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Original article

Time-series Analysis of Geodetic Reference Frame Aligned to International Terrestrial Reference Frame

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Abstract

The national geodetic reference frame of Korea was adopted in 2003, which is referenced to ITRF (International Terrestrial Reference Frame) 2000 at the epoch of January 1, 2002. For precise positioning based on the satellites, it should be thoroughly maintained to the newest global reference frame. Other than plate tectonic motion, there are significant events or changes such as earthquakes, antenna replacement, PSD (Post-Seismic Deformation), seasonal variation etc. We processed three years of GNSS (Global Navigation Satellite System) data(60 NGII CORS stations, 51 IGS core stations) to produce daily solutions minimally constrained to ITRF. From the time series of daily solutions, the sites with unexpected discontinuity were identified to set up an event(mostly antenna replacement). The combined solution with minimum constraints was estimated along with the velocity, the offsets, and the periodic signals. The residuals show that the surrounding environment also affects the time series to a certain degree, thus it should be improved eventually. The transformation parameters to ITRF2014 were calculated with stability and consistency, which means the national geodetic reference frame is properly aligned to the global reference frame.

Keywords : Global Navigation Satellite System, Minimum Constraints, Reference Frame, Transformation Parameters

1. Introduction

Since the publication of the new geodetic reference frame of Korea, the official announcement of reference coordinates for national control points were made, and followed by major revisions and several partial amendments (Lee *et al*., 2008). However, most prior studies were dealing with only a certain period of data, and the results were propagated back to the reference epoch at 2002.0. The data processing software ranges from commercial to scientific versions, furthermore different software were applied depending on the projects. In particular, the processing output was not managed to be saved in common format such as SINEX (Solution INdependent EXchange) for other research projects.

NGII (National Geographic Information Institute) is operating more than 60 reference stations and publishes

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112 reference stations(as of September 2021) when it is necessary(NGII, 2021). However, instead of the strategy of data processing and the intermediate products, the estimated final coordinates have been the primary concerns. In addition, the final product is also based on a relatively short-term period of data processing. The solution from satellite positioning eventually needs to be combined with other space geodetic products such as VLBI (Very Long Baseline Interferometer) and SLR (Satellite Laser Ranging), which is the first step to advance the geodetic reference frame of Korea. Therefore, it is mandatory to process GNSS (Global Navigation Satellite System) data on the CORS (Continuously Operating Reference Station) networks of NGII for a much longer period. The output from the satellite positioning should be explored to produce the combined solution, which is mainly investigated in this study.

We used the three years of GNSS data being operated by NGII and the scientific, high accuracy processing software, resulting in a SINEX output to analyze the solution. The combined software was applied to evaluate the quality of the CORS network based on the time series of the coordinates changes.

2. GNSS CORS Network

2.1 The strategy of GNSS data processing

The research projects were conducted by NGII several times(e.g. Year 2006, 2008, 2013 etc.), from which the reports generally summarized the period, the used software, and the final results. The processing software is different for each project, and the procedures and the adopted models are not described sufficiently. In addition, the data span is mostly restricted to the short-term and there is no plan for long-term series of data processing and their combination. Therefore, GNSS data processing procedures and models should be established for advanced national geodetic networks by combining other space geodetic techniques such as VLBI and/or SLR. The models and the required external files are summarized in Table 1.

The procedure for CORS GNSS data processing and the application of output can be categorized into three steps:

1) Data download from external sources
- Additional information that is needed for specific processing software
- Satellite orbit and clock information, ionosphere model, DCBs (Differential Code Biases)

2) Models to apply at each step
- Tropospheric delay and its gradient models
- Ionospheric delay model and its reduction technique
- Correlation issue for short baseline
- Pre-elimination of the parameters
- Constraints of geodetic reference frame, analysis of the results

3) Long-term time series of reference frame
- Daily, weekly solutions and plan for public service
- Management and combination of SINEX files for updates

Table 1. GNSS data processing scheme

Item	Model
Satellite orbit	Precise orbit (CODE)
Troposphere	Global Pressure and Temperature Model Global Mapping Function CHENHER gradient model (Steigenberger *et al*., 2009)
Geopotential	EGM2008
Planetary ephemeris	JPL DE405
Antenna phase center	igs14.atx
Precession/nutation	IAU2000
Ocean tides	FES2004
Cutoff angle	3°
Ambiguity resolution	QIF, Widelane, L1/L2

2.2 Selection of CORS data

We investigated the GNSS data of NGII CORS for the quality analysis and best selection of the network. Since it should be aligned to the ITRF, the IGS (International GNSS Service) core stations were also analyzed. The availability of the data during the period as well as the history of receiver/antenna replacement should be checked before data processing and analysis of the results. We were trying to detect the discontinuity of time series for the coordinates of the reference stations, and the seasonal variation and the effect of the PSD (Post-Seismic Deformation) correction model.

