Surface change detection, topographic and geologic mapping of Okmok volcano, Alaska, using high-resolution AIRSAR sensor data

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Abstract A study of Okmok volcano, located in the Aleutian Islands (Umnak Island - Alaska) was carried out using Airborne Synthetic Aperture Radar (AIRSAR/TOPSAR) radar data acquired in June 2000. It investigated the surface changes that resulted from the 1997 eruption that produced two large lava flows within the caldera. In addition, topographic and geologic mapping was conducted with the aid of AIRSAR data and Landsat satellite imagery. The high-resolution (5-meter) radar backscatter and digital elevation models (DEMs) generated from the SAR dataset were analysed with existing topographic data and its accuracy evaluated. For validation purposes, when compared to previous studies and ground measurements, the AIRSAR data demonstrated excellent spatial and elevation accuracies. This contribution will provide further insights regarding the uses and applications of remotely sensed AIRSAR data for volcanological studies and topographic and geologic mapping purposes.

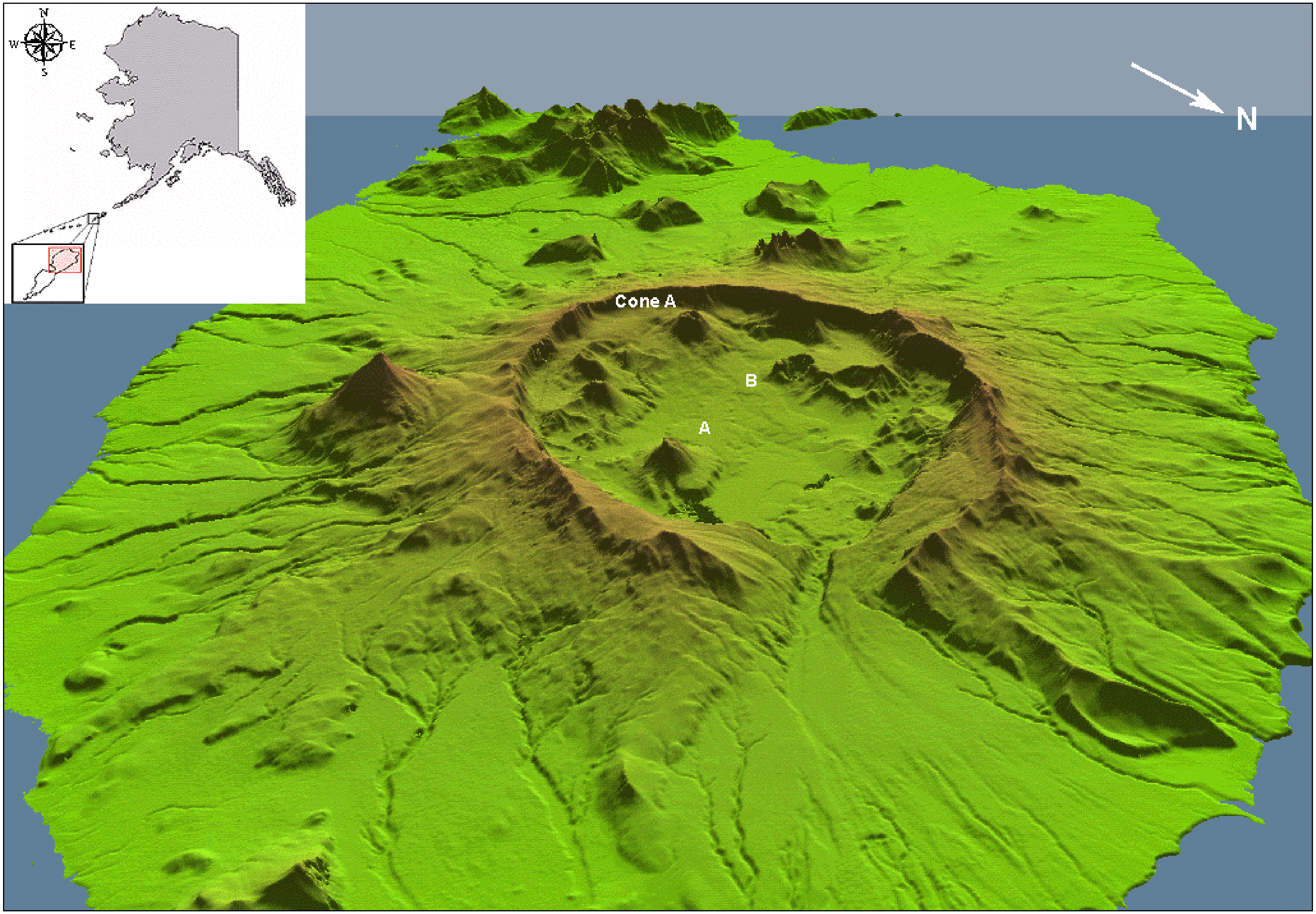
1. Introduction

Modern remote sensing techniques present researchers with unique information required for the completion of studies that involve detailed and updated spatial and spectral datasets. In remote and hazardous environments, including volcanic settings, remote sensing has proved to be a valuable tool for detecting morphological and geophysical changes within the earth's surface by complementing *in-situ* measurements (Harris et al., 1997; Lu et al., 2000; Zebker et al., 2000; Wright et al., 2001). In addition, since recent remote sensing instruments have been designed with increasing resolutions, it is now possible to acquire both spatial and altimetry data that can be used for creating updated topographic and geologic maps.

Following a volcanic eruption, the use of remote sensing can aid in the identification of anomalies or alterations within the volcanic edifice. Despite recent advances in the fields of volcanology and geophysics regarding the understanding of mechanisms that drive volcanic eruptions, the threat of active volcanoes cannot be underestimated. Because of this, remote sensing has become an important tool capable of acquiring data required for investigating and understanding volcanic manifestations.

On 13 February 1997, Okmok volcano, a shield volcano located in the NE region of Umnak Island (central Aleutian Islands) (Figure 1) entered a moderate Strombolian eruption (Lu et al., 2000). This eruption continued until March 26 (Moxey et al., 2001), resulting in the formation of two large lava

Figure 1. Location map and perspective view of Okmok volcano utilizing the high-resolution AIRSAR DEM. *A* and *B* denote the two lava flow lobes that originated from Cone A during the 1997 eruption.



