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Assessing deep learning for seismic array processing pipelines

Andreas Köhler, Ben Dando, Nadege Langet, Steffen Mæland, Tord Stangeland

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Presentation Date: 9 September 2025

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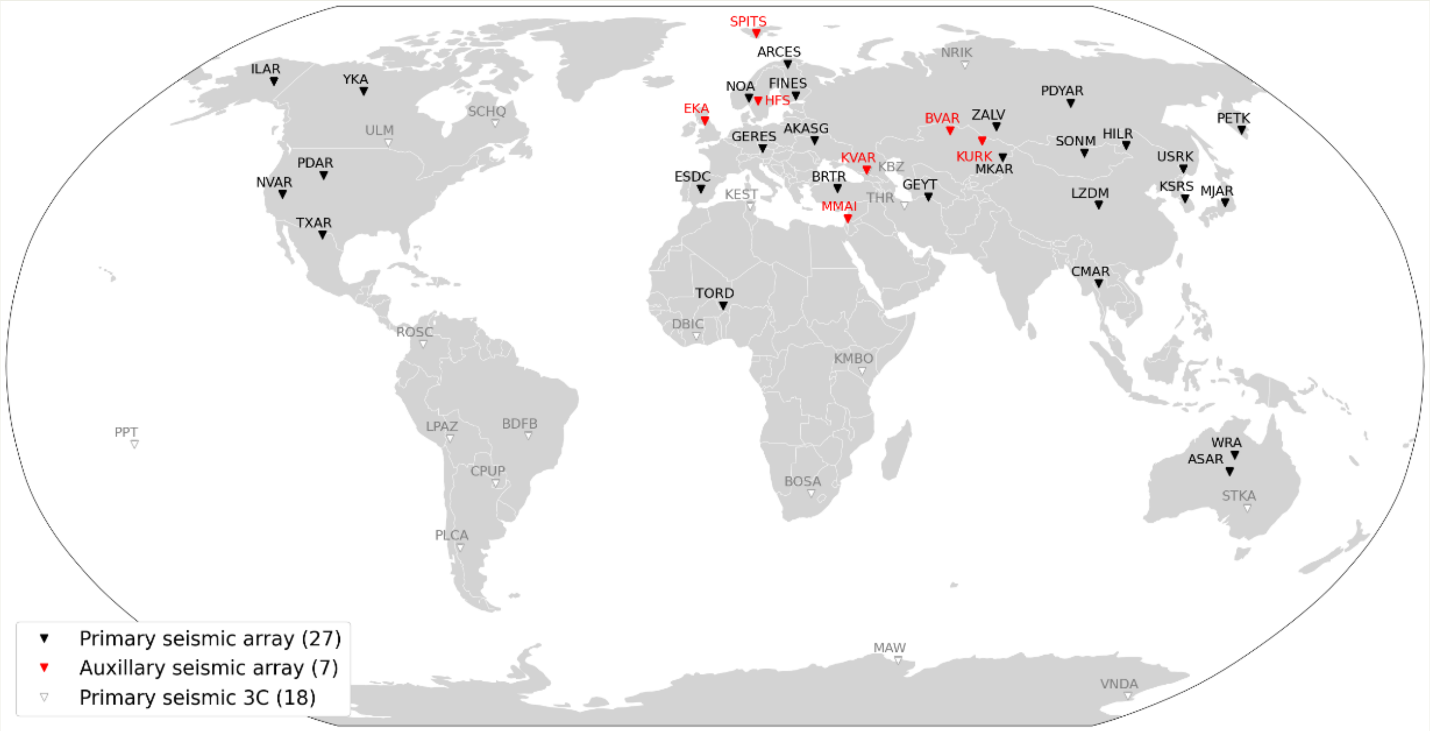
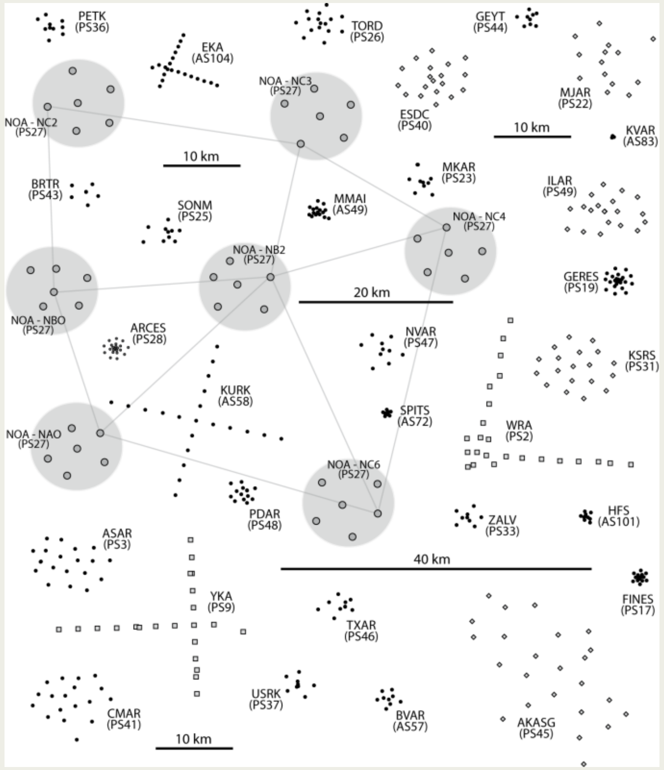
Motivation: IMS seismic arrays

