O4.4-458

# Towards Predictive Maintenance Strategy Through Waveform Anomaly Detection using Unsupervised Learning

Jiun-Ting Lin, Ana Aguiar, Qingkai Kong, Steve Myers, Amanda Price

Lawrence Livermore National Laboratory

8-12 September 2025

Prepared by LLNL under Contract DE-AC52-07NA27344
LLNL-CFPRES-2009487

**Towards Predictive Maintenance Strategy Through Waveform Anomaly Detection using Unsupervised Learning**

Jiun-Ting Lin, Ana Aguiar, Qingkai Kong, Steve Myers, Amanda Price



# Introduction

International Monitoring System (IMS):

- Consists of 300+ stations.
- Hosted by 89 countries.
- Real-time data for event monitoring.
- Station maintenance regularly for quality assurance.

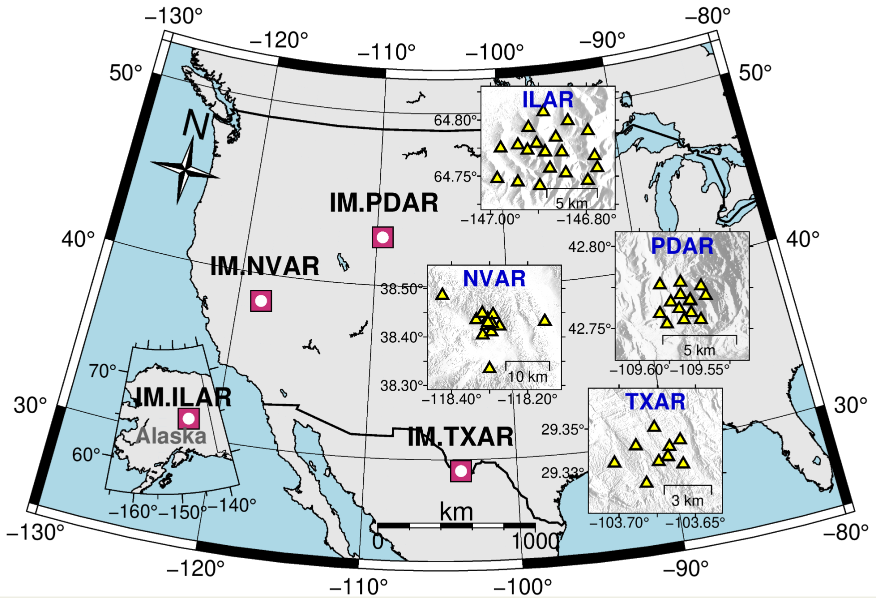
# Towards Predictive Maintenance Strategy Through Waveform Anomaly Detection using Unsupervised Learning

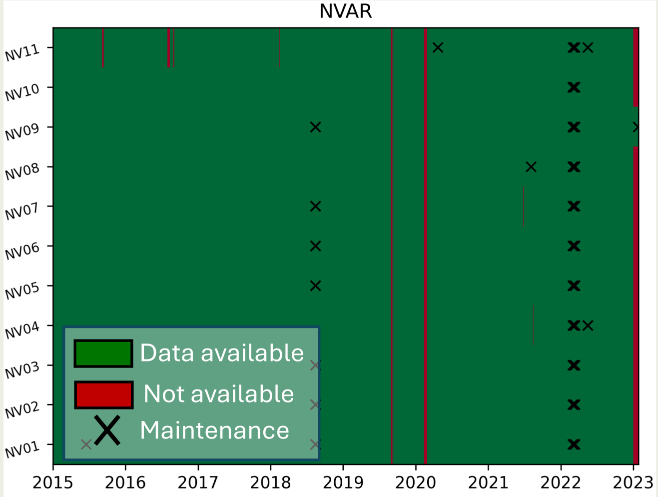
Jiun-Ting Lin, Ana Aguiar, Qingkai Kong, Steve Myers, Amanda Price

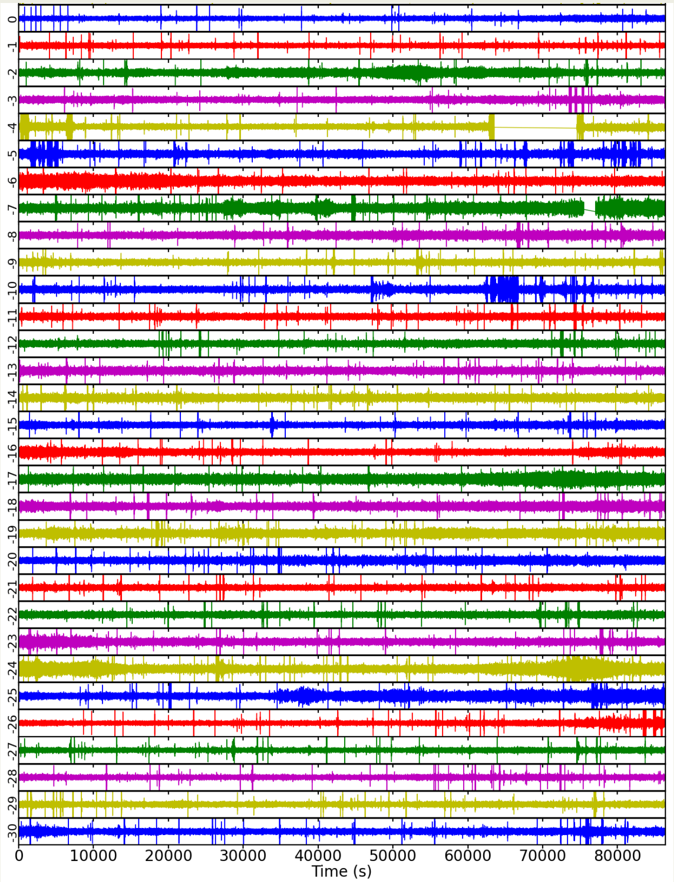
O4.4-458

## Station maintenance is costly

- Money, time, and human effort.
- Some of them are scheduled maintenances, ***NOT*** associated with actual instrument issues.
- Can we schedule maintenance more effectively?




30 days time series before maintenance



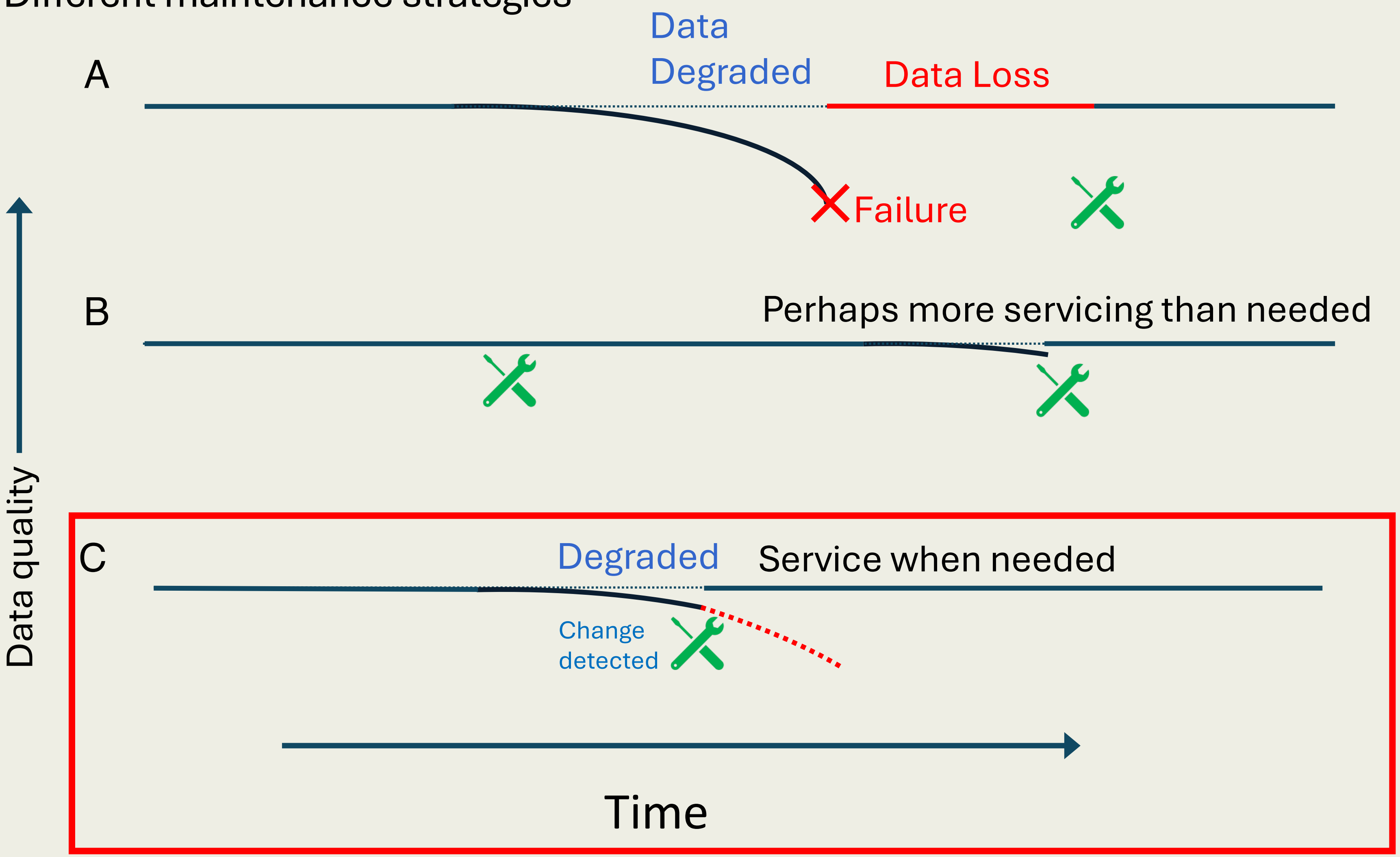
Lawrence Livermore National Laboratory

# Towards Predictive Maintenance Strategy Through Waveform Anomaly Detection using Unsupervised Learning

Jiun-Ting Lin, Ana Aguiar, Qingkai Kong, Steve Myers, Amanda Price



## Different maintenance strategies




Run-to-failure

Preventive maintenance (scheduled)

Predictive maintenance (Service when data degradation is detected)



Lawrence Livermore National Laboratory

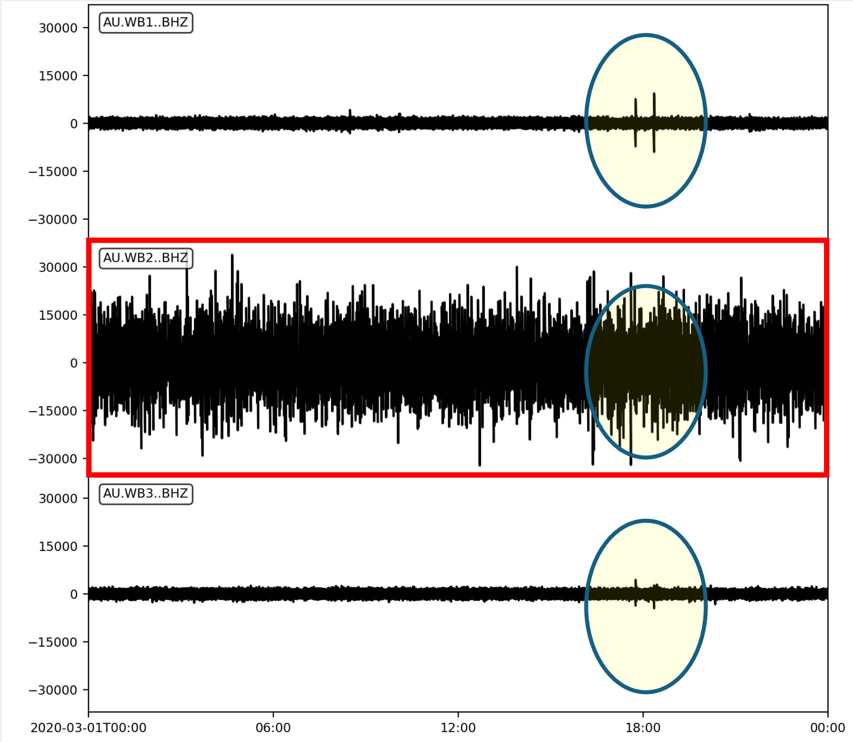
Jiun-Ting Lin, Ana Aguiar, Qingkai Kong, Steve Myers, Amanda Price

