

Institution: University of Reading
Unit of Assessment: 7 Earth Systems & Environmental Sciences
Title of case study: Mitigation of volcanic hazards using satellite- and ground-based radar
<p>1. Summary of the impact</p> <p>Researchers at the University of Reading have developed and implemented ground and satellite-based techniques that improve the monitoring of impending volcanic eruptions and their aftermath. Our systems have been mainly used in collaboration with the Montserrat Volcano Observatory (MVO) and the local government civil protection committee on Montserrat. In July 2008 the early rescinding of a precautionary evacuation was made possible by these techniques, thereby minimising disruption and lost economic revenue. The deployment of a permanent, operational ground-based instrument on Montserrat provides a capability that will reassure inhabitants and the island's commercial sector of future timely warnings, thereby enhancing their quality of life and allowing companies to return to the island.</p>
<p>2. Underpinning research</p> <p>The University of Reading (UoR) has a long-standing programme of work to develop new methods of measuring the dynamism of volcanic activity and incorporating these measurements into models that can be used to mitigate the resultant hazards (such as Pyroflow² for simulating the paths of pyroclastic flows from the Soufriere Hills Volcano on Montserrat). As part of this we have helped pioneer the practice of using radars (on the ground and in space) to monitor the state of active volcanoes, particularly those that are frequently obscured by cloud. The ground-based radars were developed in collaboration with the University of St Andrews (UoSA) and Lancaster University (LU) and the space-based radar techniques with DLR (German Aerospace Center), Astrium (Europe's largest space company) and ESA (European Space Agency). Prof. G. Wadge has been with the Unit from 1985 to the present day. Wadge led the work at UoR with contributions from PhD students H. Odbert (2004-8) and A. Toombs (2007-11) (supervised by Wadge) and technical staff in the Unit.</p> <p>The research comprised two complementary strands.</p> <ol style="list-style-type: none"> 1. A ground-based millimetre-wave radar/radiometer, the All-weather Volcano Topography Imaging Sensor (AVTIS) was proposed, built, tested and deployed in a ten-year programme that began in 2000. This was funded by a series of grants from NERC with Wadge as PI. AVTIS was specifically designed for lava dome volcanoes such as the Soufrière Hills Volcano on Montserrat. In conjunction with MVO, we demonstrated that AVTIS provided data on the topography and temperature of the growing lava dome independent of weather conditions, and provided changing hazard information on timescales of hours to weeks.^{3,4,5} A second generation of fixed and roving ground-based versions of AVTIS, was also conceived, built, installed and tested by the Unit, in conjunction with MVO. By 2011, a fixed AVTIS instrument provided continuous, 24-hour data from the volcano and has been used operationally by MVO since. AVTIS is the only such instrument in operation worldwide. 2. The application of space-borne synthetic aperture radar (SAR) for volcano monitoring was developed over the last two decades. The Unit played a significant role in this by helping to apply radar interferometry to measure subtle ground motions on volcanoes (including the first mobile ground-receiving station on Montserrat in 2000) and in using radar intensity changes to monitor the emplacement of pyroclastic flows (high-speed flows of hot ash, rock fragments and gas) and lava flows. In the early 2000's Wadge helped design satellite missions in conjunction with ESA and Astrium specifically for volcano monitoring. The Unit has pioneered the use on volcanoes of very high resolution radar intensity data from the TerraSAR-X satellite and in 2009-10 demonstrated for the case of Montserrat how the location of explosive vents and recently emplaced pyroclastic flows can be readily tracked in inaccessible and cloud-covered areas^{1,5}, and in 2010-11 how the motion of lava flows in Papua New Guinea could be tracked.⁶ The high spatial resolution and temporal frequency of these new datasets opens up a valuable source of information on the dynamics of on-going explosive and effusive volcanic activity that is of direct operational value to observatory scientists responsible for making hazard forecasts. <p>March-April 2006 provided a valuable demonstration of the value of the radar measurements. AVTIS measurements of the lava dome showed that an increase in the rate of lava extrusion was occurring⁴. This was not detected by other MVO instruments until two days later. Thus AVTIS effectively provided a 2-day improvement in early warning of an increased level of hazard. This</p>

additional warning has been an important gain in terms of planning emergency procedures.

