Vietnam Journal of Earth Sciences, 42(4), 334–350, Doi: 10.15625/0866-7187/42/4/15282

(VAST)

Vietnam Academy of Science and Technology

Vietnam Journal of Earth Sciences

http://www.vjs.ac.vn/index.php/jse

Contemporary movement of the Earth's crust in the Northwestern Vietnam by continuous GPS data

Le Huy Minh[1,5], Vu Tuan Hung[2], Jyr-Ching Hu[3], Nguyen Le Minh[1,5], Bor-Shouh Huang[4], Horng-Yue Chen[4], Nguyen Chien Thang[1], Nguyen Ha Thanh[1], Le Truong Thanh[1], Nguyen Thi Mai[1], Pham Thi Thu Hong[1,5]

[1]*Institute of Geophysics, VAST, Hanoi, Vietnam*
[2]*Institute of Geological Science, VAST, Hanoi, Vietnam*
[3]*National Taiwan University, Taiwan*
[4]*Institute of Earth Sciences, SINICA, Taiwan*
[5]*Graduate University of Science and Technology, VAST, Hanoi, Vietnam*

Received 18 May 2020; Received in revised form 10 July 2020; Accepted 1 September 2020

ABSTRACT

The paper presents an estimation of the Earth's crustal motion from the continuous GPS data at 6 stations (MTEV, MLAY, DBIV, TGIV, SMAV and SLAV) in the Northwestern and at PHUT (Hanoi) station using GAMIT/GLOBK software. The absolute horizontal displacements of the Earth's crust at 7 stations in the IGS14 frame are respectively: 34.10±0.71 mm/yr (DBIV), 34.31±0.65 mm/yr (PHUT), 34.51±0.75 mm/yr (SMAV), 34.55±0.80 mm/yr (MLAY), 34.80±0.72 mm/yr (TGIV), 34.93±0.99 mm/yr (SLAV) and 35.59±0.73 mm/yr (MTEV), in the southeastward with the azimuth range 104-108°. The Son La fault is a right-lateral slip fault with a shear amplitude of ~1.5 mm/yr. The Lai Chau - Dien Bien fault is a left-lateral slip fault with a shear amplitude of ~1.9 mm/yr. Although the absolute velocities at the DBIV, SMAV, SLAV, TGIV and MLAY stations are evaluated with the error < 1 mm/yr, the relative displacement on the Ma River fault is of ~0.5 mm/yr, and it seems that we still do not have a reliable assessment of the slip rate on the Ma River right-lateral slip fault.

Keywords: Crustal movement; GPS continuous data; IGS14; Northwestern Vietnam; GAMIT/GLOBK.

1. Introduction

The Northwest region with a complex fault network is the most active zone in Vietnam. The two strongest earthquakes with M = 6.8 occurred in the region, the Dien Bien earthquake (1935) in the Ma River fault zone and the Tuan Giao earthquake (1983) in the Son La fault zone, and many earthquakes of magnitude M ≥ 4 occurred in the area (Nguyen Dinh Xuyen et al., 2004, see Fig. 4 in the following). The tectonic movement of the Earth's crust in the Northwestern region in particular and the entire Northern one in general has also been concerned since the 1990s (Tran Dinh To et al., 1999; 2000; 2013; Tran Dinh To, 2006; Feigl et al., 2003; Duong Chi Cong et al., 2006; Vy Quoc Hai, 2009).

*Corresponding author, Email: lhminhigp@gmail.com

The crustal movements presented in these works are obtained from campaign measurements over the faults in consideration, and the absolute movement speed at the measurement points have been estimated with an error of about 1-2 mm/yr. Relative velocities at some faults have been estimated also. Analyzing the GPS measurements collected in 1994, 1996, 1998, 2000 and 2001 in Yen Bai, Phu Tho and Ha Tay, Feigl et al. (2003) concluded that at a local scale, the Red River fault does not slide faster than 1 or 2 mm/yr. The average slip rate from Pliocene to the present on Lai Chau - Dien Bien (LC-DB) fault is about 2.5 mm/yr (Zuchiewics et al., 2004). Displaced shelves and alluvial cones allow assuming that the left-lateral and normal left-lateral faults that surround the pull-apart basins in the southern part of the Lai Chau - Dien Bien fault have a minimum left-lateral slip rate from 0.6 to 2 mm/yr in Holocene and 0.5-3.8 mm/yr in Pliocene (Nguyen Van Hung, 2002). Several basins along the fault are the strongest evidence for the horizontal component of the movement along the southern part of the fault where the basin is developed by half of the trench with a growing stratum. Using the data collected from 2001 to 2012 at 22 campaign GPS sites Northwestern Vietnam, Nguyen Anh Duong et al. (2013) estimated a left-lateral slip rate of 1.8±0.3 mm/yr for LC-DB fault, 1.0± 0.6 mm/yr for Son La and Da River faults.

Since 2005, three continuous GPS receivers have been installed in Hanoi, Hue and Ho Chi Minh city, the first results of the evaluation of tectonic displacement from this data have been presented (Le Huy Minh et al., 2010; 2014). In the framework of international cooperation between the Institute of Geophysics, the Vietnam Academy of Science and Technology and the National Taiwan University, from 2009-2010, 6 continuous GPS stations have been installed in Northwestern Vietnam. Following the study in the previous paper (Le Huy et al., 2014), supplementing the observation data at the DBIV and PHUT stations from 2014 to the present, and data from 5 other stations in Northwestern Vietnam, this paper reports the horizontal crustal movement velocity with the accuracy of less than 1 mm/yr, one of the most accurate assessments of the horizontal crustal velocity in Vietnam and the estimation of relative displacement on the Lai Chau - Dien Bien, Son La and Ma River faults.

2. Data and analysis method

The data to be used is the data of 7 continuous GPS stations in the Northwest region including MTEV, MLAY, DBIV, TGIV, SLAV and SMAV, PHUT stations as well as some stations of the International GPS Service (IGS), which were used to stabilize the velocity solution of Vietnamese GPS stations. The location of stations, type of equipment, and observation period at 7 stations are presented in Table 1. It is shown that the PHUT station has the longest observation period of more than 11 years, and the SLAV station has the shortest one is of 4 years and 9 months, the remaining stations from 7 to 9 years. Table 1 also lists 27 IGS stations in Eurasian, Philippine and Indo-Australian plates whose data is used to estimate the velocity in the following sections.

MLAY, DBIV, and SLAV stations are located in the Muong Lay, Dien Bien, and Son La seismic stations, respectively. Their antennas are plugged into the concrete pillar on the top of the seismic station (Fig. 1). The antennas at MTEV, TGIV, and SMAV stations are located on the roofs of concrete houses on the bedrock. The antenna of the PHUT station (Fig. 1) was placed on the roof of the main building of Phu Thuy observatory (Dang Xa, Gia Lam, Hanoi), which has been built in 1962, whose foundation is stable. So it can be said that the antennas of these 7 GPS stations have been placed in very stable positions that satisfy the requirements of geodynamic studies.

Table 1. Locations, receiver type and observation time span of 7 GPS stations in the northern Vietnam and 27 IGS stations in Eurasian, Philippine and Indo-Australian plates

Station	Coordinates		Receiver	Antena	Observation period
	Longitude (°E)	Latitude (°N)			
MTEV	102.80720	22.38791	NETRS	Zephyr geodetic	12/2009-07/2018
MLAY	103.15385	22.04187	NETRS	Zephyr geodetic	01/2012-12/2018
DBIV	103.01829	21.38992	NETRS	Zephyr geodetic	11/2009-12/2018
TGIV	103.41804	21.59225	NETRS	Zephyr geodetic	11/2009-12/2018
SMAV	103.74972	21.05629	NETRS	Zephyr geodetic	06/2010-07/2018
SLAV	103.90664	21.32529	NETRS	Zephyr geodetic	12/2009-09/2014
PHUT	105.95872	21.02938	GSV4004B	NOV533+CR	02/2009-03/2020
MAC1	158.93583	-54.49953	IGS station		04/2005-03/2020
TIDB	148.98000	-35.39920	IGS station		04/2005-03/2020
HOB2	147.43874	-42.80471	IGS station		04/2005-03/2020
DARW	131.13274	-12.84370	IGS station		04/2005-03/2020
SHAO	121.20045	31.09964	IGS station		04/2005-03/2019
PIMO	121.07773	14.63572	IGS station		09/2005-03/2020
TCMS	120.98740	24.79798	IGS station		04/2005-03/2020
PERT	115.88526	-31.80196	IGS station		04/2005-03/2020
WUHN	114.35727	30.53165	IGS station		04/2005-09/2016
BAKO	106.84891	-6.49106	IGS station		04/2005-03/2020
IRKT	104.31625	52.21902	IGS station		04/2005-01/2014
NTUS	103.67996	1.34580	IGS station		09/2007-03/2020
KUNM	102.79720	25.02954	IGS station		04/2005-01/2013
ANMG	101.50660	2.78465	IGS station		02/2014-03/2020
CUSV	100.53392	13.73591	IGS station		10/2008-03/2020
CMUM	98.93238	18.76088	IGS station		01/2014-03/2020
COCO	96.83398	-12.18834	IGS station		04/2005-03/2020
LHAS	91.10400	29.65734	IGS station		04/2005-01/2007
HYDE	78.55088	17.41726	IGS station		04/2005-03/2020
IISC	77.57038	13.02117	IGS station		04/2005-03/2020
POL2	74.69427	42.67977	IGS station		04/2005-03/2020
DGAR	72.37025	-7.26968	IGS station		04/2005-03/2020
KIT3	66.88545	39.13477	IGS station		04/2005-03/2020
ARTU	58.56046	56.42982	IGS station		04/2005-03/2020
ZECK	41.56507	43.78839	IGS station		04/2005-03/2020
JOZE	21.03154	52.09728	IGS station		04/2005-03/2020
POTS	13.06610	52.37930	IGS station		04/2005-03/2020

