Long-term analysis of tropospheric delay and ambiguity resolution rate of GPS data

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Abstract

Long-term GPS data analysis was performed in order to analyze the seasonal variation of tropospheric delay and the success rate of the ambiguity resolution. For this analysis, a total of 57 stations including 10 IGS stations in East Asia were processed together with double-differenced observables using Bernese GPS Software V5.0. The time span for this study ranges from 2002.0 to 2012.5 (10.5 years). The average baseline length is 339.0 km and the maximum reaches up to 2,000 km. The analysis is focused on two things: the annual variation of the tropospheric delay and the ambiguity resolution rate. The tropospheric delay is closely related to the weather condition, especially relative humidity, therefore it was estimated that the maximum would be in summer, while reaching its minimum in winter with the apparent seasonal variations. On the contrary, however, the success rate of the ambiguity resolution shows the opposite pattern: its maximum was in winter and minimum in summer. The fact seems to be induced by the surrounding conditions; that is, the trees thick with leaves near the GPS antenna interfere with GPS signals in summer. This seems to confirm partly that there is a distinct trend in the decreasing success rate since 2006 because the trees are growing every year. It is necessary to eliminate the factors that degrade the GPS quality and the tropospheric modeling for Korea needs to be studied further.

Keywords : Ambiguity resolution, GPS, Time series, Tropospheric delay

1. Introduction

Although GPS (Global Positioning System) was originally designed for military purposes by the US Department of Defense (DOD), it is now widely used in many different fields, such as geodetic applications, surveying, communication, and weather forecasting. In addition, many researchers have studied the calculation of precise coordinates of a GPS CORS (Continuously Operating Reference Station) and its dynamic movement by analyzing the long-term time series. Song and Yun (2006) have studied the crustal displacements and velocities of eight CORS being operated by National Geographic Information Institute (NGII) for three years using the PPP (Precise Point Positioning) technique, and compared them with the results from the plate tectonic models. Analogous research has been performed by Cho et al. (2001) where the characteristics of crustal movement are

analyzed and the relative displacement is computed after 30 months of precise baseline processing of 40 GPS tracking stations.

Besides the continuous movement of the crust over a long period, research on the discontinuities in the plate such as earthquakes is also being carried out. Kim and Bae (2012) analyzed the effect of the Tohoku earthquake that occurred in 2011 on the national reference frame for Korea (the southern part of the Korean peninsula) through the static baseline processing and kinematic positioning of NGII CORS. The analysis of long-term tropospheric delay and ambiguity resolution, however, has not been fully discussed so far, especially seasonal variation and the relationship with the surrounding conditions.

The strategic policy of decreasing the positioning quality by the US DOD, that is, Selective Availability (SA), was cleared on May 2, 2000. The relatively large error sources

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in the absence of SA such as the atmospheric delay and the multipath effect play an important role in the precise GPS positioning (Lee, 2002). GPS signals passing through the troposphere experience a signal delay due to the water vapor and dry gas in the atmosphere. The dry part of the delay can be compensated by the models generated from the atmospheric sensors and the ground observations. However, it is very difficult to predict the wet part of the delay due to the high spatio-temporal variability of the water vapor (Ha et al., 2005).

In order to achieve the centimeter level accuracy of the GPS positioning, the phase rather than code observations should be used in the processing. But the ambiguity in the phase measurements should be recovered to their original integer values to achieve the most robust and precise positioning results. The integer ambiguity resolution is not an easy task and has been an issue in GPS data processing. Most of the scientific software for GPS processing shows an approximately 70-80% success rate for ambiguity resolution, depending on the baseline lengths and the data quality from the receiver.

This study covers the estimated parameters and their effects on the final precise coordinates of GPS CORS in Korea under long-term processing. It originally computed the time series of the GPS CORS on the Korean peninsula (southern part) based on the national reference stations of Korea and the IGS CORS network nearby such as those in China, Russia, the Philippines, Mongolia, and Japan. This study focuses on the analysis of the factors and their patterns affecting the estimated precision of the coordinates during the baseline processing for the daily solutions.

2. Data processing strategies

2.1 Data preparation

It is necessary to prepare the observation data systematically archived for a long time in order to establish a national reference frame using GPS data processing. Forty five (45) CORS data from NGII are primarily used in this study, and an additional two stations (ULLE and DOKD) from the DGPS central office (NDGPS) are combined for two reasons: 1) these stations are located on islands east of Korea,

thus we want to check the vulnerability to the tropospheric delay of the signal, 2) since their geographical location is close to the boundary of the plate, it is necessary to check them for the effect of the earthquake that occurred in 2011. The time span for the processing ranges between 2002.0 and 2012.5 except ULLE and DOKD (only recent data are used for these stations due to data quality).

