Monitoring the evolution of the Pasig–Potrero alluvial fan, Pinatubo Volcano, using a decade of remote sensing data

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Abstract

Since the 1991 climactic eruption of Pinatubo in the Philippines, various hazards have affected areas surrounding the volcano. The most significant of these hazards involve the redeposition of pyroclastic flow and fall deposits as lahars, deposit-derived pyroclastic flows, and ash falls due to phreatic explosions. Many of these processes occurred in areas that are inaccessible for ground observation and monitoring. We describe here how sequential remote sensing data obtained over the period December 18, 1991, to November 1, 2001, from the SPOT, ERS, RADARSAT, SIR-C/X-SAR, AIRSAR, LANDSAT 7 ETM, and ASTER sensors provide a means of monitoring the decade-long development of the post-eruption Pinatubo landscape. This method represents an efficient and safe alternative to time-consuming, physically demanding and risky field campaigns. We apply principal component analysis, image subtraction, band ratioing, and density slicing to these data to track the changes in the post-eruption landscape, estimate volumes of deposition, and allow hazard vulnerability prediction along the timeline established by the series of data sets. The maps derived from the remote sensing data agree well with the field derived maps for the first 5 years (1991–1995), provide important large-area coverage, and show details that are unobtainable from conventional ground-based mapping. The volume of lahars deposited during the first 6 months following the eruption is estimated between 0.045 and 0.075 km\textsuperscript{3}, covering an area of \textasciitilde45 km\textsuperscript{2}. Moreover, changes in the settlement patterns of the local population, as well as in the construction and modification of the engineering structures for controlling the lahar hazards, can be identified in the multi-temporal scenes spanning the entire decade of observations. These types of information are crucial inputs for local decision- and policy-making in volcanic hazard mitigation.

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Keywords: remote sensing; lahars; alluvial fan; post-eruption hazards; ignimbrite erosion; volcaniclastic sedimentation

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1. Introduction

The June 1991 eruption of Pinatubo Volcano on the island of Luzon (Philippines) produced about 5.5 km$^3$ (bulk volume) of pyroclastic flow deposits (ignimbrite) that partly buried deep valleys and covered low-lying topography within 12 km of the volcano (Scott et al., 1996b; Torres et al., 1996; Torres, 2001). Since that time, large debris flows and hyperconcentrated stream flows, which are here called lahars, have frequently been generated by typhoon and monsoon rains (Janda et al., 1996; Major et al., 1996). As much of the redeposition of 1991 deposits around Pinatubo has been into land-locked basins, the severe erosion of the ignimbrite fans upstream has been balanced by an equivalent magnitude of deposition downstream in the alluvial basin. These lahars have resulted in significant local hazards to life and property affecting large population centers and many lowland villages. Post-eruption lahar events heavily impacted the floodplains of the Sacobia–Bamban, Abacan, Pasig–Potrero, Marella–Sto. Tomas, Balin–Baquero–Bucao, and O’Donnell river systems (Fig. 1), with widespread encroachment and rapid build-up of the alluvial fans.

It has been necessary to understand the erosion and remobilization of the 1991 ignimbrite and the deposition of lahars for several reasons, including the prediction of how long this hazard would last and to identify the vulnerable areas. However, field-based determination of the accumulated volumes of volcaniclastic deposits would mean committing extensive manpower and resources to monitoring the flow discharge of major river channels around Pinatubo (Rodolfo et al., 1996; Tuñgol and Regalado, 1996; Martinez et al., 1996; Arboleda and Martinez, 1996) and in mapping the entire alluvial fan (Punongbayan et al., 1993) every time new deposition had taken place. It is for this reason that we explore the application of orbital remote sensing in this analysis.

Detailed field monitoring of the changes to the Pasig–Potrero drainage system by PHIVOLCS staff continued only until the end of 1995 when other pressing volcanological and seismological concerns required the diversion of people and resources to other areas in the Philippines. Here we demonstrate that multiple optical and microwave remote sensing data sets are well suited to providing observations suitable for long-term analysis of surface changes resulting from the erosion of pyroclastic deposits and cumulative deposition by lahars. We do this for the Pasig–Potrero River system but the methodology is applicable anywhere. We use several different data sets, including SPOT, ERS, SIR-C/X-SAR, RADARSAT, LANDSAT 7 ETM+ and ASTER scenes, and have reconstructed the sequential development of the post-eruption Pinatubo landscape during the time period from December 18, 1991, to November 1, 2001. These data sets were not specifically collected for the study of Pinatubo, nor does any one sensor provide complete spatial and temporal coverage during the decade of observation because of the differing methods of data acquisition that have existed over the time interval. As we will show, the satellite data represent a viable alternative to conventional ground monitoring and field mapping over difficult and dangerous landscapes, such as fresh ignimbrite sheets and lahar deposits. In addition, we provide guidelines for future studies specifically intended to detect surface changes on volcanoes using data from different satellite- or aircraft-borne sensors.

1.1. Ignimbrite erosion and lahar generation at Pinatubo Volcano

Although not the main focus of this study, we include here a brief account of the post-June 15, 1991, events at Pinatubo to put the significance of the remote sensing data in perspective. After the climactic eruption, the surrounding area within 12 km of the Pinatubo’s vent region was covered by non-welded ignimbrite that in some places attained a thickness in excess of 200 m along the axis of the steep-walled pre-eruption valleys (Scott et al., 1996b). Erosion and remobilization of the valley-ponded ignimbrites and pyroclastic materials on the interfluves (Torres et al., 1996) occurred mainly as a series of short-lived, intense events that peak at the passage of tropical storms and typhoons. Perhaps significantly, the proximity of Typhoon Yunya and its associated heavy rainfall at the time of the climactic eruption (Oswalt et al., 1996) established the initial drainage channels that were enlarged and developed by later typhoon-induced surface runoff (Pierson et al., 1996). The Pinatubo ignimbrite sheet has eroded much faster (60% remobilized in the first 6 years) than comparable examples, such as the 1912 Valley of Ten Thousand
Smokes (VTTS) ignimbrite (S. Self, personal observation), a difference that cannot be solely attributed to the non-welded nature of the ignimbrite at Pinatubo. Headward erosion and gullying during torrential rain was the most significant trigger of lahar generation at Pinatubo (Pierson et al., 1996) and most of the major lahar events were initiated in this way. A series of spectacular mass movements in the easily erodable, hot, “fluffy” ignimbrite formed large scarps and led to a series of deposit-derived flows or secondary pyroclastic flows, redepositing the pyroclastic materials further downslope than the vent-derived or primary-deposited ignimbrite fan (Torres et al., 1996; Torres, 2001). Although decreasing in volume and frequency with time, the remobilization of hot ignimbrite from cliffs and steep channel walls persisted for several years after deposition of the vent-derived flows on June 15. Cumulatively, these events have delivered great amounts of material into the valleys and supplied the materials for lahars that eventually built up the alluvial

