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# NEAR-FAULT STRONG-MOTION ARRAY RECORDINGS OF THE $M_w$6.3 ÖLFUS EARTHQUAKE ON 29 MAY 2008 IN ICELAND

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## ABSTRACT

The $M_w$6.3 Ölfus earthquake occurred on 29 May 2008 in the westernmost part of the South Iceland Seismic Zone. The event took place on two separate and parallel faults that ruptured nearly simultaneously. The earthquake strong-motion was recorded on 11 stations of the ICEARRAY, the first small-aperture strong-motion array in Iceland. The array has an aperture of ~1.9 km, minimum interstation distance of ~50 m and consists of CUSP-3Clp three-component accelerographs of Canterbury Seismic Instruments. The ICEARRAY recordings, being in the extreme near-fault region of one of the causative faults ($r_{JB}$~1-2 km), exhibit high-intensity ground motion of short duration (4-5 s), large horizontal peak ground accelerations (38-88%g) and large amplitude, long-period velocity components, characteristics of near-fault motions, both on the strike-normal and strike-parallel components. The linear response spectra indicate that the long-period energy of the velocity pulse seen along the strike-normal direction is not present in the strike-parallel direction. Additionally, along the strike-normal direction, the Eurocode 8 "Type 2" design spectrum combined with a recently published design spectrum for near-fault pulses appears to capture well the overall spectral composition of the ICEARRAY response spectra. The acceleration time histories have been corrected based on a novel wavelet transformation approach and integrated to velocity and displacement. The correction reveals that both the strike-normal and strike-parallel components are associated with significant permanent tectonic displacement. The displacement estimates are in accordance with GPS measurements in the region.

## Introduction

The ICEARRAY small-aperture strong-motion array, located in the town of Hveragerdi in South Iceland, was designed (and installed in 2007) to have the ability, once data had been collected, to provide insight into details of fracture processes at the earthquake source (e.g., Spudich and Cranswick 1984), the heterogeneity levels of the medium (e.g., Sato and Fehler 1998), site

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effects (e.g., Ansal 1999) and the spatial variability of earthquake ground motion (e.g., Abrahamson and Bolt 1987). Amazingly on 29 May 2008, the ICEARRAY was in the extreme near-fault region of a $M_w$6.3 earthquake that occurred on a pair of vertical right-lateral strike-slip faults (Sigbjornsson *et al*. 2009) and produced high-quality near-fault records of the intense strong-motion. These records are globally unique due to the sparcity of near-fault array records during earthquakes of this magnitude and at such short distances. The uncorrected velocity time histories calculated from the raw acceleration records reveal significant long-period velocity pulses, both along the strike-normal (SN) and strike-parallel (SP) components (Halldorsson and Sigbjornsson 2009). The significant (~19 cm northwest) permanent tectonic displacement close to Hveragerdi as revealed by geodetic measurements (Hreinsdottir *et al.* 2009) indicate that baseline correcting the ICEARRAY acceleration records will reveal the temporal details of how that displacement occurred.

One of the problems associated obtaining estimates of displacement is that standard filtering methods cannot extract the low frequency displacement from the acceleration time history. This is partly due to baseline shift brought about by integrating noise buried in the time history and partly by integrating distortions due to instrument tilts, cross-axis excitations and angular accelerations brought on by the seismic wave perturbing the ground. Usually the correction schemes try to locate time points at which to adjust for baseline shift evident after double time integration's of the acceleration time history recorded by the instruments. Therefore a scheme proposed in the literature, based on the wavelet transform (see Chanerley and Alexander 2009, and references therein), which recovers the low frequency displacement and which is used to correct for baseline shifts, tilt and noise. Though absolute measurements of tilt are not available, the wavelet-based baseline correction method also uses a least squares method with which to estimate the residual angles of tilt for the horizontal components.

In this paper we present the ICEARRAY small-aperture strong-motion array and its extreme near-fault recordings of the $M_w$6.3 Ölfus earthquake of 29 May 2008 in South Iceland. Chanerley *et al*. (2009) and Rupakhety *et al*. (2009) have carried out a baseline correction of the ICEARRAY data and showed some examples of the results. Here we expand on their work and show the corrected velocity and displacement time histories of Chanerley *et al*. (2009) in reference to the ICEARRAY geometry, focusing on the description of the earthquake strong motion across the array. In particular, we discuss the permanent coseismic displacement time histories and their characteristics.

## ICEARRAY small-aperture strong-motion array

The Earthquake Engineering Research Centre (EERC) of the University of Iceland operates the Icelandic Strong Motion Network (IceSMN), the only accelerograph network in Iceland. The network has been in operation for over a quarter of a century and its largest part is located in the South Iceland Seismic Zone (SISZ, see Figure 1), a transform zone of high seismicity and a history of destructive earthquakes (Sigbjornsson *et al.* 2004). The SISZ is a populous agricultural region with numerous towns and villages, along with essential modern-day infrastructure and lifelines, such as pipelines, electric transmission systems, bridges, hydro-electric powerplants and dams. As a consequence, the seismic risk in the SISZ is relatively high.

