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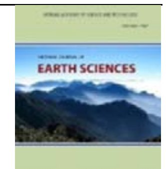

Determination of ground displacement of 25 April 2015 Nepal earthquake by GNSS precise point positioning

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ABSTRACT

The April 2015 Nepal earthquake (known as the Gorkha earthquake) occurred at 06:11:25 (UTC) on the 25th of April, with a magnitude of 7.8Mw. It was the worst natural disaster to strike Nepal since the 1934 Nepal-Bihar earthquake. Precise determination of ground displacement in this area will provide important information to better understand the structure and scope of the earthquake, contributing to faster and more accurate earthquake prediction. In this paper, we use precise point positioning to determine the displacements of 17 GNSS stations around the epicenter for the day of the earthquake. The processing results show that the common displacement direction is close to south-southwest with the largest value being approximately 2 m and the affected area being about 160 km in the southeast direction centered around the earthquake epicenter. However, a detectable GNSS signal was still observed at a station some 647 km away from the epicenter.

Keywords: April 2015 Nepal earthquake; GNSS; PPP.

1. Introduction

The Gorkha earthquake killed more than 9,000 people and injured more than 23,000. It occurred at 06:11:25 (UTC) on 25 April 2015, with a magnitude of 7.8Mw or 8.1Ms and a maximum Mercalli Intensity of IX. Its epicenter locates at the east of the district of Lamjung, latitude 28.231°N, longitude 84.731°E and at a depth of approximately 8.2 km. It was the worst natural disaster to strike Nepal since the 1934 Nepal-Bihar earthquake. According to the United States Geological Survey (USGS) (USGS, 2015), the Gorkha earthquake occurred as the result of thrust faulting on or near the main frontal thrust between the subducting Indian plate and the overriding Eurasian plate to the north. At the location of this earthquake, approximately 80 km to the northwest of the Nepalese capital of Kathmandu, the Indian plate is converging to the Eurasian plate at a rate of 45 mm/year towards the north-northeast, driving the uplift of the Himalayan mountain range.

Geophysicists and other experts had warned for decades that Nepal was vulnerable to a deadly earthquake, particularly because of its geology, urbanization, and architecture. For this reason, some scientific organizations had set up instruments and facilities to monitor earthquake activity over this region. University Navstar Consortium (UNAVCO), a non-profit university-governed consortium, facilitates geoscience research and education

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using geodesy, is currently supporting retrieval of high-rate and standard Global Navigation Satellite System (GNSS) data from stations within Nepal (UNAVCO, 2015). These data can be accessed through the UNAVCO Data Archive as they become available (Figure 1).

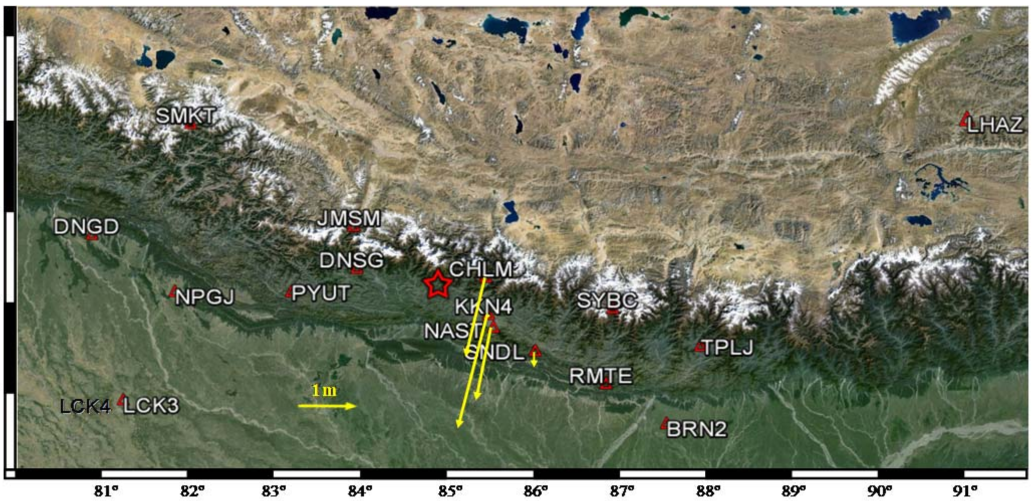

Figure 1. Epicenter (star) and GNSS station (triangle) displacement vectors

With UNAVCO support, we collected some GNSS data from 17 GNSS stations around the epicenter on the day of the earthquake. These stations are listed in Table 1 and Figure 1. This permanent GNSS station network is a favorable condition for applying existing GNSS positioning methods to accurately determine the displacement of the station over time.

