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Paper:

Feasibility Study on a Multi-Channeled Seismometer System with Phase-Shifted Optical Interferometry for Volcanological Observations

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A new Phase-Shifted Optical Interferometry seismometer system was tested in terms of its feasibility for multi-channeled volcanological observations in two volcanos in Japan. The system is capable of both sensing ground motions and transferring its signals through optical means. The prototype of this system comprises three optical-wired stations and optical components, and was deployed in Sakurajima Volcano in 2016 and in Asama Volcano in 2017. The system successfully operated for 134 days in total and provided seismograms that are in good agreement with those obtained using conventional systems. Several obstacles for putting this system to practical use that need to be solved were found through tests. Their solutions will be explored in subsequent research.

Keywords: volcano observation device, seismometer, optical engineering, early warning system

1. Introduction

1.1. Demand from Volcanology and Disaster Mitigations

The objective of this work was to deploy and operate an existing prototype of a seismometer system with Phase-Shifted Optical Interferometry (hereafter referred to as the "optical sensor system") in volcanic areas for a certain period in order to verify the system's compatibility with previous observation systems and its resistance to the environmental conditions peculiar to volcanic zone and to determine any problems occurring during continuous operation. The final objective of this study is to extend the seismometer system with Phase-Shifted Optical Interferometry to a multi-point (multi-channeled) seismic array system, establish a practical seismometer system suitable for volcano observations for the next generation, and provide it on the site for volcanic studies and volcanic disaster prevention.

In volcano observations, seismic waves coming from the underground of the volcano as volcanic earthquakes and volcanic tremors are a precious source of information to ascertain what is occurring or will occur beneath the volcano. Vibration sensors, i.e., seismometers, which measure such seismic waves, are located under the severest conditions during volcano observations and therefore must endure corrosive gases, such as hydrogen sulfide and sulfur dioxide, lightning, high temperatures, etc. Under such conditions, previous seismometer systems, which are based on the electric conduction of metals, would frequently deteriorate rapidly and sustain damage owing to fires caused by lightning surges.

Optical sensor systems can detect ground motion caused by seismic waves via the phase difference of laser light and transmit this phase difference directly as an optical signal through an optical fiber (**Fig. 1(a)**). Because optical sensor systems are not equipped with electric circuitry at its sensor and channel parts, it is free from electrical problems such as contact failure and electric breakdowns, which were common in previous seismometer systems based on electric signals. Accordingly, the sensor of the proposed system would be able to endure electric shocks, such as lightning surges, temperatures as high as circa 200°C, and corrosive gases, such as hydrogen sulfide and sulfur dioxide.

The advantages of optical sensor systems, namely lightning resistance, heat resistance, and anti-corrosiveness, are suitable for the long-term monitoring of volcanos. If the system was put to practical use, it would be able to detect any intensification of volcanic activity more precisely and as early as possible.

Furthermore, if an optical sensor system were expanded to become multi-channeled to carry out seismic array observations for a long period, accurate information on volcanic activity could be surely obtained more than ever before. Recently, studies have been conducted on employing not only the traditional deployment of seismometers, but also the high-density deployment of multiple seismic stations (seismometer array) to better understand volcanic activities. In Japan, researchers observed

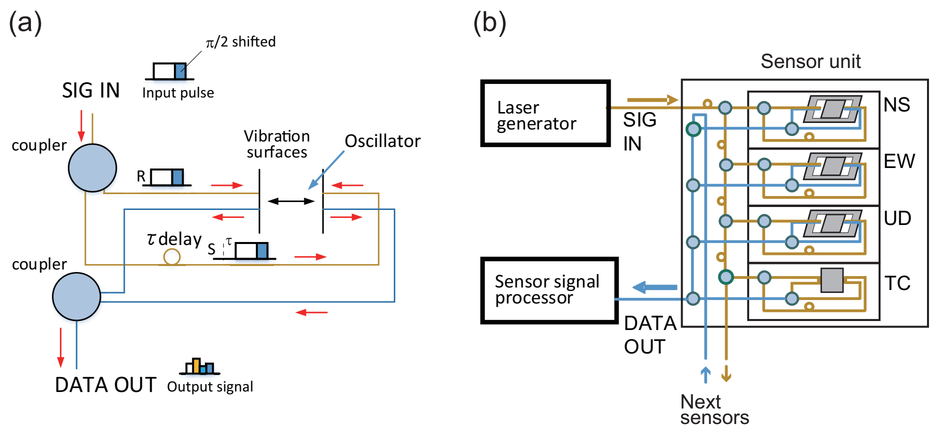

Fig. 1. Phase-Shifted Optical Interferometry seismometer system. (a) Principle of operation of a sensor. (b) JOGMEC PHASE1 prototype system. TC is a compensation channel.

the volcanic tremors triggered by the eruption of Shinmoedake at Kirishima Volcanos on Feb. 2, 2011 using two seismometer arrays and tracked the migrations of the seismic source from immediately before the eruption until the end of it by analyzing the instantaneous changes in the back-azimuth [1]. Their work has contributed to the study of the process of volcanic eruption because they traced the rupture front accompanied by the volcanic eruption. Additionally, in another work, researchers observed seismic waves from a controlled source using a high-density seismic array composed of 250 observation stations to find clues about the location and depth of the magma chamber beneath Sakurajima Volcano and the changes in the internal physical properties of the magma chamber during volcanic activity [2]. Moreover, the iMUSH project for Mount St. Helens is now in progress overseas [3]. The aim of this project is to observe natural and artificial earthquakes by deploying seismometer arrays with more than 900 observation stations around Mount St. Helens and to determine the detailed structure from the Mohorovicic discontinuity beneath Mount St. Helens to the upper mantle.

1.2. State of the Proposed System in Optical Engineering and the History of its Development

There are several methods to measure acceleration using an optical fiber. Among them, methods that use interferometry, fiber Bragg gratings (FBGs), and distributed acoustic sensing (DAS) are often adopted as methods fit in terms of frequency and resolution to observe ground motions and volcanic tremors.

Interferometry is a method by which an optical fiber is used as a path for the transmission of laser light to observe the displacement of an oscillator using single-mode laser light. This method has the merit of having high sensitivity. Accordingly, it is possible to design a seismometer with high sensitivity using interferometry [4–6]. In the optical sensor system, Phase-Shifted Optical Interferometry with an enhanced dynamic range [7] was adopted.

