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# Ground and Satellite Monitoring of Volcanic Aerosols in Visible and Infrared Bands

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**Abstract**
Methods of continuous monitoring of volcanic clouds from the ground are discussed, including NIR monitoring of volcanic aerosols, high temperature anomalies, and vegetation using an appropriate filter set and CCD camera. A combination of satellite and ground-based remote sensing techniques is effective for understanding various volcanic phenomena.

## 1. Introduction

Satellite-based remote sensing is used to analyze large eruption clouds, in order to detect otherwise unreported eruptions, identify ground and aviation hazards, evaluate eruption intensity and research the eruptions' climatic impacts. Satellite images showing the large-scale dispersion of volcanic clouds enable us to study long-range transport of atmospheric pollutants from fixed sources. On the other hand, ground-based monitoring of the clouds is also important for the observation of their occurrence, vertical structure and other dynamical characteristics in both large and small scales. Ground-based monitoring is often possible even when satellite observation is obscured by clouds, and can also be used to identify interactions between volcanic and meteorological water/ice clouds, such as orographic or convective clouds over the volcano. Visual recording of volcanic clouds has been done for quite a long time at Sakurajima in southern Kyushu, Japan, and gradually extended to other volcanoes as summarized in [1]. Recently, Near Infrared (NIR) observations of high temperature anomalies using the "night-shot" function of video cameras were reported [2, 3]. Here, the night-shot removes the NIR cut-off filter. The use of an IR filter further highlights the anomalies by the cut-off of visible light. In the daytime, the night-shot mode with the IR filter may give a NIR view from the ground similar to satellite imagery [4]. Such a view may be useful not only to study vegetation on the volcanoes, but also to distinguish clouds from the background sky on misty days. Furthermore, faint aerosols almost invisible in the ordinary view can be clearly recognized in the NIR view. In this report, we discuss the problems of continual observation of volcanic aerosols and other phenomena with visible and NIR bands, together with satellite remote sensing in visible and various infrared bands.

## 2. Ground monitoring of volcanic clouds

The Kagoshima University Volcanic Cloud Research Group is now conducting continual monitoring from the ground at three active volcanoes; Sakurajima, Satsuma-Iwojima and Suwanosejima in southwest Japan [1]. The latter two are located in the Nansei Islands south of Kyushu as shown in Fig. 1. A reason for observing the volcanic clouds is that the visible image of the cloud is a good approximation of the flow of invisible volcanic gases emitted from the crater. In order to analyze the gas concentration data at the foot of Miyakejima Volcano, the group members studied NOAA/AVHRR satellite images of volcanic plumes, and web-camera observations between September 2000 and May 2002 by the Earthquake Research Institute, University of Tokyo [1, 5]. Furthermore, the group, in collaboration with Philippine Institute of Volcanology and Seismology (PHIVOLCS), started continual observation of volcanic clouds at Mt. Mayon in the Philippines [6]. We summarize here the methods and problems in automatic continual recordings of volcanic clouds.

