J Geod (2006) 79: 682–688
DOI 10.1007/s00190-005-0020-x

ORIGINAL ARTICLE

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Short note: Crustal deformation in the Key Stone network detected by satellite laser ranging

Received: 17 October 2005 / Accepted: 14 December 2005 / Published online: 13 January 2006

Abstract The paper presents the results of crustal deformation, as evidenced by changed station coordinates, in the Tokyo metropolitan area detected by the satellite laser ranging (SLR) technique. The coordinates of two Key Stone SLR stations, Tateyama and Kashima, were determined from 4 weeks of orbital arcs of the LAGEOS-1 and LAGEOS-2 satellites with respect to 16 SLR stations kept fixed in the ITRF2000 reference frame. The station coordinates were calculated using the NASA GEODYN-II orbital program. The orbital RMS-of-fit for both satellites was 16 mm. The standard deviation of the estimated positions was 3 mm. A jump of about 5 cm in the baseline length between the Kashima and Tateyama stations was detected in June–August 2000 by VLBI and GPS techniques. This work confirms this crustal deformation as determined by SLR and vice versa. Analysis of coordinates of these stations shows that this effect was caused by a 4.5-cm displacement of the Tateyama station in the north-east direction. The change in the vertical component was not significant.

Keywords Satellite geodesy · Geodynamics · Satellite laser ranging (SLR) · Satellite orbit determination · Key Stone Project

1 Introduction

The National Institute of Information and Communications Technology (NICT), Japan (formerly the Communications Research Laboratory, CRL), developed a regular geodetic observation system using very long baseline interferometry (VLBI), satellite laser ranging (SLR) and global positioning system (GPS) to demonstrate their effectiveness for the determination of the crustal deformations around the metropolitan area of Tokyo. It was named the Key Stone Project (KSP) after the Japanese legend of earthquake prevention. In this paper, the crustal deformation is inferred in terms of changes in coordinates and baseline lengths, and is thus not a full analysis in geophysical terms.

Very long baseline interferometry (VLBI) observations of the baseline vector between Kashima and Tateyama were made continuously in the frame of KSP from December 1996 to November 2001. GPS observations started from January 1998. The KSP observations of all three space-geodetic techniques were completed at the end of November 2001. In the KSP program, colocated observing systems have been deployed at four sites (Koganei, Kashima, Miura and Tateyama) around the Tokyo area to monitor crustal deformation (Fig. 1). Target precision was a few millimeters in the baseline length between the four stations. CRL designed the VLBI and SLR to be as much automated as possible.

In the summer of 2000, crustal deformation was observed in the KSP network. Two months' movement was observed continuously by the VLBI and GPS systems. The results were presented in several papers (Yoshino et al. 2001, 2002; Ichikawa 2001, 2002). A large change in the baseline length

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Table 1 Activity of the KeyStone satellite laser ranging (SLR) stations

Stations	SLR activity periods	Number of normal points	Initial coordinates ITRF2000 (m)
Koganei 7328	Nov 1998 – Jul 1999	918	$X = -3,941,961.4490$
	Sep 1999 – Mar 2000	2989	$Y = 3,368,148.5067$
	Jun 2000 – Jul 2000	133	$Z = 3,702,208.6608$
Kashima 7335	Apr 1999 – Sep 1999	506	$X = -3,997,483.5242$
	Oct 1999 – May 2000	2353	$Y = 3,276,844.2240$
	Aug 2000 – Jan 2001	737	$Z = 3,724,307.2954$
Miura 7337	Nov 1998 – Apr 1999	366	$X = -3,976,171.8906$
	Oct 1999 – Apr 2000	1935	$Y = 3,377,941.7174$
			$Z = 3,656,691.9742$
Tateyama 7339	Nov 1998 – Jul 1999	1125	$X = -4,000,964.7806$
	Oct 1999 – May 2000	3335	$Y = 3,375,308.9843$
	Aug 2000 – Jan 2001	1223	$Z = 3,632,199.5749$
	May 2001 – Oct 2001	366	