FBG are diffraction gratings within fibers used to detect the expansion and contraction of the space of the gratings using oscillations. Methods using FBGs mainly consist in exploiting the measurement principle of contact-type hydrophones, having wound optical fibers around the seismometer (such as moving coil-type fibers) in order to convert the oscillation of the weight into the expansion and contraction of the optical fiber so as to detect the oscillation [8, 9]. Other methods involve using the optical fiber directly as an accelerometer [10]. With the exception of one previous study [11], it is usually necessary for to employ FGBs with different central reflection wavelengths depending on number of multipoints. Additionally, FGB-based methods have a demerit in that wide-bandwidth light sources and frequency-sweep light sources are necessary to cover all the wavelengths of interest.

DAS is a method for measuring the phenomenon of backscattered light caused by Rayleigh scattering, which occurs when inputting laser light into an optical fiber and changes depending on the temperature and the displacement of fiber where scattering occurs [12, 13]. However, in this method, the dynamic range is as low as approximately 60 dB and the signal-to-noise ratio is not sufficient. Therefore, data stacking is needed and is often generated using an controlled seismic source, such as Vibroseis®, for surveying the ground.

2. Principle of the System

The optical sensor system used in our experimental observations is a prototype that was developed under the Technical Solutions Projects during the years 2014–2015 by an independent administrative agency, namely Japan Oil, Gas and Metals National Corporation (JOGMEC). This prototype will hereafter be referred to as the JOGMEC PHASE1 system. The prototype adopts the Phase-Shifted Optical Interferometry approach described in a previous study [7].

An outline of the principles of Phase-Shifted Optical

Fig. 2. Three component sensor units.

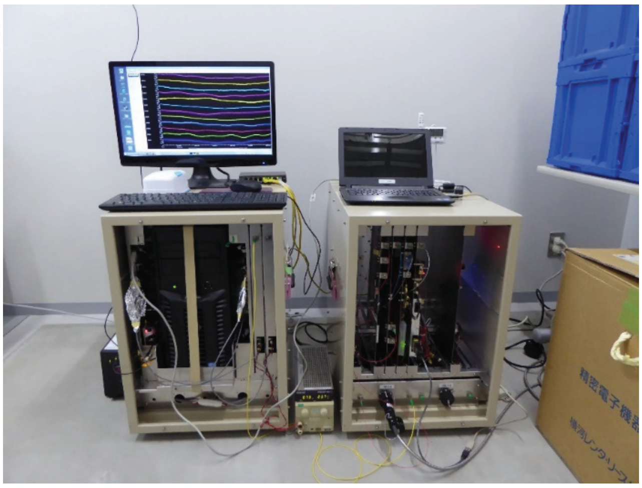

Fig. 3. Laser generator (right) and sensor signal processor with a built-in server (left).

Interferometry is presented below, based on **Fig. 1(a)**. The light pulse input in SIG IN is divided into pulse R and pulse S by means of a coupler. Pulse R is irradiated directly into the oscillator, whereas pulse S is delayed by time τ and irradiated onto the surface opposite to the oscillator. Then, pulse R and pulse S are reflected from the surface of the oscillator and are received by the optical fiber again. By letting both pulses interfere in the coupler, a signal containing the optical phase difference corresponding to the displacement of the oscillator comes out at DATA OUT.

According to a previous study [7], the following two points are noted as the main advantages of Phase-Shifted Optical Interferometry. 1) By delaying either the measurement light or the reference light appropriately and letting both lights interfere, not only the interference light but also the input light can be observed in order to remove effects caused by environmental changes. 2) By shifting the phase of a part of the input light pulse by $\pi/2$ and letting it interfere, it is possible to measure displacements exceeding $1/2$ of the wavelength of the laser light in order to extend the dynamic range.

In the JOGMEC PHASE1 system used in this study, pulsed light is used as an input. An appropriate delay is applied in each sensor and multiple sensors are connected in cascade using a set of optical fibers (**Fig. 1(b)**). The JOGMEC PHASE1 system was constructed so that three sets of three-component sensor unit (A, B, C; **Fig. 2**) are connected in series with a laser generator and a sensor signal processor (**Fig. 3**). The specifications of the JOGMEC PHASE1 system are shown in **Table 1**. In the laser generator, a laser oscillator, an intensity modulator for generating light pulses, and a phase modulator for generating phase shifts of $\pi/2$ are built-in, whereas the sensor signal processor has a built-in general-purpose server to compute light signal. Moreover, in each three component sensor unit comprises four elements, two horizontal movement elements (NS and EW) and the single vertical movement element (UD), and a reference element (TC). TC is a fixed reflector channel to detect noise caused by certain phenomena, such as temperature changes, and compensate it.

Table 1. Specifications of the JOGMEC PHASE1 prototype system.

	Sensor	Transceiver
Components	3 Three-dimensional motion units (A, B, C)	A Laser generator and a Sensor Signal Processor
Frequency range	0.1–50 Hz	
Dynamic range	120 dB +	
Natural frequency	52.2 Hz	
Damping factor	0.6	
Size	20 cm × 20 cm × 20 cm	60 cm × 43 cm × 65 cm each
Weight	7 kg	40 kg each
Sampling frequencies	200 Hz and 1 kHz	
Sensing time	200 ns	
Fiber length	Cascaded. 150 m to sensor A, 30 m to sensor B, 30 m to sensor C	
Power consumption	0	500 W total

3. Field Test and Results

In the 2016 and 2017 fiscal years, volcano observations were conducted using the optical sensor system on a trial basis. In the 2016 fiscal year, three sensors were deployed in an almost linear arrangement in the Komen tunnel (KMT) of the Sakurajima Volcano Research Center, Disaster Prevention Research Institute, Kyoto University to operate the prototype of the optical sensor system for observing the actual volcano and accumulate know-how on the practical implementation. The observation station is generally referred to as KMTO.

In the 2017 fiscal year, three sensors were deployed on the surface under the premises of the Asama Volcano Observatory (AVO), Earthquake Research Institute, The University of Tokyo that they are arranged as a triangle. Observations were carried out to solve the problem of repeated missing observations, which was found in the observations of the previous fiscal year, and to verify the lightning resistance and long-term operation of the system. The observation station is generally referred to as AVO-OPT.

In both cases, the laser generator and the sensor signal processor were installed to convert the optical signal into ordinary records of earthquake in a building. Each of three component sensor units was oriented the V component to the vertical direction, the L component to the crater, and the T component to perpendicular direction to the L component.

