



1 Lava dome collapse detected using passive seismic interferometry

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4 [1] The collapse of the lava dome at the Soufrière Hills
5 Volcano on Montserrat in July 2003 is the largest recorded
6 in historical times. I use noise correlation Green's functions
7 to measure the changes in seismic properties that resulted
8 from this collapse. Continuous three component seismic
9 data recorded at two pairs of stations were cross-correlated
10 to retrieve three-component Green's functions along two
11 paths that intersect the volcanic edifice before and after the
12 dome collapse. Particle motion analysis shows that the
13 Green's functions are dominated by Rayleigh waves and
14 are consistent with the expected Green's tensor for a
15 vertical point force source at one station recorded by a
16 three-component receiver at the other. Following the
17 collapse, there is a clear decorrelation and phase shift in the
18 Green's functions corresponding to a change in velocity of
19 approximately 0.5% that can be interpreted in terms of the
20 unloading of the lava dome. **Citation:** Baptie, B. J. (2010),
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23 1. Introduction

24 [2] Recent advances in theory [e.g., *Wapenaar, 2004*] have
25 shown that the cross correlation of ambient noise recorded at
26 two seismic stations can be used to yield the elastic impulse
27 response of the Earth, or Green's function, between the two
28 stations as if one were a source and the other a receiver. This
29 has been confirmed using seismic data [*Campillo and Paul,*
30 2003; *Shapiro and Campillo, 2004*] and the method has
31 been widely applied to Earth imaging [e.g., *Sabra et al., 2005;*
32 *Shapiro et al., 2005*]. However, the method has also been
33 applied to continuously monitor small changes in seismic
34 velocity in the subsurface over a period of time. *Snieder et al.*
35 [2002] show that scattered coda waves are more sensitive to
36 small changes in seismic velocity. *Sens-Schönfelder and*
37 *Wegler* [2006] identify a relationship between velocity varia-
38 tions at Merapi volcano measured from passive seismic
39 interferometry and a depth dependent hydrological model.
40 *Brenguier et al.* [2008] use ambient seismic noise recorded at
41 Piton de la Fournaise volcano to measure very small seismic
42 velocity perturbations, that they link to pre-eruptive inflation
43 of the volcanic edifice. Both these studies demonstrate the
44 potential of this method to monitor changes in volcanic
45 behaviour over long periods of time.

46 [3] The Soufrière Hills Volcano (SHV), Montserrat, is an
47 andesite dome-building volcano in the Lesser Antilles arc
48 (Figure 1). After a period of dormancy of several centuries
49 the current eruption began in July 1995 [*Young et al., 1998*].

The eruption has been characterised by a number of phases 56
of lava extrusion to form the lava dome and subsequent 57
collapses involving pyroclastic flows and vulcanian explo- 58
sions. The first phase of dome growth lasted from 1995 to 59
1998 with variable extrusion rates reaching up to 10 m³/s 60
[*Sparks et al., 1998*]. The second phase of dome growth 61
lasted from 1999 to 2003 with more modest extrusion rates 62
reaching up to 4 m³/s [*Herd et al., 2005*]. The lava dome 63
reached its maximum height and volume in July 2003. The 64
subsequent collapse of the lava dome, beginning on 12 July, 65
is the largest recorded in historical times, with approxi- 66
mately 210 million m³ of material removed in 18 hours 67
[*Herd et al., 2005*]. A swarm of over 9500 hybrid earth- 68
quakes preceded the dome collapse [*Ottmöller, 2008*], most 69
of which had nearly identical waveforms, suggesting a 70
highly repeatable source. 71

[4] In this paper, I use seismic interferometry to identify 72
changes in the Green's functions obtained from cross-cor- 73
relation of ambient noise at the time of the collapse of the 74
lava dome at SHV in July 2003. The measured decorrelation 75
and phase shift can then be related to a velocity change under 76
the volcano. The aim is to show that lava dome collapse had 77
a measurable effect on seismic velocity but also that noise 78
correlation functions can provide a simple means to measure 79
changes in volcanic behaviour over a period of time. 80

2. Data Processing and Results

[5] Noise correlation Green's functions (NCFs) are ex- 82
tracted from continuous seismic data recorded at pairs of 83
permanent broadband stations operated by the Montserrat 84

