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Automatic and Real-time Processing of Tilt Records for Prediction of Explosions at Semeru Volcano, East Java, Indonesia

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Abstract

Eruptive activity of Semeru Volcano, East Java, Indonesia, is characterized by intermittent occurrence of strombolian and vulcanian types in intervals of 15 – 45 minutes. The explosive eruptions accompany explosion earthquakes and tilt changes of ground around the summit crater. Prior to the explosions (16 – 300 s before), gradual upward tilts of the crater side were detected with amounts of 0.3 – 20 nrad. The upward tilts turned to downward after start of explosive eruptions and tilt decreased by 0.7 – 50 nrad for 30 – 70 s. In order to detect the precursory tilt changes in real time automatically by using the tilt record, software coded by Visual Basic was developed. The software receives UDP packet data from A/D converter for the tiltmeter and shows the record on PC display. The software judge stages of volcanic activity (pre-eruption or eruption) based on the tilt change. In a test, 72% of increase in tilts prior to explosions was successfully detected.

Keywords: *Semeru volcano, Explosive eruption, Tilt, Real-time data processing, Prediction*

1. Introduction

Semeru is a strato-volcano located in East Java, Indonesia (8°06' S and 112°55' E; Figure 1). Recent eruptive activity of Semeru is characterized by repetition of explosions at Jonggring Seloko crater, southeast of the summit named Mahameru. The eruptive activity has vulcanian or strombolian style with plume height of <1000 m. Vulcanian eruption destroyed lava dome and tongue formed in the crater. Strombolian eruption was followed by formation of a new lava dome and tongue[1]. The explosive eruptions sometimes generated pyroclastic flows. On February 2, 1994, an explosive eruption generated lava avalanche and pyroclastic flow from the lava dome and tongue which had been formed since 1992. The pyroclastic flow reached the southeastern village about 11.5 km away from the crater and entered Kobokan River killing 7 lives[2]. In December 2002, a big explosion occurred and was followed by lava avalanche from the lava tongue near the summit crater. Pyroclastic flow was generated toward southeast direction as far as 11 km and entered Bang River.

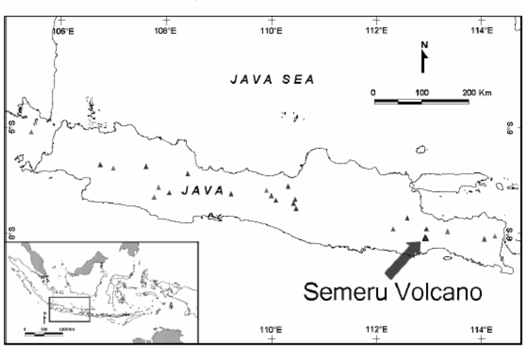


Figure 1. Location of Semeru volcano

Inflation of ground deformation is one of the reliable precursory phenomena prior to explosive eruptions. At Sakurajima Volcano, Japan, inflation tilt of crater-side-up and tensional strain have been observed by water-tube tiltmeters and extensometers in underground tunnel, 5 min to 7 hours before the explosions[3]. Upward tilt of crater side was also detected by shallow borehole tiltmeters associated with explosive events at Asama volcano in 2004[4]. Shallow borehole tiltmeters was also available to detect minor tilt change as observed in a subplinean explosion from Voragine crater at Etna volcano on July 22, 1998[5]. By using the tilt data, real time and automated alert system has been developed by detecting inflation tilt at Sakurajima volcano[6]. At Semeru volcano, Center for Volcanology and Geological Hazard Mitigation (CVGHM), collaborating with Sakurajima Volcano Research Center (SVRC), installed a broadband seismometer and tiltmeters at the summit area. Although the tiltmeter was installed near the ground surface, it successfully recorded minor inflation tilt prior to explosions[7]. However, the data are stored in the data logger at the site and are manually picked up periodically and the inflation could not be detected in real-time.

In this study, we have developed software to receive the tilt data and detect the inflation tilt in real-time automatically, showing the records on the PC display. The characteristic tilt patterns and results of experiment of prediction of the volcanic eruptions by the software are reported.

2. Monitoring system

Activity of Semeru Volcano has been monitored by CVGHM using 5 seismic stations equipped with a short-period (1 Hz) vertical seismometer (Mark Product, L4-C). The seismic signals are transmitted by FM radio telemetry to Gunung Sawur Volcano Observatory (GSVO) and are recorded on analog drum recorders (Kinemetrics, PS-2) and digital data logger (Hakusan, Datamark LS-7000).