Data on recent earthquakes have also been collected and processed using GNSS (Ji C. et al., 2004; Yue H. et al., 2013). In Vietnam there is also similar research on the Tohoku earthquake in Japan on March 11, 2011 (Nguyen Ngoc Lau, 2012). However, only at the Gorkha event, can scientists first observe earthquakes occurring in an area with many high-rate GNSS stations near the epicenter and covering the affected area completely (Galetzka J. et al., 2015).

The displacement of a set of stations over the earthquake area is an important source of information that provides quantitative data for a better understanding of tectonic activity in the area. This can help to make earthquake prediction faster, more accurate, and prevent similar disasters.

To accurately determine the displacement of each GNSS measurement station, the coordinates of the stations over time are determined by the GNSS processing in relative or absolute terms. If an earthquake occurs and moves the station, we can calculate the displacement by comparing its coordinates before and after the earthquake.

The GNSS relative (or differential) method was mainly used in the 1980s and early 1990s, when GNSS absolute method had not yet achieved the desired accuracy. The disadvantage of this method is that it is difficult to provide high positioning accuracy when handling long baselines. We have applied the relative method to calculate the ground displacement caused by the Tohoku earthquake in Japan on 11-03-2011 (Nguyen Ngoc Lau, 2012). In order to handle the long baselines of up to 1000 km, we had to apply special techniques to simultaneously process GPS and GLONASS measurements to get the desired accuracy (Nguyen Ngoc Lau et al., 2011).

GNSS Precise Point Positioning (also known as PPP) is being used today to gradually replace the relative method. The reason is that its positioning accuracy is increasingly improved and its advantages compared to relative method. PPP is also the method we choose to use for this paper. It will therefore be introduced in more detail in Section 2.

2. GNSS precise point positioning method

GNSS 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. PPP can provide a common position accuracy of centimeter level in 24h static and decimeter level in kinematic modes (Zumberge J.F. et al., 1997; King M. et al., 2002). The most prestigious organization providing precise GNSS orbit and clock products for civilian users is the International GNSS Service (IGS) (Kouba J., 2009).

PPP has an advantage over traditional differential techniques in that the method removes the need for the user to establish a local base station. Therefore, the spatial operating range limit of differential techniques is negated, as well as the need for simultaneous observations at both rover and base for real-time applications (King M. et al., 2002).

In recent years, the accuracy of PPP has improved gradually because the quality of GNSS orbit and clock correction products have been enhanced, and the number of GNSS has increased rapidly. PPP with multi-GNSS potentially can provide an accuracy of better than 1 cm in 24h static and better than 1 decimeter in kinematic modes (Rabbou M.A. et al., 2015; Afifi A. et al., 2016). With such an accuracy, PPP can be used to detect any displacements larger than several decimeters in station coordinates.

The current direction of PPP development is real-time positioning and improvement of positioning accuracy. The direction to improve accuracy for PPP focuses on resolving ambiguity for carrier phase measurements (Geng J. et al., 2012) and processing mixed measurements from multi-GNSS such as GPS, GLONASS, GALILEO, BEIDOU (Rabbou MA et al., 2015; Afifi A. et al., 2016).

In Vietnam, we have researched PPP since 2010 with GPS only (Nguyen Ngoc Lau, 2009; 2010), and then expanded to GPS and GLONASS (Nguyen Ngoc Lau et al., 2012, Nguyen Ngoc Lau, 2013).

