DESIGN AND INSTALLATION OF ICEARRAY, A NEW SMALL-APERTURE STRONG-MOTION ARRAY IN SOUTH ICELAND

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ABSTRACT

The tectonically unique and populated South Iceland Seismic Zone (SISZ) has been the location of numerous destructive earthquakes in the past. Its capability to produce earthquakes that may exceed magnitude 7 is a constant threat to lifelines in the region, such as pipelines, electric transmission systems, dams and bridges. In terms of engineering design and earthquake safety the spatial variability of earthquake ground motion is of particular importance to such horizontally extended structures. Up to now reliable regional quantitative models of the spatial variability have not been available due to lack of strong-motion arrays. Furthermore, quantification of the complexity of earthquake source processes and their effects, of paramount importance to near-fault sites, has not been possible in the region for the same reason. Therefore ICEARRAY, the first small-aperture strong-motion array in Iceland, has been installed in the SISZ. The array's purpose is: 1) monitoring future significant events in the region; 2) quantifying spatial variability of strong-motion over short distances; and 3) shedding light on earthquake source processes. ICEARRAY is equipped with CUSP-3Clp three-component, Internet-based digital accelerograps with GPS timing system and a perpetual connection to the Internet via wireless GPRS. The CUSPs are low cost, but have a high-dynamic range and possess a very low noise floor (~70 micro-g), thus additionally rendering the array useful for studying the weak-to-strong motion transitions over a wide magnitude range. We optimize its recording efficiency via a novel real-time common-triggering scheme, which also intelligently minimizes the analyst's need to review data discerning between earthquakes and noise. The number of array stations and their arrangement were based on an optimisation of the shape of the corresponding array transfer function (ATF). The optimal ICEARRAY configuration comprises 14 stations, has an aperture of ~1.9 km, and a minimum interelement distance of ~50 m, and possesses a near-azimuthally independent ATF with a sharp main lobe, negligible sidelobes and a wavenumber range of 1.5-24 rad/km. Accordingly, the ICEARRAY has the intended capabilities of capturing seismic waves in the frequency range of 1-20 Hz, which is of main interest to earthquake engineering and engineering seismology applications.

KEYWORDS: strong-motion, array, Iceland, design, earthquakes, array transfer function

1. INTRODUCTION

Iceland is located on the Mid-Atlantic Ridge, the diverging plate boundary of the North American and Eurasian plates in the North Atlantic Ocean. The boundary outlines Iceland's active volcanic zones, which are offset from west to east by two transform zones in the north and the south of the island, respectively. The transform motion in southern Iceland is taken up in the South Iceland Seismic Zone (SISZ, see inset in Figure 1), a belt approximately 80 km long by 20 km wide on which large destructive earthquakes have occurred in the past on north-south trending faults (Stefánsson et al, 1993). The SISZ has the capacity for earthquakes as large as M7 and is the region of the greatest earthquake hazard and seismic risk in Iceland (Sigbjörnsson et al, 2006). The latest destructive earthquakes in the SISZ took place on 17 and 21 June, 2000, respectively. Their fault planes are denoted in Figure 1 in reference to the recording sites of the Icelandic Strong-motion Network (IceSMN, Sigbjörnsson and Ólafsson, 2004).

The rapid attenuation of ground motion amplitudes with distance from these events suggests that scattering of seismic waves is considerably stronger in the SISZ than in most other earthquake prone regions worldwide (Halldórsson et al, 2007). This in turn suggests that spatial variability of high-frequency (_1-20 Hz) seismic ground motions would also be greater in the region, but no such estimates exist due to the large (a few kilometers, at least) interelement distances of the IceSMN. The spatial variability is of great interest to earthquake engineers involved in the earthquake resistant design of lifelines (pipelines, bridges, power lines, dams, etc.) and can only be quantified using smallaperture arrays. Furthermore, as arrays are dependent on stable and accurate timing of all array stations they are useful for earthquake detection (Schweitzer et al, 2002), and studying the details of earthquake source properties, such as rupture propagation (Spudich and Cranswick, 1984). For the above reasons, the ICEARRAY (Icelandic Strong-motion Array), has been deployed in the SISZ. Its specific goal is the establishment of quantitative estimates of spatial variability of strongmotions, and the investigation of earthquake rupture processes and source complexities of future significant earthquakes in the region.

