Observing Plate Motions in S.E. Asia: Geodetic results of the GEODYSSEA project

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Abstract. This paper presents the final geodetic results obtained in the framework of the 'GEODYnamics of South and South-East Asia' (GEODYSSEA) project. The goal of this project is to study the overall plate motions in this region. For this purpose, a network of 42 stations was observed with GPS during two field campaigns in 1994 and 1996. The data were analyzed independently by four groups using different software packages and analysis strategies. The resulting individual network solutions were combined into 2 campaign averaged coordinate solutions. The precision of both coordinate solutions was found to be 4-7 mm for the horizontal, and 1 cm for the vertical component. Subsequently, these campaign solutions were merged into one unique solution, which was accurately mapped into the International Terrestrial Reference Frame solution of 1996 (ITRF-96) [*Boucher et al.*, 1997]. The global accuracy of this solution with respect to ITRF-96 is of the order of 1 cm, while the resolution of the relative horizontal velocities is estimated to be at the level of 2-3 mm/yr. This solution represents the latest official geodetic result of the GEODYSSEA project and it is used as the basis for all scientific interpretations, which have been and will be published in separate papers. As an immediate result the velocity estimates of a part of the network provided the first direct measurement of a relative motion of the Sundaland block with respect to Eurasian plate.

Introduction

The 'GEODYnamics of South and South-East Asia' (GEODYSSEA) project [*Wilson et al.*, 1998] was initiated in 1991 as a joint EC-ASEAN project, to study the complex geodynamic processes in S.E. Asia. These result from the convergence and collision of the Eurasian, Philippine and Australian plates at relative velocities of up to 10 cm per year. A detailed geological description of the geodynamics of S.E. Asia can be found in e.g. [*Rangin et al.*, 1990].

Previous investigations in S.E. Asia using GPS for both regional and more localized surveys were mostly restricted to a single national territory. By contrast, the GEODYSSEA project aims to determine the tectonic motions across the entire S.E. Asia region and provides a reference frame into which all detail networks can be fitted. The project was carried out by a large international group of participants, including 22 agencies and institutions in 14 different Asian and European countries.

This paper describes the geodetic results of the project which are based on two GPS measurement campaigns in 1994 and 1996. A solution for the station coordinates and velocities was obtained by combining the results of four different analysis groups.

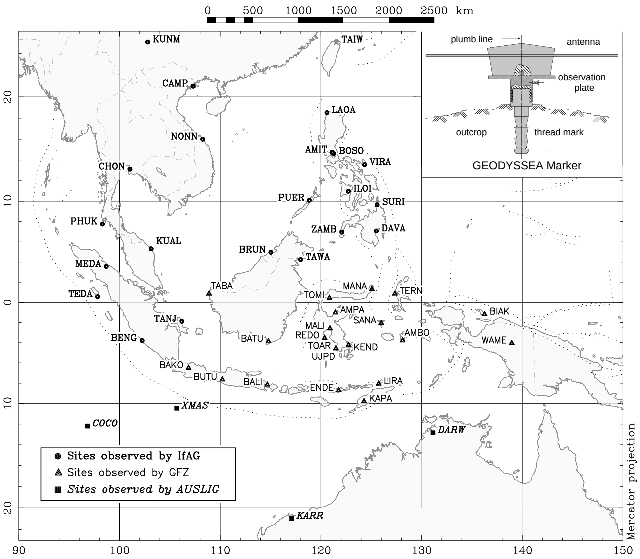

Figure 1. The GEODYSSEA Network and the major tectonic boundaries in South-East Asia.

The GEODYSSEA Network

The GEODYSSEA network (Fig. 1) covers an area of about 4000 by 4000 km, and includes 42 observation points throughout South and South-East Asia. The selected points provide a good coverage of all the major tectonic blocks in the region. Prior to the first GPS measurements, the observation points were monumented in bedrock with specially designed markers, yielding a re-centering accuracy of 0.2 mm (Fig. 1, [*Reinking et al.*, 1995]).

