Machine Learning for earthquake detection in Oklahoma

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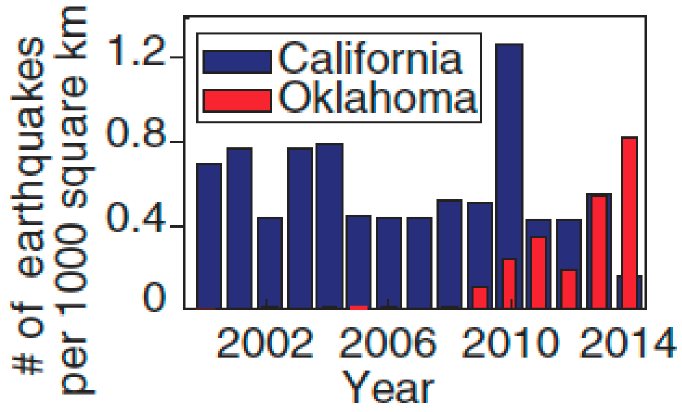
Oklahoma Seismicity

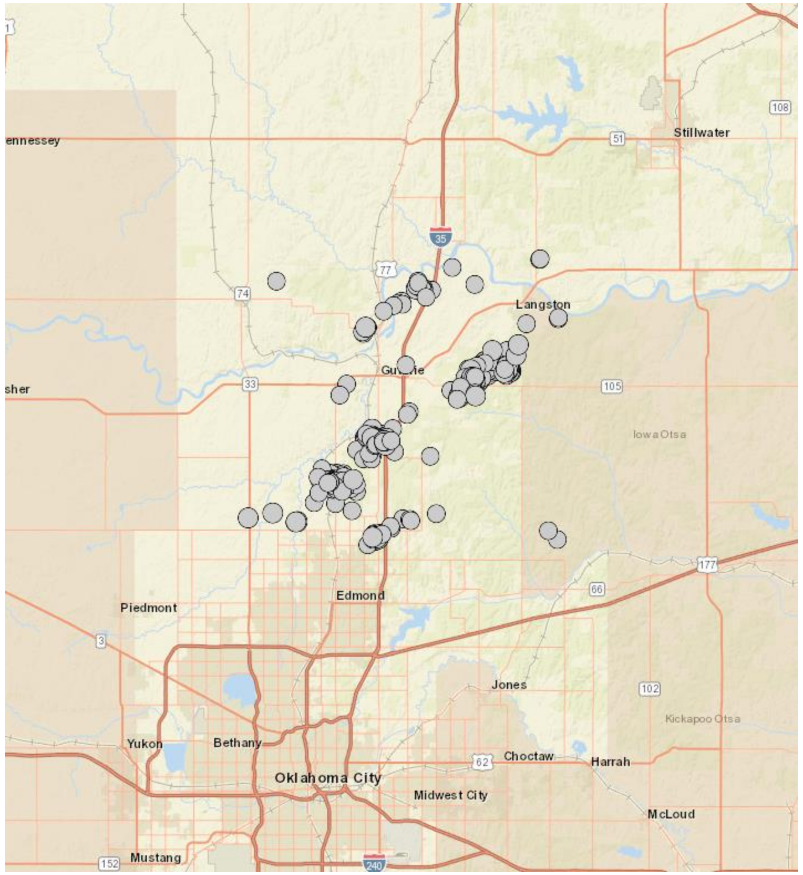
- The seismicity was low in Oklahoma region, because it is in the middle of the north America Plate
- Recent waste water injection in the ground has increased the seismicity
- Seismicity in Oklahoma contributes to 45% of magnitude 3 and larger earthquake in central US between 2008 and 2013



Earthquake Numbers(Keranen et al., 2014)

Oklahoma Seismicity

- Nine earthquakes with magnitude larger than 5 have happened between 2008 and 2017.
- A complete earthquake catalog can help understand the mechanics of earthquake in the region and estimate the earthquake possibility in the future.
- A complete catalog is important information for engineering and mitigate disaster.