Fig. 1. Distribution of 1991 pyroclastic flow (black) and 1991–1996 lahar deposits (gray) around Pinatubo Volcano, Luzon Islands, Philippines, based on the SPOT image acquired in February 12, 1996. The eight main drainage systems are shown by larger letters. The Pasig–Potrero alluvial fan (darker gray) and the outer man-made dike system (heavy lines) are shown together with surrounding towns (open circles). Dashed lines enclose area of coverage of other figures. Inset shows the setting of the study in Southeast Luzon, Philippines.
fan. Some of these secondary pyroclastic flow events involved materials with volumes of several million cubic meters, and their deposition rapidly aggraded the valley floor by a thickness of several meters (e.g., 5–7 m in Sacobia during the April 4, 1992, event; Torres et al., 1996). Most secondary flow events coincided with major typhoons and rainstorms, causing the channel-confined deposit-derived pyroclastic flows to bulk up almost instantly into lahars. In instances when extremely large deposit-derived flows occurred, the entire valley floor was overwhelmed by aggradation of dry pyroclastic deposits, locally preventing the bulking and generation of lahars. Deposit-derived pyroclastic flows sometimes temporally blocked tributary channels, which created localized ponded water that subsequently generated lake-breakout lahars. Meanwhile, the removal of thick ignimbrite sections from sites at the interfluvres of river valleys sometimes resulted in stream piracy. One notable example led to the capture of the upper Sacobia watershed by the Pasig–Potrero River as an aftermath of the October 5, 1993, event, which was accompanied by intense typhoon-borne rains and continuous lahar generation (GVN, 1993).

Post-depositional processes on the scale of those described here are difficult to document in the field by virtue of the size of the affected area (i.e., ~2000 km²), remoteness and roughness of the terrain, and the level of exposure to dangerous phreatic explosion, avalanche, and lahar hazards. Moreover, frequent cloudiness hampers conventional aerial observation and photography at Pinatubo as with many tropical volcanoes. Overall, lahar events have caused greater devastation to populated areas and have been responsible for more damage to life and property than the eruption itself. Thus, it is significant that remote sensing techniques have yielded important complementary information to field observations and, as in

Fig. 2. (A) December 1998 RADARSAT image showing the location and the general viewing direction of ground photos (B). Viewing directions of the photos are indicated by arrows. Outer dike system is drawn in solid white lines. Location of image shown in Fig. 1. ©RSI 1998. (B) Surface characteristics of the Pasig–Potrero alluvial fan and immediate surrounding areas. Shown here are water saturated sediments in the channel (1); thick lahar deposits with dry and smooth surface outside the channel (2); and vegetated areas inside (3, 5, 7) and outside (4, 6, 8) the dike system. Concrete-armored dike segment of the transverse dike (5) with a man in the foreground for scale. Houses (6) in Bacolor, Pampanga, were buried by the 1991–1995 lahars.
Fig. 2 (continued).
some cases, provide the primary source of data in areas that are inaccessible from ground observations (Mouginis-Mark et al., 1993). In particular, radar data are useful for imaging the landscape irrespective of weather conditions or time of day.

1.2. Previous work on remote sensing of Pinatubo lahars

Past efforts to characterize the changes on the Pinatubo landscape have been conducted on various regions of the volcano within shorter time periods. Quantification of up-slope erosion at Pinatubo has also been attempted as an indirect way to estimate the volume of lahar deposits in the Sacobia drainage system (Daag, 2003). Daag and Van Westen (1996) studied geomorphic changes in the Sacobia watershed region and examined the sediment budget in the Sacobia River system from 1991 to 1993 by using a series of aerial photographs and constructing Digital Elevation Models (DEMs). Chorowicz et al. (1997) used ERS-1 radar images to characterize lahar deposit surfaces in the depositional fan of Balin–Baquero drainage on the western flank. In their work, Chorowicz et al. (1997) examined two ERS-1 images that were obtained in the summer of 1993, including a day when lahar channels were active. Radar backscatter characteristics for both active and inactive lahars were identified, but because the radar data were only obtained at a single incidence angle and wavelength, there were a number of non-unique surface morphologies that were identified using ratio images. Recent lahar deposits were distinguished from unaffected areas by their distinctive dark tones in radar scenes (Fig. 2A) caused by water saturation, surface humidity, and characteristic roughness, which all tend to yield weak backscatter signals. However, because Chorowicz et al. (1997) studied ERS-1 data that had a wavelength of 5.6 cm, the strength of the radar return was dominated by the influence of topography (roughness) at this scale, rather than moisture. Thus, their analysis provided mainly textural information on fresh lahar deposits.

1.3. Lahar deposit characteristics and how various sensors detect them

The decade-long evolution of post-eruption landscape at Pinatubo took place at a time when innovative technologies in satellite and airborne remote sensing were just being introduced and made publicly accessible. Some spacecraft only operated for part of the time period, while data from other platforms were available only from commercial systems and so had a high purchase price. Only when special research opportunities were available for the free access to these data was it possible to include these data sets in our analysis. In addition, the manner in which data could be obtained on the ground varied during the decade, so that not all observations from a particular spacecraft were recorded on the ground. A more complete discussion of the problems associated with building an archive of satellite data sets such as the one used here is provided by Mouginis-Mark and Domergue-Schmidt (2000). Information on the data sets used in our analysis, including their spectral coverage, spatial resolution, and the acquisition date for each image, is given on Table 1. Further details on the performance of the sensors, and their use in volcanic terrain, can be found in Mouginis-Mark et al. (1993), Stofan et al. (1995), Mouginis-Mark (1995), Hess et al. (1995), MacKay and Mouginis-Mark (1997), Rowland et al. (1999), Abrams (2000), and Arvidson et al. (2001).