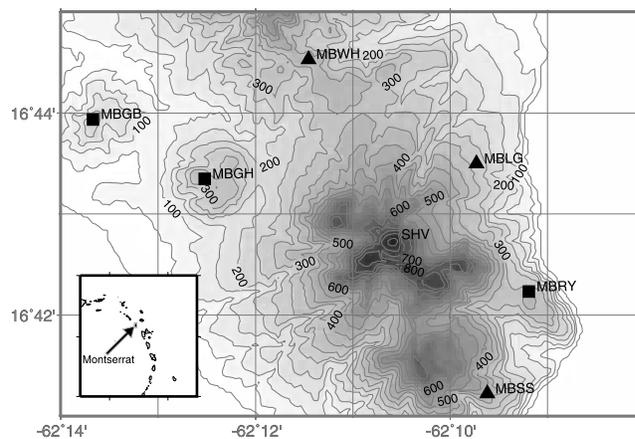


Figure 1. Southern part of the island of Montserrat. The Soufrière Hills Volcano is marked by the letters SHV. The inset shows the position of Montserrat in the Lesser Antilles arc. Seismograph stations operated by the Montserrat Volcano Observatory during 2003 are shown by squares (broadband) and triangles (short period).

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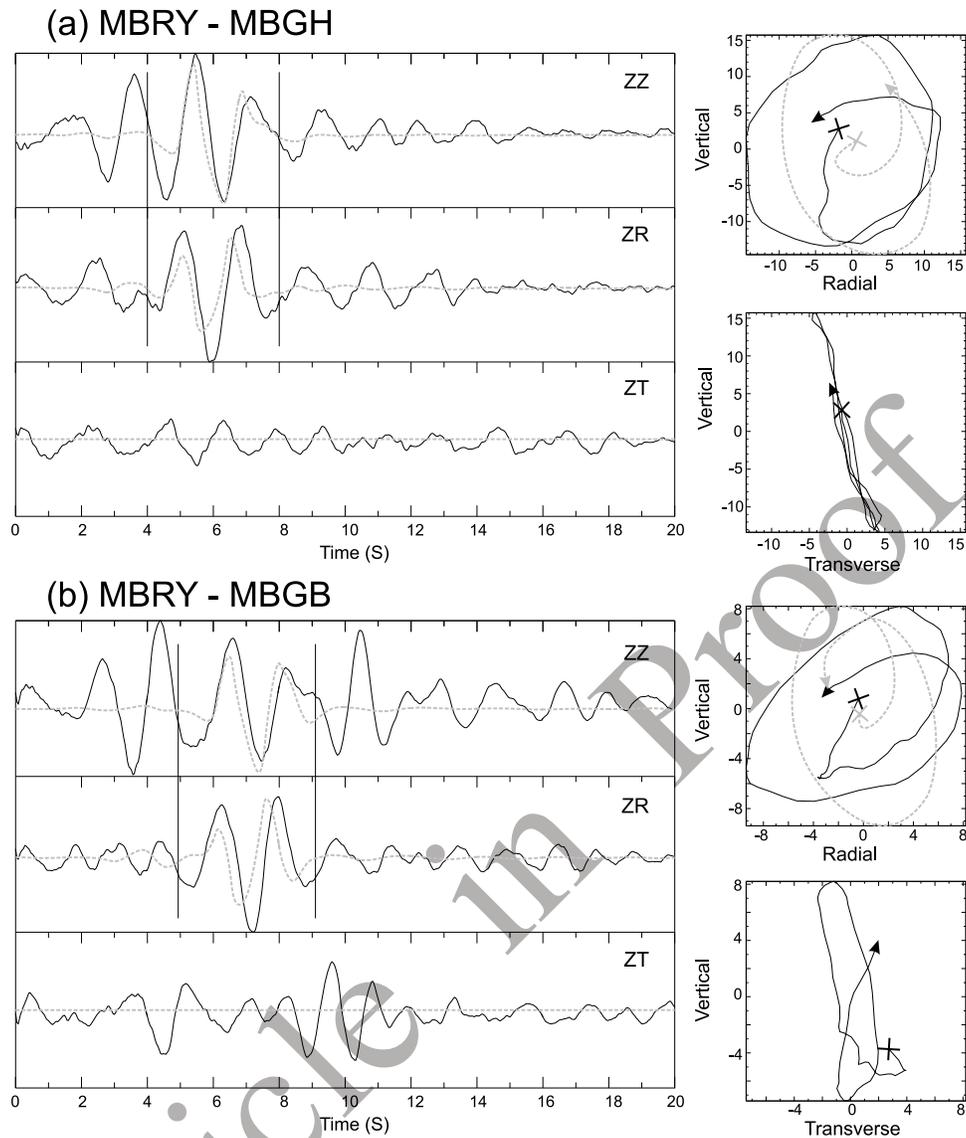


