A Recent Result of Topographic Measurements by the GSI's Airborne SAR: A Case Study of the Volcanic Island of *Miyake-jima*

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Abstract

The Geographical Survey Institute (GSI) introduced an airborne SAR system in fiscal 1996 and 1997 in order to confirm its usefulness and to develop and advance the latest technology of topographic measurement that replaces photogrammetry. The system has been experimentally operated since fiscal 1998 and one of its most dramatic results has been its observation of the volcanic island of Miyake-jima. The major purpose of the observation by the GSI-SAR was to understand the current situation of the topography of Miyake-jima that has greatly changed at the summit as a result of the series of volcanic activities that began in 2000. Another purpose is the confirmation of a new method for generating detailed DEM by single-pass interferometry of the GSI-SAR. The results were very satisfactory. The GSI succeeded in showing the cave-in topography of the summit of Miyake-jima after its eruption in 2000 and generating its DEM with 5 meters precision in height. This is one of the most successful cases to show the strong points of SAR observation because the flight was ventured under a lot of clouds and volcanic smoke. Though several issues such as funding and legal restrictions remain, the GSI-SAR has clearly been proved to be a useful tool and we should continue to improve its effectiveness.

1. The introduction of an airborne SAR to the GSI

The synthetic aperture radar (SAR) of the airborne type has several major advantages:

a) Observations can be made both in the daytime and at night and are less affected by weather.
b) Higher resolution and higher mobility than the satellite SAR.
c) Digital elevation models (DEMs) and contour maps are easy to produce because of tridimensional measurement of the topography by the single-pass interferometric process.
d) Slight movements on the earth's surface can be detected by repeat-pass interferometry.

One of the main reasons for these advantages is that the SAR is an active sensor whose emitting wavelength corresponds not to visible rays but to microwaves. The Geographical Survey Institute (GSI) introduced an airborne SAR system in fiscal 1996 and 1997 in order to confirm these strong points and to develop and advance the latest technology of topographic measurement that replaces photogrammetry. The system has been experimentally operated since fiscal 1998 and several interesting data have been obtained to study. For instance, Okatani *et al* (1999) and Watanabe *et al* (1999) reported on the results of the first observation by the GSI's airborne SAR (GSI-SAR) of the *Izu* peninsula, Okatani *et al* (2001) introduced the method of generating DEM by GSI-SAR data, and Koarai *et al* (2000a, 2000b) published papers about the results of the experimental flights carried out up to then.

The GSI prepares and maintains a geospatial database of whole Japan whose accuracy is equivalent to the 1/25,000 scale topographic map. It is one of the most fundamental sources for geographic information. Above all, the GSI has no rival in providing information about landforms. The results of every topographic survey are open to the public in principle both as 1/25,000 topographic maps in classic paper form and as DEM in the recent digital style that is easy to process by GIS.

Landforms are transformed both by human workings such as housing developments and by natural phenomenon such as slope collapse and volcanic eruptions. Especially in case of a natural disaster, it is necessary to understand precisely and promptly the condition of the stricken site, including the transformation of the topography. The airborne SAR mentioned above meets these requirements. Thus, since the introduction of the airborne SAR, the GSI has been engaged in the practical development of this system.

In order to improve the research and development, several field surveys were taken to grasp the real-time progress of a disaster through a General Technology Development Project run by the former Ministry of Construction[1)] after the introduction of the GSI-SAR.

Table 1 The main specifications of the GSI-SAR

【Sensor unit】	
Emitting center frequency	9.555GH (X-band, wave length=3.14 cm)
Band breadth	100 MHz
Off-nadir angle	55 - 75 degrees
Quantum bit number	4 bit/8 bit (selective)
Polarization	Horizontal both in transmitting and receiving (HH)
Transmitting pulse breadth	10 μsec
Swath width	5 - 10 km
Maximum resolution	Range: 1.5 m/Azimuth: 1.5 m
Weight	170 kg (375 lb.)
Electric power of consumption	1 kW
Maker	NEC Corporation
【Platform unit】	
Aircraft	Cessna 208
Width × Length	15.88 m × 11.46 m
Flight altitude in observation	3,000 - 4,250 m (10,000 – 14,000 ft.) by ordinary
Ground speed in observation	260 - 300 km/hr (140 – 160 knots) by ordinary
Engine	Turboprop gas turbine engine
Flight range	Approximately 2,000 km (1,300 miles)
Ownership	HONDA Airways Corporation
【Data processing unit】	
Hardware	SUN Blade1000 900MHz UltraSPARC III (Required memory 512 Mb and more, Required HD 20 GB and more)
OS	Solaris 8 (Japanese version)
Main functions of software	RAW data input
	Level 0 data generation
	SAR visualized image generation Azimuth condensation by frequency method or time and space method etc.
	SAR interferometry Map projection processing, output of XYZ data text etc.
	Imaging Output in TIFF format
Software builder	NEC Corporation