The evolving landscapes being formed by lahar deposition are visible from space-borne monitoring because of the size of the encroached area, tonal contrast of lahar deposits with surrounding albedo, and the development of man-made structures around it. Lahar deposits rapidly built up the alluvial fans in response to the erosion of pyroclastic flow deposits, which exponentially decrease to near ambient level within a decade. The surfaces of lahar deposits are generally flat, but form a topography with terraces and braided stream landforms, the extent of which depends on the duration of erosion or deposition in the adjacent channel. Lahar terraces exhibit a smooth surface consists of moderately sorted ash-derived sand with occasional pebble-to gravel-sized pumice clasts. Areas in alluvial fan where water had locally ponded are veneered with silt and mud deposits when the water has evaporated. On the other hand, braided lahar landforms display greater surface roughness with the formation of gravelly channel bars. During daytime, an alluvial fan experiences a rapid loss of soil moisture due to the characteristic porosity and permeability of unconsolidated lahar deposits, allowing the regions of the fan away from the active channel to quickly
develop a dry dusty surface. Meanwhile, older lahar deposits are increasingly covered by vegetation as wild tall grasses and woody shrub growths colonized the landscape. Fig. 2B shows the surface conditions of lahar deposits at various locations (see Fig. 2A) in the Pasig–Potrero alluvial fan. Several alluvial fans are visibly outlined or shaped by man-made structures, which were constructed to mitigate lahar hazards and control sediment disaster. The largest of these structures was emplaced at Pasig–Potrero River and locally known as “Megadike”, which was designed as a large sediment trap. The

<table>
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<tr>
<th>Satellite</th>
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<th>Spatial resolution (m)</th>
<th>Images used in this study</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPOT</td>
<td>N87° to S87° latitude</td>
<td>VNIR</td>
<td>0.50–0.59, 0.61–0.68, 0.79–0.89 μm</td>
<td>20</td>
<td>04/01/88; 12/18/91</td>
</tr>
<tr>
<td></td>
<td>Sun-synchronous</td>
<td>SWIR (SPOT 4)</td>
<td>1.58–1.75 μm</td>
<td>20</td>
<td>12/11/94; 02/12/96</td>
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<td></td>
<td>60 km swath</td>
<td>Panchromatic</td>
<td>51–0.73 μm (SPOT 1, 2, 3)</td>
<td>10</td>
<td>12/05/98</td>
</tr>
<tr>
<td></td>
<td>26 days revisit at nadir</td>
<td>C-band (VV)</td>
<td>61–0.68 μm (SPOT 4)</td>
<td>10</td>
<td>12/05/98</td>
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<td>ERS</td>
<td>Fixed incidence angle: 23°</td>
<td>C-band (V)</td>
<td>61–0.68 μm (SPOT 4)</td>
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<td>11/07/93, 04/23/94</td>
</tr>
<tr>
<td></td>
<td>Sun-synchronous</td>
<td>100 km swath</td>
<td>11/07/93, 04/23/94</td>
<td>30</td>
<td>04/04/95; 01/09/96</td>
</tr>
<tr>
<td></td>
<td>60 km swath</td>
<td>03/19/96; 05/28/96</td>
<td>11/07/93, 04/23/94</td>
<td>30</td>
<td>09/11/96; 06/18/97</td>
</tr>
<tr>
<td></td>
<td>26 days revisit at nadir</td>
<td>01/14/98</td>
<td>11/07/93, 04/23/94</td>
<td>30</td>
<td>01/14/98</td>
</tr>
<tr>
<td>SIR-C/X-SAR</td>
<td>Shuttle-borne</td>
<td>C-band (HH, HV, VH, VV)</td>
<td>5.8 cm</td>
<td>30</td>
<td>04/14/94</td>
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<tr>
<td></td>
<td>Fixed incidence angle: 23°</td>
<td>L-band (HH, HV, VH, VV)</td>
<td>5.8 cm</td>
<td>30</td>
<td>04/14/94</td>
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<tr>
<td></td>
<td>Interferometry at C and L-band</td>
<td>C-band (HH, HV, VH, VV)</td>
<td>5.8 cm</td>
<td>30</td>
<td>04/14/94</td>
</tr>
<tr>
<td></td>
<td>Two antennas 2.6 m apart</td>
<td>C-band (HH, HV, VH, VV)</td>
<td>5.8 cm</td>
<td>30</td>
<td>04/14/94</td>
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<tr>
<td>RADARSAT</td>
<td>45–500 km swath</td>
<td>C-band (HH)</td>
<td>6.8 cm</td>
<td>8–100</td>
<td>02/13/97</td>
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<td></td>
<td>Sun-synchronous</td>
<td>45–500 km swath</td>
<td>6.8 cm</td>
<td>8–100</td>
<td>02/13/97</td>
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<td>LANDSAT 7 ETM+</td>
<td>185 km swath</td>
<td>VNIR (Bands 1–4)</td>
<td>0.55–0.56, 0.56–0.64, 0.65–0.70 μm</td>
<td>30</td>
<td>10/04/99</td>
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<tr>
<td></td>
<td>16 days revisit</td>
<td>SWIR (Bands 5,7)</td>
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<td>30</td>
<td>10/22/00</td>
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<td></td>
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<td>30</td>
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<td></td>
<td>View at nadir</td>
<td>Panchromatic (Band 8)</td>
<td>0.52–0.59 μm</td>
<td>15</td>
<td>10/22/00</td>
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<td>ASTER</td>
<td>Multispectral data; sun-synchronous polar orbit 60 km swath</td>
<td>VNIR (1, 2, 3N, 3B)</td>
<td>0.6–0.63, 0.63–0.69, 0.78–0.86 μm</td>
<td>15</td>
<td>11/01/01</td>
</tr>
<tr>
<td></td>
<td>60 km swath</td>
<td>SWIR (4–9)</td>
<td>2.16–2.18, 2.18–2.22, 2.22–2.28, 2.36–2.43 μm</td>
<td>30</td>
<td>10/04/99</td>
</tr>
<tr>
<td></td>
<td>TIR (10–14)</td>
<td>8.12–8.47, 8.47–8.82, 8.82–9.27 μm</td>
<td>90</td>
<td>11/01/01</td>
<td></td>
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</tbody>
</table>