Figure 2. Stacked correlation functions for June 2003 computed from vertical component records at station MBRY and vertical (ZZ), radial (ZR) and transverse (ZT) component records at (a) MBGH and (b) MBGB). The particle motion plots are in the time window of the Rayleigh wave pulse shown by the vertical black lines. The theoretical Green tensor computed for a vertical point force in a simple isotropic four layer crustal model and convolved with a 1.8 s parabolic pulse is shown by the dashed gray lines.

85 Volcano Observatory (MVO) for monitoring activity at the
 86 SHV. In 2003, three broadband stations were operational,
 87 MBGB, MBGH and MBRY (Figure 1). The NCFs derived
 88 for station pairs MBRY-MBGB and MBRY-MBGH, should
 89 synthesize elastic waves propagating directly under the vol-
 90 canic edifice and provide an excellent means of measuring
 91 any changes in seismic properties.

92 [6] Processing applied to each twenty-four hour continu-
 93 ous data segment consisted of: 1) rotation of the horizontal
 94 components into the radial and transverse directions with
 95 respect to the great circle path between a given station pair; 2)
 96 a high pass filter applied at 0.5 Hz; 3) one-bit normalisation
 97 to reduce the effect of amplitude variations in the ambient
 98 wavefield. The corresponding data segments for all three
 99 components of ground motion at each station were then
 100 cross-correlated, resulting in a nine component noise corre-

lation function for each day, corresponding to each compo- 101
 nent of the Green's tensor for a given station pair. 102

[7] Stacked daily NCFs for the month of June 2003 103
 computed from cross correlating the vertical component 104
 records (Z) at station MBRY with the vertical, radial and 105
 transverse component records (Z, R and T) at stations 106
 MBGH and MBGB are shown in Figure 2. Uniform scaling 107
 has been applied to all traces. A clear 1.8 s pulse is observed 108
 on the radial component for MBRY-MBGH between 4 – 8 s 109
 and for MBRY-MBGB between 5 – 9 s. The particle motion 110
 for this pulse is mainly restricted to the ZR plane and shows 111
 the retrograde elliptical motion typical of a Rayleigh wave. 112
 Given inter-station distances for MBRY-MBGH and 113
 MBRY-MBGB of 6.26 km and 8.55 km respectively, the 114
 arrival times of the Rayleigh wave is consistent with group 115
 velocities of 0.8 – 1.7 km/s. A significant amount of energy 116
 also arrives before the Rayleigh wave pulse and is visible 117