3.1. Tunnel Operation in Sakurajima in 2016

The system was installed in the KMT in the active Sakurajima Volcano during the period from Nov. 13 to Dec. 8, 2016 to obtain data (**Fig. 4**). The observation points were named KMTOA2, KMTOB2, and KMTOC2 in order from the entrance of the tunnel and will hereafter be referred to as the stations A, B, and C.

In the continuous seismograms obtained for 26 days, 70 natural seismic events and 14 artificial ones were recorded. By also referring to the hypocenter catalog of the Meteorological Agency [14], the catalog of the USGS, and the V-net data around Sakurajima of the Meteorological Agency, the volcanic earthquakes occurring at Sakurajima Volcano were distinguished among the recorded natural seismic events and were classified in reference to [15–17].

Although the operation of the system was mostly smooth, observations over very short times were missed several times. Such missing observations were triggered by jumps in the bias voltage of the intensity modulator. Because the intensity modulator is an important part that generates the light pulses for the sensors, its bias voltage is automatically regulated to keep the On/Off ratio of the light pulses normal. When the bias voltage exceeded the device's tolerance, observation were missed.

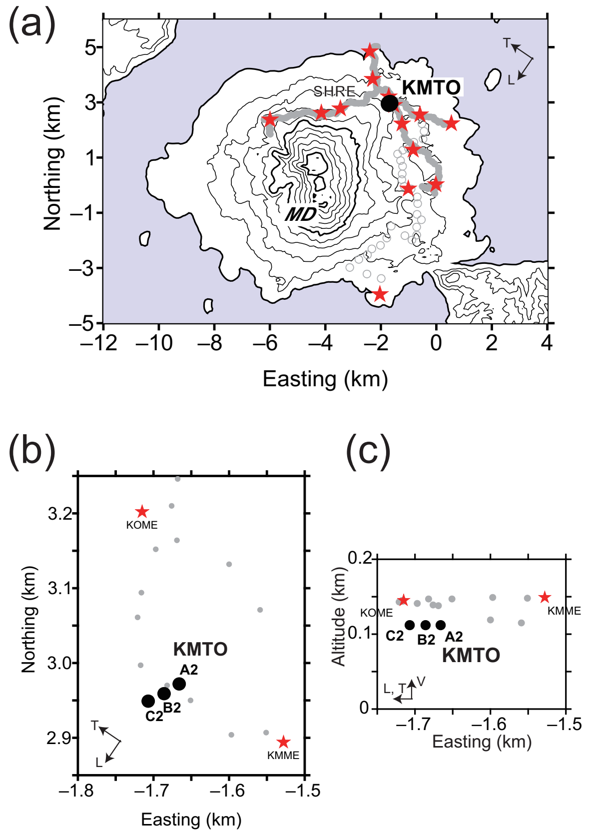

Fig. 4. Operation in Sakurajima Volcano, 2016. (a) KMTO and shot points, (b) close-up around KMTO, (c) vertical section. Stars represent shot points and gray dots represent temporary stations for the seismic experiment. The MD label marks Minamidake, which has an active crater.

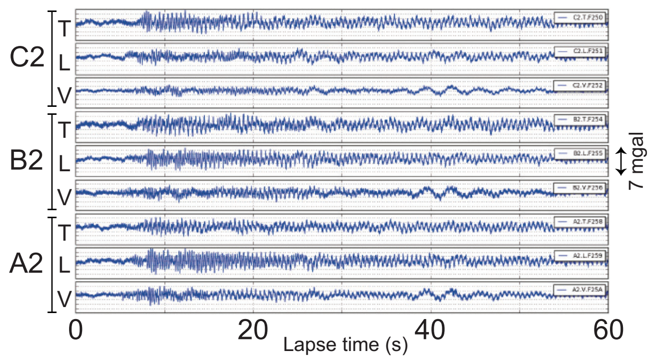

Fig. 5. Seismograms of the C-type volcanic earthquake recorded with the optical system on 11/22 03:36. All seismograms are in the same scale.

3.1.1. C-Type Volcanic Earthquake

At approximately 1:47 on Nov. 19 and at approximately 3:36 on Nov. 22, characteristic seismic events (C-type volcanic earthquake events; [16]) with a long duration and a predominant frequency component of approximately 2 Hz were recorded. Although C-type volcanic earthquake events do not frequently occur compared with other more general types, this type of events is not few. The C-type volcanic earthquake event that occurred at approximately 3:36 on Nov. 22 (**Fig. 5**) is described below. In this event, high frequency was predominant for 10 s from the first arrival; then, frequency component at approximately 2 Hz became predominant and the quake continued for more than 180 s. **Fig. 5** shows the seismograms recorded for over a period of approximately one minute from the initial duration of the event.

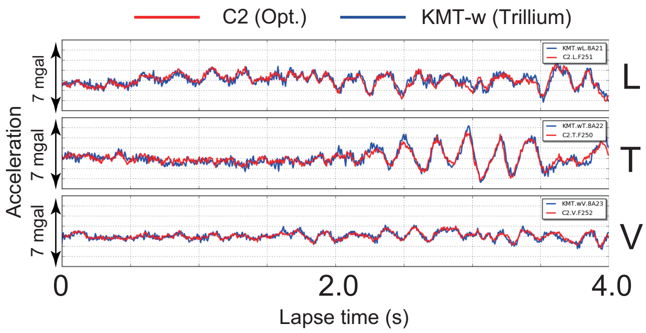

Fig. 6. Close-up of the first break of the C-type event of **Fig. 5**.

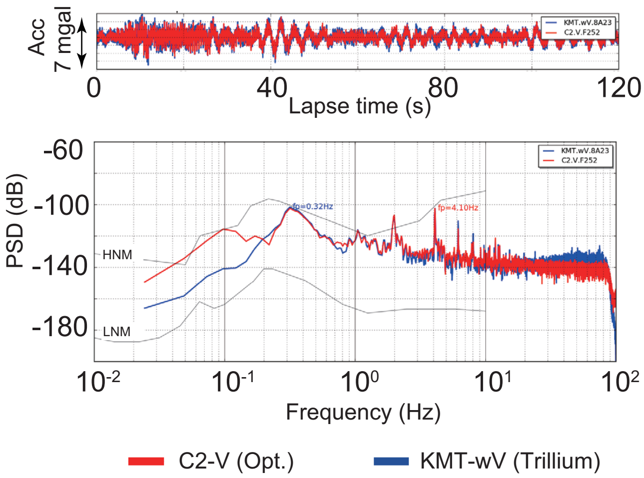

Fig. 7. Frequency analyses of the optical system and the Trillium system. The 0 dB point of the PSD is 1 $(m/s^2)^2$/Hz.