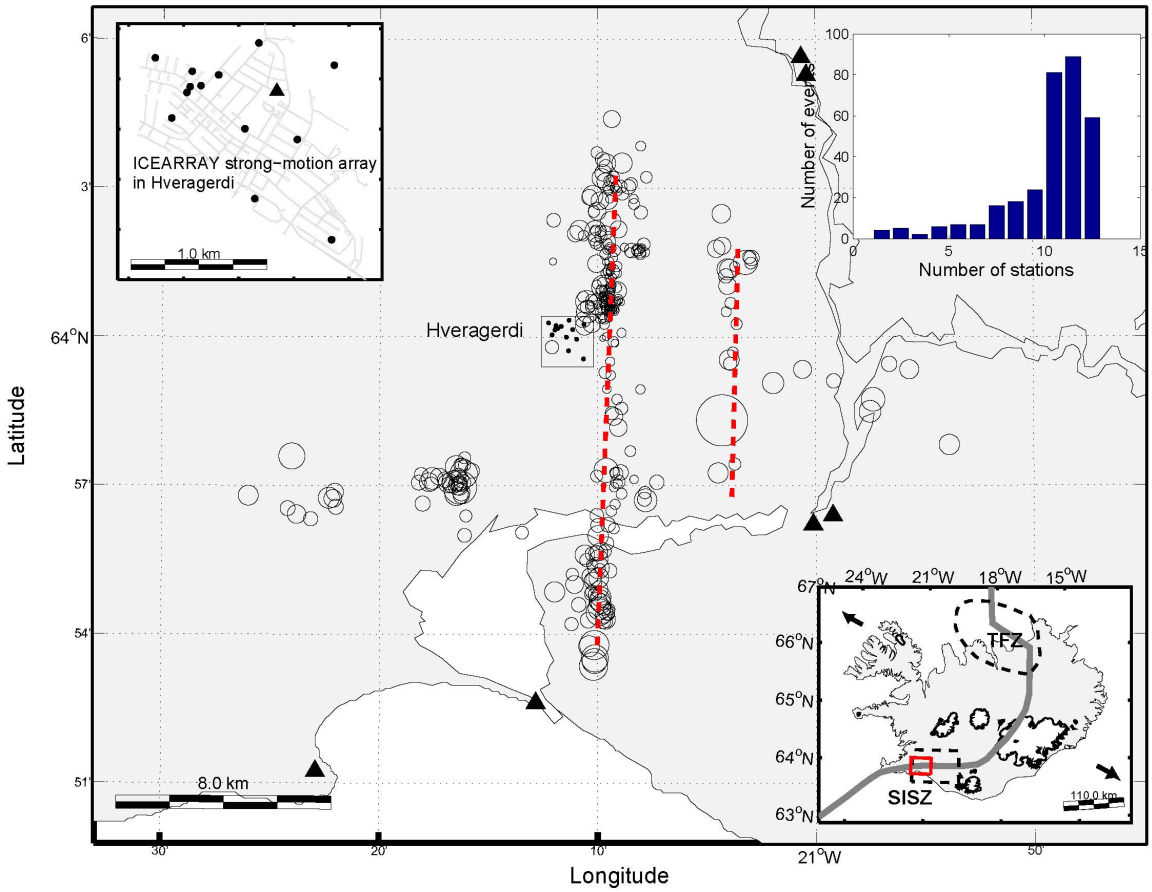


Figure 1. The small map inset at bottom right shows Iceland, an island in the North Atlantic Ocean, in reference to the present-day boundary (gray line) of the Eurasian and North American tectonic plates. Seismic zones are indicated with dashed lines, notably the SISZ. The solid red rectangle within the SISZ indicates the macroseismic area of the Ölfus earthquake of 29 May 2008 (shown in the larger map) where the recording sites of the IceSMN are denoted as triangles and those of the ICEARRAY as dots (seen in the small map at top left along with the street layout of Hveragerdi). The ICEARRAY recordings of aftershocks that match the parametric list from the Icelandic Meteorological office are shown in circles, outlining the causative faults (red dashed lines). The diameter of the circles indicates their relative magnitudes. The histogram indicates the number of events shown recorded by a given number of ICARRAY stations.

