Updating the Thai Coordinate Reference Frame to ITRF2005 Using GPS Measurements: Observation on a Diversion Between ITRF2000 and ITRF2005 In Southeast Asia Region

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Key words: GPS, Reference Frame, Thai geodetic network, Precise Point Positioning.

SUMMARY

The Thai geodetic network has been regularly observed with Global Positioning System (GPS) since 1994 thru several collaborative EU-ASEAN projects such as GEODYSSEA, SEAMERGES and RTSD-Delft. This geodetic network has long been served as a reference frame for Thailand. Previous realisations of Thai coordinate reference frame were therefore tied to the global International Terrestrial Reference Frame (ITRF) at epochs 1994, 1996 and 2000. After the occurrence of the 9.2 Mw Sumatra-Andaman earthquake on the 26th December 2004, horizontal displacements were evident at different magnitudes in many surrounding countries. The geodetic network within Thailand was also significantly deformed during the earthquake at the centimetre to decimetre level. Large co-seismic horizontal displacements were observed in the southern part of Thailand, while moderate and small displacements were seen in the central and northern parts of Thailand. The Royal Thai Survey Department (RTSD) has been carrying out multiple GPS field campaigns to monitor the post-seismic displacements. This paper will analyse the GPS observations obtained from the RTSD GPS campaigns up to the end of 2008 using the Precise Point Positioning (PPP) strategy of the GIPSY-OASIS II software. It has been demonstrated that by employing the state of the art PPP technique, the users could achieve mm-level of repeatability in the horizontal components and centimetre precision in the vertical direction, for a 24-hr data span from a static site occupied by a geodetic-quality receiver. Coordinate results obtained from each campaign are then mapped to ITRF2000 and ITRF2005 using a number of well-determined global International GNSS service (IGS) sites. By comparing coordinate results between ITRF2000 and ITRF2005, it is evident that there is a significant diversion in the north component at a rate of 1.7 mm per year over Southeast Asia region. Finally, ITRF2005 coordinate results obtained from the latest RTSD GPS campaign (November 2008) will be served as a new coordinate reference frame for Thailand.

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1. INTRODUCTION

The Thai geodetic network has been regularly observed with GPS since 1994 thru several collaborative projects such as GEODYSSEA, SEAMERGES and RTSD-Delft. This geodetic network has long been served as a national reference frame for Thailand. Previous realisations of Thai coordinate reference frame were therefore tied to the global International Terrestrial Reference Frame (ITRF) at epochs 1994, 1996 and 2000. After the occurrence of the 9.2 Mw Sumatra-Andaman earthquake on the 26^{th} December 2004, horizontal displacements were evident at different magnitudes in many countries surrounding Indonesia (e.g. Singapore, Malaysia, Thailand). The giant earthquake caused significant (co-seismic) surface displacements up to a couple thousand kilometres away from its epicentre (Stein and Okal, 2005; Vigny et al., 2005a). The geodetic network within Thailand has been co-seismically displaced and subsequently undergoing a decreasing (post-seismic) deformation at the centimetre to decimetre level that will continue for many years (Satirapod et al., 2007a). Large co-seismic horizontal displacements were observed in the southern part of Thailand, while moderate and small displacements were seen in the central and northern parts of Thailand. Thailand basically has been pulled apart in NE-SW direction, with the position shifts increasing towards the epicentre of the Sumatra-Andaman earthquake, which lies about 600 km southwest from the island of Phuket. Following this giant earthquake, these land shifts continued as post-seismic displacements. Although other large earthquakes as the so-called Nias (Mw 8.6) and Bengkulu (Mw 8.5) earthquakes occurred (on respectively March 28^{th}, 2005 and September 12^{th}, 2007), the internal deformation of Thailand almost entirely results from the first 9.2 Mw event due to its much larger scale of impact in Southeast Asia Region.

Acting as a national mapping agency, the Royal Thai Survey Department (RTSD) has been carrying out multiple GPS field campaigns to monitor the post-seismic displacements. By the end of 2006 the northern and north-eastern regions of Thailand were displaced by 6 cm while the southern parts of Thailand were shifted up to 55 cm (Satirapod et al., 2008). As a result, Thailand had already been stretched in the NE-SW direction by more than half a meter. This paper will analyse the GPS observations obtained from the RTSD GPS campaigns up to the end of 2008. This paper is organised as follows. The details of the GPS measurement campaigns and other used data are briefly described. The strategy used in the processing of available GPS data is explained and current co- and post- seismic offsets of the zero-order

Thai geodetic network are updated. Then, a comparison of coordinate results between ITRF2000 and ITRF2005 is presented. Finally, some concluding remarks are made.