2. SITE SELECTION

ICEARRAY's location was required to: (a) possess a relatively high background seismicity; (b) be in the nearfault region of destructive earthquakes; and (c) be collocated with an urban area and modern infrastructure, including lifelines. In the SISZ four areas with an extent of approximately 10 km in the east-west direction had been shown to be deficient in relative strain release during strong ($M_w \geq 6$) earthquakes since 1700 (Stefánsson et al, 1993). The two earthquakes of June 2000 took place in two of these areas, the other two potential locations being near the farm of Selsund (see Figure 1) in the east, and near the towns of Selfoss and Hveragerdi in the west. Therefore, the western and eastern margins of the SISZ were considered for ICEARRAY's permanent location. Of the two, the western margin is more densely populated and the array's collocation with an urban area is useful as it provides for a direct earthquake engineering application. Furthermore, Hveragerdi has the greatest background seismicity due to its proximity to the volcanic zone. Finally, the geology of South Iceland is dominated by stacked layers of basaltic lava rock and sediments. The present day top soil consists of sediments with a variable thickness, and the thickness in Hveragerdi is much less than in Selfoss. Therefore, Hveragerdi provides for an easier deployment of the recording instruments collocated with existing structures (in basements or on the base wall) because most residential buildings here are built directly on top of the lava rock. Hence, Hveragerdi was chosen as the location for the ICEARRAY network.

Ensuring the recording of complete waveform information (body and surface waves) 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 triaxial low-noise (~70 μg rms) MicroElectroMechanical (MEM) accelerometers with a highdynamic range (± 2.5 g) and a wide frequency passband (0-80 Hz at 200 Hz sampling frequency). Each unit possesses a continuous GPS timing system, acts in triggered mode and saves datafiles directly to a hard disc. The units draw their power from the mains of the respective building, although a battery ensures several days worth of functionality in case of power failures. The units were configured with perpetual Internet connectivity using wireless GPRS, enabling remote connectivity for maintenance, control, and a direct upload of recordings to a central server after recording an event. The latter is especially useful as it provides a near immediate data accessibility and ensures backup.