In this study, we used the Bernese GNSS Software V5.2(Dach *et al.*, 2015) for three years of NGII CORS GNSS data processing. A total of 111 stations(60 NGII CORS stations, 51 IGS core stations) were simultaneously processed, and the relevant external information such as satellite orbit/clock, global ionospheric model, DCB was downloaded from the corresponding websites(GNSSDC, 2019; IGS, 2019).

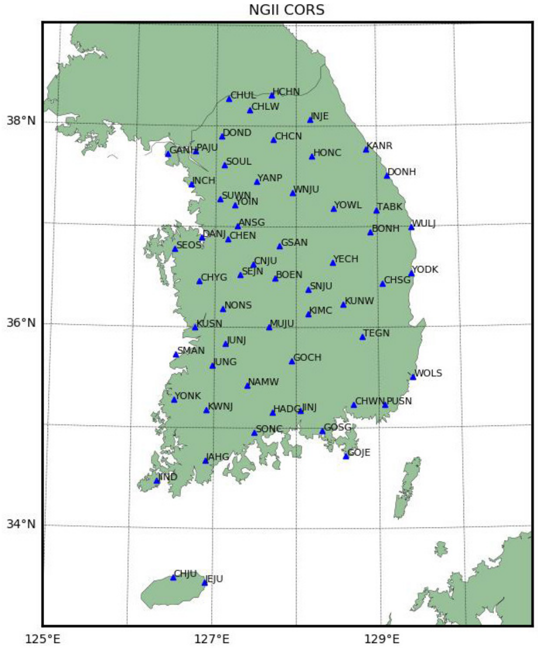

Fig. 1. The configuration of NGII CORS (NGII, 2019)

Fig. 1 shows the configuration of NGII CORS, which is almost evenly distributed over the southern part of the Korean peninsula. There are some cases of total data deficiency before mid-2009, but the data archiving is sufficiently stable for more than 50 stations since 2010. Although the whole data is missing on a specific date, it seems not to affect seriously the long-term time series analysis.

IGS core stations(51 stations in IGS14 reference frame) play a key role in realizing the ITRF coordinates and are almost evenly distributed on a globe in terms of geometric point of view(see Fig. 2). The percentage of active working stations is about 80%(over 40 out of 51 stations) daily based on the pre-screening, which is generally well-maintained condition.

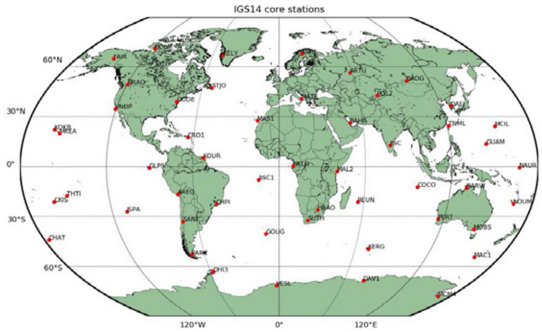

Fig. 2. IGS14 core stations (NGII, 2019)

3. Optimal Selection of CORS

3.1 Time series analysis of coordinates

The coordinates of CORS and the stability of the sites were analyzed for three years of coordinates based on GNSS data processing. The quality of data and horizontal/vertical components of coordinates should be examined, along with the discontinuities(or offsets) due to the earthquake or antenna replacement. The quality checks for unstable time series of coordinates are also necessary, which results in diagnosis and/or relocation of the site. In addition, the signal of seasonal variation and the PSD correction model should also be considered in long-term time series analysis.

We estimated the coordinates and velocity at 2016.0(January 1, 2016), and plotted the horizontal and the vertical components separately to figure out the tectonic motion of the plate and the displacement of the sites(e.g. due to subsidence, antenna replacement, or tropospheric delay by the surrounding environment).

Fig. 3 shows some examples of the typical cases of unusual time series in local frame from 2000 to 2018 where all coordinates are relative to the starting epoch of the site. The first case is the bias introduced by the antenna replacement (Fig. 4a). Since the change history is not updated in the log file, it came out the offset in the vertical component of GNSS processing result. Therefore, the details of the change, as well as the antenna types, should be documented in an international standard format if a similar event happened in the future.

