Maximizing seismic and aseismic deformation detection.

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Induced seismicity has gained attention due to increasing well stimulation projects like CCS, geothermal, and unconventional oil and gas. Detecting low-magnitude earthquakes is critical for safety, but challenges arise from array geometry limitations and ambient noise (e.g., roads, weather). Machine Learning (ML/DL) algorithms have significantly improved detection thresholds, but optimizing seismic arrays remains a key challenge. We developed a probabilistic method using numerical modeling to evaluate wave attenuation and identify high-sensitivity areas. Our algorithm generates optimal array configurations, balancing detection capabilities with environmental constraints. The best designs minimize the magnitude threshold to detect an event from a minimum number of 5 stations.

1. Magnitude Sensitivity

Detecting low-magnitude events requires high-resolution networks, yet challenges such as array geometry limitations and ambient noise persist. Studies by Meng & Ben-Zion (2018), and Schorlemmer & Woessner (2008) highlight the importance of network density and sensitivity. Existing deterministic methods for evaluating network detectability are often proprietary (e.g., De Landro et. al., 2020 and Nanjo et. al., 2010). This study introduces a probabilistic approach for optimizing seismic network design, considering high-risk seismicity zones, access constraints, and topography. For each input design, we calculate the moment magnitude (Mw) at each grid point and each station. The parameters used for the calculations are the wave velocity, the attenuation of the medium and the distance between stations and event. The process can run either as deterministic approach to test the capabilities of an array design or as probabilistic to create a new array and optimize the geometry to reach a minimum magnitude threshold.

2. Example study for magnitude sensitivity and array design

The following graph describes the process of magnitude and array design optimization: 1) The first step is identifying areas to avoid, such as physical boundaries (e.g., coastlines) or regions with high environmental noise (e.g., busy roads).2) Then we set up the areas we want to have lower magnitude detection threshold (e.g. injection wells and nearby active faults) and assigning higher weigh on those areas. 3)The algorithm designs an array based on the map with the weights from the previous step making the network denser in the areas with higher weight. It then calculates the magnitude sensitivity for the designed array geometry. 4) The initial array is modified and recalculating the new magnitude sensitivity. This process is iterated until the optimal design achieves the minimum magnitude threshold within the area of interest.