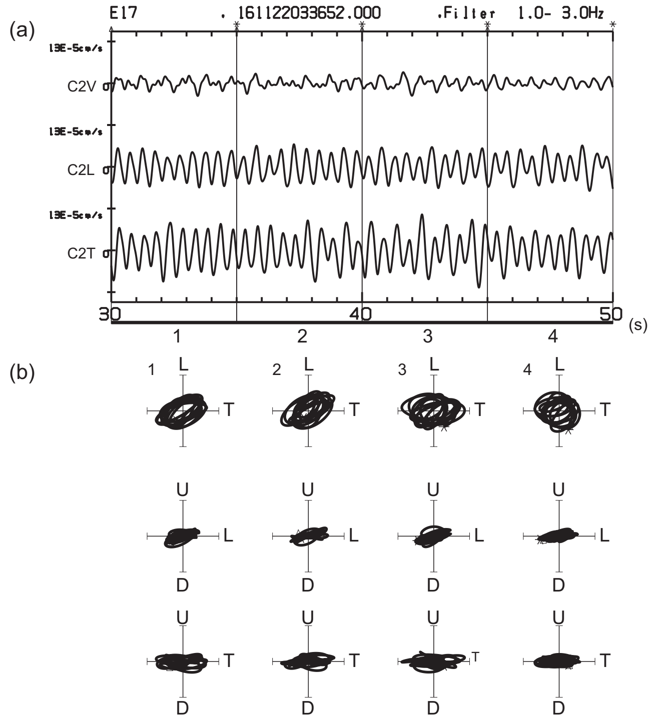

Fig. 8. Particle motions at KMTOC2. (a) Seismogram, (b) particle motions.

Figure 6 shows the acceleration seismograms at the C observation station recorded with the optical sensor and the derivative seismograms measured using an existing broadband seismometer, Trillium240 (manufactured by Nanometrics Inc.; KMT observation station), around the onset of the seismic event shown in **Fig. 5**. In both cases, the seismograms were not instrumentally corrected.

Figure 7 shows the spectra of the event shown in **Fig. 6**. Sharp peaks can be seen at 2 Hz, 4 Hz, 6 Hz, and 8 Hz. In the band below 0.2 Hz, the spectrum of the optical sensor and that of the Trillium240 do not match, which seems to be caused by the system noise of the optical sensor.

Particle motion and apparent velocity are analyzed below. The output of the optical sensor system is expressed as an acceleration seismogram. However, the polarity of this acceleration seismogram is inverted, and the acceleration seismogram was converted to a velocity seismogram via time integration to obtain positive polarity in a uniform manner for each ground motion in the V, L, and T directions.

First, the particle motions during the period from the onset to 30 s, where the component at approximately 2 Hz was predominant, were surveyed. **Fig. 8** shows the particle motions at the station C, as well as the converted velocity seismograms in the corresponding interval. The acceleration seismographs were converted into velocity seismographs and filtered using a band-pass filter of 1–3 Hz to obtain the particle motions. At all the observation stations, particle motions in which the horizontal component makes a circular motion (as shown in **Fig. 8**) were commonly recognized. Such particle motions have also been reported in previous works [16, 18].

These previous works indicate that the later part of C-type volcanic earthquake events exhibit surface wave nature [16] and, by employing a borehole seismometer in addition to the surface seismometer, that such ground motion has a Rayleigh-wave nature [18]. However, it is remarkable in this observation that the surface of the ground motion is not parallel to the direction from the crater but nearly vertical to that direction. Supposing that the characteristic seismograms of simple harmonic motions are Rayleigh waves, this indicates that the motion should come from the other direction rather than from that of the crater. The back-azimuth of seismic wave also exhibits a similar tendency. Accordingly, this is thought to be caused by the structure of the shallow part of the eastern part of Sakurajima.

Furthermore, the evolution of the back-azimuth of the arrival in the interval shown in **Fig. 8** was analyzed. In **Fig. 9**, the three observation stations were treated as a linear array and the apparent velocity along the direction from the inner part to the entrance of the tunnel and the semblance value are plotted against time. A positive apparent velocity indicates a propagation in the direction from the entrance to the inner part of the tunnel, namely

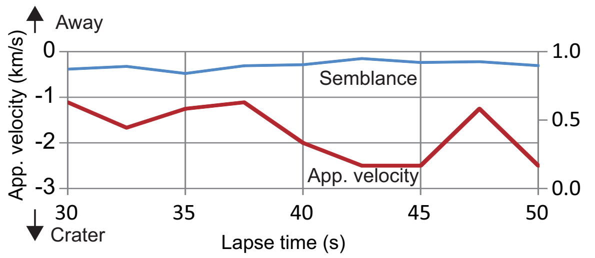

Fig. 9. Sequential variation of apparent velocity and semblance at KMTO.

the direction approaching the crater. Contrarily, a negative apparent velocity indicates a propagation in the direction from the inner part to the entrance of the tunnel, namely the direction moving away from the crater. Semblance is a measure of coherence normalized by energy [19]. It takes a value between 0 and 1; the closer this value is to 1, the higher the coherence within the time window of the object analyzed.

It is shown in **Fig. 9** that, in all the time windows, the apparent velocity takes negative values ranging from 1.1 to 2.5 km/s. That is to say, the wave motion corresponding to the later part of C-type volcanic earthquake event had a wave number component moving in the direction toward crater.

3.1.2. Artificial Seismic Sources

On Dec. 8, 2016, detonations were carried out at 14 locations in the island of Sakurajima as a part of the Repeated Seismic Experiments (**Fig. 4(a)**). From the observations made using the optical sensor system, the seismograms caused by the detonations at the 14 locations were obtained. Among these seismograms, some were converted to velocity after the detonation at the shot point SHRE located 1.8 km west of KMTO and are shown in the upper parts of **Figs. 10(a)–(d)**.