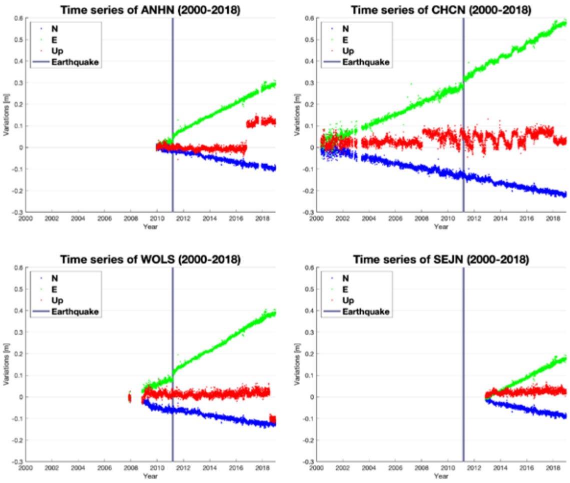

Fig. 3. The typical cases of unusual time series (North: blue, East: green, Up: red) (NGII, 2019)

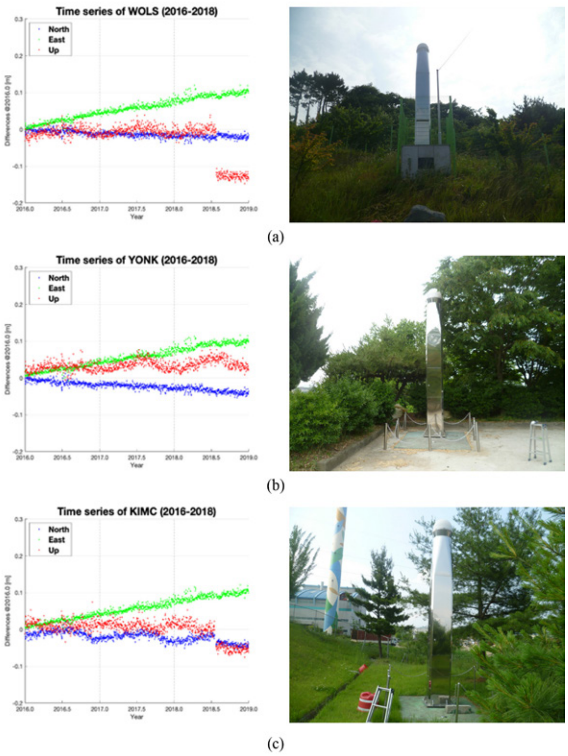

Fig. 4. Sample cases: (a) antenna replacement, (b) seasonal variation in vertical component, (c) periodic variation in horizontal component (North: blue, East: green, Up: red) (NGII, 2019)

The second case is the seasonal variation in the vertical component (Fig. 4b). It is generally affected by the tropospheric delay, the surrounding environment of the site, and the multipath due to the lush trees in summer. In the case of a non-open environment, it is necessary to reduce the effect of the trees or sometimes relocate the CORS antenna.

Lastly, besides the vertical component, the horizontal components also show seasonal patterns(as well as antenna replacement) for some stations(Fig. 4c). As can be seen in the figure, the periodic behavior in a north-south component is observed as well, which seems to be related to the trees on a single side. Therefore, it is desirable to take suitable action if the signal might be blocked in a certain direction.

3.2 Estimation of velocity

The daily solutions for three years(2016 to 2018) were accumulated to estimate the velocity of NGII CORS to estimate the three-dimensional velocity of the station based on time series coordinates (see Fig. 5). Since there are no large-scale events(e.g. earthquakes) in Korea after the Tohoku earthquake in 2011(Kim and Bae, 2018), the determined velocity vector did not change much. However, it might be affected by the unpublished antenna offset of the CORS. Therefore, it is very important to maintain the history of large-scale events and antenna replacement to estimate the reliable velocity vector.

