https://doi.org/10.20965/jdr.2019.p0006

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A Newly Installed Seismic and Geodetic Observational System at Five Indonesian Volcanoes as Part of the SATREPS Project

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[Received August 8, 2018; accepted January 4, 2019]

"Integrated Study on Mitigation of Multimodal Disasters Caused by Ejection of Volcanic Products" Project was launched in March 2014 for the Galunggung, Guntur, Kelud, Merapi, and Semeru volcanoes. The objectives of the project include the development of an observational system for the prediction and real-time estimations of the discharge rate of volcanic products. Under the project, a team from the Sakurajima Volcano Research Center, Center for Volcanology and Geological Hazard Mitigation (CVGHM) and the Balai Penyelidikan dan Pengembangan Teknologi Kebencanaan Geologi (BPPTKG) initiated the installation of a digital seismic and global navigation satellite system (GNSS) observational network for the volcanoes in December 2014, and finished the installation in September 2015. The seismic and GNSS data are transmitted by wireless local area networks (WLANs) from the stations to an observatory at each target volcano. We introduced three Windows PC software for data analysis: the first for estimating the equivalent rate of ejected ash from a volcano, the second for continuous smoothing of tilt data and detecting inflation and deflation in the volcanic sources, and the third for continuously evaluating eruption urgency to predict the eruption time. The seismic and GNSS data were routinely transmitted to the Support Systems of Decision Making (SSDM) at CVGHM or BPPTKG. Data completeness varied from volcano to volcano; for example, the data acquired for Kelud volcano were relatively stable, while those for Merapi volcano were problematic, owing to a communication disruption in the WLAN. We obtained the seismic and GNSS data at the target volcanoes in the observation period since 2015 when they have been relatively quiet.

Keywords: seismic observation, global navigation satellite system, digital seismogram, wireless local area network, volcano observatory

1. Introduction

Seismic signals and ground deformation exhibiting the deflation of the volcano edifice are observed during or after eruptions, which are essential to evaluate the occurrence and magnitude of eruptions [1, 2]. The magnitude and duration of seismic waves that are excited by eruptions may reflect not only the total amount of erupted materials but also the explosivity of eruptions. For example, the average discharge rate is the value of the total volume of ejected ash divided by the duration of the eruption tremor [3]. The empirical relationship between seismic amplitudes and discharge rate was examined for the Sakurajima volcano, Japan [4]. The relationship between magma discharge rate and plume height both of which reflect the differentiating pressure decrease within a magma chamber with time was tested by observations using the global navigation satellite system (GNSS) and tilt data [5, 6].

Recent explosive (2010 Merapi and 2014 Kelud) eruptions and long-duration dome forming and explosive (Sinabung, 2013-present) eruptions were targeted in this research. Several experiments for predicting the occurrence time of volcanic eruptions have been conducted using precursory seismicity. For example, the fitting procedure between seismic amplitude and an analytical function can explain the timings of the eruptions of Merapi in 2010 [7] and Kelud in 2014 [8]. The seismic amplitude at Kelud was saturated immediately prior to the eruption because of the narrow dynamic range of the analog telemetry between the station and observatory. For an analog telemetry system, the seismic amplitude is underestimated, and the estimation of the predicted eruption time is sometimes difficult owing to saturation [8]. Therefore, it is important to introduce a digital telemetry system with wide dynamic-range digitizers between seismic stations and an observatory to correctly assess the volcanic activity.

The Center for Volcanology and Geological Hazard Mitigation (CVGHM), Geological Agency of Indonesia have been continuously monitoring active volcanoes by seismic and geodetic techniques for several decades at 76 observatories. However, seismic observations use analog telemetry and geodetic observations have only been conducted intermittently using high-precision leveling and electronic distance measurements, respectively. Compared to instruments in volcano observatories of other countries such as Japan, Italy, and USA, many instruments for monitoring volcanoes in Indonesia are relatively old, and their modernization, such as the introduction of digital seismographs and GNSS receivers is required urgently.

Volcano observation in Indonesia has been supported by agencies of other countries. The Volcano Disaster Assistance Program (VDAP) of the U.S. Geological Survey urgently established observational networks on volcanoes, demonstrating volcanic crises by providing instrumentation to modernize the monitoring networks. Although Japan has no official agencies such as the VDAP, a team of scientists was dispatched urgently during the crises and has continued to assist in constructing volcano observational networks in several countries. For example, a digital telemetric observational network of Tungurahua and Cotopaxi volcanoes in Ecuador was constructed via a technical cooperation project of the Japan International Cooperation Agency (JICA), and the data of the 2006 Tungurahua eruption were successively provided [9]. A Science and Technology Research Partnership for Sustainable Development (SATREPS) project, funded by JICA and the Japan Science and Technology Agency, named "Multi-disciplinary Hazard Reduction from Earthquakes and Volcanoes in Indonesia," was conducted from 2009 to 2011, where digital observational networks at Guntur, Merapi and Sinabung volcanoes were installed [10].

A new SATREPS project, "Integrated Study on Mitigation of Multimodal Disasters Caused by Ejection of Volcanic Products," was launched in March 2014 for the target volcanos of Galunggung, Guntur, Kelud, Merapi, Semeru, and Sinabung (added in 2017) in Indonesia. The objectives of this new project are the development of an observational system for the prediction and real-time estimations of the discharge rate of volcanic products, utilizing ground deformation and seismic data. Our team of SATREPS and CVGHM constructed seismic and geodetic observational systems for Galunggung, Guntur, Kelud, Merapi, and Semeru volcanoes (**Fig. 1**).