Perhaps the best example of employing our SAR system was the observation of the large deformation of *Miyake-jima* volcanic island in 2000. Though Miyawaki *et al* (2002a, 2002b) and Iida *et al* (2002) already reported on this, the author would like to discuss the SAR operation by the GSI, adding the general information about the GSI-SAR system from the author's previous report in Japanese (Sato *et al*, 2002).

2. Overview of the GSI-SAR

2.1 Basic specifications

Table 1 shows the basic specifications of the GSI-SAR. The system consists of three major units: 1) sensor unit (Fig. 1), 2) platform unit (Fig. 2) and 3) data processing unit. The sensor unit should be mounted on the platform unit and be detachable. The data processing unit

Fig. 1 Sensor Unit.

Fig. 2 Platform Unit.

is at the photogrammetry laboratory in the main building of the GSI in Tsukuba.

2.2 Sensor unit

The emitting center frequency of the sensor is 9.555 GHz, which corresponds to the X-band. Generally speaking, the relief of the landforms, especially in less vegetated land, is much more clearly and minutely observed with X-band rays than with L-band rays whose emitting center frequency is from 1 to 2 GHz. On the other hand, reflected waves tend to be observed from the upper parts of the land surface such as trees or crops in areas where vegetation is abundant. This point requires special attention for the topographic measurements, but it can still provide information on the spread of vegetation.

Other features of the GSI-SAR sensor can be enumerated as follows:

a) The polarization is horizontal both in transmitting and in receiving (H-H).
b) The interferometric mode can be selective.
c) The off-nadir angle can be varied between 55 and 75 degrees, though the angle has to be fixed before the observation and cannot be changed during the flight.
d) The maximum resolution is 1.5 meters in both the range and azimuth.

The sensor consists of five units, i.e. an antenna, a transmitting and receiving device, a data-recorder, a positional detector and a signal-processing device. The acquired observing data and the positional data of the platform obtained by GPS observations are recorded on a magnetic tape of the data-recorder in order to analyze at the laboratory after returning.

2.3 Platform unit

The platform of the GSI-SAR is a Cessna 208 manufactured in the U.S. The GSI has its own aircraft for aerial survey nicknamed *Kunikaze II*, but it is not equipped for mounting the SAR sensor unit because *Kunikaze II* is more than twenty years old. It was thus necessary to remodel the plane and have it pass inspection so that the SAR sensor can be mounted on *Kunikaze II*. However after careful consideration of the procedures and costs involved, the GSI decided that it was the most effective to rent a plane from an air service company. Consequently, the GSI charters a specific plane for every SAR observation.

2.4 Data processing unit

The basic flow of analyzing SAR data is as follows: 1) Data conversion from raw data to level 0 data, 2) Processing the SAR visualized imaging and interferometry, 3) Phase unwrapping (the radar shadow and layover area should be masked out), 4) Elevation conversion, 5) Map projection conversion and 6) Generating the DEM. These tasks are done by a dedicated work station. For the DEM generation, the GSI introduced a new program of analysis for time and space in 2001 that enables the generation of detailed DEM if the plane meets turbulence and the obtained raw data are disturbed.