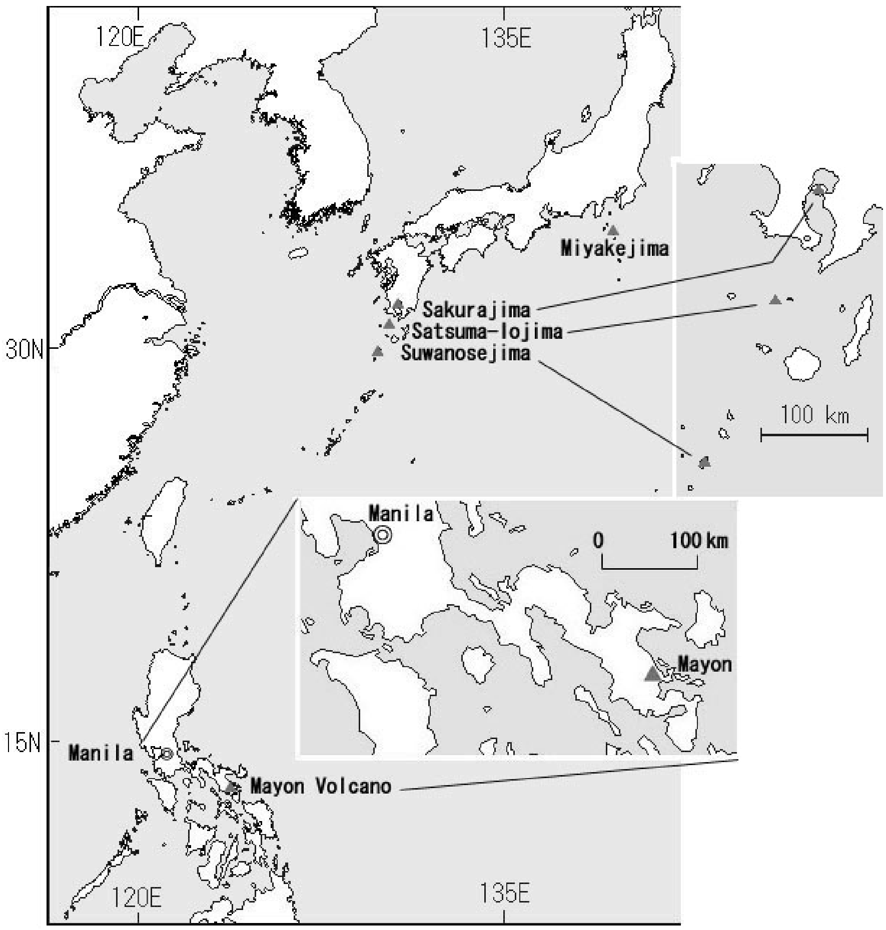



Fig. 1. Volcanoes Sakurajima, Satsuma-Iwojima, Suwanosejima and Miyakejima in Japan, and Mayon in the Philippines.

2.1 Methods of automatic recordings

There are basically three methods for automatic long-time recording of volcanic clouds using a digital camera head with a CCD sensor, as illustrated in Fig. 2.

*(i) Digital still camera*

Automatic recording with a fixed time interval is possible without changing the digital recording media for a few or several months, as long as the power supply is constant. Very few cameras have such specifications. A Sharp MD-PS1 was used successfully at Satsuma-Iwojima between July 1998 and February 2003, and at Tarumizu station to observe Sakurajima between December 1998 and February 2003[1], and is operating now at Mayon since June 2003[6]. This is a pioneering camera, allowing recording with hourly intervals, with 1950 pictures in a 160 MB mini disk (MD). A Casio QV-R4, using a 512 MB SD memory, is now operating in Changchun, China for the study of Asian dust since March 2003, also recording with an hourly interval [7]. Such records are useful to see diurnal changes, and are appropriate to make CD-R archives, or to display on the Internet

Though the production of these cameras has ceased, we found that a new camera, "Ricoh Caplio G4wide" inherited the interval recording function, and we began operating one at Satsuma-Iwojima in December 2003.

*(ii) Interval video recording*

As the ejection of volcanic clouds is rather stationary most of the time, interval video recording is suited for covering a long duration in a cassette tape. The interval length is at most ten minutes with a half second recording in some recent video cameras such as the SONY DCR-TRV series, allowing the 100 days record in a 2 hour mini-DV cassette. Such recordings are now operating at Changchun and Mayon, as back-ups for the digital cameras. It should be noted that the continuity of rapid phenomena such as explosive eruption clouds is lost in ten-minute intervals. Smoother motion can be

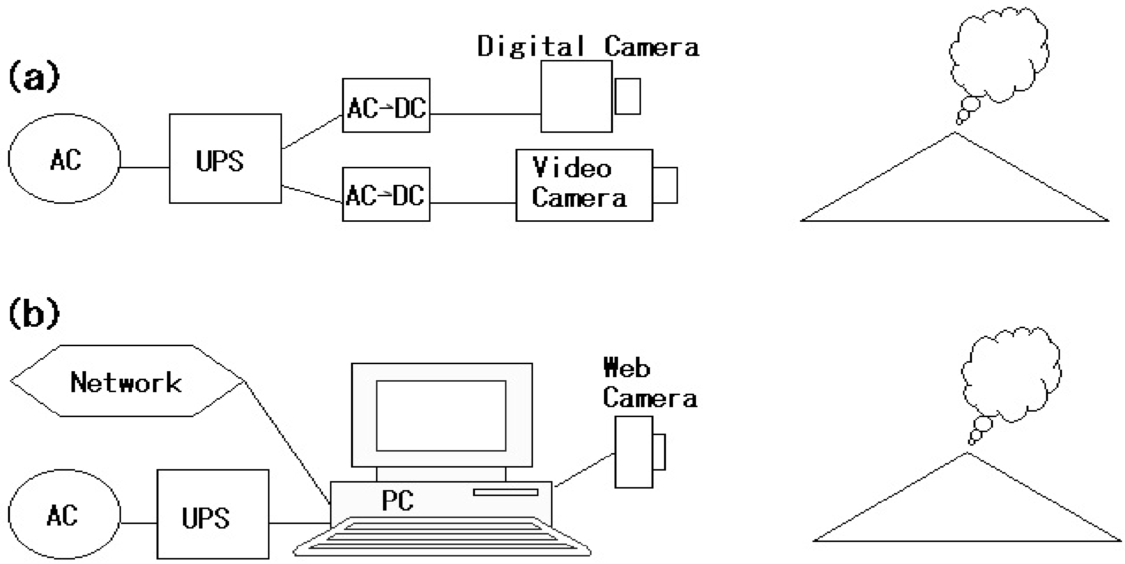


Fig. 2. Systems for automatic recording of volcanic clouds. (a) Digital and video cameras. (b) Web camera system.

obtained by frame recording with 8 sec. (or less) intervals by time-lapse video recorders such as the SONY SVT series, which has been used at Sakurajima since 1992. Random access to video records is now possible by converting them into mpeg files to be stored on CD-R or DVD.