NGII provides the CORS data online (NGII, 2012) but it applies only for most recent two years. Ten years of archived data are obtained with the help of NGII by sending official notice. Since NGII does not allow ftp access to the server, the recent daily RINEX observation files are manually downloaded every day. The 24 hours of observation data are stored in RINEX format with a 30 second time interval. Figure 1 shows the location map of the domestic stations used in this study. The initial coordinates of CORS are obtained from the official announcement made by NGII (NGII, 2010).

It is generally known that at least three reference stations are required in order to connect the local geodetic network with the International Terrestrial Reference Frame (ITRF) using IGS CORS. Although more IGS reference stations are preferred for a highly reliable, consistent, and robust solution, it is recommended to use an appropriate number of stations for the efficiency of the processing. According to Hu (2009) who studied the effect of the station numbers for GPS baseline processing, the maximum error in the final coordinates reaches about 2 mm depending on the number of CORS in the processing. Furthermore, a different set of CORS networks

Figure 1. Domestic stations used in this research

does not change the final solution considerably (Tregoning et al., 1999).

Based on this research, it was decided to choose a total of ten IGS tracking stations for this study. This is because some of the IGS stations can be excluded in the processing of a daily solution due to the absence of quality observations. Another reason is that they cannot satisfy the criteria for the Helmert transformation between the estimated daily solution and the IGS reference stations.

The final tracking network stations are illustrated in Figure 2, where the geometric strength of the configuration is the key issue in the selection procedure. As mentioned above, a total of ten stations, including one station in Korea (DAEJ),

Figure 2. IGS stations used in this research

were chosen from nearby countries: four stations from China (BJFS, WUHN, KUNM, SHAO), one station from Japan (TSKB), two stations from Russia (KHAJ, IRKT), one station from the Philippines (PIMO), one station from Mongolia (ULAB).

The reference frame for the IGS CORS used in the processing is the IGS08 that provides coordinates and velocities. This is because the ITRF is basically compatible with the IGS reference frame, and GPS satellite orbit is given in IGS08. The GPS tracking stations used in this study are summarized in Table 1.

It is well-known that GPS measurements contain many different kinds of errors, thus it is indispensable to correct them by modeling. Most of the satellite-related errors can be cancelled out by differential techniques such as double-differenced observables. However, it is important to use accurate GPS satellite orbit for the processing because the satellites play a role for the reference stations to estimate the user position. Therefore, the most precise ephemerides, that is, the final product is used for GPS orbit.

Along with the published GPS orbit, the polar motion of the earth's spin axis and the earth's rotation rate are also important to regenerate the Keplerian GPS orbit from the ephemerides. This is because Newton's law of motion works in the inertial frame, therefore, the GPS orbit in the terrestrial frame should be transformed into the inertial frame based on the polar motion and the earth's rotation. The precession and nutation model is provided by the International Earth Rotation and Reference Systems Service (IERS). The GPS orbit, satellite clock, and Earth's rotation information used in this study is

Table 1. GPS CORS used in this study

Period		2002.01.01 - 2012.06.30			
Format		RINEX (24 hours, 30-second interval)			
CORS	NGII	SUWN, KANR, GOCH, GSAN, KUNW, KIMC, NAMW, NONG, TEGN, DOND, MUJU, PUSN, SNJU, SEOS, SOUL, SONC, YANP, YONK, YOWL, YECH, WULJ, WNJU, INJE, INCH, JAHG, JUNJ, JUNG, CHJU, JEJU, CHNG, CHEN, CHLW, CHSG, CHYG, CHCN, TABK, PAJU, HADG, HONC, CNJU, JINJ, BOEN, WOLS, KWNJ, CHWN			
	NDGPS	ULLE, DOKD			
	IGS	South Korea	DAEJ	Philippines	PIMO
		China	BJFS, WUHN, KUNM, SHAO	Russia	KHAJ, IRKT
		Japan	TSKB	Mongolia	ULAB

obtained from IGS, which is a combined solution by weighted averaging the solutions from each analysis center. The IGS product is automatically downloaded from Crustal Dynamics Data Information System (CDDIS) through ftp.

The ionospheric delay is a nuisance parameter for most of the user positioning applications because its effect is not negligible and related to the ambiguity parameters. The Center for Orbit Determination in Europe (CODE) provides a global ionosphere model for each day with a time interval of two hours. Once the external ionosphere information is given, the ambiguity parameters for longer baselines (up to 2,000 km) can be resolved more easily. The Differential Code Bias (DCB) information is also downloaded from CODE.