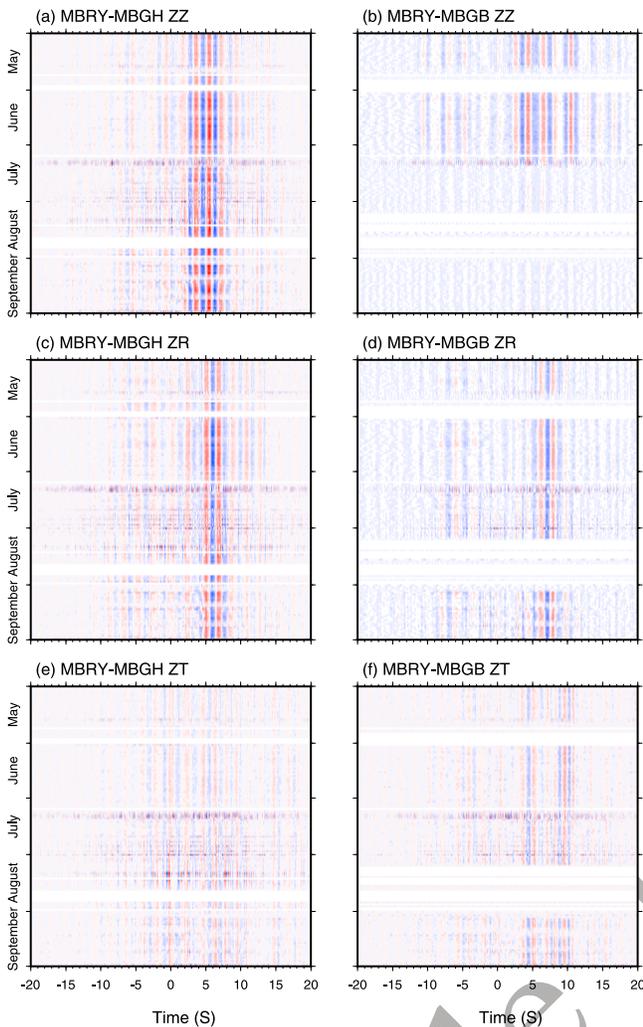


Figure 3. Daily NCFs from the vertical component at MBRY with the vertical, radial and transverse components from MBGH and MBGB. The colour scale denotes signal amplitude and the same uniform scaling is applied to all traces for each station pair and each component.

118 mainly on the vertical component of ground motion for
 119 both MBGH and MBGB (ZZ) between 2–4 s and 2–5 s,
 120 respectively. This results in a linearly polarized arrival. Roux
 121 *et al.* [2005] show the presence of P-waves in NCFs between
 122 stations at short ranges in the Parkfield network, and I sug-
 123 gest that these initial arrivals may also be P-waves. There is
 124 very little energy observed from the transverse component at
 125 MBGH, which is consistent with a vertical point force
 126 Green’s function in an isotropic, 1-D, velocity model.
 127 However, station MBGB shows a strong arrival after the
 128 Rayleigh wave pulse that is dominantly polarized in the
 129 vertical transverse plane. This is not consistent with the ar-
 130 rivals expected at MBGB from a vertical point force at
 131 MBRY in a simple Earth model, and suggests more complex
 132 propagation characteristics. The theoretical Green tensor
 133 computed for a vertical point force in a simple isotropic four
 134 layer crustal model [Aspinall *et al.*, 1998] and convolved
 135 with a 1.8 s parabolic pulse is shown by the dashed gray
 136 lines. The same high pass filter is applied to the synthetics as

to the observed data. This provides a reasonable match for
 the observed Rayleigh wave arrivals on both stations, but
 does not capture the arrivals either before or after.

[8] The resulting daily NCFs from the vertical component
 at MBRY with the vertical, radial and transverse compo-
 nents from MBGH and MBGB are shown in Figure 3. The
 colour scale denotes signal amplitude and the same uniform
 scaling is applied to all traces for each station pair and each
 component. Both the causal (positive lags) and acausal
 (negative lags) parts of the NCFs are shown. For both station
 pairs, the causal amplitudes are significantly larger than
 acausal as a result of the asymmetry in the background noise,
 which comes mainly from the Atlantic Ocean side of the
 island, and can be thought of as propagating across the array
 from east to west. The NCFs are reasonably stable as a
 function of time, with good signal to noise ratio, though there
 are some obvious variations, such as the strong reduction in
 the amplitude of the MBRY-MBGB ZZ NCF after early July
 2003. Lack of data at individual stations at various time
 periods results in an absence of noise correlation functions
 for certain times.