Though a network of continuously operating stations would provide the best results, it is expensive and difficult to operate in remote areas in S.E. Asia. The campaign style observations of the GEODYSSEA project provide a good alternative in this case, al-

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though the results have to be carefully interpreted, because they might have been affected by transient site effects, temporal variations and episodic motions. To remove at least partially these effects, and minimize the effects of common errors, almost all points in the GEODYSSEA network were occupied simultaneously and continuously measured for a campaign period of 5 days. To each GPS campaign data set, the available data for 4 stations of the Australian Survey and Land Information Group (AUSLIG) on the Australian plate was added. To facilitate the positioning of the network in a global reference frame, data from 6 stations of the International GPS Service for Geodynamics (IGS) tracking network [*Beutler et al.*, 1994] in the region was included.

Two major observation campaigns were conducted in the course of the project by GFZ and BKG (formerly IfAG), and a third was recently completed in November 1998. Only standardized Trimble 4000 SSE GPS receivers and antennae were employed, though data supplied by AUSLIG and obtained from the IGS was collected with (Turbo)Rogue and Ashtech receivers connected to Dorne Margolin antennae. The GEODYSSEA-94 zero epoch GPS campaign took place from 28 November to 2 December 1994, and contained 231 station-days (254 including one additional day with only part of the network observed) of GPS data. The network was re-observed during the GEODYSSEA-96 first repetition campaign, between 18 and 22 April, 1996. 220 station-days (280 including 4 additional days) were collected this time. The loss of data during both campaigns due to receiver failures, operational mistakes and logistical problems is almost negligible.

GPS Data Analysis

Four analysis groups (DEOS, ENS, GFZ and BKG) computed solutions for the complete GEODYSSEA 1994 and 96 campaign data sets, using their favored software and analysis strategy. The GPS packages used include four of the state-of-the-art systems currently in use, i.e. GIPSY-OASIS II v2.1 [*Blewitt et al.*, 1988], GAMIT v9.4 [*King and Bock*, 1993], EPOS v3.0 [*Angermann et al.*, 1997] and BERNESE v4.0 [*Rothacher and Mervart*, 1996].

All analysis centers computed daily fiducial-free network solutions using the ionosphere-free linear combination of GPS phase and pseudorange data. To account for tropospheric effects, the zenith path delay was estimated (continuously or at regular time intervals, depending on the GPS software) for each station. Because different antennae were used in the network, the groups applied antenna phase center corrections of [*Rothacher and Mader*, 1996]. The datum of the solutions was defined by the combined IGS orbits and the corresponding earth rotation parameters, which were held fixed. Further and more detailed information on the individual analyses can be found in [*Angermann et al.*, 1998].

Multi-day averaged coordinate solutions

The daily solutions of each group were combined into multi-day averaged solutions for each group with the 3D-Motion software [*Noomen et al.*, 1993], which eliminated any systematic differences between the various network solutions by computing optimized 7 parameter Helmert transformations using a least squares adjustment. In this process, station solutions identified as outliers with respect to the averaged solution were removed. The preliminary multi-day solutions were compared, so that common and/or individual processing problems could be detected and resolved. Where required, the groups re-processed the GPS data, after which the final multi-day averaged solutions were computed. At this point, an unique opportunity arose to also compare the performance of the various GPS packages.

Table 1. Daily Coordinate Repeatabilities of Each Analysis Group.

Computing Center		Software	RMS Residuals (mm) North	East	Up
		1994 Campaign			
DEOS	(6 days)	GIPSY	3.2	6.9	9.5
ENS	(5 days)	GAMIT	3.5	4.9	8.8
GFZ	(5 days)	EPOS	3.6	6.3	8.7
BKG	(5 days)	BERNESE	4.0	6.9	10.3
		1996 Campaign			
DEOS	(9 days)	GIPSY	3.2	6.7	10.1
ENS	(9 days)	GAMIT	3.3	6.0	8.5
GFZ	(9 days)	EPOS	3.0	6.3	8.1
BKG	(5 days)	BERNESE	3.1	4.8	9.5

Please note that not all groups processed the additional campaign days. Inclusion of these smaller networks in 1996 slightly degraded the repeatability, but this was necessary because a few sites could not be occupied during the offical campaign days. ENS also resolved the phase ambuigities in their solutions, which shows up in the east component of the coordinate repeatabilities. Therefore, these values should not be interpreted as a direct measurement of the performance of each GPS software.