Figure 1. Antenna at the DBIV station (left) and at the PHUT station (right)

GAMIT/GLOBE software (Herring et al., 2015, 2018a, b) was used to calculate the time series of station coordinate components and evaluate the velocity of the Earth's crustal movement at the station. This software was used to analyze the data of continuous GPS stations in Vietnam in previous publications (Le Huy Minh et al., 2010; 2014; Tran Dinh To et al., 2013 and some references in these papers). This is open-source software built to run under any UNIX operating system that supports X-Windows, including LINUX and MacOS, the latest version 10.71 released on the 10th March 2020. The logical parameter of the software that allows the most processing is 99 stations. However, today thanks to parallel processing on high-performance computing systems, it is possible to simultaneously handle data of large networks, for example, processing data of the international GPS service network (IGS) at MIT (Massachusetts Institute of Technology) with more than 300 stations, processing in New Mexico Tech for the North American segment with more than 1,000 stations. The processing procedure consists of three-step: (1) Calculation of the daily stations' coordinates using GAMIT software, (2) The daily loose constrained solutions of site coordinates from the first step are combined to generate time series of station coordinates using sh_glred command in GAMIT software, and then to identify and remove the outliers, (3) Time series of site coordinates from the second step and their covariance matrices are combined in a Kalman filter to estimate station velocities using GLOBK software. In order to process long-time data, calculations are accumulated at various stages, so the software is regularly updated to have accurate information about satellite systems, type of receiver, type of antenna, as well as the update information related to the satellite astronomy calendar, the lunar and solar tidal models, the polar position... The calculation of time series of station coordinates by GAMIT with a large station distance (500 km or more) requires the BASELINE mode and the data for more than 10 IGS stations. In fact, we have taken the data of 27 IGS stations listed in Table 1 and presented in Fig. 2, not only in Southeast Asian countries near Vietnam but also in some more remote stations in Eurasian, Philippine and Indo-Australian plates. Taking the data of many such IGS stations for processing the local station data has the disadvantage of consuming the computational time, but this makes it easy to choose stations to stabilize time series solutions. The IGS stations have been selected to stabilize the time series of station coordinates, ensuring the following conditions: the length of time series must cover the entire time range of station data series to be analyzed, the coordinates of the station must be continuously changed without any jump, the distribution of stations must be on all sides of the network of Vietnam stations, the stations should be in a stable base area not near the plate boundaries. Previously, some stations in China were often selected such as KUNM, SHAO or WUHN (Tran Dinh To et al., 2013, for example), but these stations have recently stopped providing data (KUNM from early 2013, WUHN from the end of 2016 and SHAO from the beginning of 2019), so we have selected more remote stations such as DARW in Australia, HYDE in India, TCMS station in Taiwan, POL2 station in Kyrgyzstan,... With the right choice of stations to stabilize the GAMIT's solution, the time series of coordinate components of the stations to be analyzed will continuously change, showing a clear linear trend. However, in the obtained time series there still would be some outliers beyond the general trend of the day solution, or daily solutions of too great errors. We can remove that date from time series by declaring this information in the eq_rename file in the tables subdirectory of the GAMIT running directory and rerunning the command to create the time series. After running the program that creates the time series of coordinate components, there are HYYMMDD*.GLX files in the gsoln subdirectory which will be used to run the GLOBK to evaluate the absolute velocity of the GPS stations. The selection of IGS stations to stabilize the velocity solution for the local GPS stations could be taken the same stations to stabilize the time series of the coordinate components as mentioned or some other stations could be added according to the experience of the GAMIT/GLOBK's user.

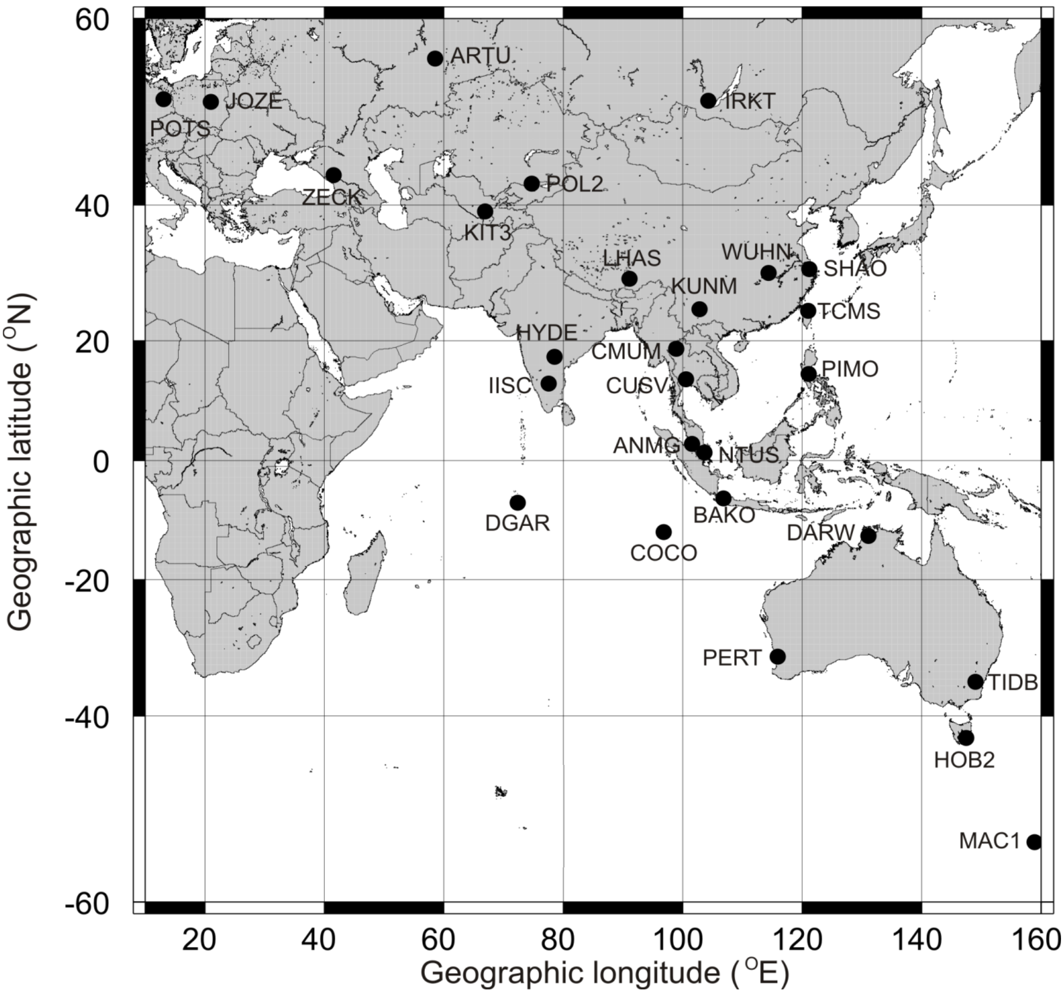


Figure 2. Some IGS' stations in Eurasian, Philippine and Indo-Australian plates

3. Results and discussion

3.1. Time series of the station coordinates

As mentioned above, the output of GAMIT software is the time series of three station coordinates: North N component, East E component, and vertical Up component. In the GPS technology, the two components N and E are determined with high reliability, the Up component often has larger errors due to the influence of the atmosphere. Figs. 3a-g shows the time series of N, E, and Up components of the 7 stations in the time period of consideration. In comparison with the time series of the DBIV and PHUT stations in Le Huy Minh et al. (2014), these time series are not only longer, but also more carefully dealt with by removing all outliers and the daily site solutions with too large errors. From the obtained time series it can be seen that for the SLAV station with the shortest observation period of 4.7 years, the seasonal effects can still be clearly observed in the N component. This shows that the data series length is very important in geodynamic studies. The quality of the time series evaluation of station coordinate components is expressed by two parameters: normalized root mean square (NRMS) and weighted root mean square (WRMS). These parameters for the 7 stations of interest are listed in Table 2. According to Herring et al. (2018b), the time series with NMRS ~1 are the well-defined ones. From Table 2, we see that the NRMS at the three components at all 07 stations satisfies the above condition. This information adds information on the velocity field accuracy at the stations shown below. Figures 3a-g also show that the vertical component is strongly influenced by seasonal fluctuations, this implicates that the horizontal coordinate components are estimated more precisely than the vertical component.