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flows within Okmok's 10-kilometer wide caldera. Remotely sensed datasets acquired before, during and after the eruption allowed for the monitoring of this remote volcanic region, providing researchers with important spatial, spectral and geophysical information.

The purpose of this study is twofold: first, to demonstrate the advantages of utilizing the high-resolution (5-meter) Airborne Synthetic Aperture Radar (AIRSAR) sensor data acquired over Okmok for surface change detection purposes following the 1997 eruption and for the assessment and quantification of the erupted material. Second, to demonstrate the advantages of using AIRSAR data for topographic and geologic mapping purposes. In addition, the AIRSAR dataset is also compared and combined with imagery collected by different instruments.

2. Background

Okmok volcano (53° 25' N, 168° 07' W) is one of the most active volcanoes within the Aleutian Islands. In 1997, after numerous historic eruptions, two large lava flows originated from Cone A (Figure 1). Initial reports confirmed the existence of steam and ash plumes during the early stages of the eruption (Smithsonian Institution, 1997a). Satellite observations during this period identified thermal anomalies that resulted from each individual flow. The Advanced Very High Resolution Radiometer (AVHRR) satellite imagery collected by the US Geological Survey - Alaska Volcano Observatory (USGS-AVO) was utilized for monitoring the eruption (Dehn et al., 2000; Harris et al., 2000). Okmok volcano presents a well-defined caldera complex that originated from two violent eruptions dated at 8250 and 2400 BP (Byers, 1959; Miller et al., 1998). During the Holocene, a large lake that filled most of the caldera was violently drained in a cataclysmic event, giving rise to the gorge currently observed in the NE sector of the island. Okmok, which has a height of 1073 meters ASL, contains numerous cones that originated from secondary volcanic processes. In addition, several permanent and seasonal lakes exist within the caldera complex.

Okmok volcano represents an ideal case study for the utilization of AIRSAR radar data. The use of a radar-based sensor for studying Okmok allowed for the collection of high-resolution spatial, spectral and altimetry data. The recent volcanic activity and the AIRSAR PacRim data collection mission over the Aleutians represented a unique opportunity for studying the effects of the latest effusive eruption of this volcano. In June 2000, eight overlapping radar swaths were acquired by a McDonnell Douglas DC-8 mounted AIRSAR/TOPSAR sensor over Okmok. The aircraft, operated by the Jet Propulsion Laboratory, was flown over the NE sector of Umnak Island as part of the PacRim 2000 campaign and the Alaska DEM Project. Previous to the AIRSAR campaign over Alaska, other spaceborne instruments also acquired radar imagery, including the Radarsat SAR, JERS and ERS satellites.