- ¹. Wadge, G. (2009) Satellites offer crucial data for volcano safety. <http://bit.ly/1dFiNHu>. For more information about this source see <http://www.scidev.net/en/content/what-we-do/>

3. References to the research

Publications

The numbers of citations to each journal paper are given, as found using ISI Web of Knowledge in October 2013. Another metric of the quality and originality of the research is the fact that, following tests, the ground-based radars and satellite information was put into operational use by MVO and that the new systems are unique, being the only such operational system in the world. The three main references for evaluating research quality are marked with an asterisk.

- ². *Wadge, G. et al. (1998). [Computer simulations of pyroclastic flows from dome collapse](#). *Geophys. Res. Lett.* 25, 3677-3680. doi:10.1029/98GL00710. (23 cites)
- ³. *Wadge, G., et al. (2005). [AVTIS: a novel millimetre-wave ground based instrument for volcano remote sensing](#). *J. Volcanol. Geotherm. Res.*, 146,307-18, doi: 10.1016/j.volgeores.2005.03.003. (15 cites)
- ⁴. *Wadge, G. et al. (2008). [Lava dome growth and mass wasting measured by a time series of ground-based radar and seismicity observations](#). *J. Geophys. Res.* 113, B08210, [doi:10.1029/2007JB005466. (14 cites)
- ⁵. Wadge G., et al. (2011) [Rapid topographic change measured by high-resolution satellite radar at Soufrière Hills Volcano, Montserrat, 2008-2010](#), *J. Volcanol. Geotherm. Res.*, 199 (1-2), 142-152. doi: 10.1016/j.volgeores.2010.10.011. (3 cites)
- ⁶. Wadge, G., et al. (2012) [Pulsatory andesite lava flow at Bagana volcano](#). *Geochem., Geophys., Geosyst.* 13/11 Q11011, doi: 1029/2012GC004336. (no cites yet)

Selected Research Funding

NER/A/S/2001/01001 (NERC, Standard, £282k) Measuring and modelling the collapse of volcanic domes. (2002-2005) Wadge (PI), Pinkerton (Lancaster), Smith (St Andrews).

NE/D00859X/1 (NERC, Urgency, £12k) Measuring the growth of the new lava dome at Soufriere Hills Volcano, Montserrat. (Oct-Nov 2005) Wadge (PI), Pinkerton (Lancaster), Smith (St Andrews).

NE/D001734/1 (NERC, Urgency, £37k) A time series of measurements of magma flux at the lava dome of Soufriere Hills Volcano, Montserrat. (Mar-Apr 2006) Wadge (PI), Pinkerton (Lancaster), Smith (St Andrews).

NE/EO15352/1 (NERC, Standard, £368k) Measuring incipient lava dome collapse. (2007-2011). Wadge (PI), Pinkerton (Lancaster), Smith (St Andrews).

MVO contributed approximately £50K over ten years in the form of laboratory use, staff time and helicopter flights for testing our radar system.

Satellite data grants were made by DLR (German Space Agency) to the UoR, together with MVO and Rabaul Volcano Observatory (Papua New Guinea):

GEO-0436 (DLR, TerraSAR-X, 40 images) Mapping morphological and structural changes on a lava dome as a precursor to surface activity, Soufriere Hills Volcano, Montserrat. (2008-2010) Wadge (PI).

GEO-0879 (DLR, TerraSAR-X, 22 images) Measurement of the rate of growth of Bagana Volcano. (2010-2011) Wadge (PI).

4. Details of the impact

The eruption that began on Montserrat in 1995, and continues to date, has resulted in 19 deaths (all in 1997), the emigration of two thirds of the population and an estimated £1bn in economic costs⁷, mainly borne by the UK government.