Since November 2005, CVGHM cooperating with SVRC have installed a broadband seismometer (STS-2, Streckeisen), a water-tube tiltmeter and a bi-axial tiltmeter (Applied Geomechanics, 701-2) at a station in the summit area, 0.7 km NNE of the Jonggring Seloko crater. Signal of the bi-axial tiltmeter is stored in a data logger (Hakusan Datamark LS-3000) every minute, and the data are manually picked up from GSVO using a wireless modem. The tilt signal is also digitized by a data logger (Hakusan Datamark LS-7000XT) with 24-bit resolution in voltage rage of +/- 10 V at a rate of 1 s, in addition to the signals from the water-tube tiltmeter and the broadband seismometer, sampled at a rate of 1 Hz and 100 Hz, respectively, and the data are transmitted to GSVO via UDP protocol using wireless LAN.

3. Automated and real time processing

3.1 Visualization of digital data

The data loggers Datamark LS-7000 and LS-7000XT send packet data formatted by WIN (Earthquake Research Institute, 1996; http://eoc.eri.u-tokyo.ac.jp/cgi-bin/show_man_index) from Ethernet port with UDP protocol. We developed software “Tilt Monitoring” coded by Microsoft Visual Basic 6.0 in order to receive the WIN packet data from data logger Datamark LS-7000/LS-7000XT via Ethernet and to store the data with WIN format and show trend of the data as graphic on the display of the PC. This software can be applied to several kinds of data, for example, seismic, tilt, infrasonic and others, independently of sampling rate.

3.2 Characteristic of tilt change

This software has also been developed to evaluate volcanic activity based on the tilt records. As shown in Figure 2b, raw tilt record is dominated by ground vibration with period of 6–7 s. The record shows strong upward tilt, which was caused by upward first motion of explosion earthquake (Figure 2a). The following downward tilt was generated by instantaneous increase in atmospheric pressure due to arrival of air-shock by the onset of explosive phenomena. Correspondence of tilt records to the explosion earthquakes and air-shock is confirmed by simultaneous observations of seismic, tilt and infrasonic methods[8]. To reduce ground vibration with period of 6–7 s, moving average method with 60-s time window is applied to the record. By smoothing the raw tilt record, the ground vibration of 6–7 s and abrupt upward and downward motions are reduced. An example of smoothed curve of tilt record is shown in Figure 2b.

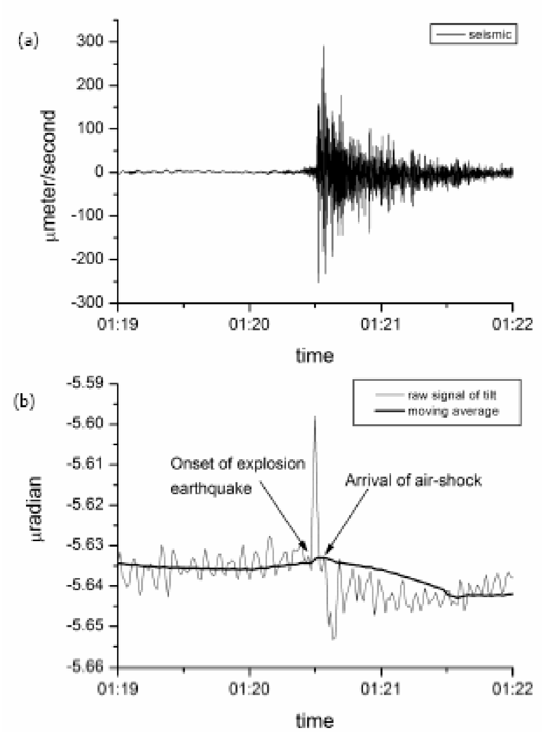


Figure 2. (a) An example of seismogram of explosion earthquake observed by the broadband seismometer at 01:20 on March 20, 2007. (b) Tilt record associated with the explosive eruption. Raw signal is shown by gray curve. Curve of the radial tilt record smoothed by moving average method with 60-seconds time window is shown by bold line.

