ARTIFICIAL SATELLITES, Vol. 48, No. 1 – 2013
DOI: 10.2478/arsa-2013-0001

TESTING THE NUMBER OF IGS STATIONS REQUIRED FOR ACCURATE ALIGNMENT OF THE THAI GPS NETWORK AND ITRF2005 USING THE GIPSY SOFTWARE

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ABSTRACT

Since its introduction in 1990s, the GPS Precise Point Positioning (PPP) technique has been widely used for many high precision positioning applications such as the study of tectonic plate motion, establishment of national and regional reference frames and so on. Among the GPS PPP software packages, the GIPSY-OASIS II software package is the one of the most popular software package used by many research institutes worldwide. The processing of GPS data with the GIPSY-OASIS II software requires three main steps. The first step is to compute a daily GPS solution for each station and the second step is to combine daily GPS solutions into a multi-day averaged solution. The final step is to transform these multi-day averaged solutions into the International Terrestrial Reference Frame (ITRF) coordinate solution and this step generally requires the use of available International GNSS service (IGS) stations to compute the required transformation parameters. In order to obtain high precision ITRF coordinate solutions, an investigation on a selection of IGS stations used for aligning the multi-day averaged solution into ITRF is therefore needed. This study aims to investigate the effect of number of IGS stations used for aligning the multi-day averaged solutions into the final ITRF coordinate solution in Thai region. Data from two different GPS campaigns (with epochs before and after the 2004 Sumatra-Andaman earthquake) measured by the Royal Thai Survey Department (RTSD) were used in this investigation. By varying the number of IGS station used in the alignment step, results indicate that the use of at least 16 IGS stations in the alignment process can produce reliable and accurate ITRF solutions especially those impacted by the large earthquake.

Keywords: GPS, PPP, IGS, ITRF, GIPSY-OASIS II, Thailand

1. INTRODUCTION

One of the most essential today's application of the GPS Precise Point Positioning (PPP) technique is time transfer for short and long distances (Defraigne and Baire, 2011; Guyennon et al., 2009; Lejba et al., 2011). The GPS PPP technique has been extensively employed in many high precision applications including studies of tectonic plate motion (Munekane and Fukuzaki, 2006; Simons et al., 1999), the establishment of national and regional reference frames (Overgaauw et al., 1994; Satirapod et al., 2011), the determination of crustal deformations due to earthquakes (Satirapod et al., 2007a; Vigny et al., 2005). As stated in Zumberge et al. (1997), the PPP technique can produce daily solutions with a few millimetres in the horizontal components, and about a centimetre in the vertical component, for data from a static site occupied by a dual-frequency GPS receiver. The GIPSY-OASIS II (GNSS-Inferred Positioning System and Orbit Analysis Simulation Software) software package developed by the Jet Propulsion Laboratory (JPL) is the one of the most widely used GPS PPP software packages by scientists (Gregorius 1996; Webb and Zumberge, 1997). The processing of GPS data with the GIPSY-OASIS II software consists of three main steps. Firstly, an estimation of a daily GPS solution for each individual station is carried out. Secondly, daily GPS solutions are combined into a multi-day averaged solution. Finally, each multi-day averaged solution is transformed into the ITRF coordinate solution.

To enable an accurate alignment of the GPS coordinate results into the ITRF global reference frame, IGS data are usually added to GPS campaign data sets. The multi-day averaged solutions can then be transformed into the ITRF using the coordinates and velocities of a subset of well-determined regional and global IGS stations by estimating 7-parameter Helmert transformations. The inclusion of a substantial IGS sub-network in the data analyses allows for an independent (JPL also offers so-called XFILES with pre-determined daily transformation parameters) and one-step transformation of multi-day averaged solutions into any ITRF global reference frame solution. Under the effect of the 2004 Sumatra-Andaman earthquake especially in the SE Asian region, the transformation of weekly averaged solutions into the ITRF solutions may not be as accurate since regional IGS stations also have been affected by co- and post-seismic deformations that are not completely accounted for in the ITRF solutions to date (e.g. ITRF-2000, 2005 and 2008). This study aims to investigate an effect of number of IGS stations used for the alignment process both before and after the 2004 Sumatra-Andaman earthquake. This paper is organised as follows. The details of the GPS measurement campaigns and other used data are firstly described. Next, the detailed data processing steps using the Precise Point Positioning (PPP) technique are given. Subsequently, the concept on how we vary the number of IGS stations used for a mapping step is explained. Then, a comparison of mapping and coordinate results is presented. Finally, some concluding remarks are made.