The daily repeatabilities of the station coordinates (Table 1), ranging from 3 to 6.5 mm for the horizontal components and averaging at about 9 mm in the height, provide sufficient evidence that the various solutions are of similar quality. This shows that the internal precision of the GEODYSSEA network is very high, at a level comparable to the IGS global network solutions.

Campaign averaged coordinate solutions

For each campaign, the multi-day averaged solutions from DEOS, ENS, GFZ and BKG were combined with the 3D-Motion software into one 1994, and one 1996 campaign coordinate solution. The campaign solutions were both based on four equally weighted contributions, since the multi-day averaged solutions of each group were of the same quality.

The internal consistency of all contributing individual solutions is 2, 4, 7 mm and 3, 5, 8 mm in the north, east and up components, for the 1994 and 1996 GEODYSSEA campaigns respectively. This result demonstrates the high quality of the computations. Furthermore, it proves the high quality standard and high performance of the four software packages GIPSY, GAMIT, EPOS and Bernese. However, for an overall quality assessment of the network accuracy, this result may be too optimistic because it does not account for possible biases caused by the commonly used IGS combined orbits, the same IGS station data, and the identical antenna phase center corrections applied by all groups. These biases have to be considered for an overall quality assessment of the network accuracy. The effect of different IGS orbits and the constellation of the IGS station on the station coordinates has been investigated by [*Angermann*, 1998]. The influence of the IGS orbits on the internal network accuracy is in the order of 1-3 mm, while the effect of different IGS station constellations is 1-2 mm. Taking into account these biases the campaign averaged station coordinates have an accuracy between 4-7 mm for the horizontal component and 1 cm for the height. The final combined 1994 and 1996 coordinate solutions have a higher resolution than their individual contributions, and have been used to obtain a single set of GEODYSSEA station coordinates and derived velocities in a common reference frame.

Combining the campaign solutions in ITRF-96

Although the available time series for the GEODYSSEA network at present only contains two solutions, they are of high qual-

Table 2. Final results network solution mapping in ITRF-96.

	1996 Solution (1)			**1994 Solution (2)**		
IGS Station	North	East	Up	North	East	Up
Cocos Island	7.5	9.7	9.9	6.3	9.5	-5.7
Kitab	5.8	20.6	0.1	8.9	3.6	12.2
Taiwan	4.7	-4.5	-10.6	-9.5	3.8	-14.5
Tidbinbilla	-4.0	4.8	15.0	1.6	9.5	22.5
Tsukuba	4.9	-8.2	-1.6	9.3	-14.7	-3.3
Yarragadee	-2.8	-2.8	-4.2	7.0	-9.0	1.8
RMS	5.2	10.3	8.7	7.6	9.2	12.3

Coordinate residuals for the 6 IGS stations included in the GEODYSSEA coordinate solutions (in millimeters) after transformation w.r.t. (1) their ITRF-96 coordinates and (2) the ITRF-96 velocity constraints used between the 1996 and 1994 campaign epochs.

ity and cover a time interval of 16.5 months. This is sufficient to obtain an accurate first estimate of the horizontal station velocities in this region. When the final combined solution was computed and distributed among all participants of the project, the ITRF-94 reference frame [*Boucher et al.*, 1994] was the latest one available. In this paper, the final GEODYSSEA results are presented in ITRF-96 because this is a more accurate reference frame which contains improved IGS station coordinates and velocity estimates. This is especially true for some of the regional IGS stations (Kitab and Taiwan) that were included in the GEODYSSEA data analysis. Also the station coordinates and velocity estimates for the AUSLIG station at Cocos Island, which became part of the IGS global network in 1996, are given in ITRF-96. Therefore 6 IGS sites (instead of 5 with ITRF-94) could be used to map the GEODYSSEA solution in ITRF-96.