*(iii) Web camera system*

For real time monitoring via Internet and archiving on a hard disk, a web camera system composed of a camera head and a computer is useful. Real time monitoring is especially important for aviation safety. This type of system has been operating at the Faculty of Education, Kagoshima University for Sakurajima monitoring since December 2000 [1], and at Satsuma-Iwojima since February 2003. A network camera server is a small all-in-one apparatus with the camera and server computer built-in. This type has been adopted at Nakanoshima to monitor Suwanosejima 25 km to the southwest, and also at Nansei-Toko Observatory, Kagoshima University and Tarumizu City Office to monitor Sakurajima from different directions [1]. As the network camera server is not suited for large archives, another computer with enough storage is necessary, which may be connected by a local or remote network.

For web-camera systems in general, the interval to get still images can be arbitrarily adjusted by programming. In the above systems, we use 5-20 minute intervals, which is not a problem for hard disks with enough capacity.

## 2.2 Environment for continual monitoring

We summarise the conditions for automatic long-term recording of volcanic clouds for up to a few months.

*(i)* An appropriate observation site inside a building with a window to see the volcano, hopefully with a wide view undisturbed by nearby obstacles and direct sunshine in the scene. Otherwise, outside a building or in the field, an apparatus housing is necessary.

*(ii)* Reliable electric power supply, equipped with UPS (uninterrupted power supply) against power shortages and surges.

*(iii)* A person to look after the performance of the apparatus, restart it after an unexpected stop, and exchange the media. There are many important points to adjust for the initial set-up at the restart, to be listed later.

*(iv)* Internet connection. If a continuous Internet connection is available, a network camera server alone is enough at the observation site for live monitoring with remote control, and the archived data can be stored on another server at remote laboratory. A permanent Internet connection is very useful for such a system, although not available in many regions. Otherwise, the data should be stored on a server in the local area network at the monitoring site, and downloaded daily to a remote server using a dial-up connection.

If the conditions (i)-(iii) are fulfilled, continual observation is possible by using interval recordings with digital still and/or video cameras, changing the media every few months. For real-time or near-real time monitoring, condition (iv) should

be met.
Even if any of the above conditions is not satisfied, it may be possible to leave a digital camera for a month with an appropriate battery* in a sealed package with a transparent window. This risks theft or vandalism of the equipment, and protection against damage from sunshine, rain and wind should also be considered. For the same reason, it is often much more practical to use relatively cheap 'off-the-shelf' equipment for this purpose, rather than more expensive dedicated imagers (* An alternative to AC power supply is to use rechargeable battery pack for digital camera.)

2.3 Initial set up
Finally let us consider the essential points for the initial set up of interval recording mentioned in 2.2 (iii).
White balance: Outdoor, so as to record color information properly.
Focus: Infinity. (Manual focusing is necessary for the NIR observation, to be discussed in 3.2.)
Flash and Beep: Off.
Liquid Crystal Display: Off, to avoid its degradation and save power.
Framing: Relatively wide with a horizon or other horizontal line near the bottom.
There are many other points to be adjusted at the beginning of automatic recordings, depending on the type of apparatus.

**3. Methods of visible and infrared observation of volcanic phenomena**

3.1 Satellite imagery
A number of techniques have evolved over recent years to detect volcanic clouds or sense activity at volcanoes, which we briefly summarize here. In general, these techniques exploit differential reflective or absorptive properties of ash or sulfates in the volcanic cloud. The main gaseous eruption component is usually water, which can often interfere with detection techniques. However, clouds with a sufficiently high ash content, or with sufficient sulfate content, which induces a smaller particle size and inhibits cloud evaporation, are usually distinguishable from water/ice meteorological cloud, provided higher clouds do not obscure the satellites' view.

*(i) Visible bands*
Many eruptions are distinguishable in visible wavelengths because of the relatively low albedo of ash. The color of the cloud can be distinguished using satellites with the appropriate 'true-color' wavelengths (e.g. LANDSAT/(E)TM, SeaSTAR/SeaWiFS and EOS/MODIS), and may be white, light- or dark-gray or brown, depending on the ash content of the cloud.

