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Bayesian Seismoacoustic Source Location: Acoustic Approach

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Introduction

Seismic waves and infrasound are key technologies in the International Monitoring System (IMS) to monitor explosive events in the solid Earth and atmosphere. Energetic man-made or natural events (e.g., chemical/nuclear explosions, volcanic eruptions, and earthquakes) near the Earth's surface produce both ground motion and atmospheric pressure disturbances which propagate as seismic waves and infrasound, respectively. Seismic waves have been generally used to detect and identify underground and near-surface events (Myers, et. al., 2007), and infrasound are sensitive to events near the surface or in the atmosphere (Modrak et. al., 2010). Due to their different sensitivities to events, they can complement to each other to improve the event detection and discrimination. The framework of joint seismoacoustic event location has recently reviewed by theoretical research (Koch and Arrowsmith, 2019). Although the early applications showed promising results to improve the accuracy of event location, their application were still limited to a small set of events selected to prove the concepts, and practical capability of the method for operational purpose is not fully evaluated with data. Our final goal is to apply the method of seismoacoustic event location to a larger set of events and evaluate its applicability for operational event location in practice. To that end, we focus on developing and verifying acoustic source location method in this study.

Dataset

We use the seismic and acoustic waveform data associated with the 2018 Dynamic Network Experiment, hereafter called DNE18. The primary purpose of DNE18 was to provide data to quantitatively evaluate the effectiveness of geophysical technologies and algorithms for meeting the goal of the Low Yield Nuclear Monitoring (LYNM). This is well aligned with our study to evaluate the capability of seismoacoustic event location for the monitoring purpose. The DNE18 includes seismic, infrasound, electromagnetic (EM), and radionuclide (RN) from December 2010 through February 2011. These data are curated and/or created from publicly available data repositories. DNE18 seismic and acoustic (infrasound) data are mainly collected from the state of Utah. Utah has a dense seismic network (182 stations) whose data is publicly available through the Incorporated Research Institution of Seismology Data Management Center (IRIS DMC). In addition, infrasound data from six temporary infrasound arrays are available from the same period. To promote the comparison of testing algorithms, seismic catalogs (with a limited number of associated infrasound detection) were built for DNE18, which includes a high-resolution analyst seismic event catalog (January 1-14, 2011), the University of Utah (UU) event catalog (1981-2017), the UU non-earthquake catalog (December 2010-February 2011), labeled event catalog (July 2008 – June 2016), and a list of all known mines in the states of Utah. In this study, we use 82 seismoacoustic events observed both in seismic and acoustic stations of DNE18. The seismoacoustic event catalog will be compared with the results of event location by using seismic and acoustic analysis.

