Co- and Post-Seismic Displacements of Permanent GPS Stations Associated with the December 26, 2004 and March 28, 2005 Sumatra Earthquakes

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Summary

On December 26, 2004 and on March 28, 2005 earthquakes of magnitudes $M_w = 9.0$ and $M_w = 8.7$ respectively occurred off the west coast of northern Sumatra. In order to assess the impact of these seismic events on the nearest permanent GPS stations, the observations collected by a network of 9 stations from October 2004 to mid June 2005 were analyzed. Sites in southern India moved 2 cm southward due to the December earthquake. Both earthquakes caused westward displacements of a station in Singapore of between 2 cm and 2.5 cm. By far the largest effects occurred at a station on the northeast coast of Sumatra which experienced co-seismic movements of 15 cm and 20 cm towards west and southwest respectively. The March 28 earthquake caused also an exponentially decaying post-seismic motion of this site.

Zusammenfassung

Am 26. Dezember 2004 und am 28. März 2005 ereigneten sich Erdbeben der Stärke $M_w = 9.0$ bzw. $M_w = 8.7$ vor der Westküste Nord-Sumatras. Um die Auswirkungen dieser Beben auf die nächstgelegenen permanenten GPS-Stationen zu bestimmen, wurden die Beobachtungen eines Netzes von 9 Stationen von Oktober 2004 bis Mitte Juni 2005 analysiert. Stationen in Süd-Indien wurden durch das Erdbeben im Dezember 2 cm südwärts verschoben. Beide Beben verursachten Verschiebungen einer Station in Singapur zwischen 2 cm und 2,5 cm in westlicher Richtung. Die bei weitem größten Effekte traten bei einer Station an der Nordostküste Sumatras auf, die ko-seismische Verschiebungen von 15 cm bzw. 20 cm nach Westen bzw. Südwesten erfuhr. Bei dieser Station erzeugte das Erdbeben vom März zusätzlich eine exponentiell abnehmende post-seismische Bewegung.

1 Introduction

Terrestrial reference frames are realized by specifying coordinates for a number of selected sites on the surface of the Earth at a certain reference epoch and parameters describing the time evolution of these coordinates. Reference station networks serve as basis for many scientific and practical applications, actual ones being studies related to weather forecasting and sea level variations. Many applications require a high long-term stability and consistency of the reference frame. So far the time evolution is generally parameterized by linear site velocities. Therefore, the maintenance of a reference frame requires a careful monitoring of all phenomena that might affect the station positions non-linearly. In particular in the case of Global Positioning System (GPS) stations, which constitute the majority of the reference network sites, there are not only real but also apparent effects that cause discontinuities in the position time series. Apparent position variations may be due to changes in the antenna environment, changes in the equipment configuration, temporary malfunctioning of the receiver or the antenna or variations in the data analysis strategy. Examples of real site displacements with respect to a linear velocity are atmospheric pressure or continental water loading which cause mainly height variations. The most important real site displacements are due to tectonic activities such as earthquakes. As an example, heavy earthquakes of magnitudes 8.4 and 7.6 respectively close to the Pacific coast of Peru in June/July 2001 did not only cause large co-seismic displacements of a permanent station at Arequipa, but also a post-seismic motion which differed completely from the site velocity prior to the seismic events (Kaniuth et al. 2002).

On December 26, 2004 an earthquake of magnitude $M_w = 9.0$ occurred about 100 km off the west coast of northern Sumatra. This was the fourth largest earthquake ever recorded since 1900 and the largest after the Alaska earthquake of 1964. The Sumatra earthquake was caused by the release of stress accumulated, as the India tectonic plate subducts beneath the overriding Burma microplate. The released energy generated a devastating tsunami which killed more than 280,000 people in the surrounding countries. There are initial geodetic analyses of the effects of this earthquake. Chao and Gross (2005) modelled changes in the rotation and oblateness of the Earth due to the global gravitational effects. Sabadini et al. (2005) discussed the possible regional changes of the Earth's gravity field induced by the earthquake and also the capability of upcoming space missions to detect such gravity changes. Khan and Gudmundsson (2005) determined the co-seismic displacements of the two permanent GPS stations closest to the epicentre. However, that analysis covers only four weeks of observations after the main shock. In addition, permanent GPS stations located in southern India and on the Maldives were not included.