The stations and periods used in the present analysis are typed boldface

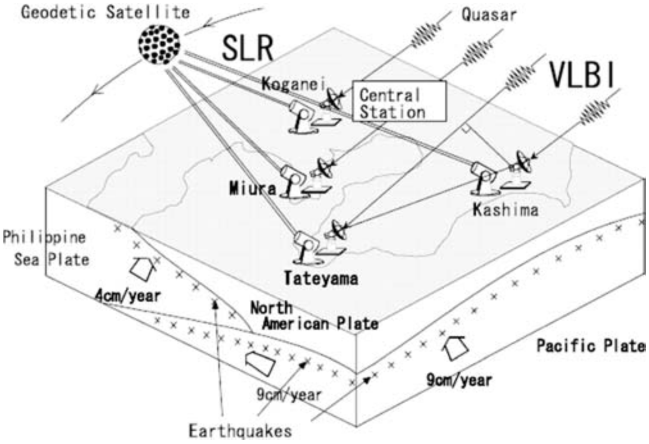

Fig. 1 The Key Stone project stations (Yoshino et al. 2001)

(2 cm/month) between the Kashima and Tateyama stations was observed since the end of June 2000 until August 2000. Hitherto, the analysis of SLR data was not presented.

Table 2 The 16 fixed reference stations

Stations	International Laser Ranging Service site occupation designator (SOD)	Number of normal points	RMS (mm)
McDonald	70802419	5773	15.0
Yarragadee	70900513	13895	12.8
Greenbelt	71050725	11756	13.4
Monument peak	71100411	11357	15.2
Papeete	71240802	1810	12.8
Arequipa	74031303	1126	20.2
Zimmerwald	78106801	4103	18.2
Borowiec	78113802	2368	18.1
Grasse SLR	78353102	6534	14.4
Potsdam	78365801	2858	14.0
Simosato	78383602	2859	31.4
Graz	78393402	8515	16.4
Herstmoceux	78403501	11220	12.2
Grasse LLR	78457801	3562	14.1
Mount Stromlo	78498001	13059	12.8
Wettzell	88341001	4742	19.6

Station Koganei instead of Simosato was used in 1999 and Haleakala instead of Papeete was used in the last arc

2 Observations at the Key Stone SLR stations

The generation of SLR data for the KSP began in November 1998. The results of the four SLR stations' activity in the frame of KSP are presented in Table 1. Unfortunately, all four SLR stations ended their activity in the spring of 2000 when the time limit of the project was reached. However, SLR stations at Tateyama and Kashima resumed observations starting from August 2000 to observe the effect of crustal deformation. The observations of these two stations were continued until January 2001 (Kashima) and October 2001 (Tateyama). A brief report about SLR results was presented in Yoshino et al. (2002).

The present paper presents the first detailed analysis of the crustal movement as determined by SLR. It also shows the possibility of determining a few centimeters of change in station positions by SLR. The best results of the Kashima and Tateyama SLR stations were achieved in the periods October 1999 – May 2000, and August 2000 – January 2001 (Table 1, boldface). The data were divided and analysed in two populations: eight 4-week arcs before the displacement (October 1999 - May 2000) and six 4-week arcs after the displacement (August 2000 – February 2001). The different time periods for both populations of Kashima and Tateyama are the result of the best quantity and quality of data for these periods for both stations.

3 Determination of SLR station coordinates

The coordinates of the Key Stone SLR stations were determined by the method presented in Schillak et al. (2001), Schillak and Wnuk (2002) and Wnuk et al. (2002). The station coordinates were determined from the orbits of the

Table 3 GEODYN-II force model and parameters

Force model
- Earth gravity field: EIGEN-GRACE02S 20×20 (Reigber et al. 2005)
- Earth and ocean tide model: EGM96 (Lemoine et al. 1998)
- Third body gravity: Moon, Sun and all planets – DE200 (Standish 1990)
- Solar radiation pressure: C_R coefficient = 1.14
- Earth albedo (McCarthy et al. 1993)
- Dynamic polar motion (McCarthy et al. 1993)
- Relativistic correction (McCarthy et al. 1993)
- Thermal drag (McCarthy et al. 1993)

Constants
- Gravitational constant times the mass of the Earth (GM): $3.986004415\times10^{14}\,\mathrm{m}^3/\mathrm{s}^2$ (EIGEN-GRACE02S Earth gravity field model)
- Speed of light: 299792.458 km/s (McCarthy and Petit 2004)
- Semi-major axis of the Earth: 6378.13646 km (EIGEN-GRACE02S Earth gravity field model)
- Inverse of the Earth's flattening: 298.25642 (McCarthy and Petit 2004)
- Tide amplitudes – k_2, k_3 and phase k_2: 0.3, 0.093, 0.0

