Lava Dome Collapse Detected Using Passive Seismic Interferometry

B. J. Baptie,[1]

B. J. Baptie, Earth Hazards and Systems, British Geological Survey, West Mains Road, Eddinburgh, UK. (bbap@bgs.ac.uk)

[1]Earth Hazards and Systems, British Geological Survey, UK.

The collapse of the lava dome at the Soufrière Hills Volcano on Montserrat in July 2003 is the largest recorded in historical times. I use noise correlation Green's functions to measure the changes in seismic properties that resulted from this collapse. Continuous three component seismic data recorded at two pairs of stations were cross-correlated to retrieve three-component Green's functions along two paths that intersect the volcanic edifice before and after the dome collapse. Particle motion analysis shows that the Green's functions are dominated by Rayleigh waves and are consistent with the expected Green's tensor for a vertical point force source at one station recorded by a three-component receiver at the other. Following the collapse, there is a clear decorrelation and phase shift in the Green's functions corresponding to a change in velocity of approximately 0.5% that can be interpreted in terms of the unloading of the lava dome.

1. Introduction

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

The Soufrière Hills Volcano (SHV), Montserrat, is an andesite dome-building volcano in the Lesser Antilles arc (Figure 1). After a period of dormancy of several centuries the current eruption began in July 1995 [*Young et al.*, 1998]. The eruption has been characterised by a number of phases of lava extrusion to form the lava dome and subsequent collapses involving pyroclastic flows and vulcanian explosions. The first phase of dome growth lasted from 1995 to 1998 with variable extrusion rates reaching up to 10 m^3/s

[*Sparks et al.*, 1998]. The second phase of dome growth lasted from 1999 to 2003 with more modest extrusion rates reaching up to 4 m^3/s [*Herd et al.*, 2005]. The lava dome reached it's maximum height and volume in July 2003. The subsequent collapse of the lava dome, beginning on 12 July, is the largest recorded in historical times, with approximately 210 million m^3 of material removed in 18 hours [*Herd et al.*, 2005]. A swarm of over 9500 hybrid earthquakes preceded the dome collapse [*Ottemöller*, 2008], most of which had nearly identical waveforms, suggesting a highly repeatable source.

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

2. Data Processing and Results

Noise correlation Green's functions (NCFs) are extracted from continuous seismic data recorded at pairs of permanent broadband stations operated by the Montserrat Volcano Observatory (MVO) for monitoring activity at the SHV. In 2003, three broadband stations were operational, MBGB, MBGH and MBRY (Figure 1). The NCFs derived for station pairs MBRY-MBGB and MBRY-MBGH, should synthesize elastic waves progating directly under the volcanic edifice and provide an excellent means of measuring any changes in seismic properties.

Processing applied to each twenty-four hour continuous data segment consisted of: 1) rotation of the horizontal components into the radial and transverse directions with respect to the great circle path between a given station pair; 2) a high pass filter applied at 0.5 Hz; 3) one-bit normalisation to reduce the effect of amplitude variations in the ambient wavefield. The corresponding data segments for all three components of ground motion at each station were then cross-correlated, resulting in a nine component noise correlation function for each day, corresponding to each component of the Green's tensor for a given station pair.

Stacked daily NCFs for the month of June 2003 computed from cross correlating the vertical component records (Z) at station MBRY with the vertical, radial and transverse component records (Z, R and T) at stations MBGH and MBGB are shown in Figure 2. Uniform scaling has been applied to all traces. A clear 1.8 s pulse is observed on the radial component for MBRY-MBGH between 4 - 8 s and for MBRY-MBGB between 5 - 9 s. The particle motion for this pulse is mainly restricted to the ZR plane and shows the retrograde elliptical motion typical of a Rayleigh wave. Given inter-station distances for MBRY-MBGH and MBRY-MBGB of 6.26 km and 8.55 km respectively, the arrival times of of the Rayleigh wave is consistent with group velocities of 0.8 - 1.7 km/s. A significant amount of energy also arrives before the Rayleigh wave pulse and is visible mainly on the vertical component of ground motion for both MBGH and MBGB (ZZ) between 2 - 4 s and 2 - 5 s, respectively. This results in a linearly polarized arrival. *Roux et al.* [2005] show the presence of P-waves in NCFs between stations at short ranges in the Parkfield network, and I suggest that these initial arrivals may also be P-waves. There is very little energy observed from the transverse component at MBGH, which is consistent with a vertical point force Green's function in an isotropic, 1-D, velocity model. However, station MBGB shows a strong arrival after the Rayleigh wave pulse that is dominantly polarized in the vertical transverse plane. This is not consistent with the arrivals expected at MBGB from a vertical point force at MBRY in a simple Earth model, and suggests more complex propagation characteristics. The theoretical Green tensor computed for a vertical point force in a simple isotropic four layer crustal model [*Aspinall et al.*, 1998] and convolved with a 1.8 s parabolic pulse is shown by the dashed gray 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.

