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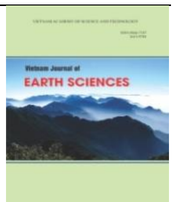

Determination of tectonic velocities of some continuously operating reference stations (CORS) in Vietnam 2016-2018 by using precise point positioning

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ABSTRACT

Determining the speed of tectonic plate displacement helps us to better understand tectonic activities of the area, and is a prerequisite to help forecast earthquakes. The determination of tectonic plate displacement by GNSS technology in Vietnam has been conducted since the 2000s, mainly using the relative positioning technique. The increasing accuracy of precise point positioning technique, and the number of CORS in Vietnam, will facilitate the accurate determination of tectonic velocities. Based on the GNSS data of some CORSs in Vietnam from 2016-2018, we have determined accurately their three-dimensional coordinates using a precise point positioning technique. After modeling periodic variations on the time series, we calculated the tectonic movement rate of 7 Vietnamese stations and 3 other stations in the region. Through analysis and comparison with other geology/plate motion models and GPS results, we conclude that this result is reliable. The velocity of tectonic motion in the North, East and Up components of Ha Noi, Da Nang and Ho Chi Minh City are respectively (-13.1, +32.8, -1.3), (-9.9, +31.0, +2.6) and (-10.3, +26.9, +2.7) mm/year.

Keywords: Tectonic velocities, GNSS, PPP, Vietnam.

1. Introduction

Plate tectonics is a scientific theory describing the large-scale motion of the number of plates of the Earth's lithosphere. From the original 7 large plates, there are now 52 smaller tectonic plates in the new PB2002 model of Peter Bird (2003). The plates move relative to each other and interact along their boundaries, where they converge, diverge, or slip cross each other. These interactions are assumed to be relevant to most of Earth's seismic and volcanic activity, although earthquakes and volcanoes can occur in plate

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interiors. Scientists now have a fairly good understanding of how the plates move, their boundary locations, and the type of plate boundary, such as an oceanic spreading ridge, etc. Accurate knowledge of tectonic motion allows us to better understand related natural events, such as earthquakes, landslips, volcanic activity.

Currently, the Global Navigation Satellite System (GNSS) has been the most useful for studying the Earth's crustal movements. Initially, relative positioning techniques were used to measure repeatedly distances between specific points, and then scientists could determine the movement along faults or between plates. However, these techniques have the disadvantage of not allowing us to determine the absolute displacement of each point. Since its inception in the late 1990s, precise point positioning (PPP) has quickly replaced relative techniques because of a number of advantages (King et al., 2002).

Based on the multi-year data of permanent GNSS stations distributed across the earth's surface, scientists were able to use PPP to determine their movement rate, providing a better understanding of the tectonic plates (JPL, 2019). For the first time in the International Terrestrial Reference Frame (ITRF) history, the ITRF2014 was generated with enhanced modeling of nonlinear station motions, including seasonal (annual and semiannual) signals of station positions and post-seismic deformation for sites that were subject to major earthquakes (Drewes, 2017; Altamimi et al., 2016).

In Vietnam, the installation of CORS only commenced in 2016 (or earlier for military and defense purposes only) (Vietnam+, 2016). Therefore, the determination of their tectonic plate movement is not included in previous ITRF studies (Fig. 1). In this paper, we use the PPP technique to process GNSS data from 2016-2018 of 7 CORS in Vietnam to determine their tectonic movement rate. Since these Vietnamese stations are not installed for geodynamic purposes, we will compare the results with 3 permanent GNSS stations in Thailand and Hong Kong within the same EURASIA tectonic plate. Our results are also compared with previous studies in Vietnam.