On March 28, 2005 a further shallow thrust earthquake of magnitude $M_w = 8.7$ struck northern Sumatra, causing only a moderate tsunami compared to the previous earthquake. The epicentre was again located off the west coast approximately 200 km southeast of the December 26 epicentre. The main characteristics of both earthquakes are summarized in Tab. 1. The present contribution determines the impact of both seismic events on permanent GPS stations in the area by analyzing the time series of daily position estimates from October 2004 to June 2005.

Tab. 1: Epicentre locations and magnitudes of the Sumatra earthquakes (USGS 2004, 2005)

Date	Time (UTC)	Magn. (M_w)	Lat. (°)	Long. (°)
2004, Dec. 26	00:58:53	9.0	3.31	95.95
2005, March 28	16:09:36	8.7	2.07	97.01

2 GPS Network

The positions and velocities of the sites included in the global network of the International GPS Service (IGS) provide the most actual reference frame realization. For this analysis, the sites nearest to the epicentres of the earthquakes were selected. One more distant station at the northwest coast of Australia was included because its position could be considered as being definitely not affected by the seismic events. In addition, observations from a permanent GPS station at the northeast coast of Sumatra were available which does not belong to the IGS network. There are two stations in southern India at a distance of only 6.5 km from each other, which are both included because their displacements, if there are any, should be very similar. Thus, the agreement between their results could be an indication of the achieved accuracy. The distances from each of the other stations to the nearest site range from 600 km to 2300 km.

The reliable determination of co-seismic displacements and possibly post-seismic deformations requires the analysis of sufficiently long time spans of observations before the first earthquake, after the second and between the events. Therefore, in total 256 days from 2004, day 277 to 2005, day 166 have been processed. The number of observation days available for each station during the three periods are documented in Tab. 2. Incomplete observations were excluded as soon as the data loss exceeded about 50 %. A rather incomplete series appears for MALD.

There exist further permanent GPS stations on Sumatra. The California Institute of Technology and the

Tab. 2: Number of observation days available at each station during the three periods

Period (Years, Days)	BAKO	BAN2	COCO	DGAR	IISC	KARR	MALD	NTUS	SAMP
2004,277–2004,360	82	82	80	84	77	77	58	81	83
2004,361–2005,087	86	92	93	93	92	93	77	93	78
2005,088–2005,166	72	72	79	79	54	79	45	66	72

Indonesian Institute of Science initiated the »Sumatran Plate Boundary Project« which is a multi-disciplinary effort aiming at studying the tectonic processes at a plate boundary which is determined by the oblique convergence of oceanic and continental plates (http://www.tectonics.caltech.edu/sumatra). In the frame of this project the Sumatran GPS array (SUGAR) of more than 15 stations has been established since 2002. However, obviously the operation of the stations is not remotely controlled, and the collected data has to be retrieved in the field. Very recently, observations from a number of stations up to January 20, 2005 were made available to the public (http://www.tectonics.caltech.edu/sumatra/rinex).

The SUGAR data sets are rather incomplete, but there are five stations providing continuous observations between day 342 of 2004 and day 12 of 2005 which could be used to assess any impacts of the December 26 earthquake. All these five sites are located in southern Sumatra, and their distances to the epicentre are already in the order of 500 km and more. Probably due to memory restrictions the sampling rate is 120 seconds, compared to the usual 30 seconds. Nevertheless, these observations were included in the analysis as well. Fig. 1 displays the locations of the earthquake epicentres and of all involved global and SUGAR stations with their four-character identifications.