2. GPS OBSERVATIONS AND OTHER USED DATA

This study used the GPS campaign data collected at the zero-order Thai geodetic network by the RTSD. In this investigation, we chose two GPS campaigns which were observed in October of 2004 (at epoch before the Sumatra-Andaman earthquake) and in November of 2008 (epoch after the Sumatra-Andaman earthquake). It should be noted that the GPS data from each RTSD campaign were collected for 7 consecutive days. Both campaigns have 6 common zero-order network points (OTRI, UTHA, SRIS, CHON, BANH and PHUK) and these GPS points will be used in a subsequent analysis. Figure 1 shows an overview of the zero-order Thai geodetic network points.

Apart from using Thai GPS campaign data, GPS data obtained from IGS are introduced in the data processing step to enable an accurate mapping of the Thai GPS coordinate results into the ITRF2005 global reference frame (Altamimi et al., 2007). Initially, a total of 132 IGS stations were considered. Then, we performed several preliminary screening steps (for example, only selecting stations that are not earthquake affected or close to plate boundary deformation zones, have data available during the campaign period, have continuous and already long (in time) data records (i.e. at least 10 years), stations located on bedrock, no multiple jumps in their coordinate time series, and no frequent changes of GPS antenna or receiver. Finally, a total of 29 IGS stations were selected for the 2004 campaign while 32 IGS stations were chosen for the 2008 campaign. Table 1 shows the list of selected IGS stations for each campaign. The additional information required for processing are the JPL precise orbits, information of time, polar motion and earth orientation as well as satellite eclipse information. These data were obtained from ftp://sideshow.jpl.nasa.gov.

Table 1. IGS stations used for mapping of the Thai GPS coordinate results into the ITRF2005.

Campaign	**Selected IGS stations**				
2004	ALGO	BAKO	COCO	FAIR	GOLD
	GUAM	KARR	KERG	KIT3	KOSG
	KUNM	LHAZ	MAS1	MKEA	NTUS
	ONSA	PERT	PIMO	SHAO	TIDB
	VILL	WUHN	YAR1	YELL	DARW
	IISC	KOKB	MAC1	TSKB	
2008	ALGO	ALIC	BAKO	COCO	DARW
	DGAR	GUAM	HYDE	IISC	KARR
	KERG	KIT3	KOKB	KOSG	KUNM
	LHAZ	MAC1	MAS1	MKEA	ONSA
	PERT	PIMO	SHAO	TIDB	TNML
	TSKB	VILL	WUHN	YAR1	YELL
	FAIR	NTUS			

Fig. 1. Overview of the zero-order Thai geodetic network points.

3. PRECISE POINT POSITIONING (PPP) PROCESSING

The GIPSY-OASIS II was used to process the dual-frequency GPS data from the RTSD points and IGS by employing the PPP technique. With the PPP processing, each station can be solved individually by fixing the satellites orbit and satellite clocks parameters. The PPP processing consists of three main steps as shown in Figure 2. The detailed explanation for each step is described below.

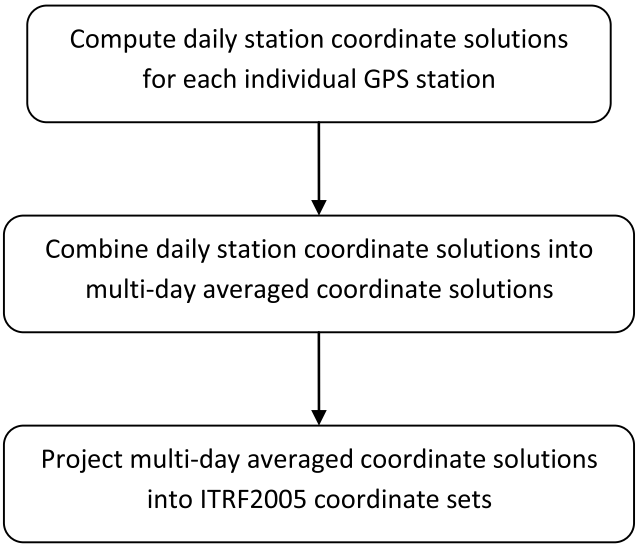

Fig. 2. PPP data processing steps (Satirapod et al., 2008).