*(ii) Reflective infrared bands*
Both NIR (e.g., 1.6 $\mu$m) and middle infrared (e.g., 3.7 $\mu$m) are highly sensitive to particle size and composition, a fact which has been exploited for volcanic ash detection [8] and detection of ash-poor, sulfate rich plumes such as from Miyakejima [9]. These images are also useful for the studies of the topography and vegetation coverage in order to investigate the effects of volcanic gas, and are also highly useful for 'hot-spot' (high temperature anomaly) detection as summarized in [10].

*(iii) Thermal infrared bands*
The difference of 12 and 11 $\mu$m bands is very effective in distinguishing lithic aerosols (in dry air) from water clouds, and is utilized for detection of ash cloud [11-14] and Asian dust [15]. The 8.6 $\mu$m band is utilized, combined with other thermal bands in Terra/ASTER [16] and MODIS, for the detection of $SO_2$ in the volcanic gas [17]. Ultra-violet reflection is also utilized to detect $SO_2$ in TOMS, but only with low resolution (39x39 km pixel size for Earth-Probe TOMS at nadir). MODIS data is highly useful for monitoring ash clouds because of its many useful channels [18-21]

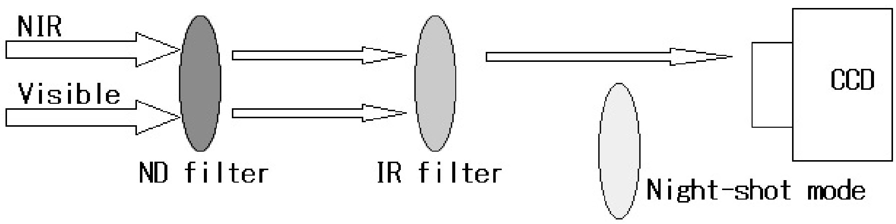



Fig. 3. Visible and NIR radiations versus filters for a CCD camera head.

3.2 Ground observation

Here we discuss a simple use of NIR images to supplement visible imagery, using filters as described in Fig. 3.

*(i) Night-shot* : Ordinary CCD sensors in video and digital cameras have some sensitivity to wavelengths up to about 1.1 μm such as gray line in Fig. 4. In the night-shot mode, the NIR cut-off filter is removed to increase the sensitivity under dark conditions, with the sacrifice of the color balance. The mode was utilized to detect the NIR radiation as a very hot anomaly at the vent of Mayon volcano in the Philippines, though it was invisible to the naked eye [2].

*(ii) IR filter* : Recently, IR filters to cut-off the visible band with the boundary around 840 nm are available, such as broken line in Fig. 4. In the night shot mode equipped with such a filter, one can get NIR images similar to MODIS band2, 841-876 nm. Very hot anomalies are enhanced by IR filters, as studied at the crater of Aso volcano [3]. It is preferred to avoid outdoor light even in twilight, as it contains NIR radiation originating from the sun.

*(iii) ND filter* : In the daytime, the night-shot mode with IR filter may give a NIR view from the ground similar to satellite imagery, when the solar reflection is adequately reduced by a neutral density (ND) filter. Such a view may be useful not only to study vegetation on the volcanic surface, but also to distinguish the clouds from the background sky on misty days. Furthermore, faint aerosols almost invisible in ordinary view can be clearly recognized in the NIR view, as shown in the next section.

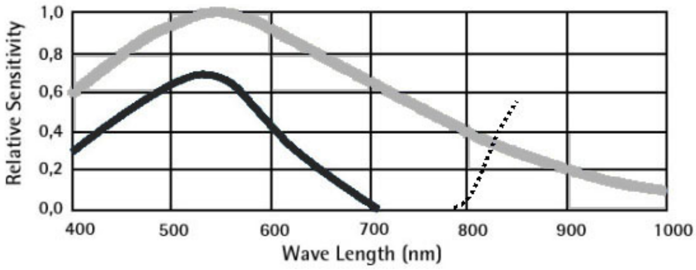
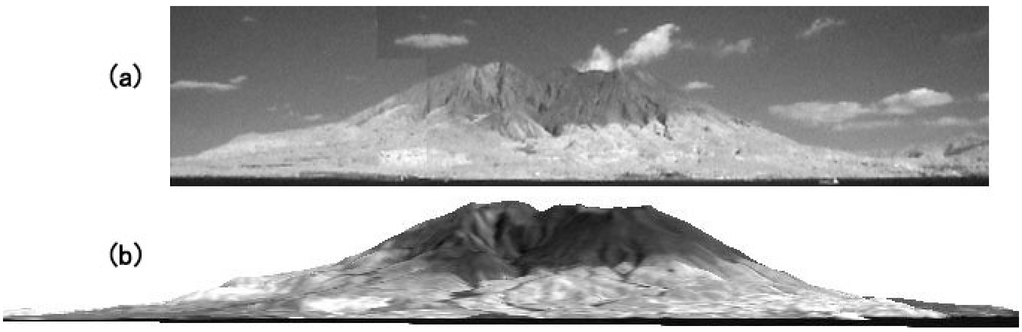



Fig. 4. Sensitivities of color (solid line) and IR (gray line) cameras of the network camera AXIS2420 series, and the IR filter of Fujifilm IR-84 (broken line).



