Introduction

In recent years high pressure fluid injection into rock has become a common process in a number of applications resulting in the potential for triggered seismic events. As such, induced seismicity monitoring is essential in order to understand and limit the hazards of such processes. Seismic networks for induced seismicity monitoring are sometimes mandated to be installed to detect and locate events. In some cases protocols require that operations be stopped or other procedures be followed if events larger than a specified magnitude occur within a specified volume. This sort of protocol is often called a “traffic light”.

To implement a traffic light protocol the network operator must be certain that any event in the volume of interest will be detected. If no event is detected, some certainty is needed that no event happened, i.e. there can be no “false negative” results. For this reason, magnitude of completeness is the primary measure of microseismic monitoring network performance.

Once an event is detected, the next question will be: where did it happen? An estimate of the hypocentral location indicates whether it was inside or outside the volume of interest, and will furthermore guide the response to the event. Location accuracy is thus an important secondary measure of performance.

Most current methods of estimating magnitude of completeness (Mignan, Wermer, Weimer, Chen, & Wu, 2011)(Woesnner & Weimer, 2005) and location accuracy (Lienert, 1997) (Billings, Sambridge, & Kennet, 1994) require that an earthquake catalogue exists. We have developed a tool which can assess network performance without an earthquake catalogue. We take into account spatial variability and frequency-dependence of site noise, accurate models of sensor self-noise, and a 1D seismic velocity model. Because we do not require an earthquake catalogue, we can apply this method to both existing and hypothetical arrays. This allows designers of seismic networks to optimize station distribution and to assess the value of installing additional stations. It furthermore allows stress tests to be performed on the network, for example to examine the effect of outages or episodes of higher than normal cultural noise on network performance.

Methodology

Our method requires three essential ingredients: the first is site noise. The site noise field is mapped using data from existing stations in the region and/or from temporary deployment of a site noise survey network. A power spectral density (PSD) probability density function (PDF) is computed for the available stations (McNamara & Buland, 2004). We then interpolate between stations and extrapolate outside the polygon which bounds them. Interpolation is done using the “nearest neighbour” method; extrapolation for points outside the bounding polygon of the survey station locations is done by finding the nearest point on that polygon, and using the interpolated site-noise spectrum at that point. This ensures realistic estimates of site-noise spectra can be queried for any point near the site-noise survey area.

A second ingredient is the array configuration. Station locations of existing and hypothetical stations are specified by latitude and longitude. Instrument self-noise is constructed from models of published seismometer and digitizer self-noise specifications. Instrument noise is then summed with site noise to obtain the station noise for each station in the array. A third ingredient is a one-dimensional velocity model, including estimates of the errors in the boundary depth and velocity of each layer, and an estimate of the local attenuation factor or Q. The velocity model is important in determining the expected spectra of events.

Magnitude of completeness is estimated by computing the minimum detectible magnitude at each station for an event occurring at each point on a grid. The minimum detectible magnitude is determined by successively computing the signal-to-noise ratio (SNR) for different magnitudes of events and requiring a certain minimum SNR. Event spectra are estimated according to Brune (1970) except for an additional factor to account for attenuation (Ackerley, 2012)(Stabile, et al., 2013). Isotropic radiation is assumed.

Location accuracy is estimated by Lagrange's method of undetermined multipliers (Peters & Crosson, 1972). Computation of travel times and their derivatives is based on the source code for LOK (Zivčić & Ravnik, 2002). These are then used to construct a covariance matrix. Event detectability is assessed as described above, except that the dominant frequency of the event is computed along with the SNR, and this is used to estimate trigger timing errors.

Case study – Alberta, Canada

Traffic light protocols are being developed by the Alberta Energy Resources Conservation Board. These protocols dictate that events larger than M1 must be detected within a specified detection zone. A network of nine Trillium Compact 750-20 seismometers equipped with Centaur-3 digitizers has been deployed. These stations were used to generate a noise field survey for the region of interest.