Reference frame
- Inertial reference system: true of date defined at 0^h of the first day of each arc (McCarthy et al. 1993)
- Station's 'coordinates and stations' velocities: ITRF2000 solution, epoch 1997.0 (Boucher et al. 2004)
- Precession: IAU 1976 (Lieske et al. 1977)
- Nutation: IAU 1980 (Seidelmann 1982)
- Polar motion: C04, Bulletin B IERS (IERS 2001)
- Tidal uplift: Love model H2 = 0.609, L2 = 0.0852 (McCarthy et al. 1993)
- Pole tide (McCarthy et al. 1993)

Estimated parameters
- Satellite state vector
- Key Stone station geocentric coordinates
- Acceleration parameters along-track, cross-track and radial at 4-day intervals

Satellites: LAGEOS-1 and LAGEOS-2
- Centre of mass correction: 25.1 cm (ILRS 2005)
- Cross-sectional area: 0.2827 m^2 (ILRS 2005)
- Mass of LAGEOS-1: 406.965 kg, mass of LAGEOS-2: 405.380 kg (ILRS 2005)

Measurement model
- Observations; 2-min normal points from Eurolas Data Center
- Laser pulse wavelength: 532 nm (Zimmerwald 423 nm)
- Tropospheric refraction: Marini/Murray model (Marini and Murray 1973)
- Editing criteria;
- $5\sigma\pm10$ cm for arc
- cutoff elevation 10°

Numerical integration
- Integration: Cowell's method
- Orbit integration step size: 120 s
- Arc length: 28 days

Table 4 Orbital arcs for fixed stations from LAGEOS-1 and LAGEOS-2

Arc interval	Number of normal points	Arc RMS [mm]
99.10.03–99.10.30	10602	14.5
99.10.31–99.11.27	9387	15.0
99.11.28–99.12.25	9066	15.8
99.12.26–00.01.22	6358	16.7
00.01.23–00.02.19	8988	14.3
00.02.20–00.03.18	6097	14.8
00.03.19–00.04.15	6657	16.3
00.04.16–00.05.13	7221	16.2
00.08.27–00.09.23	8726	15.0
00.09.24–00.10.21	6971	15.3
00.10.22–00.11.18	6829	15.3
00.11.19–00.12.16	7122	16.5
00.12.17–01.01.13	7394	14.9
01.01.14–01.02.10	6412	15.5

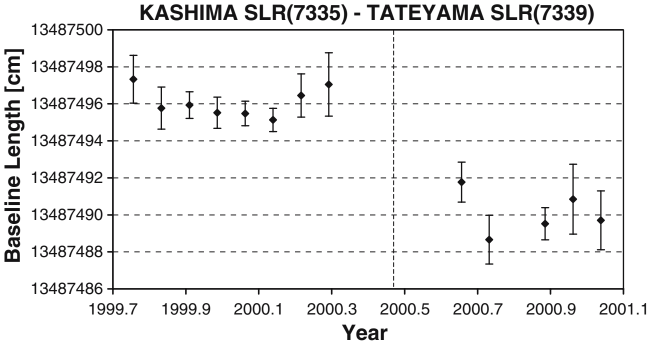

Fig. 2 The length of Kashima – Tateyama baseline from satellite laser ranging (SLR) observations (October 1999 – January 2001)

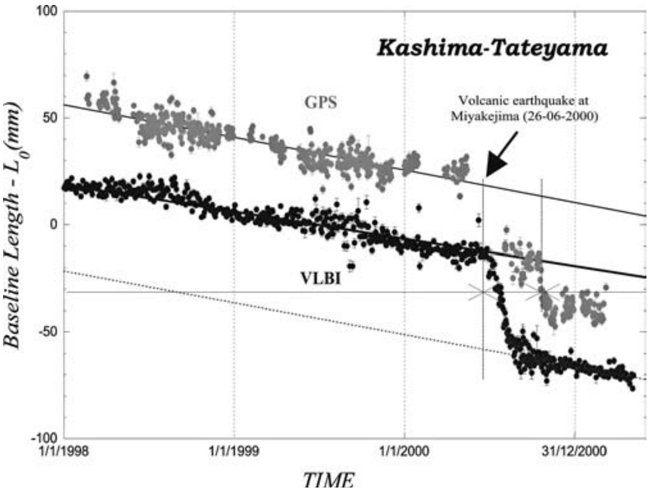

Fig. 3 The length of Kashima – Tateyama baseline from very long baseline interferometry (VLBI) and global positioning system (GPS) observations (Ichikawa 2002)