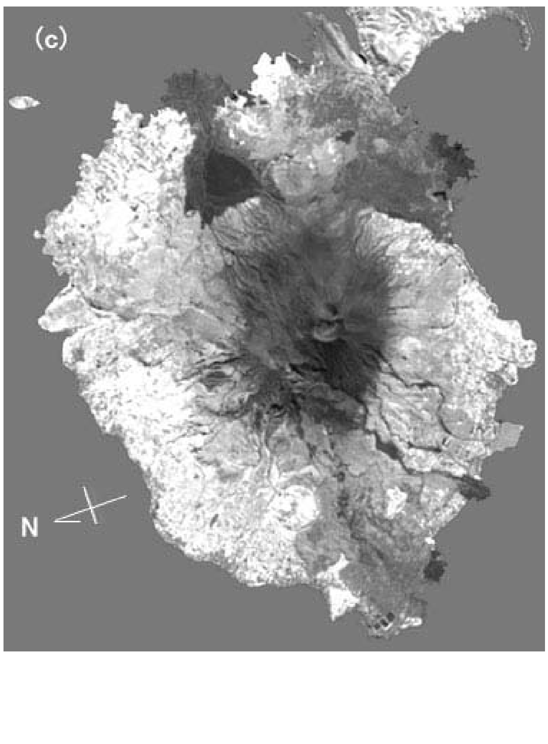




Fig.5. NIR images of Sakurajima.

(a) Ground observation at 9.8 km WSW from the crater on Oct. 2003 at 13:40, recorded on mini-DV tape in SONY DCR-TRV30with IR-84 filter in night-shot mode.

(b) A 3D view of the LANSAT-5/TM-4 data on 26 Aug. 1998 at 10:10 from WSW by using the SiPSE system.

(c) The top view of TM data as in (b).

## 4. Results

4.1 Sakurajima

Previous works of ground observations and satellite imagery of Sakurajima volcano are summarized in a booklet [22]. The first tests of NIR observation of Sakurajima volcano from the main campus of Kagoshima University, about 10 km west of the crater, were summarized in [23]. Here we report a few additional results.

*(i) Vegetation*

Fig. 5 shows a comparison of NIR images from the ground (a) as described in 3.2 (iii), and the LANSAT-5/TM-4 (b and c), where 3D representation (b) of TM data combined with the DEM data of Geographical Survey Institute of Japan is obtained by using Satellite Image Presentation System for Education (SiPSE) [24]. We see that the vegetation is absent near the summit, because of the adverse conditions. It should be noted that the range of the ground observation, 0.84-1.1 μm, is not quite the same as that of TM-4, 0.76-0.90 μm, aside from the difference of the solar elevation and direction. As a result, the reflections from rocks and barren lands are somewhat stronger in the ground observation than TM-4. This problem will be discussed in more detail in near future.

*(ii) Aerosol*

Ground observation of a faint plume at Sakurajima in fine weather is shown in Fig. 6, where (a), (b) and (c) are NIR, red and green components of visible picture. We see that the contrast of the plume against the background sky is stronger in longer wave lengths, i.e., the plume is clear in (a), not so clear in (b) and almost invisible in (c). In the blue color not shown here, there is no contrast. This situation is quite opposite to the satellite image of a faint plume over the sea [25]. In the case of Fig. 6, the morning sun is right of the scene, and the background sky is most dark in NIR, while the scattering by plume aerosol is seen. Similar results are obtained in other configurations of the sun.