The resulting daily NCFs from the vertical component at MBRY with the vertical, radial and transverse components 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.

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-correlation 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 maximum 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 independent 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.

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

3. Discussion and Conclusions

Three-component Green's functions have been successfully calculated from ambient seismic noise for station paths that intersect the Soufrière Hills Volcano. The NCFs calculated by cross-correlating the vertical component of ground motion at station MBRY and the radial, vertical and transverse components of ground motion at stations MBGH and MBGB appear consistent with the Green's tensor expected from a vertical point force source at MBRY recorded at MBGH and MBGB, and show clear evidence of Rayleigh waves with elliptical particle motion propagating at low group speeds along both paths. A dominantly vertically polarised arrival is observed before the Rayleigh wave for both station pairs and may suggest the presence of body waves in the NCFs. The observed difference between the causal and acausal parts of the NCFs is consistent with an asymmetry in the noise source, with oceanic noise from the Atlantic Ocean east of Montserrat dominating the observed noise field.

The NCFs in the one-month period prior to the collapse of the lava dome in July 2003 are found to be extremely stable with only very small changes in both correlation coefficient and relative velocity measured from the Rayleigh wave arrival between the daily NCFs and a reference function. However, following the collapse, there is a clear change in the NCFs for both station pairs. Maximum cross correlations are reduced and the change in $\delta v/v$ suggests a small reduction in velocity of approximately 0.5%. Rayleigh waves with the observed periods of a few seconds are sensitive to velocities in the top few kms of the Earth's crust as well as any change in topography of the free surface. The strong reduction in the amplitude of the MBRY-MBGB ZZ NCF following the collapse is difficult to explain. This is unlikely to be due to a change in sensor coupling since the amplitude on the ZR and ZT components are unaffected.

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

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

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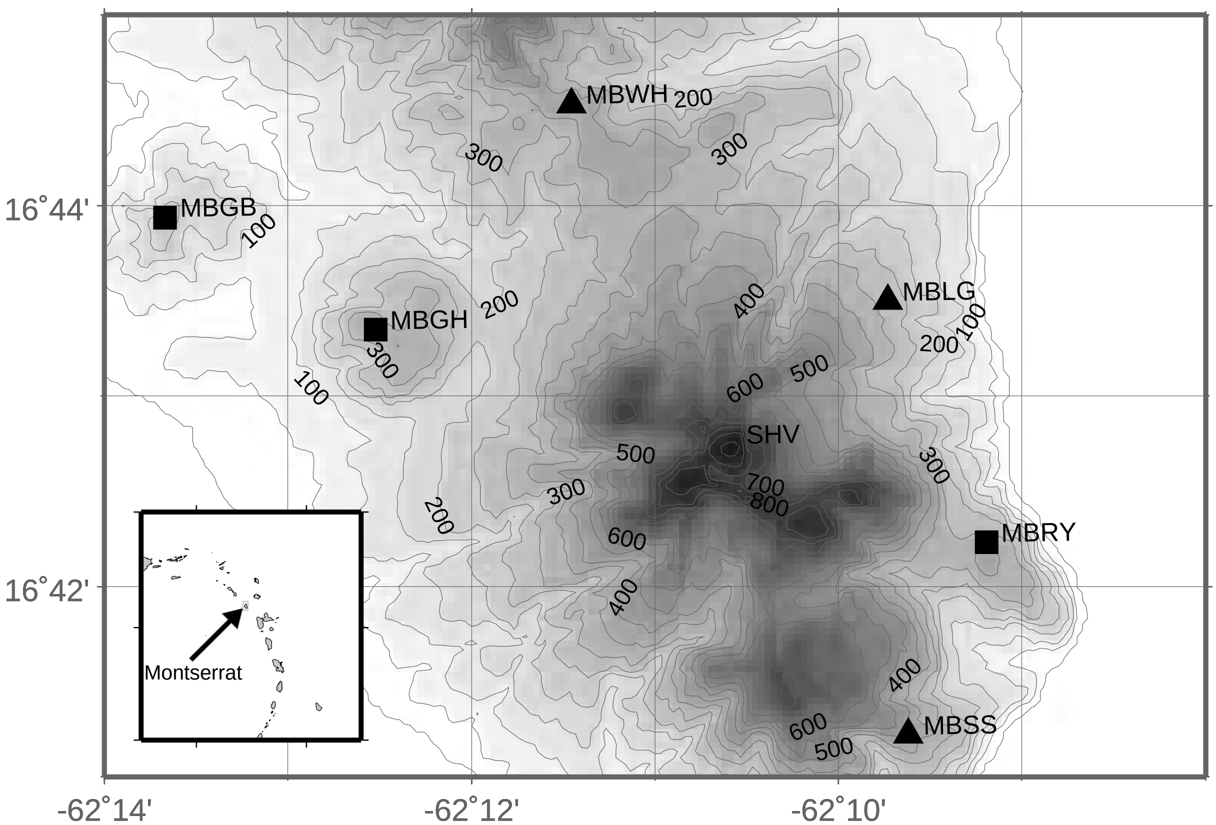