This was done, by first projecting one campaign solution with 3D-Motion onto an ITRF-96 solution, that contains the positions of the selected IGS stations at the time of the campaign. This ITRF-96 mapped campaign solution was then used as a reference solution in a second 3D-Motion run to map the other campaign solution upon, thereby applying this time fixed velocity constraints to the IGS stations according to ITRF-96. This technique perfectly aligns the IGS station velocities (misfits show up completely in the coordinate residuals), and delivers a single averaged station coordinate set and corresponding station displacement rates in ITRF-96 with the best (formal) representation of the accuracy. The epoch for the final combined solution was set at 1996, since any difference in the actual station velocity with respect to ITRF-96 would propagate through time, making the GEODYSSEA 1996 solution more suited to be first transformed to ITRF-96, and then used as a reference solution for the 1994 campaign solution.

With the 6 nearby IGS tracking sites included in the GEODYSSEA solutions (Kitab (Usbekistan),Taipei (Taiwan), Tsukuba (Japan), Cocos Island, Tidbinbilla and Yarragadee (all in Australia)), an accurate representation of the GEODYSSEA network in ITRF-96 was obtained. Table 2 shows the coordinate residuals of the IGS sites for the 1994 and 1996 solution transformations. These coordinate residuals are quite consistent for both campaign solutions and have an Root-Mean-Square (RMS) value of 5 to 10 mm for the horizontal, and 9 to 12 mm for the vertical position. Some slightly higher coordinate differences can be noticed in Table 2 for the IGS sites Kitab and Tidbinbilla, which are located at the edges of the network relatively far away from the dense core of GPS sites. This may be due to the chosen regional-type approach of including only available nearby IGS sites in the local network to transform the network onto ITRF-96. Also, although 2 IGS stations (Taiwan and Tsukuba) are located on or close to possible active deformation zones, their coordinate residuals confirm that their observed motion in between both GEODYSSEA campaigns was aseismic and in agreement with ITRF-96.

Comparison of the IGS station coordinates in the final averaged GEODYSSEA solution, with their ITRF-96 values, reveals RMS coordinate residuals of 5, 8 and 7 mm for the three components. This shows that the global accuracy with respect to the ITRF-96 is of the order of 1 cm for both the horizontal and the vertical station position. The station velocity estimates in ITRF-96 have a formal (1-σ) accuracy of 2-3 mm/yr for the horizontal directions, and 5 mm/yr for the height. An exception are the velocity estimates for the stations KEND and REDO on Sulawesi, which are less accurate because these sites could only be occupied 1 to 3 days in both campaigns (in 1996 only outside the nominal 5 day period).

Results and Discussion

An important outcome of the data analysis are the station velocities computed along with the station coordinates. The final combined solution containing the coordinates and velocity estimates of 39 GEODYSSEA sites (in ITRF-94) can be found in [*Simons et al.*, 1998], and is now also available (in both ITRF-94 and ITRF-96) from the GEODYSSEA web site (http://www.geologie.ens.fr/ vigny/geodyssea-e.html). Only those stations which were observed during both the GEODYSSEA campaigns, have been included. The velocities in ITRF-96 are shown in Fig. 1. For reference, the velocities predicted by the No-Net-Rotation (NNR) NUVEL-1A model [*DeMets et al.*, 1994] are also included. The estimation of magnitudes and directions of the kinematic features active in the region, proved to be possible with a (based on formal statistics that may be too optimistic) relative horizontal resolution of 2-3 mm/yr. These results have been interpreted by the geologists and geophysicists participating in the project. An important finding was that the results seem to confirm that the Sundaland block has a distinct relative motion with respect to the stable part of the Eurasian plate [*Wilson et al.*, 1998; *Chamot-Rooke et al.*, 1998]. Furthermore, the precise locations of the active plate boundaries in the region covered were identified and significant new information on local deformation processes and measurements of co-seismic displacements at various sites was obtained [*Michel et al.*, 1998]. The latter is clearly visisible in Fig. 1. the station on the island Biak (BIAK), Indonesia, which moved more than a meter horizontally (ten times more the normal rate) due to two heavy earthquakes there in February of 1996. Earthquakes also affected the station velocities of the stations on Tomini (TOMI), Indonesia and LaoAgo (LAOA), Philippines.