[9] To identify any temporal changes in the characteristics
 of the NCFs, I compute both the correlation and phase shift,
 δt , between the Rayleigh wave pulse on the ZR component
 of the stacked NCF in Figure 2 with both the daily NCFs in
 Figure 3 and a five day running stack of these NCFs over the
 period June 2003 to end September 2003. The correlation is
 measured from the maximum in the normalised cross-correl-
 ation function between the two signals. Error estimates
 are obtained by computing the cross-correlation in series of
 1.28 s moving windows, then calculating the mean and
 standard deviation for those windows coincident with the
 Rayleigh pulse. The phase shift or time delay, δt between
 the two signals can be computed from the slope of the phase
 of the cross-spectrum [Poupinet *et al.*, 1984; Ratdomopurbo
 and Poupinet, 1995]. Here I use the time lag of the maxi-
 mum in the normalised cross-correlation function as a
 measure of the time delay, δt , between the reference NCF and
 the daily NCFs. Time delays are computed in overlapping
 1.28 s windows at different lapse times, τ , in a time window
 around the observed Rayleigh wave arrival. Assuming that
 any measured time delay is caused by a homogeneous
 velocity change $\delta v/v$, the time delay δt should be inde-
 pendent of the lapse time τ at which it is measured and
 $\delta v/v = -\delta t/\tau$. Again, error estimates are obtained from the
 mean and standard deviation of all time windows around
 the Rayleigh pulse.

[10] The resulting decorrelation and velocity variations
 measured from the ZR component of the NCFs between
 station pairs MBRY-MBGH and MBRY-MBGB are shown
 in Figure 4. Results for both the individual daily NCFs
 (blue) and a five day running stack of the NCFs (red) are
 shown. Throughout June and the first few days of July the
 daily NCFs for both station pairs are very well correlated
 with the reference NCF, with cross correlation coefficients
 of greater than 0.98. No significant velocity variations are
 observed. At the time of the collapse, there is a sudden change
 in both correlation coefficient and the relative velocity for
 both station pairs, with the correlation coefficient reducing to
 around 0.9 and the relative velocity falling by approximately
 0.5%. The relative velocity, although scattered, does not
 change greatly from this value over the next three months.

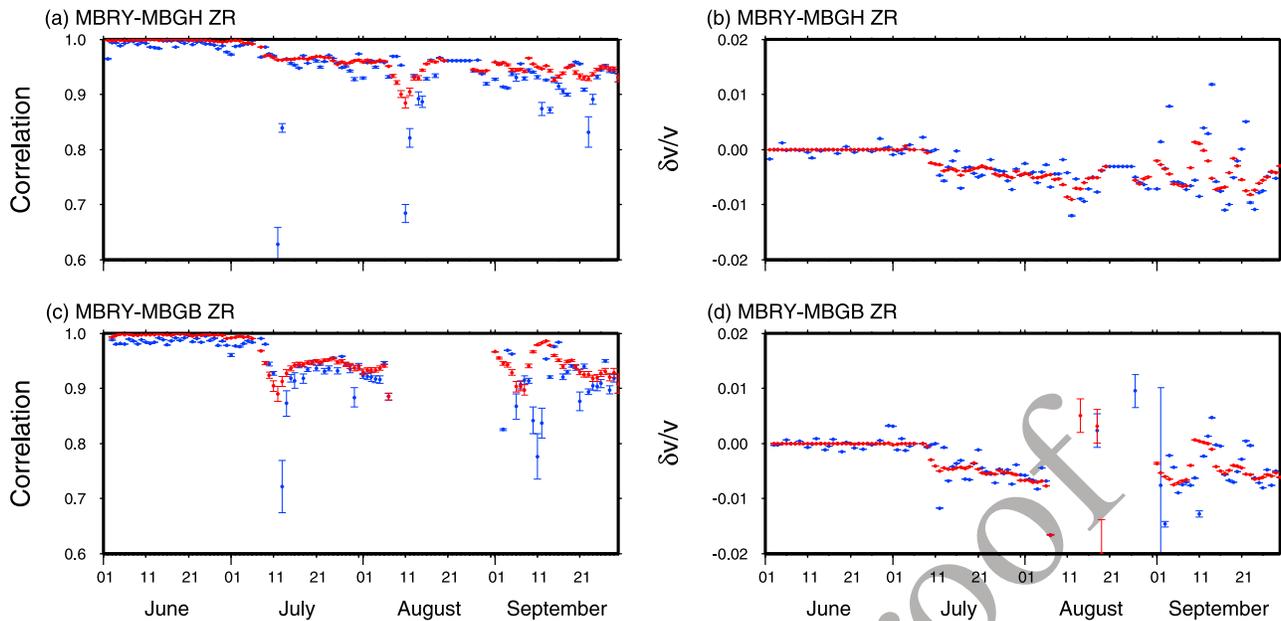


Figure 4. Correlation and velocity variations measured from the ZR component of the NCFs between station pairs MBRY-MBGH and MBRY-MBGB. Results for both the individual daily NCFs (blue) and a five day running stack of the NCFs (red) are shown.