Fig. 1: Station and earthquake epicentre locations

3 Data Analysis

The GPS data processing was done with the Bernese software version 4.2 (Hugentobler et al. 2001). The main characteristics of this software system is the so-called double difference approach where the processed observables are phase measurement differences between two stations and two satellites. This approach requires the generation of baselines which was not done automatically but manually, considering in particular the inter-station distances and the data coverage and quality. The main features of all single baseline or network adjustments can be summarized as follows:

- The satellite orbits, satellite clock offsets and Earth orientation parameters were fixed to the combined IGS solutions which refer to the International Terrestrial Reference Frame 2000 (ITRF2000).
- The elevation mask was set to 10°, and all available observations were used, i.e. 30 seconds data rate in case of the global stations and 120 seconds for the SUGAR stations; elevation dependent weighting was applied.
- The phase ambiguities were resolved using the Quasi Ionosphere Free (QIF) strategy; on the average, about 75 % of the ambiguities could be fixed.
- No a-priori troposphere model was introduced, instead the total zenith path delay at each site was estimated unconstrained for two hours intervals, and the Niell (1996) dry mapping function was applied to the total delay.

Daily single baseline solutions were performed for the entire period of 256 days. Analyzing the time series of daily coordinate differences allowed to identify any outliers, discontinuities and those sites which were not affected by the seismic events. These stations could then be used for realizing the datum. This analysis showed that the stations BAKO, COCO, DGAR and KARR of the global IGS network were definitely not affected by the earthquakes. The latter three belong to a subset of high performance core stations selected by the IGS (ftp://macs.geod.emr.ca/pub/requests/sinex/rfwg). This solution IGSb00 refers to ITRF2000 but it comprises at least three more years of observations and should therefore provide a more reliable reference frame. Tab. 3 lists the IGS velocity estimates of COCO, DGAR and KARR as well as those of IISC and NTUS. The numbers show that the horizontal velocities of some sites exceed 6 cm/yr with standard deviations of 1.5 to 2.5 mm/yr, but also that the vertical velocities are not well determined yet.

Daily network adjustments were then performed saving the normal equations for a combined solution of all 256 days. These daily normal equations were free in the sense that no station coordinates were constrained. The combined adjustment solved then for the following parameters:

- Station positions at the reference epoch 2005.0 and displacements at the earthquake epochs,
- linear site velocities, if necessary new estimates after an earthquake,
- optionally daily position estimates instead of a linear velocity, e.g. after a co-seismic displacement.

The reference frame was realized by adding to the accumulated normal equation system the IGSb00 positions at 2005.0 and the linear velocities of COCO, DGAR and KARR as pseudo observations with high weights constraining them within their standard deviations.

4 Results and Discussion

Although most of the sites involved move rather fast, highly accurate and reliable velocity estimates could not be expected from only 8.5 months of observations. Therefore, in addition to the constraints described in the previous section also the IGSb00 velocities of IISC and NTUS (Tab. 3) were introduced as pseudo observations in order to further stabilize the solution. This seemed to be justified because the time series of both stations did not indicate any velocity change after the earthquakes. The combined adjustment did not solve for velocities of the SUGAR stations which were only included during five weeks. The estimated co-seismic displacements of these stations due to the December 26 earthquake are given in Tab. 4, but only for the north component, because there were no significant changes in east and vertical direction. The number of observation days available before and after the earthquake are also listed. Tab. 5 presents the co-seismic displacements resulting for the global stations after both earthquakes.

The formal standard deviations from the least squares adjustment based on 33.8 million double difference observations are by far too optimistic. The reason is that the stochastic model applied in the GPS data processing does not take into account any physical correlations between the observations. According to own experiences the autocorrelation function of adjustment residuals in large networks tends to approach zero after about half an hour. In case of a data rate of 30 seconds a rough estimate would then be that the formal errors should be multiplied by a factor of about 8 in order to express a more realistic accuracy. Therefore, the error estimates given in Tab. 4 and 5 are the formal standard deviations from the least squares solution multiplied by 5 and 10 respectively.