A high regional and global accuracy of the GEODYSSEA velocities is the backbone of all findings. Therefore the previous representation of the GEODYSSEA station coordinates and velocities in ITRF-94 has been replaced in this paper by a more accurate representation in ITRF-96. With respect to the previous solution in ITRF-94, the station velocities thereby have changed on average by -4, +3.5 and -3 mm/yr in north, east and up directions.

The previously observed motion of the Sundaland block was verified in ITRF-96. The Euler vector for the Sundaland block was derived by fitting a (2-dimensional) rigid block velocity model to 12 stations (NONN, CHON, KUAL, MEDA, PHUK, TABA, TANJ, BATU, BAKO, UJPD, BUTU, BALI), assumed to be located on this stable block (the open black dots in Fig. 1). The site in Brunei, also considered to be on the Sundaland block, was not included in the computations because it seems affected by intraplate deformation. The results indicate a rotation pole of about 0.37°/Myr located at 43° N and 61° W in ITRF-96. These val-

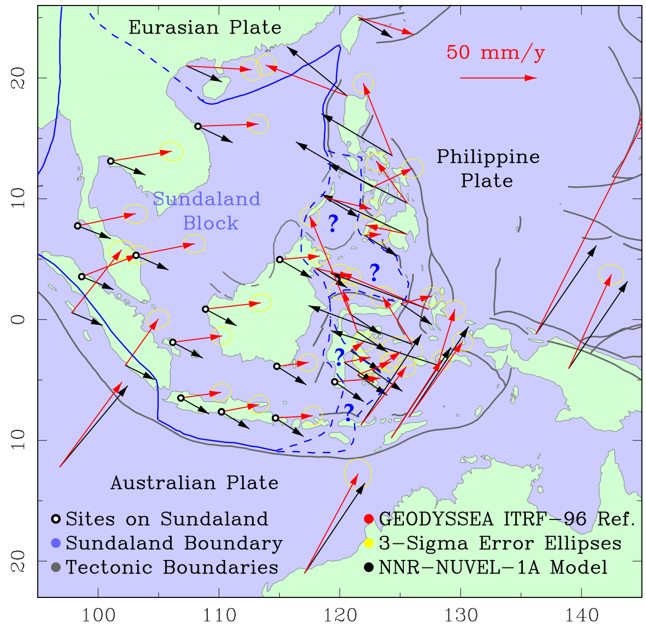

Plate 1. Predicted and Final GEODYSSEA Station Velocities.

ues differ significantly for the NNR-NUVEL-1A prediction for the Eurasian plate, which gives a rotation pole of 0.23°/Myr located at 51° N and 113° W. When the modeled Sundaland block velocities are subtracted from their actual values, small residuals are obtained for these stations, with an RMS of 3 mm/yr in the north and 4 mm/yr in the east component. As these residuals are consistent with the quality assessment of the final combined GEODYSSEA solution, this confirms that the 12 stations indeed describe the motion of a stable Sundaland block. The major tectonic boundaries of the Sundaland block are shown in Fig. 1, and are dotted in regions where the boundaries are not yet fully clear.

A third GEODYSSEA GPS campaign was successfully carried out by GFZ and BKG in November 1998. At the same time, a GPS measurement campaign was organized by DEOS on the island of Sulawesi to observe a fault transect and additional GEODYSSEA sites installed by ENS to densify the GEODYSSEA network in this region. When the data of these campaigns becomes available, further verification of the presented geodetic results will take place, and probably also a first good estimate of the vertical motions in this region will be obtained.

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References

Angermann, D., The datum definition of the GEODYSSEA network, in *GEODYSSEA final report to the Commission of the European Community*, edited by P. Wilson and G.W. Michel, GFZ Scientific Technical Report, 1998.

Angermann, D., G. Baustert, R. Galas, and S.Y. Zhu, EPOS.P.V3 (earth parameter & orbit system): Software user manual for processing of GPS networks, *GFZ scientific technical report*, STR97/14, GFZ Potsdam, 1997.

Angermann, D., M. Becker, W.J.F. Simons, and A. Walpersdorf, The solutions of the European analysis centers for the GEODYSSEA 94/96 GPS campaigns, in *GEODYSSEA final report to the Commission of the European Community*, edited by P. Wilson and G.W. Michel, GFZ Scientific Technical Report, 1998.

