A new Digital Elevation Model of the Soufrière Hills Volcano, Montserrat

3D perspective view, looking south into the 2010 collapse scar, of the photogrammetry DEM of the lava dome at the Soufrière Hills Volcano, Montserrat.

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Executive Summary

This report describes the development of a new digital elevation model (DEM) for the Soufrière Hills Volcano, Montserrat that combines a LiDAR-derived DEM from 2010 with a photogrammetry-derived DEM of the lava dome from 2014. A brief overview of the image acquisition and processing methodology is provided along with information about the properties of the resulting 2014 SHV DEM. Details on how to acquire the DEM and associated orthophoto for research purposes are also provided.
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1. Introduction

Digital elevation data is an essential part of monitoring the growth of the lava dome at the Soufrière Hills Volcano (SHV), Montserrat. Data collected during the course of an eruption can provide information on extrusion rates and morphology of the dome. It is also used for determining the volume of deposits associated with dome collapses and for hazard assessments.

Since the present eruption of SHV began in 1995, a series of Digital Elevation Models (DEMs) have been produced with a range of areas, resolutions and time periods, some of which were modified versions of the original pre-eruption DEM.

Following the large partial collapse of the lava dome on 11 February 2010 at the end of Phase 5 (Stinton et al., 2014a,b) a new DEM covering the southern two-thirds of Montserrat was commissioned by MVO. This new DEM was necessary due to the significant topographic changes that had occurred on the lava dome, in the surrounding ghauts and along the coast of Montserrat as a result of activity in Phases 3, 4 and 5, since the last DEM was created in 2007. Unfortunately, due to cloud cover, the resulting DEM did not include the lava dome and flanks above approximately 700 m elevation.

This report describes a new DEM (herein referred to as the photogrammetry DEM) covering the lava dome and its subsequent merger with the 2010 LiDAR DEM to create a new high-resolution DEM of the southern two-thirds of Montserrat (herein referred to as the 2014 SHV DEM). The new DEM has been developed in-house by MVO using images acquired with a GoPro action camera and processed with the structure-from-motion software package AgiSoft Photoscan Professional.

2. 2010 LiDAR DEM

In June 2010, a LiDAR survey of the SHV commissioned by MVO/DFID was undertaken by Terrapoint Inc. The resulting DEM consisted of a 1 m gridded bare earth elevation model and a full-feature hillshade image. Unfortunately, due to cloud cover at the time of the survey, the DEM did not include the dome above 700 m elevation. The bare earth DEM has a root mean square error (RMSE) of 0.15 meters for vertical accuracy and 0.4 meters for horizontal accuracy.
3. Data Collection and Processing

Figure 1 summarises the workflow used in acquiring and processing the images to generate the 2014 Soufrière Hills DEM.

Aerial photogrammetry surveys usually require expensive, high-resolution cameras. Routine use of photogrammetry at MVO is an essential part of dome monitoring and an inexpensive, but reliable camera was needed. The camera used by MVO to acquire the images for the aerial survey is a GoPro Hero3 Black, capable of capturing 12 megapixel images. With a 170 degree field of view, the GoPro is not a photogrammetric camera, but is an inexpensive, simple and effective tool to rapidly collect aerial photographs over a wide area. GoPro cameras have been used in archaeological surveys to acquire detailed 3D information about historic sites and in DEM generation (Illsley, 2012, Balletti et al., 2014).

During image acquisition, the GoPro camera was set to acquire an image automatically every second using the camera’s built-in timelapse mode. Acquiring an image every second maximises overlap between images, ensuring that there is enough imagery to counter loss of data during the distortion correction and image cropping described below. Geolocation information was collected using a Garmin GPSmap 60CSx unit, located inside the helicopter cabin. This was also set to record positions along the flight track every second. Although the GPS unit is capable of determining locations to within ±2 m, the error of individual waypoints is not recorded. Also, no information on the pitch, yaw and roll of the helicopter is recorded. Due to the powerful nature of the Agisoft PhotoScan Professional software used, the lack of this information is not detrimental to the processing. In order to ensure the images are correctly located, photos of the GPS unit were taken to determine any offset in time between the camera and the GPS unit.
Due to the very wide field of view, images acquired with the GoPro camera suffer from significant distortion (Figure 2). In order to extract the best information from the images, the distortion was corrected using the commercial software DxO Optics Pro 9, which includes a lens correction module specifically designed to work with the GoPro camera. Following distortion correction, the images were cropped to remove distortion around the edges of each frame (Fig. 2).