3.1 Computing Daily Solutions

The GPS data were firstly processed in daily batches. Each point position was based on the ionosphere-free combination of the zero-difference GPS observations at 5 minute intervals, with a cut-off elevation angle of 15 degrees. To ensure the highest precision solutions, observations from GPS satellites that were undergoing maintenance during part of the processed day (ftp://tycho.usno.navy.mil/pub/gps/) were removed. To account for the tropospheric bias, the zenith path delay using the Neil model (Neil, 1996) and gradients were estimated at 3-hr interval. Ocean loading effects were modelled with the GOT00.2 model (Scherneck, 1991). To account for different GPS antennas, relative antenna phase centre corrections from the U.S. National Geodetic Survey (NGS) were applied. The details of GIPSY-OASIS II standard processing setting can be found in Gregorius (1996). The daily station coordinate repeatabilities for each GPS station in Thailand from both campaigns range from 1 to 4 mm for the horizontal component and from 3 to 12 mm for the vertical component (Satirapod et al., 2007b; Satirapod et al., 2011). The internal precision of the Thai sites is comparable to the performance of the IGS stations and the present 'state-of-the-art' level of high precision GPS data processing.

3.2 Combining Daily Solutions into multi-day Averaged Solutions

The 7-daily PPP coordinate solutions obtained from the previous step were subsequently combined into a multi-day averaged solution. In this process, the median algorithm as proposed in Simon et al. (2009) was applied to detect outliers prior to the computation of final coordinate repeatabilities. Any daily station solution identified as outliers are down-weighted and the obtained daily coordinate repeatabilities give a realistic indication of the internal precision of each station. The overall repeatability statistics of each averaged solution were used to scale the formal errors in their variance/covariance matrices. Formal errors are typically underestimated in GPS PPP processing results. By assigning realistic error estimates to the coordinate, this results in more realistic estimated uncertainties. It should be noted that the multi-day averaged coordinate solution is still in an unknown local reference frame. This is a direct result of the loose constraints that were applied in the PPP strategy. Therefore, the multi-day averaged solution has to be mapped in a known reference frame. This can be independently achieved by using the IGS stations that were included in the data processing.

3.3 Mapping a Weekly Averaged Solution into ITRF2005

Subsequently, each weekly averaged solution was projected into ITRF2005 coordinate sets, each containing the positions of the included IGS stations at the middle epoch of each analyzed week. The ITRF2005 GPS SINEX file (http://itrf.ensg.ign.fr/ITRF_solutions/2005/ITRF2005_files.php) is propagated to each of these epochs, and contains the full covariance matrix for the IGS stations subset. From past experience with mapping local networks in SE Asia region, 10-20 IGS stations were usually used in the mapping of each weekly averaged solution into ITRF (Simons et al., 2007; Satirapod et al., 2007b; Satirapod et al., 2010; Panumastrakul et al., 2012). However, in this study we aim to investigate an effect of number of IGS stations used on the final ITRF2005 coordinate solution in Thai region. All IGS stations were firstly used to perform a first round mapping step to check the quality of each IGS station. It was found that five IGS stations (DARW, IISC, KOKB, MAC1 and TSKB) and two IGS stations (FAIR and NTUS) were rejected during the mapping process for respectively the 2004 and 2008 campaign epochs because of large RMS values (larger than the mean RMS value ± 2 S.D.). Hence, a total of 24 IGS stations for the 2004 campaign and 30

IGS stations for the 2008 campaign are considered as usable for an accurate mapping process. Figure 3 shows IGS stations used for mapping of the 2004 and 2008 campaign results into the ITRF2005.