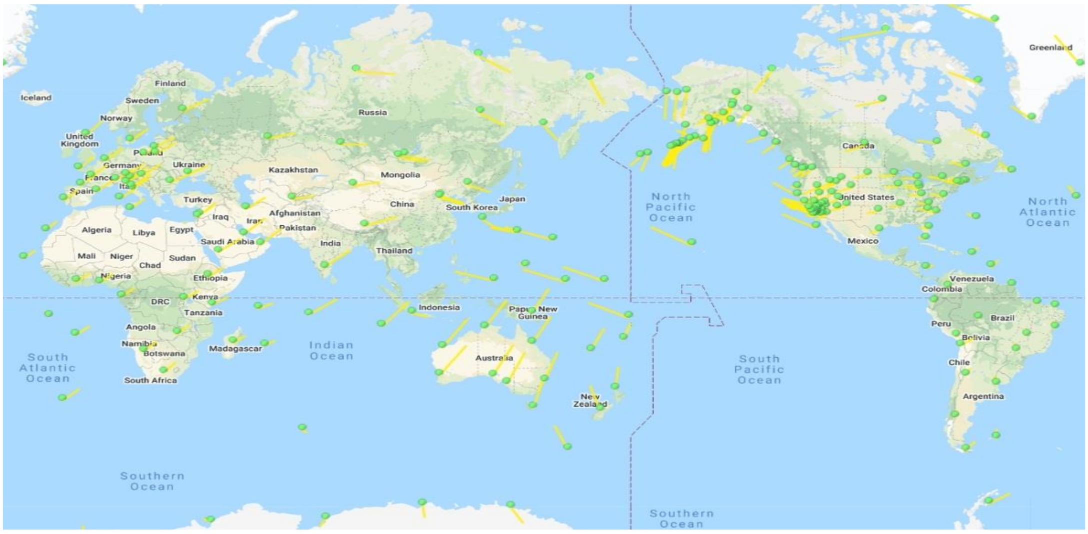

Figure 1. Tectonic motion of some GNSS stations from 2000 (referred from JPL)

2. GNSS data used for research

Data from 10 GNSS stations were collected from 4 different organizations: CDDIS (The Crustal Dynamics Data Information System), JPL (Jet Propulsion Laboratory), JAXA (The Japan Aerospace Exploration Agency), and Tuong Anh Company - Vietnam. Some characteristics of these stations are summarized in Table 1. Their positions on the map are shown in Figure 4. All the GNSS receivers are high quality and dual-frequency type, capable of receiving signals from many satellite systems such as GPS, GLONASS, GALILEO, BEIDOU, and QZSS.

Figure 2 shows the different types of antennas and installation methods at the CORSs. CDDIS and JPL stations use choke ring antennas that are highly resistant to multipath interference and are installed on sturdy pillars. Meanwhile, Tuong Anh company's antennas are ordinary types, mounted on small columns placed on structures of unknown stability. Therefore, GNSS data from Tuong Anh's stations may be affected by the vibration of the antenna column and the settlement or movement of the structure.

On the other hand, GNSS data of CDDIS and JPL is continuous 24 hours a day, year-round. JAXA and Tuong Anh data have missing data for many days of the year. There are also days when the receiver did not record enough 24 hour data. Station DANA only started operation in 2017. All of Tuong Anh's CORSs lost the majority of data in 2018 due to the change of GNSS receiver firmware.

Table 1. Some features of 10 CORSs (2016-2018)

No.	Station	Organisation	Location	Receiver	Antenna	Interval
1	HKSL	CDDIS	Hong Kong, China	LEICA GR50	LEIAR25.R4 + LEIT	30s
2	CUSV	JPL	Bangkok, Thailand	JAVAD TRE_3 DELTA	JAVRINGANT_DM NONE	30s
3	CMUM	JAXA	Chiang mai, Thailand	TRIMBLE NETR9	JAV_GRANT-G3T NONE	30s
4	NAVI	JAXA	Ha Noi, Vietnam	TRIMBLE NETR9	JAVRINGANT_DM + SCIS	30s
5	HPHO	Tuong Anh company	Hai Phong, Vietnam	TRIMBLE NETR9	TRM55971.00 NONE	15s
6	NADI	Tuong Anh company	Nam Định, Vietnam	TRIMBLE NETR9	TRM55971.00 NONE	15s
7	DANA	Tuong Anh company	Da Nang, Vietnam	TRIMBLE NETR9	TRM55971.00 NONE	15s
8	HCMC	Tuong Anh company	HCMC, Vietnam	TRIMBLE NETR9	TRM55971.00 NONE	15s
9	TAYN	Tuong Anh company	Tay Ninh, Vietnam	TRIMBLE NETR9	TRM55971.00 NONE	15s
10	BTRE	Tuong Anh company	Ben Tre, Vietnam	TRIMBLE NETR9	TRM55971.00 NONE	15s