The AIRSAR instrument consists of a side-looking radar sensor capable of collecting radar backscatter and topographic data in the C-band (0.057 meter), L-band (0.25 meter) and P-band (0.68 meter). In addition, the instrument can obtain cross-track interferometric (TOPSAR) and along-track interferometric (ATI) data. In the C- and L-bands, the TOPSAR collects high-resolution (5-meter) data for creating 3-dimensional digital elevation models (DEMs). The continuous cloud coverage, poor light levels and adverse meteorological conditions at this location did not hinder the acquisition process, as it would typically occur with conventional (optical) instruments. The energy transmitted by the radar waves can penetrate clouds, haze and smoke. Furthermore, this feature makes it possible to use the instrument for both daytime and nighttime operations. Due to the specular reflectance properties that calm water bodies have, the energy transmitted by the radar waves is scattered away from the sensor, leading to dark tones within the radar image.

In the past, numerous studies have utilized AIRSAR radar data for a wide variety of studies, including forestry (de Grandi et al., 1994; Ranson and Sun, 1997; Musik et al., 1998), geology (Arvidson et al., 1993; Weeks et al., 1997) and volcanology (Ansan and Thouvenot, 1998). In recent years, Okmok volcano was studied by means of both airborne and satellite radar platforms (Lu et al., 2000; Moxey et al., 2001) mainly for geophysical and volcanological purposes.

3. Datasets and Methodology

In order to perform both topographic and geologic mapping and surface change detections, eight unprocessed AIRSAR/TOPSAR radar swaths (Vertical-Vertical Polarization) were obtained from the Jet Propulsion Laboratory in June 2001. In addition, USGS DEMs and two Landsat-2 MSS and Landsat-7 ETM+ images (acquired on 30 August 1981 and 17 August 2000 respectively) were also used.

The AIRSAR C- and L-band datasets were processed independently at the NASA-Alaska Synthetic Aperture Radar Facility (ASF). Each processed AIRSAR swath generated one radar backscatter image and one DEM. A total of eight high-resolution (5-meter) radar backscatters and eight DEMs were generated. A modified AIRSAR geocoding algorithm was applied to each swath, and the radar backscatter brightness was adjusted accordingly to minimize the effects of target proximity and incidence angles. The processed AIRSAR radar swaths were then combined in a pre-defined sequence to eliminate the radar shadow regions that resulted from the acquisition angles and steep topography of the study area. After utilizing GPS information from the National Imagery and Mapping Agency (NIMA) and USGS-AVO, ground truth analyses were performed on the resulting AIRSAR backscatter and DEM mosaics. In addition, for visualization purposes, Landsat satellite images were merged with USGS and AIRSAR DEMs.

4. Results and Discussion

4.1. *Surface change detections in Okmok Volcano: visualization and analysis*

A variety of remote sensors are commonly used for collecting morphological, thermal and spectral measurements for monitoring surface variations in active volcanic centers. In the past, SAR imagery from the SIR-C, ERS and AIRSAR/TOPSAR sensors has been used successfully for detecting subtle morphological variations in volcanic environments (Amelung et al., 2000; Lu et al., 2000; Zebker et al., 2000). In addition, optical sensors have also been used for detecting thermal anomalies, which often occur from the formation of new features that have high thermal radiances, including lava lakes and flows (Harris et al., 1997; Wooster and Rothery, 1997; Schneider et al., 2000; Wright et al., 2000; Wright et al., 2001).

Thermal anomalies detected by the AVO on 13 February 1997 confirmed the effusive activity of Okmok volcano. Detailed field and satellite observations revealed the existence of two newly formed lava flow lobes that originated from Cone A, a cinder cone within Okmok's caldera that was last active in 1945 (Dehn et al., 2000). Thermal emissivity data obtained from ground and satellite measurements during the eruption indicated that the first and second lava flows began on 13 February and between 1-4 March, respectively (Smithsonian Institution, 1997b; Dehn et al., 2000; Harris et al., 2000; Moxey et al., 2001).