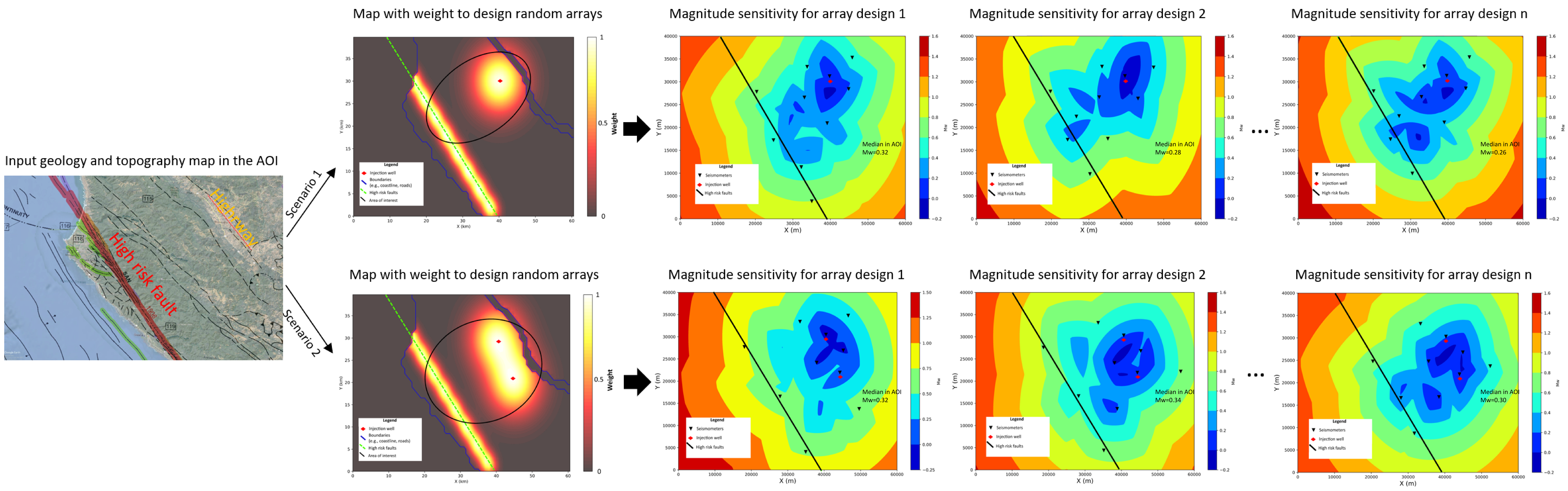
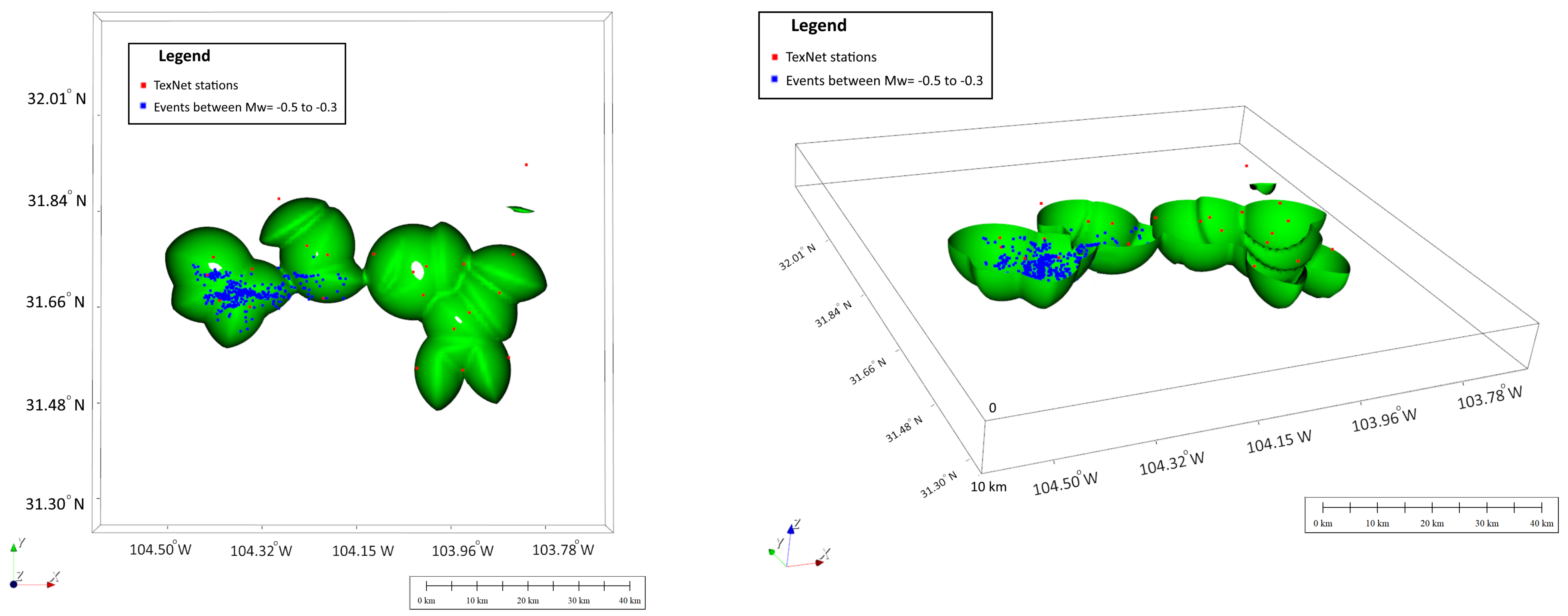