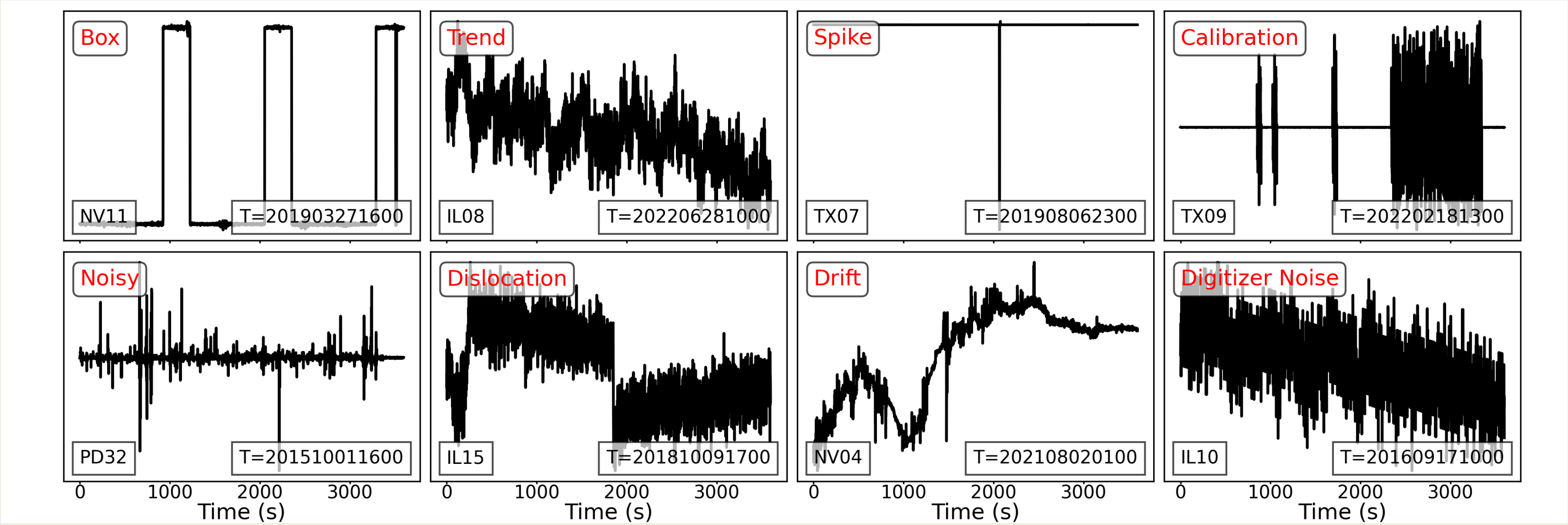


# Challenges in detecting degraded signals

- Degraded signals or anomaly can be anything: No clear definition.
- Signals may be subtle and hidden within the data.
- No ground truth data to learn or compare.

2020-03-01
AU.WB1, AU.WB2, AU.WB3 (BHZ)





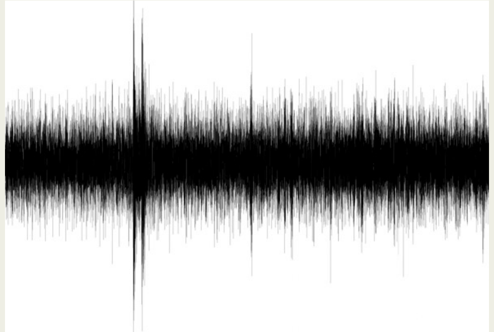

Lawrence Livermore National Laboratory

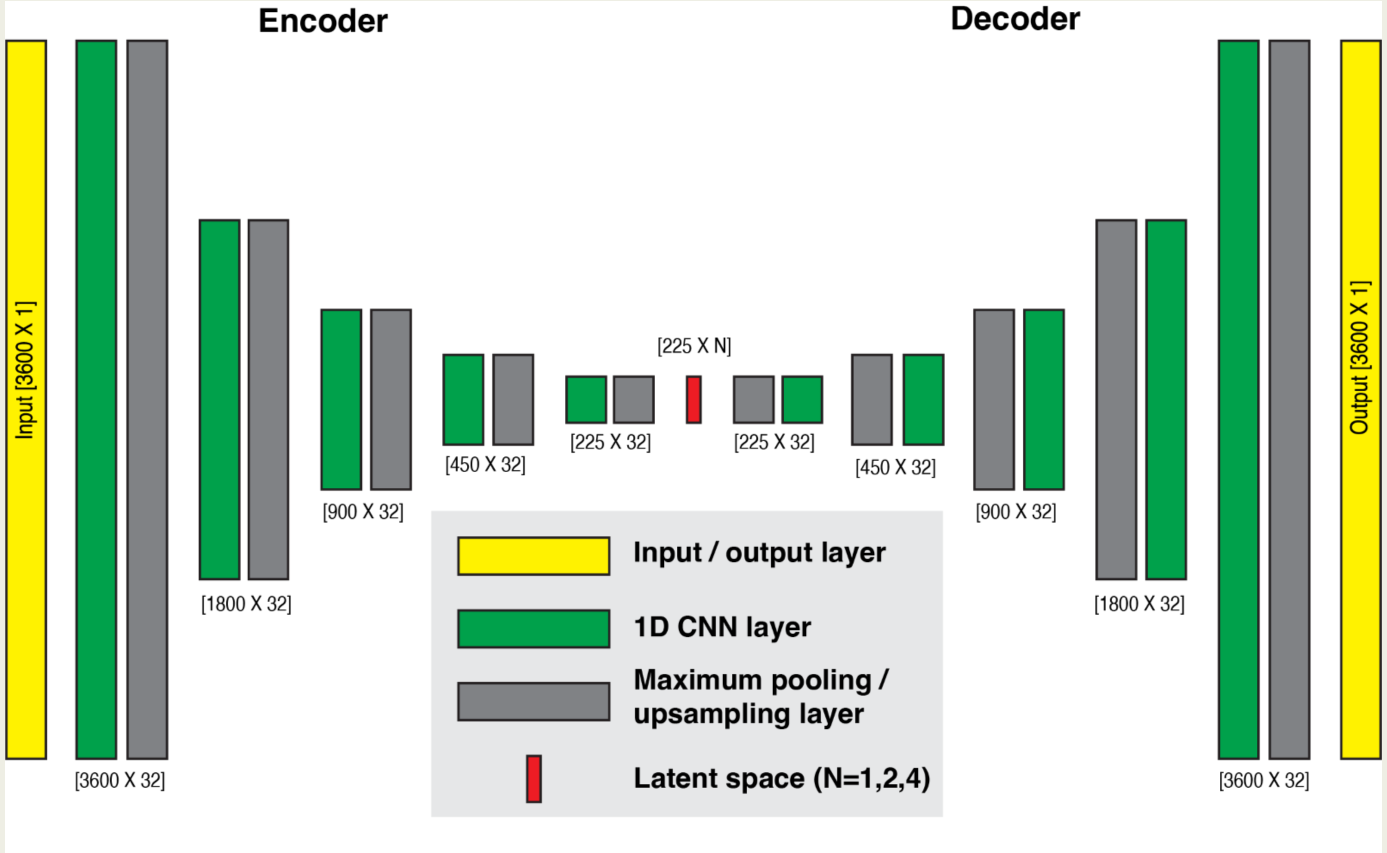
Jiun-Ting Lin, Ana Aguiar, Qingkai Kong, Steve Myers, Amanda Price



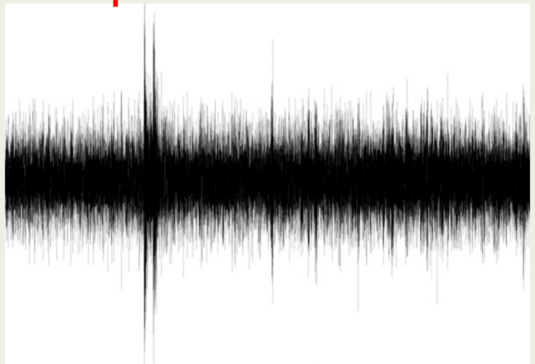
# Unsupervised learning model: autoencoder

Input






Output



Compare the input and output waveform by the correlation coefficient (CC).

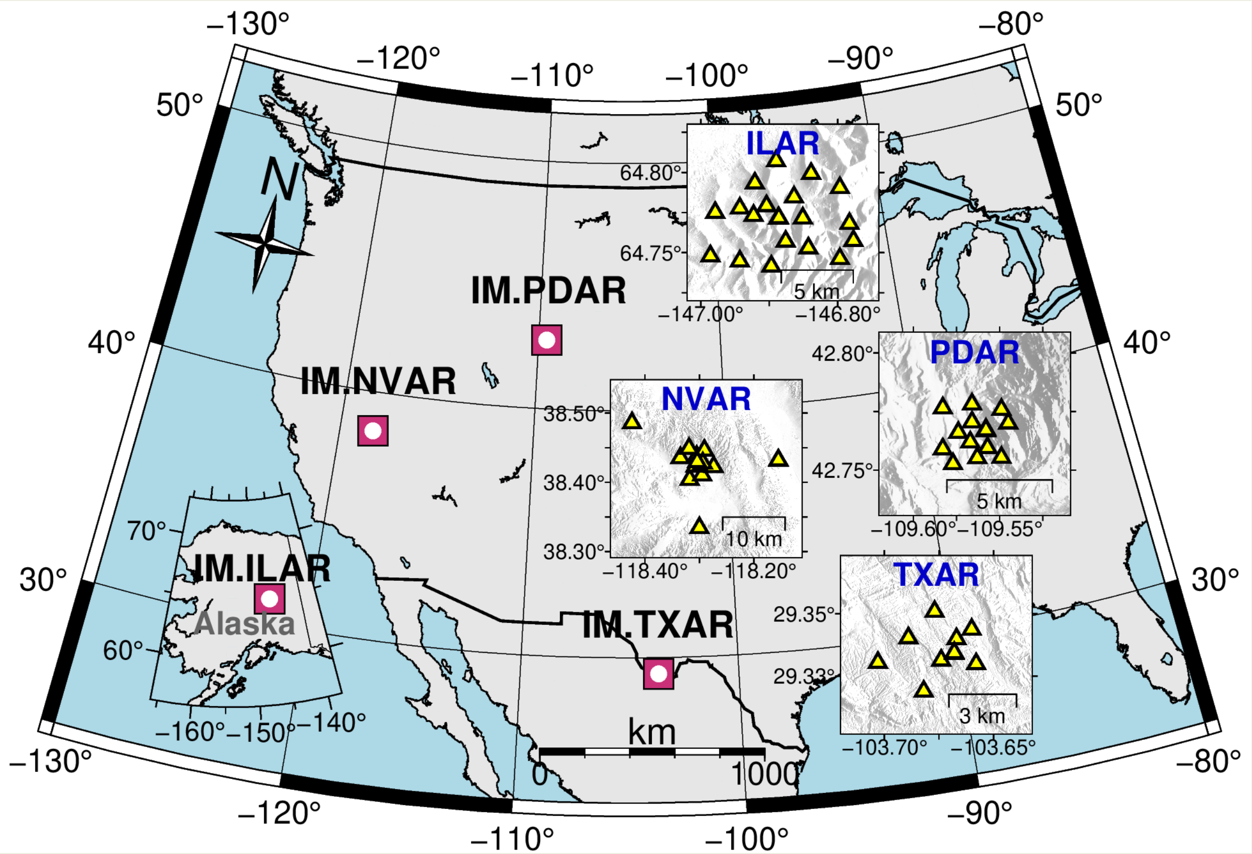
1. No assumptions on anomalous signals.
2. Exploring information in seismic data.

**Towards Predictive Maintenance Strategy Through Waveform Anomaly Detection using Unsupervised Learning**

Jiun-Ting Lin, Ana Aguiar, Qingkai Kong, Steve Myers, Amanda Price

O4.4-458

# Training Data




Randomly select a total of 5,000 days (120,000 hours) of data.