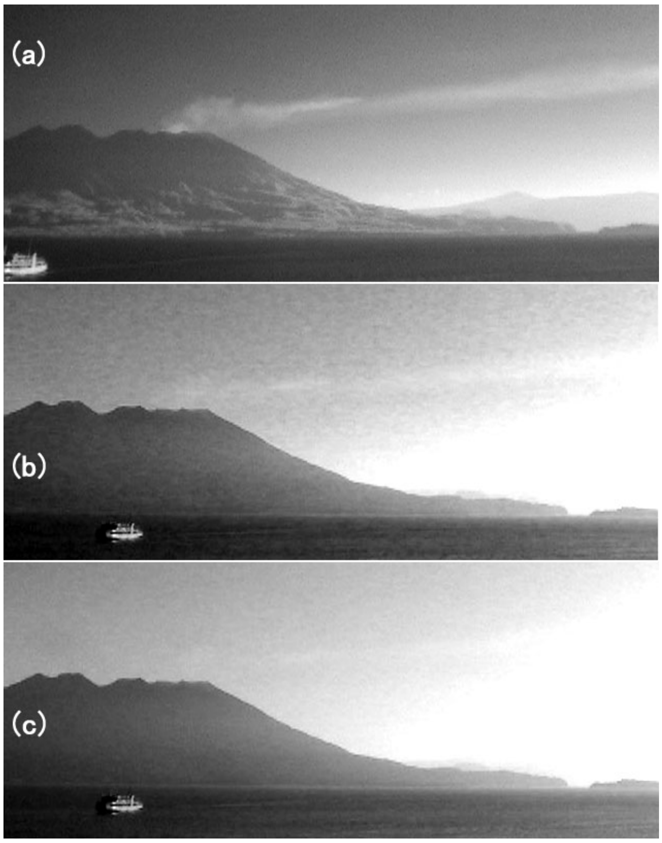



Fig. 6. A faint plume at Sakurajima on 2 Dec. 2003 at 8:00, with the camera as in Fig. 5(a). (a) NIR, (b) and (c): Red and green components of a visible image.

<u>4.2 Satsuma-Iwojima</u>

Since July 1998, hourly volcanic cloud observations such as those in Fig. 7 have been displayed on a homepage. Recently, we started the observation in the NIR band.

*(i) Hot anomalies*

In the nighttime, hot anomalies inside the crater and on the outside wall have been observed in LANDSAT-5/TM images [26]. From the ground, it is expected to observe the anomalies on the outside wall. We started NIR observation of 0.85-1.1 μm by using a Kenko IR-85 filter on a SONY DCR-TRV30 in the night-shot mode since the end of July 2003. The first trials, lasting until November 2003 were unsuccessful.

*(ii) Volcanic clouds and aerosols*

In the night-shot mode with IR-85 filter mentioned above, the daytime images were over-exposed except for in the morning before sunrise, and during the evening. Therefore, we have added a ND filter (1/100) to reduce over-exposure since 2 Dec. 2003. On the other hand, the Creative Webcamplus web-camera, having a CMOS sensor, has been used equipped with a Fujifilm IR-84 filter for recording with 30 min. interval between 7:00 and 17:30 on a server computer. Though this head has neither the night-shot mode nor the NIR-cut filter, a color image may be obtained by a software cancellation of IR components. We see that NIR image is obtained by using the IR filter. In the interval recording, faint plumes are obtained successfully, as shown on the homepage, http://arist.edu.kagoshima-u.ac.jp/volc/iwo/ .

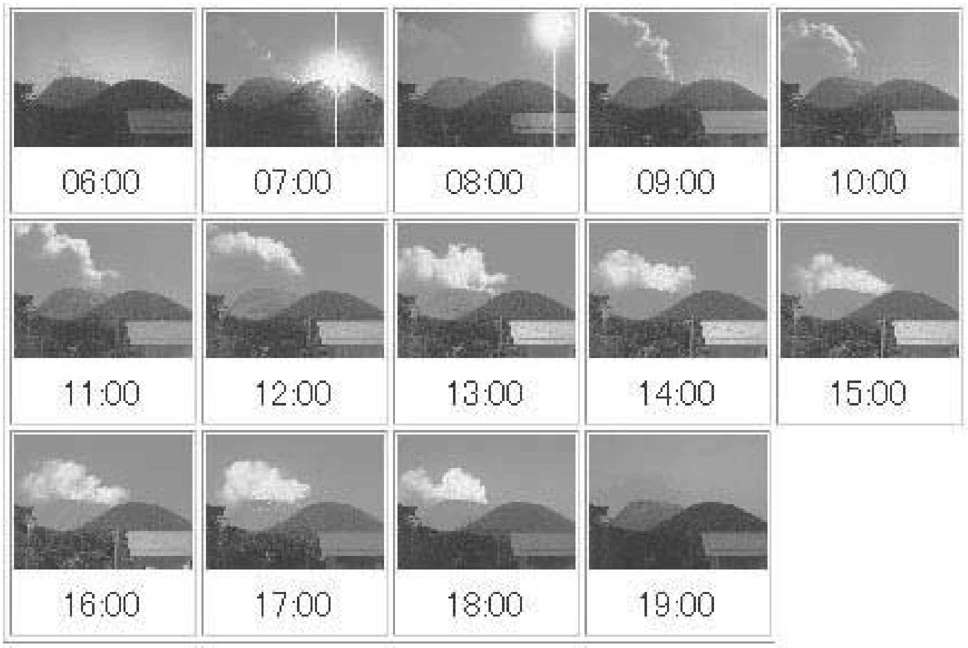



Fig. 7. Volcanic clouds of Satsuma-Iwojima observed from 3 km west of the crater, with one-hour interval on 22 Aug. 2002.