In addition, the particle motions for the observed seismograms are shown in **Figs. 10(a)–(c)**, and the results of the analysis of the back-azimuth are shown in **Fig. 10(d)**. In **Fig. 10**, **(a)** shows the particle motions along with the corresponding seismograms at the station A, whereas **(b)** shows those at the station B and **(c)** those at the station C. Finally, **(d)** shows the transition of the back-azimuth and the apparent velocity estimated from the vertical component along with the corresponding seismograms.

In **Fig. 10**, the seismic wave arriving from west of the KMTO can be observed, but the direction of the predominant motion at the onset of the event (time window III) was generally toward the source. However, the behavior of the motion at the later part differed depending on the arrival time. Similarly, the distribution of apparent velocity shown in **Fig. 10(d)** shows the different patterns depending on the arrival time. The arrival that should be paid attention to is indicated with an arrow. There is an arrival of a wave with small slowness, in other words, large apparent velocity, to the shot point SHRE which comes from the west (**Fig. 10(d)**) at approximately 3.5–3.7 s. In all cases, apparent velocity exceeded 2 km/s. This suggests the existence of waves arriving in vertical to the extended direction of the KMTO array. Moreover, the particle motions in the corresponding time window V in **Figs. 10(a)–(c)** exhibit an up-and-down nature. This later phase with a large apparent velocity corresponds to the reflected wave coming from the reflecting surface α located 5.8 km below the sea level in the eastern part of Sakurajima. This reflecting surface α responds to magma movement accompanied by volcanic activity, as pointed out in a previous study from the viewpoint of travel time [2].

3.2. Surface Operation in Asama in 2017

In the 2017 fiscal year, a volcano observation was carried out in the Asama Volcano, which was active at that time. This observation was aimed at verifying the applicability of the optical sensor system using a multipoint seismic array method, which is the final objective of this project. We used AVO with the cooperation of the Earthquake Research Institute, The University of Tokyo, because this region is frequently struck by lightning during summer, making it is easy to secure power, and its accessibility for maintenance is better.

In this observation, to estimate the location and the depth of the source of the seismic waves, each observation station was established at the apex of a triangle with sides of approximately 20 m. The observation stations were named OPT-A, OPT-B, and OPT-C in order according to their proximity to the laser generator and the sensor signal processor; they will be hereafter referred to as the stations A, B, and C. In each observation station, the sensor unit was set so that the X(N) component was directed toward the crater, the Y component was directed in the direction perpendicular to the crater, and the Z component was directed in the vertical direction. These components will be hereafter referred to as the L, T, and Z components. The locations of the main building and each sensor unit in AVO are shown in **Fig. 11**. The laser generator and the sensor signal processor were installed in the neighboring main building of the stations and the connections with the optical sensors were established using optical fiber cable.

The optical sensor system was set for 133 days from Sep. 13, 2017 to Jan. 23, 2018. The actual operation days amounted to 108 days. During the operation, a continuous data stream worth 124 GB were recorded and 417 events of natural earthquakes were included in the data. By referring to previous works [14, 15], the observed volcanic earthquakes were identified and classified. One A-type and 51 B-type volcanic earthquake events were recorded using this system.

For the observations made in the 2017 fiscal year and to mitigate missed observations, which were triggered repeatedly by jumps in the bias voltage of the intensity modulator during the observations made during the previous year, the system was improved. Nonetheless, the intensity modulator deteriorated so significantly that light pulses could not be generated even via a manual regulation of the

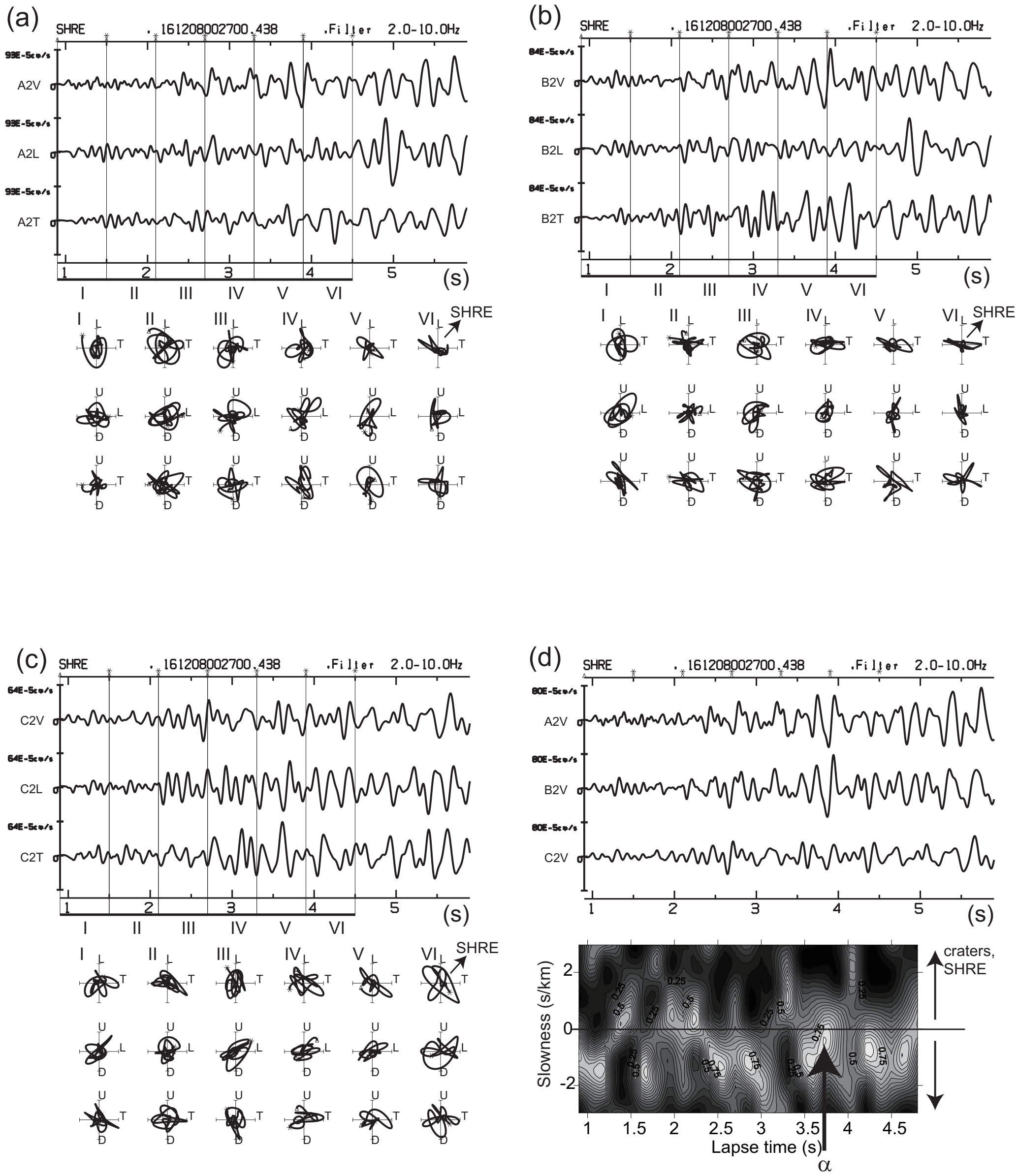

Fig. 10. (a)–(c) Shot SHRE seismograms and their particle motions at each station, (d) apparent velocity.

