THE APPLICATION OF TERRESTRIAL LIDAR TO VOLCANO MONITORING – AN EXAMPLE FROM THE MONTSERRAT VOLCANO OBSERVATORY

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INTRODUCTION

There can be few more hazardous situations than that of monitoring a volcanic andesite lava dome for signs of an impending collapse. Partial collapse of a lava dome generates hot, fast-moving pyroclastic density currents - superheated rock avalanches that can travel at speeds of over 300 km/h, with temperatures exceeding 1000°C. The volcano also generates plinean eruptions – sustained, explosive events sending high, jet-like columns of pumice and ash 30km, or more into the stratosphere. Plinean eruptions can last several hours and cover surrounding areas in thick layers of pumice, and ash, up to 15cm deep. Monitoring in such circumstances requires that measurements are taken from a distance that minimises the threat from eruption and from asphyxiation by volcanic gases. The method also needs to be rapid to minimise the time spent by the monitoring team in the hazardous zone (Jones, 2006). Terrestrial laser scanning surveys represent at the moment one of the most powerful tools to accurately map inaccessible surfaces such as volcano craters (Conforti et. al., 2006).

The island of Montserrat is only 16km long by 10km wide, and is located in the northern part of the Lesser Antilles volcanic island arc which formed as a result of subduction of the North Atlantic tectonic plate beneath the Caribbean plate (Figure 1). The Soufrière Hills Volcano (SHV) began to erupt in 1995 after at least 400 years of dormancy, generating primary and secondary volcanic hazards, including pyroclastic flows, lahars, ash falls, landslides and earthquakes. By measuring and monitoring changes in the profile of the volcano scientists at the Montserrat Volcano Observatory (MVO) can detect long-term ground deformation and short-term rapid movements that can act as precursors to failures in the flanks of the volcano or dome. A series of papers can be found in Druitt and Kokelaar (2002) covering all aspects of these eruptions and their consequences.

DOME VOLUME MEASUREMENTS

Prior to August 2005 dome volume measurements were made using compass and Abney level surveys, supplemented by photographs and theodolite measurements

(Sparks *et al*., 1998), but the estimates from this type of survey are subject to both systematic and non-systematic errors. The use of terrestrial LiDAR (Light Detection and Ranging) enables the accurate location of a network of points that can be used to create a detailed 3-D terrain model, or DEM (Digital Elevation Model), of greater coverage and accuracy than conventional methods, without the associated errors, and with almost complete safety of the operators (Jones, 2006). The British Geological Survey (BGS) supplied the MVO with a Riegl LPM-2K long range laser scanner (Figure 2), in order to create an accurate 3D terrain model of the volcanic area and provide continuous measurements of the profile without venturing onto the unstable slopes. Subsequent surveys can be compared to the previous models and differences in morphology can be assessed both quantitatively and qualitatively, following the methods described in Hobbs *et al*. (2002), for example. The lava dome topography changes rapidly, extruding lava at rates of 4 to 10 m3 per second, with visible changes being seen daily, therefore the ability to collect thousands of millimetre accurate measurements on a daily basis is fundamentally important to the work being carried out on the island.

The Riegl LPM-2K is specifically designed for the automatic and manual collection of surface profile measurements at ranges up to 2.5km. Combined with a Global Positioning System (GPS), to geographically reference survey measurements, the unit can record up to 4 readings per second with a resolution of 10mm, and a typical accuracy of 50mm. The unit is integrated in a robust, dust and water-proof housing and is therefore well suited to the harsh volcanic environment. The laser uses 'last-pulse' time-of-flight detection to determine the distance to a reflective surface from the instrument position, along with its azimuth and elevation. It is controlled and logged using a ruggedised 'Toughbook' PC and, typically, 8,000 points can be data-logged in one hour in most weather and light conditions. The data may be transformed to a grid co-ordinate system using PC software by means of back-sighting to a known target in manual mode, or by independent survey (e.g. GPS). Using the transformed x, y, z data points, 3-D contoured surface models may be created in various CAD and mapping software packages. In addition, reflectivity values are recorded which may be used to distinguish between rock types and most rock/soil materials provide a good reflective surface. An additional advantage of LIDAR scanning is that where features are obscured by cloud or gas, as is often the case in the crater, a zero reading is obtained which can be filtered out and replaced by true data obtained when the cloud or gas has moved away. Thus, if necessary, a full coverage can be obtained by combining scan data from several partially obscured views.