Beutler, G., I. I. Mueller, and R. E. Neilan, The International GPS Service for Geodynamics (IGS): Development and start of official service on January 1, 1994, *Bull. Géod.*, *68*, 39–70, 1994.

Blewitt, G., W. G. Melbourne, W. I. Bertiger, T. H. Dixon, P. M. Kroger, S. M. Lichten, T. K. Meehan, R. E. Neilan, L. L. Skrumeda, C. L. Thornton, S. C. Wu, and L. E. Young, GPS geodesy with centimeter accuracy, in *Lecture Notes in Earth Sciences*, edited by E. Groten and R. Strauss, Springer-Verlag, New York, 1988.

Boucher, C., Z. Altamimi, M. Feissel, and P. Sillard, Results and analysis of the ITRF94, *IERS technical note No. 18*, Observatoire de Paris, 1994.

Boucher, C., Z. Altamimi, and P. Sillard, Results and analysis of the ITRF96, *IERS technical note No. 24*, Observatoire de Paris, 1997.

Chamot-Rooke, N., X. Le Pichon, C. Rangin, P. Huchon, M. Pubellier, C. Vigny, and A. Walpersdorf, Sundaland motion in a global reference frame detected from geodyssea gps measurments; part i: implications for subduction motion along java, sumatra and burma trenches, submitted to Geophys. J. Int., 1998.

DeMets, C., R. G. Gordon, D. F. Argus, and S. Stein, Effect of recent revisions to the geomagnetic reversal timescale on estimates of current plate motions, *Geophys. Res. Lett.*, *21*, 2191–2194, 1994.

King, R.W., and Y. Bock, *Documentation for the MIT GPS analysis software : GAMIT*, Massachussetts Institute of Technology, Cambridge, 1993.

Michel, G.W., D. Angermann, P. Wilson, C. Reigber, and J. Klotz, Transient versus secular motion: the possible impact of earthquakes and interseismic loading on the GEODYSSEA site motions, in *GEODYSSEA final report to the Commission of the European Community*, edited by P. Wilson and G.W. Michel, GFZ Scientific Technical Report, 1998.

Noomen, R., B. A. C. Ambrosius, and K. F. Wakker, Crustal motions in the Mediterranean region determined from laser ranging to LAGEOS, *Contributions of Space Geodesy to Geodynamics*, *23*, 331–346, 1993.

Rangin, C., L. Jolivet, M. Pubellier, and the Tethys Pacific working group, A simple model for the tectonic evolution of South-East Asia and the Indonesian region for the past 43 my., *Bull. Soc. Geol. Fr.*, *6*, 889–905, 1990.

Reinking, J., D. Angermann, and J. Klotz, *Zur Anlage und Beobachtung grossraeumiger GPS-Netze fuer geodynamische Untersuchungen. Allgemeine Vermessungsnachrichten*, H. Wichmann Verlag, 1995.

Rothacher, M., and G. Mader, *Combination of Antenna Phase Center Offsets and Variations: Antenna Calibration set IGS_01*, IGS Central Bureau / University of Berne, Berne, Switzerland, 1996.

Rothacher, M., and L. Mervart, *Bernese GPS Software Version 4.0*, Astronomical Institute, University of Berne, Berne, 1996.

Simons, W.J.F., D. Angermann, B.A.C. Ambrosius, M. Becker, R. Noomen, A. Walpersdorf, P. Wilson, and C. Vigny, The final geodetic results of the GEODYSSEA project: the combined solution, in *GEODYSSEA final report to the Commission of the European Community*, edited by P. Wilson and G.W. Michel, GFZ Scientific Technical Report, 1998.

Wilson, P., J. Rais, C. Reigber, E. Reinhart, B.A.C. Ambrosius, X. Le Pichon, M. Kasser, P. Suharto, A. Majid, P. Awang, R. Almeda, and C. Boonphakdee, Study provides data on active plate tectonics in southeast asia region, *Eos Trans. AGU*, *79*(45), 545–549, 1998.

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