Training & Validation (80%)

Testing (20%)

+ Anomalous & Synthetic data

Evaluation

- Continuous waveform data from 2015-2023.
- Downsampled to 1 Hz, cut into hourly input segments.

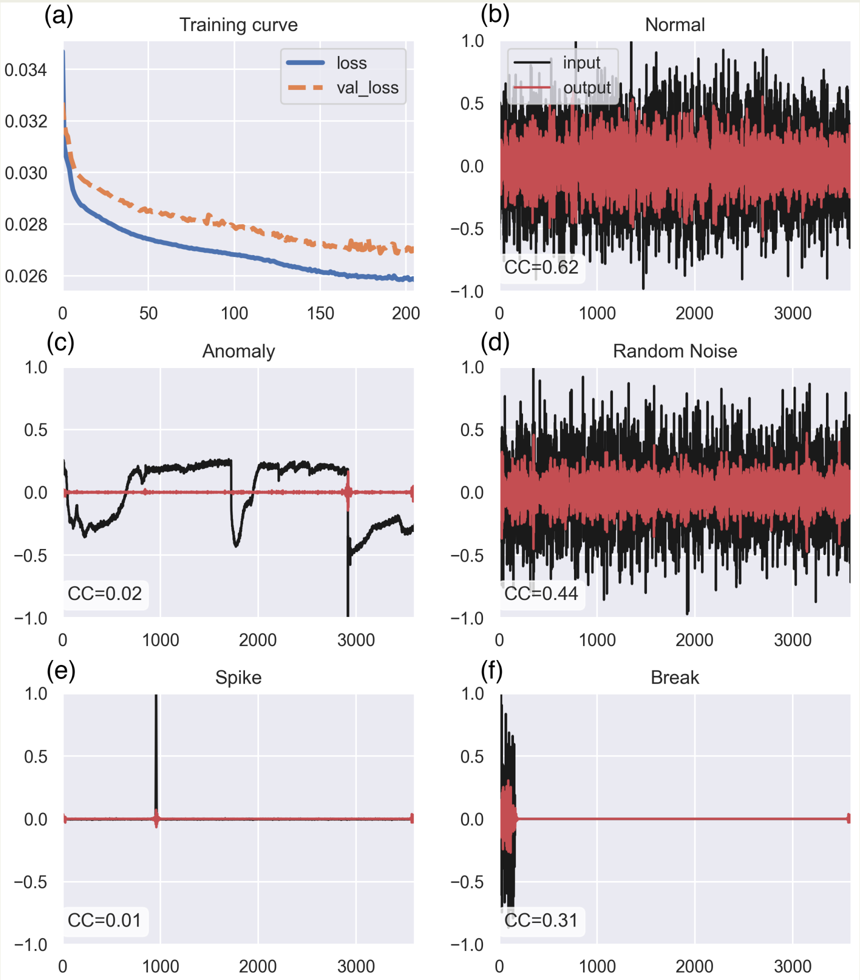
LLNL-CFPRES-2009487

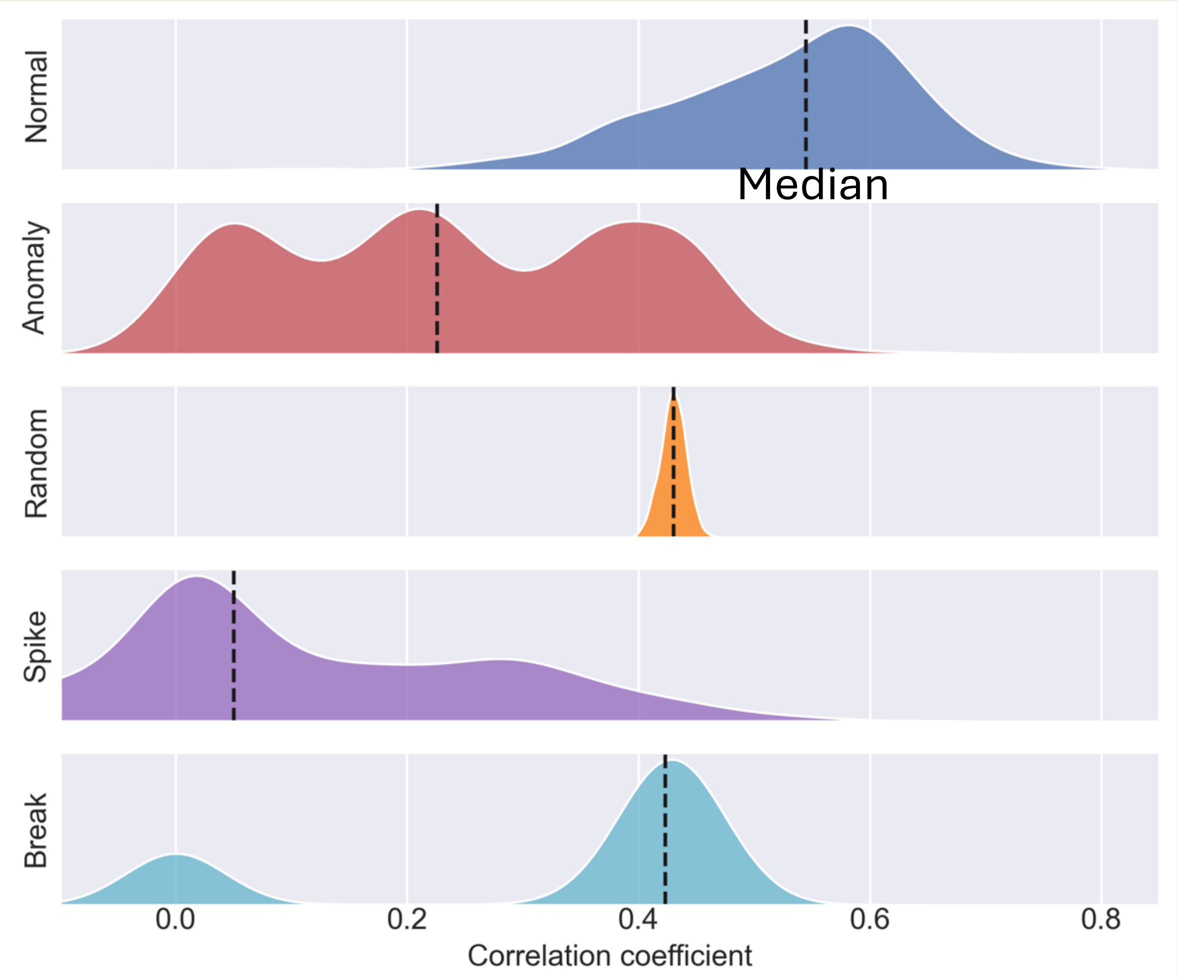
# Towards Predictive Maintenance Strategy Through Waveform Anomaly Detection using Unsupervised Learning

Jiun-Ting Lin, Ana Aguiar, Qingkai Kong, Steve Myers, Amanda Price



## Results



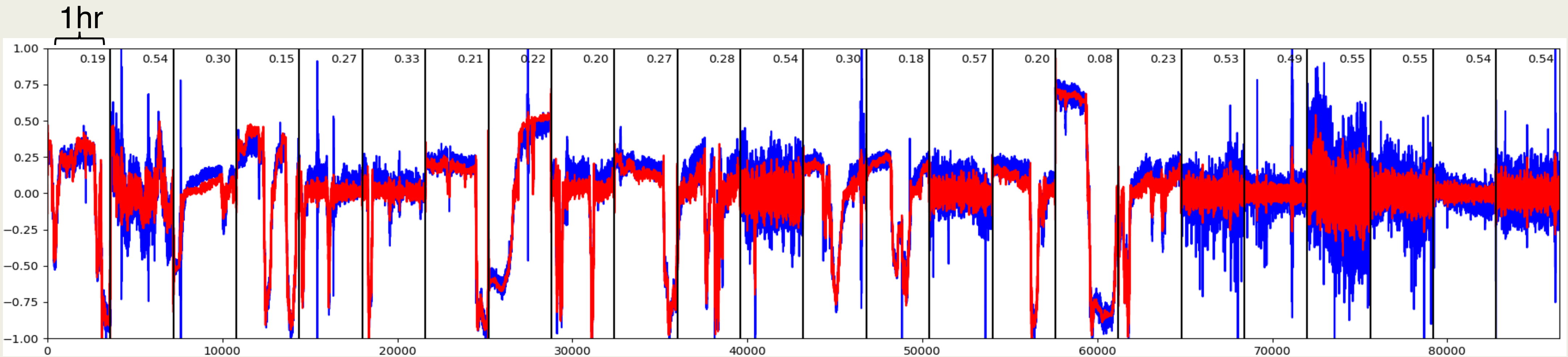




- Normal data → higher CC
- Anomalous data → lower CC

Jiun-Ting Lin, Ana Aguiar, Qingkai Kong, Steve Myers, Amanda Price


# Apply to continuous data

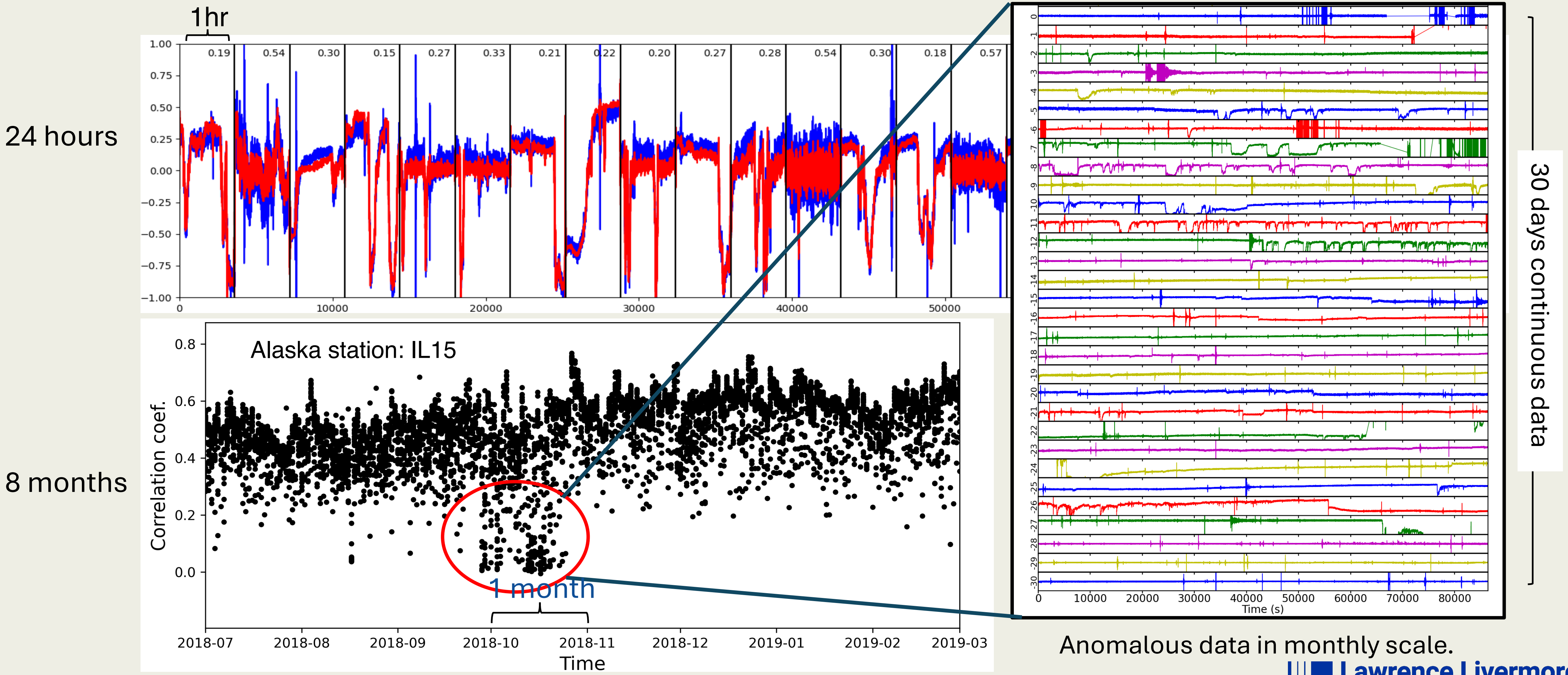
24 hours



Jiun-Ting Lin, Ana Aguiar, Qingkai Kong, Steve Myers, Amanda Price



# Apply to continuous data



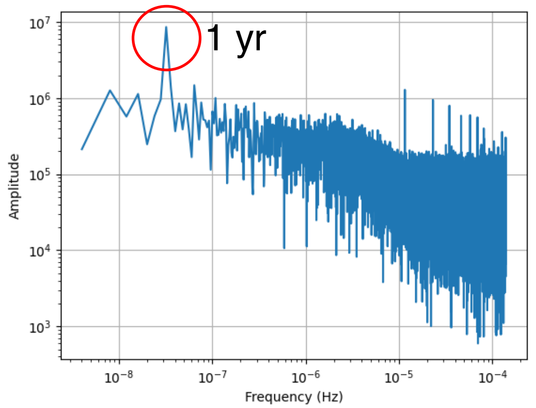

Anomalous data in monthly scale.