Figure 3 shows enlargement of s the tilt record after moving average in 60-s time window. The smoothed tilt record typically can be divided into 5 stages. 0: Nominal change. Tilt change was within a range +/-0.001 μrad. In this stage, no eruptions are observed. I: Gradual increase in tilt. Gradual upward tilt of the crater side was detected before explosive eruption occurred, and the rate of the upward tilting was nearly constant. II: Rapid increase in tilt. The rapid increase in tilt is caused by abrupt upward motion due to upward P-wave first motion of the explosion earthquake as shown in Figure 2b. Affect of upward motion of explosion earthquake still remained in the enlarged record smoothed by moving average in 60-s time window. The stage II is interpreted to be the beginning of explosive eruption. For prediction of volcanic eruption, the stage II is not essential. III: Rapid decrease in tilt. Downward tilt of the crater side was observed. Rapid decrease in tilt at the beginning of stage III is caused by downward motion due to arrival of compression infrasonic wave as shown in Figure 2. Ejection of volcanic ash and gas induced the following downward tilt. The stage III corresponds to eruption. IV: Post increase in tilt. Upward tilt of the crater side continued till reaching a stability point and the stage returned to the stage 0. Among the 5 stages, stage I is a precursor of the explosions. The eruptions at Semeru volcano can be automatically predicted by detecting the increase in tilt in stage I in real-time. Here, stages of volcanic activity 0, I and III are defined as “dormant”, “pre-eruption” and “eruption” from tilt record.

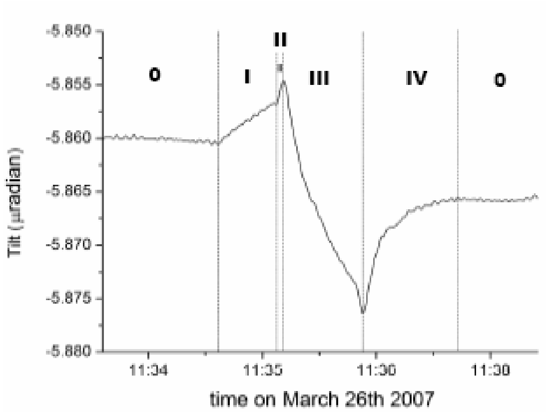


Figure 3. Tilt change pattern after moving average. The pattern is composed of 5 stages; 0: no remarkable change, I: increase in tilt, II: rapid increase in tilt, III: decrease in tilt, VI: post-increase in tilt as transition stage toward stage 0. Explosive eruption started in stage II.

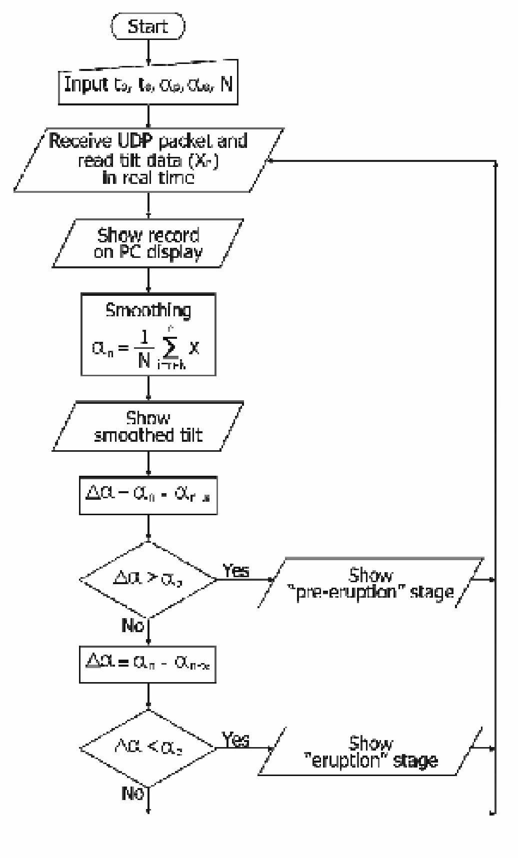


Figure 4. Flowchart of the software

3.3 Data processing

Procedure of data processing for tilt record to judge volcanic activity is shown by flow chart (Figure 4).