- Seismic arrays are a critical part of the IMS and the processing pipeline for nuclear explosion monitoring
- Recent developments in machine learning have largely neglected seismic array processing



Seismic arrays of the IMS



Gibbons 2014

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Simplified array processing pipeline

1. Phase detection
2. Phase classification and back azimuth estimation
3. Event generation
4. Event classification

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Simplified array processing pipeline

1. Phase detection
Beam deployment with STA/LTA detectors

→

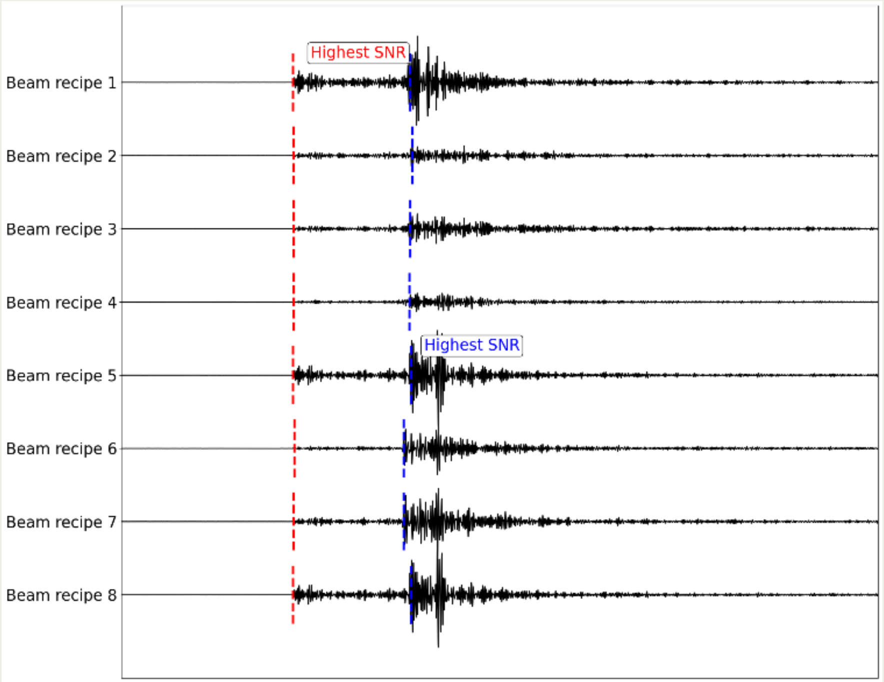
2. Phase classification and back azimuth estimation