Earthquake in Oklahoma region in 2014. There were about 300 events.(From USGS)

Methods for earthquake detection

- Traditional method: STA/LTA method based on ratio of short to long term energy density. Difficult to detect small events
- Waveform correlation method
  - use the similarity between different waveforms from the same region. It is capable of detecting event of similar source mechanism
  - Computationally expensive
- FAST(Fingerprint And Similarity Thresholding) method: reduce the similarity search through locality-sensitive hashing.
- ConvNetQuake: use classification method to detect and locate events

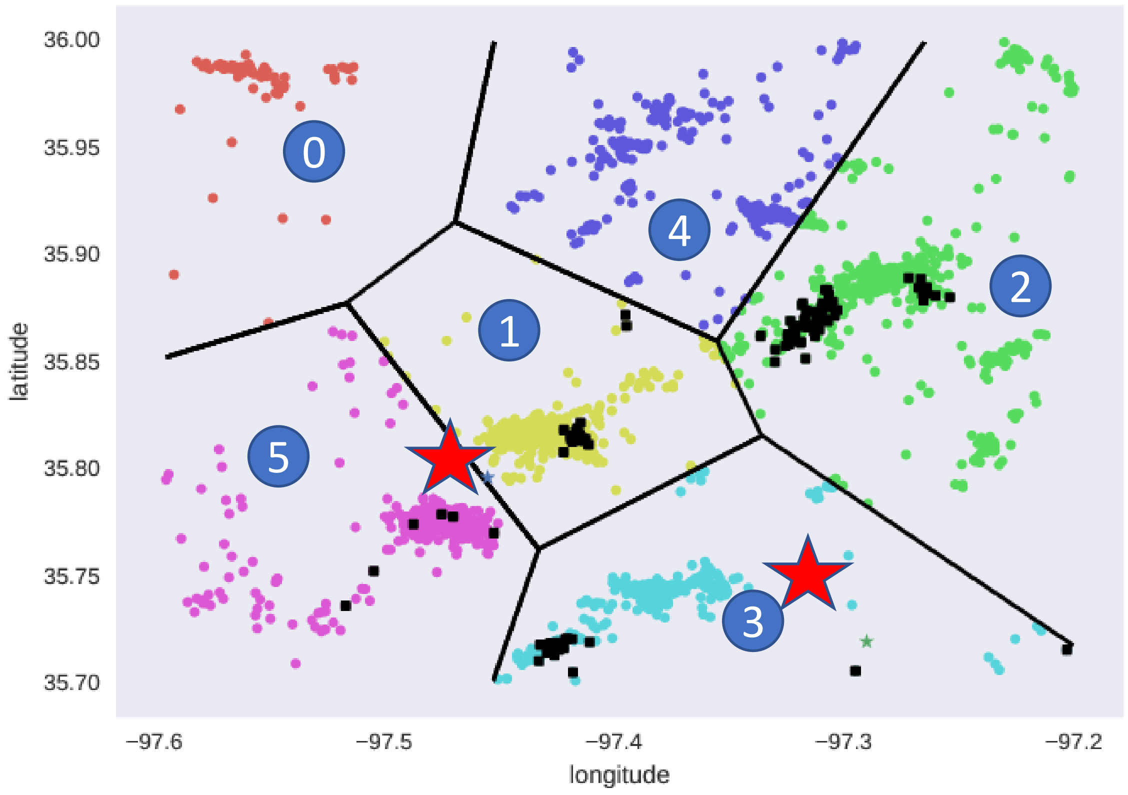
Neural Network in earthquake detection

- Perol et al: 8 convolutional and one fully connected layers, able to detection events with 95% accuracy in the Oklahoma region
- Wu et al: 7 fully connected layers. It is able todetection earthquake in Laboratory
- Ross et al: use 4 layer convolutional and 2 fully connected layers. The model is able to detected new event with different waveforms
- Mousavi et al: one very-deep encoder and three separate encoders. The model detected two times more earthquake during 2000 Tottori earthquake in Japan

Data

- Data source: Oklahoma seismic waveform data in monthly stream.
- We normalize each stream and extract 10-second-long windows.
- Two types of windows: windows containing events and windows containing only noise.
- The test set contains all the windows for July 2014 (209 events and 131,072 windows of noise).
  The training set contains the remaining windows from Feb 2014 to Nov 2016 (2709 events and 700,039 noise windows).
- Our goal is to predict each window's label either as seismic noise or event with its geometrical cluster.