2. GPS CAMPAIGN OBSERVATIONS AND OTHER USED DATA

This study focuses on the zero-order Thai geodetic network, using GPS data from the GPS stations of the RTSD, which has been regularly measured since 1994. This was also done in October 2004, at a relatively short time period before the Sumatra-Andaman earthquake occurred. The complete zero-order Thai geodetic network was repeatedly re-measured in February, July and October of 2005, in April, July and November of 2006, in May and November of 2007 and again in November 2008. The last measurement round in November 2008 was organized to both check the present level of deformation in Thailand and also to redefine the coordinates of the first-order Thai geodetic network. Therefore, in addition to the 7 zero-order network points also 11 first-order network points were measured by the RTSD. Figure 1 shows an overview of the geodetic network points in Thailand. To enable an accurate mapping of the GPS coordinate results into the ITRF2000 and ITRF2005 global reference frames, the widely-distributed IGS data of up to 30 carefully selected global IGS stations was added to the GPS campaign data sets (ALGO, BAKO, COCO, DARW, DGAR, FAIR, GOLD, GUAM, IISC, KARR, KERG, KIT3, KOKB, KOSG, KUNM, MAC1, MAS1, MKEA, NTUS, ONSA, PERT, PIMO, SHAO, TIDB, TNML, TSKB, VILL, WUHN, YAR1 and YELL). The inclusion of a substantial IGS sub-network in the data analyses allows for an independent (not using predefined ITRF transformation parameters or IGS coordinate constraints) and one-step (no additional tying to a global IGS network solution) transformation of Thai GPS coordinates into any ITRF global reference frame solution. The majority of the IGS stations were chosen because they have long (1994-present) and stable position time series. More recent (regional) IGS stations were also included as they become useful for remapping into future ITRF solutions. Figure 2 shows the IGS stations used for mapping the results. 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.