Figure 2. GNSS antennas of HKSL, CUSV (top, left to right), CMUM, NAVI and HCMC (bottom, left to right)

3. PPP processing and calculating tectonic motion

Precise Point Positioning (PPP) is a positioning method that processes phase and code measurements from a single GNSS receiver together with precise GNSS orbit and clock correction products (Zumberge et al., 1997). Therefore its positioning accuracy can be reached at mm-cm level, far beyond conventional absolute positioning in which only code measurement is processed and satellite broadcast ephemerid is used.

The accuracy of the PPP has increasingly improved thanks to the ambiguity resolution of the phase measurements and the integrated processing of various existing navigation satellite systems such as GPS, GLONASS, GALILEO, and BEIDOU (Bertige et al., 2010; Geng et al., 2012; Afifi and El-Rabbany, 2016).

The traditional relative positioning technique can achieve the same accuracy, but it needs at least two receivers to measure simultaneously and returns the result of baseline vector components between the two receivers. The relative positioning accuracy is poorer for the longer baseline (Rizos, 1997; King et al., 2002).

For applications determining the ground displacement due to tectonic movement, or due to earthquakes, volcanoes, tsunamis,... If using relative positioning, it is common to design long baselines so that the origin point is outside the affected area, resulting in a decrease in the desired accuracy. In contrast, PPP is not affected by this factor, so it is naturally suitable for the aforementioned applications.

Data of 10 GNSS stations measured from 01/2016 to 12/2018 was processed using Precise Point Positioning by using C language software (PPPC) developed by us since 2010 (Nguyen et al., 2010). PPPC software is capable of handling GNSS data in both static and dynamic modes and for various satellite systems such as GPS, GLONASS, GALILEO, BEIDOU, and QZSS. Most recently, we have upgraded PPPC to add ambiguity resolution capability for GPS when using CNES (Centre National d'Etudes Spatiales) products. The accuracies of PPP with ambiguity resolution when processing 24h static GPS data are 2.8, 3.5, and 8.6 mm for the North, East, and Up components (Nguyen, 2017). Some general settings for PPP processing are shown in Table 2.

Table 2. Setting parameters in PPP processing

Contents	Values
Satellite ephemerides and clock corrections	CNES products (Laurichesse, 2012)
Measurements	P_3 and Φ_3 in between satellite differenced form of GPS and GLONASS
Satellite elevation cutoff angle	5°
Weighting scheme	Exp(-ε/9°), ε is the satellite elevation angle
Tropospheric delay treatment	One TZD parameter per 30 minutes and 2 gradients per 12 hours
Mapping function	VMF1 (Boehm et al., 2006)
Ambiguity resolution	Wide-lane parameter first, then narrow-lane for GPS. Floating ambiguity parameter for GLONASS
Coordinate Reference Frame	ITRF2014 (Altamimi et al., 2016)
Solid Earth Tide corrections	apply
Ocean tide loading correction	FES2012 (updated from Lyard et al. (2006))

PPP processing results of the ten stations are shown in Fig. 4. We can clearly see the periodic variations with a period close to 1 year occurring over the time series of all North, East, and Up components of all stations. Therefore, to accurately determine the tectonic displacement rate, it is necessary to model these periodic variations. Bogusz1 and Klos (2016) indicated that the oscillations are caused by two main seasonal changes: a tropical year (365.2421 days) and a draconic year (~351 days). These variations can be modeled by the set of the harmonic functions as shown in Amiri-Simkooei et al. (2007). With our data time series of only 3 years or less, modeling both types of seasonal variation is not appropriate and unnecessary. Instead, we are only concerned with the second type of oscillation (draconic period), and rely on the research results of Amiri-Simkooei (2013). Amiri-Simkooei analyzed JPL data processed at the GPS Analysis Center to obtain a significant signal with a period of 351.6±0.2 days and its higher harmonics in the North, East, and Uptime series.