Over this 18-year period, the scientific, governmental and social responses to the volcano have evolved. At the start of the eruption there was no observatory on the island, but now the MVO has a custom-built home and a sophisticated network of monitoring instruments, that now includes the radars developed by UoR, and warning procedures. The activity at the volcano has waxed and waned, but one constant is that the main threat to life has been from pyroclastic flows produced by collapses of the lava dome that can grow for years on end. The short-term threat from these flows largely changes depending on how fast the dome is growing (the faster the more dangerous) and in which direction (the remaining populated areas lie to the north and west of the volcano). MVO faced a major problem in assessing these two hazard factors operationally: the lava dome at the

top of the Soufriere Hills Volcano is often covered in cloud, sometimes for weeks on end. The Unit recognised the significance of this at an early stage. Satellite radar data, that were of sufficiently high resolution to play a useful role, were available only infrequently and under very limited access. By 2000, the Unit had identified that some type of ground-based, cloud-penetrating radar was required that could be focused on the most dangerous parts of the lava dome. The development of AVTIS in conjunction with MVO followed from that need.¹³ The development to a second-generation operational version of this entirely new class of instrument took ten years.

The ability to demonstrate an impact with AVTIS and with the high-resolution civilian satellite radars (TerraSAR-X) has varied depending on the state of activity at the volcano and the state of development of the instruments.

A well-documented example of impact comes from July-August 2008. After several days of earthquakes, a major explosion occurred on 29 July depositing ash on inhabited areas of Montserrat. Unfortunately, cloud covered the upper part of the volcano and MVO initiated an evacuation of part of the island closest to the volcano until the state of the volcanic dome could be determined, and asked for help from us to do this. AVTIS was under development in the UK at that time, so we used satellite radar data instead. Wadge invoked the International Charter on Space & Major Disasters^{8,9} via the UK Cabinet Office on MVO's behalf. This Charter gives privileged access to satellite remote sensing instruments (radars mainly in this case) owned by all the major space agencies across the world, to immediately focus on the crisis (Montserrat in this case) and provide free data. In association with the British Geological Survey these data were interrogated by us.¹⁵ The TerraSAR-X data proved the most valuable and within 3 days of the explosion we were able to provide MVO with clear evidence that the explosion had produced a new vent but that this vent had not destabilised the dome as had been feared. MVO reported this to the civil authorities on Montserrat and the evacuation was revoked. It took another 10 days before the cloud lifted sufficiently to confirm radar observations. This early "all-clear" was welcomed by the evacuated inhabitants and boosted confidence in the technique and the public's confidence in MVO. It also demonstrated the UK's continued commitment to international disaster response and in particular the application of space technology to this domain. It was always the intention of this work to effectively transfer the technology to MVO. As of 2011 both the space-borne and the ground-based radar techniques are a routine part of MVO operations. No event has yet tested the eruption early-warning capability but the deployment of a permanent, operational instrument on Montserrat shows that the system provides a capability for more advanced and timely warnings than was available during the last major eruption in 2010.

The main beneficiaries of the impact are the people and the businesses of Montserrat. In 2008 the government's Disaster Management Coordination Agency (DMCA) deployed a radio-based early warning system to disseminate information on the risk posed by the volcano to everybody in the areas at risk.¹¹ The island's population is estimated to be just over 5000 and is now growing by about 400 p.a. but has yet to recover to the over 12000 estimated before the 1995 eruption.¹² Prior to then, the island had an export economy based on agriculture, clothing, electronic parts, tourism, building sand and plants, with a GDP of £30m. After the eruption GDP is now at about £15m and the DFID support for 2012/3 was £15m, which finances roughly half of all expenditure.¹² It is very difficult to put a figure on the monetary impact of our research because there has been no official audit of the impact of the eruption from the Government of Montserrat and our work is, rightly, bound up in the operations of MVO. The economic benefits in avoiding false alarms and in the ability to generate earlier safe all-clears are considerable as evacuations cause relocation costs and emergency provisions costs and the commercial activities in affected areas to cease. Since 1997 there have been no deaths due to the volcano. The constant effort at MVO to forecast impending hazards and judge local risks has been helped by our work both to avoid tragedies and engender justified confidence in public safety. As noted in a report¹⁰ financed by the European Commission (EuropeAid Cooperation Office) "The Montserrat Volcano Observatory provides the Government with an organisation for managing this [volcanic] environmental hazard, and ensuring the continuing safety of the island's inhabitants." The importance of the volcano early warning capability is stressed in the Montserrat Sustainable Development Plan.¹⁶