PPP method has been described in detail in many documents (Nguyen Ngoc Lau, 2009, Nguyen Ngoc Lau et al., 2010; 2012, Nguyen Ngoc Lau, 2013). So in this article, we only mention our self-developed PPP software package, the so-called PPPC. This is the product of two ministry-level projects chaired by us (Nguyen Ngoc Lau et al., 2010; 2012). PPPC version 3.2 can process code and phase measurements from GPS, GLONASS, GALILEO and BEIDOU satellite systems for both static and kinematic modes. Using PPPC to process GPS + GLONASS data at some IGS stations has proven that positioning accuracy is better than 2 cm for 1h static data and better than 1 cm with 24 hours (Nguyen Ngoc Lau, 2013).

With particularly advantage, PPPC is able to estimate coordinates before and after an indicated epoch. This option is very suitable for precise calculation of station coordinate slips if they have occurred. We use PPPC to process GNSS data in Table 1.

Table 1. GNSS stations are located around the Earthquake epicenter

No.	GNSS Station	Interval (sec)	GNNS satellite systems	Distance to the epicenter (km)
1	CHLM	15	GPS	56
2	KKN4	15	GPS	68
3	NAST	15	GPS	81
4	DNSG	15	GPS	94
5	JMSM	15	GPS	119
6	SNDL	15	GPS	137
7	PYUT	15	GPS	169
8	SYBC	15	GPS	202
9	SMKT	15	GPS	348
10	RMTE	15	GPS	227
11	NPGJ	15	GPS	305
12	TPLJ	15	GPS	310
13	BRN2	15	GPS	311
14	LCK3	30	GPS, GLONASS	394
15	LCK4	30	GPS + GLONASS	394
16	DNGD	15	GPS	411
17	LHAZ	30	GPS + GLONASS	647

3. Results

Firstly, we use PPPC to process all of the GNSS stations in the kinematic mode with some options as follows:

- Using IGS precise orbit and clock corrections;
- Using P3 code and L3 carrier phase measurements of GPS and GLONASS (only for LCK3, LCK4 and LHAZ);
- Setting the elevation cut off angle as 5°;
- Estimating one tropospheric zenith delay every 2.5 hours with the Niell mapping function;
- Applying IGS08 antenna model and solid Earth model.

After screening the processed station coordinates epoch by epoch, we detect 4 stations which have large slip values at epoch 6:12:15 (GPST) as shown in Figure 2. Therefore at the time of the earthquake (6:11:25 UTC~ 6:11:41 GPST), the stations were not affected immediately. The shift starts only about 26 seconds later.