bias voltage on Jan. 7, 2018. Under these circumstances, precious knowledge was obtained on the characteristics of the deterioration of the intensity modulator and the accompanying behaviors of the system.

Furthermore, because the commencement of the observations in the 2017 fiscal year were delayed and the season with frequent occurrence of lightning was missed, the performance of the system in terms of lightning resistance could not be verified.

3.2.1. A-Type Volcanic Earthquakes

Figure 12 shows the seismograms of the A-type volcanic earthquake of Dec. 3, 2017 (hereafter referred to as event 03153110) obtained by passing the recorded data through a 1-Hz low-pass filter. The results of the application of these seismograms to beamforming using semblance [19] are placed below.

According to a bulletin [14], the epicenter of event 03153110 was estimated to be located 4 km immediately under Mt. Maekake, and the event occurred at 15:31:14.5 on Dec. 3, 2017 (**Fig. 13**). The seismic wave arrived at the optical sensor at 15:31:15.7. The vertical components are shown in the upper part of **Fig. 14**. The seismograms shown in **Fig. 14** were processed using a 1-Hz low-pass filter. At the onset of the event, a relatively sharp rising-up trend can be seen. Moreover, the later phases, i.e., I, II, and III, can be clearly recognized at approximately 1.2, 1.5, and 8 s after the onset of the event.

The results of an analysis of the back-azimuth are shown in the lower part of **Fig. 14**. In addition, the results of an analysis of the particle motions at the station OPT-C are shown in the lower part of **Fig. 15**. In **Fig. 14**, the ideal propagation direction of the seismic wave coming from the epicenter are shown with long arrows. At

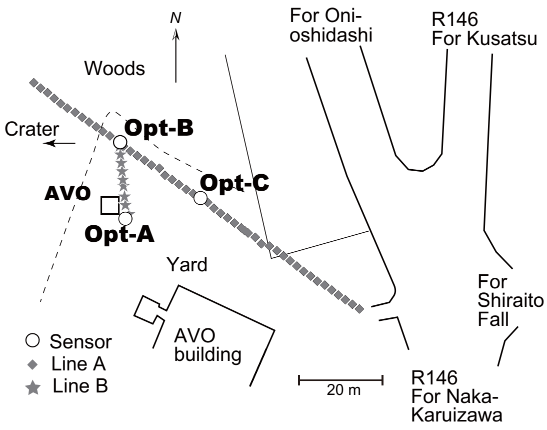

Fig. 11. Operation in Asama Volcano, 2017. Sensors were deployed in the yard of the observatory. Gray stars and diamonds represent the seismic lines on the surface.

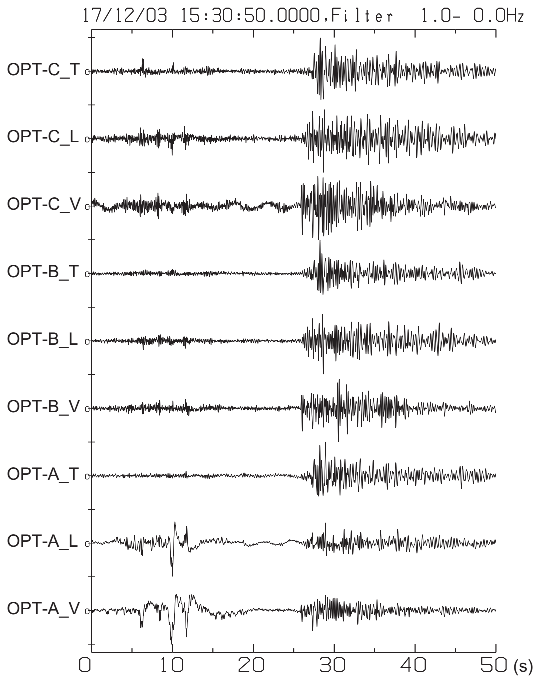

Fig. 12. Seismograms of the A-type earthquake of event 03153110.

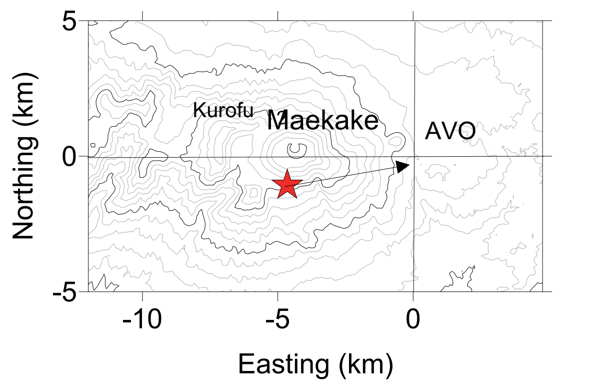

Fig. 13. Epicenter of event 03153110 (a star) and AVO. Mt. Maekake includes the active crater.

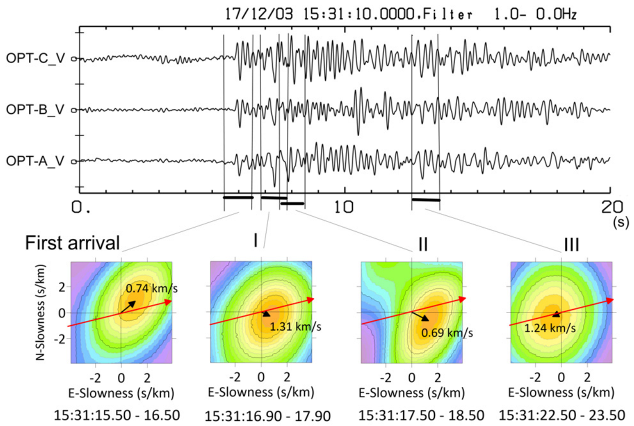

Fig. 14. Apparent velocity and azimuth of event 03153110.

the onset of the event, the motion came from the southwest. The seismic wave at the onset propagated in a more northerly direction than the ideal one. During phases I and II, the seismic wave propagated in the same direction, although the apparent velocities were different. Contrarily, during phase III, it propagated toward the epicenter.