LIDAR SURVEYS

The baseline survey was carried out on 16th August, 2005. Weather conditions were good, but conditions underfoot were difficult, mainly due to the excessive vegetation between the helicopter landing site and the scanning location. Two scans were carried out from the new fixed-camera position at Perches Estate, on the flanks of the volcanic crater (Figure 3). The first (general) scan covered an area of the crater approximately 900m wide (north-south) and 700m long (east-west) and the second (detailed) scan covered a small area approximately 300m wide and 150m long, centred on the area of new dome growth, between [380700, 1846700] and [381600, 1847400]. Approximately 1.5 hours were spent on the flanks scanning, with access and egress via the waiting helicopter, approximately 30m from the scanning location. The raw data consisted of approximately 3,000 *x, y, z* points. This does not appear to be a vast amount of data, for the area scanned, but it is over ten times more than previously used when calculating the dome volume using photogrammetric methods. The results from the first scan demonstrated the effectiveness of the technique in gathering data accurately, rapidly and safely, and determined that further scans should be carried out.

In May 2006 the dome had grown to an impressive volume of 100 million m^3, filling the crater and towering above the islands highest mountain, Chances Peak. On 11th May one scan was carried out from the fixed pin at Galway's, on the crater rim (Figure 3). A general scan was in progress when a rockfall occurred on the flanks of the dome, throwing up clouds of impenetrable ash (Figure 4), these continued for about an hour with less than 1,200 *x, y, z* points being collected. On 18th May three scans were carried out from Galway's. The first (general) scan covered the same crater area as previously, the second (detailed) scan covered the whole dome, and the third (small) scan concentrated on the top of the dome. The final scan was carried out as the cloud lifted and, therefore, the full extent of the dome could be seen (Figure 5). In total, the data consisted of approximately 3,000 *x, y, z* points. In the early hours of the morning of 20th May the dome began glowing on its northern side and heavy rain began to fall, a dome collapse had begun. A boiling cloud of ash was sent 20km into the air as the dome exploded. Ash and stones rained down on the residents of

Montserrat, and the massive pyroclastic flows that hit the sea caused 1m high tsunamis in Antigua and Guadeloupe. Later that day, when the MVO scientists were able to see into the crater the whole lava dome, and some of the crater rim, had been removed leaving an empty crater floor (Figure 6). On 25th May four scans were carried out from Galway's, covering the whole of the crater area, plus some of the run-out area down the Tar River valley. This scan, totaling approximately 4,000 *x, y, z* points, revealed that a new dome was already growing in the base of the crater, and it was growing fast. This scan would form the 'zero' baseline for any successive scans.

Subsequent scans were carried out in October 2006 from Galway's, February 2007 from Perches, and June 2007 from both Perches and Galway's. By October 2006 the new dome had grown to a volume of 100 million m^3, taking just 23 weeks to overhaul the 20th May dome, which took 43 weeks to reach this size. By April 2007, after 43 weeks, the dome stood at 208 million m^3, where it has remained (Figure 7). The volcano appears to have entered a state of pause with little, if any, changes in morphology with low seismic activity and gas emissions, and the occasional rockfall or pyroclastic flow. However, it remains a large mass of partially molten lava capable of collapsing or exploding at any time.

3-D MODEL

The terrestrial LiDAR data produced by the oriented laser scan and GPS surveys were processed in RiPROFILE™ to create spatially oriented 'point-clouds' which could be output as ASCII files, made up of *x*, *y*, *z* and intensity values. The data were imported into Surfer™ (a surface mapping program) and manipulated using a geostatistical gridding method, named Kriging, to produce a visually appealing 3-D model of the crater and the lava dome, from the irregularly spaced data points. The data were also imported into Quick Terrain Modeler™ (a digital 3-D modeling package) and 'surfaced' using a triangulation method to produce a solid 3-D model that can be viewed from any orientation (Figure 8). Although the scanner has a resolution of 50mm the surfaces were created at 0.5m grid intervals, this is due to inaccuracies that could be caused by the spread of the data, and by the ability of the PC and the software to carry out the gridding calculations. Intensity images, change plots and cross-sections can also be produced from these surface models. The successful creation of 3-D terrain models using LIDAR scanning in the extremely hazardous conditions of an active volcano demonstrates the effectiveness of the technique for gathering data for the assessment of dome instability monitoring and dome volume calculations. Repeat surveys can be carried out accurately, rapidly and safely with regard to the health and safety of the survey team and the work requirements.