The latest addition to the IceSMN is the ICEARRAY, the first small-aperture strong-motion array in Iceland, installed in the SISZ for the specific purpose of establishing quantitative estimates of spatial variability of strong-motions, and investigating earthquake rupture processes and source complexities of future significant earthquakes in the region (Halldorsson *et al.* 2009). The ICEARRAY has been in operation since October 2007 and was installed in the village of Hveragerdi on the western edge of the SISZ (see Figure 1). The SISZ is collocated with high population densities in numerous towns and villages along with the infrastructure essential to a modern society. The optimal ICEARRAY geometry and number of stations was attained via analyses of the corresponding array transfer functions and their properties. The final layout of the array, shown in Figure 1, comprises $N$ = 14 stations over an area of aperture $D$ = 1.9 km with the smallest inter-station distance of $d$ = 50 m (Halldorsson *et al*. 2009). The recording system at each ICEARRAY station consists of a single CUSP-3Clp strong-motion accelerograph unit manufactured by Canterbury Seismic Instruments Ltd. The units are equipped with 24 bit triaxial low-noise (~70 µg rms) Micro-Electro-Mechanical (MEM) accelerometers with a high maximum range (± 2.5 g) and a wide-frequency passband (0-80 Hz at 200 Hz sampling frequency) (see e.g., Halldorsson and Avery 2009).

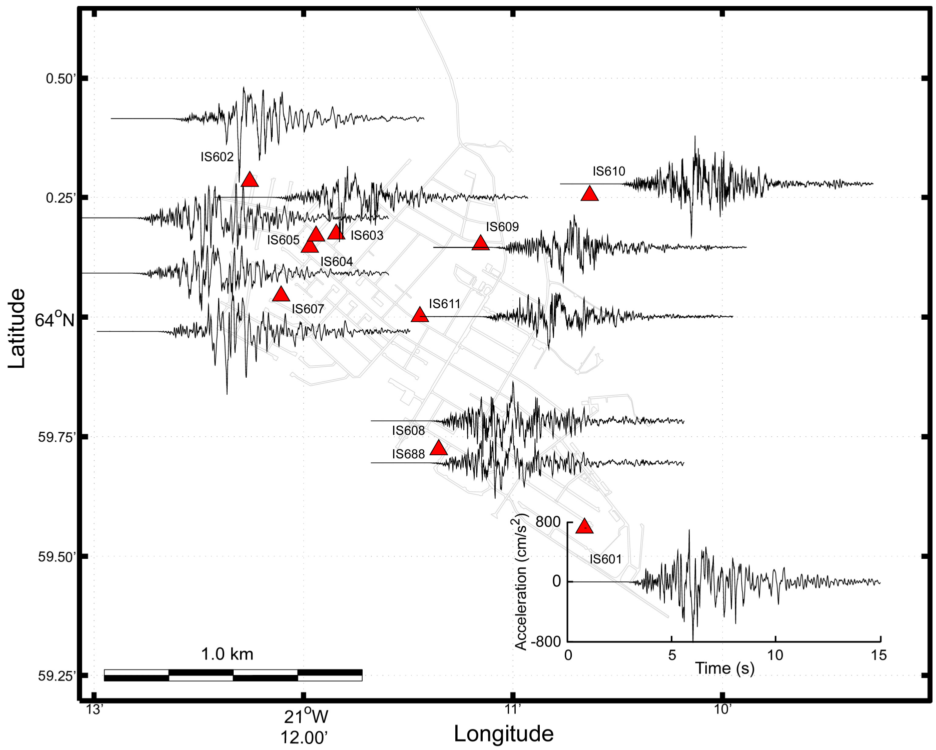


Figure 2. Segments of the east-west (SN) component of recorded acceleration time histories on the ICEARRAY stations during the Ölfus earthquake. The triangles denote the station locations (stations IS608/688 are collocated) and the gray lines show the street layout of Hveragerdi.

### The ICEARRAY recordings of the $M_w$6.3 Ölfus earthquake

At 15:45 UTC on 29 May 2008, a strong earthquake took place in the district of Ölfus, South Iceland, in the western part of the SISZ. The moment magnitude of the earthquake was 6.3 according to the CMT database and the INGV. The earthquake shares similar characteristics to other historical damaging earthquakes in the SISZ: shallow crustal earthquakes rupturing a near vertical north-south trending, right-lateral strike-slip fault (Sigbjörnsson *et al*. 2009). In this case however, the spatial distribution of aftershocks (from SIL network database, see e.g., Stefánsson *et al*. 1993) suggests that a pair of faults ruptured during the earthquake, as indicated in Figure 1. The north-south trending distribution outlines an almost 10 km long north-south trending vertical fault, from which the first motions originated, according to the strong-motion data. The main aftershock activity, however, shows nearly twenty km long alignment of epicentres indicating a north-south trending fault passing less than a couple of km east of the town of Hveragerdi. This hypothetical fault is ~4 km west of the source creating the initial motion. However, the rupture of the second source started with slight delay, roughly two seconds, relative to the initial rupture (Hreinsdottir *et al*. 2009). Therefore, the strong-motion data recorded on the ICEARRAY contains the motion radiating from two distinct sources, arriving almost simultaneously.