-1 : seismic noise without any Earthquakes

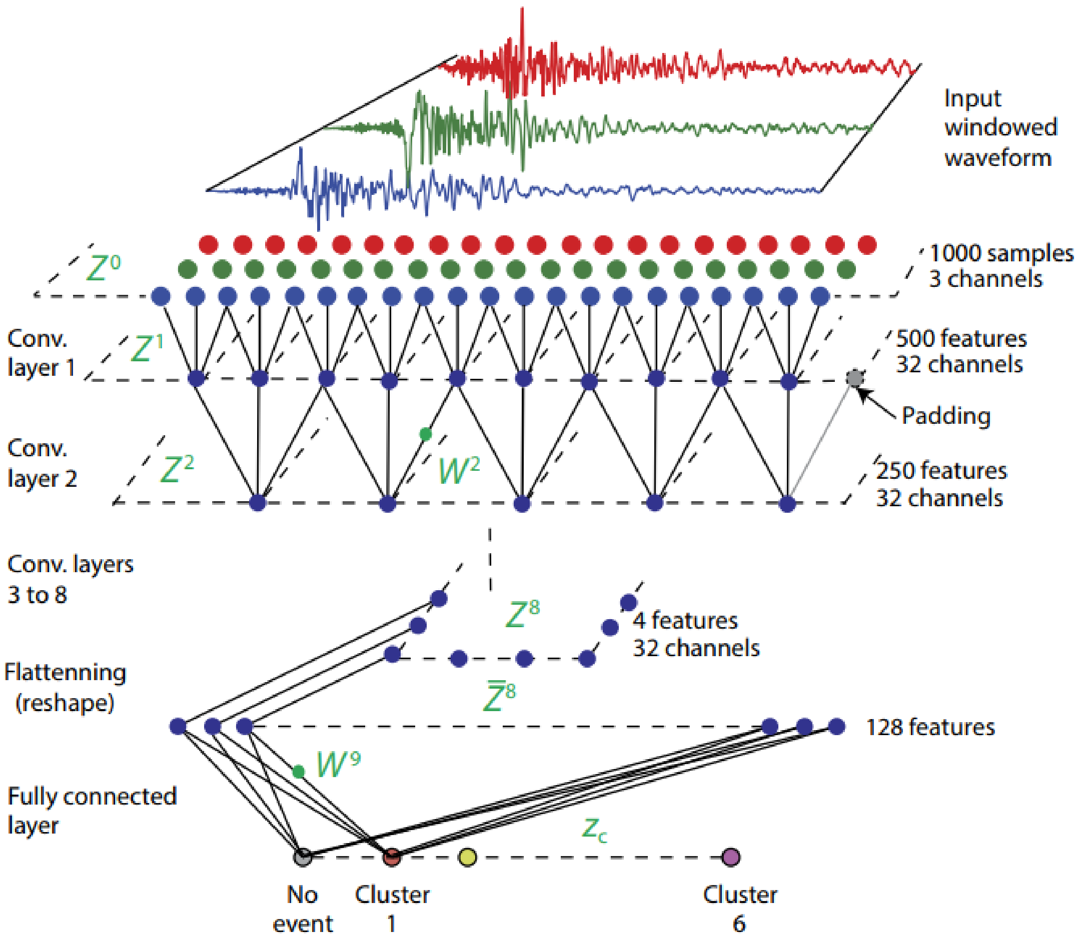


Stars denote two seismic stations
Black squares are the testing events (July 2014)

Neural network set up

- We use ConvNetQuake, an open-source CNN code in tensorflow, for earthquake detection and location.
- Input: windowed three-channel waveform.
- Convolutional layers with ReLU activation function.
- Output: softmax function to obtain probability of each class.

ConvNetQuake architecture



Perol, Thibaut, Michaël Gharbi, and Marine Denolle. "Convolutional neural network for earthquake detection and location." Science Advances 4.2 (2018): e1700578.