It was found out via shallow seismic exploration that the structure directly under the array is generally a horizontal stratification, that the velocity at the shallowest layer is approximately 0.3 km/s, and that the velocity of the lower limit of analysis is approximately 0.3 km/s. Even if such conditions are taken into consideration, it is worth noting that the velocity of the initial P wave was 0.74 km/s, which is a rather small value. Moreover, phase I, which followed the first arrival, exhibited a higher velocity of 1.31 km/s. It seems that during phase I, the seismic wave arrived with a smaller incidence angle than at the first arrival. Phase II comes immediately after phase I. However, phase II exhibited an apparent velocity of 0.69 km/s, which is smaller than that of phase I, and the arrival time coincided with the time when the horizontal motion was large, as shown in **Fig. 15**, which indicates that the seismic wave of phase II was an S wave. Furthermore, because the apparent velocity of phase III was similar to that of phase I, there is a high probability that a reflected wave could have arrived during phase III.

In **Fig. 15**, it can be seen that, at the first arrival, the vertical component was predominant. Taking the location of epicenter of event 031531100 (approximately 4 km from the optical sensor system and at a depth of 4 km below sea level) into consideration, the direction of the particle motion of the P wave was generally estimated to be 36.5° downward in the direction of L. Accordingly, supposing that the average velocity of the seismic wave near the ground surface was 0.42 km/s, the apparent velocity can be roughly calculated as 0.705 km/s ($= 0.42/\sin 36.5°$), 0.42 km/s was used as the result of the survey on the ve-

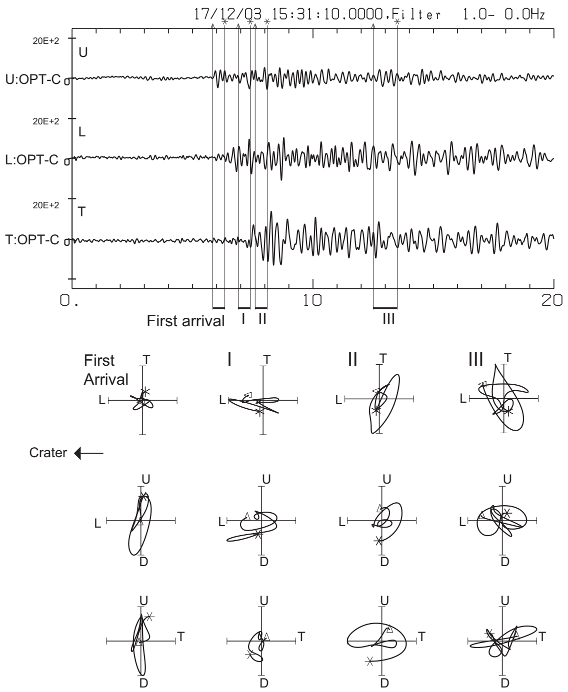

Fig. 15. Particle motions of event 03153110 at the station OPT-C.

locity of seismic waves on a shallow layer described below. In the results of the observation, a particle motion at approximately 35° in the direction of one period of the first arrival can be seen. Moreover, the back-azimuth estimated from the wave direction was located more northerly than the direction from the epicenter.

It is only during the first arrival that vertical motion is predominant. Another tendency that was also recognized is that the motion of the horizontal component becomes larger as time proceeds. It is worth noting that, in this process, the L component in time window I and the T component in time window II become predominant. The motion in the L–T plane is predominant in the direction parallel to L axis in time window I, in the first and third quadrants in the subsequent time window (II), and in the second and fourth quadrants in time window III. A predominance of the L component in time window I seems to indicate the arrival of an S wave that moves only in one direction. On the other hand, considering the location of the hypocenter of event 03153110 and the motion direction of the first arrival, the T component should be predominant in the S wave coming directly from the hypocenter. Thus, the arriving wave in time window II is rather thought to be an S wave coming directly from the hypocenter. Therefore, the arriving wave with a predominant L component observed in time window I is thought to indicate a wave that was converted from a P wave to an S one at a location nearer to the observation station than to the hypocenter. This assumption also coincides with the results of the analysis on the back-azimuth.

If the predominant motion in time window II is a direct S arrival, the back-azimuth can be estimated from the predominant direction to be in a more northerly direction than the direction from the epicenter, which also coincides with the back-azimuth of the P wave at the first arrival mentioned above as well as with the result of the analysis on the back-azimuth in the same time window.

Finally, horizontal motion was also predominant in time window III. However, the motion direction in the L–T plane was included in the second and fourth quadrants, unlike in time window II. This suggests that the motion in time window III should be an S wave. Because this wave arrived later than the direct S arrival, this hints at the possibility that this wave could be an SS reflection. From the results of the analysis on the back-azimuth in the same time window, it can be concluded that the motion arrived with a large apparent velocity from a direction opposite to the crater.

The northward deviation commonly recognized in the back-azimuths of direct P arrivals and direct S arrivals could be influenced by the high-velocity body existing in the central part ranging from the Asama Volcano to the Eboshi Volcanos, which was revealed by a previous study [20]. The differences in the correcting values for travel time brought by the heterogeneity directly under each optical sensor observation station could contribute to the differences between the motion direction at each observation station and the back-azimuth seen from the array as a whole.

4. Perspective and Unsolved Problems

Through the observations made using the JOGMEC PHASE1 prototype at the Komen tunnel of the Sakurajima Volcano in the 2016 fiscal year and at the Asama Volcano Observatory in the 2017 fiscal year, it was shown the seismograms that coincide with those obtained by the existing observation system can be obtained within the band ranging from 0.2 to 20 Hz.

Two problems which were encountered in the actual operation are mentioned below.