1) Receive UDP packet with WIN format mixture of seismic and tilt data and extract tilt data X_n at time n immediately after receiving the packet.
2) Tilt data is plotted as graphic on the screen of PC.
3) Calculate running average of tilt α_n from the sampling data X_{n-N} to X_n for N seconds.
4) Plot running average of tilt as smoothed tilt record on PC.
5) Calculate change of tilt $\Delta\alpha$ by subtracting the averaged tilt (α_{n-tp}) t_p seconds before from the current one α_n.
6) In case that tilt change $\Delta\alpha$ during t_p seconds is larger than a threshold level α_p, the software judges stage as “pre-eruption”.
7) Calculate change of tilt $\Delta\alpha$ by subtracting the averaged tilt (α_{n-te}) t_e seconds before from the current one α_n .
8) If tilt change $\Delta\alpha$ during t_e seconds is less than a threshold level α_e, the software would judge stage as “eruption”.
9) When tilt change $\Delta\alpha$ does not satisfy the conditions 6) and 8), the software declares “dormant” stage.

3.4 Parameter setting

Parameters of time interval t_p, t_e for calculation of tilt change and threshold levels α_p, α_e are determined manually by try-and-error method. To determine the parameters, tilt records during the period from March 19 to 31, 2007 were analyzed. During the period, 527 explosive eruptions occurred. Amounts of increasing tilt prior to explosive eruptions range from 0.3 to 20.3 nrad, and the increasing tilt continued for 16 to 300 s, as shown in Figure 5a. Rate of increasing tilt ranged from 0.0066 to 0.1438 nrad/s. Moving-average method can reduce background vibration of period of 6-7 s effectively. However, the noise sometimes still remained and peak to peak amplitude attained 0.5 nrad (Figure 6) and is not neglected compared with change of tilt before eruptions. The lowest rate of increasing tilt was 0.0066 nrad/s, and it would take 75 s to overcome the amplitude of noise. As the most sudden case, eruption started 16 s after appearance of inflation (explosion at 7:30 on March 22).

The amounts of decreasing tilt after eruption were -0.7 to -49.2 nrad and their duration time ranged 30 to 71 s. The durations of decreasing tilts are shorter than those of increasing tilts. The decreasing rate ranged from -0.025 to -0.833 nrad/s (Figure 5b).

Therefore, it is thought that t_p value around 75 s and α_p around 1.33 nrad for pre-eruption stage, while t_e value around 20 s and α_e around -1.66 nrad for eruption stage are appropriate for the software processing tilt records at Semeru volcano.

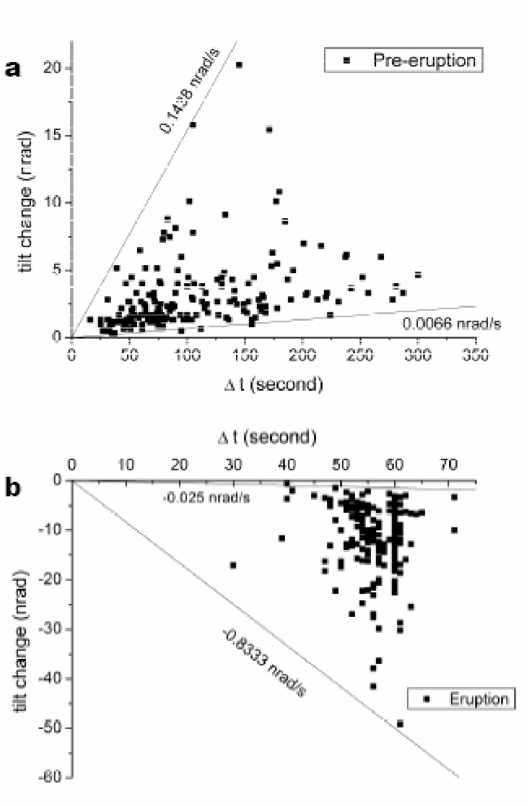


Figure 5. Relationship between amounts of tilt change and duration of pre-eruption stage of increase in tilt (a) and eruption stage of decrease in tilt (b)

3.5 Result of Experiment

Judgment of class of volcanic activity by the software is tested by using tilt records during the period from March 19 to 31, 2007. Accuracy of judgment by the software depends on the parameters. Here, 3 sets of the parameters α_p and t_p as shown in Table 1 were used for the test. As the decreasing tilt rate is larger than increasing tilt rate, the parameters α_e and t_e are fixed at -1.66 nrad and 8 s for the 3 sets. Figure 7a shows an example of judgment result which was successfully predicted as "pre-eruption" before the explosive eruption and display "eruption" after the beginning of the eruption. In the case 1, 62% of explosions are predicted by the logic before start of explosions. To increase the prediction rate, the threshold level α_p was decreased to 0.66 nrad in the case 2. The prediction rate was improved to 70%. Furthermore, in the case 3, time interval for tilt change t_p was shortened to 40 s. The prediction rate increased up to 72%.