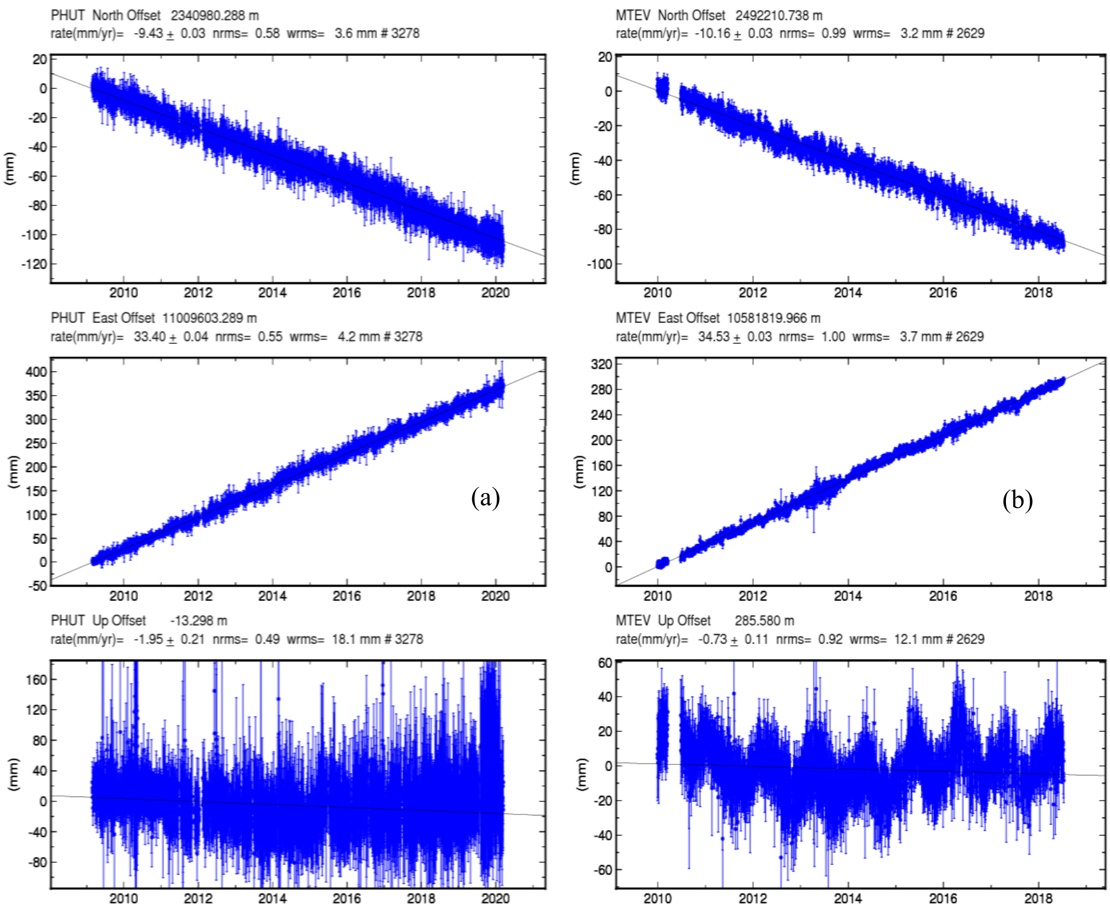


Figure 3

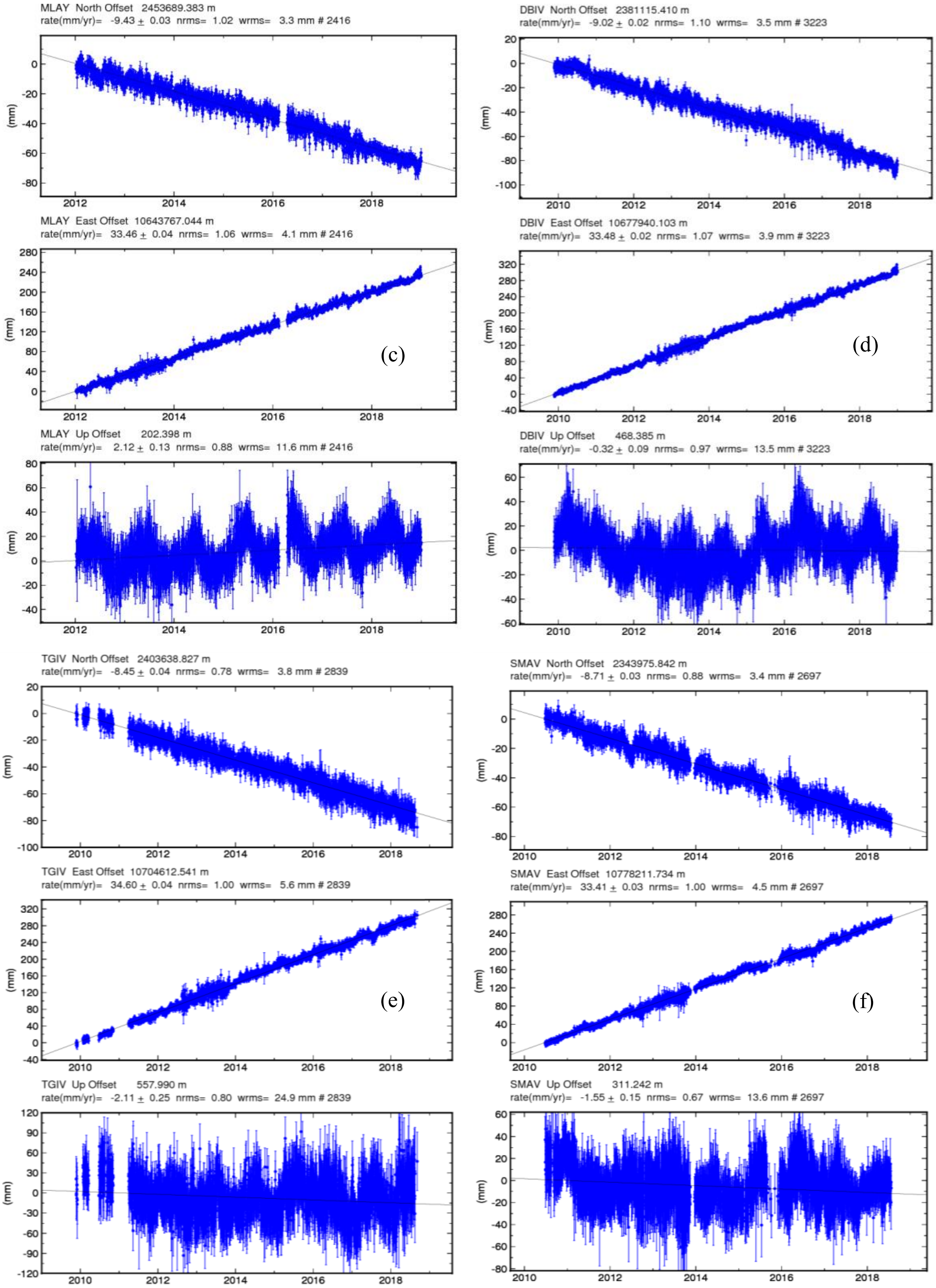
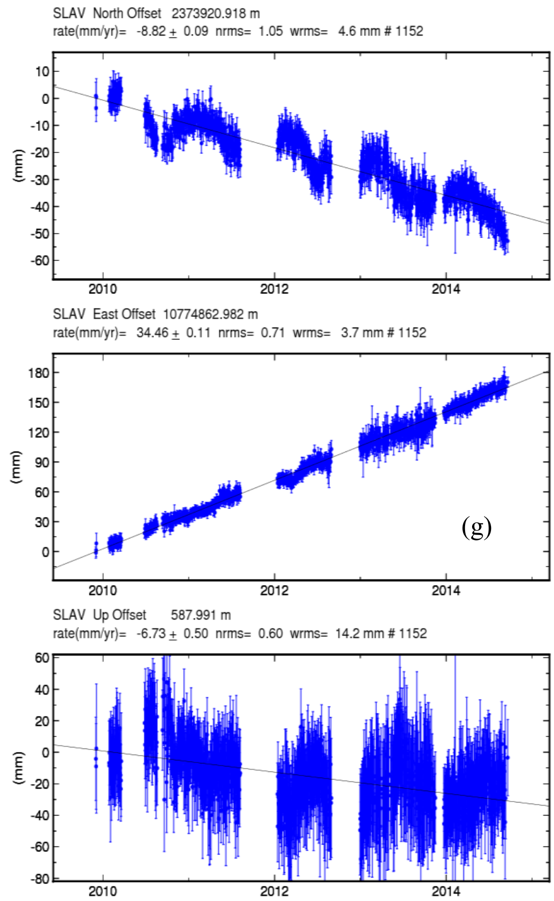