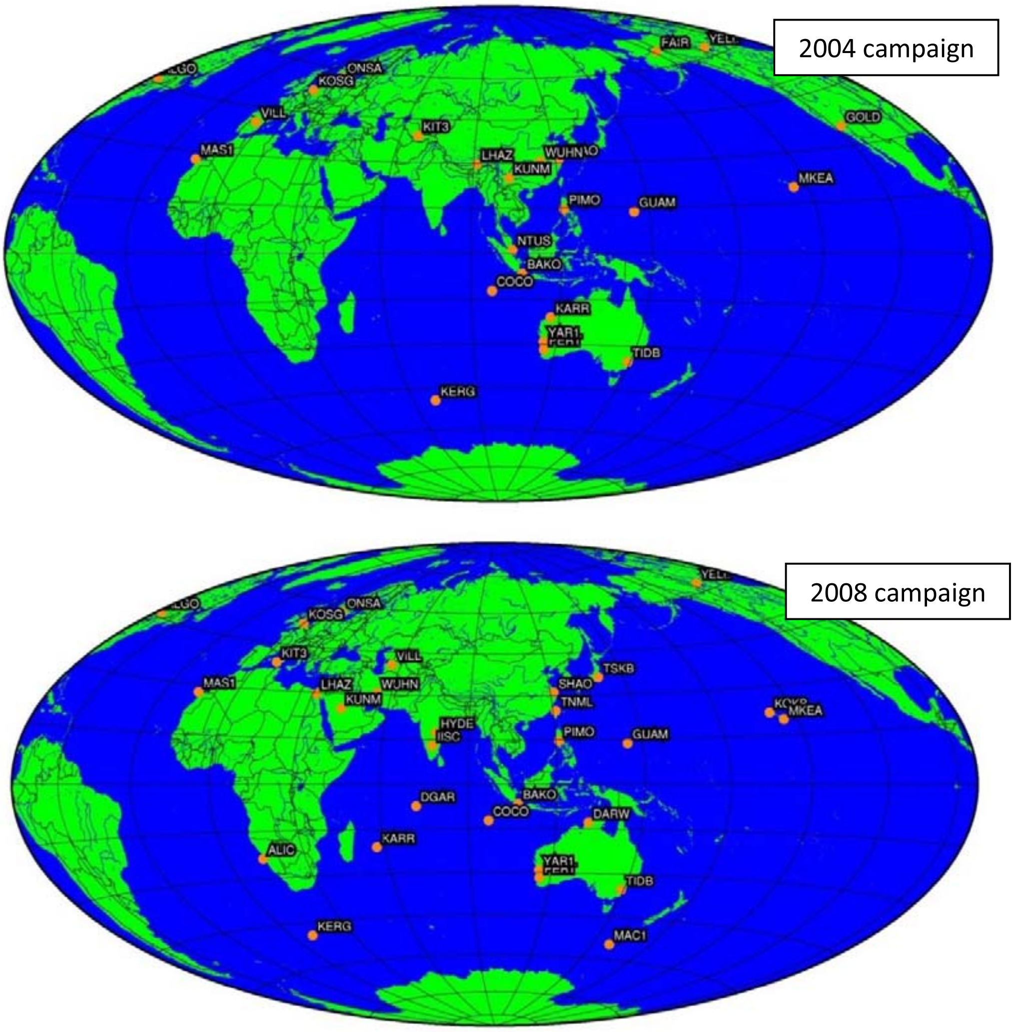

Fig. 3. IGS stations used for mapping campaign results into ITRF2005 for 2004 campaign (top) and 2008 campaign (bottom).

4. VARYING NUMBER OF IGS STATIONS USED FOR A MAPPING STEP

This study aims to provide an answer to the following question: Would the final coordinate solutions be more reliable and accurate if more IGS stations are used in mapping step? We therefore perform a test by varying the number of IGS stations used in a mapping step from 4 to 24 for the 2004 campaign and 4 to 30 for the 2008 campaign. Table 2 gives the number of possible combinations and computation load for each selected number of IGS stations. It can clearly be seen from Table 2 that the computation load is intolerable. Sampling method is thus required. According to Cochran (1977) and Yamane (1973), an adequate sample size is found to be around 400 for this study. We therefore randomly selected 500 combinations from the cases where the possible combinations are more than 500. The 500 selected samples are subsequently used to calculate the statistics in the next section.

Table 2. Number of possible combinations and computation load for different IGS selections.