Figure 2 shows the monthly number of VT earthquakes at six volcanoes from September 2010 to December 2017, three of which had erupted. Merapi erupted in October and November 2010 with a volcanic explosivity index (VEI) of 4 [11]. Sinabung erupted in August–September 2010 after a dormancy of 1200 years [12]; subsequently it erupted frequently since September 2013 [13]. At Kelud, a Plinian eruption (VEI4) occurred on February 13, 2014 [14]. VT earthquakes occurred frequently for several months prior to, during and after these eruptions. Except for these active seismicity periods, the periods after the new observational systems were installed in 2015 captured relatively quiet periods of VT seismicity. It is noteworthy that Guntur volcano has remained dormant for 160 years but its VT seismicity level was relatively high compared to those of the other volcanoes. Although the VT seismicity at Semeru volcano has remained low, the seismicity was relatively high during the operational period of the new observational system.

Herein, we explain the details of the installed instruments, the seismic and geodetic observation networks, and the data processing system that are newly introduced

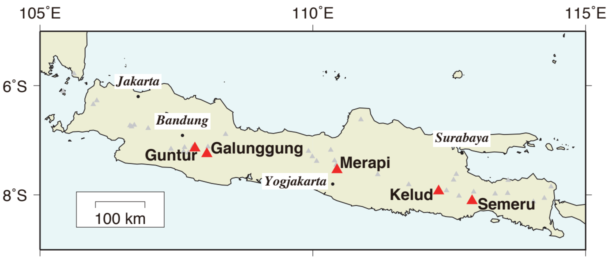

Fig. 1. Locations of the five targeted volcanoes (red triangles) in Indonesia for the SATREPS project. Sinabung volcano is in the North Sumatra Island and not depicted in this figure. The gray small triangles are active volcanoes, excluding the target volcanoes.

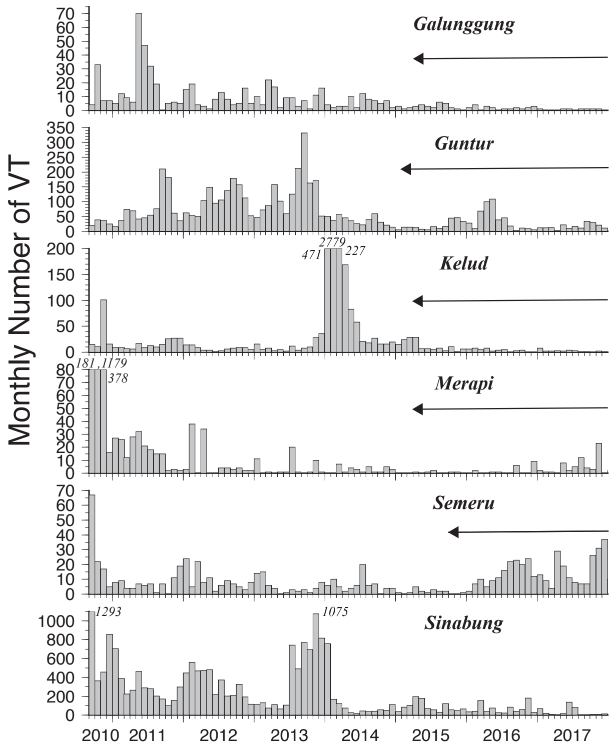

Fig. 2. Monthly frequency of volcano–tectonic (VT) earthquakes from September 2010 to December 2017. The Center for Volcanology and Geological Hazard Mitigation routinely counts earthquakes of the targeted volcanoes. The number near the vertical bar shows the monthly counts of VT earthquakes. The solid horizontal arrow shows the observational period of the newly installed instruments for each volcano.

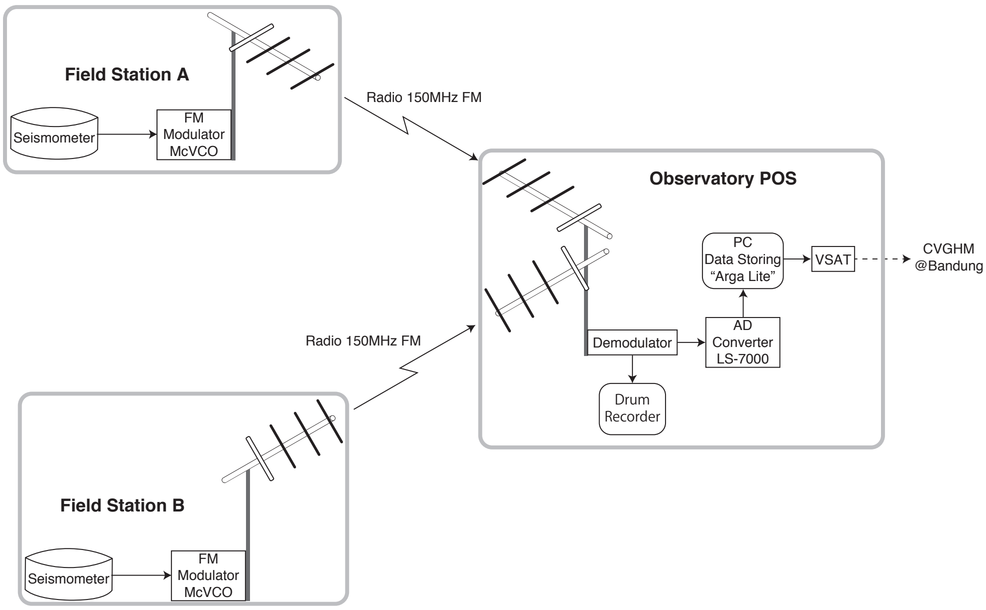

Fig. 3. Standard volcanic earthquake observation system in Indonesia using an analog frequency-modulated telemeter.

in this project. Further, we evaluate the performance of their data acquisition by presenting the ground deformation results from the GNSS observation.