Figure 3. Continue



←*Figure 3.* a. Time series of the North (top), the East (middle) and the Up (bottom) components at PHUT station; b. The same as a. at MTEV station; c. The same as a. at MLAY station; d. The same as a. at DBIV station; e. The same as a. at TGIV station; f. The same as a. at SMAV station; g. The same as a. at SLAV station

Table 2. Time series span, normalized root mean square (NRMS), weighted root mean square (WRMS) at 7 GPS stations

Station	Time series span (yr)	N Comp.		E Comp.		Up Comp.	
		NRMS (mm)	WRMS (mm)	NRMS (mm)	WRMS (mm)	NRMS (mm)	WRMS (mm)
MTEV	8.5	0.99	3.2	1.00	3.7	0.92	12.1
MLAY	6.9	1.02	3.3	1.06	4.1	0.88	11.6
DBIV	9	1.10	3.5	1.07	3.9	0.97	13.5
TGIV	9	0.78	3.8	1.00	5.6	0.80	24.9
SMAV	8	0.88	3.4	1.00	4.5	0.67	13.6
SLAV	4.7	1.05	4.6	0.71	3.7	0.60	14.2
PHUT	11	0.55	3.6	0.55	4.2	0.49	18.1

3.2. Velocity field

After creating the time series of coordinate components from the GAMIT software, in the gsoln subdirectory there are the files of the form HYYMMDD*.GLX which are the input for running the GLOBK to obtain the absolute velocity estimation. The absolute velocity at 7 continuous GPS stations in consideration is calculated in the IGS14 reference frame (Rebischung & Schmid, 2016). This is a new reference system based on the international standard reference system ITRF14 (Altamimi et al., 2016), with updated information on satellite and satellite receiver antenna standards. The IGS14 reference system replaces the previously used IGS08/igs08.atx reference system, and is widely used in geodynamic studies worldwide. The results of the evaluation of the components V_E, V_N, and V_{Up} of the absolute velocity vector, and their errors are presented in Table 3. Figure 4 presents the absolute horizontal velocity at 7 stations in consideration. In Fig. 4 and the following figures, we used the background fault map from Nguyen Dinh Xuyen et al. (2004). Figure 4 presents also the distribution of the earthquakes with M ≥ 4.0 in North Vietnam and adjacent region (Institute of Geophysics, 2020), there are many earthquakes with M ≥ 4 concentrated on the Son La, Song Ma, and Lai Chau-Dien Bien faults. Table 3 presents the absolute velocity components of some IGS stations: KUNM, SHAO, and WUHN in China, CMUM and CUSV in Thailand, ANMG in Malaysia, NTUS in Singapore, BAKO in Indonesia and PIMO in Philippines for comparison. The horizontal velocity vectors in these IGS stations are estimated with the errors from 0.48 mm/yr at PIMO to 0.88 mm/yr at ANMG depending on the length of observation data.

Table 3. Velocities of the Earth's crust at 7 continuous GPS stations

Stat.	E comp.		N comp.		Absolute horizontal velecity				Vertical comp.	
	V_E (mm/yr)	δV_E (mm/yr)	V_N (mm/yr)	δV_N (mm/yr)	$\lvert\vec{V}\rvert$ (mm/yr)	$\delta\lvert\vec{V}\rvert$ (mm/yr)	Azimut (°)	Rel. (%)	V_{Up} (mm/yr)	δV_{Up} (mm/yr)
MTEV	34.03	0.73	-10.43	0.73	35.59	0.73	107	98	-2.76	0.27
MLAY	33.28	0.80	-9.27	0.80	34.55	0.80	106	98	-1.94	0.28
DBIV	32.90	0.71	-8.96	0.70	34.10	0.71	105	98	-2.07	0.26
TGIV	33.78	0.72	-8.38	0.72	34.80	0.72	104	98	-3.75	0.35
SLAV	33.23	0.99	-10.75	0.98	34.93	0.99	108	97	-4.49	0.54
SMAV	33.38	0.75	-8.76	0.75	34.51	0.75	105	98	-4.02	0.29
PHUT	33.02	0.65	-9.32	0.65	34.31	0.65	106	98	-3.12	0.32
KUNM	32.18	0.76	-17.82	0.76	36.78	0.76	119	98	-1.11	0.27
WUHN	34.09	0.54	-11.39	0.54	35.94	0.54	108	98	2.11	0.28
SHAO	33.72	0.59	-12.53	0.58	35.97	0.59	110	98	-3.38	0.29
CMUM	32.86	0.86	-6.40	0.85	33.48	0.86	101	97	-2.31	0.31
CUSV	24.20	0.64	-9.20	0.63	25.89	0.64	111	98	-7.68	0.25
ANMG	25.61	0.88	-5.26	0.87	26.14	0.88	102	97	-3.92	0.28
NTUS	25.49	0.61	-8.16	0.61	26.76	0.61	108	98	-	-
BAKO	24.66	0.57	-8.69	0.56	26.15	0.57	109	98	-	-
PIMO	-26.86	0.48	6.84	0.48	27.72	0.48	284	98	0.90	0.29

Table 3 shows that the horizontal velocity vector at SLAV station with the shortest length of data series (4.7 years) is evaluated with an error of 1 mm/yr, in the remaining 6 stations with larger data string lengths (from 7 to 11 years), horizontal velocity vectors are assessed with an error of 0.7-0.8 mm/yr. The reliability of horizontal velocity assessments in all 7 stations is 97-98%. The magnitude of the horizontal velocity vector at 7 stations varied from 34.10 mm/yr at the DBIV station to 35.59 mm/yr at the MTEV station. The horizontal velocity vectors at 7 stations are oriented to the southeast with azimuth varying from 104° at TGIV to 108° at SLAV station. This trend is consistent with the tectonic context in Southeast Asia. The northward motion of the Indian-Australian plate with respect to the Eurasian plate has caused the east-southeastward extrusion of Southeastern Asia (Molnar & Tapponnier, 1975, Tapponnier et al., 1982; 1986; England & Molnar, 1997). This tectonic model was confirmed by the GPS measurements in Vietnam and Southeast Asia region (Tran Dinh To et al., 1999; 2000; 2013; Simons et al., 1999; Michel et al., 2000; 2001; Feigl et al., 2003; Duong Chi Cong et al., 2006; Tran Dinh To, 2006; Vy Quoc Hai, 2009; Le Huy Minh et al., 2010; 2014; Nguyen Anh Duong et al., 2013; Phan Trong Trinh et al., 2015). The results of velocity assessment in ITRF2005 of PHUT station with continuous data from Feb. 2009 to Jun. 2013 period and of DBIV station from Nov. 2009 to Nov. 2013, in Le Huy Minh et al. (2014) are 32.2 mm/yr and 33.0 mm/yr, respectively. The differences in velocity assessment at two stations PHUT and DBIV are respectively 2.1 mm/yr and 1.1 mm/yr. This difference is not only because the length of the data series used is different, but also because in Le Huy Minh et al. (2014) the velocity is evaluated in ITRF2005, in this paper the velocity is evaluated in IGS14. Vy Quoc Hai & Bui Thi Hong Tham (2015) pointed out that the differences of GUAM and LHAS stations speeds in ITRF05 and ITRF08 are of 1.1 and 1.4 mm/yr respectively, while this difference was for WHUN station is of 3.2 mm/yr, so the differences in velocities evaluated in ITRF05 and IGS14 in both PHUT and DBIV stations are possible.