1) Mitigation of noise in the side of low frequency

Large noise in the band below 0.2 Hz becomes an obstacle for observing long-period motions using this system and for employing an tiltmeter in this system. Because this long-period noise also appears at the channel TC (**Fig. 1(a)**), there is a high probability that this noise could be caused by fluctuations at the part generating the optical signal. We are now examining whether this noise can be mitigated through certain measures by taking this phenomenon into consideration.

2) Mitigation of the deterioration of the optical device

In the prototype used in this study, an obstacle caused by the deterioration of the intensity modulator was encountered on Jan. 7, 2018. This was so significant that the system could not be restored. The intensity modulator used to generate light pulses in the prototype has a history of the application of voltages out of the standard during the fabrication of the prototype. Thus, it is thought that deterioration advanced as the intensity modulator was put to use. In the future, it will be necessary to manage the voltage applied to the intensity modulator so as not to exceed the standard when a new system is produced.

Additionally, the following items are given as problems to be tackled when constructing a device for practical use.

3) Low power consumption

Although there is no need to supply power to the sensors, the unit for the generation of light pulses and that for processing the optical signals must be supplied with power. Because power capacity often cannot be guaranteed for volcano observations, low power consumption is strongly desired. A power of as much as 500 W is currently consumed by the optical sensor system, and the power consumption of the server accounts for approximately 60% of the total. It has not been verified whether the server machine currently used is the most appropriate for our purposes. We think it will be possible in the future to reduce power consumption by adjusting and limiting the functions of the optical sensor system to particular uses and by using, for example, an on-board microcomputer with a performance level suitable for the desired particular functions.

4) Cost reduction

Currently, the adoption of single-mode optical fiber and the continuous-wave method (**Fig. 16**) are being examined. The price of single-mode optical fiber is approximately 1/30 of that of polarization-maintaining fiber. When using the continuous-wave method, an expensive part currently used for the generation of light pulses is not needed. Observations made with the continuous-wave method can be carried out in only one observation station by using a pair of optical fibers. However, multiple-channeled observations are possible by connecting the laser generator and the sensor signal processor with each sensor on a one-to-one basis in a radial manner, as shown in **Fig. 16**. On the other hand, in such multiple-channeled observations using light pulses, the cascade method (**Fig. 1(b)**) was adopted, in which a pair of polarization-maintaining fibers are connected in series with each sensor and light pulses are recovered via a time-division system. In the continuous-wave method, the number of fibers drawn from the laser generator and the sensor signal processor increases. However, if the number of observation stations is limited to 18 or less, the cost of using the continuous-wave method with single-mode optical fiber is still cheaper than that of using the pulse-method with polarization-maintaining fiber.

5) Optimization of the natural period

In oscillators consisting of a simple spring–mass–damper system, sensitivity is reduced to, in principle, a frequency below the natural frequency. On the other hand, because the amplitude becomes larger as the natural frequency decreases, it becomes more difficult to construct such oscillator mechanisms. However, the natural frequency of the oscillator to be used should be lower in order to perform optimal volcano observations.

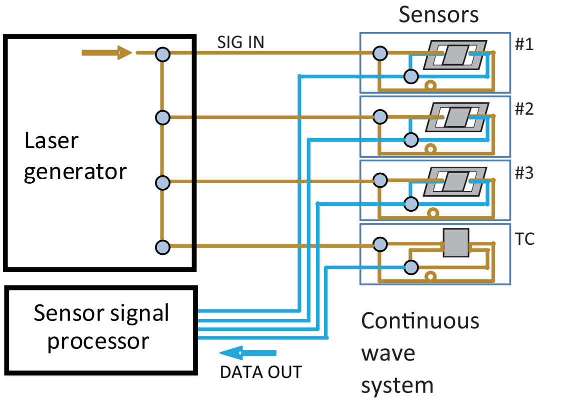

Fig. 16. A system using the continuous-wave method.

6) Miniaturization and weight saving

Considering certain cases, such as the deployment of equipment in mountains, miniaturization is essential. In the JOGMEC PHASE1 prototype mentioned in this report, the laser generator and the sensor signal processor weighed approximately 40 kg each. In contrast, the second prototype only occupies half of a 19 inch rack and its total weight is half of that of the first prototype. Thus, in this regard, we conclude that miniaturization and weight saving were improved.

7) Establishment of an examination method of operation

It is desirable to implement examination mechanisms, such as the forced oscillation of the sensor pendulum, in order to facilitate the identification of noise sources and the location of faults. If this system were applied for observations in an array with more points in the future, it would be more important to implement examination methods for its phase properties using, for example, test signals.

8) Verification of heat resistance

In order to take advantage of the characteristics of the systems, heat resistance needs to be verified in the next few years. This is so because this optical sensor system is expected to be applied for observations at locations where high temperatures are likely or deep underground.

9) Verification of lightning resistance

Lightning resistance was not verified because observations could not be carried out in the season in which lighting occurs frequently in the 2016 and 2017 fiscal years owing to various circumstances. We continue to wait for an opportunity to carry out these observations and verify the lightning resistance of the system.

In addition, the failure rate of the system should be estimated systematically.

5. Summary

In the 2016 and 2017 fiscal years, volcano observations were carried out in Sakurajima and Asama volcanos using a seismometer system with Phase-Shifted Optical Interferometry, and a feasibility study of this system was conducted. As a result of the operation of the system in both volcanos for 134 days in total, observation records on volcanic tremors, including volcanic earthquakes, were obtained.

From the seismograms of the earthquake observations, it can be seen that the seismograms obtained via the Phase-Shifted Optical Interferometry system analyzed in this paper were identical to those obtained with existing observation systems within the band ranging from 0.2 to 20 Hz. Additionally, by observing the operation of the system, certain problems were revealed, which were mainly related to the mitigation of noise in the long-period band and measures against the deterioration of the optical device. To implement such an optical sensor system practically and in addition to the solution of the above-mentioned problems, the issues of low power consumption, cost reduction, optimization of the natural period, miniaturization and weight saving, the implementation of an examination method of operation, and a verification of the system's heat and lightning resistance should be tackled in the future. By solving the problems revealed in this study and verifying and implementing the items necessary for the practical use of the system, it should be possible to apply the present volcano observation system with multi-channeled Phase-Shifted Optical Interferometry in the field, which is expected to contribute to the acquisition of valuable information for disaster prevention in real time.

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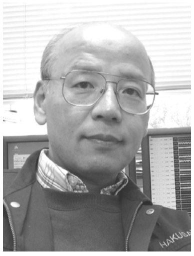

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