During the earthquake the ICEARRAY produced high-quality three-component recordings at 11 stations. The horizontal PGA values range from 38–88% g and the geometric mean of the horizontal PGA from 44–87% g (Figure 2). Moreover, the duration of strong ground motion is only 4–5 s. Additionally, the velocity records show prominent long-period velocity pulses both on the SN component (Figure 4) and the SP component. It is well known that in general, forward directivity effects of fault rupture and permanent tectonic translation effects are the two main causes of velocity pulses observed along the SN and SP directions, respectively, in the near-fault region of earthquake rupture (e.g., Mavroeidis and Papageorgiou 2003, 2010). In some cases the forward directivity effects and translation effects “build up” in the same direction and should be decoupled (Mavroeidis and Papageorgiou 2002).

We calculate the ICEARRAY linear pseudo-acceleration spectral response for 5% damping ratio (Figure 3). We compare it with the Eurocode 8 “Type 2” design spectra and for the SN component also with the corresponding design spectrum derived from the strike-normal component of near-fault motion with distinct pulses (Mavroeidis *et al*. 2004). Not only is the comparison more physically consistent in this way, but now the spectral levels for the horizontal components are better matched than before. Apparently, the long-period energy of the velocity pulse seen along the SN direction is not present in the SP direction.

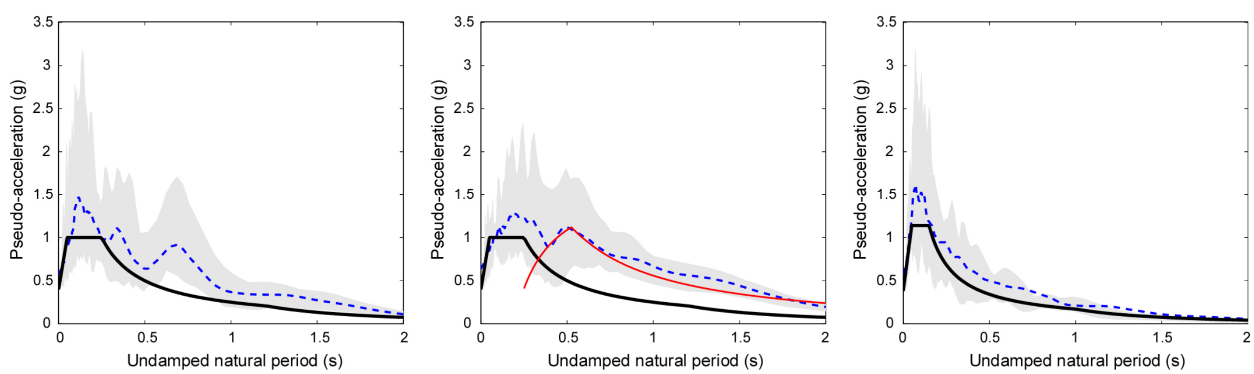


Figure 3. Eurocode 8 “Type 2” elastic response spectra for soil type A (rock) scaled applying peak ground acceleration equal to 40% g (black solid line) compared with the ICEARRAY pseudo-acceleration response spectra envelope (gray shaded region), their mean PSA values (dashed line), and the design spectrum of near-fault pulses (red line). From left to right the plots correspond to the SP and SN components, and the vertical component, respectively.

## Baseline correction procedure

In order to accurately estimate the velocity and displacement time histories from the ICEARRAY acceleration records, the latter need to be corrected for baseline shifts. This cannot be exactly done due to the instruments only recording the three translational components. However, a number of baseline correction methods exist in the literature that can be applied to this task, the most recent being, Akkar and Boore (2009), Chanerley and Alexander (2009), Chao *et al*. (2009) and Rupakhety *et al*. (2009).

In this study we apply a baseline correction scheme based on a novel, wavelet-based algorithm, which by extracting the low-frequency fling makes it possible to automatically correct for baseline shift and re-integrate down to displacement. The algorithm applies a stationary-wavelet transform at a suitable level of decomposition to extract the low frequency fling model in the acceleration time histories. The low frequency, acceleration fling should be as close as possible to the theoretical type A sine fling-model, which after correction leads to a pulse-type velocity and ramp-like displacement after first and second integration. A type B cosine fling-model gives a one sided fling in velocity, from which the displacement recovers, however in this event the low frequency profiles were only type A sine flings. The wavelet transform essentially decomposes the seismic record using maximally flat filters and these together with a de-noising scheme and non-linear scaling form the core of this approach, which is to extract the lower and higher frequency sub-band acceleration, velocity and displacement profiles and correct for baseline shift. The correction automatically selects one time point from the low-frequency sub-band and then zeros the acceleration baseline after the fling and re-integrates. This implies pure, translation without any instrument tilts. Estimates of instrument tilt angles are also obtainable from the wavelet transformed time history as well as estimates of signal-to-noise ratios (Chanerley and Alexander 2008, 2009; Chanerley *et al.* 2009).