Social science studies in relation to Montserrat show the advances in monitoring and prediction have led to an improved quality of life for many inhabitants, given they now have the knowledge that they will receive reliable early warnings of a major eruption and will not be subject to unnecessary evacuations: for example in 2004 57% of respondents felt that "the scientists have

shown in the long-term that their advice has been justified".¹⁷ Most residents are relieved that the volcano is monitored and MVO can initiate better warnings and there is better acceptance of the need for forced evacuations. However, building the required trust and a working co-operation between scientists, local government and inhabitants has not been straightforward. There is now considerable local awareness of the uncertainty inherent in the science and appreciation that it helps avoid the unpopular decisions giving long, and apparently unnecessary, evacuations before the new systems were in place.^{18,19}

The techniques we have developed have, to date, been mainly applied to Montserrat. However, their use is now being extended to Latin America and Papua New Guinea. We have run workshops to explain our techniques in Costa Rica (October 2012), Ecuador and Colombia (June 2013). In these cases, the impact on local inhabitants and commerce is yet to occur; however, the existence and proven capabilities of the techniques developed by the Unit are beginning to have an impact on local policy and planning in each case, as knowledge of them and their potential application is spread.

Background information:

7. Clay, E., et al. (1999) An Evaluation of HMG's Response to the Montserrat Volcanic Emergency. Evaluation Report EV635, December 1999. DfID, 94 Victoria St, London SW1 5JL. <http://www.dfid.gov.uk/Documents/publications1/evaluation/ev635.pdf>.
8. <http://bit.ly/17ANT3A> (On the invoking of International Charter for Space and Major Disasters)
9. NERC COMET report: http://comet.nerc.ac.uk/current_research_soufriere.html
10. Overseas countries and territories environmental profile, Part 2 - Detailed Report, Section A - Caribbean region, (prepared by J.Pearse and H. Berends) European Commission (EuropeAid Cooperation Office), 2007 <http://bit.ly/1axtug7>
11. Public Early Warning System (EWS) Case Studies: Volcanic Alerts <http://bit.ly/18QhG1X>
12. International Monetary Fund Country Report No. 12/9 United Kingdom: Montserrat: British Overseas Territory, January 2012. <http://www.imf.org/external/pubs/ft/scr/2012/cr1209.pdf>

5. Sources to corroborate the impact

13. Assessment of the hazards and risks associated with the Soufriere Hills volcano, Montserrat, 3rd Report of the Scientific Advisory Committee on Montserrat Volcanic Activity, MVO, <http://www.mvo.ms/resources/downloads/summary/45-sac-3/906-sac3technical> (also available from www.nerc-essc.ac.uk/~gw/www_data/SAC10-TR.doc).
14. Radar imaging of the volcano dome detailed in the monthly reports by the Smithsonian Institution, National Museum of Natural History, Global Volcanism Program, Soufrière Hills. <http://bit.ly/HDi8yk> (search on "radar")
15. Charter final operation report, Charter ID 213, Volcanic eruption of 29th July 2008 on the island of Montserrat, G. Ager et al., Report no: CR/08/179. British Geological Survey (Keyworth) (Available upon request)
16. Journey to Sustainable Prosperity. Montserrat Sustainable Development Plan 2008 – 2020, Ministry of Economic Development and Trade, Government of Montserrat, 2010 http://www.gov.ms/publications/SDP_MONTSERRAT.pdf (see table: Environmental and disaster management medium-term objective 4: "Develop a comprehensive disaster management framework" and 3.4.4, 3.4.5 and 3.4.5 in particular)
17. Haynes, K., Barclay, J., & Pidgeon, N. (2008). Whose reality counts? Factors affecting the perception of volcanic risk. *J. Volcanol. Geotherm. Res.*, 172(3), 259-272., doi: 10.1016/j.volgeores.2007.12.012.
18. Donovan, A.R. et al. (2013) Co-production of an institution: Montserrat Volcano Observatory and social dependence on science. *Science and Public Policy*, 40, 171-186, doi: 10.1093/scipol/scs078.
19. Donovan A.R. et al. (2012) Contested boundaries: Delineating the "safe zone" on Montserrat, *Applied Geography*, 35, 508-514. doi: 10.1016/j.appgeog.2012.10.003.
20. Testimonial letter from the Director, Montserrat Volcano Observatory. Available upon request.