Towards Predictive Maintenance Strategy Through Waveform Anomaly Detection using Unsupervised Learning

Jiun-Ting Lin, Ana Aguiar, Qingkai Kong, Steve Myers, Amanda Price

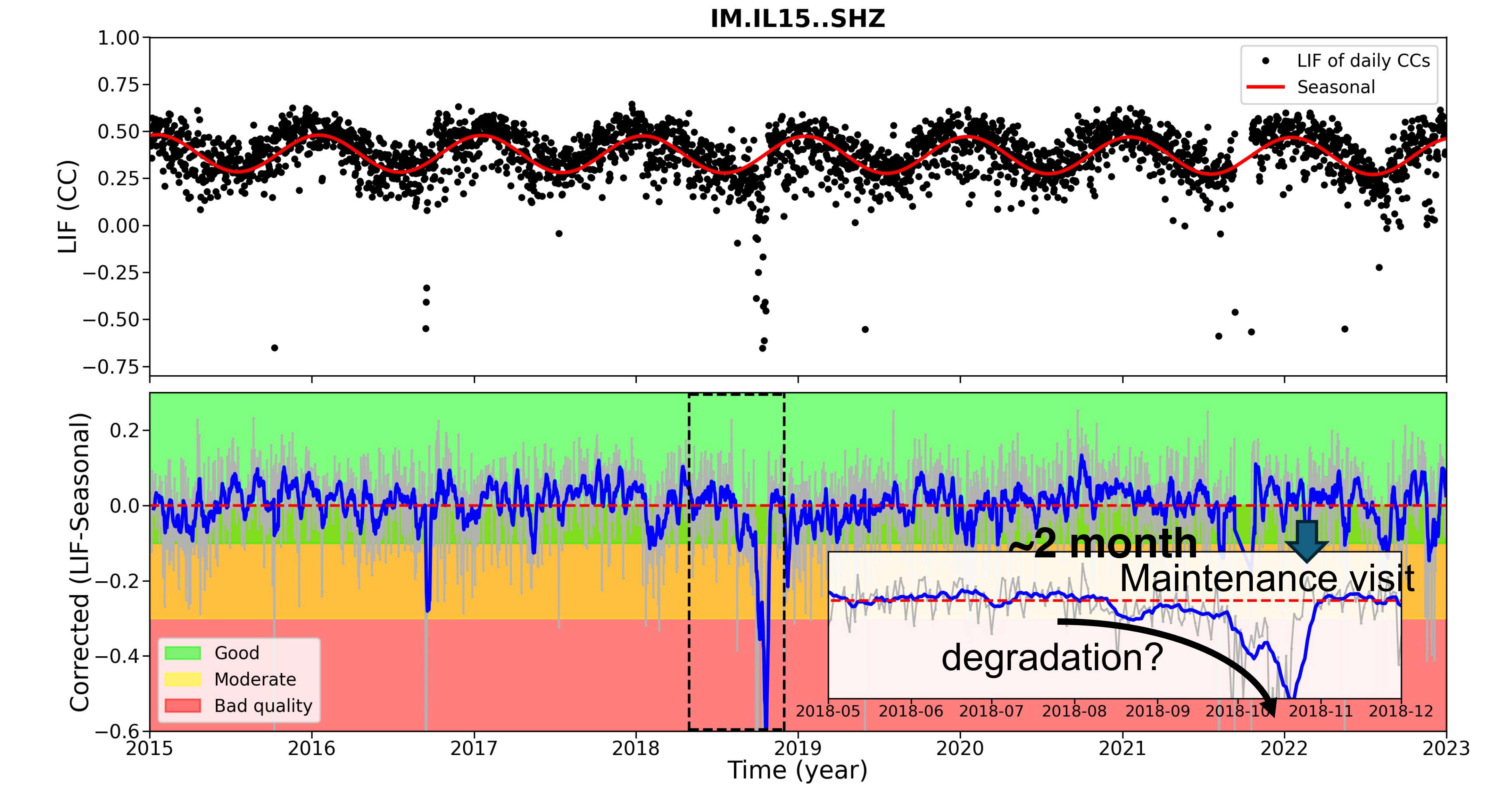


# Apply to continuous data




1. Aggregate the 24 hourly CCs into one per day by the lower inner fence (LIF=Q1-1.5IQR).

2. The results are sensitive to seasonal variation that need to be corrected.



**Towards Predictive Maintenance Strategy Through Waveform Anomaly Detection using Unsupervised Learning**

Jiun-Ting Lin, Ana Aguiar, Qingkai Kong, Steve Myers, Amanda Price

O4.4-458

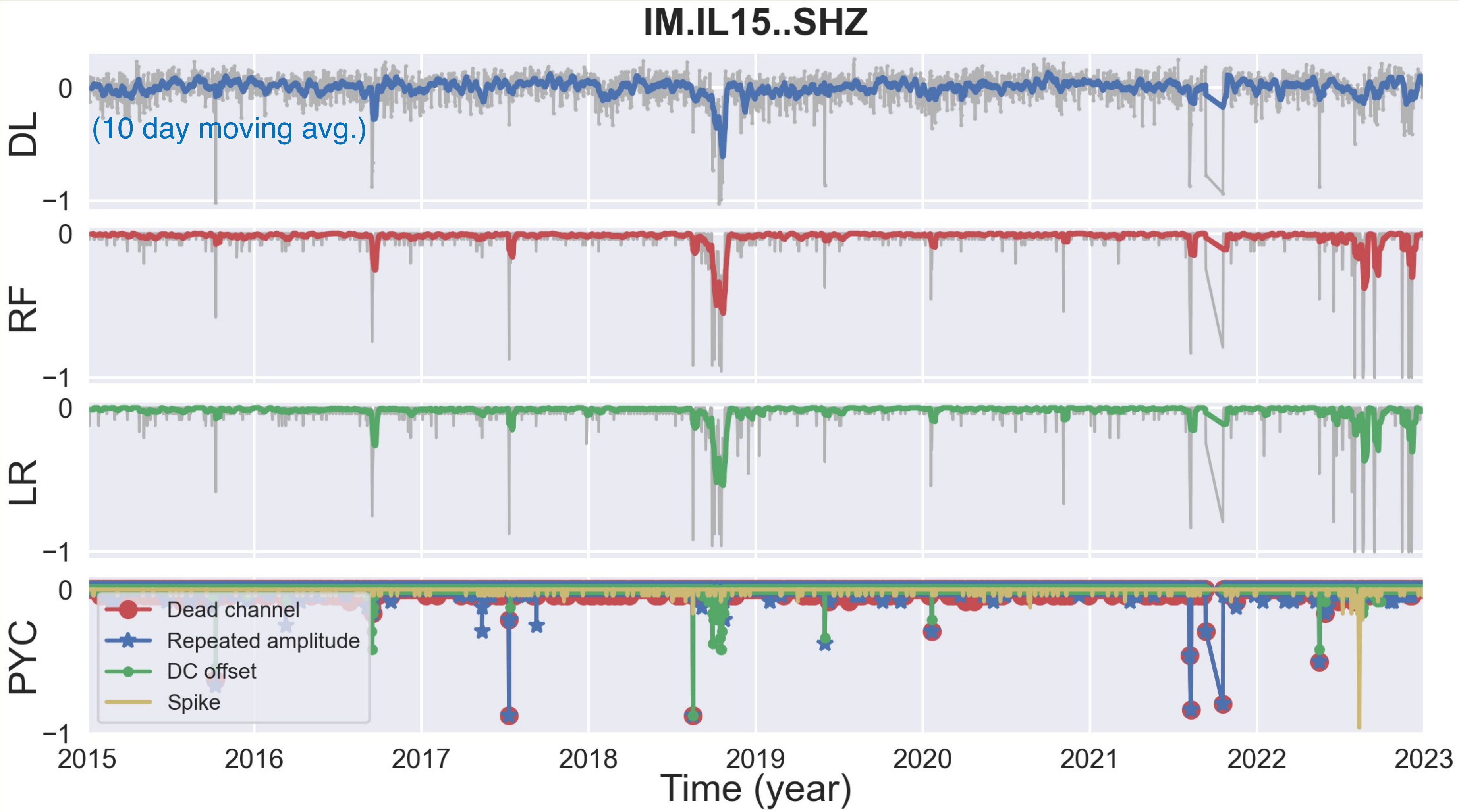
# Compare to other models

DL: Deep-learning autoencoder (unsupervised)

RF: Random Forest (supervised)

LR: Logistic Regression (supervised)

PYC: Traditional detector (Pycheron QC tool) (Aur et al., 2021)




Performance is similar for <u>known</u> types of anomalies.



Lawrence Livermore National Laboratory

Jiun-Ting Lin, Ana Aguiar, Qingkai Kong, Steve Myers, Amanda Price



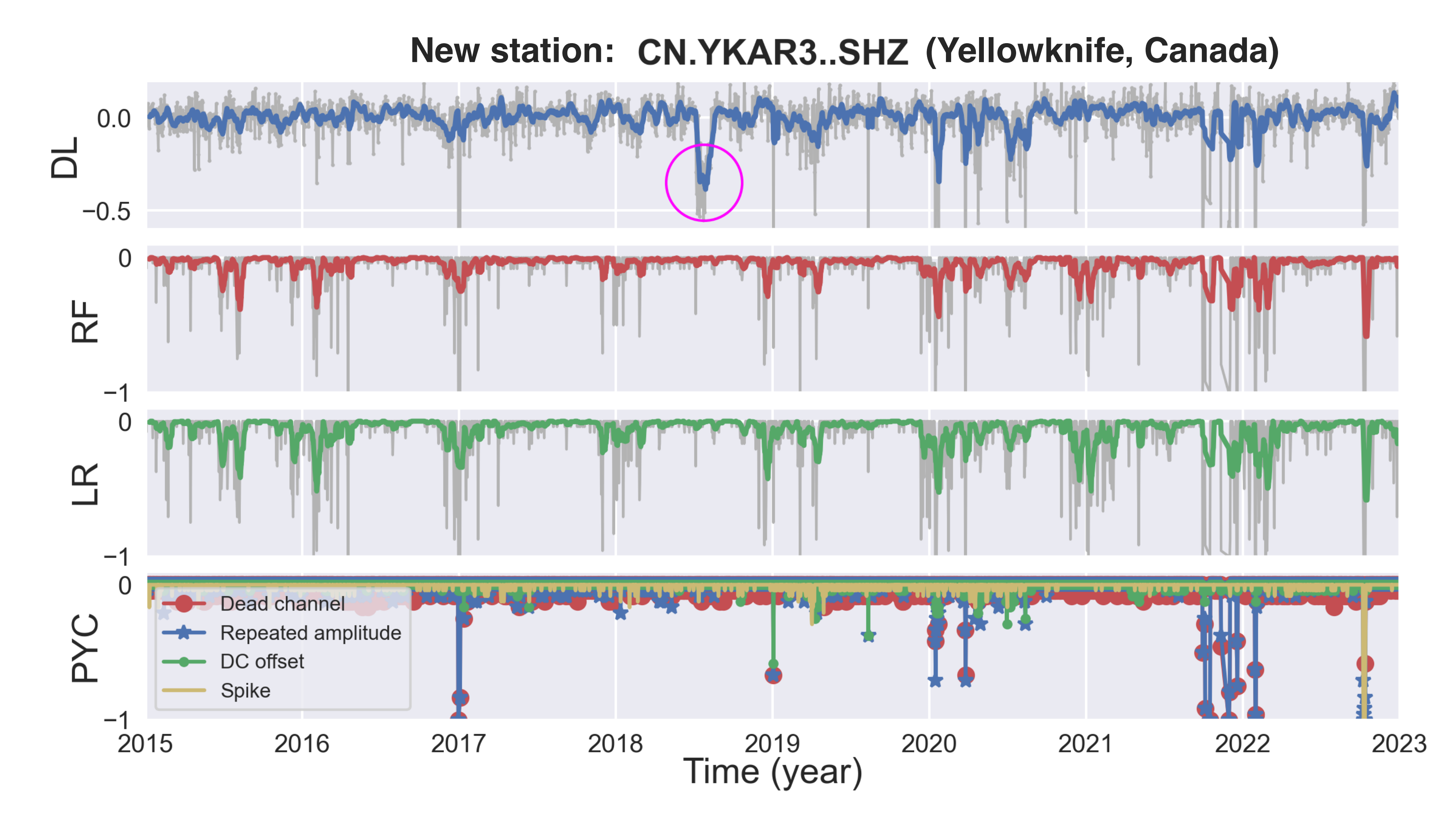
# Compare to other models

DL: Deep-learning autoencoder (unsupervised)

RF: Random Forest (supervised)

LR: Logistic Regression (supervised)

PYC: Traditional detector (Pycheron QC tool) (Aur et al., 2021)




Unsupervised learning can detect <u>unknown</u> types of anomalies.