	The 2004 Campaign (24 IGS stations)		The 2008 Campaign (30 IGS stations)	
No. of IGS stations	*No. of possible combinations*	*Computation load (day)*	*No. of possible combinations*	*Computation load (day)*
4	10,626	2	27,405	5
5	42,504	7	142,506	25
6	134,596	23	593,775	103
7	346,104	60	2,035,800	353
8	735,471	128	5,852,925	1,016
9	1,307,504	227	1,4307,150	2,484
10	1,961,256	340	30,045,015	5,216
11	2,496,144	433	54,627,300	9,484
12	2,704,156	469	86,493,225	15,016
13	2,496,144	433	119,759,850	20,792
14	1,961,256	340	145,422,675	25,247
15	1,307,504	227	155,117,520	26,930
16	735,471	128	145,422,675	25,247
17	346,104	60	119,759,850	20,792
18	134,596	23	86,493,225	15,016
19	42,504	7	54,627,300	9,484
20	10,626	2	30,045,015	5,216
21	2,024	0	14,307,150	2,484
22	276	0	5,852,925	1,016
23	24	0	2,035,800	353
24	1	0	593,775	103
25	*n.a.*	*n.a.*	142,506	25
26	*n.a.*	*n.a.*	27,405	5
27	*n.a.*	*n.a.*	4,060	1
28	*n.a.*	*n.a.*	435	0
29	*n.a.*	*n.a.*	30	0
30	*n.a.*	*n.a.*	1	0

**Remark: Computation load is based on the use of HP workstation XW4600 computer with Ubuntu version 9.0*

5. RESULTS AND DISCUSSIONS

The results are presented in two parts. The first part presents the statistics obtained from varying the number of IGS stations used in a mapping process while the second part shows the effect of varying number of IGS stations in a mapping process on final Thai coordinate solutions.

5.1 Statistics from varying number of IGS stations in a mapping process

The overall RMS values in each coordinate component are usually obtained from each individual mapping process. The mean RMS value is then computed from the 500 overall RMS values and this step is carried out for each selected number of IGS stations. In addition, the standard deviations of RMS values are calculated. Figure 4 illustrates mean and S.D. of RMS values obtained from the 2004 campaign while Figure 5 shows the statistics from the 2008 campaign. With regards to Figures 4 and 5, although the mean RMS values obtained from the use of 4 IGS stations are smaller than the RMS values from the use of more IGS stations, the S.D. of RMS values are larger than those obtained from the use of more IGS stations. This implies that the use of small number of IGS stations may lead to an unstable mapping result. Mapping results from the 2008 campaign appear to be worse than the 2004 campaign. This may be due to an undergoing post-seismic displacement from the 2004 Sumatra-Andaman earthquake (Satirapod et al., 2012). In case of an occurrence of a large earthquake (i.e. the 2004 Sumatra-Andaman earthquake), many IGS stations are affected and this becomes a limiting factor to find a large number of unaffected IGS stations to be used in a mapping process. The 2008 campaign can be used as a study case of a period under the effect of the 2004 Sumatra-Andaman earthquake. With reference to the 2008 campaign mapping result, the mean RMS becomes unchanged and the S.D. values are around 1 mm when more than 16 IGS stations are used. For the 2004 campaign, the mean RMS becomes relatively stable and the S.D. values are smaller than 1 mm when only 11 IGS stations are used.

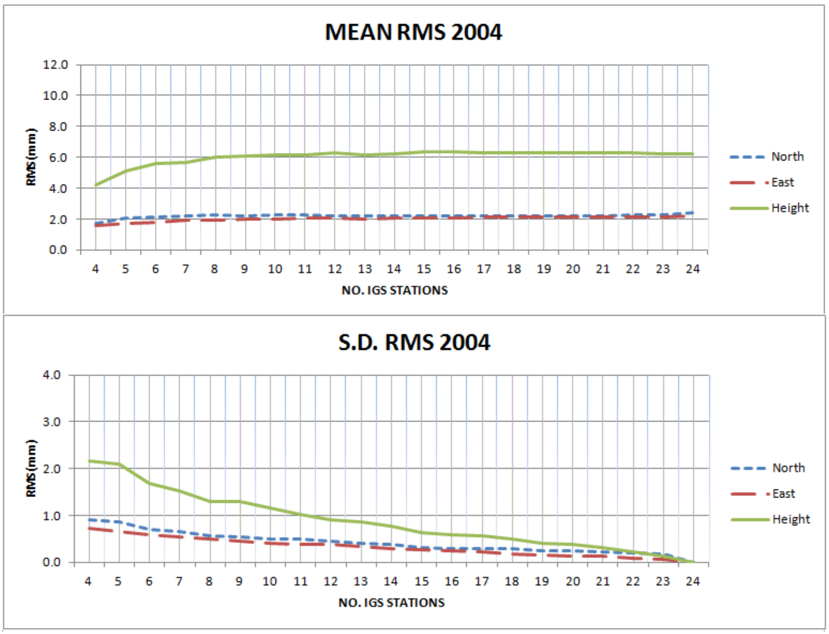

Fig. 4. Statistics obtained from varying number of IGS stations used in a mapping process for the 2004 campaign Top: Mean RMS values; Bottom: S.D. of RMS values.