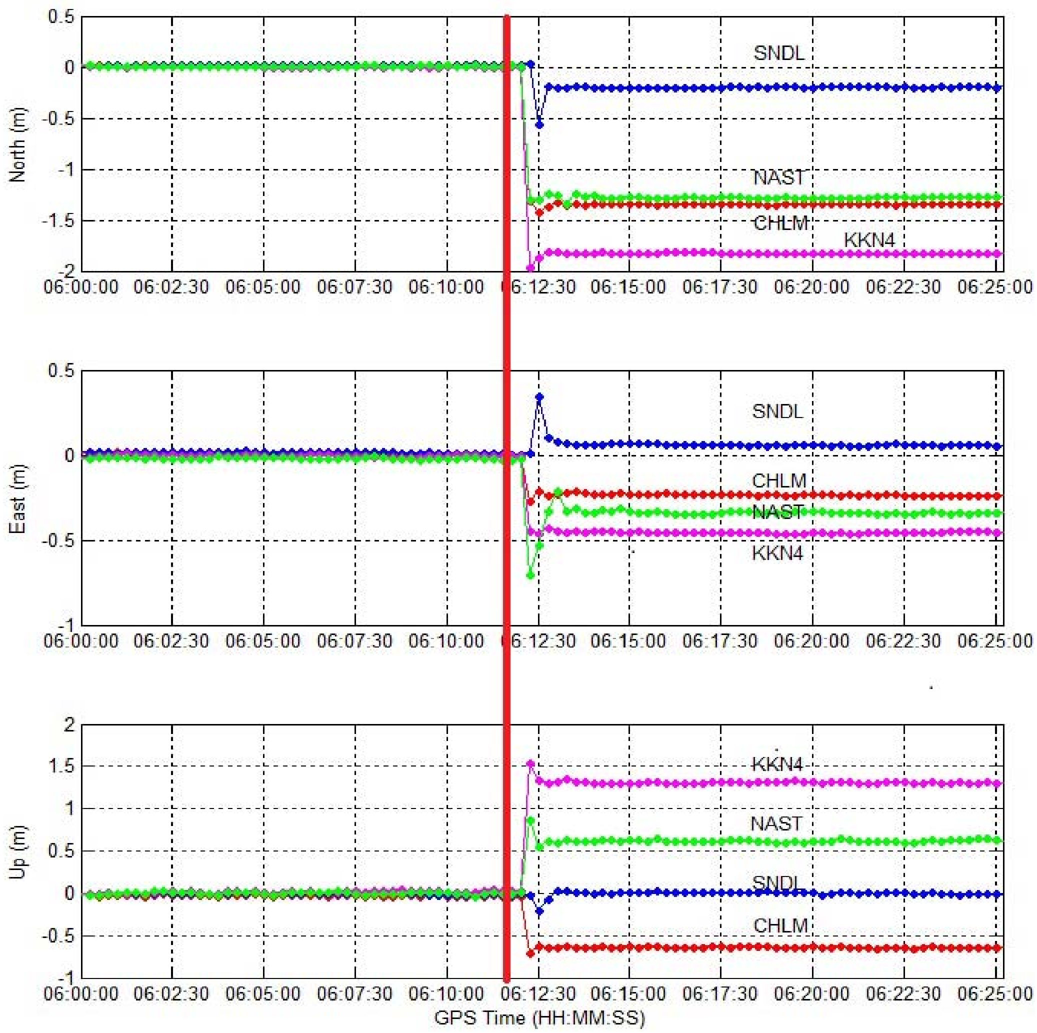

Figure 2. Station displacements by using PPPC in kinematic mode. Vertical bar indicates the earthquake epoch

Since GNSS epoch solutions have an accuracy at the decimeter level, it is not sufficient for precise calculation of station displacements. We re-processed the GNSS data by using PPPC in static mode for epochs before and after epoch 6:12:15. As a result, the displacement of each station is calculated by subtracting two processed station coordinates before and after epoch 6:12:15. These results are given in Table 2.

Table 2. Displacements of GNSS stations at epoch 6:12:15

No.	GNSS Station	Displacements (m)		
		North	East	Up
1	CHLM	-1.380 ± 0.001	-0.220 ± 0.005	-0.590 ± 0.007
2	KKN4	-1.827 ± 0.002	-0.455 ± 0.005	+1.279 ± 0.009
3	NAST	-1.293 ± 0.002	-0.318 ± 0.006	+0.623 ± 0.009
4	DNSG	+0.004 ± 0.003	+0.006 ± 0.008	+0.003 ± 0.015
5	JMSM	-0.006 ± 0.002	+0.003 ± 0.005	+0.004 ± 0.008
6	SNDL	-0.220 ± 0.001	+0.045 ± 0.004	+0.064 ± 0.006
7	PYUT	+0.001 ± 0.001	-0.005 ± 0.004	+0.012 ± 0.006
8	SYBC	-0.015 ± 0.002	-0.010 ± 0.005	+0.003 ± 0.009
9	SMKT	+0.001 ± 0.002	-0.002 ± 0.004	-0.002 ± 0.006
10	RMTE	-0.000 ±0.001	-0.005±0.004	+0.004 ±0.005
11	NPGJ	+0.002 ±0.002	-0.012 ±0.004	+0.008 ±0.006
12	TPLJ	+0.002 ±0.001	-0.001 ±0.004	+0.002 ±0.006
13	BRN2	+0.001 ±0.001	-0.003 ±0.005	+0.000 ±0.006
14	LCK3	+0.002±0.001	-0.011 ±0.002	+0.012 ±0.003
15	LCK4	+0.003 ±0.001	-0.011 ±0.002	+0.010 ±0.003
16	DNGD	+0.002 ±0.001	-0.002 ±0.002	-0.018 ±0.002
17	LHAZ	+0.004 ±0.001	-0.007 ±0.002	+0.007 ±0.003

Table 2 shows that there are only 4 GNSS stations affected by the earthquake including CHLM, KKN4, NAST and SNDL. Where KKN4 was shifted nearly 2 m in the horizontal component, SNDL is some 177 km from the epicenter but also moved horizontally more than 0.2 m. Some closer stations, such as DNSG and JMSM distributed in the northwest, are seemingly not affected. This shows that the affected area is stretched in the southeast direction.