ACKNOWLEDGEMENTS

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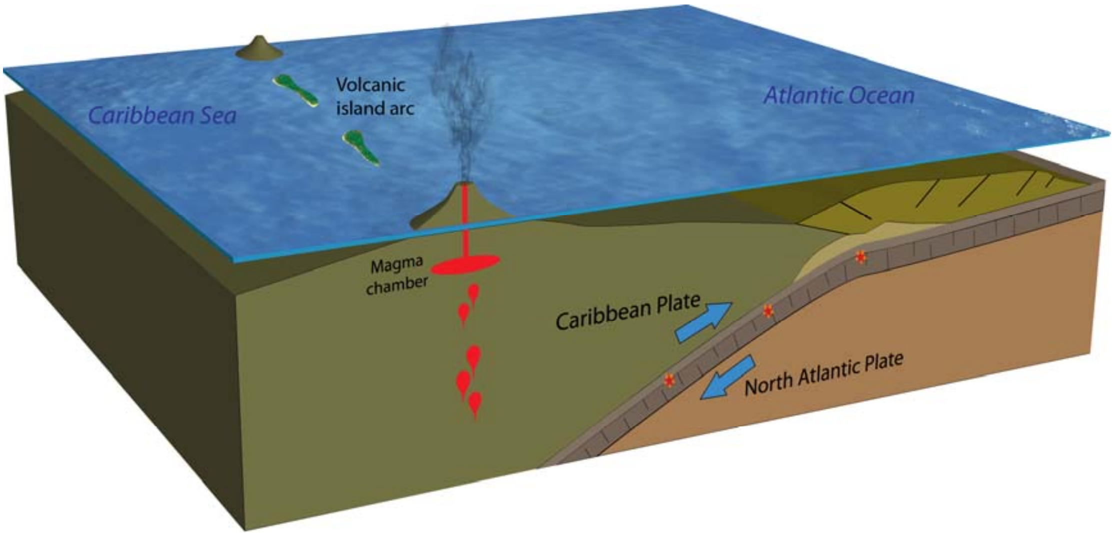


Figure 1 – Schematic diagram showing the Lesser Antilles subduction zone (not to scale).

Figure 2 – Setting-up the Riegl LPM-2K long-range terrestrial LiDAR on Perches mountain.