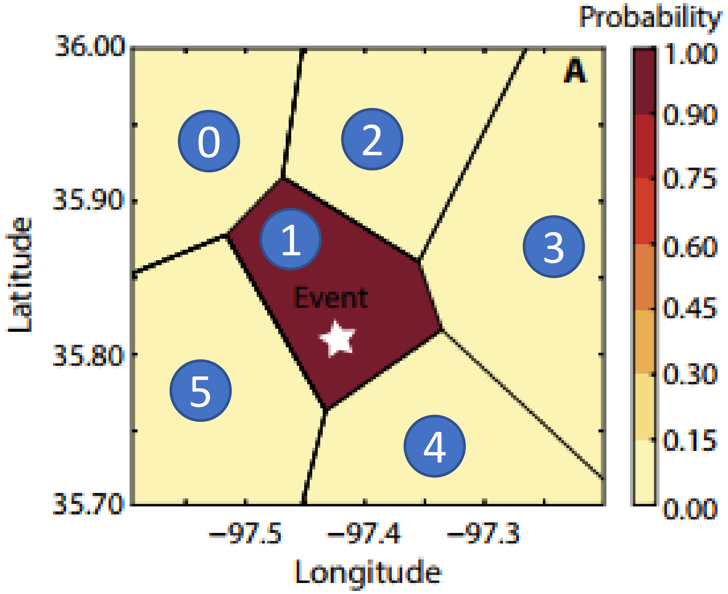
Neural network set up

Loss function: Cross-entropy loss function with L2 regularization

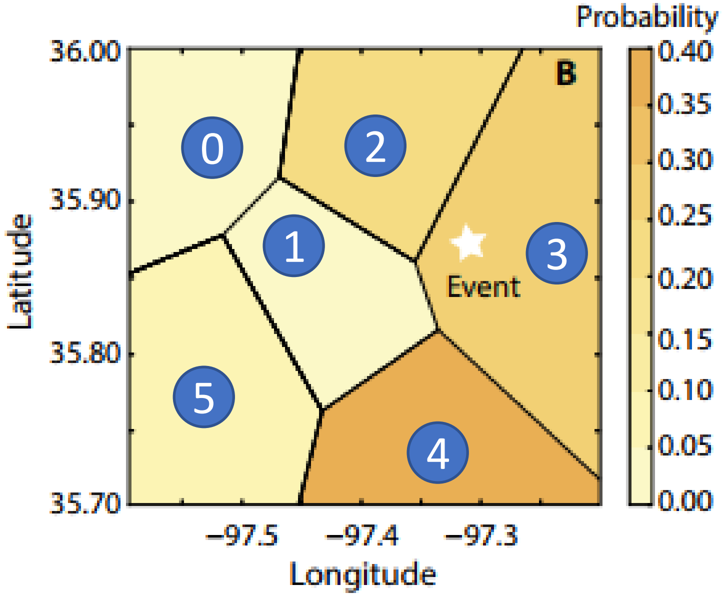
$$\mathcal{L} = \frac{1}{N}\sum_{k=1}^{N}\sum_{c=0}^{M-1} q_c^{(k)} \log(p_c^{(k)}) + \lambda \sum_{i=1}^{9} \| W^i \|_2^2$$