2. Installation of the New Volcano Observation Network

2.1. Previous Seismic Observation at Indonesian Volcanoes Using FM Telemeters

Every volcano observatory of the CVGHM has at least one short-period seismometer at each volcano. More active volcanoes typically have a few vertical short-period seismometers for monitoring. A few hazardous, high-risk volcanoes such as Guntur, Kelud, Merapi, and Semeru volcanoes (**Fig. 1**) are monitored by four or five seismic stations. Such seismic stations are equipped with L4-C vertical seismometers with a constant damping ratio of 0.8 and a 100 V/m/s generator constant, in accordance with the standard USGS-VDAP settings. Seismic signals are transmitted from the stations to the volcano observatory using frequency modulation (FM)-modulated radio telemetry with a VDAP McVCO frequency generator [15]. The signals are digitized with a sampling rate of 100 Hz and a 24-bit precision using a Hakusan LS-7000 data logger at the volcano observatory (see **Fig. 3**). The data logger not only stores WIN-formatted binary data [16] in a CF card but also transmits the WIN-formatted packet data by the user datagram protocol/internet protocol (UDP/IP) to the CVGHM via the software "Arga Lite" operating on Windows PC. Although the dynamic range (102 dB for the 100 Hz sampling) of the data logger is wide, that of the FM telemetry system is limited to 72 dB by the 12-bit analog-to-digital converter [15]. Seismic records are typically saturated when the seismic waves are large. For example, the seismic records were saturated approximately 1 h prior to the beginning of the 2014 Kelud eruption [8].

2.2. Digital Seismic and GNSS Observational Network Using Wireless LANs

To enhance the capability of monitoring the target volcanoes, the SATREPS project facilitated the installation of observational stations at the volcanoes. **Fig. 4** and **Table 1** show the locations of the newly installed observational stations at the target volcanoes and types of instruments at the stations. The typical instruments to study each volcano consist of one or two three-components short-period seismometers with a natural period of 1 s (Seismo-tech Co., Ltd. SSV-001), two or three GNSSs (Leica Geosystems GR10 receivers and AR10 antennas), and a surface-mount bubble-type tiltmeter (Jewell Instruments 701-2A) on each volcano (**Table 1**).

All instruments were prepared in Japan (till the summer of 2014) and were exported to Indonesia through JICA. The WLAN modules, solar panels and batteries were prepared in Indonesia. All instruments arrived at the CVGHM in late December 2014. The installation began in December 2014 at Galunggung and Kelud volcanoes with the construction of WLANs and repeaters. After the completion of the WLAN telemetry network, the installation of observational stations was initiated in December 2014 and completed in September 2015, as shown in **Table 1**.

The GNSS stations and WLANs were already installed at Guntur and Merapi volcanoes by the previous SATREPS project [10]; that is, since October 2010, three stations (CTSG, MSGT, and SODN) near the summit of Guntur volcano with Leica GRX1200 GNSS receivers and the station at the volcano observatory (POST) with