LAGEOS-1 and LAGEOS-2 satellites. Two-minute normal points of LAGEOS-1 and LAGEOS-2 have been taken from the Eurolas Data Center in Munich. The 4-week orbits were determined from the observations of 16 SLR stations. The station coordinates and velocities of the International Terrestrial Reference Frame 2000 (Altamimi et al. 2002; Boucher et al. 2004) were used to model the instantaneous position of all reference stations.

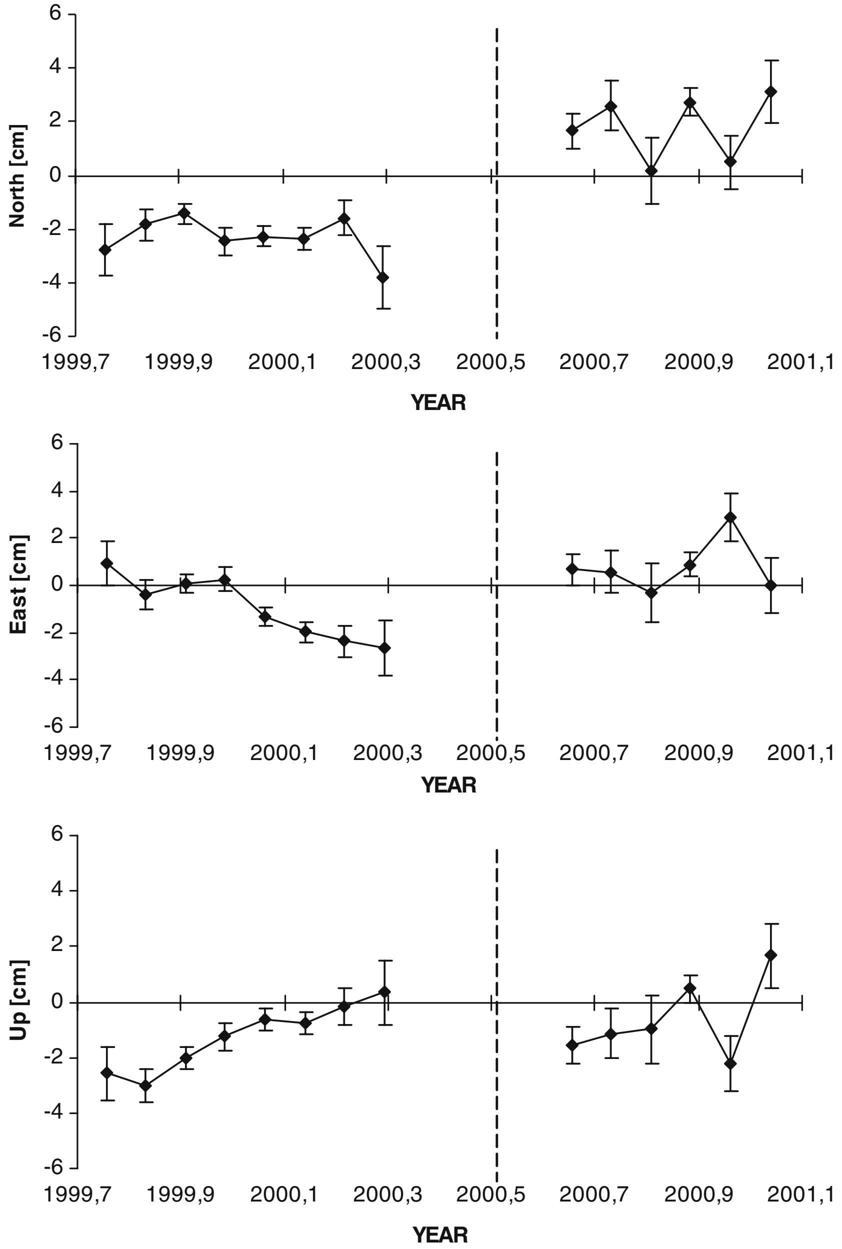

Fig. 4 The topocentric coordinates of the station Tateyama over the period October 1999 – January 2001 with reference to ITRF2000