More than 530 images were acquired during the survey flight on 11 March 2014. Of these, 292 from 8 of the 14 flight lines were imported into Agisoft PhotoScan Professional. Once imported, the first step of the photogrammetry workflow was to assign the geolocation data from the GPS flight track to each of the images. Once this was complete, a dense point cloud, a triangular irregular network and textured surface were extracted from the images using the Structure-from-Motion method (Westoby et al., 2012). From these datasets, a gridded digital surface model (with a 3 m grid spacing) and a georectified orthophoto (with a 65 cm pixel size) were exported for use in ArcGIS (Fig. 3).
Prior to merging it was necessary to resample the 2010 LiDAR DEM from its original 1 m grid spacing to match the 3 m grid spacing of the photogrammetry DEM. This was achieved with the bilinear interpolation option in the Resample tool. The resampled 2010 LiDAR DEM and the photogrammetry DEM were then merged together using the Mosaic to New Raster tool with Blend chosen as the mosaic method. Using this method the output cell value of the overlapping areas will be a blend of values that overlap; this blend value relies on an algorithm that is weight based and dependent on the distance from the pixel to the edge within the overlapping area (Fig. 4).

Figure 4: Illustration showing how the Blend method in ArcGIS works to create a single raster dataset from two overlapping datasets. The spot where the X is located has two values, the value of the pixel in dataset R1, and the value of the pixel in dataset R2. Since the X is closer to dataset R2, the value of the R2 pixel will be more heavily weighted in the output.
Various methods of mosaicking were tested before settling on Blend as this method produced the smoothest and most accurate transitions from the 2010 LiDAR DEM to the photogrammetry DEM. Other methods generated artificial cliffs or deep troughs where the two DEMs joined.

4. 2014 SHV DEM Properties

Table 1 summarises the main properties of the 2014 SHV DEM.

Table 1: Summary of the main properties of the 2014 SHV DEM compared to the photogrammetry DEM and the original 1 m resolution 2010 LiDAR DEM

<table>
<thead>
<tr>
<th>Property</th>
<th>2014 SHV DEM</th>
<th>Photogrammetry</th>
<th>2010 LiDAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal grid spacing</td>
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<td>3 m</td>
<td>1 m</td>
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<td>Vertical RMSE</td>
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</table>

4.1. Root Mean Square Error

The Root Mean Square Error (RMSE) is an assessment of how much error there is between two datasets, for example two elevation models from different sources. In order to gauge the relative accuracy of the elevation values in the 2014 SHV DEM, the RMSE was calculated for 27 points distributed across the overlapping areas of the 2014 SHV DEM, the photogrammetry DEM and the 2010 LiDAR DEM (Fig. 5, Table A1). For the photogrammetry DEM, exported directly from Agisoft Photoscan Professional, RMSE is ± 7.2 m, while RMSE for the 2014 SHV DEM is ± 5.1 m. In both instances, the DEMs were compared to the 3 m grid spacing version of the original 1 m resolution 2010 LiDAR (which had a vertical RMSE of ±0.15 m). The reduction in RMSE is most likely a result of using the Blend method during the mosaic process (see above).

An initial assessment of the RMSE for the photogrammetry DEM revealed some areas with very high RMSE (> 25 m). These areas were located around the edges of the photogrammetry DEM where there was extensive overlap with the 2010 LiDAR DEM. As a result, these areas were clipped from the photogrammetry DEM before it was merged with the 2010 LiDAR DEM. The RMSE values reported in Table A1 in Appendix A are based on this clipped version of the photogrammetry DEM.
Figure 5: Location of the selected points for RMSE calculation between the 2014 SHV DEM (blue circles), the photogrammetry DEM (red circles) with the 2010 LiDAR DEM. Basemap is the 2014 SHV DEM. White box contains the portion of the photogrammetry DEM used in the mosaicing process.