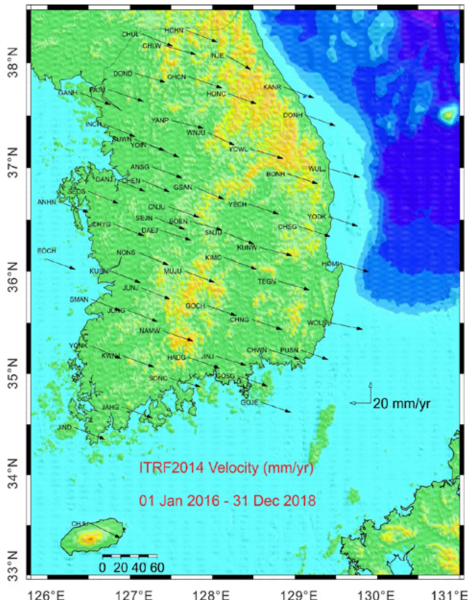

Fig. 5. The estimated velocity vector based on three years (2016-2018) (NGII, 2019)

4. Establishment of Geodetic Reference Frame

4.1 Overview of CATREF

The CATREF (Combination and Analysis of Terrestrial Reference Frames) is based on the software to combine terrestrial reference frames in the 1980s, and started with the introduction of SINEX format in 1995(Altamimi *et al*., 2007, 2016). It estimates the coordinates and velocity of the sites, Earth orientation parameters. The periodic signal estimation and PSD model were appended afterward. CATREF combines the independent solutions with multiple stations using the minimum constraints. Each solution is composed of the coordinates and velocity of the site, polar motion and Earth orientation parameters, and their variance-covariance matrix.

Table 2. Input and output data of CATREF

	Contents
Input data	✓ Coordinates and velocity of the sites in individual solution ✓ Polar motion, Earth orientation parameters ✓ Variance-covariance matrix
Output data	✓ Coordinates and velocity of all sites at reference epoch ✓ Transformation parameters between combined and individual frames ✓ Polar motion, Earth orientation parameters ✓ 6 periodic terms for each frequency and site

GNSS software produces a daily solution independently with weak constraints or minimum constraints. Before applying CATREF, the individual GNSS solutions should be stored in a common SINEX format. The daily solutions need to be stacked to obtain the combined solution of the national geodetic reference frame. In addition, the PSD model, the discontinuity due to earthquakes or antenna replacement should be implemented as well.

The principles of the combining software can be summarized as follows:

1) Remove the initial constraints from individual SINEX file
2) Apply the same minimum constraints to all solutions
3) Combine SINEX files with minimum constraints
4) Detect and remove the outliers
5) Identify the discontinuity for long-term time series solution
6) Repeat the above steps until the unit weight gets closer to 1

4.2 The combined solution

The time series GNSS solutions in SINEX format are stacked to produce the combined solution. The problematic site with an unreliable variance-covariance matrix should be removed before stacking. The discontinuities are set up in a separate file by verifying the time series data beforehand. Additional information on the period (e.g. once or twice per year) needs to be specified to represent the PSD model and the seasonal variation of the site, thus the combining software can estimate the parameters.

CATREF model is the least-squares solution with minimum constraints by setting up a mathematical model to estimate transformation parameters between two frames(see Table 2 for the input and the output of CATREF). The minimum constraints contribute two frames to be aligned in orientation. Since the reference frame is generally the ITRF, the final solution will be the Korean geodetic reference frame aligned to ITRF(Fig. 6).

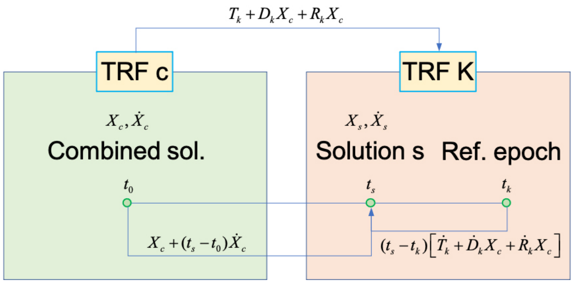

Fig. 6. The relationship between individual solution and combined solution (The detailed descriptions on the equations are omitted)

4.3 Identification of the discontinuity

Fig. 7 shows the time series of coordinates (4-digit code HONC) for three years, which covers the before and after the estimation of discontinuity. It seems that an event of antenna replacement has occurred on January 11, 2018(Figs.