Ocean loading information is required for precise positioning, which can be obtained from the Onsala Space Observatory (OSO) webpage (OSO, 2012) by providing the coordinates of the corresponding stations. The FES2004 model, recommended by the IERS (IERS, 2010), is used in this study.

2.2 Processing strategy

For the processing software to estimate the user position and other parameters, Bernese GPS Software V5.0 (hereafter Bernese) is used in order to deal with ambiguity resolution of very long baselines that reach up to 2,000 km. Bernese can handle GPS observation data in Precise Point Positioning (PPP) mode as well as the relative positioning mode. The PPP technique has a capability of estimating the position within several centimeters, the relative technique using a differential mode such as double-differenced observable should be used to achieve more accurate and consistent results.

Bernese offers an automated tool to process a large amount of data, called the Bernese Processing Engine (BPE). With the BPE, a series of steps for GPS data processing can be accomplished without any user intervention, and also the parallel processing and iteration can be done for the problematic stations. The coordinates of the reference stations are stochastically constrained to 1 millimeter for each component.

Table 2 summarizes the general options and models for data processing in the study. The absolute model for the antenna phase center variation (PCV) was used for precise positioning,

according to IGS recommendations. The tropospheric delay of the GPS signals was corrected by the Niell model which explains 90% of the delay, and the remaining delay (mostly wet component) was estimated during the processing. In addition, several models were used for GPS data processing, such as the IAU200 nutation model, JGM-3 geopotential model, and JPL DE200 planetary ephemerides.

The solution with double-differenced observables is known as the most robust one due to its integer ambiguity resolution. However, the integer ambiguity and the tropospheric delay parameters are highly correlated and the ionospheric delay is difficult to estimate. Furthermore, for a long baseline, for example, more than several hundred kilometers, the correlation for the atmospheric parameters between stations is sharply decreased, resulting in difficulty in parameter estimation. Bernese recommends the Quasi Ionosphere-Free (QIF) method for the ambiguity resolution of longer baselines. The QIF method applies the global ionosphere model to separate its effect from GPS signals. Thus, by applying QIF, it is possible to effectively resolve the ambiguity to its integer values even for a long baseline of up to 2,000km.

For the differential processing of GPS data, it is necessary to build independent baselines within the network. There are many different strategies to generate a baseline; for example, if there is only one unknown station, all baselines can be defined with this station at one end. Another popular way to create a baseline is to maximize the common satellite combination between two stations, called OBS-MAX, which is used in this study.

Table 2. Processing options adopted in this study

Antenna PCV	Absolute PCV
Troposphere model	Dry/Wet Niell model
Geopotential model	JGM-3
Nutation model	IAU2000
Celestial ephemeris	JPL DE200
Cut-off angle	10°
Ambiguity resolution strategy	QIF
Baseline selection strategy	OBS-MAX

3. Processing results and analysis

The baseline processing has been performed for about 10.5 years of GPS data, ranging from January 1, 2002 to June 30, 2012 (total 3,833 days), based on the strategies explained in Section 2. The resulting daily solution in three dimensional Cartesian coordinates was transformed into the local terrestrial coordinate systems (North, East, and Up) to better illustrate the time series of the plate tectonic motion (Figure 3). The figure represents the changes of the coordinates of SUWN that is the origin of Korean geodetic datum and one of the IGS tracking network stations.

As can be seen in the figure, there is a distinct tendency that the station has been moving more dominantly east and slightly south for last ten years. This behavior clearly agrees with the results of Lee (2005), where an annual movement of the Korean Peninsula reaches about 3 cm to the south-east direction. On the contrary, however, the vertical (Up) component does not show any particular pattern. Therefore, it can be concluded that there are no noticeable changes of the crust in vertical direction, but rather almost within an error level of GPS accuracy.

Taking a close look at the time series plot shows an abrupt change in the coordinates around early 2011, and this phenomenon commonly happens at all CORS involved in the processing. This is the effect of the 2011 Tohoku earthquake that occurred near Japan on March 11, 2011.

Figure 3. Time series of daily solution for SUWN during last 10 years in local terrestrial coordinates system [Unit: cm]

Figure 4. Histogram of baseline length

Figure 4 represents the distribution of the baseline lengths generated during GPS data processing. The baselines that are longer than 2,000 km are eliminated in this study in order to optimize the ambiguity resolution algorithm QIF. A total of 175,194 baselines were created for the whole time span; the shortest baseline is 16.6 km and the longest one reaches 1,978 km. The average baseline length is 339.0 km and about 80% of baselines belong to the group less than or equal to 400 km.