→

3. Event generation

↓

4. Event classification



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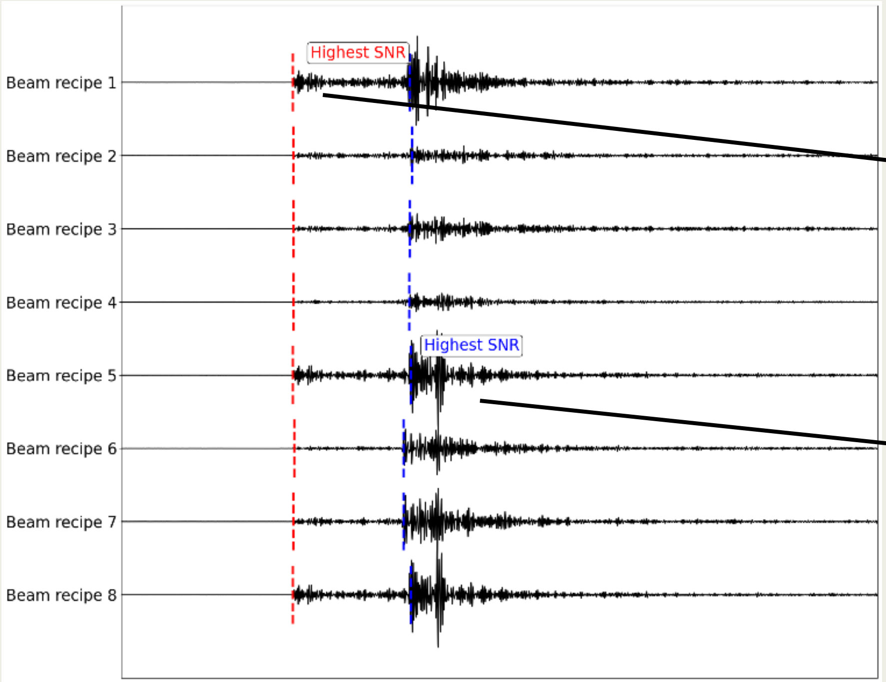
Simplified array processing pipeline

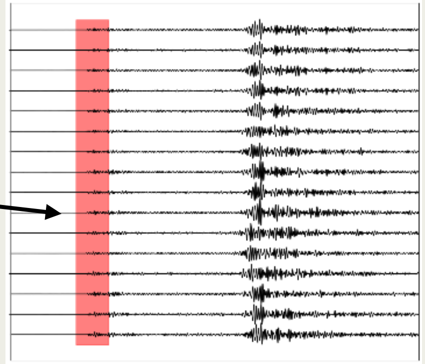
1. Phase detection
Beam deployment with STA/LTA detectors

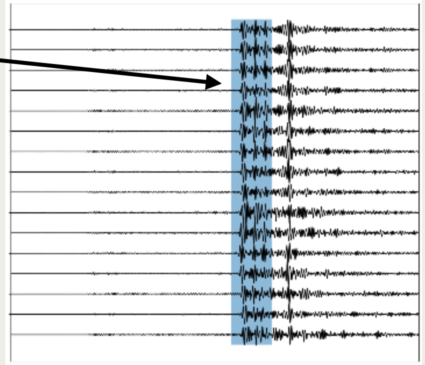
2. Phase classification and back azimuth estimation
from *f-k* analysis

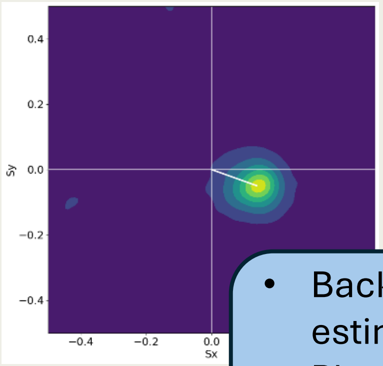
3. Event generation
Phase association and location