3. Case study

3.1 Overview of the volcanic eruption of *Miyake-jima* in 2000

The *Izu* volcanic islands that *Miyake-jima* belongs to and the surrounding area constitute one of the most remarkable regions in Japan for both volcanic and seismic activity. *Miyake-jima*, situated about 180 kilometers south of central Tokyo, is a typical stratovolcano that consists mainly of basaltic products (Fig. 3). It is well known that *Miyake-jima* erupts periodically. In recent times, it has erupted in 1940, 1962 and 1983, which indicates that the next eruption could be just around the corner. In the

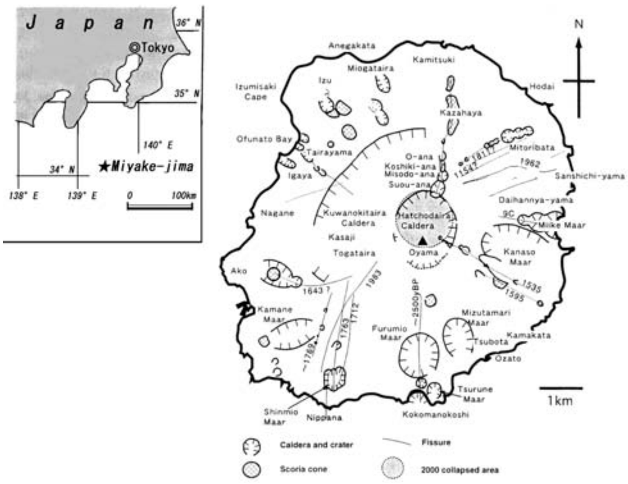


Fig. 3 Map showing distribution of craters, fissures and calderas. Shaded area collapsed in the period July-August, 2000 (partly revised from Tsukui et al, 2001).

evening of June 26, 2000, after a series of earthquakes had hit the island, remarkable seismic activities started and a small volcanic eruption occurred at the bottom of the adjacent sea. On July 8 of the same year, the summit of the island greatly caved in with an amount of smoke and formed a caldera. After this large event, the belching of a great deal of toxic volcanic gas consisting of sulfur dioxide has continuously occurred with several eruptions including a great eruption on August 18 of the same year. This type of eruption is so unusual that a lot of volcanologists are now paying close attention to changes in the situation. According to Kazahaya *et al* (2001), there is no precedent in the world for such a large amount of emitted volcanic gas.

At the end of 2002, the volcanic and seismic activities became rather tranquil compared with the peak. But the emission of volcanic gas has not declined yet, thus about 3,800 evacuees have had to stay continuously outside of the island, for example in central Tokyo, for more than two years.

3.2 The SAR observation by the GSI

The formation of the cave-in crater is a noteworthy geological event that occurred at the summit called *Oyama* that was 813 meters above the sea before these eruptions. The topography of the summit was greatly transformed because of the cave-in, but it was not easy to do a field survey on site or to take aerial photographs with conventional photogrammetry, because it was very dangerous to approach an active volcano. That was the reason why the GSI made topographic measurements employing SAR. Two observations by GSI-SAR were carried[2], that is on September 28, 2000 and on January 16, 2001, and satisfactory results were obtained in each case. Hasegawa *et al* (2001) already reported the estimated volume of the cave-in crater as approximately 600 million cubic meters based on the observations on September 28. This paper mainly describes the observing method of January 16 and examines some results from that time.

3.3 The purpose and method of the observation

The major purpose of the observation on January 16, 2001 by the GSI-SAR was to understand the current situation of the topography of *Miyake-jima* half a year after the great cave-in of the summit. There was another purpose that the GSI confirms a new method for generating detailed DEM by single-pass interferometry of the GSI-SAR.

Fig. 4 shows the courses of the observation flights at that time. Two observations were done from the north changing the distance from the crater (4 kilometers and 8 kilometers) and the same way was carried out from the other three directions. So the obtained SAR data totaled eight kinds of image. The weather on that day was cloudy and a great deal of volcanic smoke that was being emitted from the summit obscured the bottom of the crater (see Fig. 5). In addition to the data shown in Table 1, the following supplemental data were also collected on the observation day: swath width: approximately 5 kilometers; off-nadir angle: 55 degrees; flight altitude: 4,250 meters

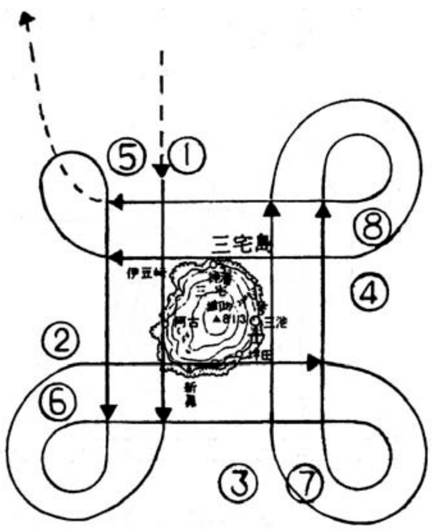


Fig. 4 Observational course around Miyake-jima on January 16, 2001.