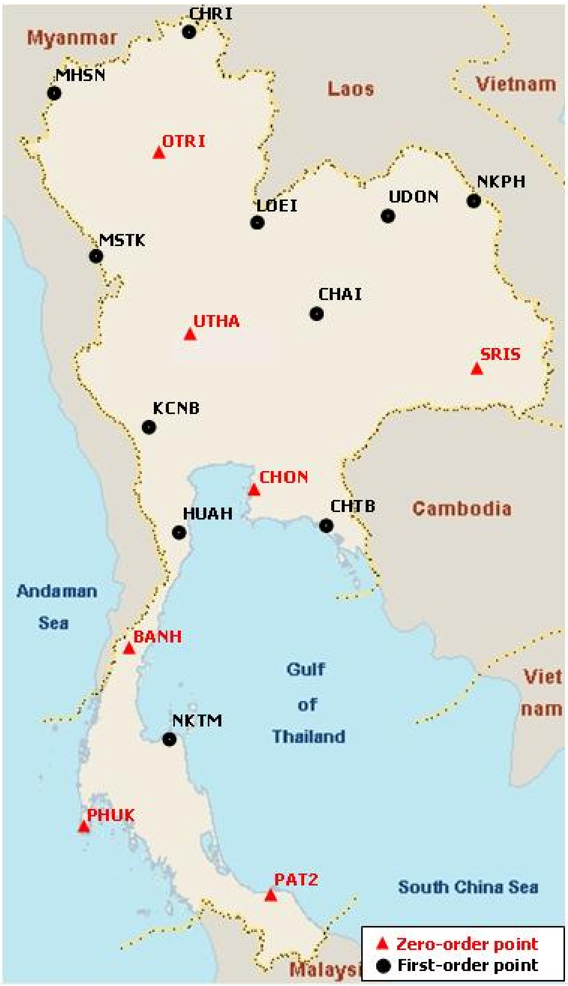

Figure 1 Overview of the geodetic network points in Thailand

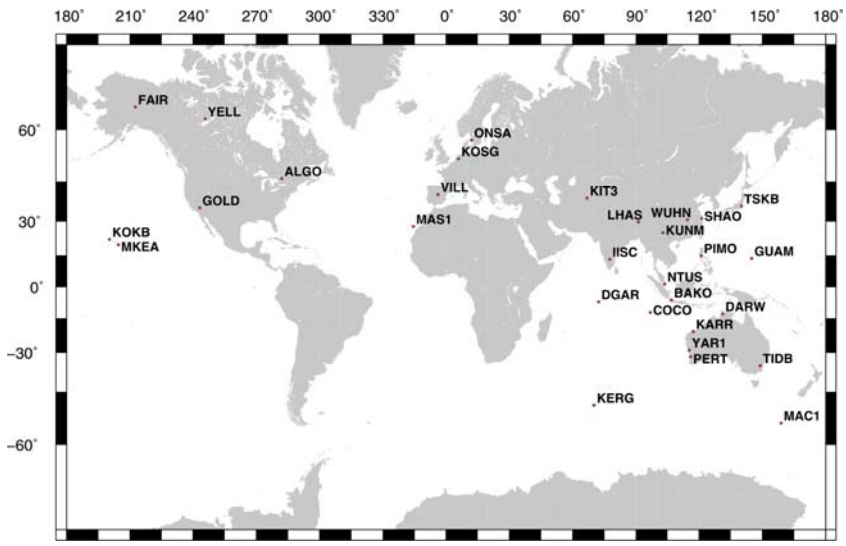

Figure 2 IGS stations used for mapping the results into the ITRF

3. GPS DATA PROCESSING STRATEGY

The absolute GPS positioning technique or so-called the GPS Precise Point Positioning (PPP) technique is selected as a processing strategy in this study. By using the PPP technique, the users could expect daily repeatability of a few millimetres in the horizontal components, and about a centimetre in the vertical component, for data from a static site occupied by a geodetic-quality receiver (Zumberge et al., 1997). All dual-frequency GPS data were uniformly processed with the GIPSY-OASIS II software developed by the Jet Propulsion Laboratory (JPL) using the PPP technique.

The GPS data were processed in daily batches with the PPP strategy. Each point position was based on the ionosphere-free combination of the zero-differenced GPS carrier phase and pseudorange 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. Tropospheric delays and gradients were stochastically estimated at each time interval. Ocean loading effects were modeled with the GOT00.2 model (Scherneck and Bos, 2009). To account for different GPS antennas, relative antenna phase center corrections from the U.S. National Geodetic Survey (NGS) were applied (NGS, 2009). The individual point positions were merged into daily full-network solutions. Due to the nature of PPP processing, the different station positions are modeled as uncorrelated. Nevertheless the phase ambiguities can still be fixed to improve the position in the east-west direction. The daily ambiguity-fixed solutions were combined into 7-day campaign averaged solutions using 7-parameter Helmert transformations. In order to condense the results and to facilitate the detection and down weighting of outliers, the overall repeatability statistics of the 7-day combination solution were used to scale the formal errors in their variance-covariance (VCV) matrices. Table 1 shows an example of the final coordinate repeatabilities for each GPS point obtained from the processing of the November 2008 campaign. The median algorithm as proposed by (Simons et al., 2009) was applied to detect and remove outliers prior to the computation of final coordinate repeatabilities. These values are direct indicators for the internal precision of each station

In general, all the GPS points perform very well, with daily coordinate repeatabilities typically ranging from 0.5 to 1.5, 1.0 to 2.0 and 3.0 to 6.0 mm for respectively the north, east and height components. The GPS points CHTB and KCNB perform slightly worse especially in horizontal component. This may be due to a less optimal local environment (i.e. trees, nearby structures). It should be noted that the campaign-averaged coordinate solution is still in an unknown local reference frame. This is a direct result of the loose constraints that were employed in the GIPSY PPP strategy. Therefore, the campaign solution still has to be mapped in a known reference frame. This can be achieved by including the IGS stations in the data processing.

Table 1 Daily repeatabilities for each GPS point from the November 2008 campaign

Station	Daily repeatabilities		
	North (mm)	East (mm)	Height (mm)
UTHA	1.1	1.2	4.1
SRIS	0.7	1.6	5.2
OTRI	0.8	0.7	3.7
BANH	1.0	1.3	7.6
CHON	1.7	2.1	4.5
PHUK	0.8	1.5	8.8
PAT2	1.2	1.5	5.7
NKPH	0.6	1.8	4.7
UDON	0.4	0.7	4.8
LOEI	0.9	1.1	2.1
CHAI	0.7	1.3	2.6
HUAH	1.3	1.4	4.5
MSTK	1.3	1.6	7.4
NKTM	1.6	1.9	5.6
MHSN	0.5	1.2	6.8
CHRI	1.0	1.4	7.3
CHTB	3.1	2.3	6.4
KCNB	2.1	2.8	14.3