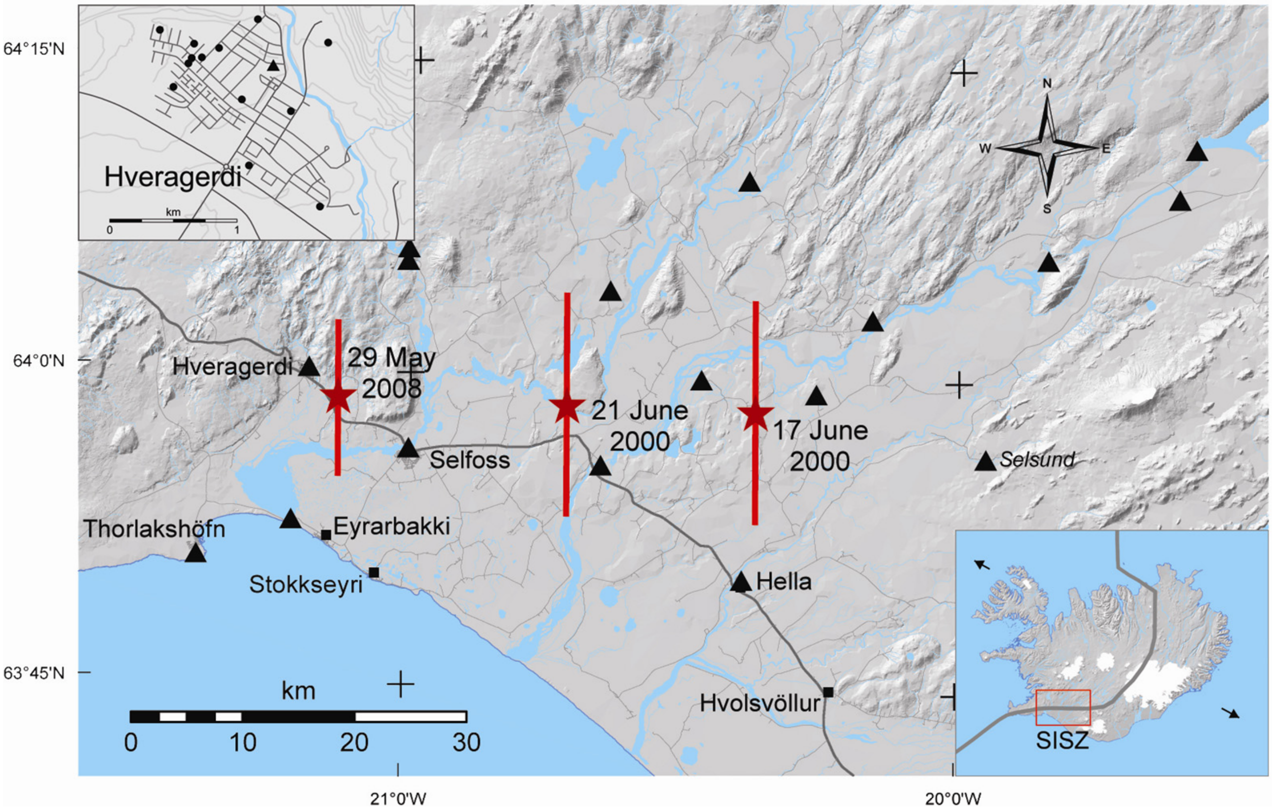


Figure 1 The small map inset at bottom right shows Iceland with glaciers in white, in reference to the present-day boundary of the Eurasian and North American tectonic plates (thick line, Sigbjörnsson et al, 2006). Their relative motion is ~2 cm/year, in the direction indicated by the bold arrows (Stefánsson et al, 1993). The rectangle indicates the area of the SISZ, shown in the larger map along with the main roads, villages, rivers and lakes. The fault planes and epicenters (stars) of the earthquakes of June 2000 and May 2008 are shown in reference to the recording sites of the IceSMN (triangles). The small map inset at top left shows the ICEARRAY recording sites (dots) on a street map of Hveragerdi village, with the single IceSMN station shown as a triangle.

Prior to ICEARRAY deployment, a two-month field study was carried out in Hveragerdi to monitor the seismicity and obtain an initial estimate of the waveform correlation over the network. Five recording units were used, including that of the original IceSMN station in Hveragerdi which has been incorporated into the ICEARRAY network (Figure 2). Five local earthquakes of M1.6-2.7 and epicentral distances of 2.5−4.6 km were recorded. The data appeared to possess a relatively high *P* phase correlation on the vertical components and indicated that the main energy passband of the recorded data is focused at the higher frequencies, as one would expect from events of small local earthquakes. This indicates that high signal correlation can also be expected across the array when recording larger event ground motions. [Parenthetically we note that 7 months after ICEARRAY's deployment, more specifically, at 15:45 on May 29th, 2008, a M_w 6.3 earthquake struck in the Olfus lowland between Hveragerdi and Selfoss (see Figure 1) (Sigbjornsson et al, 2008). The ICEARRAY recorded the main shock on 11 stations and the vast majority of its aftershocks. At present, this data comprises the largest part of ICEARRAY's dataset of 2.933 recordings since October 1st, 2007 However, when including only triggers on three stations or more the ICEARRAY has recorded 1.046 datafiles since October 1st 2007 until June 5th 2008 (Halldorsson et al., 2008: Halldorsson & Avery, 2008). The ICEARRAY recordings of this earthquake are currently being analyzed.]

3. GEOMETRY AND NUMBER OF STATIONS

The array transfer function (ATF) is the single most relevant characteristic of an array and holds information on all its aspects. It describes the sensitivity and resolution of an array for seismic signals with different frequency contents and slowness values, and for a two dimensional vector **r** of *N* station locations, the ATF is defined as

$$\left|C\left(\boldsymbol{\kappa}_0-\boldsymbol{\kappa}\right)\right|_{\mathbf{r}}^2=\left|\frac{1}{N}\sum_{j=1}^{N}e^{i\mathbf{r}_j(\boldsymbol{\kappa}_0-\boldsymbol{\kappa})}\right|^2 \tag{3.1}$$