Satellites: Satellite Pour l’Observation de la Terre (SPOT); Earth Remote-Sensing Satellite (ERS); Shuttle Imaging Radar C/X-band Synthetic Aperture Radar (SIR-C/X SAR); Airborne SAR (AIRSAR); Topographic SAR (TOPSAR); Radar Satellite (RADARSAT); LANDSAT 7 Enhanced Thematic Mapper plus (LANDSAT 7 ETM+); Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). Spectral Bands: Visible Near-infrared (VNIR), Shortwave Infrared (SWIR), Thermal Infrared (TIR).
Fig. 3. Sequential ERS scenes monitoring the evolution of engineering intervention in the Pasig–Potrero River system. The latest lahar deposits are generally darker than surrounding areas due to poor backscatter of water saturated, flat, and barren surface. Solid lines denote visible structures; dashed lines when buried or eroded during the previous season. The dike system was transformed into a large sediment catchment area between 1994 and 1996 by constructing the outer dike segments. The dikes are covered with sand and soil materials, but some segments are armored with concrete (Fig. 2B5). Field of view outlined in Fig. 1. ©ESA 1993–1998.
construction of the sediment control structure at Pasig–Potrero has evolved through the years (Fig. 3). Earlier structures have briefly contained the lahar deposition and trained the fan shape, but later dike alignment, including the “Megadike” project, apparently responded to the direction of fan encroachment. Other forms of human activities, such as settlement build-up and farming, introduce landscape alteration that provides contrast with the naturally evolving surface of the alluvial fan.

Different sensors create different levels of contrast that have important applications in mapping lahar deposits. The visible and near-infrared bands in LANDSAT TM, SPOT, and ASTER are useful for delineating the barren regions of the alluvial fan and the areas covered with vegetation, which hints at the distinction between young and old lahar deposits. These data sets also provide reliable criteria for mapping the active channels and for distinguishing the wet and relatively dry deposits. ASTER and SPOT provide higher spatial resolution images at 15 and 20 m, respectively, allowing man-made modification in the landscape, such as concrete dikes, roads, farm lots, and house clusters, to be directly mapped. On the other hand, radar bands detect surface roughness contrast created by sandy vs. gravelly, planar vs. rilled, and barren vs. vegetated surfaces. Moisture-laden young lahar deposits generate significant tonal contrasts with dry lahar deposits, such that newly emplaced lahar deposits may be better observed in radar bands than in higher resolution VNIR spectral bands. Moreover, man-made structures and vegetation produce greater backscatter, appearing with bright pixel qualities.

2. 1991–1995 field and satellite observations

2.1. Field observations relevant to lahar deposit accumulation

In this section, we document some of the surface observations made during the time of detailed field observations that complement our remote sensing observations and provide ample ground truth. Observation posts were established by PHIVOLCS at Delta 5, Mancatian and Bacolor, which provided the simultaneous monitoring of the lahar peak discharge at the upper, middle and lower parts of the Pasig–Potrero alluvial fan, respectively. The assessments of the extent of new lahar deposits were conducted during aerial inspection, but more detailed ground mapping and thickness measurements were limited to the accessible portions of the alluvial fans.

Stratigraphic work along Pasig–Potrero, where lahar deposits were found interbedded with fall tephra layers (GVN, 1991; Major et al., 1996), suggested that lahar generation along Pasig–Potrero occurred as early as June 15, 1991, during the climactic eruption, perhaps coincident with the closest approach of Typhoon Yunya to Pinatubo. Little is known of these deposits as they were rapidly buried by stream-flow sedimentation. By the late 1991 rainy season, when our first post-eruption SPOT image was collected (December 18, 1991), lahar peak discharges had noticeably increased at Pasig–Potrero along with a related increase in flow density (Scott et al., 1996a). Higher particle concentration lahars were being generated as suggested by the observation of “floating” boulders with diameters up to 1 m (Rodolfo et al., 1996).

The lahar delivery system of Pasig–Potrero became relatively more efficient by 1992, so that lahars were being generated by as little as 5 mm of rain over a 20-min duration (GVN, 1992; Arboleda and Martinez, 1996). The 1992 lahar events had triggered remobilization of pyroclastic flow deposits in upstream areas, as well as failure of engineering structures at several downstream locations along Pasig–Potrero. On July 13, 1992, the 4–5 km stretch of main channel located upstream from Delta 5 was filled with $10 \times 10^6$ to $20 \times 10^6$ m$^3$ of dry deposit-derived pyroclastic flow deposits up to 15 m thick. The rapidly aggraded channel effectively prevented the immediately succeeding lahar events from reaching the fan area, while impounding water upstream from the pyroclastic flow deposit. By late August 1992, however, the lahar conveyance system was re-established and the ensuing lahars were unusually destructive as they involved the release of impounded water (Arboleda and Martinez, 1996). Containment dikes that were designed to confine the hazards within the river system’s pre-eruption course failed to cope with rapid aggradation of the riverbed. ERS-1 radar data obtained on November 7, 1993 (see Fig. 3), show a new 6-km-long segment of the dike that was added to the original 34-km-long channel works. Segments with dimensions that are smaller than ERS spatial resolution (i.e.,}
30 m), as well as those that are partially buried by lahar deposits, are indistinct in the images.

The frequency and magnitude of lahars generated along the Pasig–Potrero River system significantly increased on October 5, 1993, after a large pyroclastic avalanche at Sacobia ignimbrite fan caused the diversion of the upstream watershed of the Sacobia River into the Pasig–Potrero system. Consequently, most of the lahar production on the Sacobia ignimbrite fan and its watershed area was routed into the Pasig–Potrero system, leaving the Sacobia River system to begin to recycle earlier lahar deposits and generate only muddy stream flows and dilute lahars from this point in time. In addition, there were at least six tropical storms and typhoons between April and October 1994 that generated major lahar events, a period that coincides with the two radar sets collected by the SIR-C shuttle radar experiment (Fig. 4). These reveal that significant surface changes took place between the two sets of observations, including extensive channel avulsions along the eastern dike walls.

In the field, the thickness of over-bank lahar deposit was measured between 0.2 and 2 m, which lies within the lower limits of TOPSAR vertical resolution (i.e., 1–3 m). Although the breakout was a small event, it concerned the local officials that the process could potentially led to the piracy of the Pasig–Potrero River by Ebus Creek. Such an event would have posed a bigger risk as Ebus Creek drains toward Angeles City and San Fernando, the two most populated towns in the province of Pampanga. Recognizing that upstream the Pasig–Potrero River was highly prone to avulsions and that too many elements were at risk on the downstream sides, the outer dike alignments were extended to this area in 1995 to prevent lahar breakouts from reaching Ebus Creek. However, the outer dike extension was constructed without enough of the armoring that was used on the inner dike segments.