Fig. 5 Weather condition at the observation. (January 16, 2001, over the crater)

above the ground; ground speed: 180-430 kilometers per hour. The position of the platform during the observation was calculated by GPS kinematic positioning method after returning to the base. The *Komuro-yama* in *Izu* peninsula was chosen as the GPS base station for the baseline analysis. The inclination of the platform was calculated by the data of GPS and IMU (Inertial Measurement Unit).

The reason for setting up the flight course as shown in Fig. 4 derives from one of the characteristics of SAR observation. That is, it is necessary to have a little distortion in the visualized SAR imagery. For instance, the radar shadow and the layover come under it. The former means the unobservable area derived from the near steep crater ridge obscured the microwaves because the GSI-SAR emits microwaves to the left-hand below. The latter is the distortion of the visualized SAR images because emitted microwaves reach the top of the far ridge faster than the bottom of the crater. That is why it is necessary to process the multiple data in order to make up for the lack of data and to correct the distortion.

3.4 Results of the analysis

The obtained raw data were transformed into visual images by each course. Fig. 6 shows one of visual images. The resolution of this image produced by employing the raw data with 1.5 meters resolution is 6 meters. Detailed features such as gullies around the crater ridge can be clearly recognized. It should be noted that this image still has some of the distortion mentioned above and the scale of the image is undetermined because it is not yet transformed into an orthophotogragh.

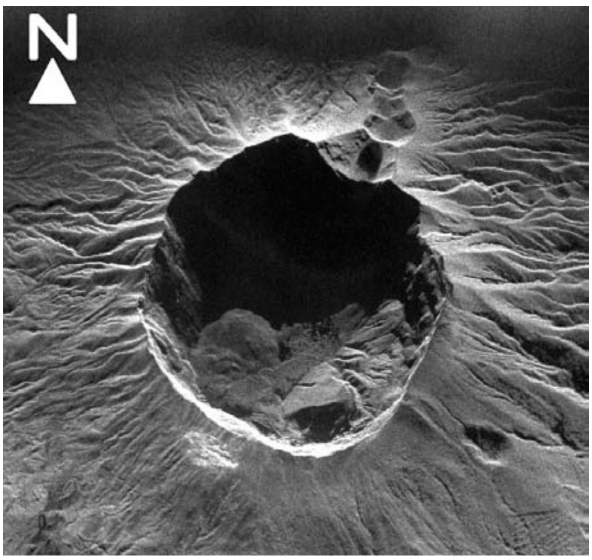
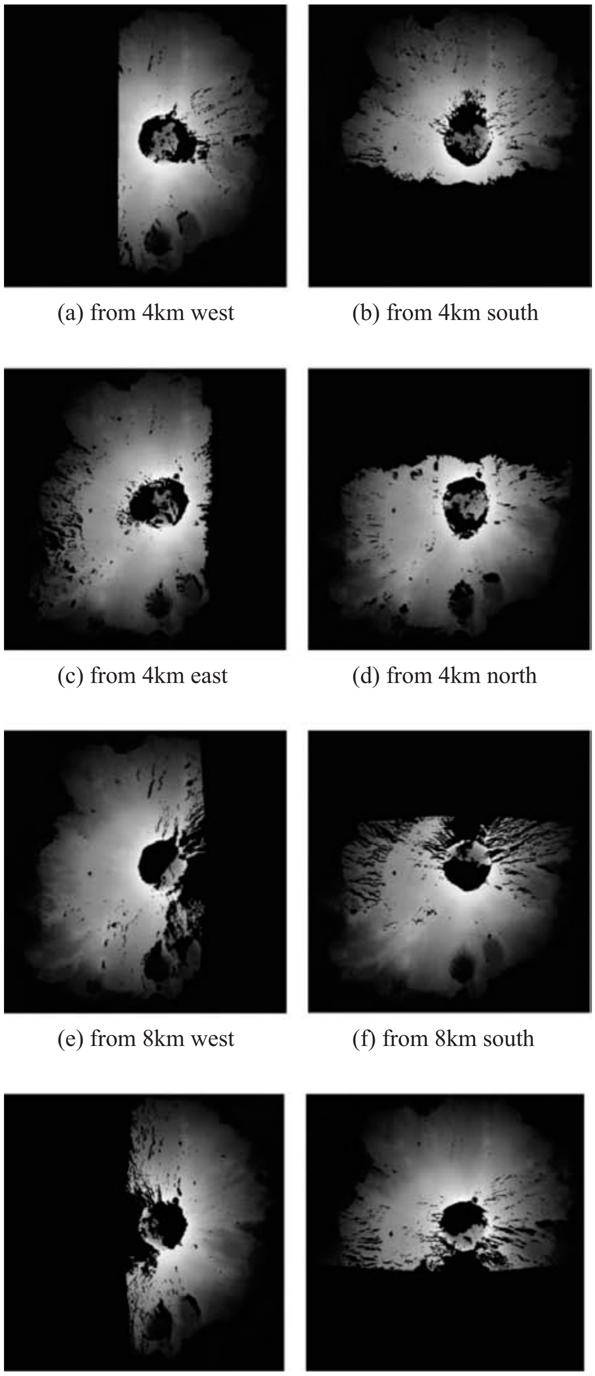