# Towards Predictive Maintenance Strategy Through Waveform Anomaly Detection using Unsupervised Learning

Jiun-Ting Lin, Ana Aguiar, Qingkai Kong, Steve Myers, Amanda Price

O4.4-458

## Compare to other models

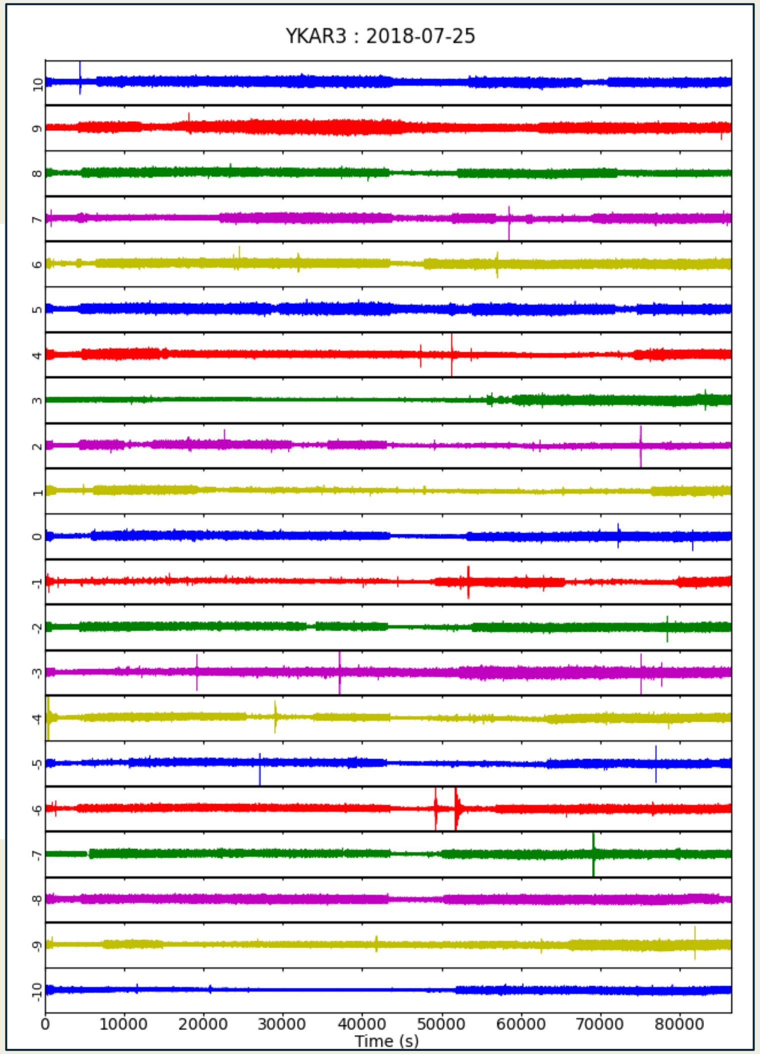
DL: Deep-learning autoencoder (unsupervised)

RF: Random Forest (supervised)

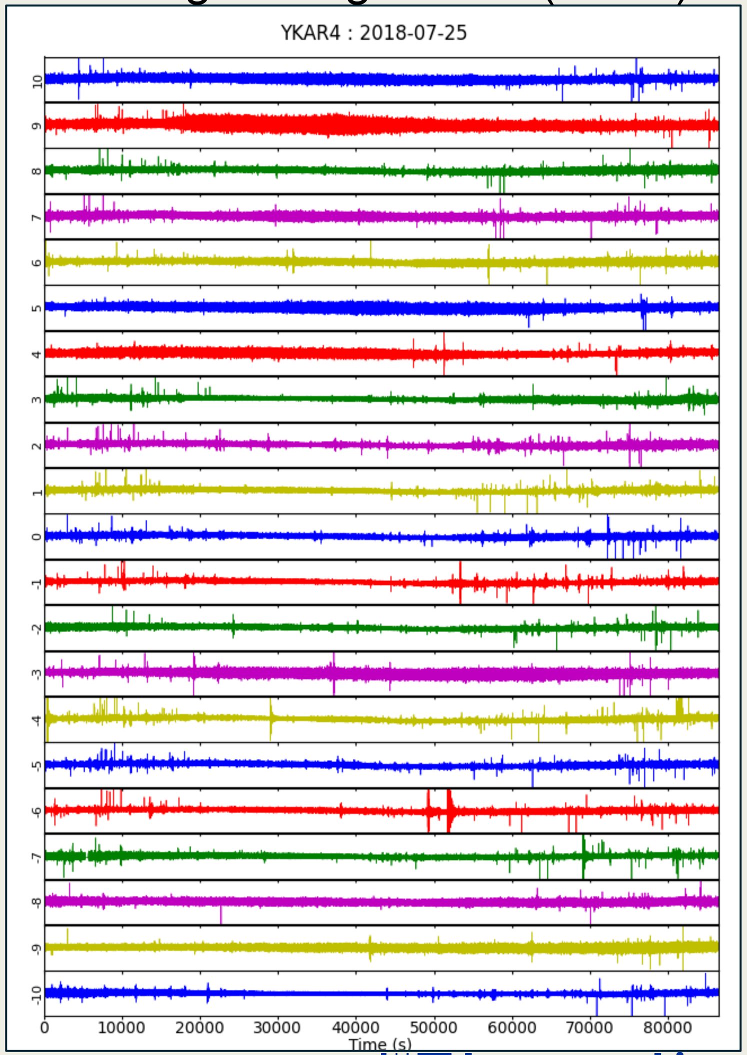
LR: Logistic Regression (supervised)

PYC: Traditional detector (Pycheron QC tool) (Aur et al., 2021)

20 days continuous data




A neighboring station (<3km)



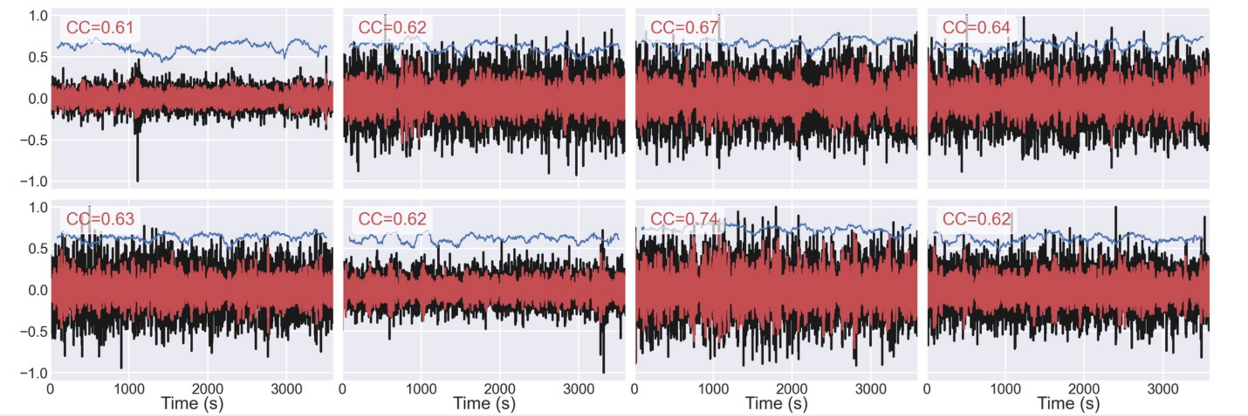

Unsupervised learning can detect unknown types of anomalies.