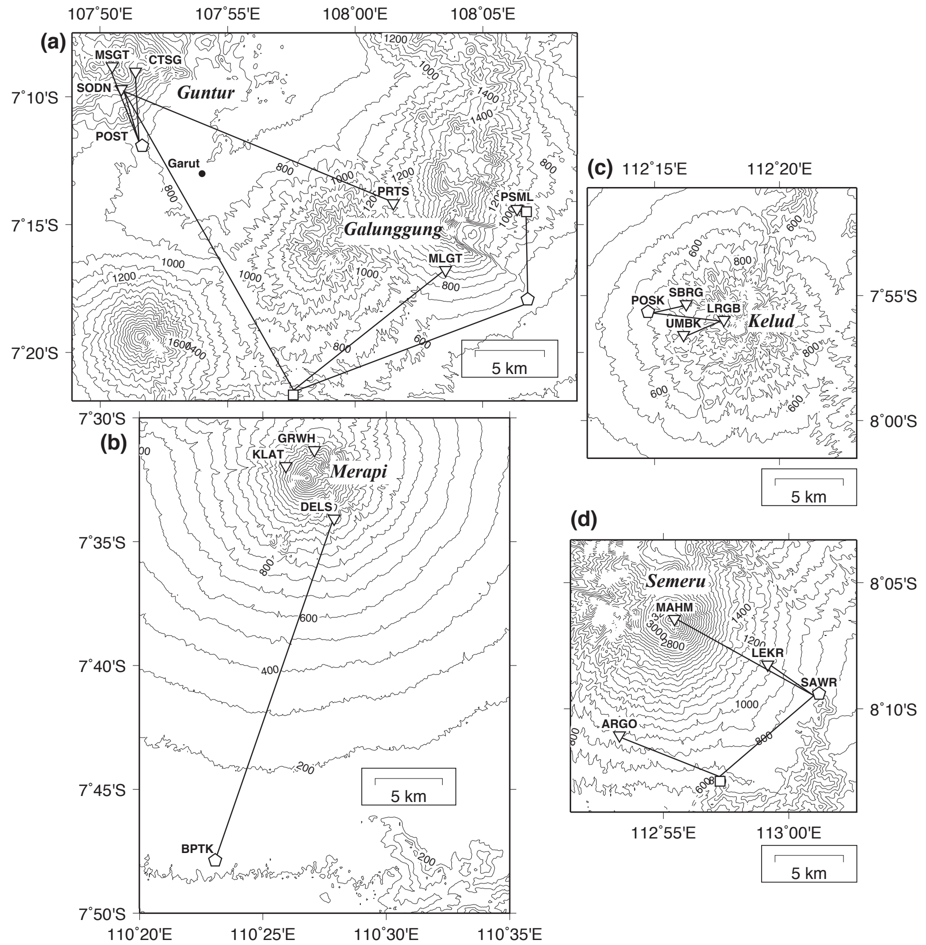

Fig. 4. Locations of stations (open inverse triangles) at (a) Guntur and Galunggung, (b) Merapi, (c) Kelud, and (d) Semeru volcanoes. The open pentagons show the locations of the volcano observatories. Thick lines show digital radio telemetry (WLAN) routes from the observational stations to the observatory. Open squares show the locations of WLAN repeaters.

Table 1. Station parameters, volcano name, station code, location, instrument type, and installation date.

Volcano	Station	Location coordinate			Instrument				Installed date
		Longitude [°]	Latitude [°]	Altitude [m]	GNSS	Seismometer	Tiltmeter	Data logger	
Galunggung	PRTS	108.02500	−7.23606	1223	GR10	SSV-002	N/A	LS-7000XT	April 17, 2015
	MLGT	108.05904	−7.27960	1019	GR10	N/A	A701-2A	AD1217	April 18, 2015
	PSML	108.10587	−7.23979	973	GR10	SSV-002	N/A	LS-7000XT	April 19, 2015
Guntur	MSGT	107.84135	−7.14686	2197	GRX1200	N/A	N/A	N/A	
	SODN	107.84716	−7.16157	1561	GRX1200	SSV-002	N/A	LS7000XT	January 27, 2015
	CTSG	107.85655	−7.15039	1720	GRX1200	SSV-002	A701-2A	LS-7000XT	January 25, 2015
	POST	107.86085	−7.19870	863	GR10	N/A	N/A	N/A	January 26, 2015
Kelud	POSK	112.24554	−7.92765	714	GR10	N/A	N/A	N/A	March 25, 2015
	UMBK	112.26938	−7.94294	953	GR10	N/A	N/A	N/A	March 26, 2015
	LRGB	112.29625	−7.93286	1378	GR10	SSV-002	N/A	LS-7000XT	March 26, 2015
	SBRG	112.27104	−7.92250	951	GR10	SSV-002	A701-2A	LS-7000XT	March 28, 2015
Merapi	KLAT	110.43233	−7.53242	1923	GR10	N/A	N/A	N/A	
	GRWH	110.45151	−7.52165	2045	GR10	N/A	N/A	N/A	
	DELS	110.46469	−7.56782	1433	GR10	SSV-002	A701-2A	LS-7000XT	March 27, 2015
	BPTK	110.38439	−7.79786	140	GR10	N/A	N/A	N/A	March 27, 2015
Semeru	SAWR	113.02007	−8.15678	827	GR10	N/A	N/A	N/A	September 18, 2015
	LEKR	112.98596	−8.13742	1082	GR10	SSV-002	N/A	LS-7000XT	September 19, 2015
	MAHM	112.92410	−8.10737	3693	GR10	N/A	Model 14000	LS-7000XT	September 21, 2015
	ARGO	112.88746	−8.18434	970	GR10	SSV-002	N/A	LS-7000XT	September 21, 2015

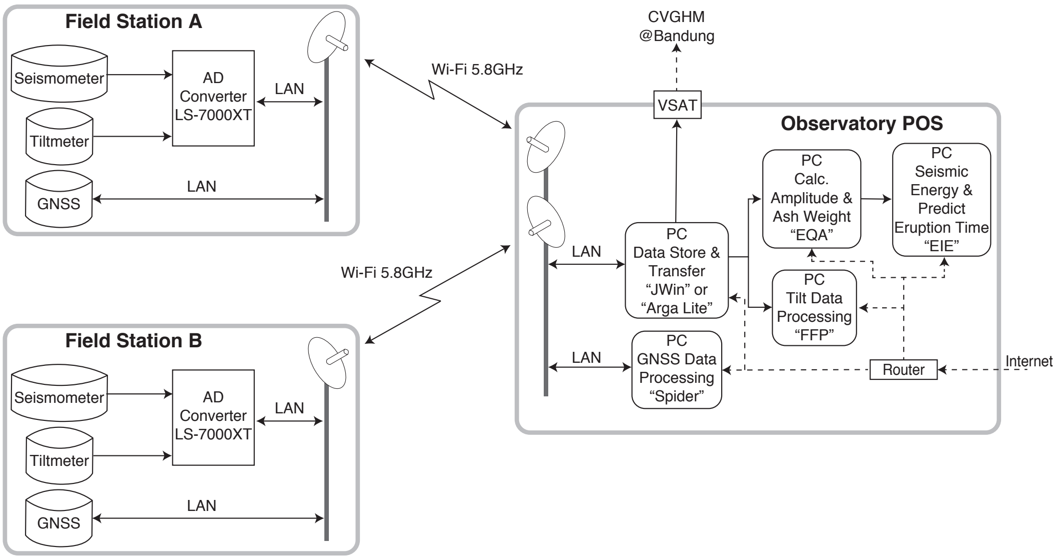

Fig. 5. A new seismic and geodetic observational system using WLANs for Galunggung, Guntur, Kelud, Merapi, and Semeru volcanoes.

one Leica SR520 GPS receiver [10]. Under the current project, we replaced the GNSS receivers with GR10 and antennas with AR10 at POST in late January 2015 (**Table 1**). At the Merapi volcano, two GNSS stations had already been installed at KLAT and GRWH by the previous SATREPS project [10].