where $\boldsymbol{\kappa}$ is the two-dimensional wavenumber vector (variable) and $\boldsymbol{\kappa}_0$ is the true wavenumber vector of a monochromatic plane wave that traverses across the array (e.g., Schweitzer et al, 2002). The scalar wavenumber is $\kappa=\omega s=\omega/c=2\pi/\lambda$ where ω is the circular frequency of a wave of wavelength λ, s is its scalar slowness, which is inversely proportional to its apparent velocity *c*. The smallest interelement distance of the array is *d* while the largest defines the array aperture, *D*. The main lobe of the ATF exists at the origin in the wavenumber domain and the 3-dB drop in main lobe amplitude defines $\Delta\kappa$ the wavenumber resolution of the array (Johnson and Dudgeon, 1993;Wang, 2002). Thus, greater sharpness of the main lobe increases the minimum wavenumber resolvable by the array. Grating lobes exist away from the origin and are indicative of aliasing in the wavenumber domain. The aliasing wavenumber, $\kappa_{\max}$, is defined by the half-distance between the main and the closest maximum grating lobe. The wavenumber passband of the array lies between $\Delta\kappa$ and $\kappa_{\max}$ and its width is a measure of the array's capability of resolving a wider range of waves of different wavenumbers (Haubrich, 1968; Mykkeltveit et al, 1983; Wang, 2002).

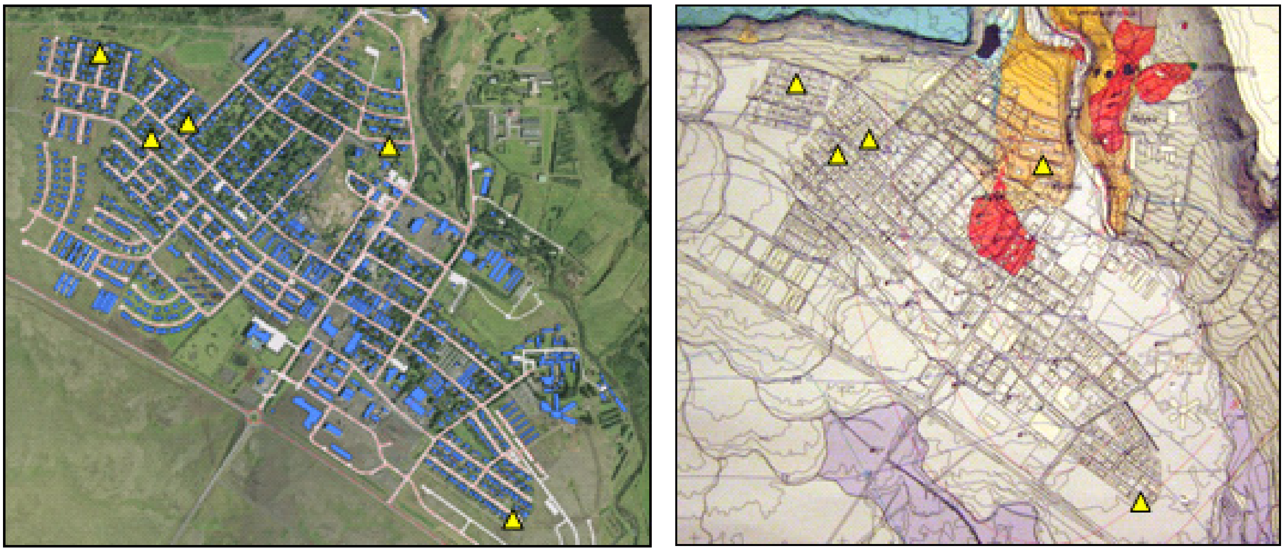


Figure 2 The street-and-structural layout (left) of the town of Hveragerdi where the pre-field study was carried out. The triangles denote the station locations of the test-setup, located in residential structures. A schematic map showing main geological features of the town area (right) shows that the town resides largely on a single lave field. The red and orange areas denote high geothermal activity.

Keeping in mind these general traits we focussed on establishing as complete an ATF as possible for the ICEARRAY. Seven station locations were predetermined, the first two stations essentially defining the aperture of *D* = 1.9 km, and the next four stations were clustered together forming the densest part of ICEARRAY. The seventh station was predetermined at the location of the existing IceSMN station (see Figure 1). We then allowed for a range of 8 to 17 stations for the ICEARRAY network to be determined on the basis of a constrained optimisation of the ATF. One constraint is the finite number of stations, N, as a greater number of stations translates into greater overall startup and maintenance costs but also enhances the array's signal-to-noise gain. Additionally, the stations should be distributed so that the array aperture is sufficient and so that the relative distance distribution covers d to D with sufficient resolution to provide a smooth coherency function vs. distance. Finally, the collocation of stations with buildings in Hveragerdi imposed a geometrical constraint on available station locations for the ATF optimisation.