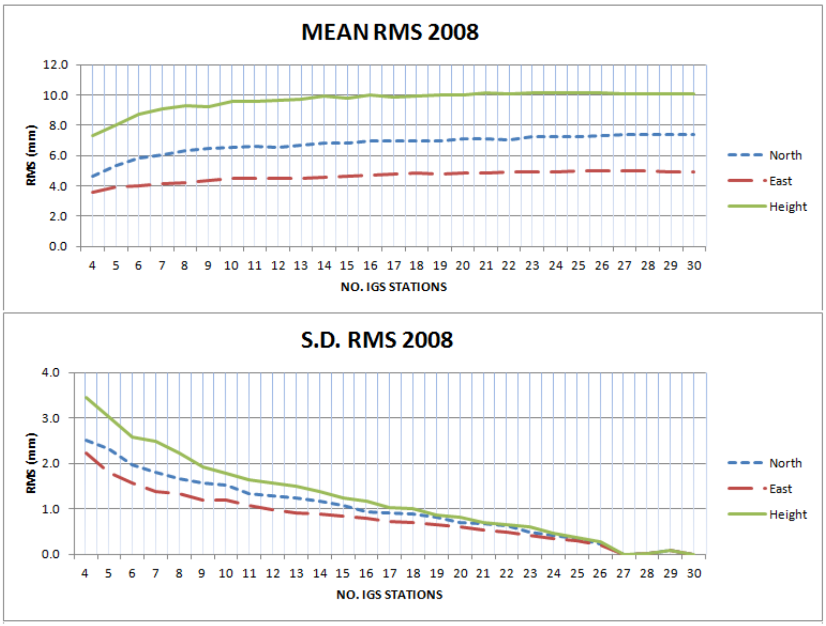

Fig. 5. Statistics obtained from varying number of IGS stations used in a mapping process for the 2008 campaign Top: Mean RMS values; Bottom: S.D. of RMS values.

5.2 Effect of varying number of IGS stations in a mapping process on final Thai coordinate solutions

In order to check for effects of different IGS selections in a mapping process on final Thai coordinate solutions, the mean and S.D. of each Thai coordinate component from both campaigns were calculated. The differences of the mean coordinates for each IGS selection are at sub-millimetre level (below 0.2mm). These differences can be considered as insignificant and they are not shown here. It should be noted that all Thai stations are affected in the same way by using different Helmert transformation parameters. The translations translate into identical position shifts for each Thai station. However, the S.D. values of final coordinate solutions from both campaigns are plotted in Figures 6 and 7. It can be seen from Figures 6 and 7 that the S.D. of Thai coordinate solutions show the same trend for all stations. The S.D. of coordinate solutions for all stations is below 2 mm when 11 IGS stations and 16 IGS stations are used for the 2004 and 2008 campaigns respectively. Thus, it is recommended that under the presence effect of the large earthquake the use of at least 16 IGS stations could produce reliable and accurate final coordinate results.