Therefore, we used a simple sinusoidal function to model the time series of our GNSS data as follow:

$$y(t) = y_0 + A.\sin(\frac{2\pi}{T}t + \varphi) + \varepsilon.t \qquad (1)$$

where y_0 is the initial value of the signal; A is the amplitude of the signal; T is the period, fixed to the value of 351.6 days; φ is the initial phase; and ε is the tilt angle of the signal sequence with the time axis. As a result, the velocity of the time series is calculated $v_y = \tan(\varepsilon)$.

We used the least-squares method to estimate values of the unknowns y_0, A, φ and ε for each component of North, East and Up, and for each station. From the estimated values ε, we calculate the corresponding velocities for each time series. The results are given in Table 3. The solid red line in Fig. 3 represents the calculated value from equation (1). Figure 4 shows the tectonic velocity vectors of the stations, plotted according to the values given in Table 3.

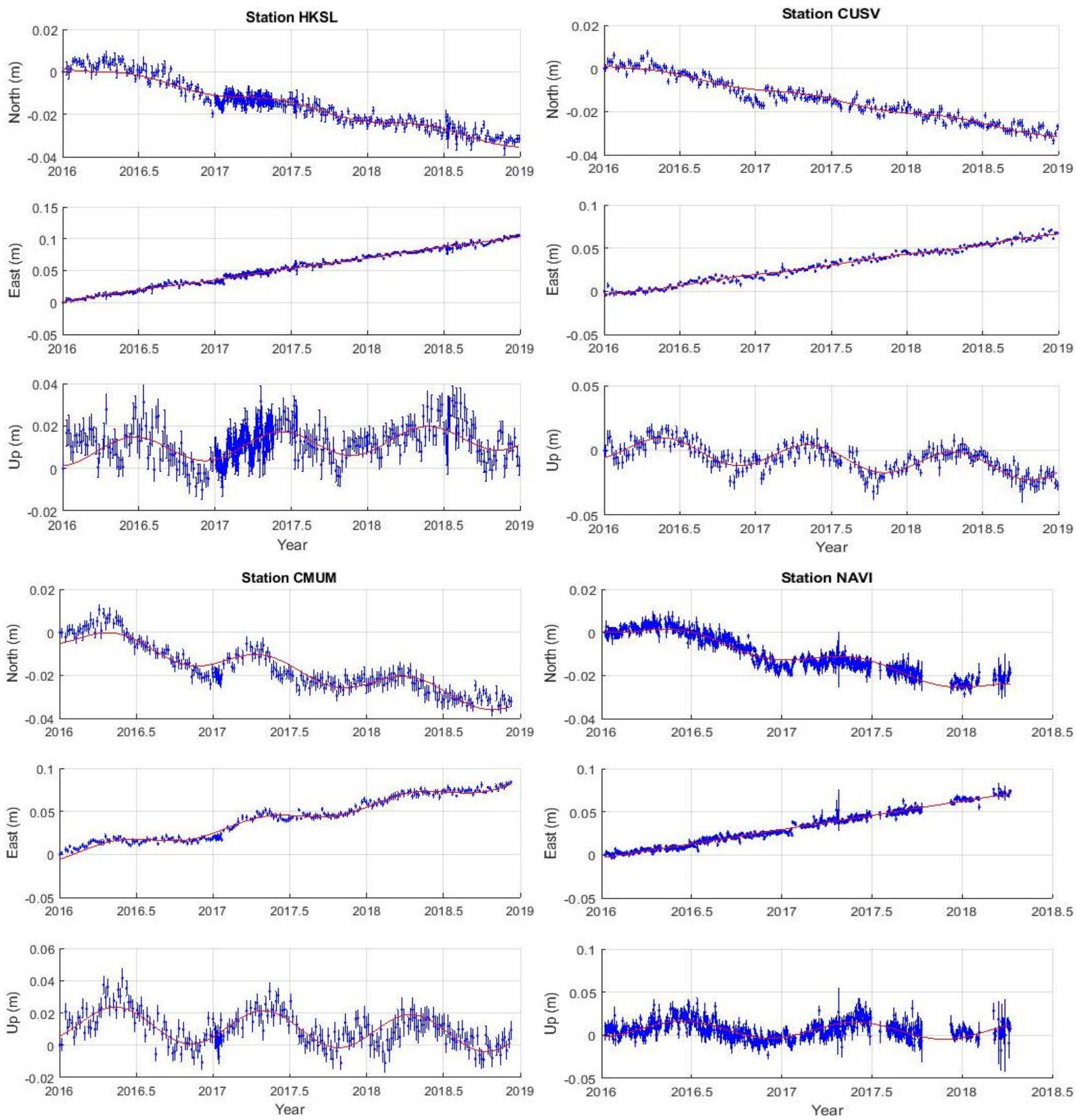

Figure 3. Time series of position in North, East and Up components

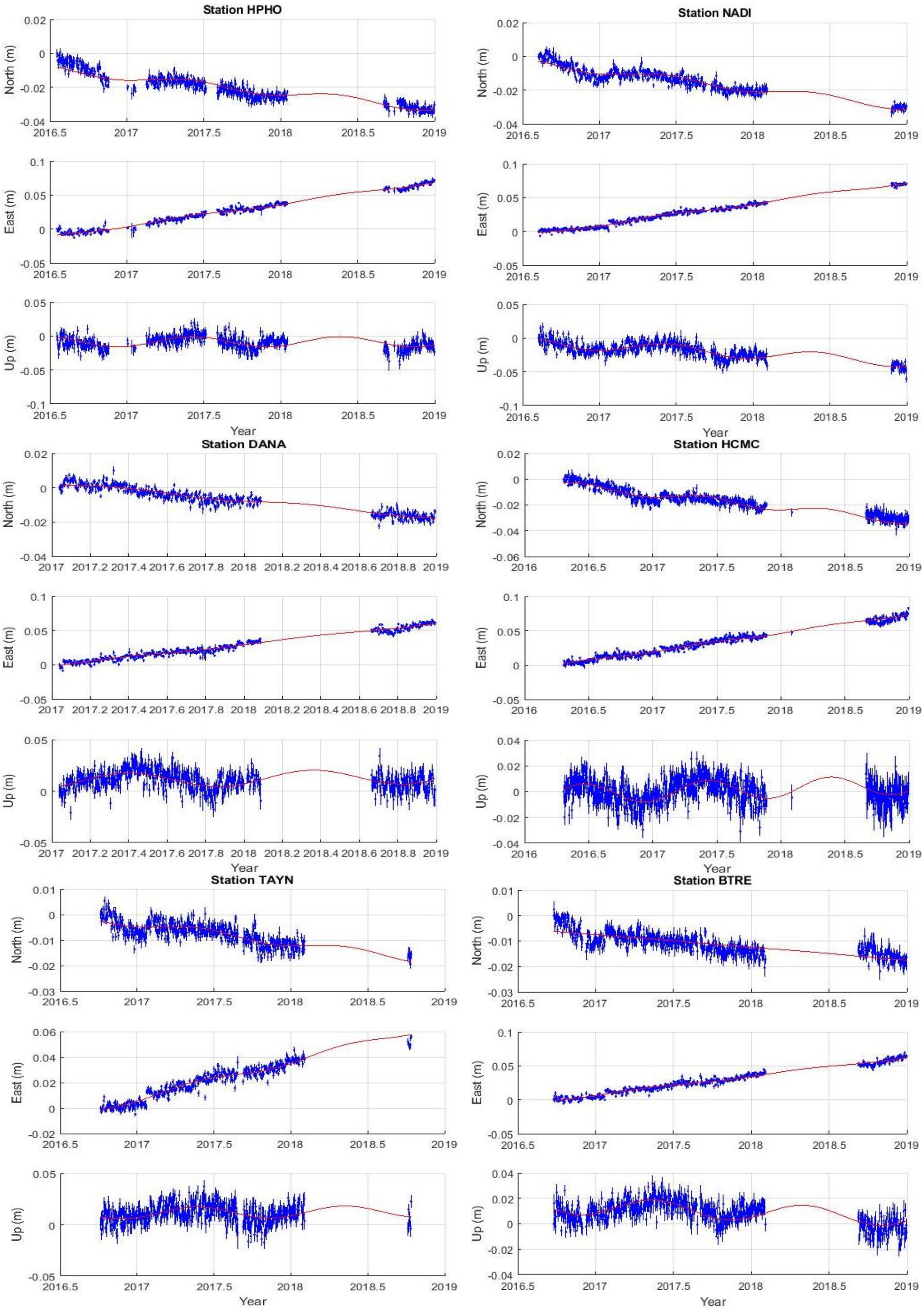

Figure 3. Continue.

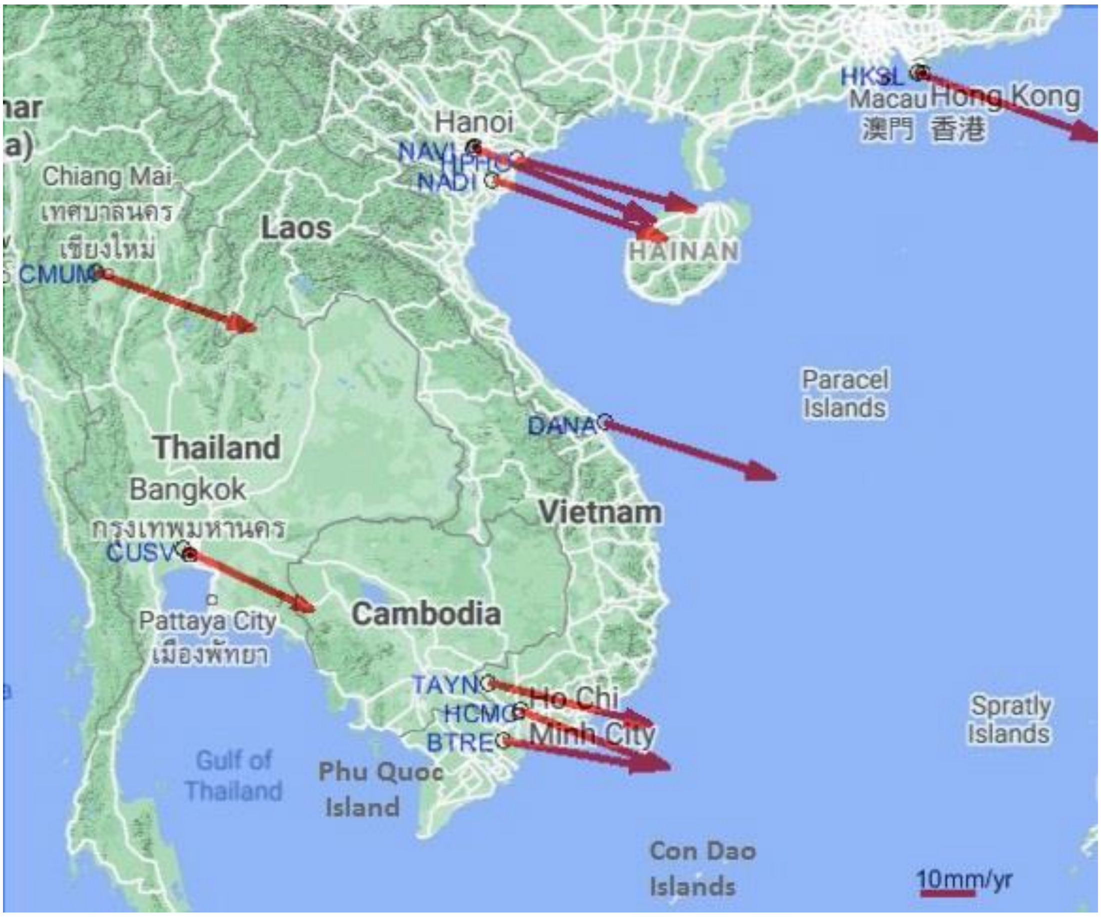

Figure 4. Location of GNSS stations used in research and their tectonic velocities