A significant proportion of lahars on July 28–30, 1995, was diverted through the breached portion of the protective dike and resulted in a cumulative deposition of $30 \times 10^6$ m$^3$ of sediments over 12 km$^2$. The low-lying areas at the boundary of San Fernando and Bacolor towns were buried by 1–2 m of lahar deposits, while San Fernando town center was flooded for several days. Twenty-five percent of this volume represents the pre-existing deposits on the alluvial fan that were recycled as lahars, resulting in bank erosion and channel floor degradation. In a field survey after the July 28–30 event, the PHIVOLCS lahar monitoring team found the channel between Delta 5 and Mancatian (see Fig. 2A) to be 10 m deeper and 100 m wider (GVN, 1995).

Another dramatic erosion event in the Pasig–Potrero channel happened during the passage of Typhoon Mameng on October 1, 1995, which produced about 340 mm of rainfall in 14 hours. It generated a major lahar event with a peak discharge of 400 m$^3$/s at Mancatian (GVN, 1996). Old lahar deposits and pre-eruption soil were evidently incorporated into the ensuing lahar, constituting as much as 40% of the bulk sediment load. Some of these old materials were transported for several kilometers as coherent clasts and deposited as a “bouldery” mass at the run-out distance of the flow and on portions of the channel where the lahar overtopped the bank. The Typhoon Mameng lahar was estimated to have deposited $50 \times 10^6$ m$^3$ of sediment volume to the lower parts of the Pasig–Potrero alluvial fan, where some areas were buried by up to 6-meter-thick lahar deposits. Subsequent channel-confined lahar events were technically hyper-concentrated flows, causing a net aggradation of 2 m of the channel floor in the medial to distal fan. Flooding and siltation affected the low-lying areas of the alluvial fan outside the dike system. By the end of 1995, the succession of lahar events had already built an extensive alluvial fan in the Porac–Bacolor area (Fig. 5) and had buried several residential communities as well as the whole town of Bacolor under several meters of lahar deposit (see Fig. 2B6). To accommodate these dramatic changes in the alluvial fan and prevent the encroachment of lahars into the densely populated towns of San Fernando and Angeles, the outer dike alignment was constructed in 1995 along the eastern margin of the alluvial fan. Incidentally, there were no large lahar events since the Pasig–Potrero dike system was completed that would have tested the design of the structure.

2.2. Remote sensing observations that support field observations

Since the end of detailed field observations in 1995, no field-based intensive monitoring and mapping efforts have been conducted and projections of lahar volume per year have been based on model
predictions. Thus, our remote sensing observations serve as a valuable temporal extension of the field data. For the first half of our decade of coverage, there is ample ground truth, but in the last 5 years the remote sensing data provide unique insights into surface processes and the engineering intervention in the Pasig–Potrero alluvial fan.

We used SPOT data (Fig. 6) to map the extent of lahar deposits acquired in December 1991, which represents up to that point the accumulated deposit during that year’s rainy season. We noted that the thickness of the 1991 lahar succession could not exceed 5 m since the deposit did not completely cover the 5 m high dike structure. In fact, the most significant lahar event in that year buried the town of Bacolor in Pampanga with 1–3 m of sediments (Arboleda and Martinez, 1996). We also observed that most of the pixels with high DN values (i.e., bright pixels)
correspond to thicker and drier portions of the fan, which have average thickness of 2–3 m. These are clustered near the active channel or have features that suggest their origins as artifacts of abandoned lahar-filled channels or crevasse splays. The low DN regions (i.e., dark pixels) were characterized in the field by muddy marshland or areas with a thin veneer of lahar deposits, which we assigned a thickness of b1 m.

Using the 20×20 m pixel dimension (i.e., the spatial resolution of SPOT images), we estimated a total area of 44.6×10^6 m^2 for the 1991 Pasig–Potrero alluvial fan. The estimated total volume for the lahar deposit ranges from 45×10^6 to 75×10^6 m^3 by assigning the thicknesses of 10 to 50 cm to low DN regions and thicknesses of 200 to 300 cm to high DN regions. If the perimeter of the deposit were under- or over-estimated by half a pixel (i.e., 10×20 m) at each point, it would equate to a change of <<1% of the total area and a negligible effect on the corresponding volume estimates. This DN-based volume of lahars in the alluvial fan, although applicable in the 1991 SPOT image of Pasig–Potrero, is difficult to replicate with SPOT scenes in 1994, 1996, and 1998. The alluvial fans in the succeeding images represent cumulative deposition where the spectral characteristics of young and old lahar deposits are not distinguishable. However, the result was comparable with other reported volumes for Pasig–Potrero in 1991 that were derived from more laborious approaches. For instance, PHIVOLCS Lahar Team calculated a volume of 50×10^6

Fig. 5. Maps of Pasig–Potrero alluvial fan showing the 1991–1995 lahars deposits based on ground mapping (top) of PHIVOLCS Lahar Monitoring Team and sequential remote sensing data sets (bottom) in this study. The dike structures, active channel, and distal end of the alluvial fan were mapped from the January 9, 1996, ERS scene. See Fig. 1 for location.
m$^3$ of lahars (Tuñog et al., 1994) based on the monitoring of channel discharge rates and duration. Meanwhile, Daag (2003) estimated a total eroded volume of $78 \times 10^6$ m$^3$ of ignimbrite materials from the watershed region of Pasig–Potrero River using the sequential digital terrain models (DTM) of the Sacobia ignimbrite fan.

To determine the area of change between the two SIR-C observations, we derived radar correlation values using ENVI software’s module for principal component analysis. SIR-C data consist of multi-polarized C, L, and P bands, from which slightly different images are generated. Principal component analysis creates a single image based on a number of spectral bands of the same area. For the Pasig–Potrero SIR-C SAR data sets, we compared the principal components of the April 14 and October 5, 1994, and generated the image difference maps (see Fig. 4C). As the image difference map indicates, the lahar deposition has encroached the areas toward San Fernando by middle to late 1994. This encroachment was facilitated by new drainages that were formed outside the existing dike system at that time. The December 1994 SPOT scene reveals the breached walls of the inner dikes, which probably marked the location of channel avulsion that occurred on August 6–7, 1994 (GVN, 1994), at the upstream end of eastern dike in the vicinity of Delta 5 (Fig. 7). As shown in Fig. 7, by December 1994, the Pasig–Potrero River had already completely eroded a segment of an inner dike alignment and threatened to erode the outer dikes at several locations. A significant proportion of the ensuing flow was diverted through the breached opening and along the margin of the earlier deposits, which in turn acted as a natural topographic barrier that prevented the flow from reuniting with the main channel.