Tab. 3: IGSb00 velocity estimates (mm/yr)

Station	North	East	Height
COCO	49.0 ± 1.2	44.8 ± 1.2	1.8 ± 2.9
DGAR	30.9 ± 0.9	46.5 ± 1.5	2.0 ± 2.6
IISC	33.5 ± 0.8	40.5 ± 0.9	0.0 ± 1.5
KARR	56.3 ± 1.8	38.4 ± 2.1	4.4 ± 2.7
NTUS	−7.4 ± 0.7	29.7 ± 1.2	1.5 ± 2.3

The small southward displacements of the SUGAR stations look homogeneous, and the largest motion appeared at ABGS, the site closest to the December 26 epicentre. Unfortunately, no observations were available at the epoch of the second earthquake which occurred nearer to these sites. The stations in southern India and on the Maldives northwest of the epicentres were significantly affected only by the first earthquake. They experienced south-southeast and southeast displacements of less than 2 cm as well as vertical shifts. Considering the error estimates, the agreement between the results for the neighbouring stations BAN2 and IISC is quite good. NTUS in Singapore was displaced by both earthquakes more than 2 cm westward. By far the largest co-seismic motion happened at SAMP on the northeast coast of Sumatra with 15 cm and 20 cm towards west and southwest respectively. In view of their standard deviations the vertical displacements on March 28 cannot be considered as real.

In order to get a closer insight into the time evolution of the SAMP position, the daily estimates of the ellipsoidal latitude and longitude in the reference frame of the

Tab. 4: Co-seismic displacements of the SUGAR stations on December 26, 2004

Station	Days	North (mm)
ABGS	19/18	−10.0 ± 0.7
LNNG	18/14	−6.1 ± 0.8
MKMK	19/14	−6.0 ± 0.8
NGNG	19/17	−8.9 ± 0.7
PRKB	19/15	−7.0 ± 0.8

Tab. 5: Co-seismic displacements of the global stations due to both earthquakes (mm)

Station	December 26, 2004			March 28, 2005		
	North	East	Height	North	East	Height
BAN2	−16.3 ± 0.9	3.5 ± 0.9	10.5 ± 2.4			
IISC	−18.0 ± 0.8	2.7 ± 0.8	16.2 ± 2.4			
MALD	−7.5 ± 0.9	7.1 ± 1.2	7.2 ± 4.3			
NTUS	−0.9 ± 0.8	−21.8 ± 0.7	−7.6 ± 1.9	−4.1 ± 0.8	−23.2 ± 0.7	2.9 ± 2.5
SAMP	−24.3 ± 0.8	−151.5 ± 1.0	15.9 ± 2.7	−143.6 ± 1.2	−135.3 ± 2.8	−2.4 ± 3.7