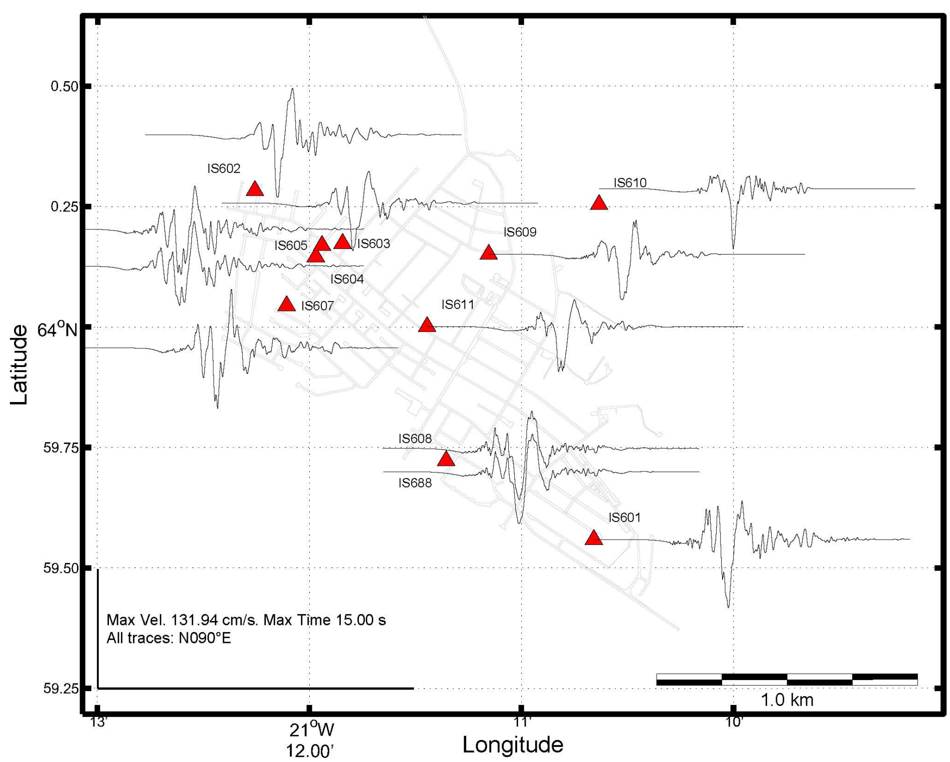


Figure 4. The corrected velocity time histories of the east-west (SN) component of recorded acceleration time histories in Figure 2.

## Results

The wavelet baseline correction algorithm was subjected to "blind" testing using mainshock data from the 29 May 2008 earthquake recorded at ICEARRAY. Figure 4 shows the SN component of corrected velocity time histories corresponding to the acceleration shown in Figure 2. The SN velocity time histories clearly show the presence of prominent long-period and large amplitude near-fault velocity pulses. It is also evident that there is considerable variability in the velocity waveforms.

The baseline corrected displacements along the SN (positive towards East) and SP (positive towards North) directions are shown for each individual station in Figure 5. It appears that that the displacement results for the SP component show much greater variability than along the SN component. Additionally, although not easily seen in the plots, there exist some pre-event deviations from zero displacement prior to the P wave onset time (at the start of the time history shown), which might indicate non-physical effects from the correction procedure. Figure 5 also shows the corresponding mean displacements along with their corresponding $\pm\sigma$.