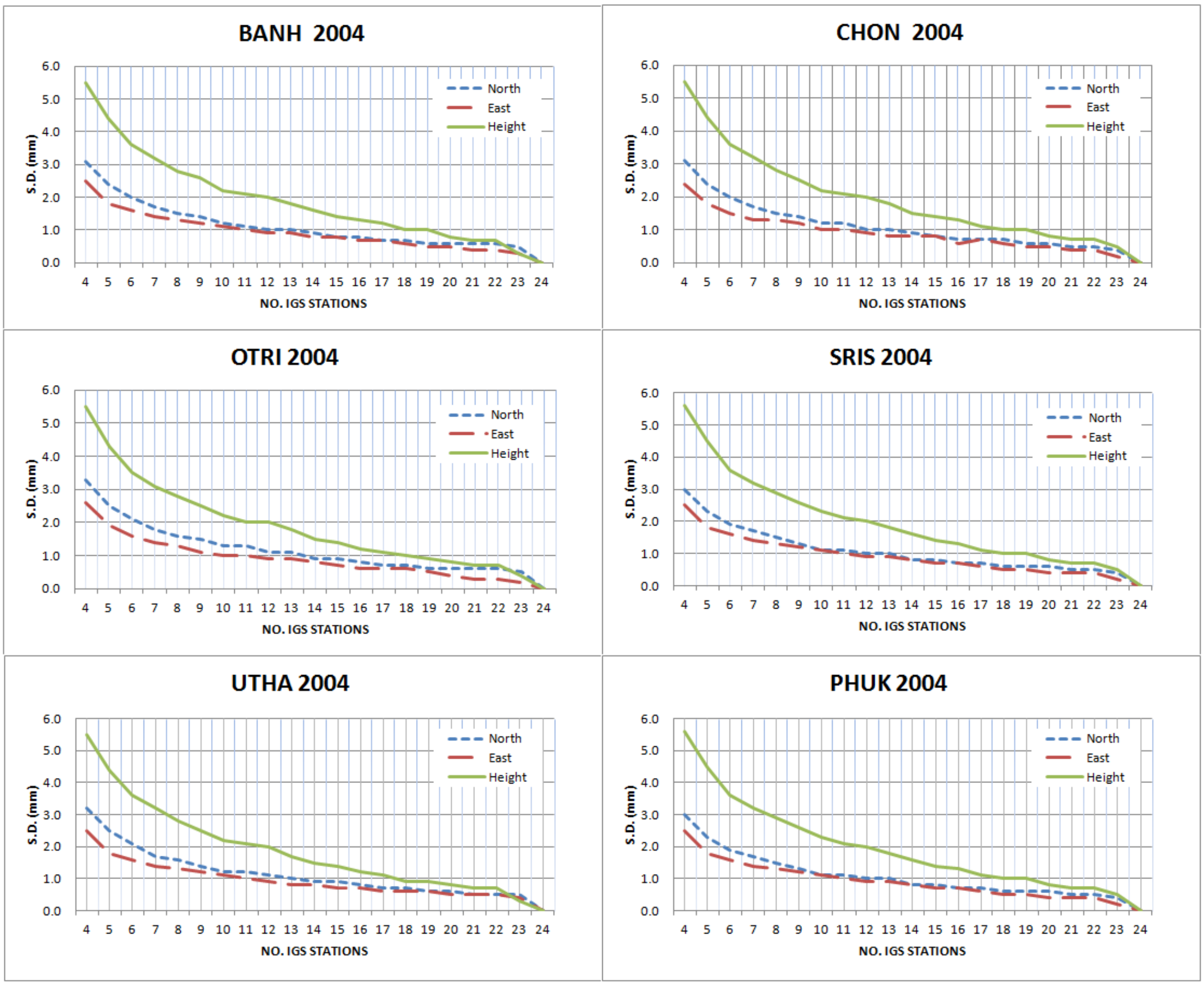

Fig. 6. Standard Deviation of final Thai coordinate solutions from the 2004 campaign.