Pre-eruption datasets obtained from the ERS 1 and 2 radar satellites (~25 meter resolution) in October 1995 (Lu et al., 2000) and USGS (DEMs) (~90 meter resolution) in 1983 provided morphological information of the original conditions at Okmok's caldera. Subsequent acquisitions of high resolution AIRSAR radar data (June 2000) detected the two still warm lava flow lobes (Figure 2a). Used in combination with ERS derived and USGS DEMs, the AIRSAR DEM mosaic of Okmok volcano allows for the assessment of spatial variations that resulted from the eruption. Figures 2a and b show the texture of the two 1997 lava flows. Analysis of AIRSAR backscatter images showed that the two lava flows cover an area of approximately 7.53 km^2, and have a perimeter of 21.64 km. These results are consistent with the findings of previous studies (Lu et al., 2000; Moxey et al., 2001). In addition, these studies also suggest that the recent lava fields have an estimated volume of 0.55 km^3.

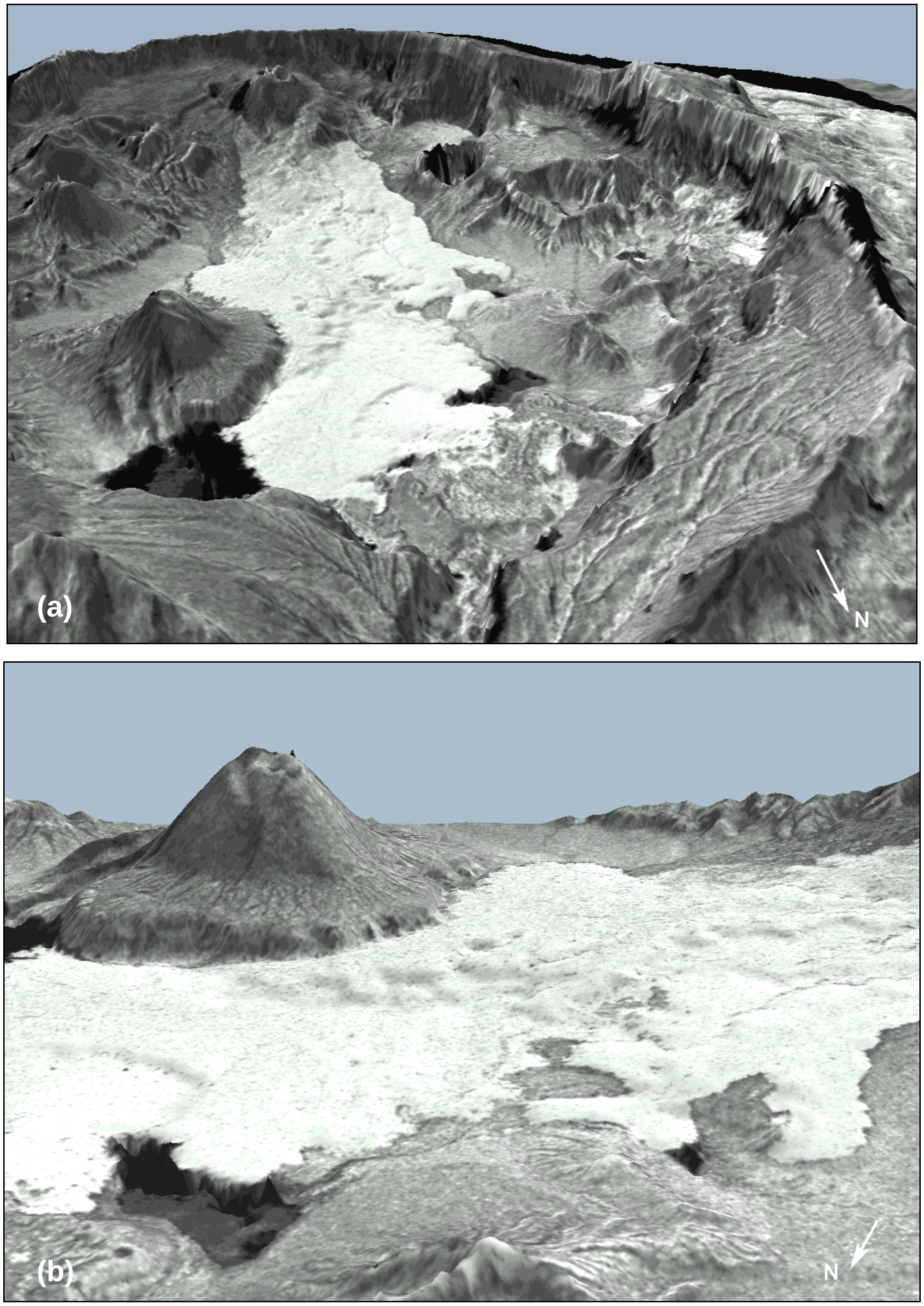

Figure 2. (a) Detailed view of the 1945 and 1997 lava flows (white). The two eruptions took place at Cone A (far left). Cone D, one of the many secondary cones within Okmok's caldera, can be seen immediately left of the flows. The 'holes' observed on the bottom left are the result of water bodies (lakes) that scattered the radar signals away from the sensor. The scene was generated from a high-resolution AIRSAR radar backscatter draped over an AIRSAR DEM. (b) A merged AIRSAR backscatter and DEM showing the rough surface texture of the 1945 and 1997 lava flows. Cone D (far left) and a permanent lake (bottom left) can be seen adjacent to the flows.