Figure 5 shows the success rate of ambiguity resolution for daily solution. Since there are a large number of baselines in a day thus the success rate for each unknown parameter of ambiguity is averaged to be displayed. The times series ranges from 58.8% to 96.7%, and 86.4% on average which shows a fairly high rate of ambiguity resolution. Overall, the results in the beginning of time series (around 2002-2003) give a relatively low resolution rate. This seems to come from the fact that GPS receivers at the stations have not been stabilized yet and, thus, less quality data affected the processing results.

One thing to be noticed is that the ambiguity resolution

Figure 5. Time series of ambiguity resolution rate

rate reaches the maximum in January (winter), and the lowest rate is observed in July (summer), repeating this pattern every year. Another interesting fact is that since 2006 the rate clearly shows a decreasing trend. This can be interpreted in many ways, but the most feasible hypothesis is that the trees

near the tracking station grow every year thus GPS signals are affected more by these trees.

As can be seen in Figure 6, there is a rather large number of trees nearby GPS receivers, which are very vulnerable to GPS signal interference like multipath. Therefore, if the

(a) KUNW station

(b) CHCN station

Figure 6. Surrounding environment of CORS GPS antenna

(a) SUWN

(b) TABK

Figure 7. Time series of tropospheric delay estimates

leaves grow thick in summer the signal is liable to be blocked, resulting in low ambiguity success rate. During the winter, on the contrary, the broadleaf trees shed their leaves, thus the opposite situation happens.

Figure 7 represents the time series of the estimated tropospheric delay and its standard deviation for station SUWN and TABK. The time series and their statistics of the tropospheric delay show an annual variation. That is, the maximum values are in summer and the minimum in winter, which is the complete opposite of the ambiguity resolution rate. The periodic variation of tropospheric delay observed in this study is the consequence of the weather characteristic of Korea, that is, high humidity in summer and dry conditions in winter. In addition, the absolute magnitude of the tropospheric delay is different for two stations, SUWN and TABK. SUWN is located in NGII at moderate altitude as mention earlier, but TABK is one of the high altitude stations in Korea. SUWN shows a delay of 2.3 meters to 2.7 meters, while the tropospheric delay of TABK is in the range between 2.1 meters and 2.5 meters. The tropospheric delay depends on the depth of the troposphere that signals pass. Since the altitudes of two stations, SUWN and TABK, are 83.8 meters and 736.2 meters, respectively, in terms of ellipsoidal height, the thicknesses of troposphere for the two stations are different. Therefore, the tropospheric delay for SUWN is about 10% larger than that of TABK which is located at a high altitude. Aside from these two stations, the others show a similar pattern in the annual variation and the magnitude of the delay.

4. Summary and conclusions

A total of 10.5 years of GPS CORS data (2002.0 through 2012.5) was processed using Bernese GPS Software V5.0 in order to analyze the crustal movement of the Korean Peninsula (especially the southern part) and the tropospheric variations. The results can be summarized as follows:

- (1) More than 10 years of GPS data processing has been performed, and its daily solution was analyzed. The time series clearly show a sudden break in the crustal movement due to the Tohoku earthquake that occurred

in March, 2011. In addition, the Korean Peninsula (the southern part) is moving in a south-east direction at a rate of about 3 cm every year.

- (2) The success rate of ambiguity resolution was analyzed, and shows a pattern of maximizing in winter and minimizing in summer. The rate also represents a periodic variation every year with the same pattern, but there is a decreasing trend after 2006. This can be interpreted that trees near the receiver interfere with the GPS signal and this situation keeps on worsening, even when the receiver is installed on a tall pillar.
- (3) The tropospheric delay time series show that the delay reaches its maximum in summer and the opposite in winter, a periodic pattern as well. This is because the tropospheric delay is closely related to the relative humidity thus clearly reflects the weather characteristics of Korea.

With the long-term time series of GPS data processing of CORS in Korea, it can be confirmed that the tropospheric delay and the ambiguity resolution rate show a periodic variation, but in the opposite direction. The tropospheric delay is closely related to the relative humidity in the atmosphere. On the contrary, however, the success rate pattern of ambiguity resolution is more affected by the surrounding situation of the receiver, especially multipath by trees. There is a necessity to reduce the problematic factors around CORS receivers in order to provide more reliable measurements. In addition, further study on troposphere modeling reflecting weather characteristics of Korea is expected in the near future.

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