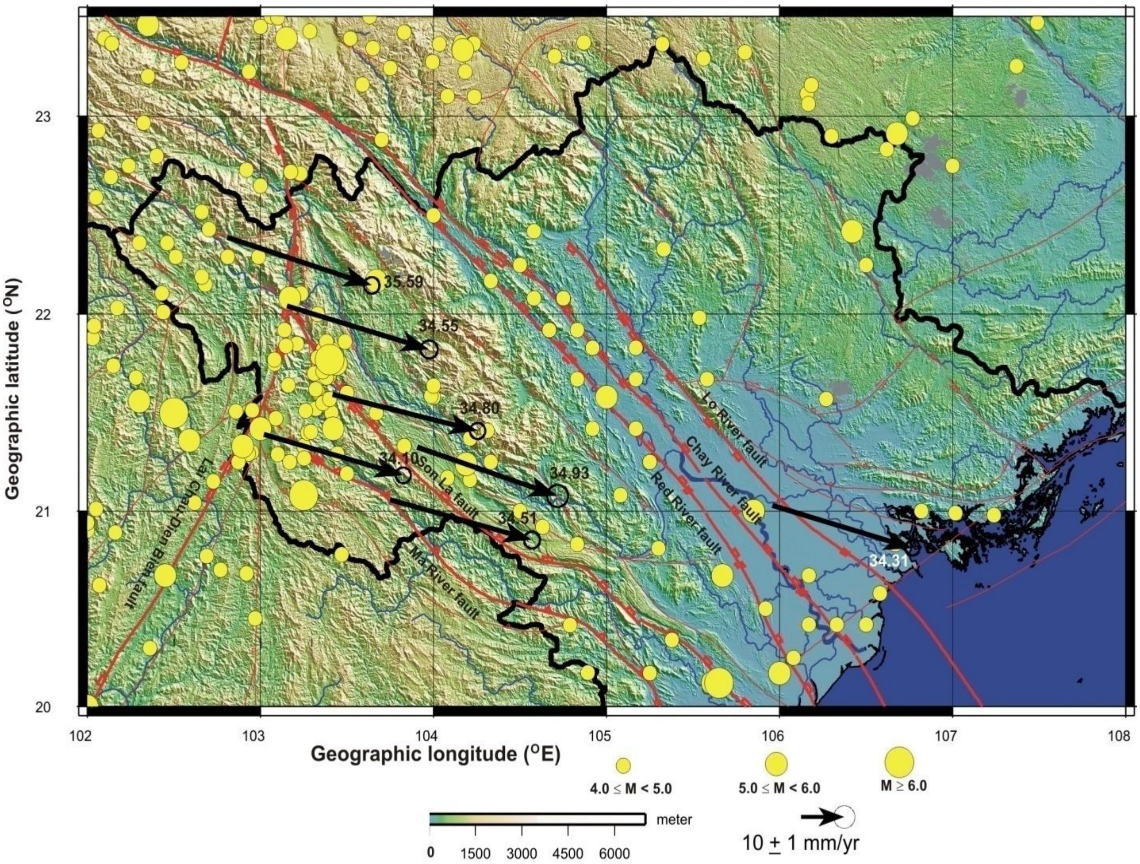


Figure 4. Absolute velocity of 7 continuous GPS stations in Northern Vietnam in IGS14. Distribution of earthquakes M ≥ 4.0 from February 1137 to December 2019 in North Vietnam and adjacent region

Table 3 shows that the horizontal velocities at 7 stations of Vietnam in consideration are close to the ones at KUNM, SHAO, and WUHN in China, and CMUM in Thailand. The results of velocity assessment of the IGS stations are consistent with the ones of Tran Dinh To et al. (2013): 35.59 mm/yr, 35.85 mm/yr, 37.61 mm/yr and 27.51 mm/yr in ITRF2000 at SHAO, WUHN, KUNM and NTUS stations respectively, compared to our respective results: 35.97 mm/yr, 35.94 mm/yr, 36.78 mm/yr and 26.76 mm/yr. The horizontal velocity at PHUT station in this paper (34.31 mm/yr) is close to the ones of some stations in the Red River fault zone (34.98 mm/yr and 34.00 mm/yr at SOC1 and BAV1 stations, respectively, estimated by Tran Dinh To et al. (2013) using the campaign measurements from 1994 to 2007. The estimation of the horizontal velocities at DON1, LEM1, NGA1, and HAM1 in ITRF2008 on the LC-DB fault zone using BERNESE Version 5.0 software and the campaign measurements from 2002 to 2011-2012 by Nguyen Anh Duong et al. (2013) is about 34.5 mm/yr which is close to our estimation in Table 3. Thus, the horizontal velocity of the Earth's crust in this paper is quite consistent with the previous research results using the campaign measurement data to be carried out in the time interval between first and last campaigns about 7 to 10 years. It is noted that with the same dataset, the error of the velocity estimation given by BERNESE software is smaller than the one by GAMIT/GLOBK, but the velocity values obtained by two software are also slightly different (Phan Trong Trinh et al., 2015). So we cannot assess the quality of the two mentioned software, while the length of observation data series plays a crucial role in determining the accuracy of the evaluation of the Earth's crustal velocity at each point, and in fact, these two soft wares are equally widely used.

Table 3 shows that the V_{up} values at 7 Vietnam stations are from -2.0 mm/yr at MLAY to -4.5 mm/yr at SLAV. They are in the same order as the ones at IGS stations in Table 3, except at BAKO and NTUS (jump in the Up component). However, it must be emphasized that the assessment of vertical displacement by GPS technology does not give reliable result, this can also be seen for MLAY station. While the vertical displacement at this station from the time series is positive, the station is being raised, the result from the GLOBK software, with the velocity modelling for the whole region, is negative, the station is in subsidence. The evaluation of vertical displacement needs to be done by other accurate geodetic methods.

3.3 Relative velocity

To assess the relative movement on a fault, one evaluates often the relative velocity between the two stations on either side of the fault. The relative displacement on the Son La fault was estimated by calculation of the relative velocity of the stations with respect to the SLAV station. The results are presented in Table 4 and are illustrated in Fig. 5. It notes that the error of a component of the relative vector is calculated as the root mean square error (RMSE) of a function $Z = x_1 \pm x_2$, and the error of the amplitude of the relative vector as the RMSE of a function $Z = f(x_1, x_2, \ldots, x_n)$ (Bui Quang Tuyen et al., 2005).

Table 4. Relative displacements with respect to SLAV

Station	E Comp.		N Comp.		Horizontal Comp.			Vertical Comp	
	ΔV_E (mm/yr)	$\delta\Delta V_E$ (mm/yr)	ΔV_N (mm/yr)	$\delta\Delta V_N$ (mm/yr)	$\lvert\Delta\vec{V}\rvert$ (mm/yr)	$\delta\lvert\Delta\vec{V}\rvert$ (mm/yr)	Azimuth (^{o})	ΔV_{Up} (mm/yr)	$\delta\Delta V_{Up}$ (mm/yr)
SLAV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TGIV	0.55	1.22	2.37	1.22	2.43	1.22	13	0.74	0.64
MLAY	0.05	1.27	1.48	1.26	1.48	1.26	2	2.55	0.61
SMAV	0.15	1.24	1.99	1.24	2.00	1.23	4	0.47	0.61
DBIV	-0.33	1.22	1.79	1.20	1.82	1.20	349	2.42	0.60
MTEV	0.80	1.23	0.32	1.22	0.86	1.23	68	1.73	0.60

From Fig. 5, we can see that from SLAV station, the movement directions of TGIV, MLAY, SMAV, and DBIV stations are right. Table 4 shows the relative vector amplitude of the TGIV station compared to the SLAV station of 2.43±1.22 mm/yr, of the MLAY station 1.48±1.26 mm/yr, of the SMAV station 2.00±1.23 mm/yr, and of the BDIV station, 1.82±1.23 mm/yr. The MLAY station is located near the intersection of Son La and Lai Chau - Dien Bien faults and is closer to the fault center than other stations. The relative displacement amplitudes estimated at these stations are greater than their errors, this means that the estimated relative displacement vectors of TGIV, MLAY, SMAV, and DBIV stations compared to SLAV stations are reliables. In the direction of the fault, the relative displacement of the TGIV station is about 1.5 mm/yr, the MLAY station ~0.9 mm/yr, of the SMAV station ~1.4 mm/yr and of the DBIV station ~1.6 mm/yr. Although the SMAV and DBIV stations are also affected by displacement on the Song Ma fault, their relative displacements with Son La station are close to the relative displacement value of TGIV station compared to SLAV station, this shows that the information about the relative movement on the Son La fault from the relative velocity of the TGIV station compared to the SLAV station is completely accurate. Therefore, it can be said that the Son La fault is a right-lateral fault with a shear amplitude of about 1.5 mm/yr, which is greater than the value of 1.0 mm/yr determined by Nguyen Anh Duong et al. (20013).