4.2. *Topographic and geologic mapping of Okmok*

In dynamic and active environments such as volcanic settings, continuous tectonic and geophysical forces lead to the formation of new geologic structures that change the overall topography of the area. Particularly in proximal areas, pyroclastic deposits dramatically upset the original morphology of the volcano.

Many of the topographic maps that are currently available of Okmok Volcano from the USGS provide limited and outdated topographic information. The need for updated and detailed topographic maps of the volcano led to the utilization of the Okmok AIRSAR dataset for high-resolution topographic mapping. Since the creation of the most recent topographic in 1983, at least three eruptions have changed its topography. Figures 3a and b show the morphological variations that resulted from these eruptions by comparing the available topographic datasets. Analysis of the altimetry data from the AIRSAR DEM has shown an average height error of 4 meters. The topographic accuracy and high pixel resolution of the AIRSAR make it ideal for topographic mapping purposes.

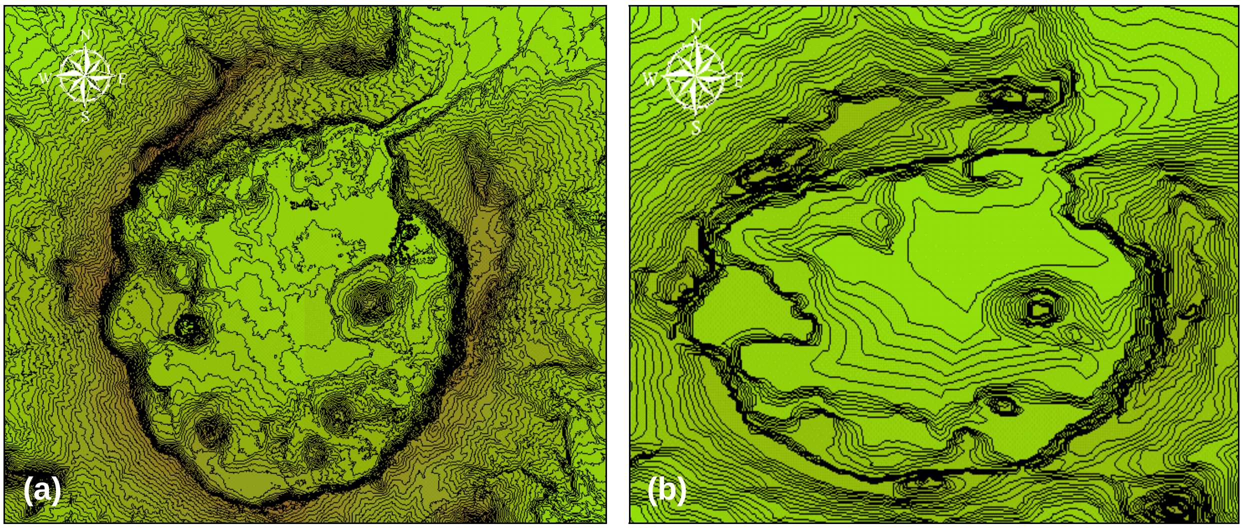

Figure 3. (a) Map view of the caldera complex showing contours at a 10-meter interval. Image was generated from a 5-meter resolution AIRSAR DEM. (b) View of Okmok created from a USGS DEM (~90-meter resolution). Contour interval: 10-meters.

