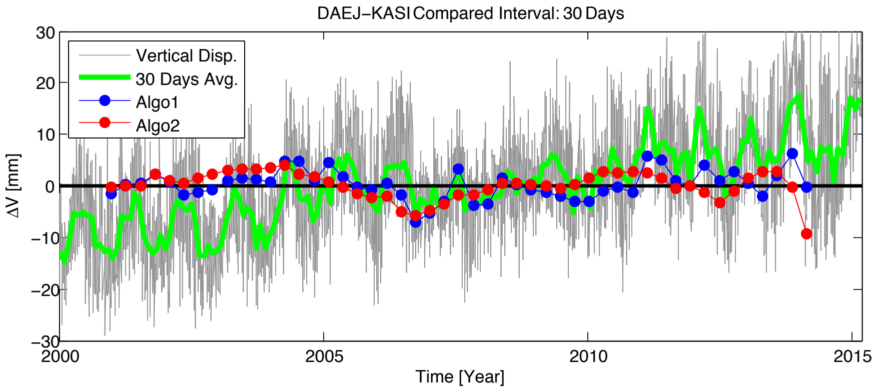

Fig. 9. Results of correction algorithm simulation (DAEJ).

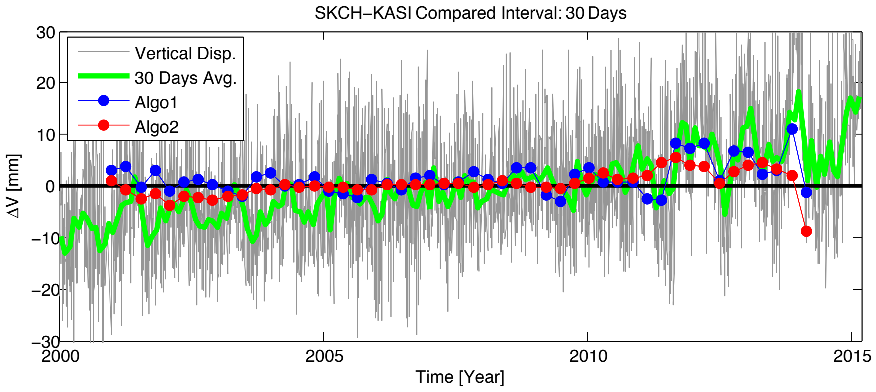

Fig. 10. Results of correction algorithm simulation (SKCH).

Figs. 9 and 10 show the simulation implementation results for DAEJ and SKCH, respectively. In this study, the result with a comparison range of 30 days was shown in the figure. The results with a comparison range of 60 and 90 days were not significantly different from the result with a comparison range of 30 days based on a figure, and thus the performances were compared using the values of Root Mean Square Error (RMSE) and mean error summarized in Table 1. In Figs. 9 and 10, the green line represents the average coordinate time series for 30 days, for examining the changes in the coordinate time series. In this simulation, the performance of the developed algorithm is outstanding when the calculated correction is close to 0, when this algorithm is arbitrarily implemented for coordinate time series with no discontinuities.

For both DAEJ and SKCH, the RMSE and the mean error of Algo2 were smaller than those of Algo1, as summarized in Table 1. The comparison of the correction calculation results in Figs. 9 and 10 showed that the simulation result of the SKCH was closer to 0 mm than that of the DAEJ between 2005 and 2010. In this regard, the comparison of the correction calculation result for each algorithm and the 30-day average coordinate time series shown in the green line indicates that stable results could be obtained when the variation in the time series was small.

When the simulation results of DAEJ were compared, Algo2 mostly showed small errors even though the variation in the time series was larger than that of Algo1. For the selection of the comparison range, Algo2 showed the smallest RMSE in the case of 90 days, but the mean error was the smallest in the case of 30 days. Also, for some stations of the MOGAHA, the oscillation of the coordinate time series changed significantly after the antenna replacement. Accordingly, the error could accumulate in the case of long-term comparison. Therefore,

Table 1. Accuracies of each correction algorithm.

	DAEJ				SKCH			
	RMSE (mm)		Mean error (mm)		RMSE (mm)		Mean error (mm)	
	Algo1	Algo2	Algo1	Algo2	Algo1	Algo2	Algo1	Algo2
30	2.77	2.64	0.28	0.12	3.41	2.42	1.58	0.33
60	2.73	2.62	0.43	0.22	3.30	2.32	1.25	0.43
90	2.78	2.61	0.57	0.31	3.11	2.25	1.20	0.53