Figure 3 shows the north, east and up series of 4 GNSS stations distributed east-southeast of the epicenter, including SYBC, RMTE, TPLJ and BRN2. The timing of the earthquake-induced movement is well documented on the charts of the stations. It is not fixed but varies with the distance to the epicenter. The time of movement of the stations SYBC and RMTE about 200 km from the epicenter is 6:13:00 GPST. Stations TPLJ and BRN2, about 300 km from the epicenter, are 6:13:15 GPST.

Figure 4 presents the processing results of the farthest GNSS station - the LHAZ (647 km). Watching the sequence of this station coordinates over time, we can still observe the effects of the earthquake occurring at 6:15:00 GPST, which is about 3 minutes slower than the stations in Figure 2 and almost 2 minutes compared to the stations in Figure 3.

We present displacement vectors of the affected stations on Figure 1 and see clearly that the common moving direction of GNSS stations is close to the south-southwest.

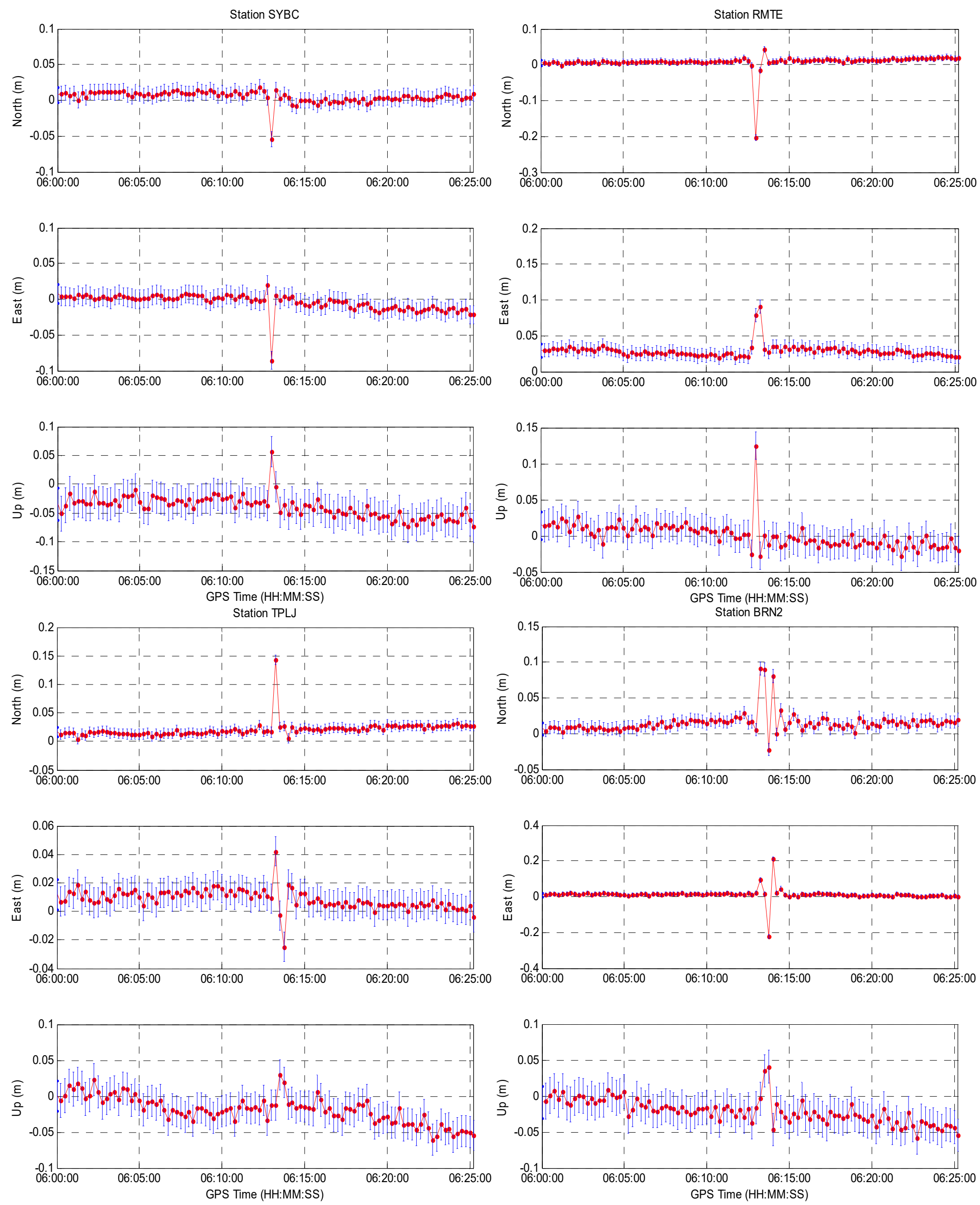

Figure 3. The coordinate series over time of the 4 GNSS stations are distributed east-southeast of the epicenter

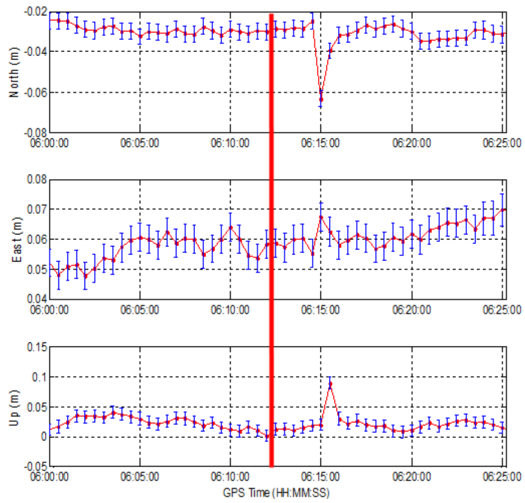

Figure 4. The time series of the LHAZ station. Vertical bar indicates the earthquake epoch

4. Discussions

Jianghui Geng in (Geng J., 2015) used GAMIT software to process relatively the GNSS data. His processing results of stations KKN4 and NAST are given in Figure 5. The visual estimates of displacement are -1.8, -0.45, +1.3 in the north, east and up components for KKN4 and -1.3, -0.3, +0.6 for NAST. These results agree with our results in Table 2.

In (Lemmens M., 2015), Lemmens analyzed the 5Hz GPS data processing results of Galetzka et al., 2015) at two stations KKN4 and NAST. He concluded that the north and eastward movements of the two stations were distinctly different behaviors (Figure 6) because the KKN4 station was located on hard rock, while NAST installed on sediment in the valley Kathmandu. NAST shows prolonged sediment resonance with a sweeping path of almost 2 m.

By applying a ScanSAR-based interferometry analysis of Advanced Land Observing Satellite 2 (ALOS-2) L-band data, Kobayashi et al. (Kobayashi T. et al., 2015) had similar conclusions that "a major displacement area extends with a length of about 160 km in the east-west direction, and the most concentrated crustal deformation with ground displacement exceeding 1 m is located 20-30 km east of Kathmandu". However, this technique does not provide precise coordinate displacement values, unlike the GNSS PPP technique.