For the sake of maximising the array resolution, a search was carried out for the station locations r that would minimise the volume under the central part of the ATF, or equivalently

$$\Gamma(\mathbf{R}) = \min\left[\iint_{\boldsymbol{\kappa}} W(\kappa)\left|C(\boldsymbol{\kappa}_0 - \boldsymbol{\kappa})\right|_{\mathbf{r}}^2 d\boldsymbol{\kappa}\right] \tag{3.2}$$

where $W(\kappa)$ are the weights that modulate the ATF, given as

$$W(\kappa) = \left[\frac{1}{2}\cos\left(\frac{\pi|\boldsymbol{\kappa}|}{|\boldsymbol{\kappa}_{\max}|}\right) + \frac{1}{2}\right]^n \tag{3.3}$$

where $\kappa_{\max}$ is the largest wavenumber used in the ATF calculations, and n is the factor controlling the sharpness of the weighting function around the origin (see Figure 3). When considering wave slowness values, using $n = 4$ effectively focusses the search on the 5 − 10 Hz frequency band which is the central frequency band of interest in this study. In addition to finding the sharpest main lobe, minimising the volume of the ATF is also equivalent to minimising the amplitudes of grating lobes, which in turn increases the wavenumber range of the array.

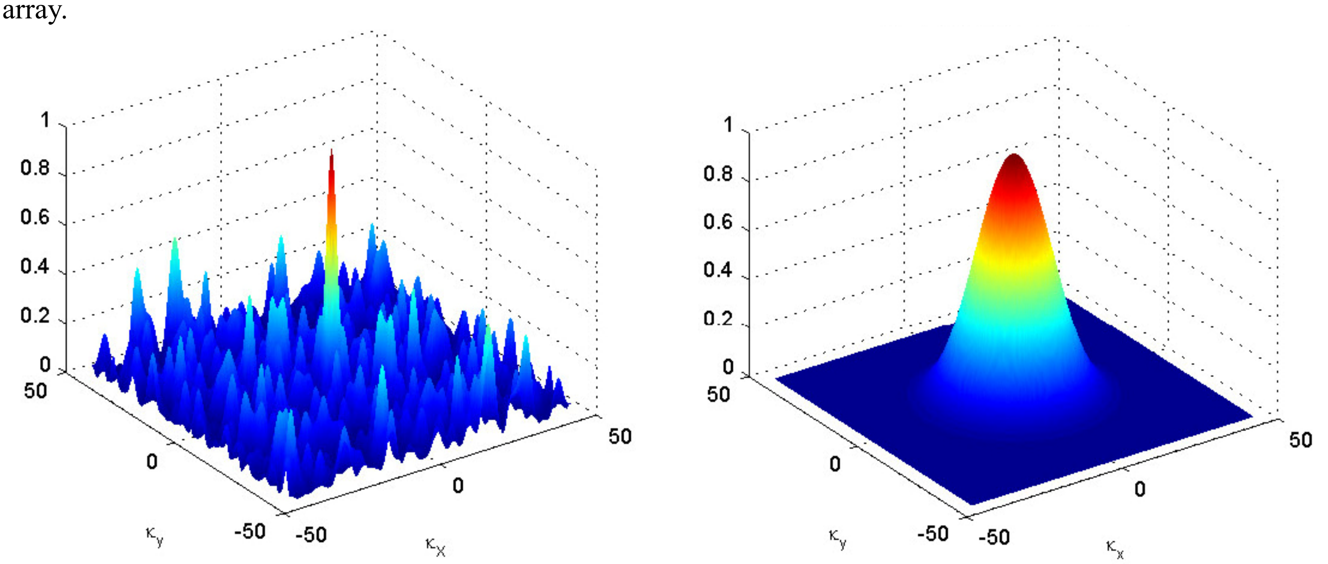


Figure 3 An example of an unmodulated ATF (left) for one random scenario of station arrangements in Hveragerdi, and the weighting function of Equation (3) for n = 4 (right).