In 1995, lahar deposition along the lower Pasig–Potrero River affected the towns of Bacolor, San
Fernando, Guagua, Sasmuan, Minalin, Santa Rita, Porac, and Angeles. The successive occurrence of major lahars caused extensive deposition in the Pasig–Potrero fan and subsequent encroachment of low-lying areas that were previously untouched by earlier flows. Although the channel within the inner dike system remained active until early to middle 1995, it was completely abandoned by the end of the 1995 rainy season. The channel widened when the segment of the inner dike between the breached openings was eroded away. Overall, the extent of the 1995 lahar impacts on the Pasig–Potrero alluvial fan are shown in the map of the alluvial fan (see Fig. 5) based on the February 12, 1996, SPOT scene, which reveals the entire area within the outer dikes to be covered by lahar deposits.

3. Post-1995 remote sensing observations

Since the onset of lahar production, the emerging alluvial fans have progressively buried large tracks of agricultural lands and encroached into populated towns. Changes in the Pasig–Potrero alluvial fan and the development of containment dikes between the towns of Porac and Bacolor are shown using series of ERS images (see Fig. 3). The rate of encroachment climaxed during the 1995 rainy season and decreased significantly after 1996, as suggested by the extent of deposition identified in the sequential remote sensing images (Fig. 8). The 10-year trend of landscape change and engineering intervention on the Pasig–Potrero alluvial fan was marked by a sharp decline in lahar production during the El Niño year of 1996. Close examination of multi-temporal remote sensing data sets also demonstrates that the active channels remained at the same general course that was established after the flows were diverted outside the inner dike system at the end of 1995.

Analysis of sequential ERS scenes enables the progression of engineering intervention to be monitored by multi-temporal ERS-1 data acquisition (see Fig. 3) from mid-1993 to early 1998. Large lahar
events in 1994 and 1995 gave convincing proof of the inadequacy of earlier dike designs to control lahars, and had shown that the brunt of lahar mitigation lies primarily in the depositional rather than fluid transport and erosional hazards of lahars. The major changes in the scale of engineering intervention at Pasig–Potrero kept abreast with the magnitude of lahar hazards, and culminated with the completion of the outer dike system in 1996. The top of the dike structure stands between 5 and 10 m high from the base (see Fig. 2B5) and shows prominently in the radar scenes. Based on the map of Pasig–Potrero produced by the Philippine Department of Public Works and Highways (DPWH), the outer dike (locally called the Mega-dike) was conceived as a multistage sediment catchment area, which was designed to hold about $200 \times 10^6$ m$^3$ bulk sediment volume. The outer dike system encloses most of Bacolor, a portion of Santa Rita, and large part of Porac. Its eastern alignment nearly follows the municipal boundary of Bacolor and San Fernando, while the western alignment extends along the Guagua–Bacolor and Santa Rita–Bacolor boundary. Transverse dikes and the elevated Gapan–Olongapo Highway were constructed across the general flow direction so as to trigger deposition and store the sediments, while allowing the muddy streamflows to exit through spillways. Concrete armoring of the outer dike rendered the structure more resilient and gave it a more pronounced definition in the May 1996 ERS scene compared to that in the April 1995 scene.

The changes in the distribution of the lahar deposits on the alluvial fan between different acquisition times are quite pronounced in the visible and near IR wavelengths of the SPOT, LANDSAT, and ASTER data sets. The spectral bands of the above satellite data sets are able to define the distribution of lahar deposits that are not overgrown with vegetation, but cannot provide an unequivocal indication of the sequential deposition. The inability of the visible bands to discriminate...
young and old deposits is shown in the map of the alluvial fan using the February 1996 SPOT scene as compared to the field-derived map of the alluvial fan in 1995 (see Fig. 5). Old and new lahar deposits exhibit similar surface characteristics, and thus, to distinguish them in mapping, one has to rely on clues that indicate a sequential deposition. For instance, recent deposition on the alluvial fan may be suggested by the absence of vegetation, high water saturation (i.e., new deposits may still exhibit a wet surface), and smooth surface texture (i.e., lack of rills and channel erosion). Moreover, channel filling and overbanked deposits at or near the active channels are arguably young deposits, considering the dynamic conditions affecting the alluvial fan evolution. On finer points of distinction, thick lahar deposits that are not overgrown with vegetation may be older than vegetation-covered thin lahar deposits, since vegetation flourishes much faster on lahar deposits that enable rooting to sublahar soils.

The 1996 El Niño phenomenon brought widespread drought to the region, and thus a remarkable drop in the frequency and magnitude of lahar events occurred at Pinatubo. As such, the ERS scene taken in September 1996 (see Fig. 8) shows that the alluvial fan is almost the same, i.e., entirely the product of the 1995 lahar deposition. There was no indication of new areas encroached outside the extent of the 1995 alluvial fan, while in the 1996 sequential ERS scenes (Fig. 9) the fan loses contrast with surrounding areas, particularly at its margins. A normal wet season returned in 1997, but lahar generation did not exceed the intensity of the previous years and appeared to be on the decline. Lahar deposits were mostly confined within the catchment basin enclosed by the outer dike and the 3-km-long transverse dike. The RADARSAT scene acquired in December 1997 shows the extent of renewed lahar deposition and the configuration of the active channel during the 1997 rainy season (see Fig. 8). In succeeding years, lahar generation declined, as there were very few lahar events and very few new lahar deposits that were
being added on the Pasig–Potrero alluvial fan. The SPOT, LANDSAT, and ASTER images still show a large area of the depositional basin that is covered with pre-1996 lahar deposits.

Lahar events from 1998 to 2001 seasons were mostly channel-confined and the overall channel configuration of the Pasig–Potrero River system did not change dramatically from 1997. Fig. 10 shows how the superposed image-derived map of lahar deposits during the 10-year remote sensing observation period compares with the latest data provided by ASTER acquisition on November 1, 2001. Evidently, the chronological sequence of deposition that was derived from multi-temporal remote sensing monitoring of the alluvial fan evolution provides important clues for the interpretation of more recent data sets.