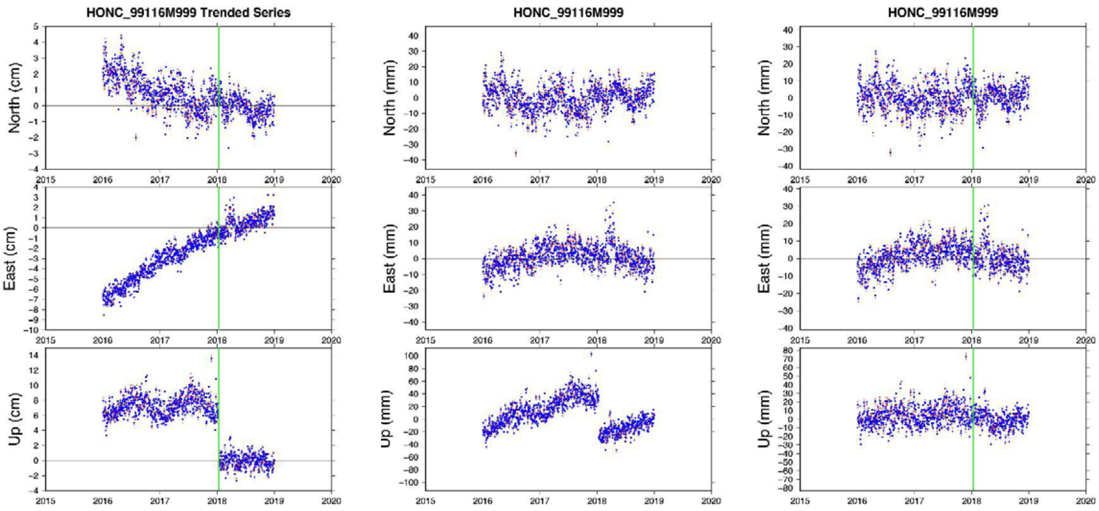

Fig. 7. Time series of coordinates with and without antenna offset information

7a&b, without/with detrend, respectively). If we estimate the combined solution by setting up the discontinuity at the specified date, the time series of the residuals becomes highly stable at the epoch denoted by the vertical green line(see Fig. 7c with detrended residuals).

4.4 Transformation parameters to ITRF2014

The daily solutions for three years were produced by Bernese GNSS Software, which was simultaneously processed with globally distributed 51 ITRF core stations. Table 3 shows the Helmert (7-parameter) transformation parameter0s(Jekeli, 2001) with respect to ITRF2014 were calculated using CATREF. It should be noted that all parameters are expressed in millimeter after unit conversion.

Table 3. Helmert transformation parameters from CATREF after unit conversion into millimeter (NGII, 2019)

Parameters	Estimated values [mm]
Tx	-21.87
Ty	16.97
Tz	16.52
Scale	5.38
Rx	44.71
Ry	54.03
Rz	7.52

The time series of the transformation parameters for three years are plotted in Fig. 8 to analyze the stability of the parameters for the Korean geodetic reference frame. As can be seen in the figure, the transformation parameters do not show any particular patterns, thus it can be stated that the processing results are suitably aligned to ITRF2014.

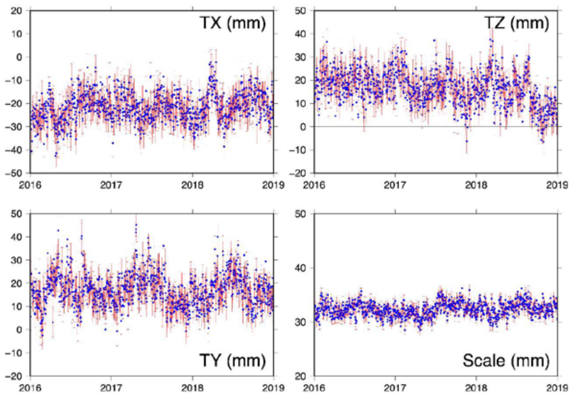

Fig. 8. The time series of transformation parameters (translation and scale only) (NGII, 2019)

5. Summary and Conclusion

The national geodetic reference frame is a fundamental basis for precise satellite positioning. The establishment and management of the frame can be done in two ways: the daily solution from GNSS-based data processing and its time series, and the combination with those from other space geodetic techniques. We processed three years of NGII CORS along with the globally distributed IGS core stations. Since both NGII CORS and IGS core stations are simultaneously processed, the resulting output is aligned to ITRF2014. We calculated the combined solution with minimum constraints least-squares principle using the time series of daily solutions. Although the PSD model and the periodic signals are set up in the combination process, the missing information of the discontinuity(e.g. large-scale earthquakes or antenna replacement etc.) may cause the residuals to behave unusual way. Other than the immediate events, the seasonal variation coming from the surrounding environment, such as growing trees or a mountain slope, is also an issue to be taken care of. Once all these factors are considered, the combining software(e.g. CATREF) can estimate the transformation parameters with confidence using the long-term data. The daily solutions as well as those from other space geodetic techniques should be archived in SINEX format for the future national geodetic reference frames.

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