The advantages of using AIRSAR data are many. The high-resolution information cannot only be utilized for creating new high-resolution topographic maps, but it can also be used for a variety of studies, including tectonic and volcanic investigations. Due to its mapping applications, the AIRSAR sensor is an important tool that will provide users, along with the recent NASA Shuttle Radar Topography Mission (SRTM), with accurate and updated datasets.

In the past, radar sensor data has been combined with field observations for generating accurate geologic maps. In addition, several studies have relied on radar data and combined it with optical images in an effort to attain more accurate results. Radar sensors are ideal for geologic mapping applications due to their unique characteristics and data collection properties. Because of this, volcanological studies often rely on radar data for generating geologic maps of volcanic centers and identifying volcanic features (Wiart et al., 2000).

The AIRSAR DEM of Okmok volcano was combined with the AIRSAR radar backscatter (Figures 2a and b) and optical satellite imagery from Landsat-7 ETM+. By merging different datasets, it was possible to achieve higher levels of accuracy and reliability. The brightness level of the AIRSAR backscatter image is controlled by the target's dielectric constant, shape, proximity, surface texture and incidence angle. Because of this, it is possible to identify geologic formations and features within the area of interest. Figures 2a and b show the strong radar brightness that resulted from the rough surface textures of the 1945 and 1997 lava flows. The combination of the AIRSAR DEM with Landsat-7 ETM+ imagery (Figure 4a) helps discriminate the geologic features from each eruption. Along with the AIRSAR backscatter, this tool was used for preliminary field reconnaissance during the summer 2001 USGS-AVO geologic field campaign to the volcano. The high-resolution imagery helped identify potential geologic study sites and other regions of interest. In addition, the use of USGS DEMs with optical images acquired before the eruption have also been used to assist in geologic mapping efforts. Figure 4b shows the conditions of the caldera floor before the 1997 eruption. The Landsat-2 MSS image was combined with USGS DEMs for creating a 3-dimensional view of the original geologic conditions that existed at Okmok. Cooperation efforts between the USGS-AVO and NASA-ASF are currently under way for combining geologic field observations and AIRSAR data for creating the most current and detailed geologic map of Okmok Volcano.