Figure 1. Example of the methodology for optimizing the array design for a hypothetical scenario of monitoring well injection near an active fault. In both scenarios we are using 10 stations and set up a minimum of 5 station picks as a detection criteria and we run the simulations for depths between 0-1 km. From left to right: 1) The topography and fault map to consider. 2) Based on the map from the previous step we design the color scale maps with the weights represents the areas with higher risk for seismicity (yellow areas) such as the fault and the injection wells, the blue lines are the boundaries of masked areas for which we cannot install any stations (e.g. coastline and noisy road) 3), the black line is the area we want to reach the minimum Magnitude by optimizing the array geometry. 3) The colored maps with magnitude sensitivity results. The areas with the dark blue color means for example that if an event of Mw=-0.2 and depth of up to 1km takes place inside that area, it will be detected by at least 5 stations of the presented array geometry. We are testing 2 scenarios. The first scenario has one injection well and an active fault, as the optimization iterates several times the median magnitude inside the area of interest (AOI) drops from 0.32 to 0.26. The second scenario has two injection wells and one active fault, since the AOI is bigger for the same number of stations the minimum Mw is larger compared to the first scenario and during the optimizing process drops to 0.30.

3. Magnitude sensitivity on existing network and validation



To validate our method we perform a magnitude sensitivity test on an existing network. Specifically, we use the TexNet seismic monitoring network in Northwest Texas, within the Delaware Basin. A previous study in this area has dropped the Mc to 0.5 by using ML method EQCCT (Saad et. al., 2023). The area has 21 permanent seismometers. We use minimum 5 stations picks and run the Magnitude sensitivity for depths up to 10 km. We then plot the detected events within the magnitude iso-surface volume to validate that events of equivalent magnitude fall within this region.

Figure 2. 2D top view (left) and 3D perspective (right) of the iso-surface for Mw=-0.5 to -0.3 (green area), showing station locations from the existing seismic network in Northwest Texas (red dots). Detected seismic events with equivalent magnitudes, identified using the EQCCT method, fall within the modeled sensitivity volume.

Conclusions

- We demonstrated that strategic array configurations can significantly lower the minimum detectable magnitude, even in geologically complex and noise-prone environments.
- Optimized array geometries with denser station placement near high-risk areas substantially improve the network's sensitivity, enabling the detection of events with magnitudes as low as Mw = -0.26.
- Validation using real-world data, such as the TexNet seismic network in the Delaware Basin, confirms the effectiveness of our approach.
- Our methodology offers flexibility for both designing new seismic networks and evaluating the performance of existing ones.
- The ability to adapt the framework to different geological settings and operational constraints makes it a valuable tool for seismic hazard assessment and risk mitigation.

References

- De Landro, G., Stabile, T., and Zollo, A. (2020). Optimizing seismic network design for induced seismicity monitoring in geothermal areas. Geothermics, 88:101871.
- Meng, H. and Ben-Zion, Y. (2018). Detection capability of dense seismic arrays: Application to the san jacinto fault zone. Geophysical Journal International, 213(3):1878–1891.
- Nanjo, K., Hirata, N., and Obara, K. (2010). Spatial and temporal variations in the magnitude of completeness in the swiss seismic network. Seismological Research Letters, 81(5):707–715.
- Schorlemmer, D. and Woessner, J. (2008). Probability-based magnitude of completeness determination. Bulletin of the Seismological Society of America, 98(4):2103–2117.
- O. M. Saad et al., "EQCCT: A Production-Ready Earthquake Detection and Phase-Picking Method Using the Compact Convolutional Transformer," in IEEE Transactions on Geoscience and Remote Sensing, vol. 61, pp. 1-15, 2023, Art no. 4507015, doi: 10.1109/TGRS.2023.3319440.