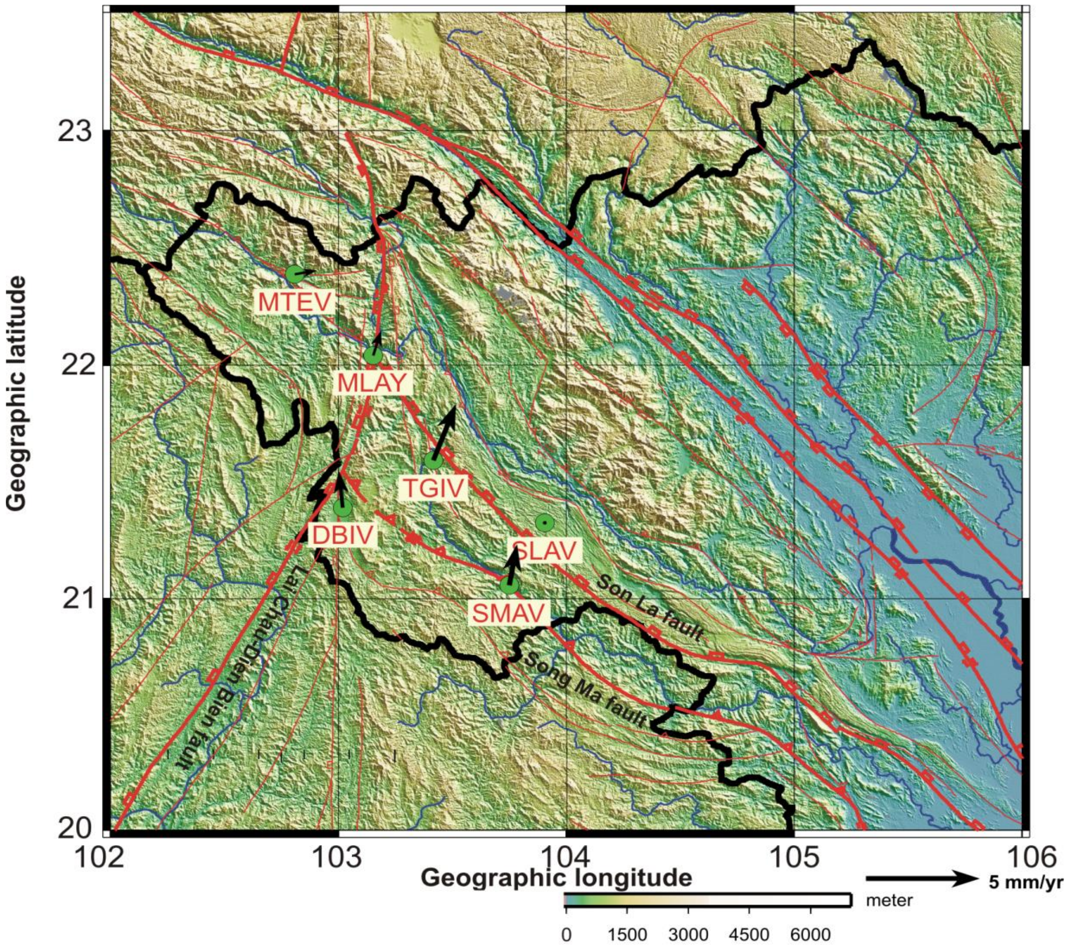


Figure 5. Relative velocity vectors of MLAY and TGIV with respect to SLAV

To assess the relative displacement on the Lai Chau - Dien Bien fault, we calculated the relative velocity of the stations with respect to the MTEV station, the results are presented in Table 5 and are illustrated in Fig. 6. Viewing from MTEV station, MLAY, DBIV, and TGIV stations are moving left. The relative shear amplitudes of MLAY, DBIV, and TGIV stations compared to MTEV station are 1.38±1.08 mm/yr, 1.85±1.01 mm/yr, and 2.06±1.02, respectively. These relative displacement vectors are also determined with amplitudes greater than their errors. In the fault direction the relative displacements of MLAY, DBIV, and TGIV stations are of ~1.0 mm/yr,

~0.6 mm/yr and ~1.9 mm/yr respectively. Thus, it can be said that the Lai Chau - Dien Bien fault has a left-lateral motion with a slip rate of 1.9 mm/yr, which is comparable with the estimation of Nguyen Anh Duong et al. (2013) is 1.8 mm/yr.

Table 5. Relative displacements with respect to MTEV

Station	E component		N component		Horizontal Comp.			Up comp.	
	ΔV_E (mm/yr)	$\delta\Delta V_E$ (mm/yr)	ΔV_N (mm/yr)	$\delta\Delta V_N$ (mm/yr)	$\lvert\Delta\vec{V}\rvert$ (mm/yr)	$\delta\lvert\Delta\vec{V}\rvert$ (mm/yr)	Azimuth (°)	ΔV_{Up} (mm/yr)	$\delta\Delta V_{Up}$ (mm/yr)
MTEV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MLAY	-0.75	1.08	1.16	1.08	1.38	1.08	327	0.82	0.39
DBIV	-1.13	1.01	1.47	1.01	1.85	1.01	322	0.69	0.37
SLAV	-0.80	1.23	-0.32	1.22	0.86	1.22	248	-1.73	0.60
SMAV	-0.65	1.05	1.67	1.05	1.79	1.05	339	-1.26	0.40
TGIV	-0.25	1.02	2.05	1.02	2.06	1.02	353	-0.99	0.44

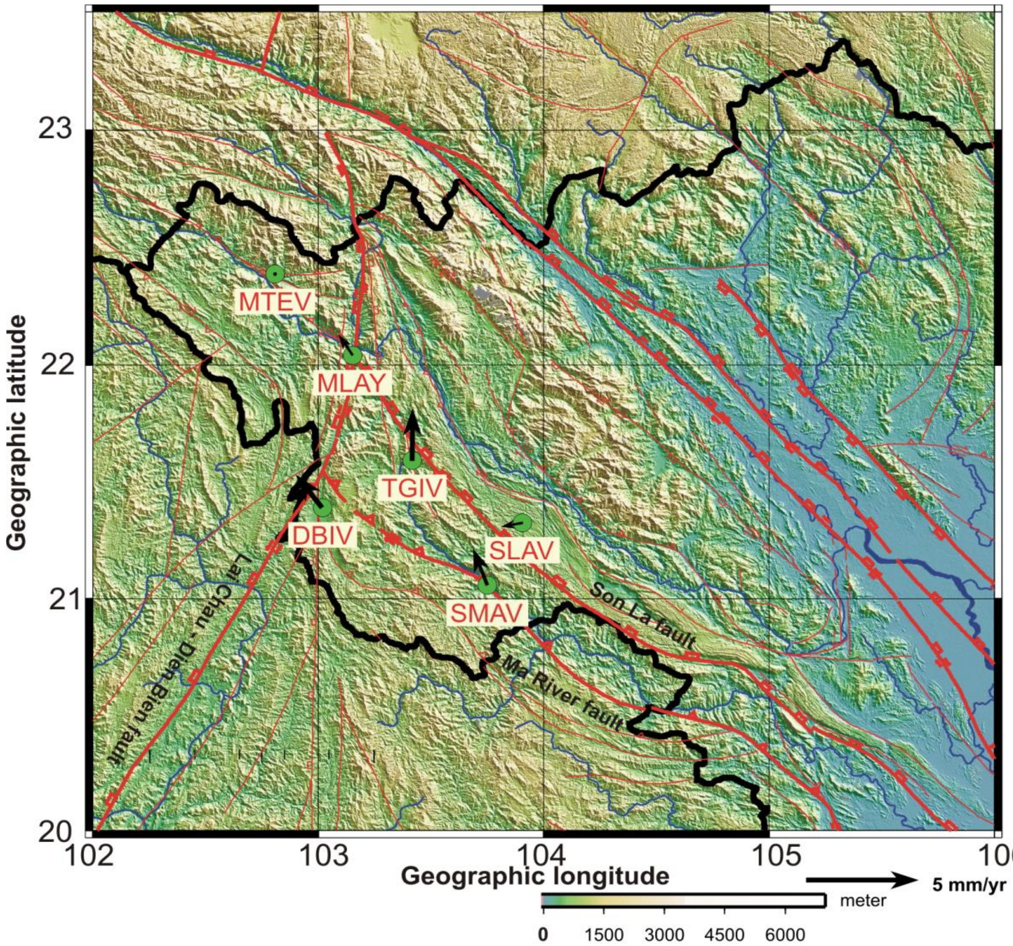


Figure 6. Relative velocity vectors of the stations with respect to the MTEV station