4.2. Coordinate System

Both the 2010 LiDAR DEM and the 2014 SHV DEM use the World Geodetic System 1984 (WGS84) ellipsoid and a Universal Transverse Mercator (UTM) datum. Due to its definition, the WGS84 ellipsoid reference surface is approximately 42 m above sea level near Montserrat (Odbert and Grebby, 2014). Consequently, all elevation values along the coast of Montserrat in both the 2010 LiDAR DEM and the 2014 SHV DEM have values that are up to 42 m below zero. This should have no effect on uses of the 2014 SHV DEM in certain applications, e.g., in numerical flow simulations, but users should be aware of the projection systems when comparing the 2014 SHV DEM with older DEMs.

5. Caveats in Using the 2014 SHV DEM

The 2014 SHV DEM has been constructed using near vertical optical aerial photographs. There are several sources of error possible from using this source of imagery. The first is that being optical images, the presence of clouds and the gas plume over the volcano reduces the ability to acquire images with
clear views of the lava dome and surrounding flanks. During the survey flight on 11 March 2014, very little cloud was present over the volcano, however, the gas plume was obscuring some of the summit and west flank of the lava dome, as shown in Fig. 3. However, the Agisoft PhotoScan Professional software has been able to extract sufficient information from the images containing the gas plume over the west flank to construct an accurate representation of that sector of the lava dome. The only area of the lava dome in the DEM that is not accurate is the explosion crater located in the summit. This is due to the presence of a thick gas plume in this location (one of the main locations of degassing on the volcano) preventing the software from extracting the topography of the crater. This is only an issue when undertaking volumetric analyses involving this DEM. A method for generating an accurate representation of the summit crater using alternative sources of elevation data or photographs with better visibility (difficult due to the presence of the gas plume) is being explored and an updated version of the 2014 SHV DEM will be released when this has been achieved.

6. Data Licensing
The following data is available from MVO:
- 3 m resolution DEM (2014 SHV DEM)
- 65 cm resolution orthophoto of the photogrammetry DEM
- 10 m resolution DEM covering the whole island (consisting of the 2014 SHV DEM merged with the earlier 1995 pre-eruption DEM for the northern part of the island).
- Outline of the Montserrat coastline in 2010.

Anyone interested in obtaining a copy of the above data from MVO should contact either of the following people at MVO to discuss data needs and use.

Primary contact: Dr Adam J Stinton, MVO Volcanologist
Email: adam@mvo.ms

Secondary contact: Mr Roderick Stewart, MVO Director
Email: rod@mvo.ms

Tertiary contact: Montserrat Volcano Observatory
Email: mvo@mvo.ms
Tel: +1-664-491-5647
Fax: +1-664-491-2423

There is no charge for using the data. However, MVO require that a data license be completed that includes a brief description of the data requested and its intended use. An example data license is included in Appendix B.
7. Summary

A new digital elevation model of the Soufrière Hills volcano has been constructed using both photogrammetry and LiDAR data. Using more than 290 images acquired with a GoPro Hero 3 Black action camera, a DEM and an orthophoto have been constructed using the Structure-from-Motion method employed in the Agisoft PhotoScan Professional software. Geolocation information was collected a handheld Garmin GPS unit.

Following mosaicking, using the Blend method in ArcGIS, with a down-sampled version of the original 2010 LiDAR DEM (1 m grid spacing), the new 2014 SHV DEM has a horizontal grid spacing of 3 m and a vertical RMSE of ±5.1 m.

Due to the presence of the persistent gas plume over the summit, the explosion crater in the summit of the dome is not accurately represented. An update to the 2014 SHV DEM with a more accurate representation will be released in due course.

Anyone interested in using the 2014 SHV DEM in research should contact MVO.

8. Software Resources

The following is a list of resources for more information about the image correction and photogrammetry software used to develop the 2014 SHV DEM.