Jiun-Ting Lin, Ana Aguiar, Qingkai Kong, Steve Myers, Amanda Price

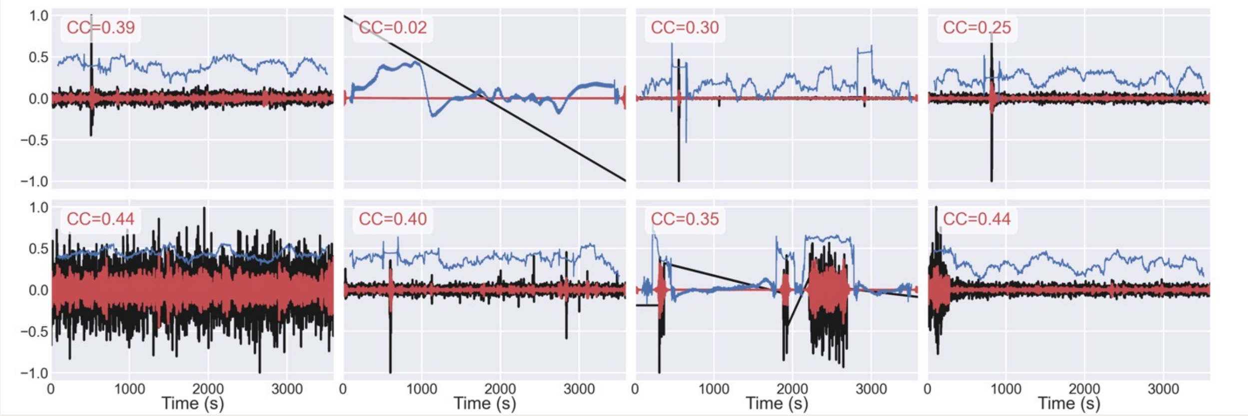


# Performance evaluation

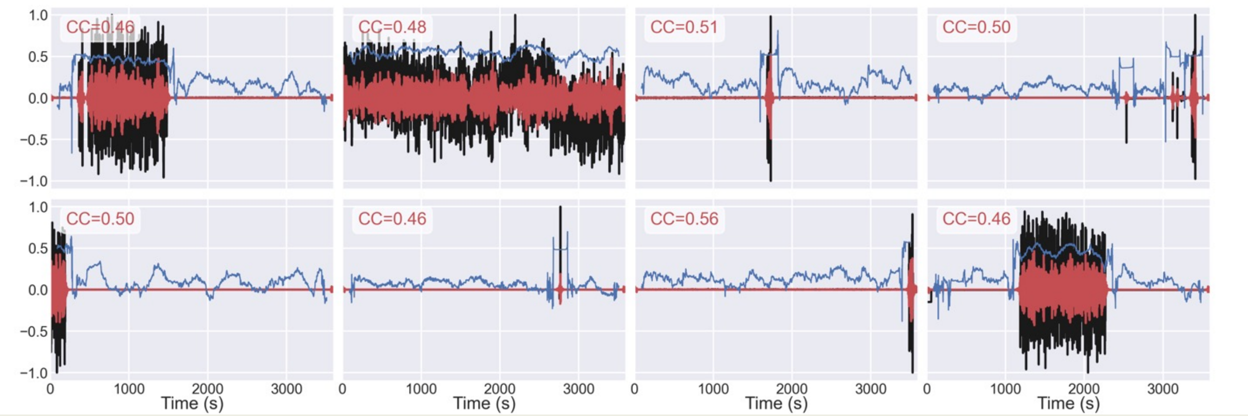
## True Negative



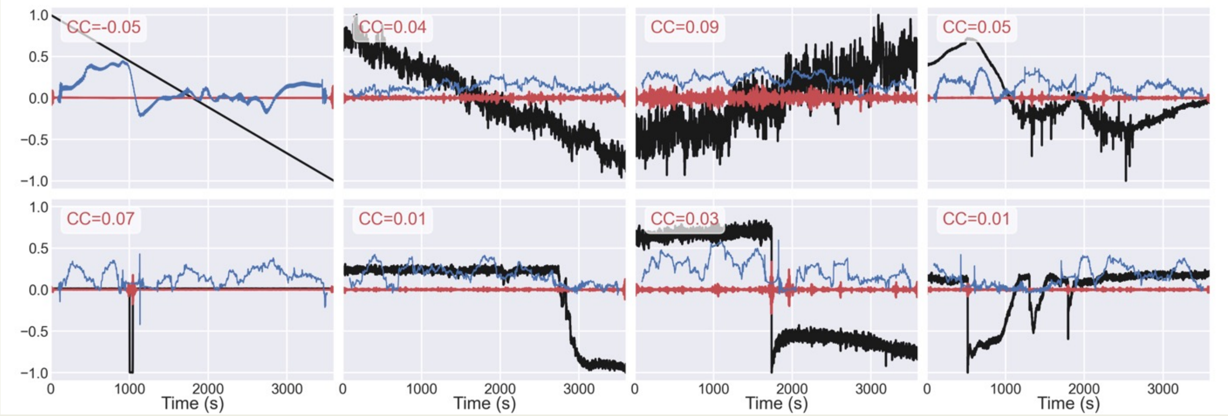

## False Positive




## False Negative




## True Positive




**Anomalous data**: Manually selected.
**Normal data**: Randomly selected (may include mislabeled instances).

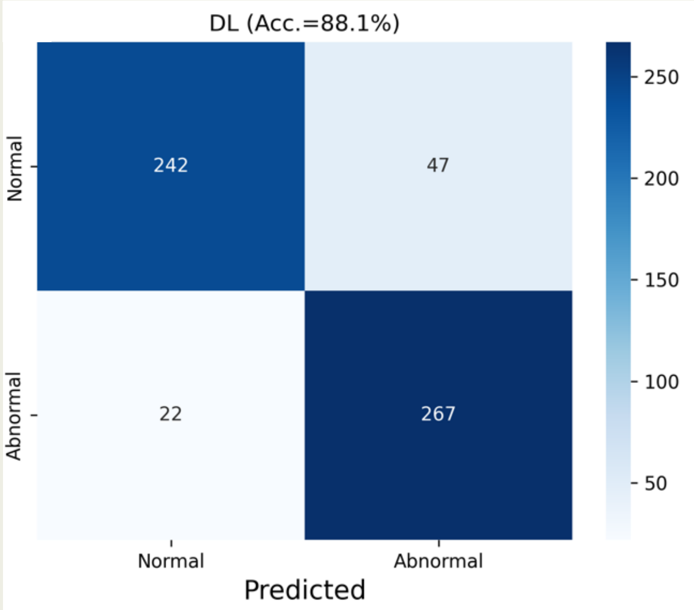
LLNL-CFPRES-2009487

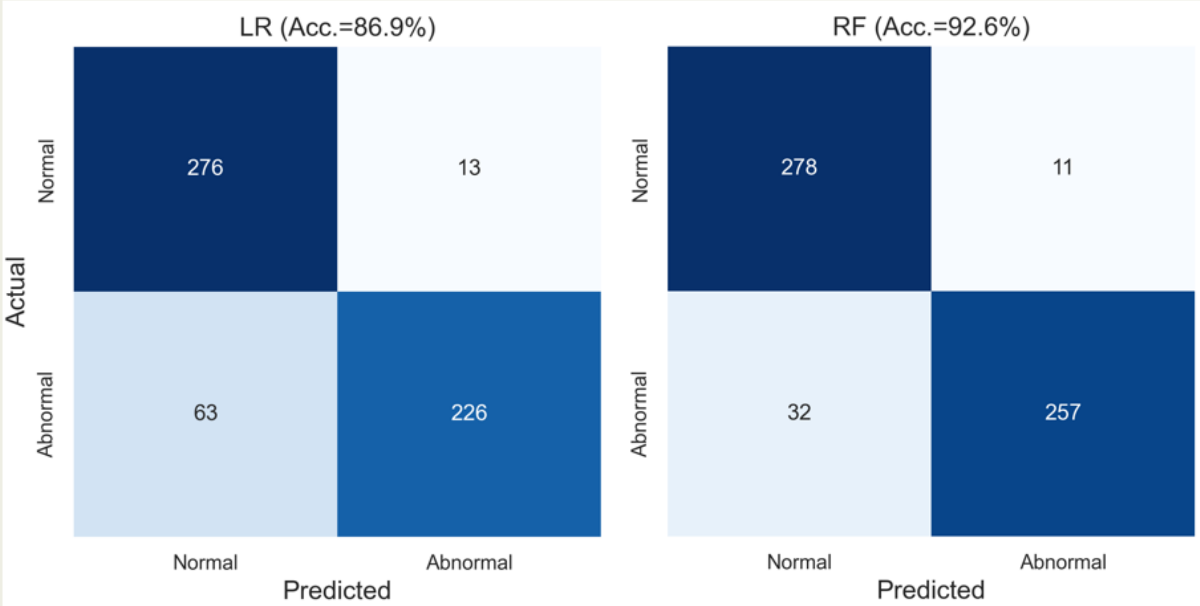
# Towards Predictive Maintenance Strategy Through Waveform Anomaly Detection using Unsupervised Learning

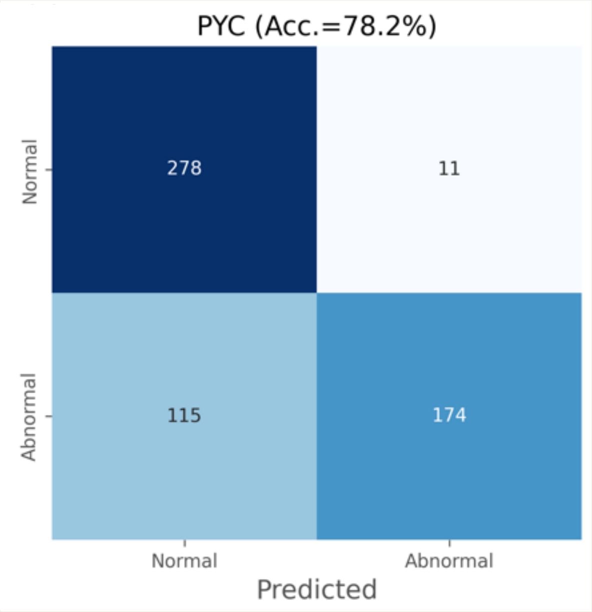
Jiun-Ting Lin, Ana Aguiar, Qingkai Kong, Steve Myers, Amanda Price

O4.4-458

## Performance evaluation




### Our approach

- Good accuracy.
- Flexibility (Can detect unknown types of signals).

### Supervised ML

- Highest accuracy.
- Less generalization capability to new types of signals.

### Traditional QC tool

- Detections are explicitly defined.
- Lowest accuracy for long-term anomaly detection tasks unless specifically designed for them.



Lawrence Livermore National Laboratory

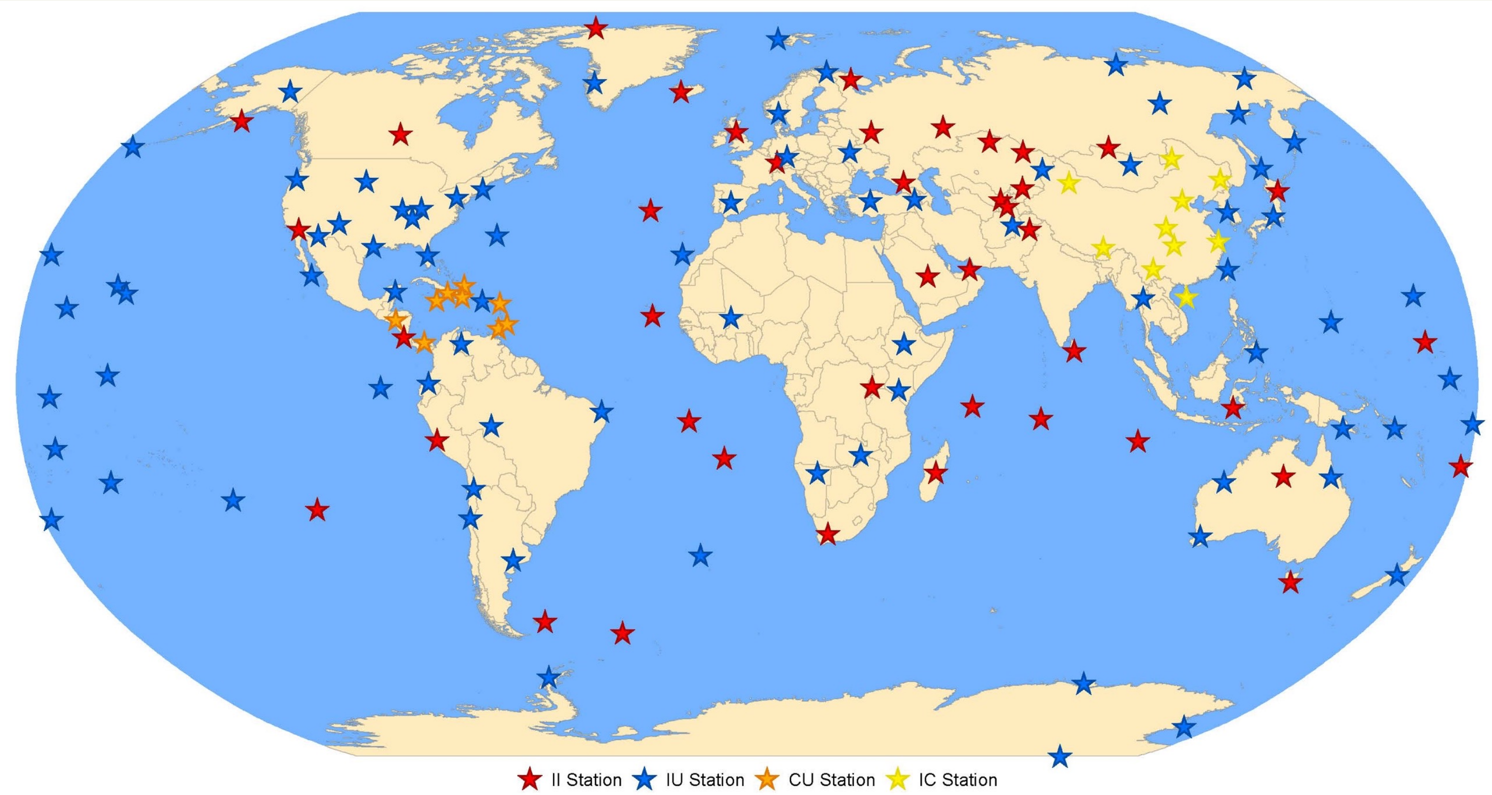
Towards Predictive Maintenance Strategy Through Waveform Anomaly Detection using Unsupervised Learning

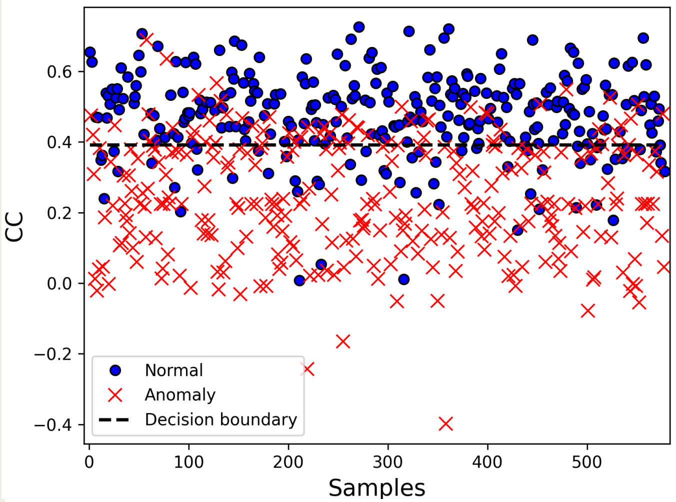
Jiun-Ting Lin, Ana Aguiar, Qingkai Kong, Steve Myers, Amanda Price