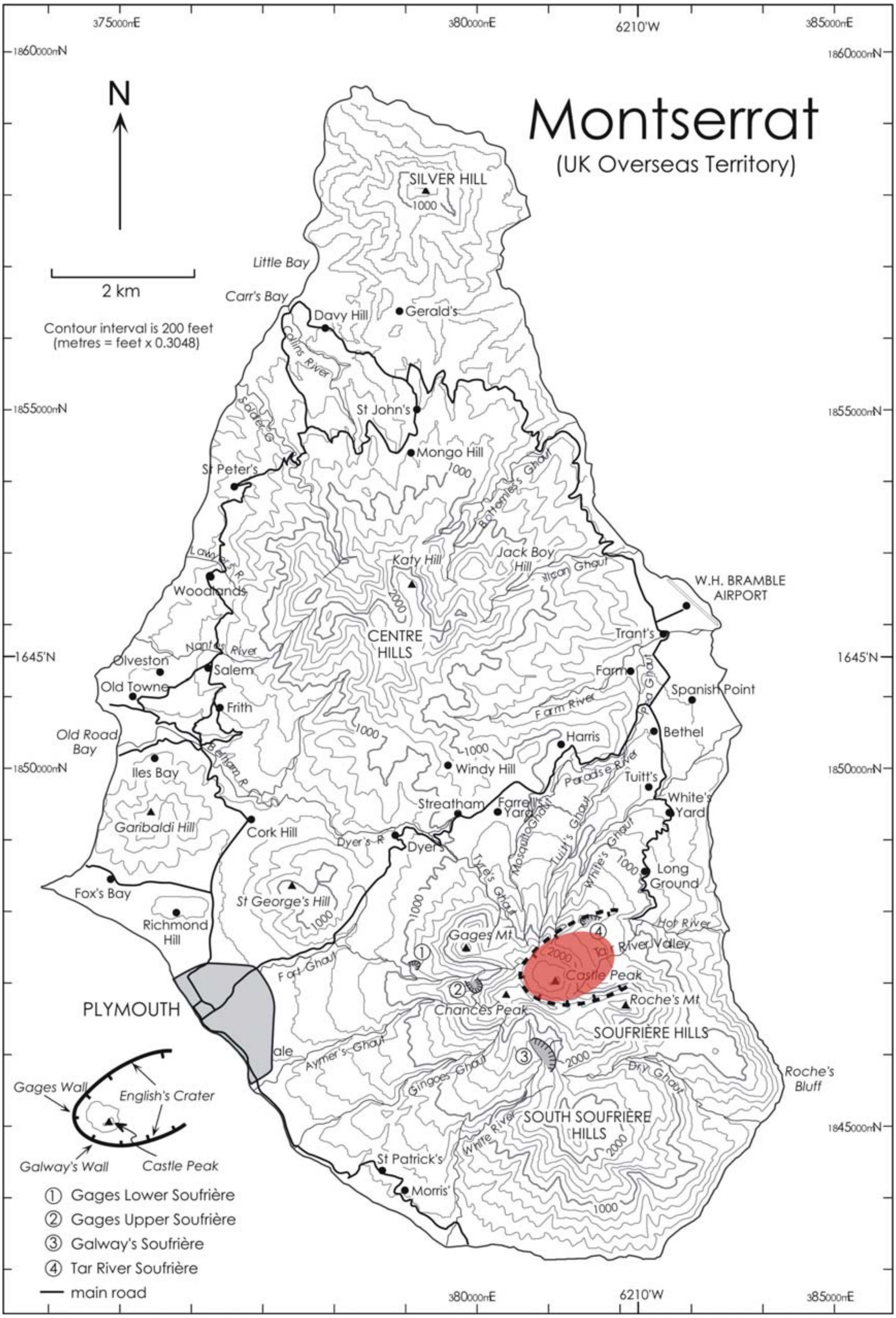
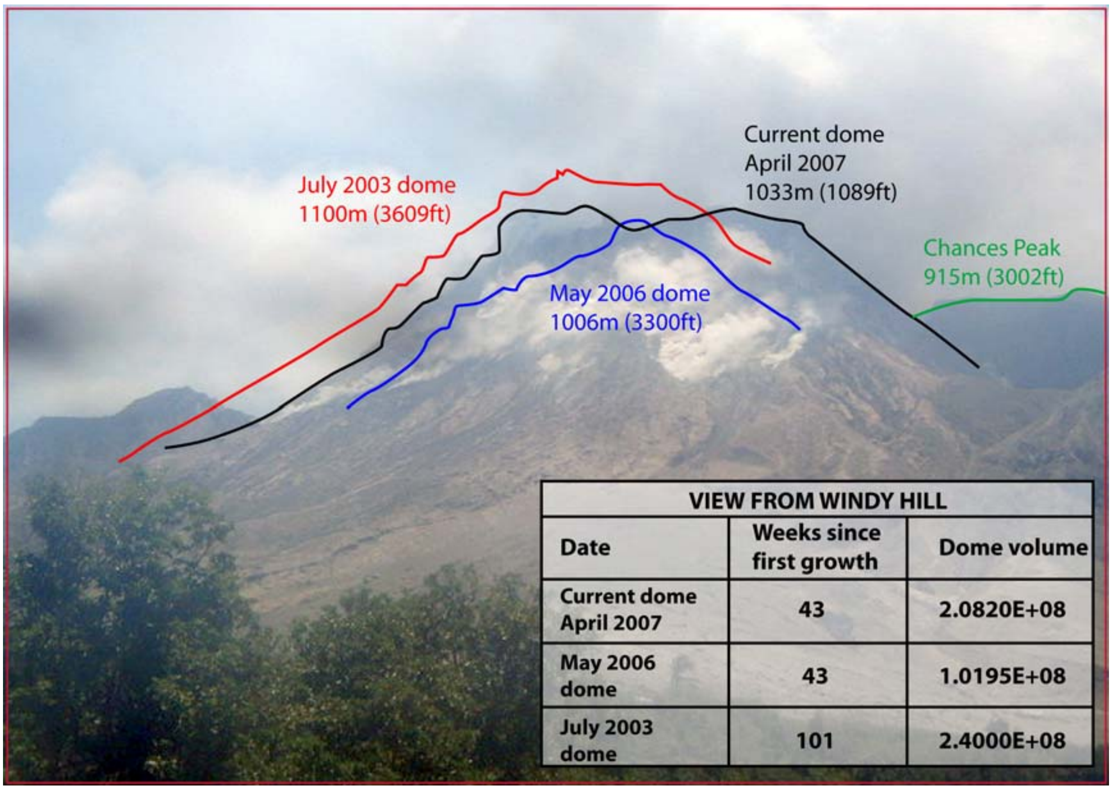