4. MAPPING CAMPAIGN-AVERAGED SOLUTIONS INTO ITRF2000 AND ITRF2005

Due to the widespread deformation, a local or national reference frame cannot be used to present the latest coordinates and displacements (Satirapod et al., 2007b; Vigny et al., 2005b). Therefore, a number of permanent GPS stations from the IGS need to be included, so that the positioning results can be given in the global ITRF solution. The campaign fiducial-free network solutions were transformed into the ITRF2000 and ITRF2005 using the coordinates and velocities of a subset of well-determined regional and global IGS stations to estimate 7-parameter Helmert transformations. It should be noted that the computation of accurate ITRF coordinates (including ITRF2005) in SE Asia is not straightforward. This dates back to the early 90's when the available IGS network in and around SE Asia was very sparse. Throughout the last decade new IGS stations in and around SE Asia became operational (e.g. WUHN, SHAO, NTUS, PIMO, BAKO, LHAS, KUNM, TNML, HYDE) but unfortunately their relatively short time series become from 26/12/2004 onwards significantly distorted by co- and post-seismic motions. The ITRF2005 only includes position time series solution up to 2005 for most of these stations. As a result, any co- and post-seismic motions (the latter predominantly from the 2004 Sumatra-Andaman Mw 9.2 giant earthquake) of IGS stations from 2005 onwards are not accounted for. Therefore from 2005 onwards the stations NTUS, IISC, HYDE, BAKO, COCO, KUNM, WUHN, SHAO can no longer be used in ITRF realizations of GPS coordinates in SE Asia. Although most of these stations have clear and increasing misfits with their predicted ITRF2005 positions, these offsets adversely can be partly absorbed by transformation parameters when position errors in predominantly the same direction exist (e.g. the ongoing post-seismic motions as a result of the Sumatran-Andaman Mw 9.2 earthquake). This could more easily occur in double-differences based (baseline solving) GPS data analysis software (e.g. Bernese and GAMIT) if only regional IGS station (constraints) are used to do the mapping in ITRF and becomes even more complicated if subsequently longer baselines need to be solved to IGS stations outside the seismically deformed region. Therefore most users here opt to connect their regional coordinate solution in an additional step to a global IGS station solution that is separately computed. For SE Asia, the zero-difference (coordinate solving) GIPSY software appears more robust as both additional regional and global IGS data can be easily added and simultaneously solved for. A similar advantage exits with computing kinematic coordinate solutions in a vast region that has been deformed (as SE Asia was on December 26th of 2004) including all regional IGS (reference) stations. Table 2 shows an example of accurate mapping results into ITRF2000 and ITRF2005 for the November 2008 campaign.

Table 2 Overall RMS values from mapping of the Nov. 2008 campaign to ITRF solutions

Solution in	Overall IGS stations RMS			No. of IGS stations used
	North (mm)	East (mm)	Height (mm)	
ITRF2000	2.4	2.6	9.8	9
ITRF2005	2.5	2.1	7.1	15

It can be seen from Table 2 that in the case of ITRF2000, many of the IGS stations are no longer usable for accurate mapping since their positions have changed too much from the prescribed positions, both due to ITRF2000 velocity errors and effect of nearby big earthquakes. Many of them have been updated and accounted for in the ITRF2005 solution which allows for more accurate coordinate transformations into the ITRF. Finally, only 9 IGS stations were usable for mapping into ITRF2000, where 15 IGS stations could be used for mapping into ITRF2005. In both mapping procedures only IGS stations that fit with their ITRF predicted positions within 5, 6 and 15 mm for respectively the north, east and vertical position were finally used. In addition a number of IGS stations are preset to be excluded from the mapping stations as they no longer fit their ITRF positions at this epoch (NTUS, BAKO, WUHN, KUNM, SHAO, COCO, IISC, HYDE, MAC1 and KERG in ITRF2005) or because they serve as an extra (unconstrained) quality check for the mapping procedure (DARW, GOLD, GUAM and DGAR in ITRF2005) Both mapping procedures appear to give similar RMS values but in ITRF2005 more IGS stations are available for realizing the mapping. The Cartesian coordinates of the Thai geodetic network points in ITRF2000 and ITRF2005 obtained from the November 2008 campaign are given in Table 3. It is important to note that there is a difference in the definition of the ITRF2000 and 2005 solutions (Altamimi et al., 2007). Thus, the ITRF2000 and ITRF2005 coordinates (and hence also station velocities) are not compatible and should not be mixed in GPS solution analyses.