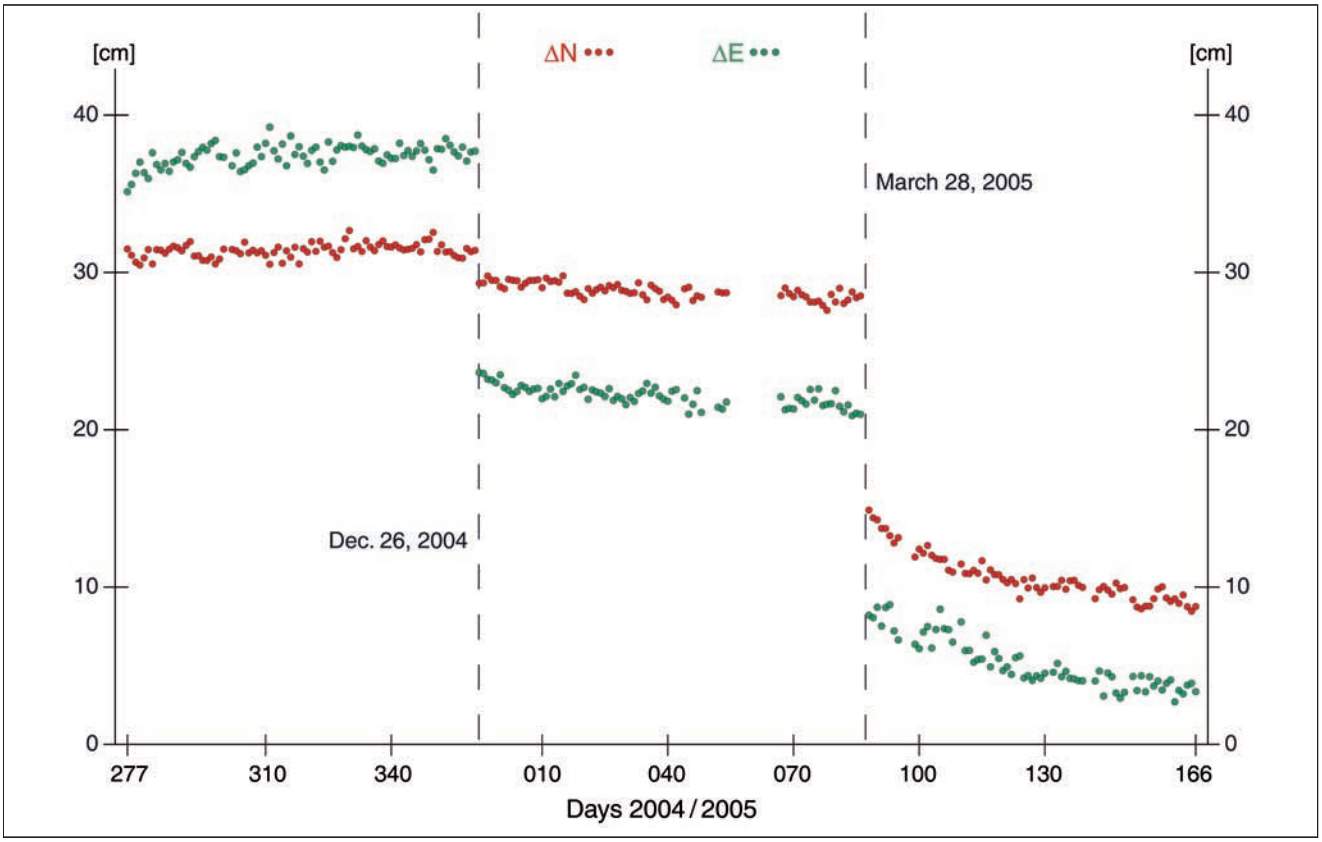

Fig. 2: Daily position estimates of SAMP, latitude = 3° 37' 17.7900'' + ΔN, longitude = 98° 42' 52.9775'' +ΔE

combined adjustment are displayed in Fig. 2. In addition to the co-seismic displacements the time series shows a non-linear site motion after the March 28 earthquake. Such decaying transient surface deformations were observed after several major strike-slip earthquakes (Savage and Svarc 1997, Ergintav et al. 2002, Owen et al. 2002).

Solving for a linear post-seismic velocity of SAMP after March 28 in north direction, which is better determined than the east component, yields an r.m.s. fit of only 6.4 mm. Extending the linear model by an exponential term

$$A \cdot e^{-t/\tau}$$

with A being the amplitude of the exponential component, t the time since the co-seismic slip and τ the exponential decay time (Hearn 2003), then the r.m.s. fit improves to 3.8 mm. The best fit decay time was in the order of 20 days. These results indicate the importance of a careful monitoring of all non-linear site effects for the maintenance of terrestrial reference frame networks. This monitoring should preferably be based on single day rather than on weekly accumulated solutions, in order to allow also a detailed geophysical modelling. Moreover, procedures for properly parameterizing episodic displacements and non-linear site motions, as analyzed in this paper, should be established.

Acknowledgement

The efforts of the institutions and individuals acquiring and providing access to the data and products used in this analysis are gratefully acknowledged.

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