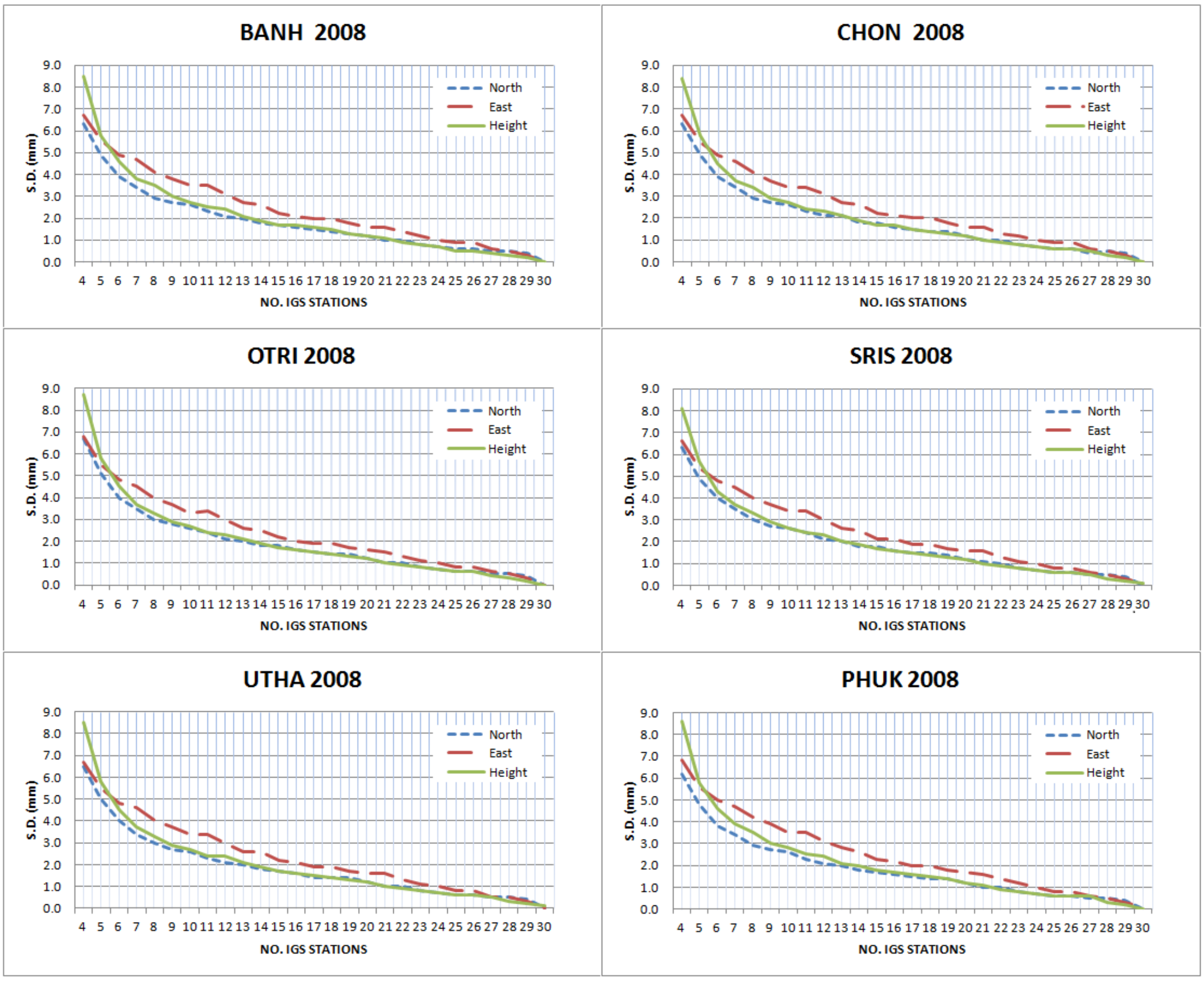

Fig. 7. Standard Deviation of final Thai coordinate solutions from the 2008 campaign.

6. CONCLUDING REMARKS

This paper describes the PPP processing of Thai GPS campaign data with special attention to the ITRF mapping strategy. Steps for screening out unstable IGS stations are explained. Tests are carried out to investigate an effect of number of IGS stations used for mapping the weekly averaged solution into the final ITRF coordinate solution in Thai region using two periods of GPS observation campaigns (before and after the 2004 Sumatra-Andaman Earthquake). Test results indicate that during the normal observation period the use of at least 11 IGS stations in a mapping process can yield reliable and accurate coordinate solutions. However, if the GPS observation campaign is in a time period following a very great earthquake, it is recommended that more than 16 (including sufficient global) IGS stations are used to produce reliable and accurate absolute coordinate solutions. This recommendation can then be used as a guideline for mapping either national or regional reference frame in any area into the latest ITRF. Our future work will focus on testing the distribution of IGS stations used for an alignment process of the Thai GPS network.

ACKNOWLEDGEMENTS

This research is supported by the GEO2TECDI-SONG project under the Thailand-EC Cooperation Facility Phase II (TEC-2) funding scheme. The authors would like to thank to the Royal Thai Survey Department (RTSD) for providing the GPS data used in this study.

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Received: 2012-12-18,

Reviewed: 2013-01-25,

Accepted: 2013-01-28.