4. Discussions and comparison with previous studies

As mentioned in item 1, the antennas of the Tuong Anh's CORSs are mounted on the roof of high buildings, affected by some impacts such as the vibration of the antenna poles, multipath due to satellite signals reflect from roofs, building settlement,... These things make them different from geodynamic pillars, which are built solidly on the ground. The displacement observed on the CORS coordinates can be caused by a variety of reasons, not just tectonic plate displacement. Therefore, the comparison and analysis to exclude the effects of the secondary causes is very necessary.

The last row in Table 3 gives velocity values of station CUSV, calculated by JPL from nearly 10 years of data (SOPAC, 2019). When compared with our results, the maximum deviation is 3 mm/year on the Up component, while only 0.5 mm/year on the horizontal components. The larger deviation of CUSV Up component may be caused by PPP processing, mostly in modelling tropospheric delay. Naturally, the accuracy of the GNSS Up component is always 2-3 times lower than the horizontal components (for example Rizos (1997)). As a result, determining the Up velocity may take more time to converge.

In Table 3, NADI has a much higher value of Up component (-12.3 mm/year) compared to other stations (0-6 mm/year). It is unlikely to be caused by the tectonic plate shift. Most likely this is due to the settlement effect of the building with the GNSS antenna installed, or the local settlement of the ground.

Except for the abnormality in the Up component of NADI mentioned above, the results in Table 3 show that our PPPC processing and modeling of the periodic variations are similar and consistent for the same EURASIA tectonic plate. The RMS values of all the stations from Table 3 are also similar to Amiri-Simkooei (2013) being 3.0, 3.2 and 6.5 mm for all three components, respectively.

Table 3. Tectonic motion velocities of the GNSS stations

Station	Coordinates		Velocity (mm/year)			RMS (mm)			Duration
	Latitude	Longitude	North	East	Up	North	East	Up	
HKSL	22°22’19”	113°55’41”	-12.4 ±0.2	+33.7 ±0.2	+2.5 ±0.5	±2.7	±2.7	±6.7	01/2016-12/2018
CUSV	13°44’09”	100°32’02”	-11.0 ±0.2	+23.5 ±0.2	-5.6 ±0.4	±2.4	±2.8	±5.5	01/2016-12/2018
CMUM	18°45’39”	98°55’57”	-10.4 ±0.3	+28.8 ±0.3	-2.4 ±0.5	±4.1	±4.0	±6.9	01/2016-12/2018
NAVI	21°00’16”	105°50’38”	-13.1 ±0.2	+32.8 ±0.2	-1.3 ±0.4	±2.7	±2.8	±7.7	01/2016-02/2018
HPHO	20°48’48”	106°37’22”	-9.1 ±0.2	+32.5 ±0.2	0.0 ±0.5	±2.8	±2.9	±7.7	07/2016-12/2018
NADI	20°26’44”	106°11’07”	-10.8 ±0.2	+31.5 ±0.2	-12.3 ±0.5	±2.5	±2.3	±6.7	08/2016-12/2018
DANA	16°01’36”	108°12’45”	-9.9 ±0.2	+31.0 ±0.3	+2.6 ±0.7	±2.2	±3.2	±7.8	01/2017-12/2018
HCMC	10°48’23”	106°40’58”	-10.3 ±0.2	+26.9 ±0.2	+2.7 ±0.4	±3.0	±3.2	±7.9	04/2016-11/2018
TAYN	11°19’21”	106°06’09”	-7.6 ±0.2	+29.5 ±0.3	+0.8 ±0.8	±2.6	±3.3	±7.8	07/2016-10/2018
BTRE	10°16’05”	106°22’09”	-5.0 ±0.2	+27.7 ±0.3	-4.3 ±0.5	±2.7	±3.0	±6.4	07/2016-12/2018
CUSV JPL			-11.5 ±0.2	+23.7 ±0.3	-2.5 ±0.5				10/2008-10/2019

The horizontal velocity values of 10 stations are approximately the same (Fig. 4). This shows that, at the Tuong An stations, the influence of antennas and the instability of the construction structure on the results, if any, exist at the Up components mostly.

