



Passive Seismic Monitoring of Induced Seismicity Using Sparse Arrays of Broadband Seismometers

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Introduction

Government regulatory bodies and the public are increasingly concerned over induced and triggered seismicity associated with oil and gas recovery, hydraulic fracturing and also potential ground water contamination associated with these activities. In particular, the Alberta Energy Regulator (AER) recently issued Subsurface Order No. 2 stating that companies operating in the Duvernay Formation will have to follow a traffic light scheme that will require AER notification for seismic events of magnitude 2 or greater and cease operation for events greater than magnitude 4. The BC Oil and Gas Commission has also introduced similar measures.

Here we present a strategy for station design and deployment, real-time monitoring and data analysis and subsequent interpretation of the results. The presentation mostly focuses on the deployment and acquisition process.

Alberta Energy Regulator (AER) Subsurface Order Number 2 (SO2)

Given recent changes imposed by the Alberta Energy Regulator (AER - <http://www.aer.ca/documents/orders/subsurface-orders/SO2.pdf>), industry has had to enhanced their Induced Seismic Monitoring (ISM).

Subsurface Order Number 2 (SO2) specifically addresses monitoring hydraulic fracturing (frac) in the Duvernay area but it will only be a short while before this is mandated province wide and most likely country wide (such mechanisms are already in place in the UK). Our approach to monitoring such induced seismicity utilises four to five broadband seismometers, similar to those used in traditional earthquake seismology. SO2 requires the operator to monitor the area near a proposed frac before, during and after the stimulation. This allows the operator to first establish the background or native-state seismicity. The traffic light regulations can be then monitored during the frac and in real time measure the induced seismicity: a green light is the state where the magnitude of the seismicity is below M2 and frac operations continue as normal; between M2 and M4 the operator is required to immediately report to the AER and to invoke a response plan; events greater than M4 require the operators to cease hydraulic fracture operations. In cases where M4 or greater events are detected, the licensee will not be permitted to resume operations without AER consent. The final phase is passive monitoring after the frac since some induced seismicity has been observed after the active frac has taken place. It may also be suggested or mandated that these regions be monitored for induced seismicity through period of production and wastewater injection.

Broadband Seismometer Array Deployment

Remote seismometers have been used for earthquake detection for decades. Early models would have had various recording media including pen on paper drum recorders, tapes (including Sony Walkman's) and now flash memory and real-time data streaming. Seismometers have improved dramatically in the past 20 years, with increasingly broadband response and low power consumption. GPS timing, high capacity data storage and the ability to interrogate systems for state-of-health and data recovery using wireless technology have allowed deployments in remote parts of the world with minimal on-site servicing.

The system requires power that is typically provided by solar panels and batteries, a sensor that is typically a 3-component broadband seismometer and a recording unit with GPS and a modem (Figure 1). See Horeleston et al. (2013) for a description of passive seismic monitoring using broadband seismometers in an oil and gas setting.



Courtesy Bristol University

Figure 1: A typical remote earthquake monitoring station showing solar panel power, batteries, GPS, cell modem, data recorder and broadband seismometer (from Bastow et al., 2013).

The Importance of Broadband Instrumentation

For the monitoring of induced seismicity, it is essential that broadband instruments be used, rather than geophones. Traffic-light schemes require that the magnitudes of events be accurately determined. To do this, the full frequency response of the signal must be captured. For larger events, the corner frequency falls below the low-frequency cut-off of standard 15Hz or 4.5Hz geophones, with the result that magnitude will be systematically underestimated (Figure 2). In contrast, where a broadband instrument is used the full response is captured, and the magnitude computed accurately.

Figure 3 shows an example of this effect in practice (Viegas et al., 2012). The same event is recorded by 15Hz and 4.5Hz phones, as well as a broadband instrument. The true magnitude of the event, as recorded by the broadband instrument, is 1.8, while the estimates provided by the 15Hz and 4.5Hz events are 1.2 and 1.5, respectively.