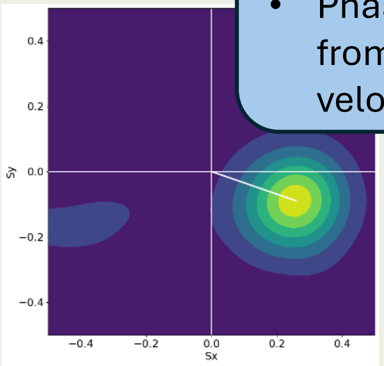
4. Event classification











- Back azimuth estimation
- Phase label from apparent velocity

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ML-assisted seismic array processing

1. Phase detection
Deep CNN architectures

→

2. Phase classification and back azimuth estimation

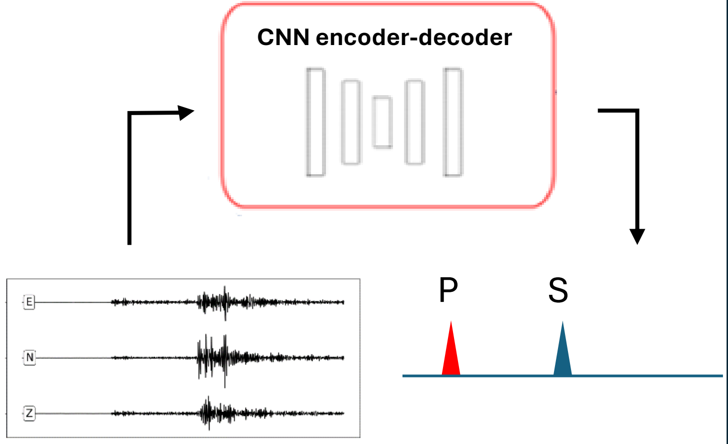
→

3. Event generation
Phase association and location

↓

4. Event classification

Deep Neural Network (DNN) pickers:
PhaseNet, EQTransformer, Epick, SkyNet ...



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ML-assisted seismic array processing

1. Phase detection
Deep CNN architectures

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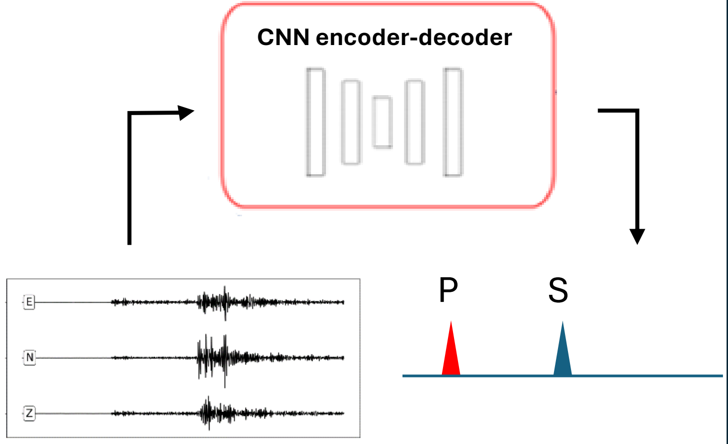

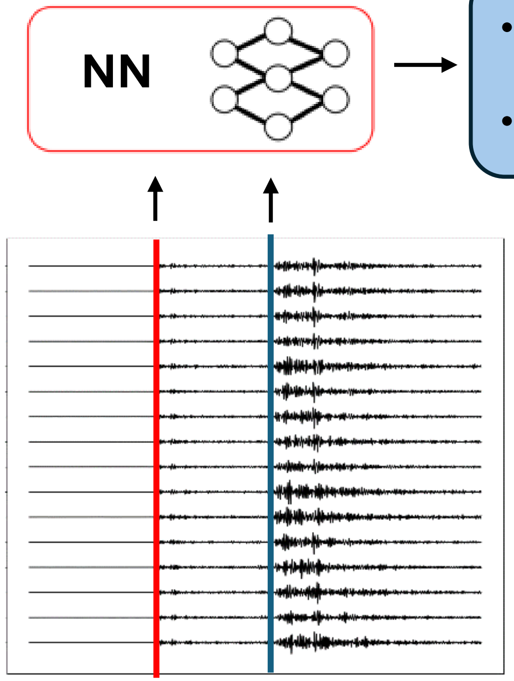

- Back azimuth estimation
- Phase label

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ML-assisted seismic array processing