Digital data telemetry is a 5.8- GHz band WLAN module known as "Ubiquiti Networks NanoBeam M5" or "Rocket M5 + Rocket Dish 5" which has a maximum power consumption of 6 W and 8 W, respectively. The power consumptions of these WLAN modules are much larger than the upper limit (250 mW) of the WLANs used in Japan. The transmission distance of the WLANs extends beyond 20 km. Therefore, we could implement the WLANs flexibly around the target volcanoes. The power for all instruments at the observational stations is supplied by solar panels and DC24V batteries, which are key for long-term maintenance of solar panels and batteries with DC power.

The seismic and tilt waveform data were digitized at a sampling rate of 100 Hz per channel with a 24-bit precision using a Hakusan LS-7000XT data logger at each station. The data logger not only stores WIN-formatted binary data in a CF as a combination of six channels, but also transmits the data by UDP/IP to the observatory via a WLAN. The seismic, tilt waveform data and GNSS data were recorded on a Windows PC disk at each observatory via a WLAN from the stations at each volcano (**Fig. 5**), except for Galunggung. The GNSS data of the stations at the Galunggung volcano were transmitted to the Guntur volcano observatory, because the WLAN networks of Guntur and Galunggung volcanoes are connected (**Fig. 4**).

3. Data Recording and Automatic Analysis System

The seismic and tilt waveform data from the stations are stored in a PC at each volcano observatory and transmitted with TCP/IP to the CVGHM by Arga Lite (**Fig. 5**). For Merapi, the recording by Arga Lite at the Balai Penyelidikan dan Pengembangan Teknologi Kebencanaan Geologi (BPPTKG), that is, the Merapi Volcano Observatory, was unstable. Although the reasons for the software's instability remain unresolved, we suspect glitches in the software and compatibility problems between the PC and the software. Therefore, we introduced the new recording software "JWin" at the BPPTKG in late December 2017 (**Fig. 6**). JWin consists of two parts: a software for WIN-formatted data relaying "JWinRelay" and another software "JWinRecord" for WIN-formatted data storing. Both softwares typically comprise two parts: one for parameter setting using GUI, and another for a process batch part of CUI, which can automatically operate in the background (**Fig. 6**). JWinRelay can receive in real time and simultaneously send WIN-formatted data packets from multiple sites (IP addresses and ports) to specified sites. The additional functions of JWinRelay are filtering specified data channels, specifying types of WIN packets (A0 or A1), and sending a request command to the data logger of each site for retransmitting the data packet. JWinRecord can store waveform data as a WIN-formatted binary file of 1-min or 1-h lengths in PC disks with a specified file name role, while maintaining the amount of free space on the disks. The environmental requirement for these softwares consists of a Java Runtime Environment (JRE) 1.8 and any operating system such as Windows, Linux, or macOS. However, we typically use a Windows PC for any data processing for this project because of its good availability and easy maintenance by the observers

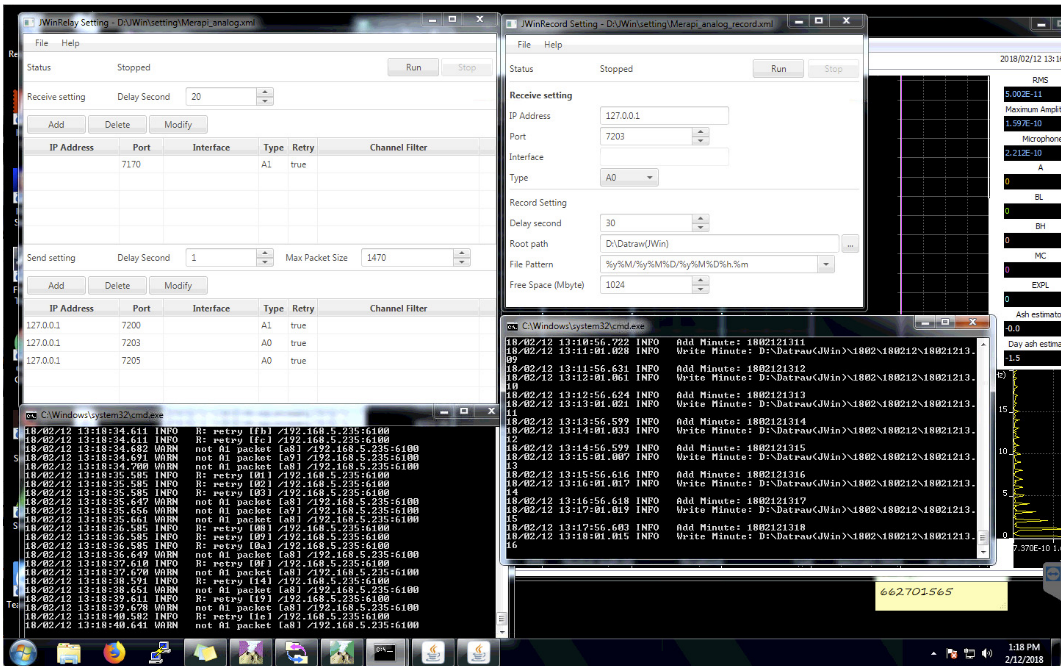

Fig. 6. Screen-shot of the software JWin at the BPPTKG. GUI windows on the left and right upper sides of the screen show the setting of the parameters for JWinRelay and JWinRecord, respectively. Command-prompt windows on the left and right lower sides of the screen show status outputs from the back-ground processes for JWinRealy and JWinRecord, respectively.