The 16 fixed stations have been chosen on the basis of the high quality of the coordinates in ITRF2000 system, the good quality and appropriately large quantity of the data. Table 2 shows the list of fixed stations with two important results for each station: the number of normal points and the orbital RMS-of-fit. The calculations were performed using the NASA GEODYN II program (McCarthy et al. 1993). The description of forces, models, constants and estimated parameters is given in Table 3. We acknowledge that these are not exactly the same as current IERS conventions, but the small differences do not have a significant effect on the results presented here.

In comparison to previous authors' solutions, a new gravity field model, EIGEN-GRACE02S (Reigber et al. 2005), instead of EGM96 (Lemoine et al. 1998) was used, which improved the accuracy of station coordinate determination (Schillak and Michałek 2005). Additionally, each station's coordinates were calculated from 4-week arcs with accelerations estimated at 4-day intervals. The summary of the results for each orbital arc of the 16 selected stations is presented in Table 4. The results show a good agreement of all arcs; the mean RMS-of-fit of arcs is 15.4 mm.

The determination of the Key Stone station coordinates was carried out in two steps. At first, the independent orbits

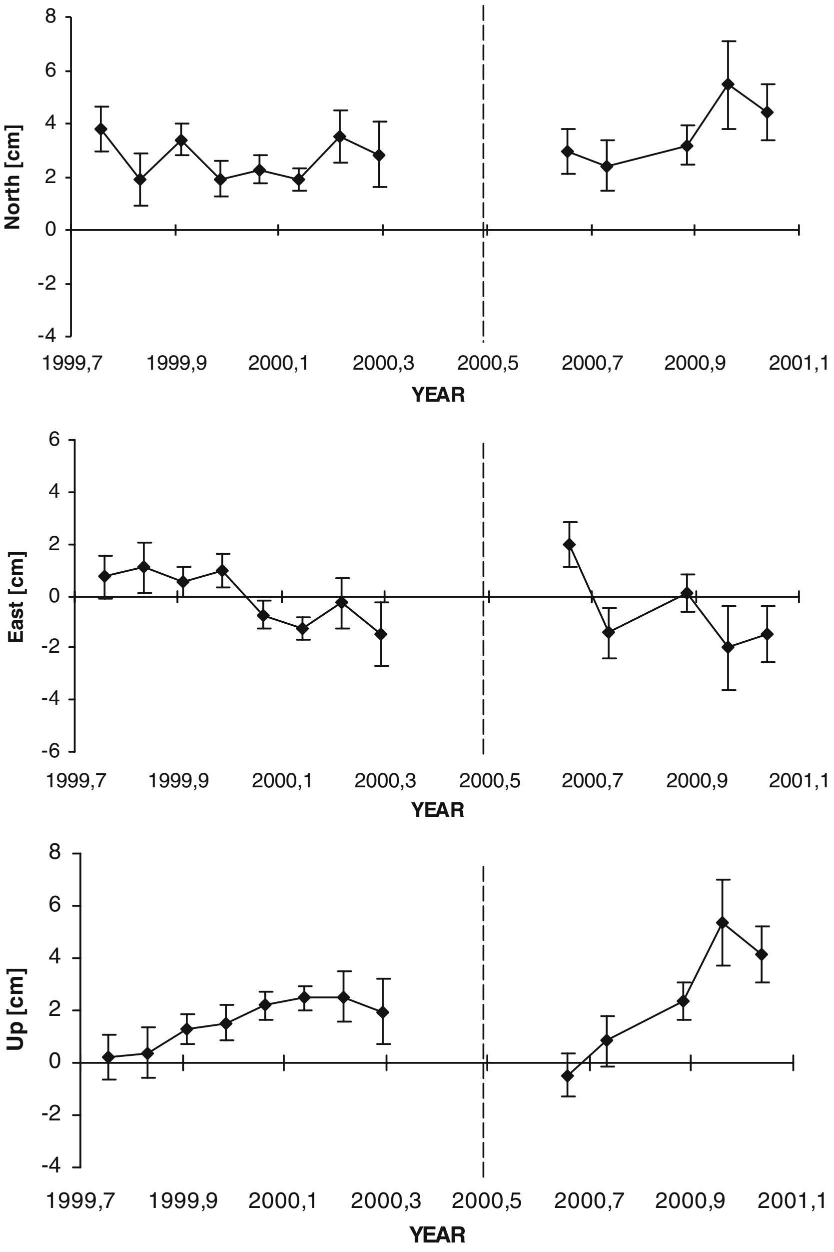

Fig. 5 The topocentric coordinates of the station Kashima over the period October 1999 – January 2001 with reference to ITRF2000