Figure 3 – Location of the Volcano, LiDAR scanning positions and extent of survey area (red shaded).

Figure 4 – Rockfall event, causing clouds of impenetrable ash and preventing completion of scan from Galway's.

Figure 5 – Clouds clear to reveal full extent of the 100 million m^3 lava dome.

Figure 6 – Empty crater, seen after the 25th May eruption.



Date	Weeks since first growth	Dome volume
Current dome April 2007	43	2.0820E+08
May 2006 dome	43	1.0195E+08
July 2003 dome	101	2.4000E+08

Figure 7 – Comparison of three dome growths at the Soufrière Hills Volcano.

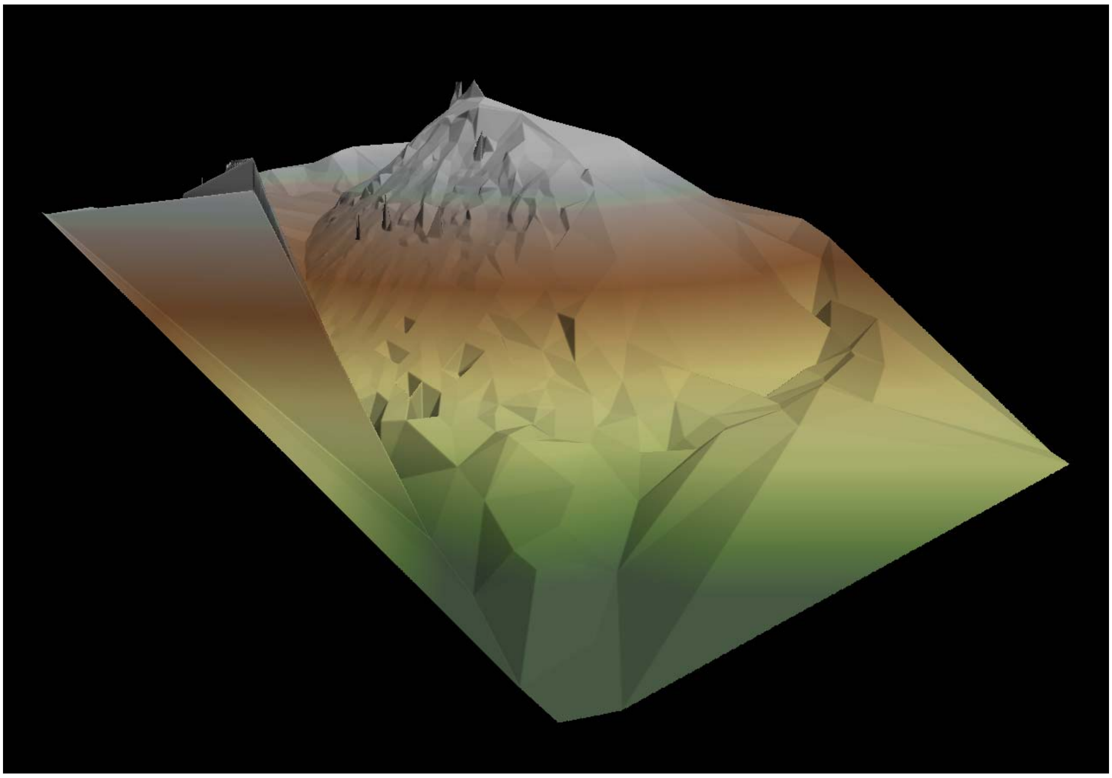


Figure 8 – 3-D Surface model (October 2006), Viewed from the SE (Quick Terrain Modeler™).