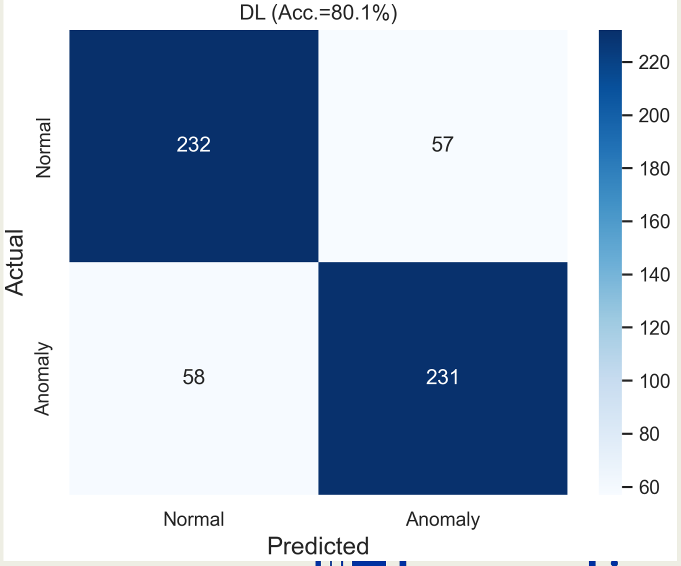
O4.4-458

# Generalization capability

A model trained with 170 GSN stations:
- Different locations and sensor types/components.




Model can transfer to new stations without significant retraining.



Lawrence Livermore National Laboratory

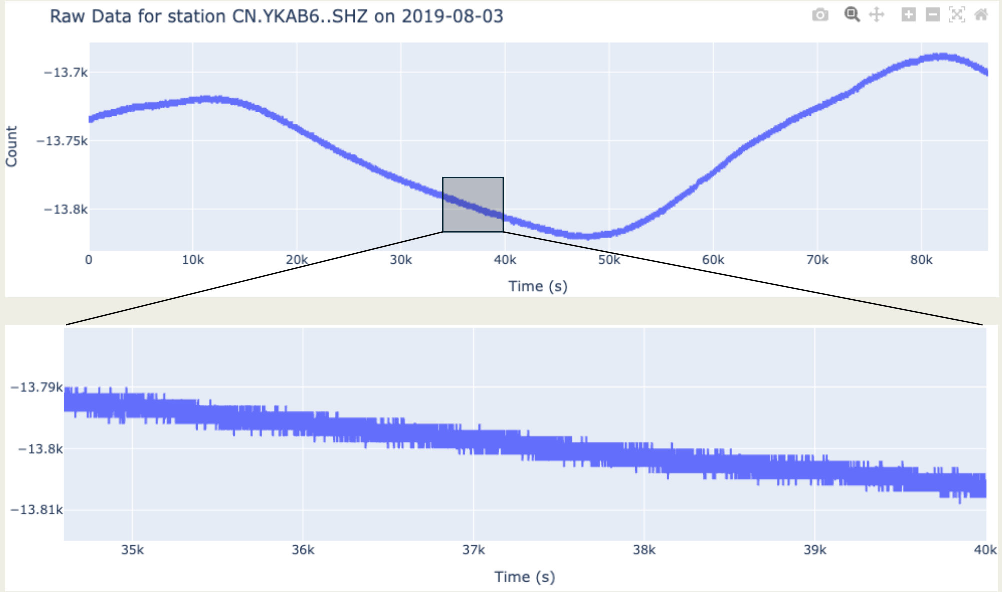
**Towards Predictive Maintenance Strategy Through Waveform Anomaly Detection using Unsupervised Learning**

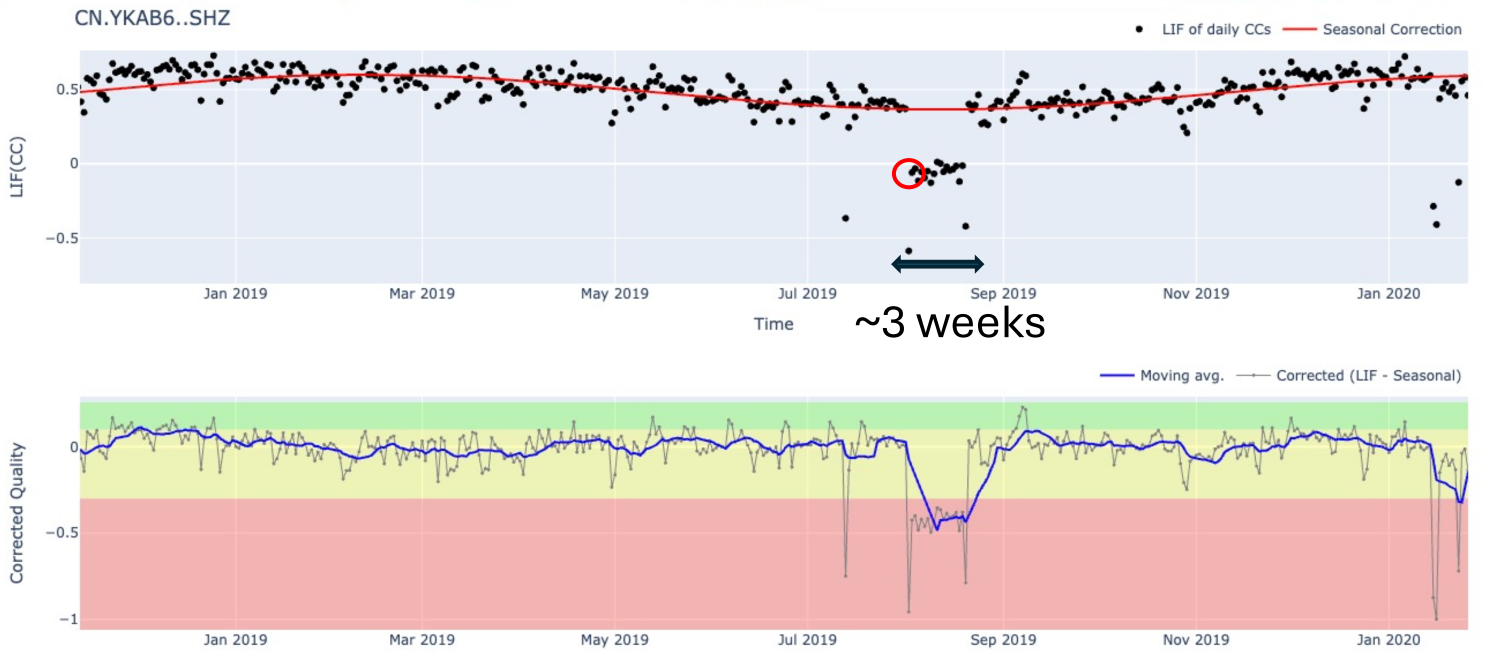
Jiun-Ting Lin, Ana Aguiar, Qingkai Kong, Steve Myers, Amanda Price

O4.4-458

# Application to other IMS

- Yellowknife Array, Canada
- Anomalies lasting three weeks were detected.

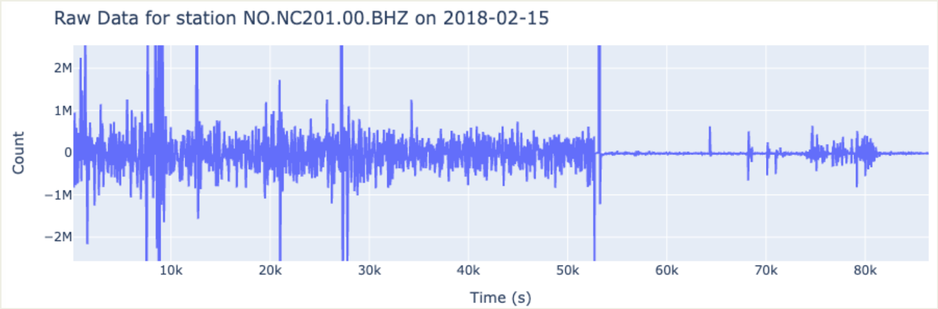
# Towards Predictive Maintenance Strategy Through Waveform Anomaly Detection using Unsupervised Learning

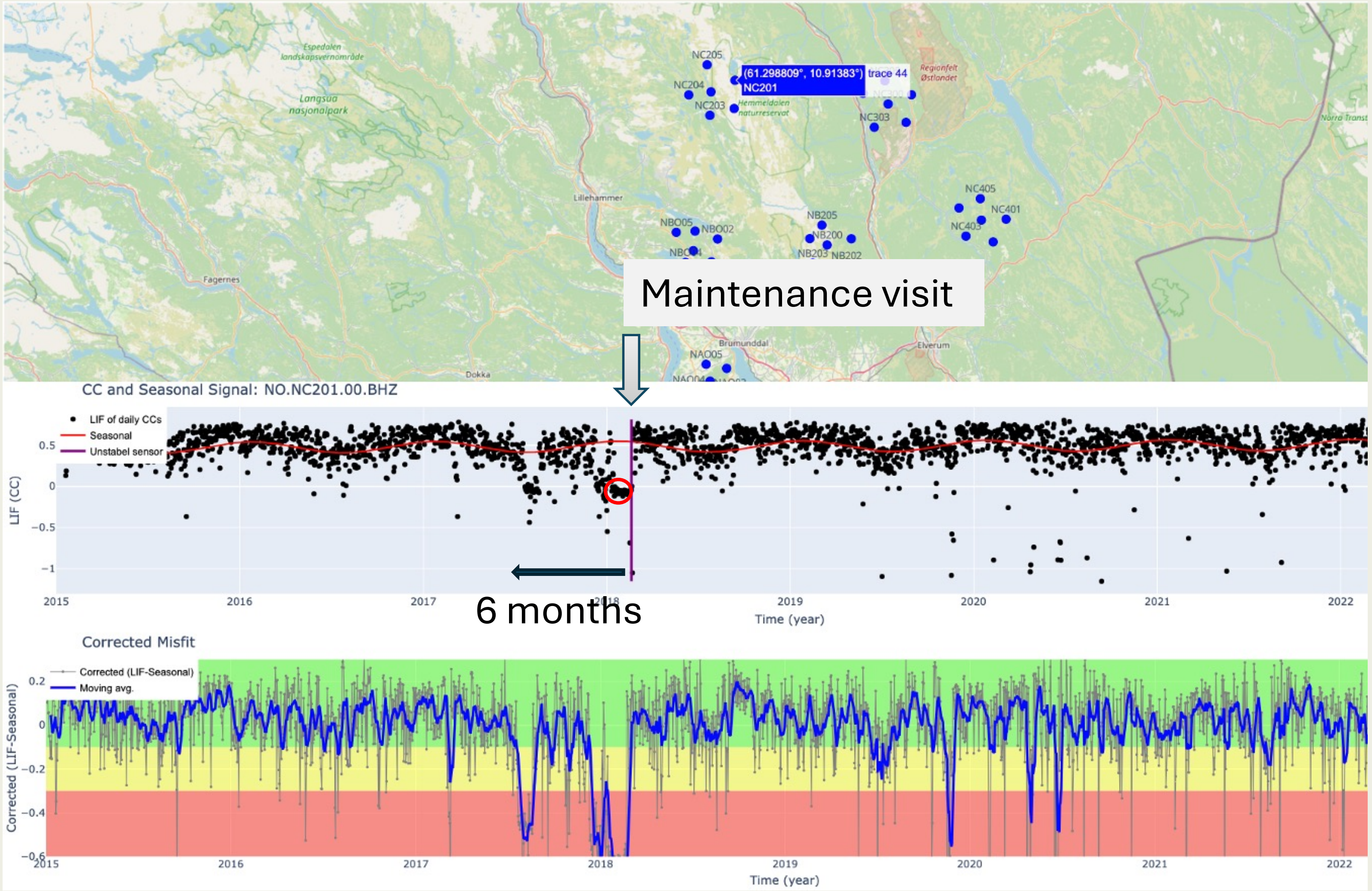
Jiun-Ting Lin, Ana Aguiar, Qingkai Kong, Steve Myers, Amanda Price



## Application to other IMS

- NORSAR Array, Norway.
- Possible to detect anomalies a few months ahead of the maintenance visit.