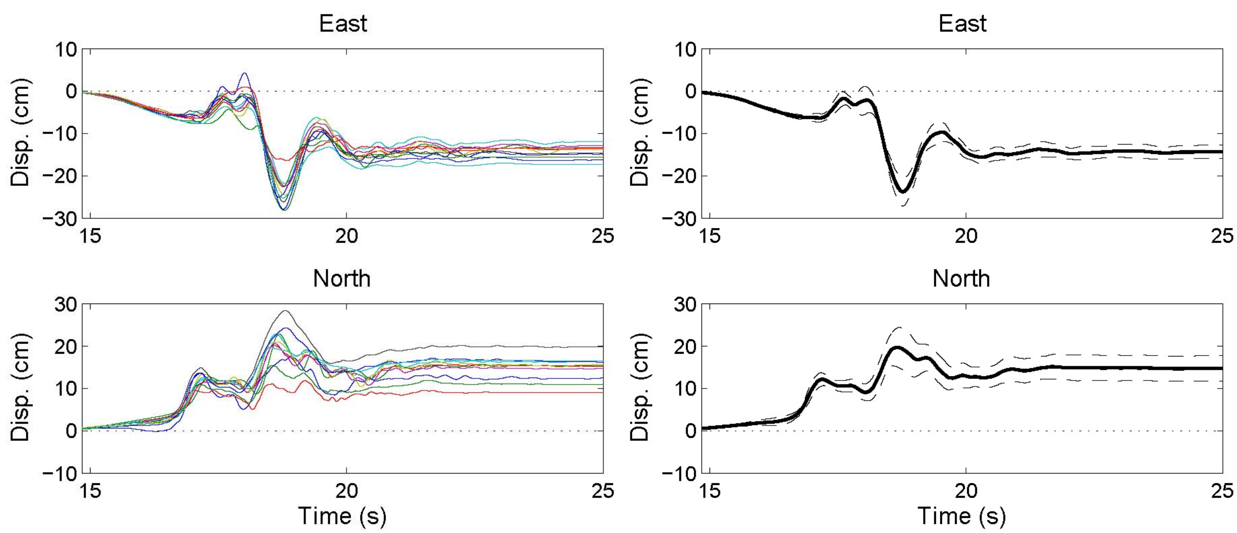


Figure 5. Left: The individual displacement time histories at ICEARRAY stations along the East and North directions at top and bottom, respectively, according to the correction method applied. Right: The mean displacement (right) and its corresponding $\pm\sigma$.

Figure 6 shows the particle trajectories in the horizontal plane with reference to the ICEARRAY geometry. In general the permanent coseismic offset across the ICEARRAY, as seen in Figures 6 and 7, reached its final value in the following way: For the first 1.5 seconds after the P wave, a relatively smooth translation of ~6 cm towards west-northwest took place, followed by an almost purely northward translation of ~10 cm that took place in just over 1 second. Then over the next ~2.5 seconds the translation occurred along a northwest-southeast trajectory starting with a southeast translation of ~5 cm followed by a large northwest translation of ~24 cm, after which it comes back ~15 cm, then forward ~5 cm where it comes to rest at a different location than before the earthquake.

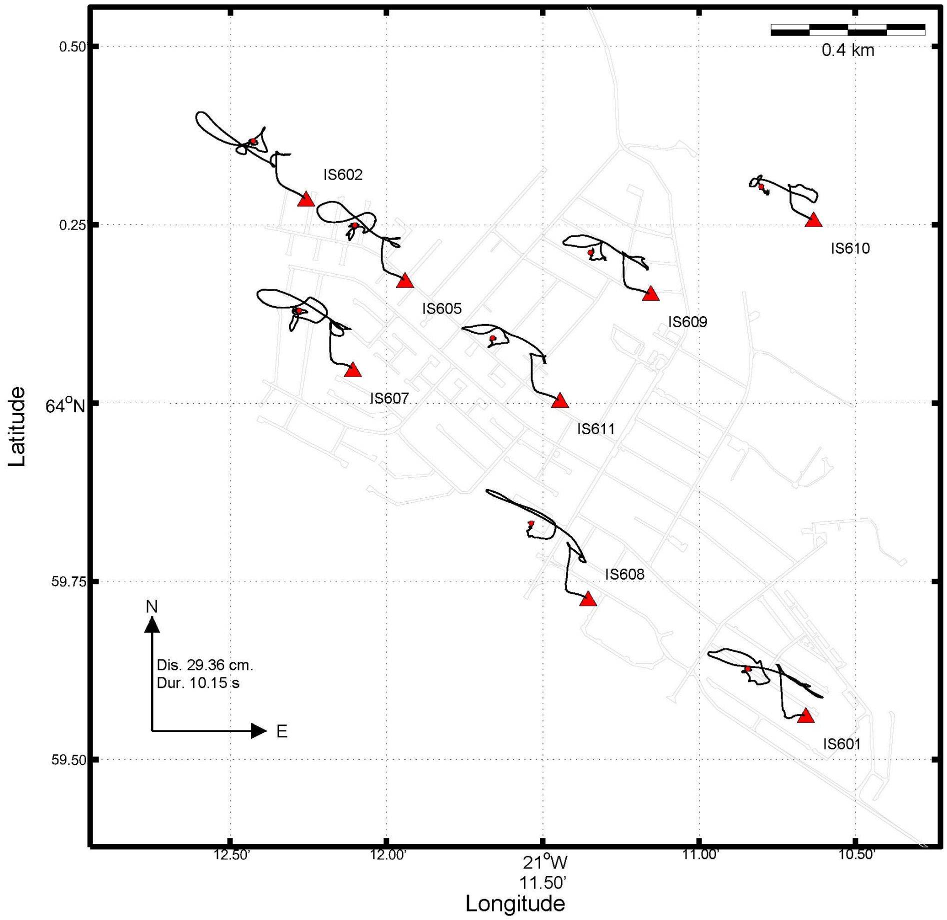


Figure 6. Coseismic particle displacements at ICEARRAY stations during the Ölfus earthquake. The triangles indicate the station locations and the solid line the particle trajectory until it reaches the final displacement (red dots). For neatness of the plot the displacements at stations IS603 and IS604 are omitted (see Figure 7).