4. Discussion

4.1. General issues

Extensive field monitoring of the flow events, and the subsequent mapping of the deposits, were only conducted during the height of the lahar crisis in the first few years after the Pinatubo eruption up until the end of 1995. The field-monitored parameters included sediment concentration, flow duration, peak discharge, area of deposition, channel degradation, and thickness of deposits. These parameters yielded important variables in analysis of channel evolution, lahar generation, and direction of alluvial fan encroachment, which were utilized for disaster mitigation. However, this exercise required considerable

Fig. 10. Map of Pasig–Potrero alluvial fan representing a decade of monitoring the sequential lahar deposition. This cumulative lahar map consists of chronologically superposed deposit maps. The ASTER scene was acquired on November 11, 2001, and is shown in grayscale (originally displayed in a false color RGB-composite consists of bands 3, 2, and 1, respectively). It shows the location of the alluvial fan and the latest condition of the alluvial fan.
manpower and resources, and involved the manning of several field stations along active channels and tributaries and the coverage of the entire fan area. As the manpower committed to lahar monitoring and observation dwindled to a smaller team in mid-1990s due to other pressing concerns (e.g., the 1993 Mayon eruption and 1994 Mindoro Earthquake), we have found that monitoring the same critical areas using remote sensing data is an effective way to extend the time series observations and provide the information needed for hazard assessment and risk analysis. Indeed, some of the field objectives can be more thoroughly covered by properly exploiting the information from remote sensing data. For instance, the depositional area of recent lahar deposits can be determined by image analysis of high-resolution remote sensing data set in a shorter time than it takes to map the deposit in the field.

Our 10-year remote sensing analysis of the Pasig–Potrero alluvial fan reveals the progressive encroachment of lahar deposit and the changing pattern of lahar conveyance system. Although the distribution of lahar deposits may have been constrained at some portions by the construction of the dike system, the sequential images also show that the design and alignment of the dike system had evolved with the spatial and temporal changes in lahar deposition. Thickness of the deposits may be gleaned, albeit subtly, from the disappearance of known man-made structures and topographic features. Apparently, the evolution of the lahar deposit fan is a predictable response of the Pasig–Potrero alluvial fan to parallel landscape changes in the source region. The major geomorphic event of October 5, 1993, when the upstream watershed of the Sacobia River was routed into the Pasig–Potrero drainage system, was reflected in the dramatic increase in lahar deposition on the Pasig–Potrero that peaked during the 1995 lahar season.

Qualitatively, Fig. 8 suggests that the rate of lahar deposition has been rapidly decreasing since 1995. We observed from sequential remote sensing images that the active channel in the Pasig–Potrero alluvial fan maintained the same drainage pattern that was established in 1995. A similar condition of dynamic equilibrium has also been observed in 1995 in the Marella and Bucaco drainage systems on the west side of Pinatubo (Bailey et al., 2001). Moreover, the downstream channel of the Pasig–Potrero has become wider and more entrenched with better-defined meander loops at the end of the 1998 rainy season, suggesting that a near steady state condition had already been attained earlier. To date, the Pasig–Potrero River conveys muddy stream flows on to the alluvial fan, while its upstream portion has already been cutting into the pre-eruption lahar and pyroclastic flow deposits below the 1991 ignimbrite sections.

4.2. Uses of radar data

Radar data are important to volcanic hazard monitoring because of their ability to provide information in any given weather and at any time of the day. Although radar is useful for studying the large-scale changes in the Pasig–Potrero alluvial fan, we recognized some limitations in the application of these data to hazard mapping. For instance, the tonal contrast on the Pasig–Potrero alluvial fan has decreased as shown in the series of ERS radar scenes (see Fig. 9) taken during the 1996 dry season (see also Chorowicz et al., 1997 for a comparison of two ERS radar scenes of lahars). During this period, no major lahar events are expected to have resurfaced the fan so that the radar backscatter of the fan is either controlled by the water content of the surface layers (making the surface dark) or by the increasing colonization and growth of vegetation. By early 1996, the alluvial fan exhibited an overall dark tonal quality, but lost its tonal contrast along the margins and on the downstream side of the transverse dike. The poor contrast with surrounding areas suggests that vegetation growth had started to affect these areas, albeit the rest of the fan remained water saturated. Under tropical conditions, coarse cogon and wild cane grasses spread rapidly on lahar deposits [see Fig. 2B(3), B(5), B(6), B(7)]. Vegetation growth increases surface roughness and moisture retention, thereby increasing the backscatter potential of the targeted land surface. Since cultivated crops such as rice, corn and sugarcane, and wild vegetation in the surrounding areas, are of similar plant morphology, revegetation of the alluvial fans resulted in similar backscatter response between lahar and non-lahar surfaces. The deterioration of tonal contrast is even more remarkable in the September 11, 1996, data, which normally is one of the wettest months of the year in this region. However, the 1996 rainy season had far less rainfall due to the prevailing drought.
Therefore, the radar backscatter characteristics of the alluvial fan suggest a surface that has not had significant resurfacing by lahars and been substantially modified by the vegetation. Some improvements in the tonal contrast in later scenes (e.g., May 28, 1996) were artifacts of the construction of outer dike alignments and maintenance of inner dike segments, which redefined the boundaries of the alluvial fan.

The radar data are particularly useful in monitoring the evolution of the dike system, as well as the distribution of human settlements. During the 1991 to 1994 period, we observed that the strategy of engineering intervention at Pasig–Potrero alluvial fan was to contain the lahar delivery along the pre-eruption drainage course and confine the bulk of fan aggradation within the inner dike system. The sequential ERS data acquisition had shown that the engineering strategy evolved into a massive dike system between 1994 and 1996, not in anticipation of larger lahars but because the lahars have already broken out of the inner dikes and encroached into densely populated settlements. All the segments of outer dike system were completed by the end of 1996. Although most dike structures are recognizable in the radar scene, some structures are more conspicuous because of their large size and the fact that they are armored with concrete. A comparison of the field and remote sensing data (see Fig. 5) shows that we missed some segments in the ERS scene, where the unarmored dikes were covered by the same type of materials that are found in the alluvial fan. In other cases, the dikes were partially eroded or nearly buried by previous lahar events such that radar spatial resolution is unable to resolve their features. Radar look-direction, which was constant in our study, may also be important as it is easiest to identify dike segments oriented perpendicular to the radar look-direction.