Lawrence Livermore National Laboratory

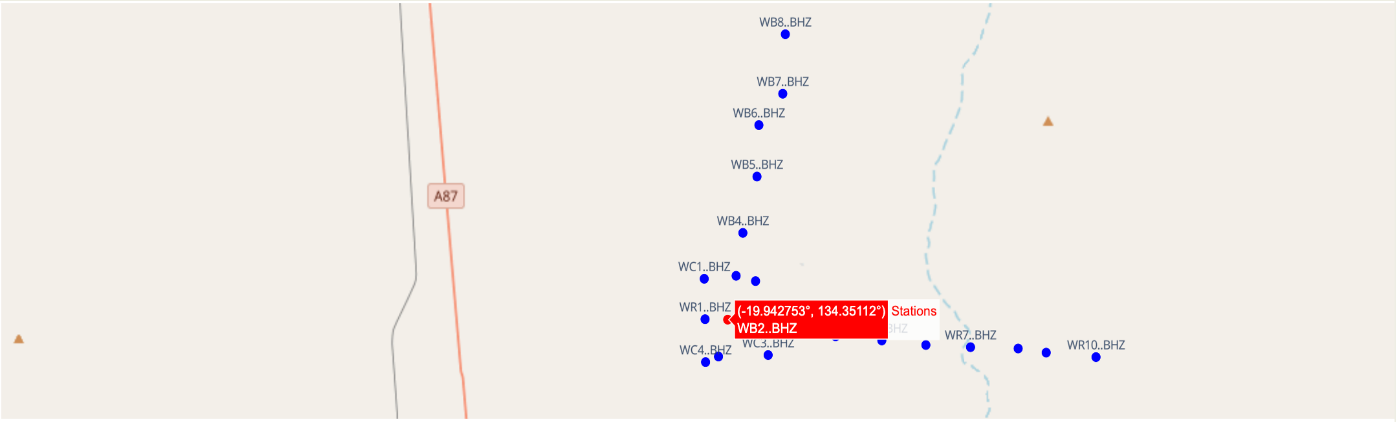
# Towards Predictive Maintenance Strategy Through Waveform Anomaly Detection using Unsupervised Learning

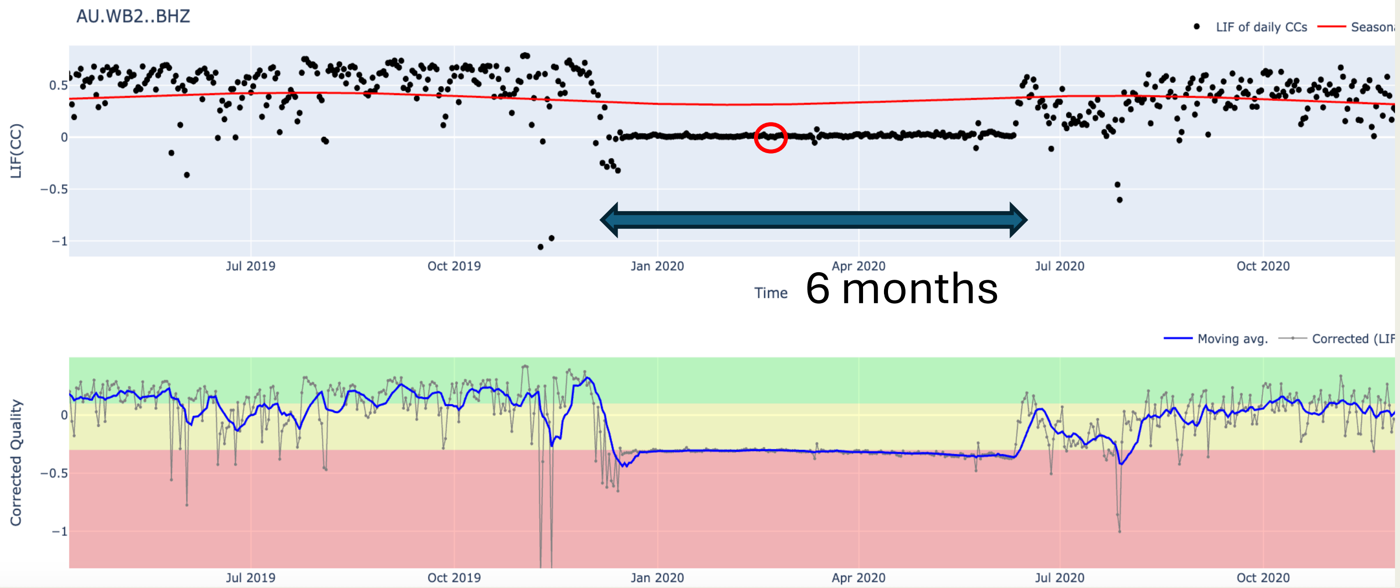
Jiun-Ting Lin, Ana Aguiar, Qingkai Kong, Steve Myers, Amanda Price

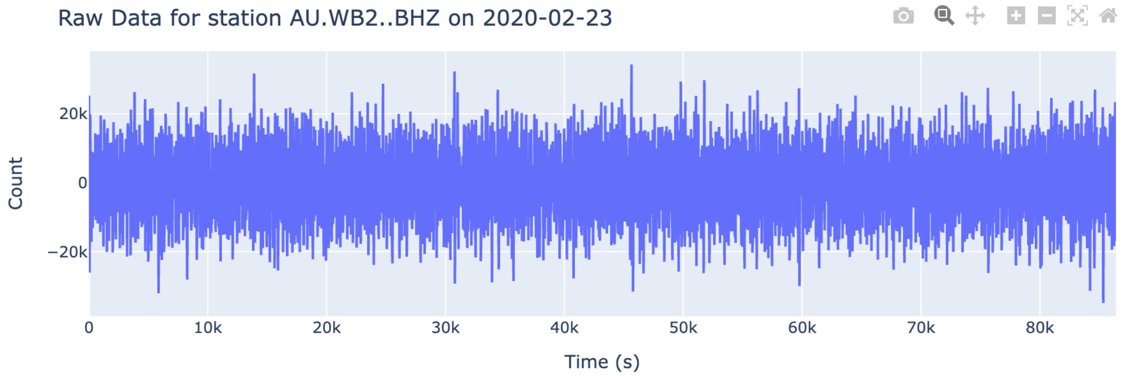
O4.4-458

## Application to other IMS

- Warramunga Array, Australia.
- The anomaly is difficult to identify from the raw data.
- Successfully detected by the model.






Lawrence Livermore National Laboratory

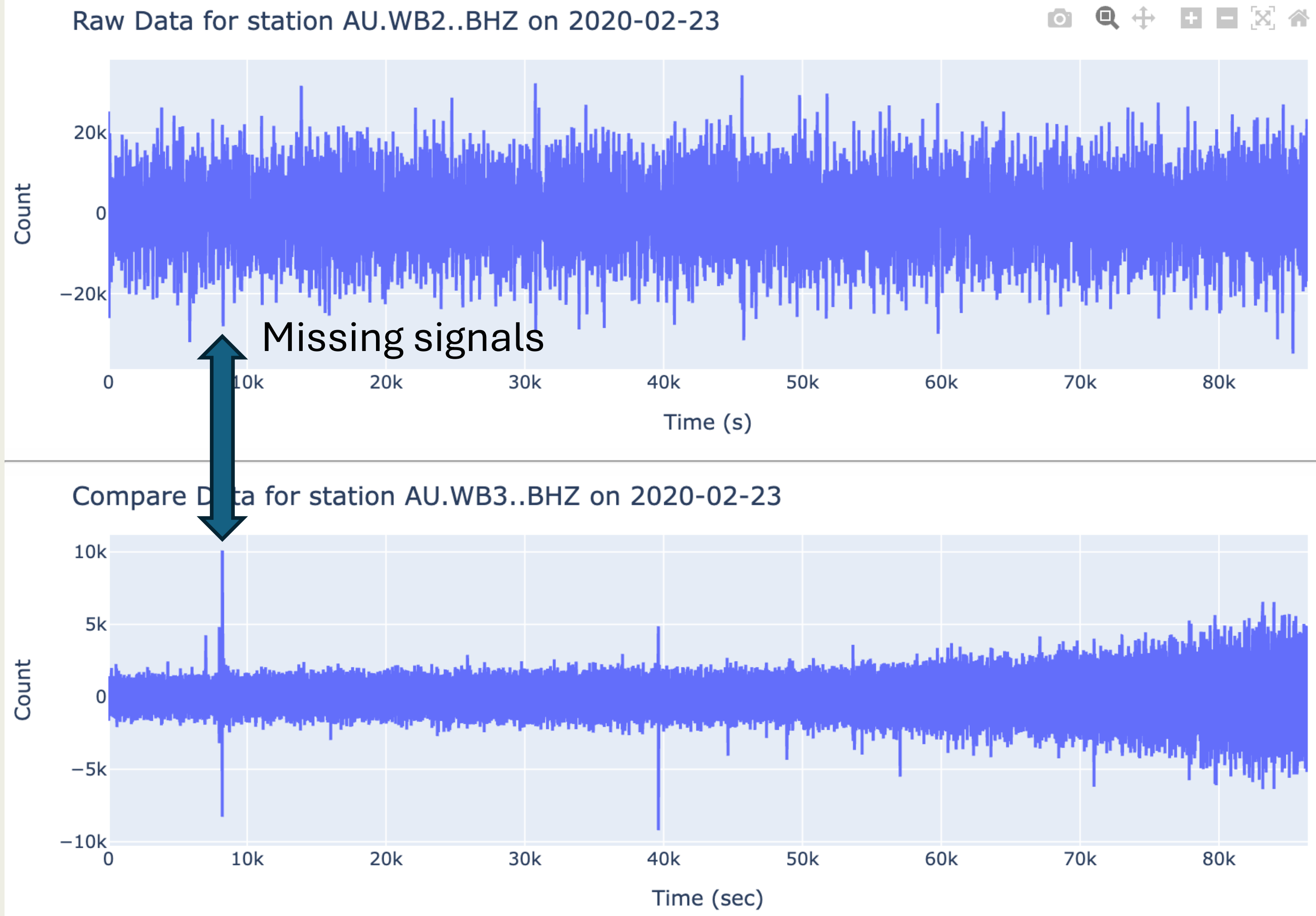
**Towards Predictive Maintenance Strategy Through Waveform Anomaly Detection using Unsupervised Learning**

Jiun-Ting Lin, Ana Aguiar, Qingkai Kong, Steve Myers, Amanda Price



# Application to other IMS

- Warramunga Array, Australia.
- The anomaly is difficult to identify from the raw data.
- Successfully detected by the model.



**Towards Predictive Maintenance Strategy Through Waveform Anomaly Detection using Unsupervised Learning**

Jiun-Ting Lin, Ana Aguiar, Qingkai Kong, Steve Myers, Amanda Price



# Conclusion

- We proposed a deep autoencoder model to detect anomalies in continuous seismic data.
- Long-term monthly anomalies can be detected by the model, allowing for the more efficient development of maintenance plans.
- The performance is similar to traditional approaches when the anomalous signals are explicit and well-defined.
- Our unsupervised approach has the capability to discover anomalous cases that were not present in the training data.
- Our approach may be expanded to other types of sensors.

RESEARCH ARTICLE | JUNE 20, 2025 Early Publication

Anomaly Detection in Seismic Data with Deep Learning: Application for Instrument Failure Detection and Forecasting

Jiun-Ting Lin; Ana C. Aguiar; Qingkai Kong; Amanda C. Price; Stephen C. Myers

+ Author and Article Information

Seismological Research Letters (2025) | https://doi.org/10.1785/0220240331 | Article history

**Thank you!**

Lawrence Livermore National Laboratory