for LAGEOS-1 and LAGEOS-2 were determined. In the second step, the geocentric *X, Y, Z* coordinates of one station were calculated on the basis of the observed minus the calculated (O−C) residuals from both satellites. The computation of each arc was performed with the additional data of either Kashima or Tateyama SLR stations.

4 Results

The results of the baseline length determination between the Kashima and Tateyama SLR stations are presented in Fig. 2 and for VLBI and GPS in Fig. 3 (Ichikawa 2002). The jump in the baseline length due to the crustal movement in June–August 2000 is clearly visible. The coordinates of Tateyama and Kashima after transformation to topocentric coordinates (N, E, U) in comparison to ITRF2000 are presented in Figs. 4 and 5, respectively. A 99% confidence level of coordinates determination is used in Figs. 4 and 5. The SLR station Tateyama has two populations of results in its north-south and east-west components, the first set for the period October 1999–May 2000 and the second set for August 2000–January 2001.

Two statistical tests have been used for the significance control of the differences between these two populations in all components for both stations Tateyama and Kashima:

Table 5 Results of the statistical tests of comparison of population 1 (Oct 1999–May 2000) and population 2 (Aug 2000 – Feb 2001)

	Tateyama			Kashima		
	North (mm)	East (mm)	Up (mm)	North (mm)	East (mm)	Up (mm)
$\bar{X}_1$	−23.2	−9.2	−12.6	26.9	−0.6	15.7
s_1	7.6	13.3	11.8	7.9	10.3	9.0
$\bar{X}_2$	18.0	7.8	−6.2	36.9	−5.7	24.4
s_2	12.3	11.3	14.3	12.2	16.2	23.7
$\bar{X}_1 - \bar{X}_2$	−41.2	−17.0	−6.4	−10.0	5.1	−8.7
F	2.62	1.39	1.47	2.38	2.47	6.93
$F_{0.01}$	7.46	10.45	7.46	7.85	7.85	7.85
t	**7.75**	**2.52**	0.92	1.81	0.70	0.95
$t_{0.05}$	2.18	2.18	2.18	2.20	2.20	2.20
$t_{0.01}$	3.06	3.06	3.06	3.11	3.11	3.11

$\bar{X}_1$, s_1 – mean and standard deviation before crustal deformation (population 1)

$\bar{X}_2$, s_2 – mean and standard deviation after crustal deformation (population 2)

Table 6 The geocentric coordinates of Tateyama and Kashima SLR stations for the epoch 1997.0

	Before crustal deformation		After crustal deformation	
	Tateyama	Kashima	Tateyama	Kashima
N	8	8	6	5
X (mm)	−4,000,964,776.9±2.3	−3,997,483,521.5±2.9	−4,000,964,773. 9±2.9	−3,997,483,519.2±3.4
V_X(mm/year)	10.6	−0.3	10.6	−0.3
Y (mm)	3,375,308,993.3±2.3	3,276,844,222.5±2.7	3,375,308,968.5±3. 6	3,276,844,227.3±3.7
V_Y(mm/year)	−18.2	5.2	−18.2	5.2
Z (mm)	3,632,199,548.8±1.8	3,724,307,326.3±2.0	3,632,199,586.0±3. 0	3,724,307,339.5±3.3
V_Z(mm/year)	−5.6	−11.8	−5.6	−11.8
S (mm)	11.2	9.1	12.7	18.0

N – number of accepted arcs S – coordinates stability $\left[S = \sqrt{\frac{s_{i,N}^2+s_{i,E}^2+s_{i,U}^2}{3}}, i = 1, 2, s_1, s_2 \text{ (Table 5)} \right]$

- The Fisher–Snedecor F test for the verification of the null hypothesis about equality of the populations,
- The Student random variable t test for the verification of the null hypothesis about the equality of means of both populations.