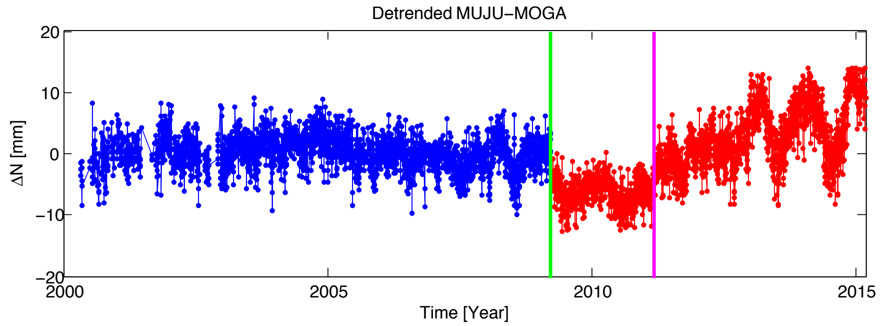

Fig. 11. Detrended ΔN time series by eliminating velocity before antenna change.

the comparison range was selected to be 30 days. Based on the simulation analysis, it is thought that the algorithm developed in this study (Algo2) could correct the discontinuities in time series at an RMSE of about 2.3~2.6 mm.

4. CORRECTION OF THE DISCONTINUITIES IN COORDINATE TIME SERIES DUE TO ANTENNA REPLACEMENT

In previous domestic research on the discontinuities in coordinate time series, only the discontinuities in vertical time series were mentioned; but in practice, relatively small discontinuities also occur in the horizontal direction after antenna replacement. This is clearly observed in a result of detrended horizontal time series. Fig. 11 shows the detrended north-south time series of MUJU. As shown in Fig. 11, the horizontal time series also showed discontinuities after the antenna replacement. Therefore, corrections for the discontinuities in the horizontal and vertical coordinate time series were calculated using the developed algorithm, as summarized in Table 2.

Table 2 shows the correction calculation results for the discontinuities in coordinate time series depending on the antenna replacement in the GPS permanent stations of the MOGAHA. Depending on the direction, the vertical direction was larger than the horizontal direction in all the stations except for CHCN, and the average absolute values were 5.7 mm in the horizontal direction and 36.5 mm in the vertical direction. The corrections for each direction increased as it went from north-south to east-west to vertical directions. The proportion of horizontal discontinuities in the entire displacement was 15.4% based on the average absolute values, which is thought to be a size that cannot be ignored in the analysis of crustal displacement.

In the case of the horizontal direction, non-directional discontinuities occurred, rather than discontinuities in a certain consistent direction, unlike the vertical direction. This means the possibility that the major cause of the discontinuities in coordinate time series observed in the stations of the MOGAHA is the change in the multipath effect due to the antenna replacement, similar to the case of Germany. For complete investigation of the cause, an experiment that implements an observation environment that is identical to this is required.

For the discontinuities in vertical time series, the result based on the correction calculated in the present study (c) was compared with those based on the correction notified

Table 2. Calculated MOGAHA coordinate correction.

SITE	Correction [mm]			2D, 3D correction amount [mm]		2D/3D [%]
	North	East	Vertical	2D	3D	
CHCN	3.13	-0.75	-2.08	3.22	3.83	84.0
CHEN	-2.89	6.34	51.64	6.97	52.11	13.4
CHLW	-4.79	-8.14	18.72	9.44	20.97	45.0
CHNG	1.49	-7.77	50.16	7.91	50.78	15.6
CHSG	4.70	-0.65	35.62	4.74	35.93	13.2
CHYG	-2.13	3.94	57.53	4.48	57.70	7.8
DOND	-5.59	2.80	27.38	6.25	28.08	22.3
GOCH	-2.91	-4.91	37.90	5.71	38.33	14.9
GSAN	-1.70	0.27	47.48	1.72	47.51	3.6
HADG	-4.65	-1.16	21.51	4.79	22.04	21.8
HONC	1.14	-3.64	45.19	3.81	45.35	8.4
INCH	0.31	-11.02	53.00	11.02	54.13	20.4
INJE	-5.32	-6.11	38.74	8.10	39.58	20.5
JAHG	-0.25	-5.24	27.71	5.25	28.20	18.6
JUNG	1.21	3.03	37.82	3.26	37.96	8.6
KIMC	0.77	-4.40	18.60	4.47	19.13	23.4
KUNW	-6.08	-2.79	40.24	6.69	40.79	16.4
MUJU	-5.64	-8.82	49.93	10.47	51.02	20.5
NAMW	4.96	1.94	8.82	5.33	10.30	51.7
NONS	-0.31	-3.41	31.14	3.42	31.33	10.9
PAJU	-4.15	-7.82	37.64	8.85	38.67	22.9
PUSN	-1.91	7.06	42.33	7.31	42.96	17.0
SONC	-2.84	-4.86	28.95	5.63	29.49	19.1
YANP	-1.99	-1.85	40.35	2.72	40.44	6.7
YECH	-0.13	-9.74	41.68	9.74	42.80	22.8
YONK	-3.70	-7.69	54.85	8.53	55.51	15.4
YOWL	-4.10	-6.27	39.01	7.49	39.72	18.9
Mean	-1.61	-3.02	36.37	6.20	37.21	20.8
Absolute mean	2.92	4.90	36.52	5.70	36.96	15.43