Two types of searches, random arrangement and grid search, were carried out. In the former, 8000 random trial station locations for the range of station numbers were calculated by brute force, and the optimal geometry chosen for each N based on the corresponding ATF properties and Eq. (3). In the latter, stations were added to the array one by one, starting with the 8th station and ending with the 17th. A station was however not added to the array until the optimal location had been found through a grid search over the possible locations (total

~1500). Figure 4 shows the comparison of the two methods. The figure shows the quality parameter, here equal to $\Gamma d\kappa_x d\kappa_y$, plotted vs. the number of stations with the dots indicating the results from the random arrangement and the solid line showing the results from the grid search. In all cases, the grid search finds the minimum of Equation (3) with the maximum efficiency. We also note that the plot indicates that the point of maximum $\Gamma d\kappa_x d\kappa_y$ curvature is at the location of a 'critical' total number of stations, N_c, beyond which less and less relative gain in ATF shape and wavenumber passband is obtained with increasing equipment costs. The 'optimal' number of stations given the above constraints thus appears to be around 10 − 14, and we have selected N = 14 for the ICEARRAY network.

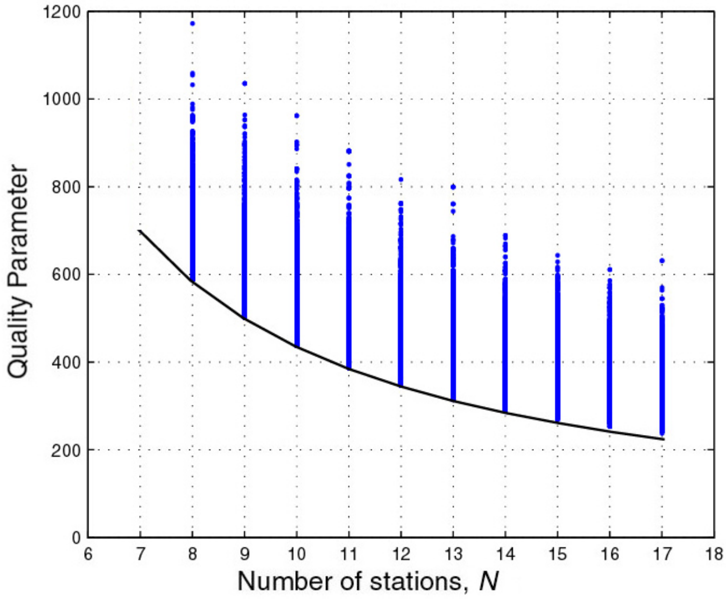
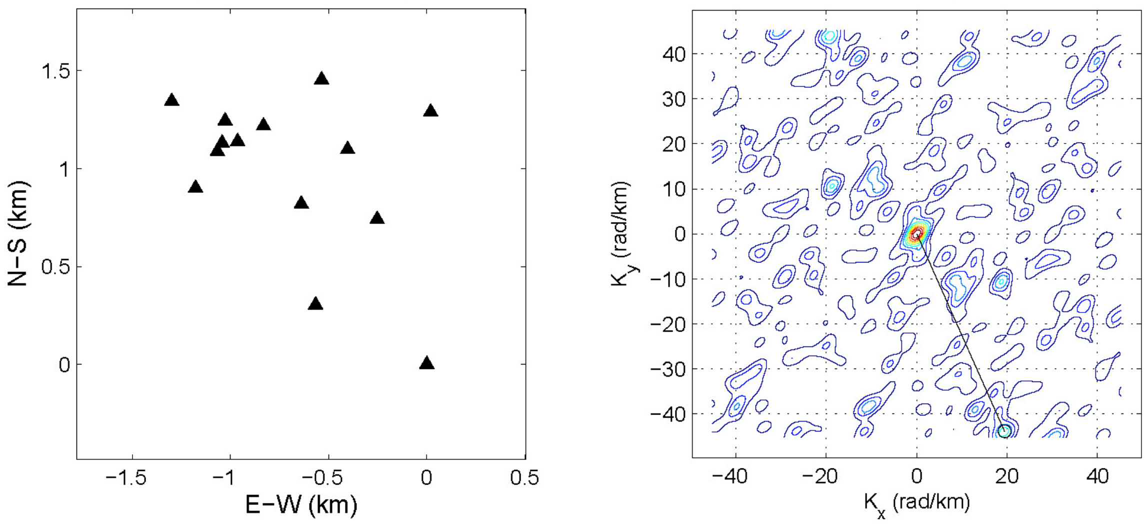


Figure 4 The performance of random station arrangement (dots) vs. grid search (line) in searching for the optimal station configuration for a given N.