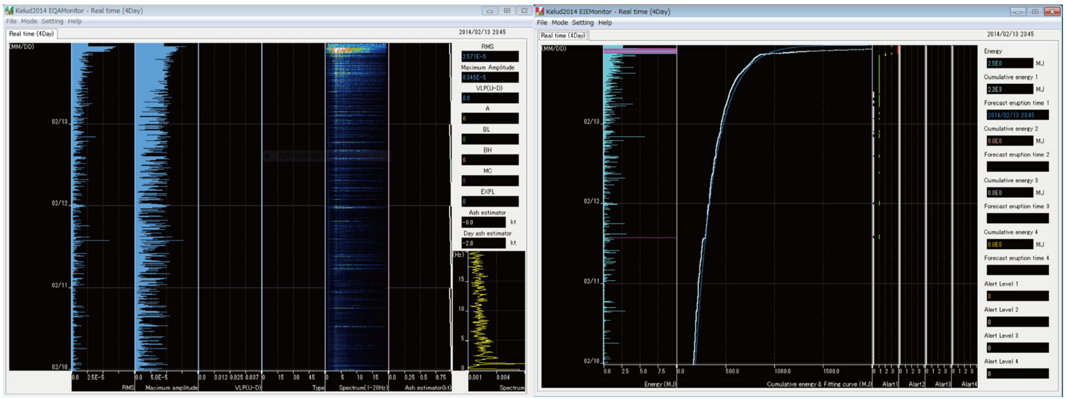

Fig. 7. Screen-shot of the software EQA (left) and EIE (right). EQA shows the RMS, maximum seismic amplitude, filtered, type of earthquake, running-spectrum, and estimated amount of volcanic ash. EIE shows the seismic energy and its cumulative energy along with a fitted logarithmic function and "eruption time" which is estimated by the function.

at any observatory.

The analysis software of volcanic earthquakes, "EQA" and volcanic ground deformation, "FFP" directly received WIN-formatted A1-type UDP packets via a specified port at an IP number of the PC (**Fig. 5**). EQA and FFP could also read WIN-formatted data in a disk for post-processing. EQA automatically classifies volcanic earthquakes as VT, LF, explosion, volcanic tremor, or non-VT earthquakes using seismic and infrasound waveforms. EQA continuously calculates a seismic power spectrum at each frequency within a band specified by a user. These spectra were used to estimate the equivalent rate of ejected ash from the volcano using an empirical relationship [4]. EQA displayed the root-mean-square (RMS) amplitude, maximum amplitude in a unit time window, running spectrum, equivalent rate, and the calculated total amount of ejected ash for a user-specified time window in the PC's display (**Fig. 7**). FFP continuously smooths the tilt waveforms and detects the inflation and deflation status resulting from the volcanic activity. The software for the eruption imminent evaluation "EIE" retrieved the RMS seismic amplitude as the output of EQA (**Fig. 7**) and sequentially predicted a material failure time as "eruption time" by fitting the logarithmic function of the material failure forecast method to a cumulative seismic energy within a specified time window [8]. The EQA, FFP, and EIE run on Windows version 7 or higher, JRE 1.7 or higher, and .Net Framework 4.5 or higher. These parameters, calculated from seismic and tilt data, were saved as binary and CSV files on a PC disk. The CSV files were routinely transmitted to the Support System of Decision Making (SSDM) that implemented the modeling of multimodal sediment movement of the volcanic deposits and an integrated Geographic Information System (GIS)-based simulator [17]. The SSDM servers are located at the BPPTKG and CVGHM.

The software "GNSS Spider" by Leica Geosystem of the PC automatically conducted a baseline analysis of the recorded GNSS data for every hour and created RINEX files at an interval of 1 s. The results of the baseline analysis were shown on the PC with the software "RIP" by Geosurf Co., Ltd. and were automatically transferred to the SSDM.

When Japanese researchers visit the CVGHM, BPPTKG, or volcano observatories, they copy the WIN and RINEX files and bring them back to Japan to maintain a long-term back-up archive of the data and for collaborative research purposes.

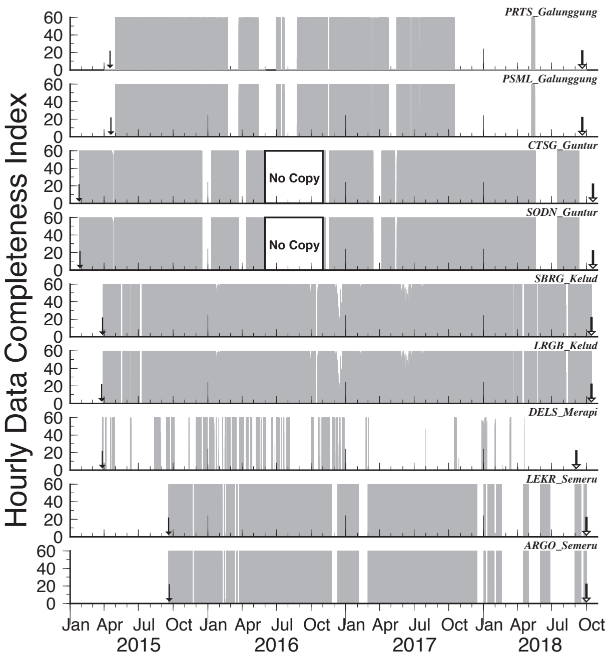

Fig. 8. Hourly data completeness (gray vertical lines) from January 2015 to October 2018. Solid arrows show the time of installation of the new instruments at each volcano site. The open arrows show the latest data copy time. The data from June to October 2016 are not analyzed for Guntur volcano.