The relative movement on the Ma River fault was assessed by calculating the relative velocity of the stations with respect to the DBIV station. The results are presented in Table 6 and are shown in Fig. 7. Figure 7 shows that viewing from the DBIV station, the

SMAV, SLAV, TGIV, and MLAY are right sliding, however, the relative displacements are 0.52±1.03 mm/yr, 1.28±1.22 mm/yr, 1.05±1.01 mm/yr and 0.49±1.07 mm/yr, respectively. Thus, only the relative shear amplitudes of the SLAV and TGIV stations are evaluated to be greater than their errors and are reliable values. In the fault direction the relative displacements of the TGIV and SLAV stations are of ~0.1 mm/yr, and ~0.5 mm/yr respectively. They are smaller than the relative displacements on the Son La and Lai Chau - Dien Bien faults mentioned above. This may be due to the DBIV station being too close to the Lai Chau - Dien Bien fault and the Son La fault, the position is almost locked, and the movement of the SLAV and TGIV stations is affected by the Son La fault. Although the absolute velocities at the DBIV, SMAV, SLAV, TGIV, and MLAY stations are evaluated with the error < mm/yr, we still do not have a reliable assessment of the slip rate on the Ma River fault. In order to accurately assess the relative displacement on the Ma River fault, we need to arrange measurement points in other locations.

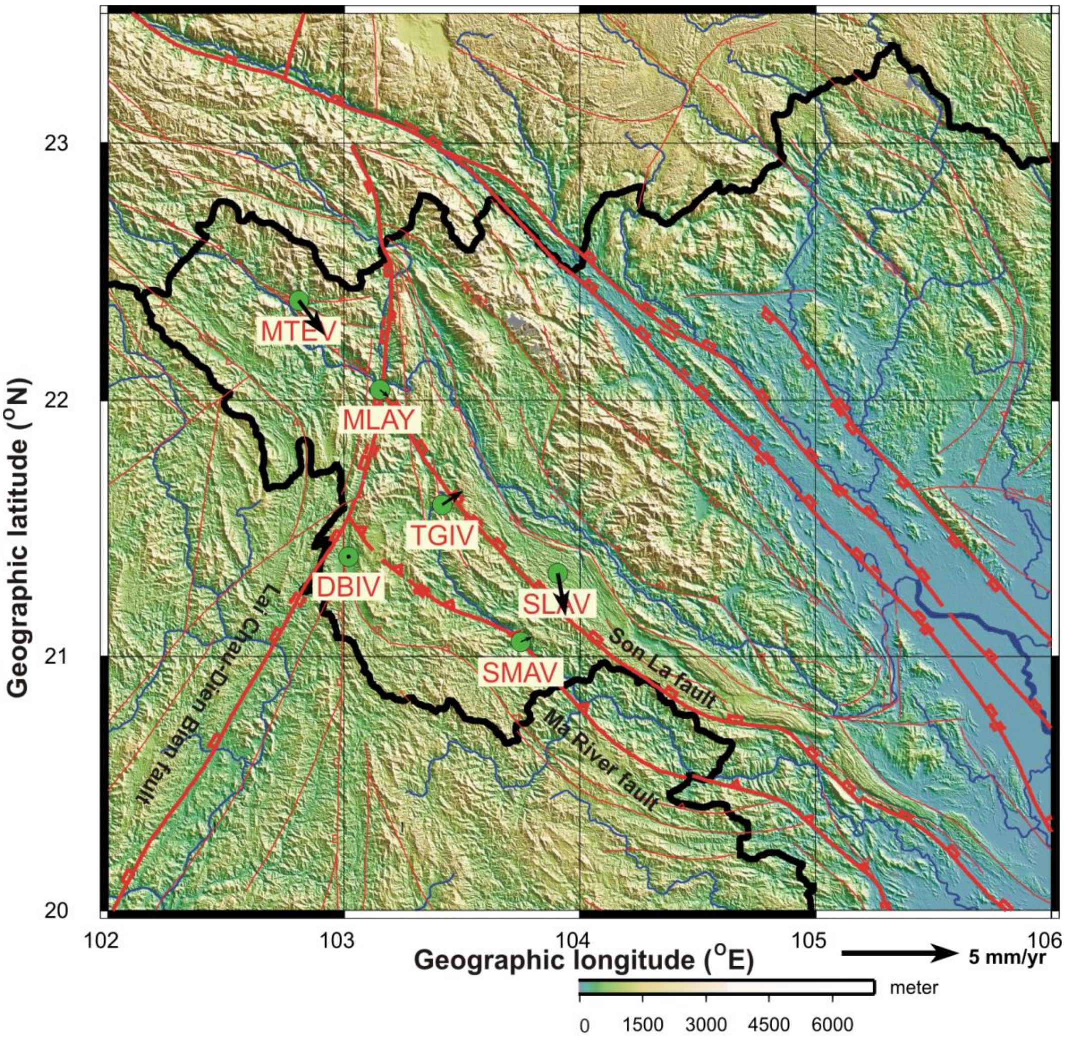


Figure 7. Relative rate of the stations with respect to DBIV

Table 6. Relative displacements of the stations with respect to DBIV

Station	E Comp.		N Comp.		Horizontal Comp.			Vertical Comp.	
	ΔV_E (mm/yr)	$\delta\Delta V_E$ (mm/yr)	ΔV_N (mm/yr)	$\delta\Delta V_N$ (mm/yr)	$\lvert\Delta\vec{V}\rvert$ (mm/yr)	$\delta\lvert\Delta\vec{V}\rvert$ (mm/yr)	Azimuth (^{o})	ΔV_{Up} (mm/yr)	$\delta\Delta V_{Up}$ (mm/yr)
DBIV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SLAV	0.33	1.22	-1.79	1.20	1.82	1.22	170	-2.42	0.60
SMAV	0.48	1.03	0.20	1.03	0.52	1.03	67	-1.95	0.39
TGIV	0.88	1.01	0.58	1.00	1.05	1.01	57	-1.68	0.44
MLAY	0.38	1.07	-0.31	1.06	0.49	1.07	129	0.13	0.38
MTEV	1.13	1.02	-1.47	1.01	1.85	1.02	142	-0.69	0.37

It is noted that because the vertical movement at each station obtained by GPS technology is not reliable, in tables 4, 5 and 6, estimates of the relative vertical velocity are given as reference data, accurate surveying results are needed to verify them.

4. Conclusions

From the analyzed results above, some conclusions can be drawn:

- GPS data at 6 stations in the Northwest region and PHUT station in Gia Lam, Hanoi have the nearly continuous data periods of 4.7 years (SLAV), 6.9 years (MLAY), 8-9 years (SMAV, MTEV, TGIV, DBIV) up to 11 years (PHUT) which are with the antenna placed on a pillar mounted on a hard rock foundation or on a concrete roof, ensuring the good data quality for geodynamic studies.
- The absolute horizontal velocities of the Earth's crust at 7 stations in the IGS14 frame are respectively: 34.10±0.71 mm/yr (DBIV), 34.31±0.65 mm/yr (PHUT), 34.51± 0.75 mm/yr (SMAV), 34.55±0.80 mm/yr (MLAY), 34.80±0.72 mm/yr (TGIV), 34.93±0.99 mm/yr (SLAV) and 35.59± 0.73 mm/yr (MTEV), in the Southeastward with the azimuth range 104-108°. The movement of these stations is suitable with the current tectonic setting in which Southeast Asia is moving Southeastward due to the collison of the Indian subcontinent and the Eurasian plate.
- The Son La fault is a right-lateral slip fault with a shear amplitude of ~1.5 mm/yr. The Lai Chau - Dien Bien fault is a left-lateral slip fault with a shear amplitude of a ~1.9 mm/yr. The amplitudes of the relative shear vector on these two faults are greater than their errors, this means that they are determined reliably.
- Although the absolute velocities at the DBIV, SMAV, SLAV, TGIV and MLAY stations are evaluated with the error <1 mm/yr, the estimated relative displacement on the Ma River fault is of ~0.5 mm/yr. It seems that we still do not have a reliable assessment of the slip rate on the Ma River right-lateral slip fault.