Fig. 8 shows a comparison of southern flank of Iwo-dake from a ferryboat without and with the IR filter on the digital camera Sharp VN-EZ5. We see that IR filter is enough to obtain NIR image, though the exposure time should be somewhat long.

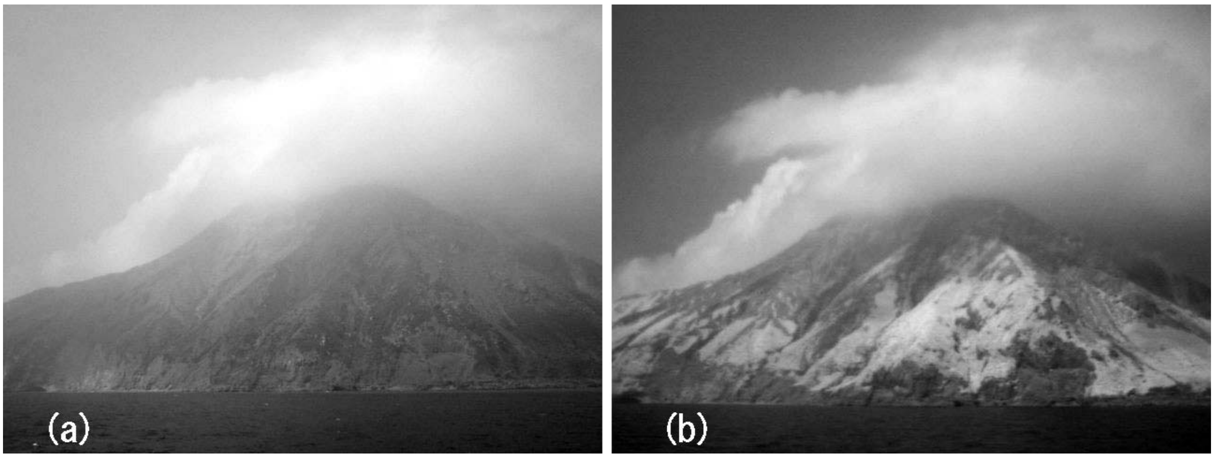



Fig. 8. Southern flank of Iwo-dake from a ferry-boat, by using the Sharp VN-EZ5 (a) without and (b) with the IR-84 filter, respectively.

4.3 Suwanosejima

In recent years, Suwanosejima volcano has been the most eruptive in Japan, with the eruption columns a few km above the crater occasionally. We have done satellite detection with NOAA/AVHRR and EOS/MODIS, and web camera observation [27, 28]. Together with manual photos from the inhabitants, we have listed them in the homepages,

Topics of SiNG-Kagoshima (in Japanese): http://arist.edu.kagoshima-u.ac.jp/sing/topics/

MODIS Database of Volcanic Eruptions in the Western Pacific: http://arist.edu.kagoshima-u.ac.jp/volc/ocean/

Suwanosejima is a target of the near real time NOAA image browsing system for volcano monitoring of Tokai University Research and Information Center, together with Sakurajima and Miyakejima [29].

*(i) Web camera observation*

The site of the web camera at Nakanoshima, started on 6 Aug. 2002, is 25 km northeast of the crater, separated by the sea. Though the eruption clouds are often well observed such as shown in Fig. 9, the images are almost always partially obscured by haze or mist. We may expect to obtain better images in NIR.

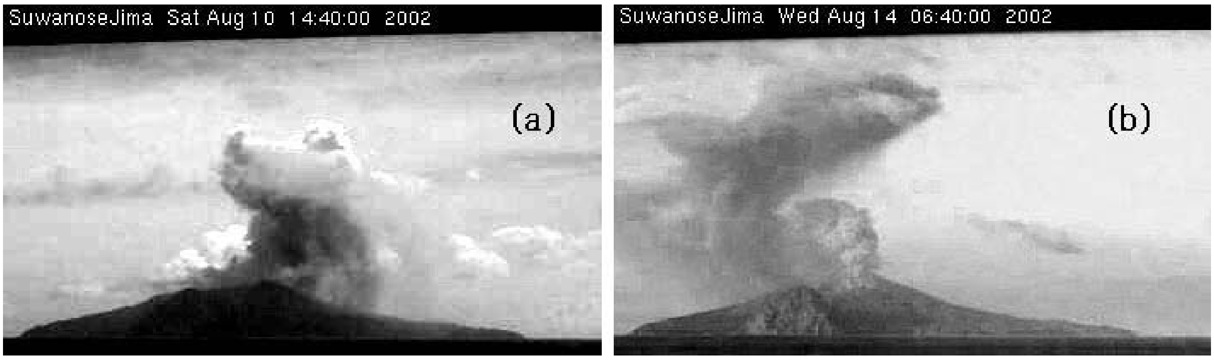



Fig. 9. Eruption clouds at Suwanosejima, imaged by the web camera at Nakanoshima, after stretching the contrast.
(a) Aug. 10, 2002 at 14:40 JST. (b) Aug. 14, 2002, 6:40 JST.