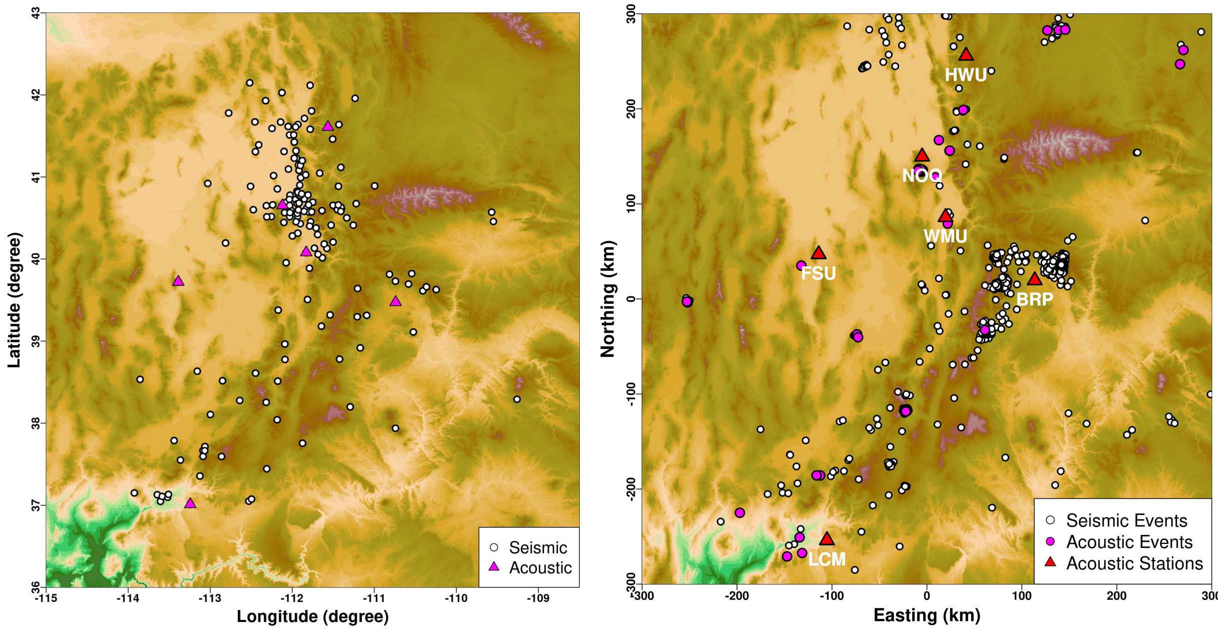

Figure 1. Seismoacoustic stations in DNE18 (left) consisting of 182 seismic stations and 6 infrasound arrays. Regional seismoacoustic events detected by both seismic and infrasound sensors (right).

Seismoacoustic Event Location Framework

This section explains the seismoacoustic event localization framework. We use a Bayesian approach to event localization with seismic and acoustic signals. The likelihood function (L) of the observed acoustic arrival time and azimuth observations depending on source location can be defined by a product of independent seismic (Ls) and acoustic (La) likelihoods as

$$L(\phi, T|x, y, z, t_0) = L_s(x, y, z, t_0) * L_a(\phi, T \vee x, y, z, t_0). \qquad (1)$$

Back-azimuth direction (ϕ) and arrival time (T) information obtained by array processing are used to determine the acoustic likelihood which can be readily combined with the seismic likelihood (Myers et al., 2007, Modrak et al., 2010). In the Bayesian framework, the posterior probability of the model parameters (x, y, z, t_0) can be written as a product of the likelihood function and the priori source location information $p(x, y, z, t)$,

$$p(x, y, z, t_0 \vee \phi, T) = L(\phi, T|x, y, z, t_0)p(x, y, z, t_0). \qquad (2)$$

Figure 2 illustrates the joint likelihood in Equation 1 assuming that the source is at the surface and the origin time is known as a prior.

The accuracy of source localization in Equation 1 depends on the back-azimuth and travel time misfit between the observation and prediction. If we assume the normal distribution for the parameters, the confidence of the estimated model is solely determined by the variances of back-azimuth and travel time misfit. However, the misfit variances of back-azimuth and arrival time are often poorly understood for acoustic source localization, and it is difficult to determine their true variances with limited events and data. In this study, we will examine the back-azimuth and travel time misfits for ground-truth events and evaluate their variability and impact on the accuracy of acoustic source location. We will also compare the acoustic likelihood function with the seismic likelihood and evaluate the improvement on accuracy by combining two likelihoods.

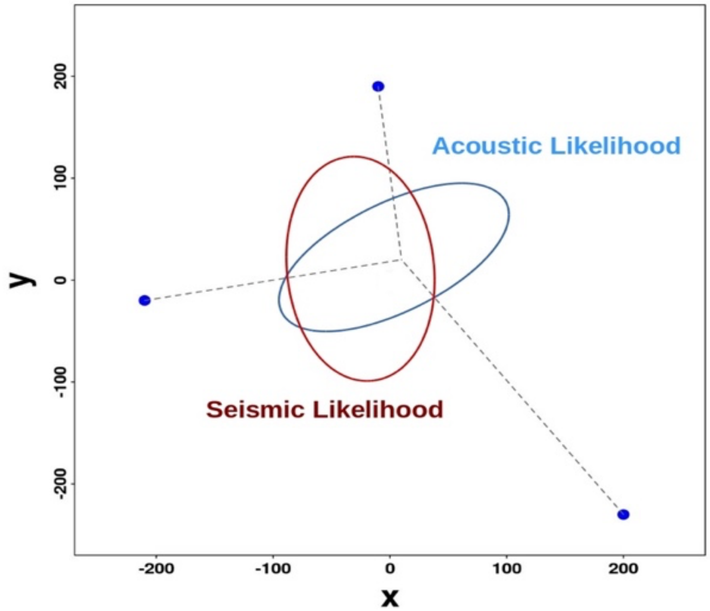

Figure 2. Illustrative figure for the combined likelihood function for source localization. The red and blue ellipses indicate seismic and acoustic likelihood in Equation 1, respectively. The acoustic likelihood is obtained by the back-azimuth and arrival time information at each station (blue circles).