The accurate estimations of the crustal motion obtained in this paper are valuable documents supplementing the more accurate understanding about the displacement on the main active faults in Northwestern Vietnam.

Acknowledgements

This research is funded by Ministry of Science and Technology (MOST) of Vietnam under grant number NDT.18.TW/16 and by VAST projects, NVCC12.03/20-20 and VAST05.01/18-19.

References

Altamimi Z., Rebischung P., Metivier L., Collilieux X., 2016. ITRF14: a new release of the International Terrestrial Reference Frame modeling nonlinear station motions, J. Geophys. Res. Solid Earth, 121. Doi: 10.1002/2016JB013098.

Bui Quang Tuyen, Nguyen Phuoc Cong, Tran Vu An, 2005. Geodetic Lectures.

https://c6f7127d-a-c47e9d37-s-sites.googlegroups.com/a/vlcc.edu.vn/https-vothanhphong-wordpress-com/bai-giang/trac-dia/tham-khao/TRACDAC-BQTuyen.pdf.

Duong Chi Cong, Yun Hong-Sic, Cho Jea-Myoung, 2006. GPS measurements of horizontal deformation across the Lai Chau-Dien Bien (Dien Bien Phu) fault in Northwest of Vietnam, 2002-2004, Earth Planet Space, 58, 523–528.

England P., Molnar P., 1997. The field of crustal velocity in Asia calculated from Quaternary rates of slip on fault, Geophys. J. Int., 130(3), 551–582. Doi: 10.1111/j.1365-246X.1997.tb01853.x.

Feigl K., Duong Chi Cong, Becker M., Tran Dinh To, Neumann K., Nguyen Quang Xuyen, 2003. Insignificant horizontal strain across the Red River Fault near Thac Ba, Vietnam from GPS measurements 1994-2000, Geophysical Research Abstracts, European Geophysical Society.

Herring T.A., King R.W., Floyd M.A., McClusky S.C., 2015. GLOBK Reference Manual, Global Kalman filter VLBI and GPS analysis program, Release 10.6, Department of Earth, Atmospheric, and Planetary Sciences, Massachussets Institute of Technology.

Herring T.A., King R.W., Floyd M.A., McClusky S.C., 2018a. GAMIT Reference Manual, GPS Analysis at MIT, Release 10.7, Department of Earth, Atmospheric, and Planetary Sciences, Massachussets Institute of Technology.

Herring T.A., King R.W., Floyd M.A., McClusky S.C., 2018b. Introduction to GAMIT/GLOBE, Release 10.7, Department of Earth, Atmospheric, and Planetary Sciences, Massachussets Institute of Technology.

Institute of Geophysics, 2020. Earthquake bulletin of Vietnam territory and adjacent areas until 2019, Vietnam Academy of Science and Technology.

Le Huy Minh, Feigl K., Masson F., Duong Chi Cong, Bourdillon A., Lassudrie-Duchesne P., Nguyen Chien Thang, Nguyen Ha Thanh, Tran Ngoc Nam, Hoang Thai Lan, 2010. Crustal motion from the continuous GPS data in Vietnam and in Southeast Asian region, Vietnam Journal of Earth Sciences, 32(3), 249–260.

Le Huy Minh, Masson F., Bourdillon A., Fleury R., Jyr-Ching Hu, Vu Tuan Hung, Le Truong Thanh, Nguyen Chien Thang, Nguyen Ha Thanh, 2014. Recent crustal motion in Vietnam and in the Southeast Asia region by continuous GPS data, Vietnam Journal of Earth Sciences, 36(1), 1–13.

Michel G.W., Becker M., Angermann D., Reigber C., Reinhart E., 2000. Crsutal motion in E- and SE-Asia from GPS measurements, Earth Planet Space, 52, 713–720.

Michel G.W., Yu Y.Q., Zhu S.Y., Reigber C., Becker M., Reinhart E., Simons W., Ambrosuis B., Vigny C., Chamote-Rookie N., Pichon X.L. Morgan P., Matheussen S., 2001. Crustal motion and block behavior in SE-Asia from PGS measurements, Earth Planet. Science Lett., 187, 239–244.

Molnar P., Tapponnier P., 1975. Cenozoic tectonics of Asia: Effects of a continental collision, Science, 189(4201), 419–426. Doi: 10.1126/science.189.4201.419.

Nguyen Anh Duong, Sagiya T., Kimata F., Tran Dinh To, Vy Quoc Hai, Duong Chi Cong, Nguyen Xuan Binh, Nguyen Dinh Xuyen, 2013. Comtemporary horizontal crustal movement estimation for Northnernwestern Vietnam inferred from repeated GPS measurements, Earth Planet Space, 65, 1399–1410.

Nguyen Dinh Xuyen, Tran Van Thang, Nguyen Ngoc Thuy, Le Tu Son, Cao Dinh Trieu, Nguyen Quoc Dung, Tran Thi My Thanh, 2004. Study on earthquake prediction and ground motion in Vietnam, Final report of National project, Institute of Geophysics, Vietnam Academy of Science and Technology.

Nguyen Van Hung, 2002. Some basic features of neotectonic faults in northwestern Vietnam, Geological Doctoral Thesis, Institute of Geological Sciences, Hanoi, Vietnam (in Vietnamese).

Phan Trong Trinh, Ngo Van Liem, Tran Dinh To, Nguyen Van Huong, Vy Quoc Hai, Bui Van Thom, Tran Van Phong, Hoang Quang Vinh, Nguyen Quang Xuyen, Nguyen Viet Thuan, Nguyen Dang Tuc, Dinh Van Thuan, Nguyen Trong Tan, Bui Thi Thao, Nguyen Viet Tien, Le Minh Tung, Tran Quoc Hung, 2015. Present-day deformation in the East Vietnam Sea and surrounding regions, Journal of

Marine Science and Technology, 15(2), 105–118. Doi: 10.15625/1859-3097/15/2/6499.

Rebischung P., Schmid R., 2016. IGS14/igs14.atx: a new Framework for the IGS Products, American Geophysical Union, Fall Meeting 2016, abstract #G41A-0998.

Simons W.J.F., Ambrosius B.A.C., Noomen R., Angermann D., Wilson P., Becker M. Reinhart E., Walpersdorf A., Vigny C., 1999. Observing plate motions in S. E. Asia: geodetic results of GEODYSEA project, Geophys. Res. Lett., 26(4), 2081–2084.

Tapponnier P., Peltzer G., Armijo R., 1986. On the mechanics of the collision between India and Asia, Geological Society, London, Special Publications, 19, 113–157.

Tapponnier P., Peltzer G., Le Dain A.Y., Armijo R., Cobbold P., 1982. Propagating extrusion tectonics in Asia; new insights from simple experiments with plasticine, Geology, 12, 611–616.

Tran Dinh To, 2006. Processing results of GPS measurement data from Son La and Song Ma fault zone, J. Geology, B(27), 115–122.

Tran Dinh To, Becker M. Nguyen Trong Yem, Duong Chi Cong, Vy Quoc Hai, 2000. Results of GPS measurements of the Red River Fault Zone at Ba Vi - Tam Dao areas, J. Geology, B(15–16), 29–37.

Tran Dinh To, Nguyen Trong Yem, Duong Chi Cong, Vy Quoc Hai, Becker M., Reinhart E., Michel G.W., 1999. GPS measurements across the Red River Fault from 1994 to 1998, AGU Fall Meeting, G51-C12.

Tran Dinh To, Nguyen Trong Yem, Duong Chi Cong, Vy Quoc Hai, Zuchiewics W., Nguyen Quoc Cuong, Nguyen Viet Nghia, 2013. Recent crustal movements of northern Vietnam from GPS data, J. Geodyn., 69, 5–10.

Vy Quoc Hai, 2009. Determination of the absolute velocity at the Tam Dao-Ba Vi GPS network, Geology, A311(3-4), 22–30.

Vy Quoc Hai, Bui Thi Hong Tham, 2015. Establishing diagram of absolute crustal movements in Vietnam using GNSS data, Vietnam Journal of Earth Sciences, 37(1), 63–69.

Zuchiewics W., Nguyen Quoc Cuong, Andrzej B., Marek M., 2004. Quatenary sediments in the Dien Bien Phu fault zone, NW Vietnam: a record of young tectonic processes in the light of OSL-SAR dating results, Geomorphology, 60, 269–302.