Figure 5a shows the final array configuration. The aperture is D = 1.9 km and minimum interelement distance is d = 50 m, which implies that the array can capture incident planar seismic wavelengths of 100 m to around 2 km. The corresponding ATF contours are shown in Figure 5b. One observes that the ATF is relatively well behaved with few significant grating lobes, the largest one far removed from the origin, thus minimising aliasing. We note that the relative distance distribution of the network provides a relatively high resolution over most of its aperture. The corresponding ICEARRAY wavenumber range is $\kappa = \tilde{1}5 - 24$ rad/km with a passband of $\log(\kappa_{\max}/\Delta\kappa) \sim 1.2$, which indicates that the frequency range for which the array is most sensitive lies between roughly 1 − 20 Hz for the majority of the slowness values observed. This range covers well the frequency band of seismic waves that ICEARRAY was intended for. Figure 6 shows the distribution of interstation distances, indicative of the resolution in the spatial domain expected for future coherency functions as a function of distance (and frequency).

4. CONCLUSIONS

The ICEARRAY is the first permanent, small-aperture, strong-motion array in Iceland and has been operational in the SISZ since October 2007. It is collocated with the village of Hveragerdi on the western edge of the SISZ where seismicity is relatively high and destructive earthquakes have occurred. Equipped with absolute timing, the array monitors future significant earthquakes in the SISZ. The array's resolution for earthquake source studies increases with greater proximity to the causative fault while the basic array processing assumption of plane-waves starts to break down. However, some array processing techniques such as beamforming can still be applied when adapted to circular wavefronts (Almendros et al, 1999). For more distant events, the array enables a clearer reception of earthquake signals than possible with a single station, which further facilitates detailed earthquake source and waveform analyses. Finally, data recorded on ICEARRAY will be used to construct provisional spatial variability models. The results from such studies, when coupled with physically realistic earthquake models (Halldórsson et al, 2007) and advanced hybrid techniques of synthesising strong ground motions (Hartzell et al, 1999), will allow a comprehensive assessment of the effects of spatially variable ground motions on lifelines in the future.



(a) (b)

Figure 5 (a) ICEARRAY geometry, including one permanent IceSMN station, and (b) a 2-D view of the ATF showing the main lobe at the centre. The line connects the main lobe and the tallest sidelobe.

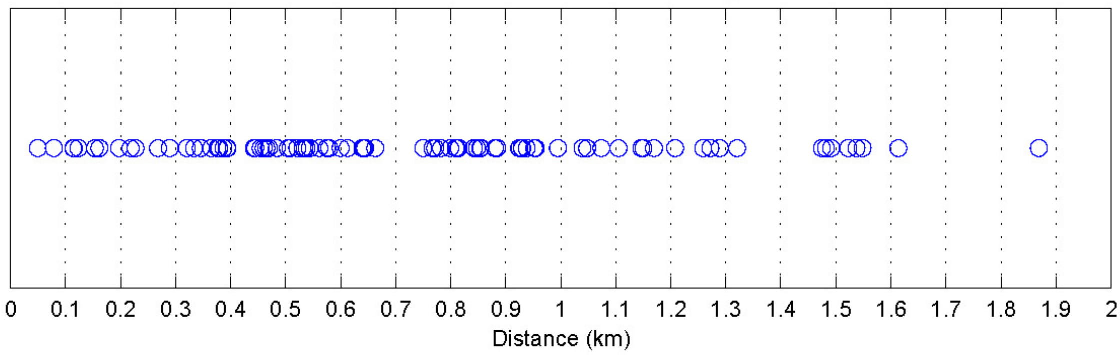


Figure 6 The distribution of interstation distances across the ICEARRAY.