Acoustic Likelihood

The acoustic likelihood in Equation (1) is defined as a product of back-azimuth and travel time components over all arrays as

$$p(x,y,z,T) = \prod_i^n \Theta(\theta|x,y,z)\Phi(A|x,y,z,T), \quad \text{Equation (3)}$$

$$\Theta(\theta|x,y,z) = \frac{1}{\sqrt{2\pi\delta^2{}_\theta}}\exp\left[-\frac{1}{2}\frac{\left(\theta_i-\theta_i^0\right)^2}{\delta^2{}_\theta}\right], \quad \text{Equation (4)}$$

$$\Phi(A|x,y,z,T) = \frac{1}{\sqrt{2\pi\delta^2{}_\Phi}}\exp\left[-\frac{1}{2}\frac{\left(A_i-A_i^0\right)^2}{\delta^2{}_\Phi}\right]. \quad \text{Equation (5)}$$

For a station i, the functions $\Theta(\theta|x,y,z)$ represents the probability of back-azimuths. The probability is determined based on the difference of predicted back-azimuth at given source location (x, y, z) and measured back-azimuth (θ_i^0) in Equation (4). The $\Phi(A|x,y,z,T)$ function is another indicator of source location affected by travel time information (T). We used the method of reverse time migration (RTM) to measure the likelihood of source location. This method is often called the back projection in seismology or time reversal in acoustics. RTM method is basically a beamforming technique. Infrasound signals recorded on stations are stacked after time-shift by the travel time prediction at a given source location. If the travel time prediction is accurate, all infrasound signals are aligned in phase, increasing the stacked infrasound energy (Walkers et al., 2011). We define the probability of RTM source location by the difference between the RTM values and its maximum across the searching domain. In this study the uncertainties of back-azimuth (δ_θ)and RTM location (δ_Φ) is assumed as 10 degree and a half of the RTM maximum value.

Discussion and Further Study

The acoustic method is verified by applying to a single event in DNE18. Figure 3 shows infrasound signals recorded by 4 arrays and back-azimuth beamforming processes. The recorded infrasound signals are characterized by distinctive multiple arrivals which can be multiple propagation paths or multiple sources. The back-azimuth measurements are consistent across the arrays.

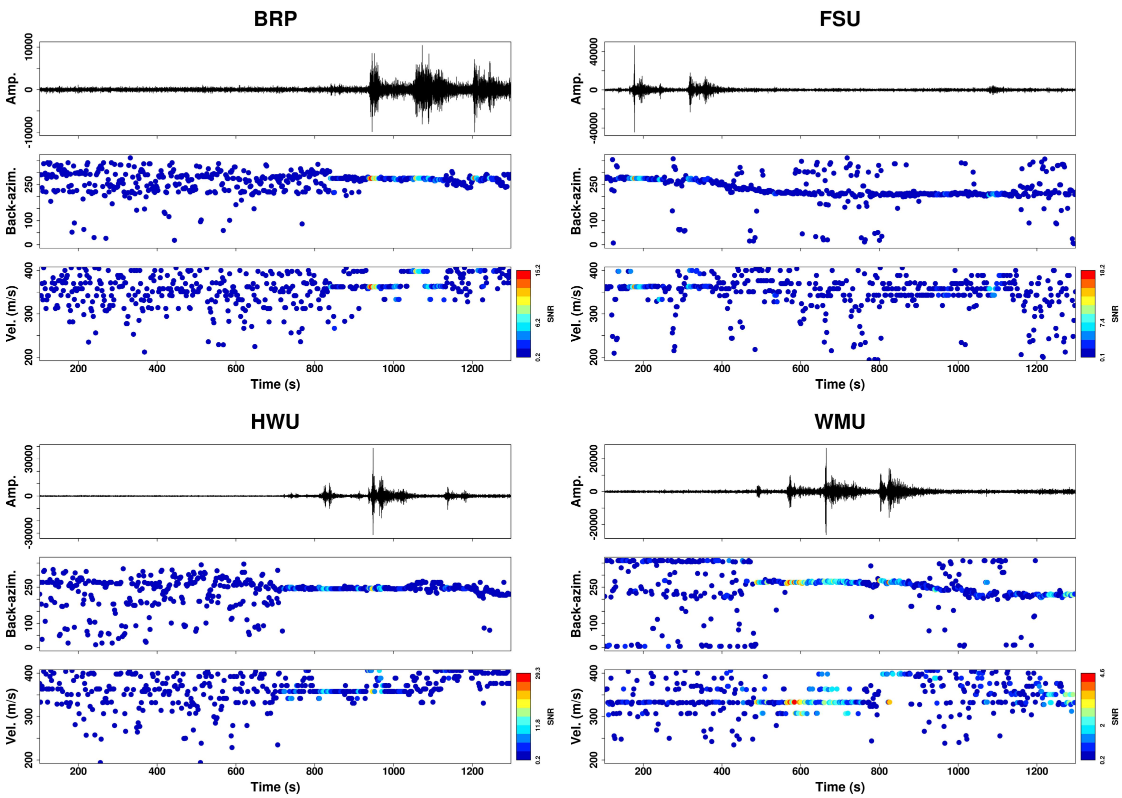

Figure 3. Acoustic back-azimuth determination based on array beamforming for 4 infrasound stations. Each subfigures include infrasound signal (top), back-azimuth estimation by beamforming (middle), and phase velocity (bottom) across the array.