Table 1. Combination of tilt change and duration parameters

Case	Parameters α_p (nrad)	t_p (s)	Actual explosions	Result number: Explosions predicted correctly	Non-eruptive event alarmed by " pre-eruption"
1	1.33	60	527	329 (62%)	94
2	0.66	60		373 (70%)	132
3	0.66	40		383 (72%)	159

α_e = -1.66 nrad, t_e = 8 s

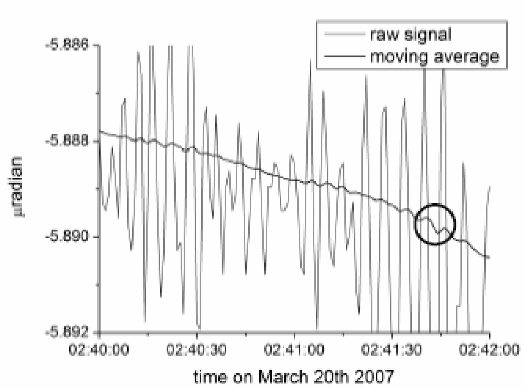
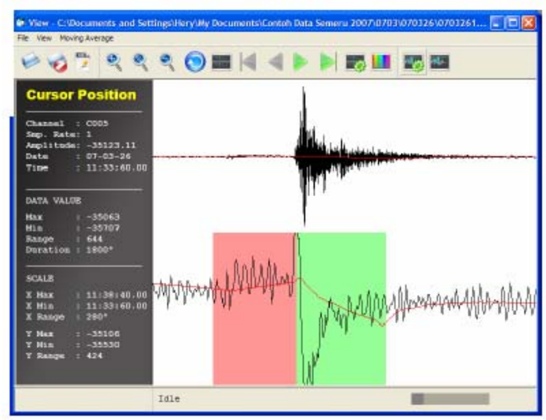
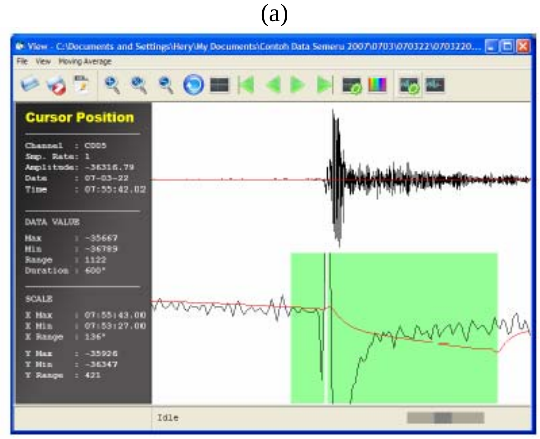


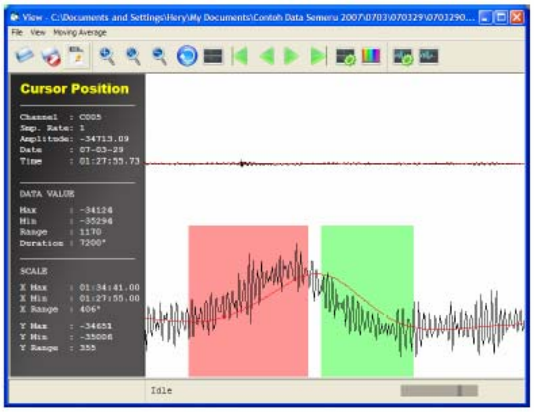
Figure 6. Short-period noise remaining on the tilt record smoothed by moving average method in 60-seconds time window. Circle indicates a part of larger amplitude of short-period noise.



(a)



(b)



(c)

Figure 7. An example of result of test for judgment of stage of eruptive activity. Red, green and white backgrounds indicate "pre-eruption", "eruption" and "dormant" stages, respectively. Upper trace shows seismogram and the lower is tilt record. (a) In this case, 50 seconds before the start of the eruption, the software successfully judges "pre-eruption" stage and "eruption" stage at the onset of the explosion earthquake. (b) The software does not issue "pre-eruption" stage before onset of the explosion earthquake due to no increasing tilt detected before the eruption. (c) In spite of no eruptive activity, the software judges "pre-eruption" and "eruption" stages for the signal at 01:27 on March 29th 2007.