Fig. 6 An example of visualized SAR imagery.
1) observed from 4km north of the crater
2) crater diameter is about 1.6km

Subsequently, the interferometry, phase unwrapping, elevation conversion and map projection were carried out in that order. As a result, eight kinds of DEM were generated in each course (see Fig. 7). Although each DEM



(a) from 4km west (b) from 4km south
(c) from 4km east (d) from 4km north
(e) from 8km west (f) from 8km south
(g) from 8km east (h) from 8km north

Fig. 7 Incomplete DEMs for 8 observations.

still lacks observation data and its imagery is distorted at this moment, each DEM is successfully compounded to minimize them (see Fig. 8). About a month was required to generate it. Further information about the process of the DEM generation is given in Miyawaki *et al* (2002a, 2002b) and Iida *et al* (2002).

The accuracy of the composite DEM was verified by comparing it with a 10-meter grid DEM produced from the GSI's volcanic base map of *Miyake-jima* surveyed in 1981 and revised in 1983 (note that the area around the crater had changed too much for comparison). As a result, mean error was -0.37 meters and mean square error was 5.26 meters. In other words, DEM with 5 meters precision in height can be generated employing the GSI-SAR.

Of course, a bird's-eye view can be produced using the generated DEM as shown in Fig. 9 and we can easily compare with the bird's-eye view of preeruption (Fig. 10).

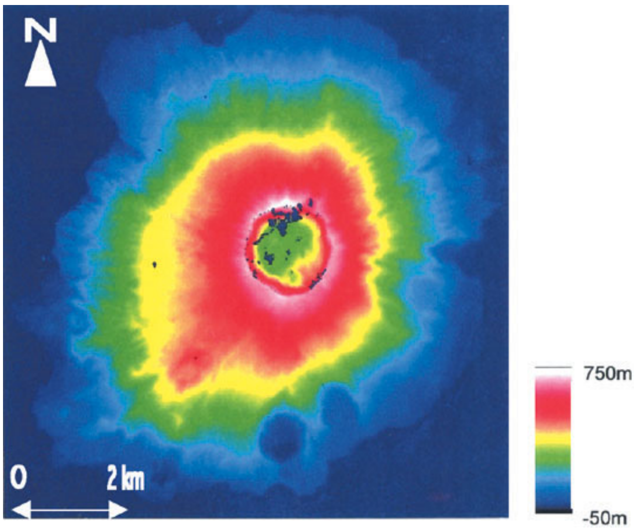


Fig. 8 Composite DEM of Miyake-jima.