Figure 4 shows the result of event location. The top panel focuses on the comparison between the RTM results and back-azimuth directions from each array. The RTM image was created with a constant sound speed of 320 m/s which corresponds to the speed of stratospheric and shows the highest RTM amplitudes. Note that all back-azimuths from the 4 arrays point to consistent source locations, but the RMT image shows possibly two different sources. As shown in the infrasound signals in Figure 3, two source locations are the result of the observed multiple arrivals. However, it is not clear whether these are the multipath arrivals of the same source or two different events. Numerical modeling with meteorological conditions may help to distinguish them. The event location from the DNE18 catalog (determined by seismic signals) is slightly out of the back-azimuth paths but shows good agreement with the RTM image. According to the RTM and seismic location, the source at the cataloged location might be larger than the other multiple, but the back-azimuth method could not distinguish them. However, the RTM uses all waveform information including travel time and resolve two possible locations. Therefore, including both the RTM and back-azimuth information can improve the source location accuracy.

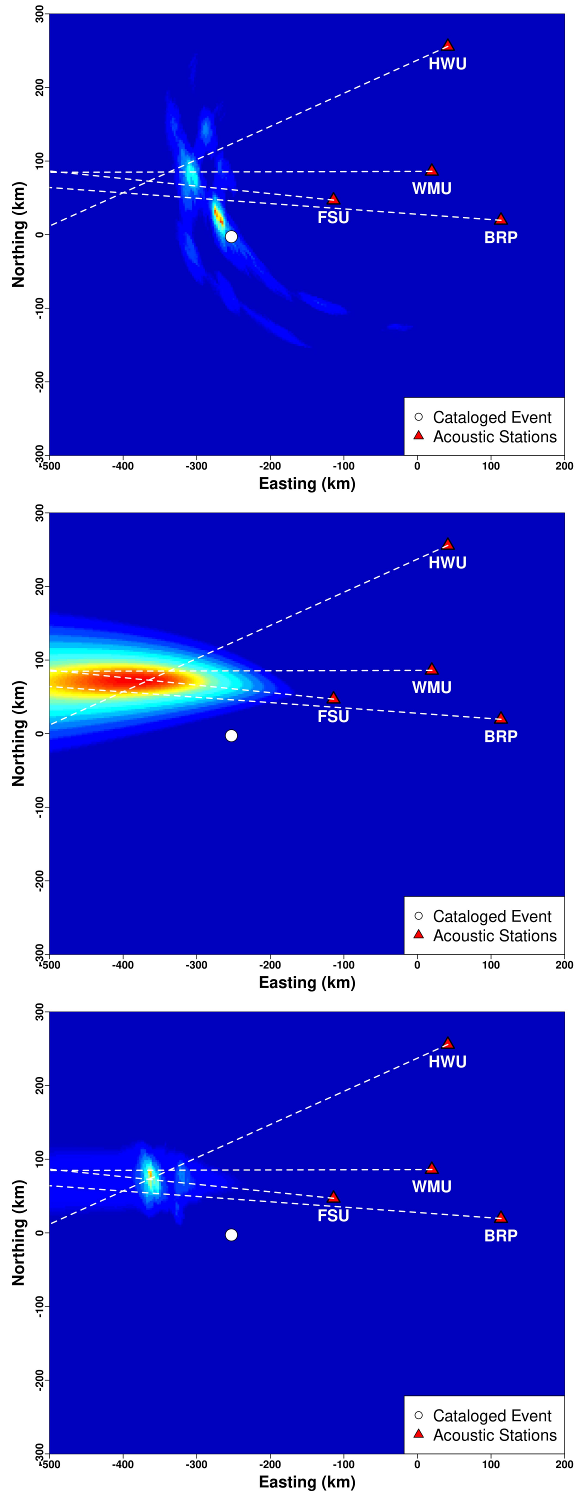

Figure 4. Acoustic event location results. The RTM back-projection result is compared with the back-azimuth measurements for 4 arrays (top). The resultant likelihood for the back-azimuth (middle) and the joint likelihood of back-azimuth and RTM (bottom) are displayed.

In this research, we defined the seismoacoustic event location framework and refined the acoustic location method by using both back-azimuths and RTM information. An application to a cataloged DNE18 event demonstrated its capability to resolve multiple arrivals and constrain source location. Further research including acoustic source location for all DNE18 seismoacoustic events and comparison with seismic source location is underway and will be reported in the next fiscal year.

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