Figure 1. Southern part of the island of Montserrat. The Soufrière Hills Volcano is marked by the letters SHV. The inset shows the position of Montserrat in the Lesser Antilles arc. Seismograph stations operated by the Montserrat Volcano Observatory during 2003 are shown by squares (broadband) and triangles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

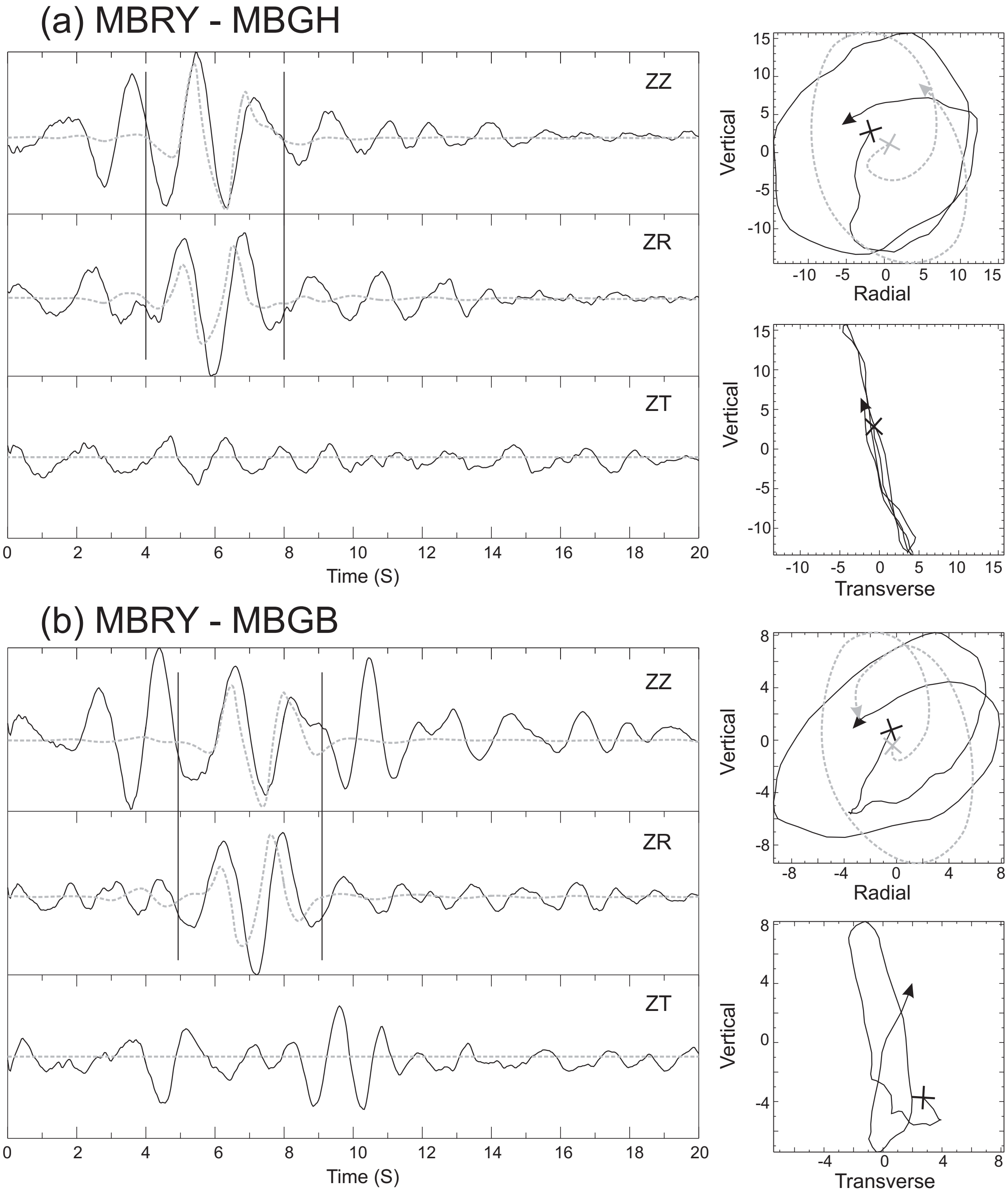
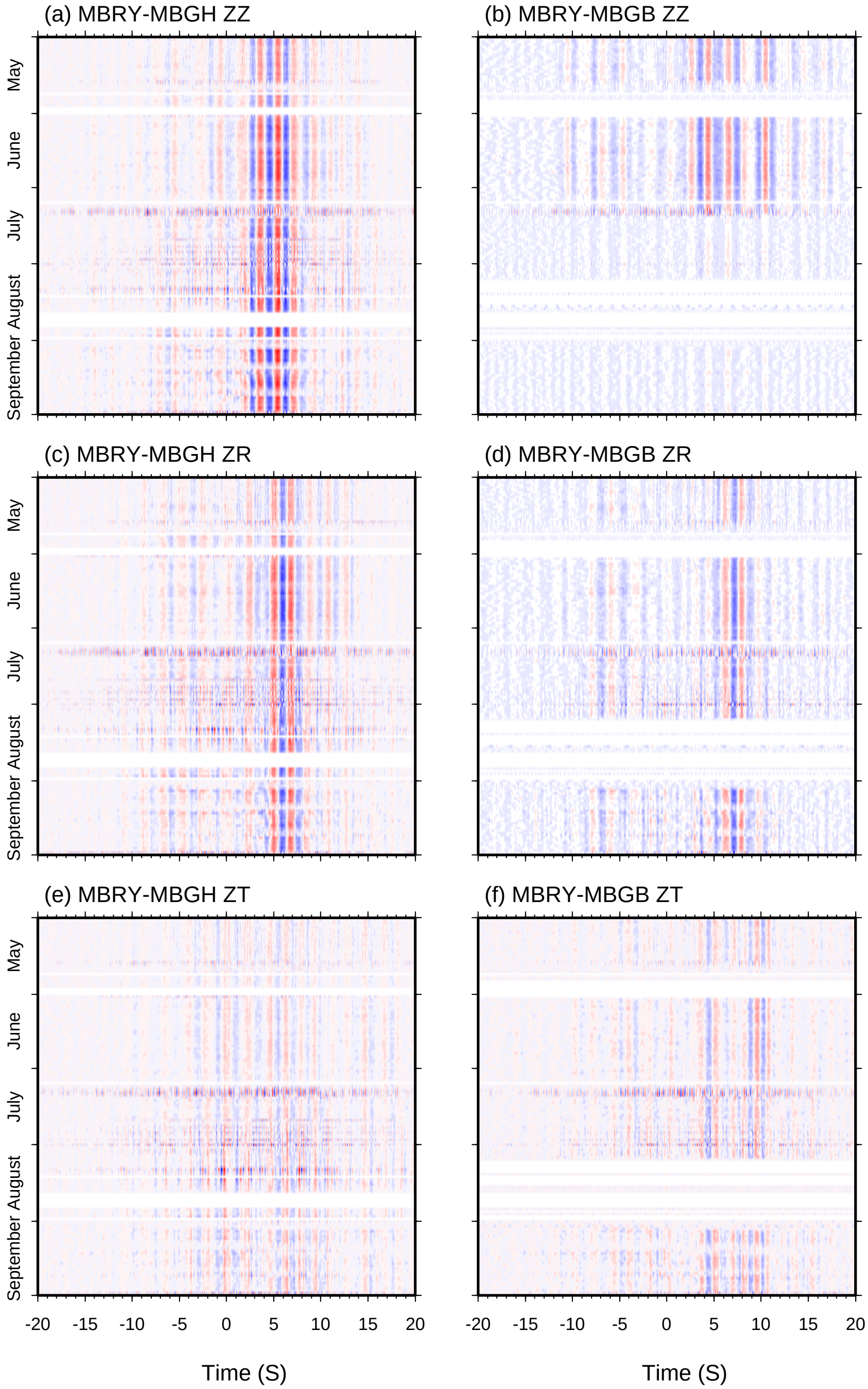