4. Results of Data Acquisition and Analysis

4.1. Stability of Data Acquisition

To evaluate the stability of the seismic data acquisition at each observatory, we examined the WIN-formatted data files on site, by verifying the presence or absence of each channel from the data, and defined an "hourly data completeness index" as a ratio of minutes of the corresponding channel data for one hour. The index value of "0" implies that the data length of the corresponding channel is less than 1 min, while the index value "60" implies no measurement absence. **Fig. 8** shows the hourly data completeness index for the seismic stations at Galunggung, Guntur, Kelud, Merapi, and Semeru volcanoes from January 2015 to October 2018. The downward solid and open arrows indicate the start and end times, respectively. Although the seismic data completeness differs significantly for each volcano observatory, the difference among stations for each volcano is slight. For example, data were missing in March, May to June, August 2016, and May 2017 for Galunggung volcano. Further, data were missing from December 2015 to January 2016 and in March 2017 at Guntur. Unfortunately, copied data from June to October 2016 were not available, because the data files had already been erased from the PC at the observatory (**Fig. 8**). The missing data for Kelud volcano was less frequent and absent for a relatively short span of time. Meanwhile, in Merapi, the successful data acquisition was short, and the duration for which the data were missing was long. In Semeru, the absence of data was frequent, for example, from late November 2016 to the beginning of December 2016, and in February and December 2017; however, the duration of absence was less than 1 month.

As previously mentioned, both seismic and GNSS data were transmitted on the same route to the observatory using a WLAN, and an automatic baseline analysis was performed on the GNSS data for Galunggung, Guntur, Kelud, Merapi, and Semeru volcanoes (**Fig. 9**). At the Galunggung volcano observatory, for example, analysis results from March to May, and in August and September of 2017 were insufficient (**Figs. 9(a)**, **(b)**). Seismic and GNSS data were absent from March to May 2017, while seismic data were available from August to September 2017. As the battery power supply was maintained during these periods, the WLAN failure from March to May 2017 was the reason for missing data. GNSS analysis results were not available from August to September 2017 and from May to August 2018 at the SODN station of Guntur volcano (**Fig. 9(c)**), although the seismic data exist during this period (**Fig. 8**). For Kelud volcano, the results of the baseline analysis are shown for two stations with respect to the LRGB station in **Figs. 9(e)**, **(f)**. Because there are no long-term missing data throughout the observational period, the data acquisition can be regarded as relatively stable. From the results of the baseline analysis at the DELS station with respect to the BPTK station (the same as at the BPPTKG), no result was available from September and December 2015, and from February to April 2016 (**Fig. 9(g)**). There were periods in which seismic data existed while GNSS analysis results were missing. Conversely, in 2017, the GNSS analysis result was stable while the seismic data recording was incomplete (**Fig. 8**). The data acquisition state of the seismic and GNSS data were independent for Merapi. The baseline analysis results were absent from January to April 2016 for Semeru, while the seismic data was recorded.