According to the procedure applied in this study and carried out by Chanerley *et al*. (2009), the average coseismic offset of the ICEARRAY is 14.33 ± 1.57 cm towards west and 14.78 ± 2.96 cm towards north, with the mean total permanent displacement of 20.70 ± 2.40 cm towards northwest. This compares well with the independently obtained result of 19.63 ± 2.24 cm by Rupakhety *et al.* (2009) using an improved and simplified, yet highly accurate, baseline correction technique based on the assumption that the displacement time history can be approximated by a ramp function.

Coseismic offset measurements in the area are available for a nearby continuous GPS station. While it is located ~1.5 km north of the ICEARRAY it is at roughly the same distance to the surface projection of the fault plane ($r_{JB}$-distance). Hreinsdottir *et al*. (2009) report that the largest offset at the station was 19.09 ± 0.09 cm towards northwest, decaying rapidly with distance away from the fault. This in turn indicates that the baseline corrections carried out by Chanerley *et al.* (2009) and Rupakhety *et al.* (2009), applying completely different techniques, can be applied with confidence in obtaining the permanent coseismic displacements from three-component data.

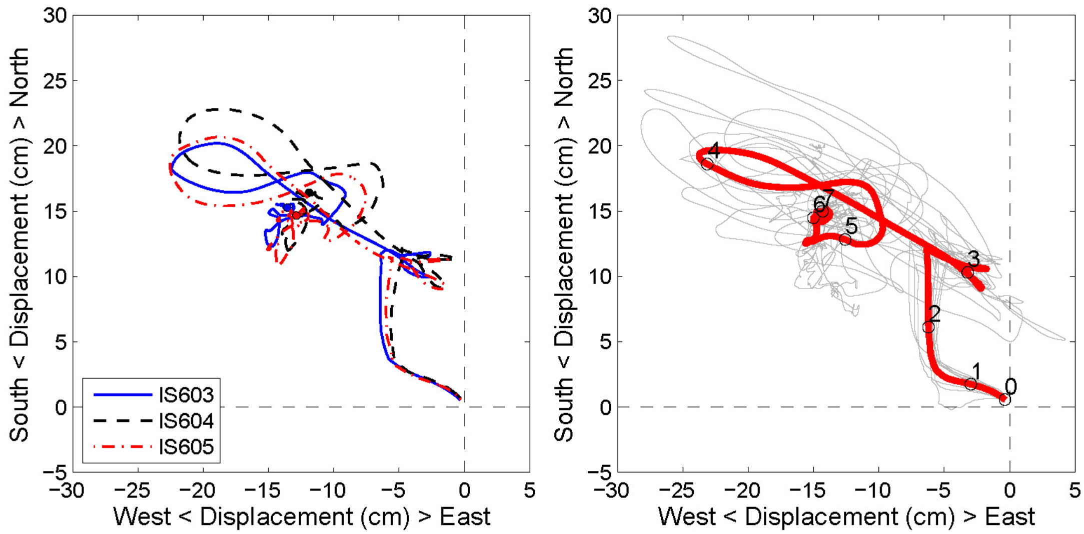


Figure 7. Coseismic particle displacement on stations IS603-5 (left) and on all stations (right, gray lines) along with the average displacement (red, numbers are seconds).

## Conclusions

We have analyzed the velocity and displacement time histories from the baseline corrected acceleration recorded by the ICEARRAY during the $M_w$6.3 Ölfus earthquake in South Iceland on 29 May 2008. The displacement records show a permanent coseismic offset along both SP and SN directions. In general the velocity and displacement time histories have strong common features, respectively, but significant variability in particle motion is observed even over very short distances (e.g., Figure 7, left). The variability is most likely caused by local site effects and in few cases by non-uniform station setup conditions. However, future work is focused on estimating this degree of variability and its causes, including comparing the baseline correction results of the two methods that have been used for that purpose on the ICEARRAY data. The purpose is to evaluate the "true" variability of ground motion across the ICEARRAY during the earthquake. Finally we note that the results indicate that aseismic design of structures in the vicinity of short strike-slip faults needs to take into account near-fault velocity pulses along both the SN and SP directions.