Optimization: ADAM

Probabilistic location map example



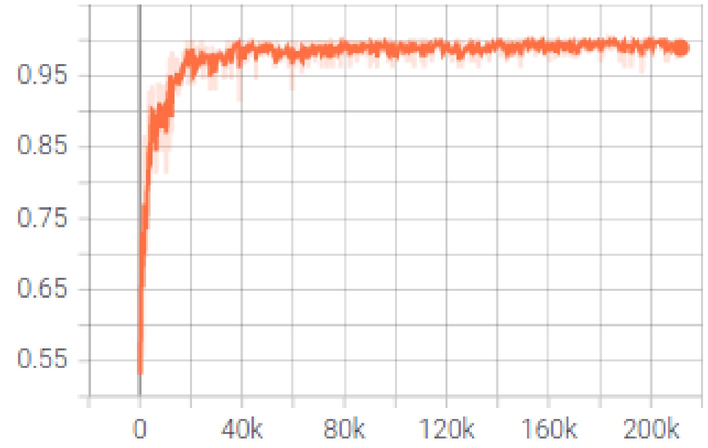
Correctly detected
Correctly located



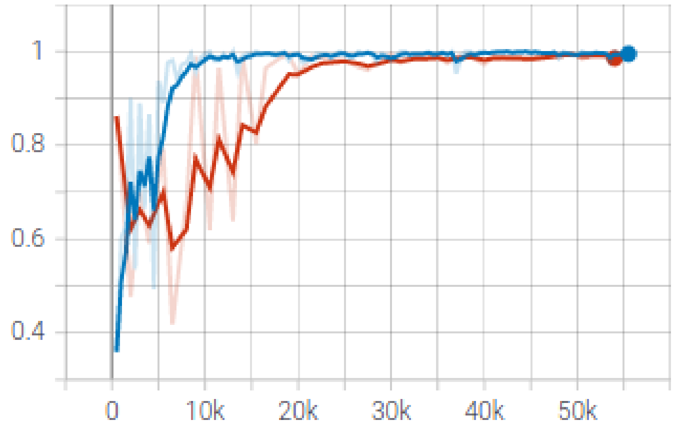
Correctly detected
Incorrectly located

Training accuracies

accuracy/detection_accuracy/train
tag: accuracy/detection_accuracy/train



detection_accuracy/val
tag: detection_accuracy/val



accuracy/localization_accuracy/train
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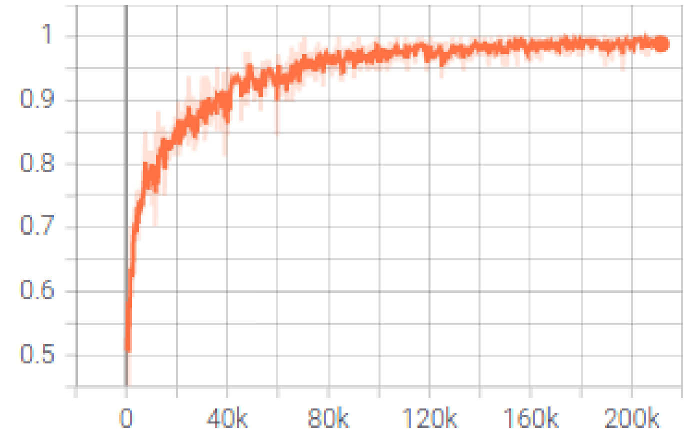
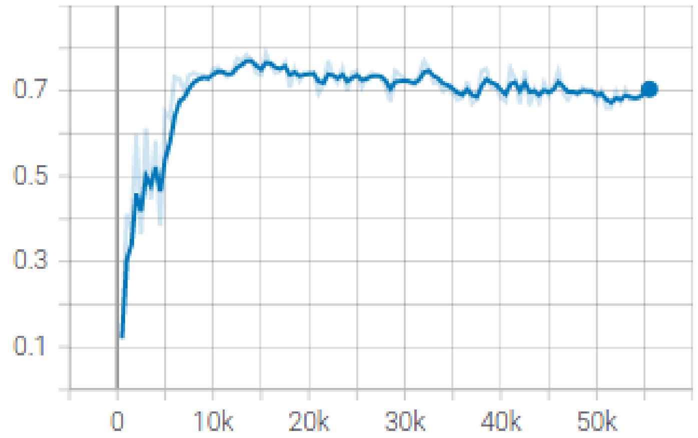


localization_accuracy/val
tag: localization_accuracy/val



Confusion matrices

Actual\predicted	-1	0	1	2	3	4	5
-1	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
1	0	0	37	0	1	0	2
2	3	1	0	78	7	27	3
3	0	2	0	9	24	3	0
4	0	0	0	0	0	0	0
5	0	0	3	0	1	0	8