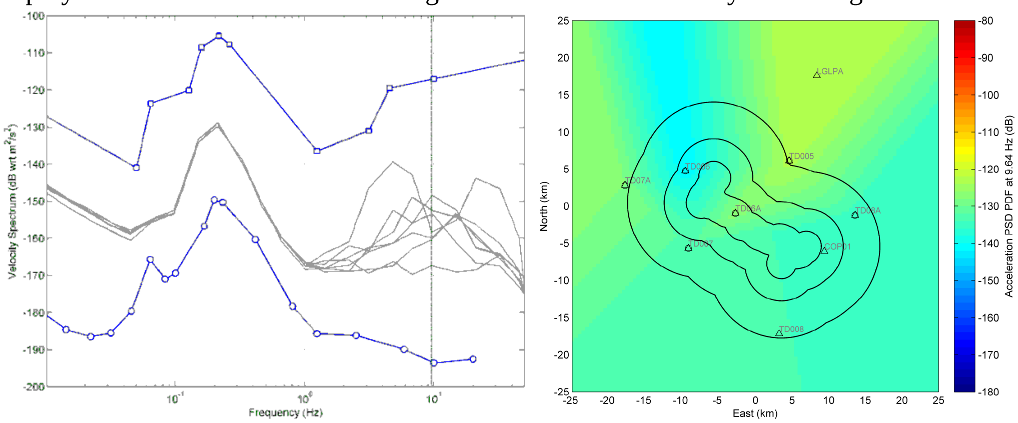

Figure 1 *Left – observed site noise spectra at the individual stations. Right – 10 Hz site noise map for region.*

Figure 1 (left) plots the survey site noise spectra as grey lines along with the NLNM and NHNM (Peterson, 1993) in blue. Figure 1 (right) plots the interpolated site noise field in colour, survey stations as circles, seismic monitoring array locations as triangles, and three zones of interest as black lines. All magnitude 1 events must be detected within the outermost "detection zone"; the two innermost zones are used to define which protocol is to be followed when an event is detected.

A one-dimensional velocity model was inferred from a published model for a nearby region (Clowes, Burianyk, Gorman, & Kanasewich, 2002). Errors in the velocity model were estimated according to the guidelines set out by Stabile et al. (2013).

Estimates of the performance of the existing array are plotted in Figure 2. The minimum magnitude detectible by four stations is predicted to be M0.2. A magnitude of completeness less than M1 is expected for most of the detection zone; there are small areas in the northwest and southeast corners where it is slightly higher. The three-station magnitude of completeness (not shown) was less than M1 for the entire detection zone. Whereas an automatic event detection system generally needs four picks in order to confidently declare an event, an experienced analyst will generally be able to place a fourth pick given just three. The innermost contour of location accuracy corresponds to 0.47 km. We can see that we have less than 1 km location error for most of the region of interest with the southeast corner climbing to a bit above 2 km at its peak.

Since no catalogue has yet developed for this network it is impossible to compare with the observed network performance. The network has detected some regional events, but no events within the monitoring zone.

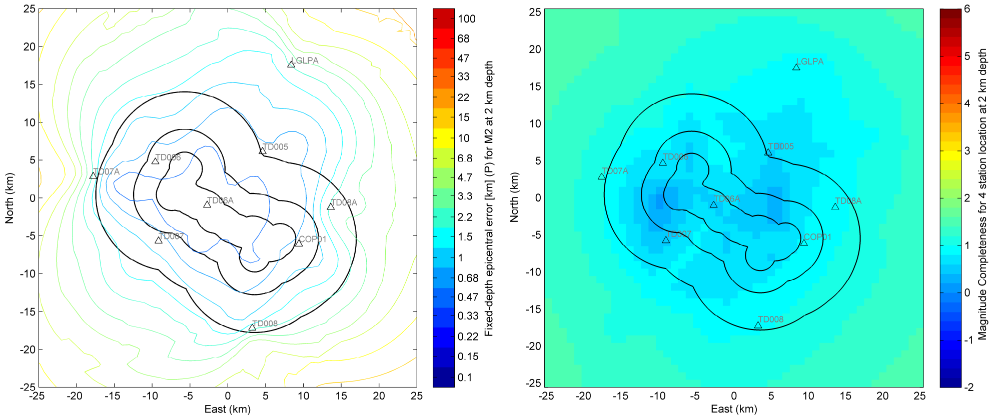

__Figure 2__ Location accuracy and four-station magnitude completeness for initial array

There are several reasons to wish to expand a network. Perhaps the network does not meet our current expectations, perhaps our expectations have changed, or perhaps increased redundancy is desired. Whatever the reason, there are three important factors to consider when selecting a site for expansion: azimuthal coverage, station density, and site noise.