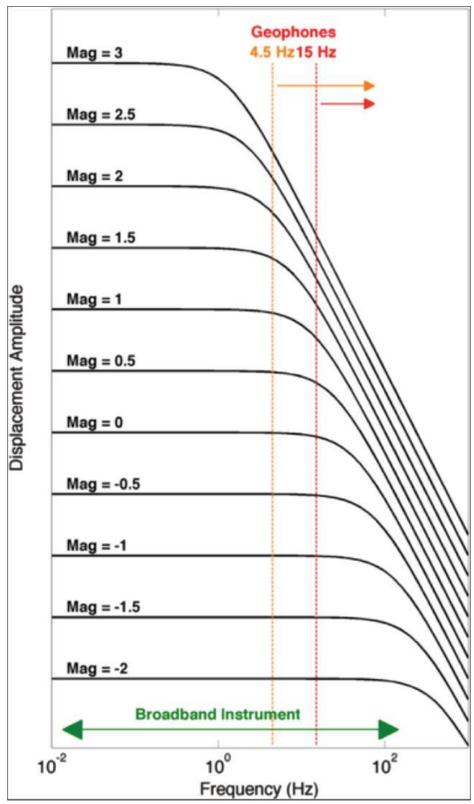


Figure 2: Expected displacement spectra for events of different magnitude. A low frequency plateau is followed by a corner frequency, after which displacement drops away. This corner must be accurately measured to generate robust magnitude estimates. 15Hz and/or 4.5Hz geophones do not accurately record corner frequencies for larger events, leading to systematic magnitude underestimates. A broadband instrument is required to record event magnitudes accurately.

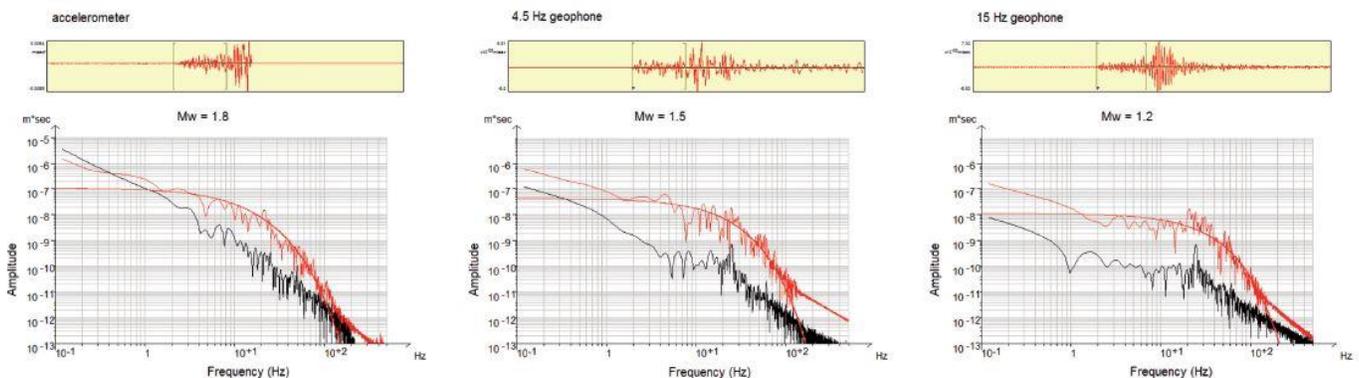


Figure 3: Waveforms (top) and displacement spectra (bottom) for the same event recorded on 3 different sensors: an accelerometer with broadband response (left), a 4.5Hz geophone (middle) and a 15Hz geophone (right). The broadband sensor accurately measures a magnitude of 1.8 while the 4.5 and 15Hz phones measure 1.5 and 1.2 respectively (Viegas et al., 2012).

Data Processing

Data from the stations are streamed in real time to the Network Acquisition Module (NAM) based in Calgary. Once collected, the data is processed in two streams: real-time, and 24hr reports.

Real Time

An automated triggering algorithm is used to process the data in real time. This uses as its threshold the expected ground motion for event magnitudes relevant to the BCOGC regulations ($M_L = 2.0$ for notification, $M_L = 4.0$ for suspension of operations). These ground motion values are computed using the standard Nuttli (1973) local magnitude scale, which is used as standard in areas east of the Rocky Mountains:

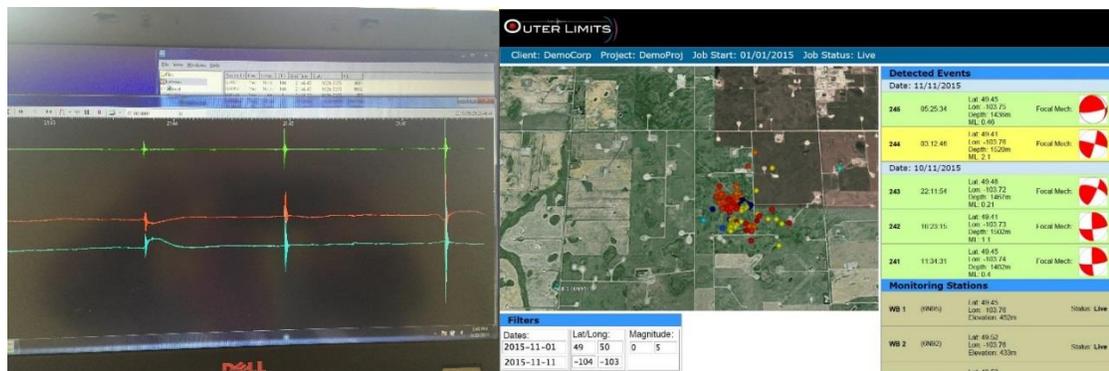
$$M_L = 3.3 + 1.66 \log_{10}(D) + \log_{10}(A/T),$$

where D is the epicentral distance (in degrees), A is the recorded amplitude (in micrometres), and T is the period of the arrival. For events that exceed the BCOGC limits, an automated alert is used to notify the operator within minutes of event detection. See Stork et al. (2014) for a more thorough discussion of the challenges in calculating accurate seismic magnitudes.

The magnitudes provided by the automated system are sufficiently accurate for regulatory reporting processes. However, in addition, any events detected by the automated trigger system will be re-processed, with updated locations and magnitude provided within 24h. A web-portal provides real-time streaming of the incoming data (Figure 4a).

24hr Reports

In addition, every 24hrs the recorded data are downloaded and re-processed, even where no events have been detected by the automated trigger system. This will allow smaller events, below the BCOGC thresholds, to be detected and located. These smaller events may allow the operator to adjust their injection practices to mitigate induced seismicity if events close to (but below) the thresholds are being detected, or to increase injection rates/pressures if no events are detected. All events detected and located are provided in a daily report. A web-portal, updated every 24h, provides maps of event locations (Figure 4b). Locations of smaller events may also be used to identify faults that the operator may wish to avoid during future operations, and to aid in geomechanical interpretations of the area (determining stress orientations, for example).



Figures 4a and 4b: Real-time streaming of waveform data through a web portal (left), and a daily report of all events detected provided every 24 hours (right).

Data Example

Figure 5 shows a real data example. The trace data are shown on the left and the magnitudes and locations are shown in the centre and right respectively. These events can be picked automatically and notifications sent in almost real-time. The final and more accurate results are picked and processed by an on-call seismologist.

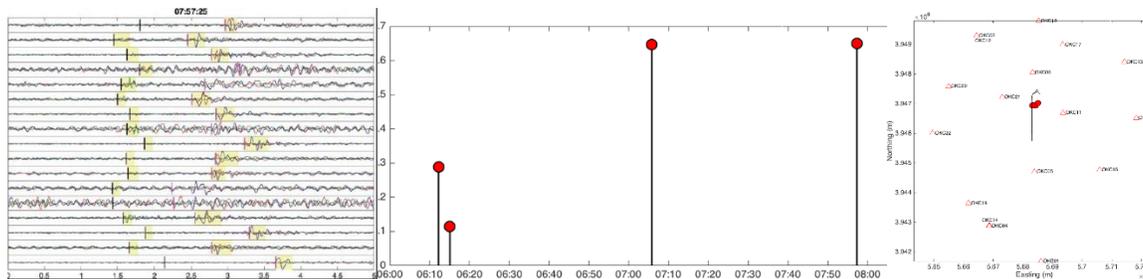


Figure 5: Figure 5 shows a real data example

Conclusions

Induced Seismicity Monitoring (ISM) is an emerging issue within the Canadian oil patch and, in particular, within the Fox Creek and Duvernay area. Transparency in the reporting and detection methods and techniques will be important in establishing a level playing field for the Fox Creek Operators and potentially elsewhere in Canada. Furthermore, real-time monitoring and reporting is an essential aspect of the industry's community involvement and Health Safety and the Environment (HSE).

References

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