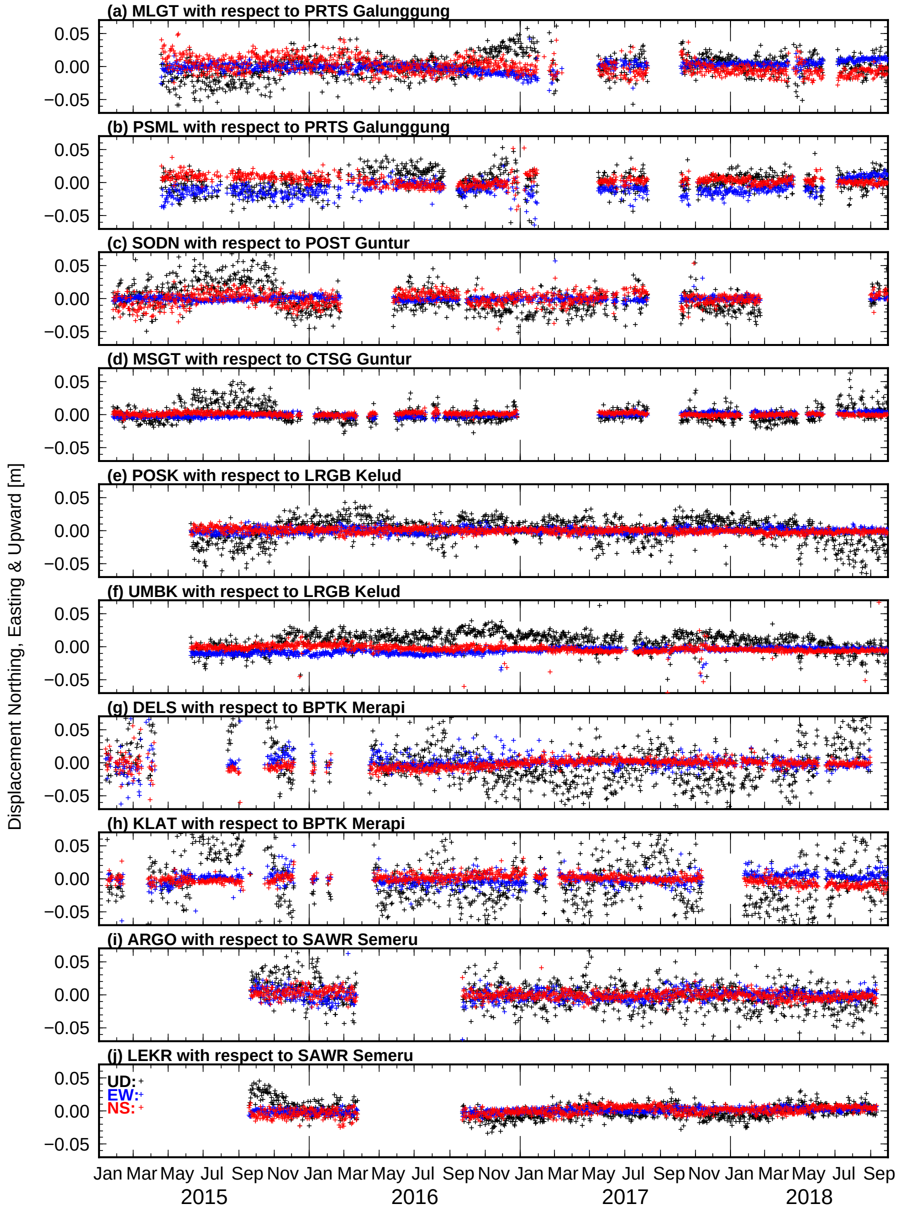

Fig. 9. Observed displacement from October 1, 2016 to September 30, 2018 at the (a) MLGT and (b) PSML stations with respect to the PRTS station for Galunggung volcano, (c) SODN station with respect to the POST station, and the (d) MSGT station with respect to the CTSG station for Guntur volcano, (e) POSK and (f) UMBK stations with respect to the LRGB station for Kelud volcano, (g) DELS and (h) KLAT stations with respect to the BPTK station for Merapi volcano, and (i) ARGO and (j) LEKR stations with respect to the SAWR station for Semeru volcano. See locations of the GNSS stations in **Fig. 4**.

In this study, we consider the cause of seismic data loss. In Kelud, although the baseline analysis with the GNSS data was nearly continuous, there were some missing seismic data. As the seismic data were sampled in high frequency, they were susceptible to a short interruption in wireless communication. The frequency band used for the WLAN module was a relatively high frequency of 5.8 GHz. Therefore, the WLAN communication was susceptible to weather conditions such as rainfall. Consequently, the seismic data collection was affected by a short communication break. During the rainy season, wireless communication becomes unstable; e.g., in December 2016 for Kelud volcano and November 2015 to March 2016, November and December of 2016, and February and December of 2017 for Semeru. As for Merapi, the severe data loss was caused by the instability of Arga Lite of the seismic data recording software, as previously described. As Merapi volcano is near the Yogyakarta metropolis and the BPPTKG is in the center of Yogyakarta, a short communication disruption and communication speed reduction occurred between the BPPTKG and the observational stations owing to the influence of WLAN crosstalk. Thus, the seismic data acquisition for Merapi was incomplete. Because the distance between the BPPTKG and station DELS was 25 km, this distance influence appeared to be severe. It may be effective to install a WLAN repeater and private wired LAN between them.

4.2. Results of the Base-Line Analysis of GNSS Data

In this section, we discuss the automatic baseline analysis results of the GNSS data (**Fig. 9**) in comparison to the seismicity at the target volcanoes as shown in **Fig. 2**. As previously mentioned, VT seismicity was relatively low for the target volcanoes during the observational period using the new instruments (**Fig. 2**). For example, at Galunggung, Kelud, and Merapi volcanoes, the VT seismicity remained low during the observational period. However, the VT seismicity increased slightly at Merapi volcano in 2017. At Guntur volcano, the VT seismicity remained at a high level compared to those of the other volcanoes. Although the VT seismicity at Semeru volcano remained low, the seismicity increased during the operational period. However, small-scale ash emissions and gas bursts have occurred frequently at Semeru volcano since January 2010 [18]. Overall, the remarkable ground deformation resulting from the magma chamber, as detected by the GNSS, was not observed clearly. However, a combination of stations and periods existed in which variations in the baseline analysis results were conspicuous; for example, during January and February 2017 at Galunggung volcano and in November 2015 at the Merapi volcano (**Fig. 9**). It has only been approximately 3 years since we started the new observations; therefore, data accumulation for the next several years is required to discuss the ground deformation resulting from volcanic sources.

5. Concluding Remarks

To estimate the amount of ejected volcanic products and to quantify eruption precursory phenomena, we installed a new seismic and GNSS observational system at Galunggung, Guntur, Kelud, Merapi, and Semeru volcanoes. The observational system was built using a WLAN and the data were recorded and analyzed in the volcano observatory. Outputs from the software that we introduced were incorporated into the SSDM. The seismic and GNSS data acquired for Kelud volcano were relatively stable, while the acquisition of seismic data was problematic for Merapi volcano. As Merapi volcano is near a large city, the congestion in WLAN communication was intense. As the five target volcanoes had been relatively quiet during the observational period, we could not estimate the release of volcanic ash of significant eruptions and quantify their precursory phenomena. If a large eruption, such as the 2014 Kelud volcano eruption had occurred at a target volcano, our systems would capture the precursory phenomena, and provide estimates of the amount and rate of the ejection of volcanic products. In addition, the SSDM would be able to support decisions in issuing warning and evacuation to people near the volcano.

Acknowledgements

We are grateful to the staff at the CVGHM and BPPTKG, members of the SATREPS project, and the project coordinator Mr. Mamoru Izumi. This research was supported by the Science and Technology Research Partnership for Sustainable Development (SATREPS) project funded by the Japan Science and Technology Agency (Grant No. 13803203) and the Japan International Cooperation Agency (Grant No. 1300744). We are grateful to the two anonymous reviewers and the editor for their constructive comments and suggestions.

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