The fulfilment of the first test is necessary for the second one. The results of these tests for the 99% confidence level are presented in Table 5. The first test was fulfilled for Tateyama and Kashima ($F < F_{0.01}$). The second test showed a very significant (99% confidence) difference between the means of both populations for the north component (t Student variable 7.75 significantly exceeded 1%) and a significant (95% confidence) for the east component (t Student variable 2.52 is between 1 and 5%) for the Tateyama station. No difference was detectable for the vertical component.

No statistically significant changes for any component have been observed for Kashima. It means that mostly the displacement of the Tateyama station is responsible for the jump in baseline length between Kashima and Tateyama in summer 2000. The horizontal displacement vector for the Tateyama station is presented in Fig. 6. The difference between both populations is equal to 4.5 cm with an uncertainty of 1.6 cm. The azimuth of this crustal movement is 22° . This result is in good agreement with VLBI (about 5 cm) and GPS (about 5 cm) results presented in Ichikawa (2001, 2002) and Yoshino et al. (2001, 2002). This crustal deformation was caused by a dyke intrusion at about 3 km depth caused by Miyakejima (Izu islands) volcanic eruptions and earthquake 100 km south-west from Tateyama.

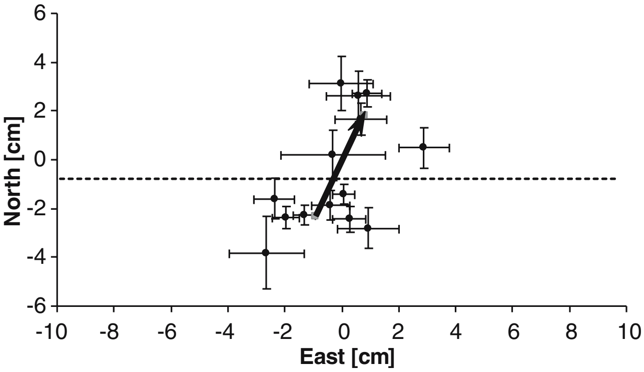

Fig. 6 Displacement of SLR Tateyama station – horizontal plane

The geocentric coordinates of the Tateyama and Kashima SLR stations before and after the displacement were determined for the first day of every arc and than transformed to common epoch 1997.0 (epoch of ITRF2000) by means of velocities of stations from ITRF2000 (Table 6). The coordinates uncertainty was determined from orbital calculations as mean value for each component. The stability of the coordinates of the stations presented in Table 6 is a scatter of all three components in the given period of time.

5 Conclusion

The results presented in this paper show the real Tateyama SLR station displacement determined by the SLR technique. The Tateyama station changed in horizontal position by 4.5 cm in a north-east direction between June and August 2000. The vertical component remained unchanged. The measurements of VLBI and GPS space-geodetic systems in Tateyama and Kashima confirm the magnitude and direction of the SLR observation. The advantage of SLR are absolute results, which means that coordinates for each station are independent of each other, whereas VLBI and GPS are relative techniques and need more stations. The same jump in coordinates detected by three independent space techniques confirm that the displacement of the Tateyama station is the real effect of crustal deformation. The accuracy of the station coordinates' determination on the level of several millimetres is sufficient to detect the real station displacements also by means of SLR.

Acknowledgements The authors wish to thank NASA geodesy group from the Goddard Space Flight Center, Greenbelt, for providing the GEODYN-II program. We are very grateful to Despina Pavlis for her help in explaining the complexity of GEODYN-II to us. We would like to thank all International Laser Ranging Service (ILRS) stations and data centers for their continuous efforts to provide highquality global SLR data for this work. Also, we like to thank Danuta Schillak from the Borowiec Astrogeodynamic Observatory for her assistance in calculations and preparing the data for the program GEODYN-II. This work has been supported by the State Committee for Scientific Research (KBN) under grant No. 9T12E 024 19.