Consider the effect of augmenting the existing network with three stations. We add the first station in the region of lowest site noise immediately to the north of TD006. A second station is added in a region of moderate noise to the southwest and a third to the southeast of the array. The revised network performance is plotted in Figure 3. The additions provide noticeable improvement especially near the edges of the array where previously the azimuthal coverage decayed quickly resulting in rapidly deteriorating location accuracy.

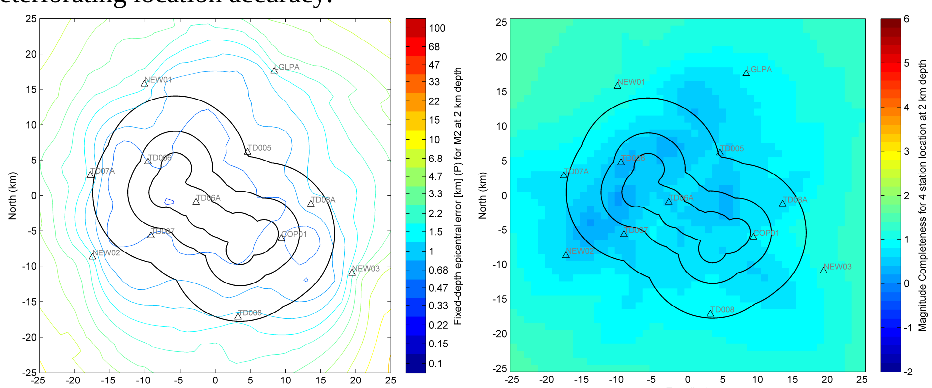

__Figure 3__ Location accuracy and four-station magnitude completeness for augmented array.

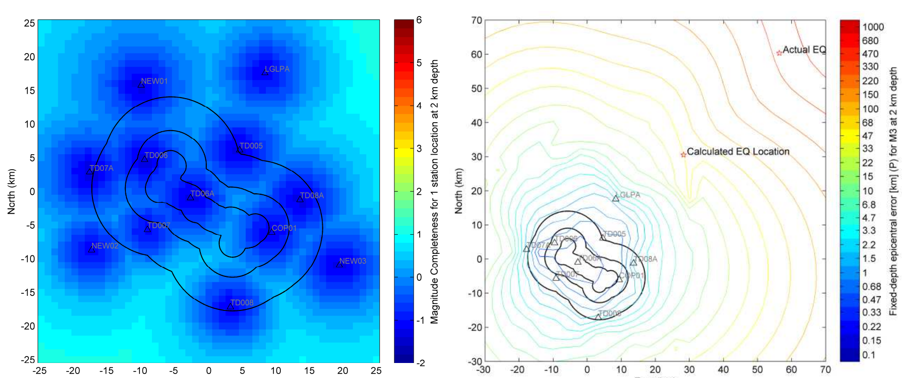

__Figure 4__ Left – Single-station magnitude of completeness for augmented array. Right – Comparison of an actual event location and predicted location for an explosion northeast of the network.

The effect of site noise on detectability is shown in the map of single-station magnitude of completeness in Figure 4. Each station has a circular feature around it corresponding to a radius of detection for a given magnitude. Consider a comparison of NEW01 (lower noise) and LGLPA (higher noise), the two northernmost stations: NEW01 has noticeably larger radii of detection in the magnitude range of 0.5 to 1. The new station thus improves network performance over a much larger area than LGLPA.

To date the only events that have been detected by the network are explosions at a mine about 80 km to the northeast. The magnitudes of these events are typically M1.5 to M2.5, and the locations are known precisely; one example is shown in Figure 4 (right). The expected location accuracy is approximately 350 km because the azimuthal coverage for an event so far outside the network is poor. The observed location error of 41 km is not unreasonable.

Conclusion

We have developed a method that can be used to estimate network performance without an earthquake catalogue. We compute the location accuracy and the magnitude of completeness from measured site noise, instrument characteristics and a one-dimensional velocity model. Addition of stations improves network performance more if they are added in areas with lower site noise. The ability to evaluate network performance accurately is essential to optimize station distribution in a seismic network and to ensure that traffic light protocol performance criteria are met.

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