Table 3 Coordinates of Thai geodetic network points in ITRF2000 and ITRF2005 obtained from the November 2008 campaign

Station	ITRF2000			ITRF2005		
	X (m)	Y (m)	Z (m)	X (m)	Y (m)	Z (m)
UTHA	-1069535.148	6057468.882	1681107.854	-1069535.146	6057468.878	1681107.873
SRIS	-1534865.240	5971007.138	1629560.004	-1534865.238	5971007.134	1629560.023
OTRI	-986191.936	5975733.382	1993725.848	-986191.935	5975733.379	1993725.866
BANH	-988985.377	6191316.391	1166580.760	-988985.376	6191316.387	1166580.780
CHON	-1190208.442	6097682.826	1438406.181	-1190208.440	6097682.822	1438406.201
PHUK	-912741.643	6253870.516	855385.118	-912741.641	6253870.513	855385.138
PAT2	-1224111.683	6214332.217	748673.868	-1224111.681	6214332.214	748673.888
NKPH	-1520611.086	5887264.527	1919685.399	-1520611.084	5887264.523	1919685.417
UDON	-1380724.234	5931000.665	1890808.747	-1380724.233	5931000.661	1890808.766
LOEI	-1177660.307	5977457.381	1882543.467	-1177660.305	5977457.378	1882543.486
CHAI	-1283028.474	6001605.581	1731192.174	-1283028.472	6001605.578	1731192.193
HUAH	-1078744.686	6133361.476	1373229.453	-1078744.684	6133361.472	1373229.473
MSTK	-912434.158	6041795.614	1823363.110	-912434.157	6041795.611	1823363.129
NKTM	-1076519.285	6204160.640	1011427.705	-1076519.283	6204160.637	1011427.725
MHSN	-834443.808	5964417.160	2093566.433	-834443.806	5964417.157	2093566.452
CHRI	-1050863.605	5893813.844	2193418.486	-1050863.604	5893813.840	2193418.505
CHTB	-1318613.799	6087816.469	1366593.171	-1318613.797	6087816.466	1366593.190
KCNB	-1021921.658	6104984.703	1532936.274	-1021921.656	6104984.699	1532936.293

Since most GPS points of the zero-order Thai geodetic network have long coordinate time series (1994-present), their absolute coordinates and velocities (in ITRF2000, and more recently also in ITRF2005) were well known prior to the Sumatra-Andaman earthquake. By removing these continuous tectonic motions being part of the tectonic Sundaland block (Simons et al., 1999; Simons et al, 2007), their actual total co- and post-seismic displacements due to the Sumatra-Andaman and the Nias earthquakes could be accurately monitored. Because also permanent regional GPS data (in Thailand kindly provided by the Department of Geology, Chulalongkorn University) were available during the two major earthquakes, it was also possible to differentiate between the co-seismic and post-seismic displacements at each of the Thai sites that were observed in campaign-style. By comparing the coordinate results obtained from the latest measurement campaign with the coordinates on the 25th December 2004 (before the Sumatra-Andaman earthquake), the horizontal displacements due to the earthquakes at each zero-order Thai geodetic network site up to November 2008 are illustrated in Figure 3. It should be noted that there is no coordinate solutions for the PAT2 station before the Sumatra-Andaman earthquake, and hence the displacement at this station could not be derived.