References

Altamimi Z, Sillard P, Boucher C (2002) ITRF2000: A new release of the International Terrestrial Reference Frame for earth sciences applications. J Geophys Res 107 (B10):2214, doi:10.1029/2001JB000561

Boucher C, Altamimi Z, Sillard P, Feissel-Vernier M (2004) The ITRF2000. IERS Technical Note No. 31, BKG, Frankfurt am Main

Ichikawa R (2001) Analysis Center at Communications Research Laboratory. In: Vandenberg NR, Baver KD(eds) IVS 2000 annual report, Kashima, Japan

Ichikawa R (2002) Analysis Center at Communications Research Laboratory. In: Vandenberg NR, Baver KD (eds) IVS 2001 annual report, Ibaraki, Japan

IERS (2001) Bulletin B IERS. http://hpiers.obspm.fr/iers/bul/bulb/

ILRS (2005) LAGEOS-1, 2 http://ilrs.gsfc.nasa. gov/satellite_missions/list_of_satellites/lageos.html

Lemoine FG, Kenyon SC, Factor JK, Trimmer RG, Pavlis NK, Chinn DS, Cox CM, Klosko SM, Luthcke SB, Torrence MH, Wang YM, Williamson RG, Pavlis EC, Rapp RH, Olson TR (1998) The development of the joint NASA GSFC and the National Imagery and Mapping Agency (NIMA) Geopotential Model EGM96. NASA/TP-1998-206861, Goddard Space Flight Center, Greenbelt

Lieske JH, Lederle T, Fricke W, Morando B (1977) Expression for the precession quantities based upon the IAU (1976) system of astronomical constants. Astron Astrophys 58:1–16

Marini JW, Murray CW (1973) Correction of laser range tracking data for atmospheric refraction at elevations above 10 degrees. Preprint X-591-73-351, Goddard Space Flight Center, NASA, Greenbelt

McCarthy DD, Petit G (2004) IERS conventions (2003). IERS technical note no.32, BKG, Frankfurt am Main

McCarthy JJ, Moore D, Luo S, Luthcke SB, Pavlis DE, Rowton S, Tsaousi LS (1993) GEODYN-II. vol. 1–5. Hughes STX Systems Corporation, Greenbelt

Reigber C, Schmidt R, Flechtner F, Koenig R, Meyer U, Neumayer KH, Schwintzer P, Zhu SY (2005) An Earth gravity field model complete to degree and order 150 from GRACE: EIGEN-GRACE02S. J Geodyn 39(1):1–10

Schillak S, Kuźmicz-Cieślak M, Wnuk E (2001) Stability of coordinates of the SLR stations on the basis of LAGEOS-1 and LAGEOS-2 laser ranging in 1999. Artif Satellites 36(3):85–96

Schillak S, Wnuk E (2002) The SLR stations coordinates determined from monthly arcs of LAGEOS-1 and LAGEOS-2 laser ranging in 1999–2001. Adv Space Res 31(8):1935–1940

Schillak S, Michałek P (2005) Monitoring of the International Terrestrial Reference Frame 2000 by satellite laser ranging in 1999–2003. Journées 2005. Earth dynamics and reference systems: five years after the adoption of the IAU 2000 Resolutions, Warsaw, (in press) http://jsr2005.cbk.waw.pl:8080/∼JSR2005/Presentations/Ses1. 2/Schillak.pdf

Seidelmann PK (1982) 1980 IAU nutation: the final report of the IAU Working Group on Nutation. Celest Mech 27:79–106

Standish EM (1990) The observational basis for JPL's DE200, the planetary ephemerides of the astronomical Almanac. Astron Astrophys 233:252–271

Wnuk E, Schillak S, Kuźmicz-Cieślak M (2002) Stability of coordinates of the Borowiec SLR station (7811) on the basis of satellite laser ranging. Adv Space Res 30(2):413–418

Yoshino T, Kunimori H, Katsuo F, Amagai J, Kiuchi H, Otsubo T, Kondo T, Koyama Y, Ichikawa R, Takahashi F (2001) Crustal deformation around Tokyo area observed by the Keystone network in the summer of 2000. In: Huang Cheng, Qian Zhihan (eds) Proceedings of the 4th workshop Asia-Pacific space geodynamics program, Shanghai

Yoshino T, Kunimori H, Katsuo F, Amagai J, Kiuchi H, Otsubo T, Kondo T, Ichikawa R, Takahashi F (2002) Comparison of the baseline between the Keystone sites by different space geodetic techniques. In: Vandenberg NR, Baver KD (eds) IVS 2002 general meeting proceedings, Tsukuba, Japan