4. Conclusion

The GSI has carried out several experimental observations with airborne SAR since fiscal 1998 in order to prove its usefulness for topographic measurements. Above all, the GSI succeeded in grasping the cave-in landform of the summit of *Miyake-jima* after its eruption in 2000 and generating its DEM with 5 meters precision in height. This is one of the most successful cases to show the advantages of SAR observations because the flight was made under a lot of clouds and volcanic smoke. It would be impossible to make observations with conventional optical sensors under such tough conditions.

On the other hand, we have to recognize that there are still some problems with the GSI-SAR. For example, each flight costs at least ten million yen. Another issue is the regulation by the Japanese radio wave law. SAR observation is currently restricted because of the emission of microwaves. Experimental observations are much easier, but the regulation will be much tighter if the GSI begins to carry out periodic observations by SAR. As a matter of fact, it is almost impossible to do it under the present radio wave law.

Though several problems still remain, the GSI-SAR has been clearly proved to be a useful tool and we should continue to improve its effectiveness.

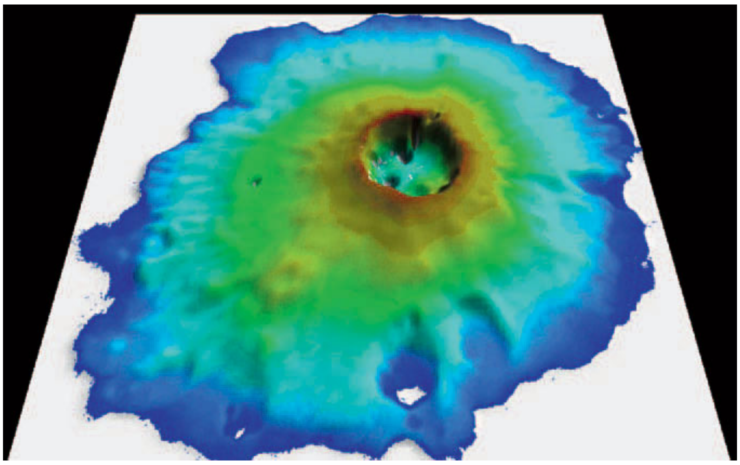


Fig. 9 Bird's-eye view of Miyake-jima derived from the generated DEM.

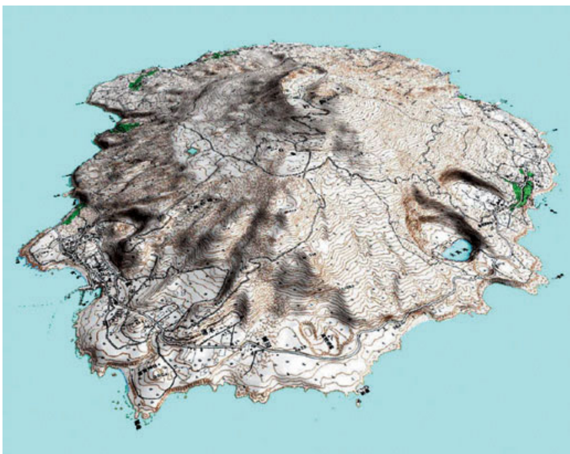


Fig. 10 Bird's-eye view of Miyake-jima before the eruption in 2000 (cited from the GSI home page).

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Notes

1) The General Technology Development Projects are programs that address such sweeping goals as "Development of technology for earthquake disaster prevention in large metropolitan areas," and "Development of methods for assessing fire safety performance." Systematic research should be done based on three-way collaboration among business, academia and the government in which government agencies play a central role in promoting plans. From fiscal 1972, when the first such project was begun by the former Ministry of Construction, to the end of fiscal 2001, 45 projects were completed and the same plans are being continued by its successor, the Ministry of Land, Infrastructure and Transport. The GSI has combined two programs to encourage greater use of GSI-SAR. One project is titled "Research on Technology Utilizing Artificial Satellites for Dealing with Disasters" (fiscal 1999-2001) and the other is "Development of High National Land Management Technology" (fiscal 1999-2002).
2) The observation on September 28, 2000 was a joint effort of the GSI, NEC Corporation and HONDA Airways Corporation. The observation on January 16, 2001 was planned by the GSI while the field work was handled by NEC Corporation.

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