- **DxO Optics Pro**
  
  [www.dxo.com](http://www.dxo.com)

  A standalone software package that can correct distortion and other imperfections in images acquired by consumer-grade digital cameras.

- **Agisoft PhotoScan Professional**
  
  [www.agisoft.com](http://www.agisoft.com)

  A powerful standalone software package for photogrammetric processing of digital images to generate high resolution georeferenced orthophotos (up to 5 cm accuracy with GCP) and exceptionally detailed DEMs/textured polygonal models. Data can be exported in a variety of formats, e.g., geotiff, suitable for further processing and analysis in any GIS software.
9. References


Appendix A: RMSE values

Table A1: Comparison between elevation values at select positions in the 2010 LiDAR, the photogrammetry and the 2014 SHV DEMs and the associated RMSE values for the Photogrammetry and 2014 SHV DEMs.

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RMSE 7.20  5.10
Appendix B: Example Data License

An example data license, required in order to use the 2014 SHV DEM and associated orthophoto, is presented in the following pages. Potential licensees should contact MVO to discuss data use.
LICENCE TO USE 2014 Digital Elevation DATA HELD BY MVO

THIS AGREEMENT is made the XX day of <Month, Year>

BETWEEN:

(1) The Montserrat Volcano Observatory (“MVO”)
(2) Name, Address (“the Licensee”)

IT IS AGREED as follows:

(1) Definitions

The following terms shall have the following meanings:

“Project” As described in Appendix 1 to this licence.

“Data” As described in Appendix 2 to this licence.

“Rights” The non-exclusive right by way of license to use and where necessary to copy the Data solely for the purpose of the Project.

(2) Recitals

2.1 The MVO (“the Licensor”) is the owner of the copyright and all other rights in the Data.
2.2 The Licensor has agreed to grant the Rights to the Licensee subject to the following terms and conditions.

(3) Grant of Rights

The Licensors as beneficial owners of the Data grant the Rights to the Licensee for a period of two years from the date of this Agreement.

(4) Licensor’s obligations

The Licensor agree with the Licensee to supply to the Licensee within 1 (one) month of specific request for data covered by this Agreement 1 (one) copy of the Data.
(5) Licensor’s warranties

The Licensor warrants that:
5.1 The Licensor is the sole owners of the copyright and all other rights in the Data and has full power to enter into this Agreement and to give the warranties contained in this Agreement.
5.2 The Data does not infringe the copyright or any other rights of any other person.

(6) Licensee’s obligations

The Licensee agrees with the Licensor:
6.1 Not to assign or sublicense the Rights
6.2 Not to permit others to use the Data except for the purpose of assisting the Licensee on the Project.
6.3 To provide reports on the use of the Data to the Director of the MVO at intervals no less frequent than once every 6 (six) months.
6.4 To notify to the Director of the MVO any changes in the Project objectives and collaborators within 1 (one) month of the change.
6.5 To involve at least one MVO staff member as a collaborator on the Project.
6.6 To acknowledge MVO as the source of the Data in any publications, including theses.
6.7 Immediately upon completion of the Project or within two years of the date of this Agreement, whichever is the earlier, to return all the copies of the Data supplied by the Licensors together with any further copies made by the Licensee.
6.8 To provide MVO with digital copies of all publications which make use of the Data, including theses.
(7) General

7.1 All rights not specifically and expressly granted to the Licensee by this Agreement are reserved to the Licensors.

7.2 The Licensors assert to the Licensee their moral right to be identified as the copyright owners of the Data in any publications arising from the project.

7.3 This Agreement contains the whole agreement between the parties and supersedes any prior written or oral agreement between them in relation to its subject matter and the parties confirm that they have not entered into this Agreement on the basis of any representations that are not expressly incorporated into this Agreement.

7.4 Headings contained in this Agreement are for reference purposes only and shall not be incorporated into this Agreement and shall not be deemed to be any indication of the meaning of the clauses to which they relate.

IN WITNESS WHEREOF the parties have hereunto set their respective hands the day and year first above mentioned.

Mr. Roderick Stewart
Director
Montserrat Volcano Observatory. Montserrat

Name
Address