Actual\predicted	Noise	Events
Noise	130173	899
Events	0	0

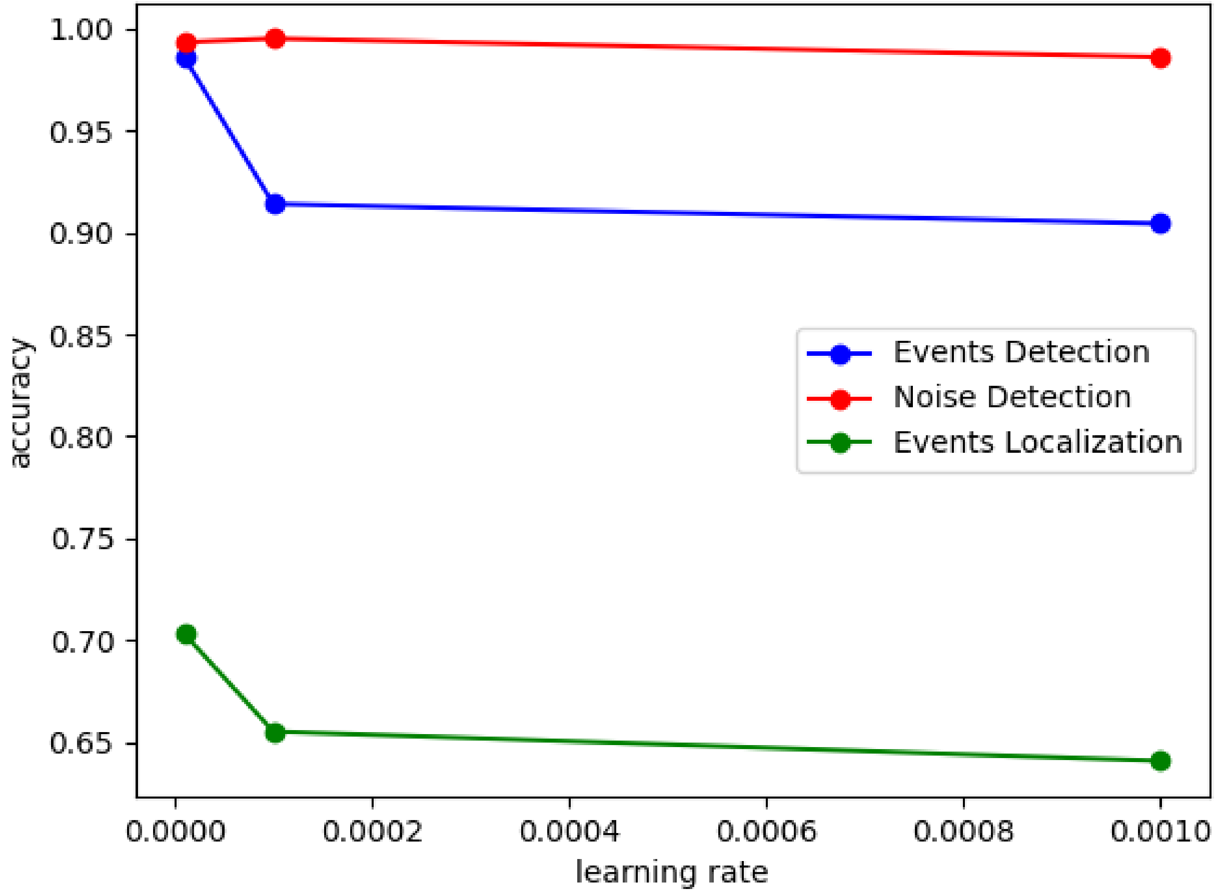
Events:

- Detection accuracy = 98.56%
- Localization accuracy = 70.33%

Noise:

- Detection accuracy = 99.31%

Optimization: Learning Rate

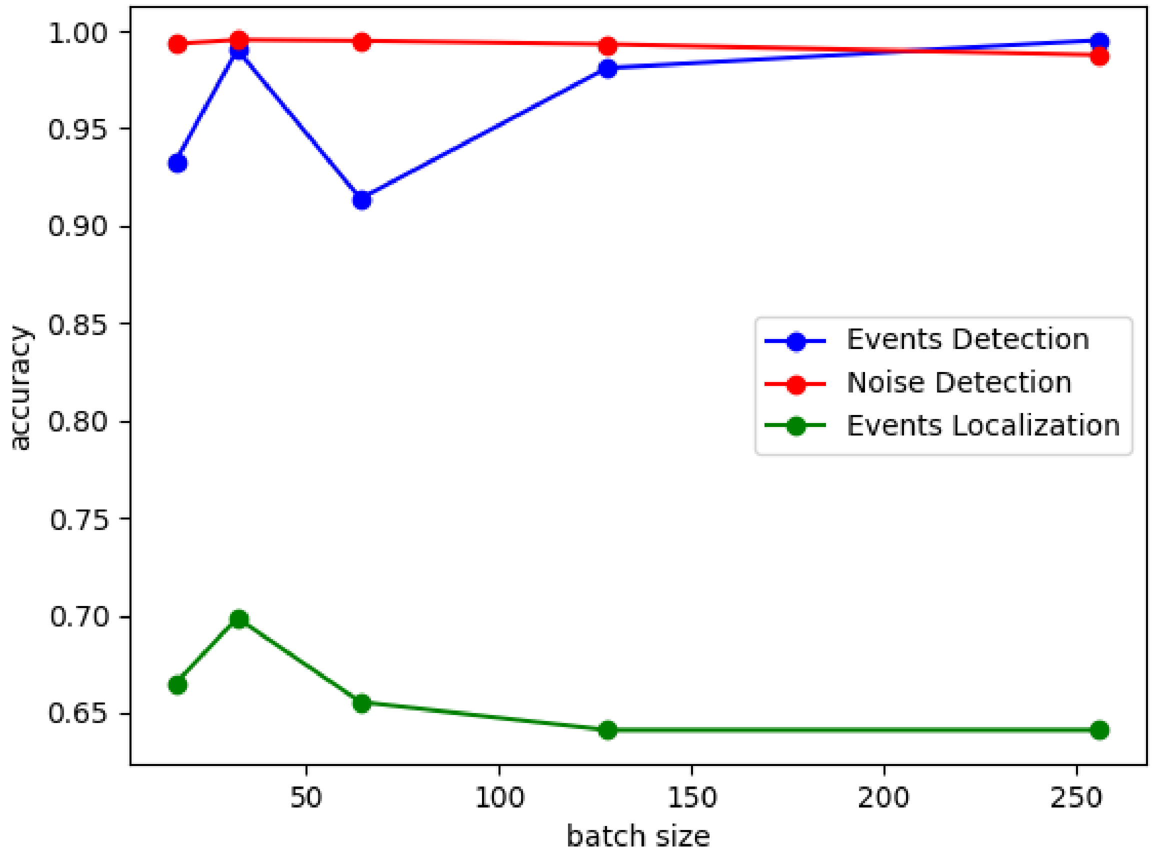


- Events detection accuracy and events localization accuracy improve significantly with the decreasing of the learning rate
- Noise detection accuracy does not change much
- The time it takes for training dramatically increases :

  Learning rate 1e-4 ~ 1 Hour

  1e-5 ~ 9 Hours

Optimization: Batch Size



- Events detection accuracy and noise detection accuracy oscillates/not changing with batch size
- Localization accuracy has a maximum at batch size 32

Optimization: Layers and Activation function

Layers	Learning rate	Activation functions	Events detection accuracy	Noise detection accuracy	Localization accuracy
12	1e-5	tanh	0.90	0.88	0.27
9	1e-4	tanh	0.86	0.78	0.50
9	1e-4	Leaky_relu	0.79	0.58	0.11
9	1e-4	relu	0.96	0.84	0.52

- Relu and tanh took 100k step to reach 99% training accuracy
- Leaky Relu took 150k step to reach 99% accuracy

What to do next

- Improve precision:

1. Training with more data (include noise for two stations)
2. Further optimization:

i. Try to tune more parameters
ii. Take the average of multiple runs

- Analyse performance

References

- Perol, T., Gharbi, M. and Denolle, M.,Convolutional, neural network for earthquake detection and location, *Science Advances 4(2) (2018)*
- Mousavi, S. M., Ellsworth, W. L., Zhu, W., Chuang, L. Y., & Beroza, G. C. (2020). Earthquake transformer—an attentive deep-learning model for simultaneous earthquake detection and phase picking. *Nature communications*, *11*(1), 1-12.
- Wu, Y. et al. DeepDetect: a cascaded region-based densely connected network for seismic event detection. IEEE Trans. Geosci. Remote Sens. 57, 62–75 (2018).
- Code: https://github.com/tperol/ConvNetQuake

Conclusion

- Update the code to be python 3 and tensor flow 2 compatible
- Test the number of layers (8, 9 ,12 layers)
- Test the activation function (relu, leaky relu, tanh)
- Test the batch size (16, 32, 64, 128, 256)
- Test the learning rate (1e-5, 1e-4, 1e-3)

Conclusion

- CNN network ConvNetQuake works well on earthquake detection and localization
- The precision of ConvNetQuake module stands out among other detection methods
- The precision of the localization needs to be further improved