*(ii) Highlights of ground and satellite observations*

In 2002, Suwanosejima volcano was especially eruptive. Here we make a brief list of remarkable events [27, 28].

April 12: In the nighttime, a hot spot was observed on AVHRR band3, and in MODIS (22:20 JST). Next day, plumes about 400 km long were seen in AVHRR and MODIS.

June 18: Eruption column of height 3 km was recorded in photos and AVHRR imagery.

July 23-24: Inhabitants observed several eruptions, and their photos and AVHRR were obtained.

Aug. 19-22: Several strong eruptions were observed accompanied with roaring sounds and vibrations, and also with volcanic lightning and red sky in the nighttime. Web camera images, photos were obtained as well as AVHRR and MODIS images.

Dec. 5: The volcanic plume rose high over the island during 10:00 to 11:00, 15:00 to 16:00JST, with 11-15 explosive eruptions, in spite of strong winds for the whole day, as recorded by the web camera, photos, MODIS and GMS-5 visible images.

4.4 Vegetation of volcanic island Miyakejima

Volcanic clouds at Miyakejima are discussed in [9, 18] in terms of ground observation and satellite images. Here we show the Terra/ASTER images of Miyakejima Island in Fig. 10, in which the damage of the vegetation due to the gas is evident at specific directions, consistent with the appearance of high concentration events of $SO_2$ around the island [1, 9, 18].

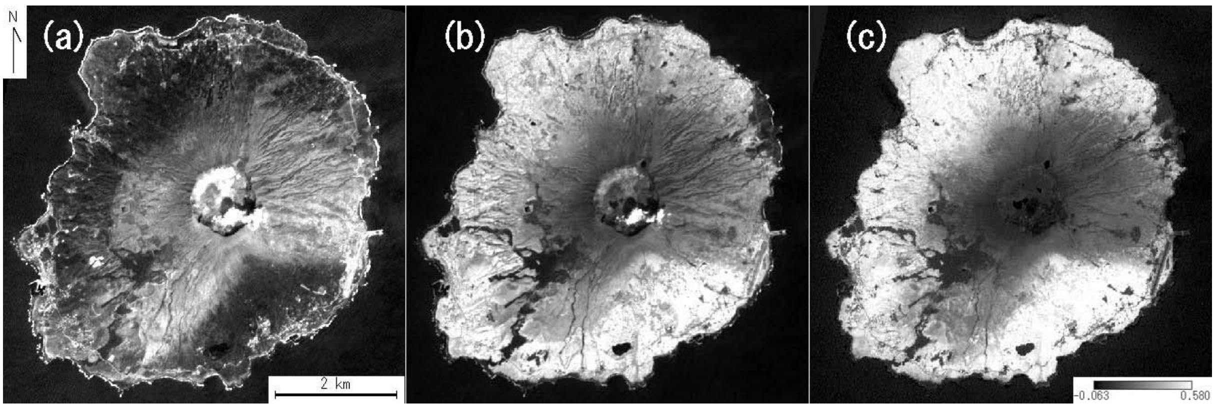



Fig. 10. ASTER images of Miyakejima on 7 April 2003.
(a) VNIR-2 (0.63-0.69 μm). (b) VNIR-3 (0.78-0.86 μm). (c) NDVI.

We note that the NIR image gives a similar result for the vegetation as the normalized vegetation index (NDVI) defined as NDVI = (NIR-Vis) / (NIR+Vis), where we have used the red band of VNIR for Vis.

**5. Concluding remarks**

Long-interval, automatic, ground-based camera observation is useful for studies of volcanic clouds, Asian dust, and meteorological clouds. Real-time cameras are important for disaster prevention, and the archived records serve to understand the phenomena scientifically. The use of 'off-the-shelf' equipment has great practical advantages over more expensive infrared equipment. Combining these data with satellite information is very effective.

The use of the NIR band has opened a new era of the ground observation. It is very desirable that the makers disclose the detailed properties of the CCD sensors and filters. Then, the cameras may be used as a measuring apparatus similar to the satellite sensors, and the manipulations by using different bands such as tried in [23] may find firm basis. The calibration studies of them are important problems to be done.

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