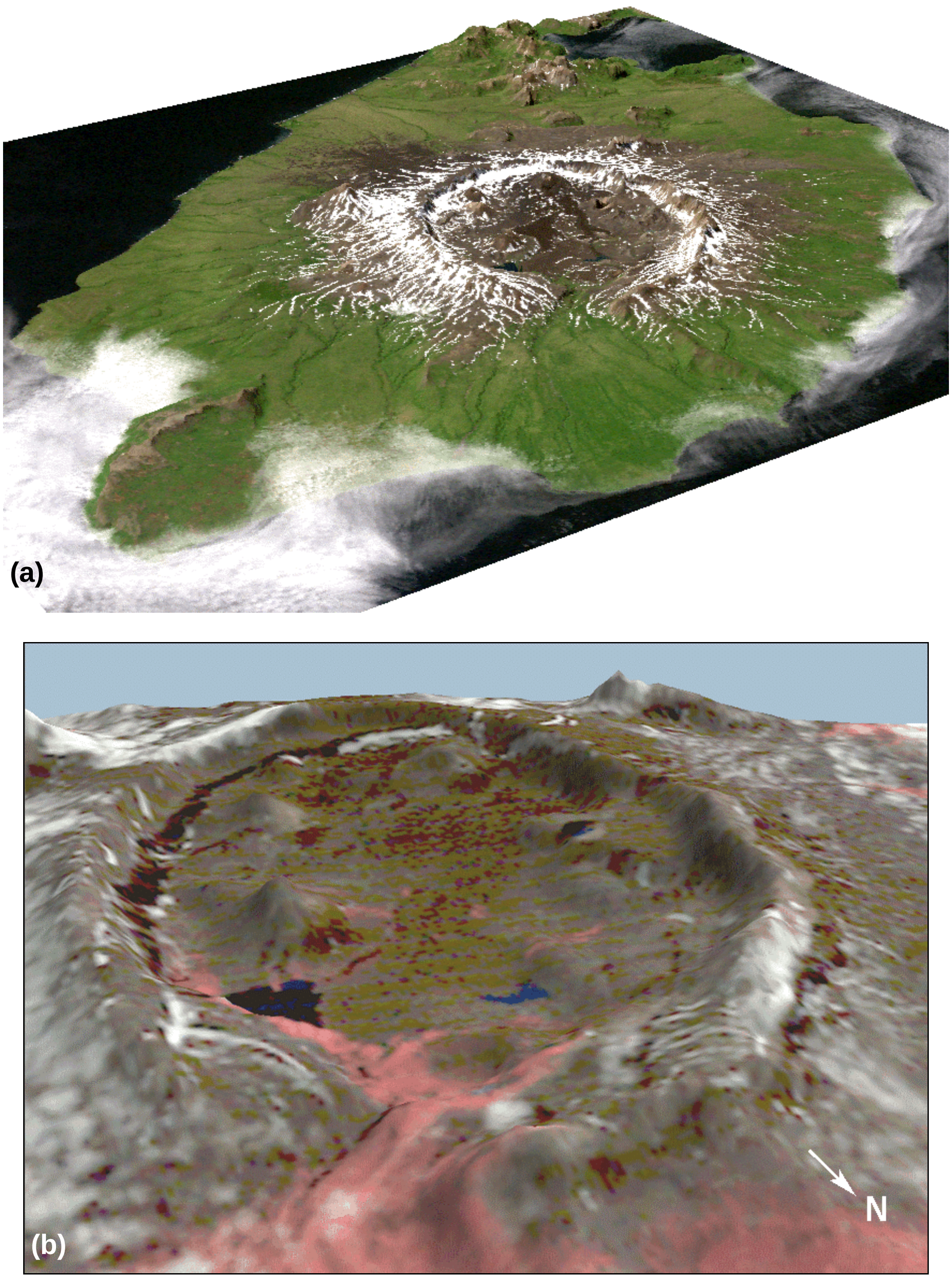

Figure 4. (a) Landsat-7 Bands 4, 2, 1 (R, G, B) colour composite acquired on 17 August 2000, draped over the AIRSAR DEM mosaic, showing the topography of the NE sector of Umnak Island. The two lava flow lobes from the 1997 eruption can be clearly distinguished from the 1945 flows. (Image courtesy of ASF/JPL/NASA) (b) Full view of the caldera before the 1997 eruption. The Lansat-2 MSS Bands 4, 2, 1 (R, G, B) image was draped over a USGS DEM that exhibits the topography of the caldera before the last eruption.

5. Conclusions

This paper demonstrated the value of using AIRSAR data for conducting surface change detection studies as well as topographic and geologic mapping of remote and isolated volcanic environments. The all-weather characteristics of the instrument allowed for the data collection despite the dense cloud cover that is commonly found in the Alaska Peninsula. Additionally, the measurements from the radar products displaying the erupted material helped to assess and quantify the extent of the lava flows. When compared with measurements from other studies, the spatial and elevation accuracy of the high-resolution sensor become apparent, proving that the scientific applications of this instrument are numerous.

This contribution has presented and analysed different datasets collected by a variety of sensors. From this, it is clear that the combination of field measurements and remotely sensed observations represents a powerful tool that offers numerous advantages for researchers. In addition, SAR data fussed with optical (Landsat) imagery also presented a powerful visualization tool that can be utilized for numerous applications, including surface change detections and geologic mapping. Furthermore, the dielectric constant from the targets illuminated by the AIRSAR radar backscatter help identify specific geologic units and features, including lava flows. This characteristic serves as a powerful tool that can be applied for geologic mapping purposes. When compared with optical instruments, SAR data can easily discriminate between geologic units and also identify bodies of water.

The high-resolution AIRSAR datasets can further contribute in the understanding of the geophysical processes associated with volcanic eruptions. Because of this, the AIRSAR sensor represents a valuable source of accurate information that can be merged with different datasets in order to perform diverse studies that include volcano hazard mapping, vegetation cover, hydrologic modelling and flooding hazard mapping.

In addition to this contribution, an on-line scientific press release prepared by JPL and NASA on the Okmok AIRSAR campaign can be found at http://www.jpl.nasa.gov/releases/2001/release_2001_193.html. Further full-resolution AIRSAR images of Okmok Volcano are available at http://www.jpl.nasa.gov/images/earth/volcano.

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