## Acknowledgments

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## References

Abrahamson, N. A., and B. A. Bolt (1987). Array Analysis and Synthesis Mapping of Strong Seismic Motion, Seismic Strong Ground Motion Synthesis, B. A. Bolt (ed.), Academic Press, Orlando, 55-90.

Akkar, S. and D. M. Boore (2009). On baseline corrections and uncertainty in response spectra for

baseline variations commonly encountered in digital accelerographs. Bulletin of the Seismological Society of America, 99(9), 1671-1690.
Ansal, A. M. (1999). Strong Ground Motions and Site Amplification, Proceedings of the Second International Conference on Earthquake Geotechnical Engineering, P. Seco and S. Pedro (eds.), A. A. Balkema, Rotterdam, p. 879-894.
Chanerley, A. A. and N. A. Alexander (2008). Automated Baseline Correction, Fling and Displacement Estimates from the Chi-Chi Earthquake using the Wavelet Transform. 9th International Conference on Computational Structures Technology, 2-5 September 2008, Athens, Greece.
Chanerley, A. A. and N. A. Alexander (2009). Obtaining estimates of the low-frequency 'fling', instrument tilts and displacement timeseries using wavelet decomposition, Bulletin of Earthquake Engineering (accepted, online first).
Chanerley, A. A., N. A. Alexander and B. Halldorsson (2009). On fling and baseline correction using quadrature mirror filters. 12th International Conference on Civil, Structural and Environmental Engineering Computing (CC2009), Funchal, Madeira, Portugal, 1-4 September 2009.
Chao, W.-A., Y.-M. Wu and L. Zhao (2009). An automatic scheme for baseline correction of strong-motion records in coseismic deformation determination, Journal of Seismology, DOI 10.1007/s10950-009-9178-7.
Halldorsson, B. and H. Avery (2009). Converting strong-motion networks to arrays via common-triggering, Seismological Research Letters, 80(4), 572-578.
Halldorsson, B. and R. Sigbjornsson, 2009. The Mw6.3 Ölfus Earthquake at 15:45 UTC on May 29 2008 in South Iceland: ICEARRAY strong-motion recordings. Soil Dynamics and Earthquake Engineering, 29(6), 1073-1083.
Halldorsson, B., R. Sigbjornsson and J. Schweitzer, 2009. ICEARRAY: the first small-aperture, strong-motion array in Iceland. Journal of Seismology, 13(1), 173–178.
Hreinsdóttir, S. Th. Árnadóttir, J. Decriem, H. Geirsson, A. Tryggvason, R. A. Bennett and P. LaFemina (2009). A complex earthquake sequence captured by the continuous GPS network in SW Iceland, Geophysical Research Letters, 36, L12309.
Mavroeidis, G. P. and Papageorgiou, A. S. (2010). Effect of fault rupture characteristics on near-fault strong ground motions, Bulletin of the Seismological Society of America, (accepted).
Mavroeidis, G. P., G. Dong and A. S. Papageorgiou (2004). Near-Fault Ground Motions, and the Response of Elastic and Inelastic Single Degree-of-Freedom (SDOF) Systems, Earthquake Engineering and Structural Dynamics, 33, 1023-1049.
Rupakheti, R., B. Halldorsson and R. Sigbjornsson (2009). Estimating coseismic deformations from near source strong motion records: Methods and case studies. Bulletin of Earthquake Engineering (in review).
Sato, H., and M. C. Fehler (1998). Seismic Wave Propagation and Scattering in the Heterogeneous Earth, Springer Verlag, New York, U.S.A.
Sigbjörnsson, R., J.Th. Snæbjörnsson, S. M. Higgins, B. Halldórsson, S. Ólafsson (2009). A note on the M6.3 earthquake in Iceland on 29 May 2008 at 15:45 UTC. Bulletin of Earthquake Engineering, vol. 7(1), 113-126.
Sigbjörnsson, R., Ólafsson, S. and Thórarinsson, Ó. (2004). Strong-Motion Recordings in Iceland Proceedings of the 13th World Conference on Earthquake Engineering (13WCEE), Vancouver, BC, Canada, Mira, Paper No. 2370.
Spudich, P., and E. Cranswick (1984). Direct Observation of Rupture Propagation During the 1979 Imperial Valley Earthquake Using a Short Baseline Accelerometer Array, Bulletin of the Seismological Society of America, 74(6), 2083-2114.
Stefánsson, R., R. Böðvarsson, R. Slunga, P. Einarsson, S. S. Jakobsdóttir, H. Bungum, S. Gregersen, J. Havskov, J. Hjelme, and H. Korhonen (1993). Earthquake Prediction Research in the South Iceland Seismic Zone and the SIL Project. Bulletin of the Seismological Society of America, 83, 696-716.