We also recognize that the single wavelength/polarization radar systems such as ERS and RADARSAT are not ideal for this type of mapping even before the potential high commercial cost of these data is considered. A comparison between ERS and SIR-C SAR scenes that were both obtained in April 1994 (Fig. 11) shows the lahar deposit that is barely

![Fig. 11. Comparison of ERS scene acquired on April 23, 1994 (left), and SIR-C scene acquired on April 14, 1994 (right). ERS imaged the surface using C-band (wavelength 5.6 cm) with vertical transmit and receive polarization, while the SIR-C image was generated using C-band horizontal transmit and receive, C-band horizontal transmit-vertical receive, and L-band horizontal transmit-vertical receive. The extent of the lahar deposits is barely recognizable in the ERS scene as they blend with the surrounding area. Lahar deposits are more readily mappable in the SIR-C scene, which employs C and L bands and cross-polarization of transmitted radar and backscatter signals. ©ESA 1994.](image)
distinguishable in the ERS scene. Fig. 11 also suggests that the SIR-C radar can distinguish recent lahar deposits from old lahar deposits. Evidently, the SIR-C scene shows the lahar deposits that accumulated mostly during the previous 1993 rainy season, as it significantly differs from the alluvial fan that was observed in November 1991 SPOT image. Much of the improvement in tonal contrast between the alluvial fan and surrounding areas is probably attributed to SIR-C system’s ability to acquire data in the multi-wavelength and multi-polarized modes. The enhanced contrast can also be observed, albeit more subtly, between old and new lahar deposits. Fig. 4 shows the image difference of the April and October 1994 data sets, highlighting the areas that were encroached during the period of lahar generation, as well as the areas that remained essentially unchanged. Neutral gray tone defines the regions in the image difference where zero and near-zero DN values are clustered. As such, these areas are expected to have experienced essentially little or no change between the April and October 1994 observation periods. In the image difference map (Fig. 4C), areas in neutral gray tone correspond to settlement concentration. The density slice function in ENVI highlights the positive DN values with colors that appear light gray, and the negative DN values with colors that appear dark gray in Fig. 4C. The wide distribution of areas in light gray reflects the extensive surface alteration due to cultivation, crop growth, vegetation density, and rill erosion. The regions that are distinguished by darker gray indicate the areas that had been encroached by the alluvial fan between April and October 1994. The image difference map reasonably approximates the field-based map (Fig. 4D), although this agreement could be an artifact of deposition outside of the earlier fan. Some of the new lahar deposits that were laid on top of the pre-April 1994 fan are missing in the image difference map, except at the corner of the dike system where ponding occurred.

It is also important to note some remote sensing techniques that were not appropriate for the analysis of Pinatubo. Much progress has been made in the analysis of volcano deformation and surface change via radar interferometry techniques using both ERS and RADARSAT (Massonnet et al., 1995; Lu et al., 1997; Amelung et al., 2000). However, these spacecraft have site revisit intervals of 24 and 35 days, respectively, and we have found that atmospheric water vapor and/or changes in the distribution of surface scatterers (e.g., wind moving the leaves on vegetation) precludes the construction of acceptable radar interferograms. This means that we are unable to develop DEMs over the period of radar observations, so that it has not been possible to calculate the rate of change of lahar volume over time. Although radar coherence maps have been used to detect changes on Kilauea volcano (Zebker et al., 1996), the formation of new lahar deposits is most clearly seen in optical data such as SPOT and LANDSAT 7, so that there is less need to study radar interferograms for the small areas of Pinatubo where coherence is high.

Potentially, the use of time-series DEMs from the TOPSAR system could also be used to study the changing volume of the Pinatubo lahrs. Rowland et al. (1999) used TOPSAR and a second high-resolution DEM for Kilauea volcano to estimate the rate of lava emplacement over a decade of activity of the volcano. Although two DEMs have been collected of Pinatubo by TOPSAR, in 1996 and 2000, we have found that the vertical accuracy of the TOPSAR system is insufficient to confidently map changes in thickness of the lahrs in the lower Pasig–Potrero system. Moreover, TOPSAR data acquisitions on steep terrain are usually affected by a large number of data dropouts and radar “shadows” that prevent wholesale volume estimates by the DEM difference method. Targeted inspection of the “cleaner” TOPSAR data indicates that changes in topography can be detected up-slope where significant topographic changes in the ignimbrite are taking place.

4.3. Future trends on remote sensing applications at Pinatubo

There is a good indication that the current changes on the flanks of Pinatubo will continue for the next few years. Due to the cost of monitoring these changes, and the large geographic area over which they may occur, it is pertinent to consider a strategy for remote sensing observations as an integral part of this monitoring effort. While the SIR-C experiment will not fly again aboard the Space Shuttle, other multi-polarization radars may be able to detect surface changes on Pinatubo. In early 2002, ENVISAT was launched by
ESA, with the capability to observe the Earth in either HH- or VV-polarization and at several different incidence angles. An L-band (24 cm wavelength) radar on the Japanese ALOS spacecraft is planned for launch in 2005, and this radar may provide a greater possibility of conducting interferometric experiments as these longer wavelength data may suffer less from decorrelation than the ERS (5.6 cm) data. Planning is also underway for very high resolution (~1–3 m/pixel) X-band (3.0 cm wavelength) data from a German radar in the 2007–2009 time frame. There will also be great value in the continued observation of the development of lahar fans at SWIR wavelengths. Particularly as ASTER data are currently cheaply priced, this data set is preferable for routine observations during each dry season. Higher spatial resolution (<1 m/pixel) commercial sensors (Ikonos and QuickBird) offer the ability to study small segments of the lahar in great detail, but currently these data are very expensive to purchase, and there is no on-going strategy to obtain images of Pinatubo every year without a customer already willing to pay for the data.

Finally, we recognize the value in starting the collection of targeted high-resolution remote sensing data as soon after an eruption as is possible, which has implications for monitoring future eruptions. When cloud-free conditions permit, the acquisition of LANDSAT 7 or ASTER data should be a high priority. To extend this coverage throughout the year, multi-polarization radar data from ENVISAT are expected to be of greater value provided that the viewing geometry is held constant. In this way, we believe that satellite remote sensing will provide important additional information relevant to hazard mitigation in a timely manner and will augment field observations in areas where personal safety and/or cost are important.

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