Some records of tilt did not show inflation. In this case, the software did not indicate "pre-eruption" before the occurrence of the explosion as shown in Figure 7b. On the other hand, increase and decrease tilt patterns were sometimes recorded without explosive eruptions as shown in Figure 7c. The pattern is similar to tilt changes before and after explosions. Therefore, the software judges the pattern as "pre-eruption". Large long-period noise of 6-7 s as shown in Figure 6 is also identified as "pre-eruption". The ratio of detection of the non-eruptive events with inflation tilt increased when threshold level α_p or time interval of t_p was decreased (Cases 2 and 3; Table 1).

4. Discussions and conclusion

Tilt change associated with explosive eruption at Semeru Volcano shows characteristic pattern and is divided into 5 stages:

1) Nominal change of tilt between explosive eruptions.
2) Upward tilts of crater side gradually increased before explosion. The tilts increased by 0.3 - 20.3 nrad for 16 - 300 s. The tilt changes show inflation of the ground around the crater.
3) The upward tilts rapidly increased by 0.3 - 6 nrad in 1 - 10 s. The upward tilts show the beginning of explosions and were caused by upward displacement of the first motions of explosion earthquakes.
4) The rapid increases in upward tilt were followed by rapid downward tilt and the tilt change amounted 0.7 - 49.2 nrad for 30 - 71 s. The rapid downward tilts correspond to ejection of pyroclastic material from the vent.
5) After the eruption ceased, post increase in tilt continued till attaining at a stability point of the tilt.

The characteristic pattern makes it possible to predict explosive eruption by PC automatically in real time. The software to judge the stages of volcanic activity was developed, based on the tilt records in order to predict volcanic explosions at Semeru volcano. Judgment test was done using data during the period from 19 to 31 March in 2007 and it was shown that 72% of the explosive eruptions could be predicted. This software can predict more precursors before eruptions by adjusting parameters of threshold of tilt change α_p and time interval t_p. However, increase in number of precursor of eruption lead increase in number of incorrect judgment of prediction. Much more events of tilt change, which were not followed by eruptions, were identified as precursors of eruptions (Case 3 in Table 1). Incorrect prediction was particularly caused by noise. Short-period noise due to ground vibration could be reduced by installing the tilt sensor at the deeper part (>2 m). Long-period noise due to temperature change may cause incorrect prediction. In Indonesia, daily temperature change is almost same through a year. To improve reliability of this software, temperature effect should be taken into account of the calculation.

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References

1. K. Kusumadinata, Data Dasar Gunungapi Indonesia, Direktorat Vulkanologi, 1979 (in Indonesia).
2. I.N., Dana, Panduan aktivitas gunung Semeru, Direktorat Vulkanologi, 1995 (in Indonesia).
3. K. Ishihara, Pressure sources and induced ground deformation associated with explosive eruptions at an andesitic volcano: Sakurajima volcano, Japan, in: Ryan, M. (Ed.), Magma Transport and Storage. John Wileys & Sons, Chichester, 335-356, 1990.

4. M., Churei, and H. Katayama, Ground tilt change associated with the 2004 eruption at Asamayama volcano, Japan, Bull. Volcanol. Soc. Japan, **50**, 91-101, 2006 (in Japanese with English abstract).
5. A., Bonacarso, Explosive activity at Mt. Etna summit craters and source modeling by using high-precision continuous tilt, Jour. Volcanol. Geotherm. Res., **158**, 221–234, 2006.
6. K. Kamo, and K. Ishihara, A preliminary experiment on automated judgment of the stages of eruptive activity using tiltmeter records at Sakurajima, Japan, in: Latter, J. H. (Ed.), IAVCEI Proceedings in Volcanology 1, Volcanic Hazards, Springer-Verlag, 585-598, 1989.
7. K. Nishi, et al., Micro-tilt changes preceding summit explosions at Semeru volcano, Indonesia, Earth Planets Space, **59**, 151-156, 2007.
8. M. Iguchi, *et al.*, Mechanism of explosive eruption revealed by geophysical observations at the Sakurajima, Suwanosejima and Semeru volcanoes, Jour. Volcanol. Geotherm. Res., 2008 (in press)