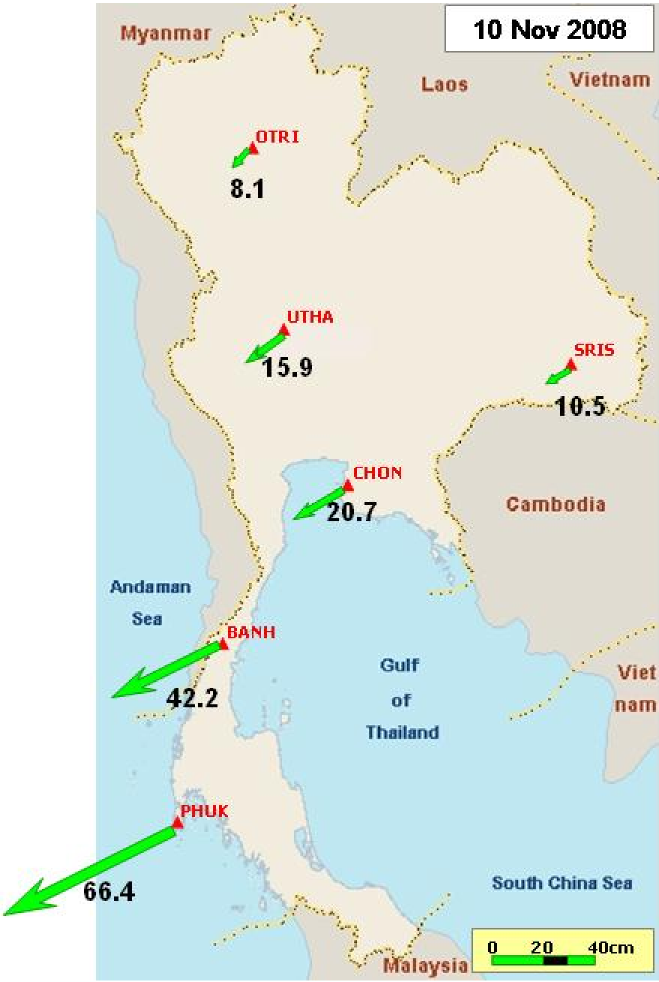

Figure 3 Horizontal total displacements due to the Sumatra-Andaman and Nias earthquakes at each zero-order Thai geodetic network site up to November 2008

5. OBSERVATION ON DIVERSION BETWEEN ITRF2000 AND 2005 IN SE ASIA REGION

Although (global) transformations parameters between ITRF2000 and ITRF2005 exist (Altamimi et al., 2007), it is preferred to directly compare the mapped coordinates in both ITRF solutions. Any such prescribed transformation parameters would also transform (ITRF2000) mapping errors into the newly computed coordinates in ITRF2005. To compare the differences between ITRF2000 and ITRF2005 coordinate solutions, 3 Thai geodetic network points (PHUK, CHON and OTRI) and 2 IGS stations located in SE Asia region (NTUS in Singapore, BAKO in Indonesia) were selected. The differences are then computed at different epochs between 1998 and 2008. These differences are subsequently converted to north, east and vertical components. Since the vertical coordinates are noisy and the uncertainty values are much larger than the differences. Therefore, only differences in north and east components are presented in Table 4.

Table 4 Comparison between ITRF2000 and ITRF2005 coordinates at different epochs

DOY/YEAR	Difference between ITRF2000 and 2005 solutions in mm at each station									
	PHUK		CHON		OTRI		NTUS		BAKO	
	dN	dE	dN	dE	dN	dE	dN	dE	dN	dE
326/98	-4	0	-4	0	n.a.	n.a.	-4	1	-4	1
291/00	-7	0	-6	0	n.a.	n.a.	n.a.	n.a.	-7	1
291/01	-9	0	-9	0	-9	0	-9	0	-9	1
291/02	-12	3	-12	3	-12	3	-12	3	-12	3
305/04	-14	4	-14	4	-13	4	-14	4	-13	4
287/05	-18	-1	-18	-2	-18	-2	-18	-1	-17	1
312/06	-17	1	-17	1	-16	0	n.a.	n.a.	-17	2
326/07	-20	2	-20	1	-20	1	-20	2	-21	2
319/08	-20	1	-19	0	-19	0	-20	1	-20	2

**n.a. = no data available during the campaign*

It can be clearly seen from Table 4 that all stations (in SE Asia, besides the one in the table) show similar offsets in the north-south direction for all epochs while there is no significant offset in the east-west direction. In addition, the offset in the latitudinal direction is not constant in time. Further investigation on this was carried out by taking an average offset in the north-south direction at each epoch. A simple linear trend fitting was chosen to fit the average offsets. The best fitted linear trend is plotted in Figure 4. The Y-axis represents the magnitude of north-south offsets in mm unit while the X-axis shows the period in year unit since 1998. Figure 4 clearly confirms a significant diversion of coordinates between ITRF2000 and ITRF2005 in the north-south direction at a rate of 1.7 mm/yr within SE Asia region.