Le et al. (2014) used GAMIT software to handle a network of 10 ITRF stations and 5 GPS continuous stations in Vietnam, operated over 4 years. Some of their results at Ha Noi and Ho Chi Minh City in ITRF2005 are summarized in Table 4. Compare the results in Table 4 with our results in Table 3 at NAVI and HCMC stations, the biggest deviation in the North is 2.9 mm/year and the East is 3.6 mm/year.

Table 4. Velocities in ITRF2005 and error, referred from Le et al., 2014

Station	Location	Velocity (mm/year)		Duration
		North	East	
PHUT	Ha Noi	-10.0±1.0	+30.6±1.0	2/2009-6/2013
HOCM	Ho Chi Minh City	-11.0±0.8	+23.3±0.8	5/2005-10/2012

Phan et al. (2015) also used GAMIT and BERNESE software to relatively process GPS data measured one week each year from 2007 to 2010. They calculated the horizontal movement velocity of the seven GPS stations in the international reference frame ITRF2005. Table 5 gives the results of the two stations in Hanoi and Ho Chi Minh City. Compare the BERNESE results in Table 5 with our results in Table 3 at NAVI and HCMC stations, the largest deviation in the North is 2.3 mm/year and the East is 6.5 mm/year. Thus, although there are differences in time, GPS data source, processing and calculation methods, the results of tectonic movement velocities in 2005-2012 and 2016-2018 are still similar.

Despite the advantages of using PPP techniques in this research, we are well aware that our 3-year GNSS data (2016-2018) is quite short to accurately determine the tectonic velocities in Vietnam. Unfortunately, some of Tuong Anh's CORSs have moved to new locations since 2019, interrupting the GNSS data continuity. We expect the new CORS data from 2019 onwards will be better for this work.

Table 5. Velocities in ITRF2005 and error, referred from Phan et al. (2015)

Station	Location	Velocity (mm/year)		Software
		North	East	
LANG	Ha Noi	-12.7 ±1.3	+39.3 ±1.3	GAMIT
		-10.8 ±0.1	+39.3 ±0.1	BERNESE
HOCM	Ho Chi Minh City	-13.8 ±1.5	+22.0 ±1.4	GAMIT
		-10.1 ±0.1	+22.2 ±0.1	BERNESE

5. Conclusions

We collected data at 10 permanent GNSS stations from 2016-2018 located on the same EURASIA tectonic plate, including 7 stations in Vietnam, 2 in Thailand and 1 in Hong Kong-China. We used our own developed PPP processing software to analyse this data.

The PPP processing results, in the North, East and Up components, revealed periodic variations with period of nearly 1 year. After using a simple sine function to model this fluctuation, we accurately calculated the displacement rate of the GNSS stations.

The tectonic movement velocities of stations in Vietnam in the North, East and Up components are (-13.1, +32.8, -1.3) mm/year in Hanoi, (-9.9, +31.0, +2.6) mm/year in Da Nang and (-10.3, +26.9, +2.7) mm/year in Ho Chi Minh City. These values are similar to those in Thailand and Hong Kong at stations on the same tectonic plate.

Our tectonic movement velocities in Hanoi and Ho Chi Minh City are similar to the previous studies in the period (2005-2012) despite the differences in GNSS data sources, reference frames, processing methods and calculate.

In general, the GNSS data source in the period 2016-2018 in Vietnam is not really favorable for determining the tectonic velocities. Number of CORS is small and unevenly distributed. Their operation time is intermittent and interrupted. This will certainly affect the determination accuracy. From 2019, the number of CORS has increased significantly and distributed throughout the country. We expect to have a better source of GNSS data for determining the tectonic movement rate in the next phases.

Acknowledgements

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