5. ACKNOWLEDGEMENTS

This work is supported by the 6th Framework of the European Commision through the Marie Curie International Re-integration Grant (MC-IRG), contract No. MIRGCT-2006-036564; the Icelandic Centre for Research (RANNIS) Project Grant No. 60043021; and a NERIES Transnational Access Grant, EC Contract No. 026130, at NORSAR, Kjeller, Norway. The authors gratefully acknowledge and appreciate this support, in addition to that of the University of Iceland Research Fund. In particular, thanks to Dr. Steven Gibbons and Dr. Tormod Kværna at NORSAR for their invaluable support and guidance. The EERC is grateful to Síminn telecommunication company in Iceland for their support of the wireless communication links over the ICEARRAY network. The assistance of Hamish Avery of Canterbury Seismic Instruments and Ms. Sally Higgins at the University of Iceland proved invaluable to this study.

REFERENCES

Almendros, J., Ibáñez, J.M., Alguacil, G., Pezzo, E.D. (1999) Array analysis using circular-wave-front geometry:an application to locate the nearby seismo-volcanic source. *Geophys J Int* 136(1):159–170, DOI 10.1046/ j.1365-246X.1999.00699.x

Halldórsson, B., Ólafsson, S., Sigbjörnsson, R. (2007) A fast and efficient simulation of the far-field and near-fault earthquake ground motions associated with the June 17 and 21, 2000, earthquakes in South Iceland. *J Eq Eng* 11:343–370

Halldorsson, B., R. Sigbjornsson and J. Schweitzer (2008). ICEARRAY: The first small-aperture, strong-motion array in Iceland. *Journal of Seismology* (in press).

Halldorsson, B. and H. Avery (2008). Optimizing recording efficiency of a new strong-motion array (ICEARRAY) using common-triggering, In: *Proceedings of the 14th World Conference on Earthquake Engineering* (14WCEE), Beijing, China, October 12-18. Paper no. 11-0105.

Hartzell, S., Harmsen, S.C., Frankel, A.D., Larsen, S. (1999) Calculation of broadband time histories of ground motion; comparison of methods and validation using strong-ground motion from the 1994 Northridge earthquake. *Bull Seism Soc Am* 89(6):1484–1504

Haubrich, R.A. (1968) Array design. *Bull Seism Soc Am* **58(3)**:977–991

Johnson, D.H., Dudgeon, D.E. (1993) Array Signal Processing. Prentice Hall Inc., Englewood Cliffs, New Jersey

Mykkeltveit, S., Astebol, K., Doornbos, D.J., Husebye E.S. (1983) Seismic array configuration optimization. *Bull Seism Soc Am* **73(1)**:173–186

Schweitzer, J., Fyen, J., Mykkeltveit, S., Kværna, T. (2002) Seismic arrays. In: Bormann P (ed) IASPEI New Manual of Seismological Observatory Practice, GeoForshcungsZentrum, Potsdam, chap 9. Vol. 1, p 51

Sigbjörnsson, R, J. Th. Snæbjörnsson, B. Halldórsson, S. Ólafsson (2008. Earthquake 2008 May 29 15:45 UTC. *Bulletin of Earthquake Engineering* (in press).

Sigbjörnsson, R., Ólafsson, S. (2004) On the South Iceland earthquakes in June 2000: Strong-motion effects and damage. *Bollettino di Geofisika Teorica ed Applicata* **45(3)**:131–152

Sigbjörnsson, R., Sigurdsson, T., Snæbjörnsson, J., Valsson, G. (2006) Mapping of crustal strain rate tensor for Iceland with applications to seismic hazard assessment. In: *Proceedings of the First European Conference on Earthquake Engineering and Seismology*, Geneva, Switzerland, paper number 1211.

Spudich, P., Cranswick, E. (1984) Direct observation of rupture propagation during the 1979 Imperial Valley earthquake using a short baseline accelerometer array. *Bull Seism Soc Am* **74(6)**:2083–2114

Stefánsson, R., Böðvarsson, R., Slunga, R., Einarsson, P., Jakobsdóttir, S.S., Bungum, H., Gregersen, S., Havskov, J., Hjelme, J., Korhonen, H. (1993) Earthquake prediction research in the South Iceland seismic zone and the SIL project. *Bull Seism Soc Am* **83**:696–716

Wang, J. (2002) A scheme for initial beam deployment for the International Monitoring System arrays. *Pure Appl Geophys* **159**:1005–1020