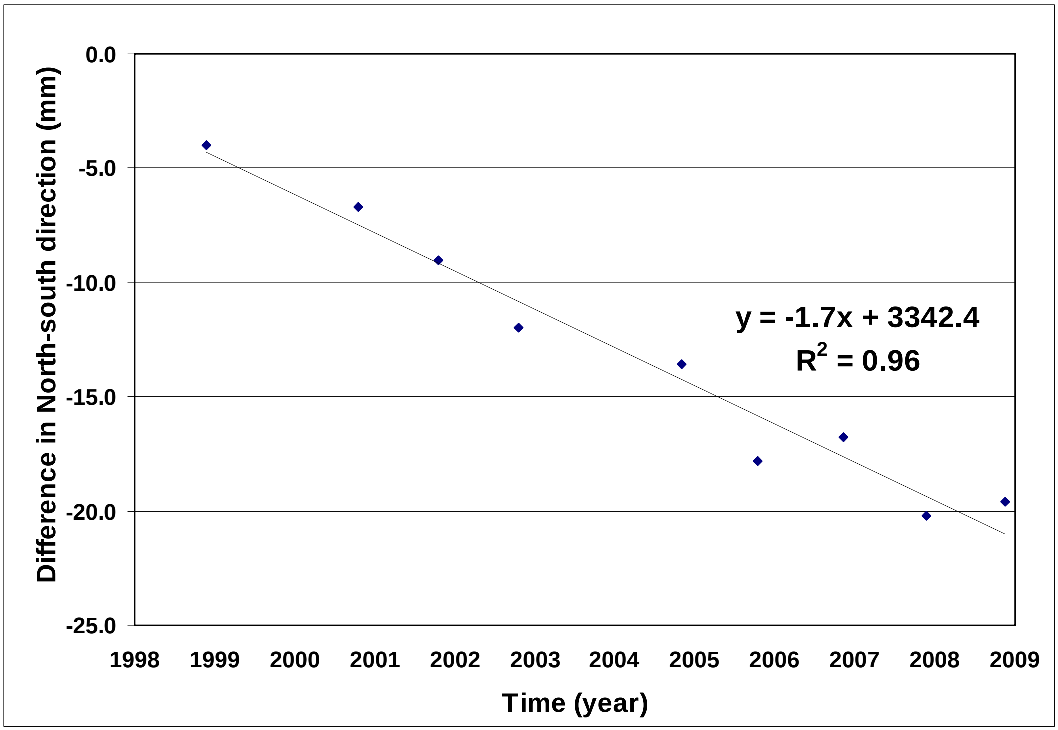

Figure 4 Best fitted linear trend to the average north-south offsets between ITRF2000 and ITRF2005 between 1998 and 2008

6. CONCLUDING REMARKS

The GPS data from the RTSD November 2008 campaign in Thailand have been successfully processed. The daily solutions have shown good repeatability for all the stations. The 7-day averaged campaign solutions were successfully mapped into both ITRF2000 and ITRF2005 using a number of well-determined global IGS sites. The RMS values obtained from the ITRF2005 mapping process were found to be of the order of 3 mm and 10 mm. respectively for the horizontal and vertical components. Approximately 4 years after the Sumatra-Andaman earthquake, the earthquake results in the horizontal displacements ranging from 66.4 cm in the south (PHUK), 20.7 cm in the centre (CHON), 10.5 cm in the north-east (SRIS), to 8.1 cm in the north (OTRI) of Thailand. It is expected that post-seismic motions in Thailand will continue well into the next decade, especially in the southern parts. It was also found that there is a significant diversion between ITRF2000 and ITRF2005 coordinate solutions in the north-south direction at a rate of 1.7 mm/yr within SE Asia region. Therefore, ITRF2000 and ITRF2005 coordinates (and all derivated products like e.g. plate motion determination) should not be combined in any analyses. Finally, the ITRF2005 coordinate results obtained from the latest RTSD GPS campaign will be served as a new national reference frame for Thailand.

ACKNOWLEDGEMENTS

This research is supported by the Ratchadaphisek Somphot Endowment Grants from Chulalongkorn University, a GO-2 grant from the Netherlands Institute for Space Research (NWO/SRON) and the GEO2TECDI project. The GEO2TECDI project has been funded under Contract No: DCI-ASIE/2008/171-181 of the Thailand-EC Cooperation Facility program. The authors would like to thank to the Royal Thai Survey Department (RTSD) for providing the GPS campaign data at Thai geodetic network sites.

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BIOGRAPHICAL NOTES

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