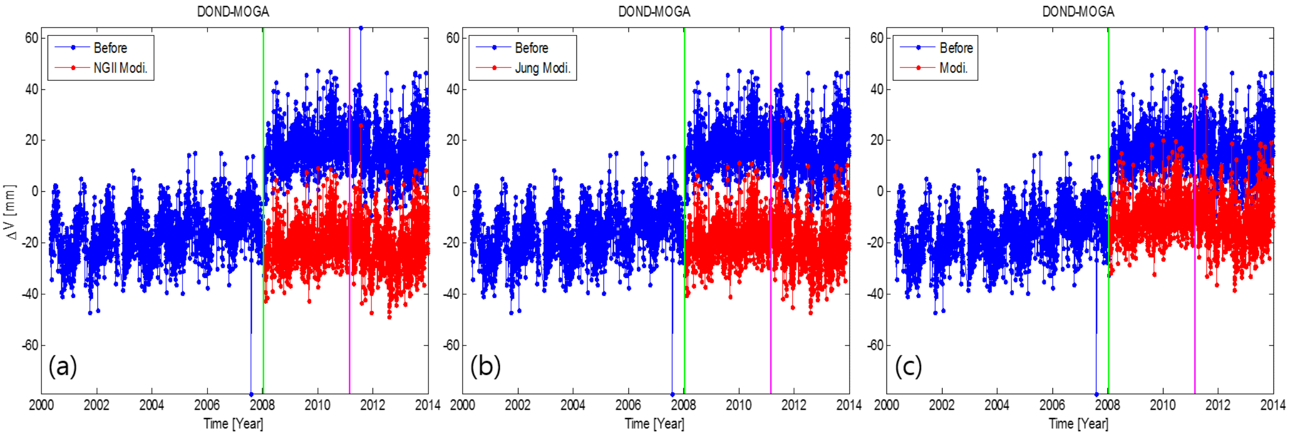

Fig. 12. Results of vertical time series correction (a) NGII, (b) Jung & Lee, (c) developed algorithm.

by the NGII (a) and based on the correction published in a domestic study (Jung & Lee 2012) (b), as shown in Fig. 12. For the comparison, the example of the DOND station was presented, where the blue and red dots represent the vertical time series before and after the correction, respectively. As shown in Fig. 12, in the case of (a) and (b), the correction was performed using only the averages of the time series values distributed before and after the time for the antenna replacement, and thus the signal characteristics of the station could not be reflected. However, in the case of (c), it is thought that the correction was performed reflecting the characteristics of the existing time series of the station.

5. SUMMARY AND CONCLUSION

In this study, an algorithm that can correct the discontinuities in time series due to antenna replacement at the stations of the MOGAHA was developed based on the coordinate time series generated by GIPSY data processing. It is thought that the developed algorithm could correct the discontinuities in time series at an RMSE of about 2.3~2.6 mm, and could be used in studies requiring long-term coordinate time series (e.g., crustal movement analysis using GPS) by reflecting a linear trend and an annual cycle signal observed in a station.

Also, in this study, it was found that there were discontinuities in horizontal coordinate time series with an average displacement of 5.7 mm due to the antenna replacement at the stations of the MOGAHA, as well as the discontinuities in vertical coordinate time series. The discontinuities in horizontal coordinate time series accounted for 15.4% of the total displacement, and this should be corrected in the analysis of crustal displacement.

The occurrence of the discontinuities in coordinate time series due to antenna replacement is a problem that could occur again during the operation of the stations in the future. In this study, it was confirmed that the cause of the discontinuities in coordinate time series could be the effect of the non-standard radome and the steel plate at the bottom of the antenna used by the stations of the MOGAHA. Therefore, to prevent this problem in the future, improvement in the structures of the GPS permanent stations in Korea is needed.

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Dusik Kim received M.S. degree from the Geoinformatic Engineering from Inha University, and he is currently at Inha University as a Ph.D. candidate. His research interests include GNSS Geodesy, Meteorology, Seismology and Ionosphere modeling.

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 he is currently at Inha University as a professor. His research interests include DGNSS/PPP-RTK algorithm development and GNSS geodesy.

Jihye Won received Ph.D. degree in Geoinformatic Engineering from Inha University, and she is currently at Research Institute of Jipyong Space Inc. as a Chief Technology Officer. Her research interests include GNSS PPP-RTK data processing algorithm and modeling of the GNSS error sources.