199 Similarly, the maximum cross correlation coefficient reduces
200 further only slightly.

201 3. Discussion and Conclusions

202 [11] Three-component Green's functions have been suc-
203 cessfully calculated from ambient seismic noise for station
204 paths that intersect the Soufrière Hills Volcano. The NCFs
205 calculated by cross-correlating the vertical component of
206 ground motion at station MBRY and the radial, vertical and
207 transverse components of ground motion at stations MBGH
208 and MBGB appear consistent with the Green's tensor ex-
209 pected from a vertical point force source at MBRY recorded
210 at MBGH and MBGB, and show clear evidence of Rayleigh
211 waves with elliptical particle motion propagating at low
212 group speeds along both paths. A dominantly vertically
213 polarised arrival is observed before the Rayleigh wave for
214 both station pairs and may suggest the presence of body
215 waves in the NCFs. The observed difference between the
216 causal and acausal parts of the NCFs is consistent with an
217 asymmetry in the noise source, with oceanic noise from the
218 Atlantic Ocean east of Montserrat dominating the observed
219 noise field.

220 [12] The NCFs in the one-month period prior to the col-
221 lapse of the lava dome in July 2003 are found to be extremely
222 stable with only very small changes in both correlation co-
223 efficient and relative velocity measured from the Rayleigh
224 wave arrival between the daily NCFs and a reference func-
225 tion. However, following the collapse, there is a clear change
226 in the NCFs for both station pairs. Maximum cross correla-
227 tions are reduced and the change in $\delta v/v$ suggests a small
228 reduction in velocity of approximately 0.5%. Rayleigh
229 waves with the observed periods of a few seconds are sen-
230 sitive to velocities in the top few kms of the Earth's crust as
231 well as any change in topography of the free surface. The
232 strong reduction in the amplitude of the MBRY-MBGB ZZ

NCF following the collapse is difficult to explain. This is
233 unlikely to be due to a change in sensor coupling since the
234 amplitude on the ZR and ZT components are unaffected.

[13] The lava dome collapse on 12 July 2003 resulted in
235 the removal of over 210 million m^3 of dome material over a
236 period of 18 hours. This removed the core of the lava
237 approximately 300 m across and 400 m high [Herd *et al.*,
238 2005], along with a large expanse of talus that accounted
239 for more than 50% of the total dome volume. It is possible
240 that the significant change in topography following the col-
241 lapse could have resulted in a change in the characteristics of
242 surface waves propagating through the volcanic edifice.
243 However, the clear reduction in velocity could be more
244 closely related to the effect of the unloading of the lava dome
245 on the Earth's crust. Voight *et al.* [2006] suggest that the
246 reduction in mean lithostatic pressure resulting from the
247 collapse caused a rapid volumetric expansion in the magma
248 chamber and created measurable strains detected by dilat-
249 ometers. I suggest that a reduction in lithostatic pressure in
250 the rock-mass below the volcanic edifice, could also result in
251 the opening of microcracks and pore space that would lead to
252 a corresponding reduction in seismic velocity [Dutta, 2002],
253 and that the computed NCFs are sensitive to this reduction.

[14] Interestingly, the NCFs do not appear to be sensitive
254 to any changes in volcanic behaviour before the collapse.
255 Intense seismic activity starting on 9 June [Ottemöller, 2008]
256 preceded the dome collapse, suggest an increase in magma
257 pressure at shallow depths below the volcano. However,
258 there is no clear evidence of any change in the NCFs in the
259 few days prior to the collapse. The NCFs also remained
260 extremely stable throughout June 2003. While this obser-
261 vation does not preclude the use of NCFs for volcanic
262 monitoring, the detailed nature of the relationship between
263 NCFs and volcanic behaviour at the Soufrière Hills Volcano
264 remains to be fully understood.

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