Figure 2. Stacked correlation functions for June 2003 computed from vertical component records at station MBRY and vertical (ZZ), radial (ZR) and transverse (ZT) component records at (a) MBGH and (b) MBGB). The particle motion plots are in the time window of the Rayleigh wave pulse shown by the vertical 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.



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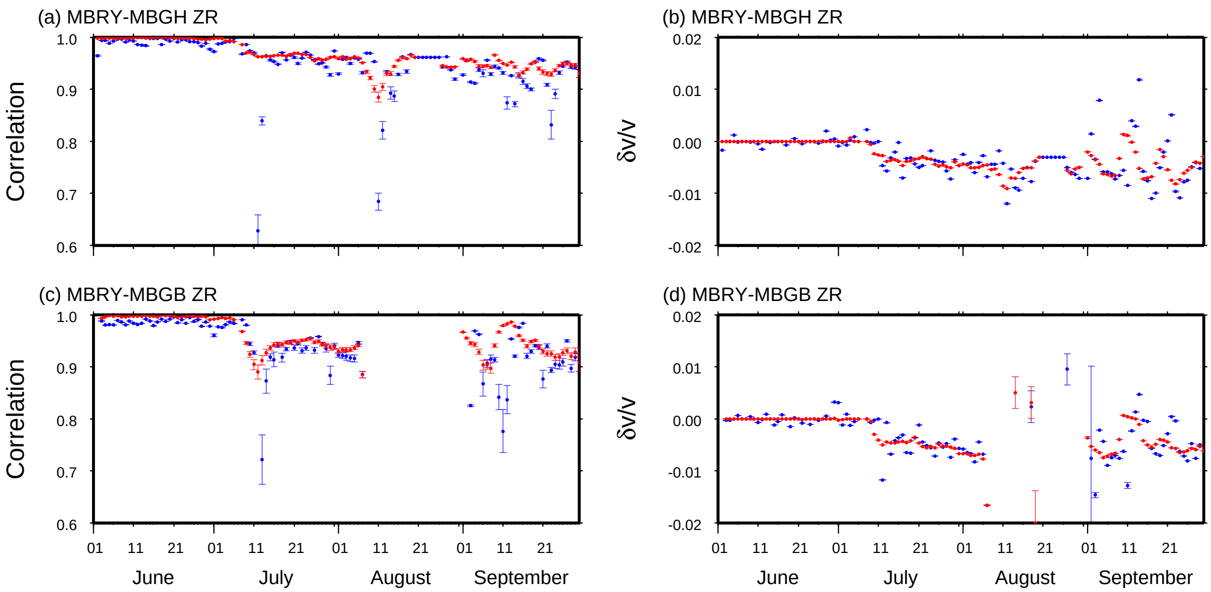

Figure 4. Correlation and velocity variations measured from the ZR component of the NCFs between station pairs MBRY-MBGH and MBRY-MBGB. Results for both the individual daily NCFs (blue) and a five day running stack of the NCFs (red) are shown.