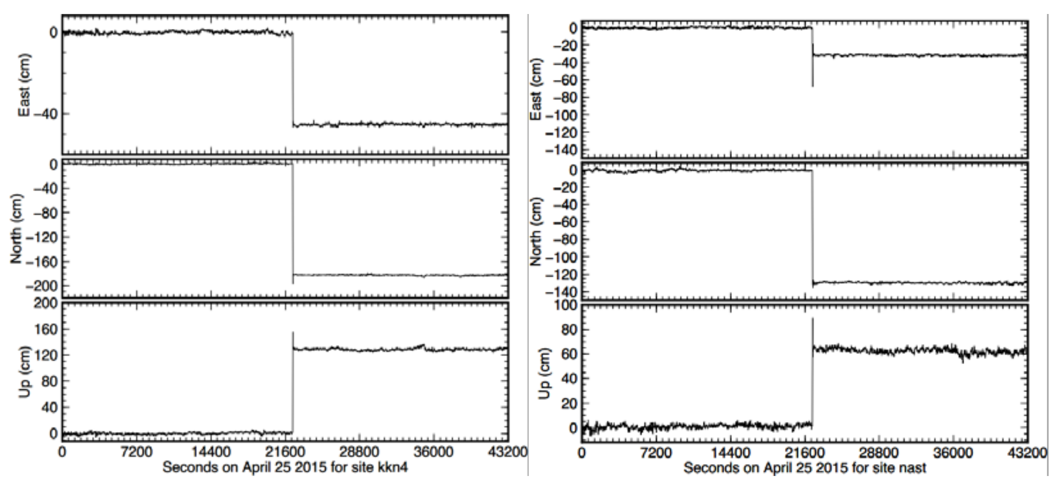

Figure 5. Jianghui Geng's processing results of stations KKN4 (left) and NAST (right), accepted from (Geng J., 2015)

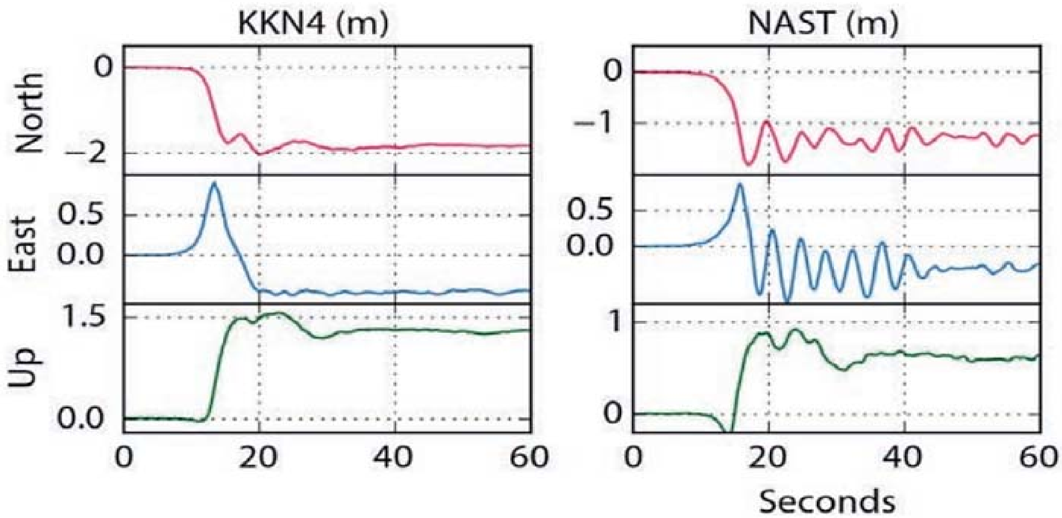

Figure 6. Displacements of stations KKN4 (left) and NAST (right), accepted from (Galetzka J., 2015)

5. Conclusions

To monitor the effect of the earthquake with the magnitude of 7.8 on 25 April 2015 in Nepal, we collected and processed GNSS data at 17 stations around the epicenter by using the GNSS PPPC method. The GNSS station displacements are calculated precisely with an accuracy of 1cm in the horizontal and the vertical components. These displacements show that the affected area stretches about 160 km in the south-east. The common moving direction is close to the south-southeast with the maximum value of 2 m in the horizontal component.

Our results are similar to other studies using different data sources or different processing methods such as GNSS relative (Geng J., 2015), high rate GNSS PPP (Galetzka J. et al., 2015; Lemmens M., 2015) and ScanSAR (Kobayashi T. et al., 2015).

In conclusion, the GNSS PPP method has proven its advantages for monitoring ground movements due to earthquakes such as position accuracy, large area coverage, availability, short-term or long-term displacement tracking.

In order to have the better determination of ground displacements, our future research direction will continue to focus on improving the positioning accuracy of GNSS PPP on the basis of ambiguity resolution of carrier phase measurements, and apply to our PPPC software.

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