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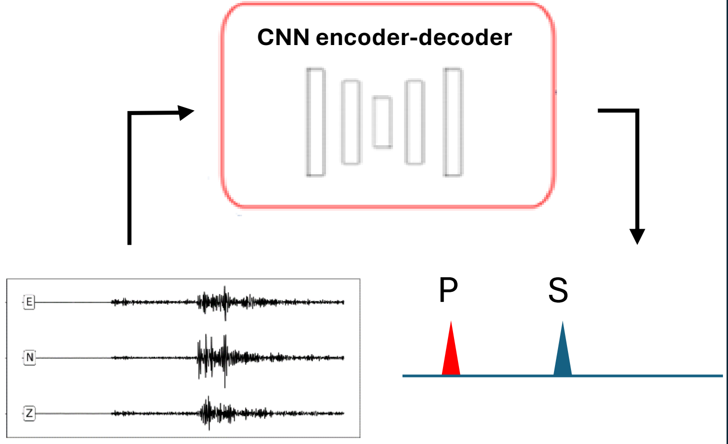
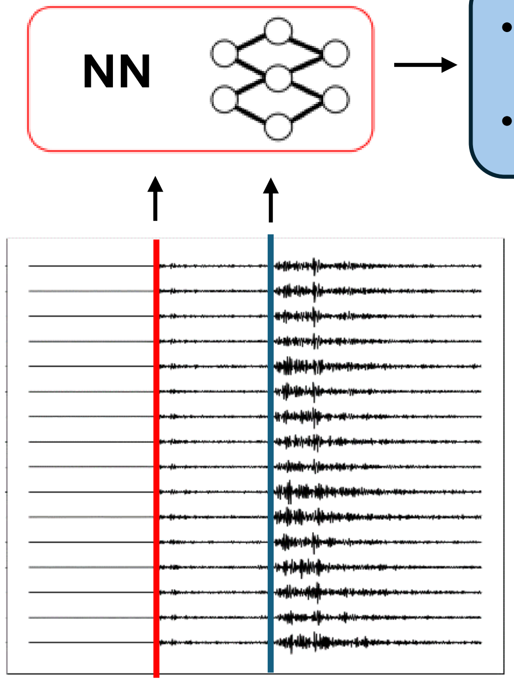
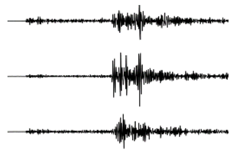
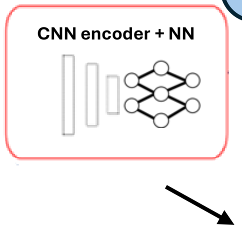




- Back azimuth estimation
- Phase label



4. Event classification



- Earthquake
- Explosion
- ...

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ML-assisted seismic array processing

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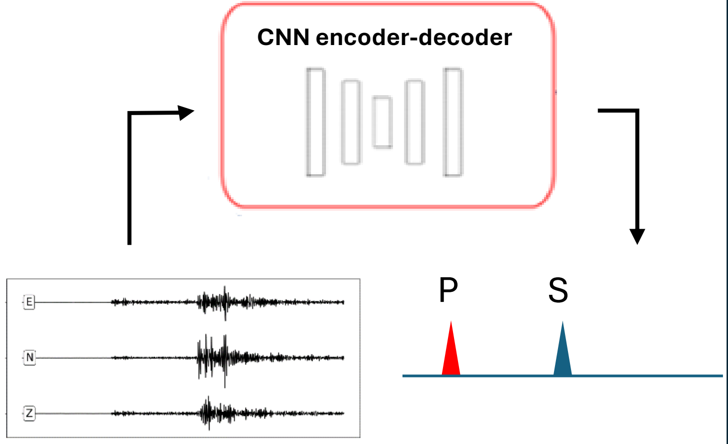
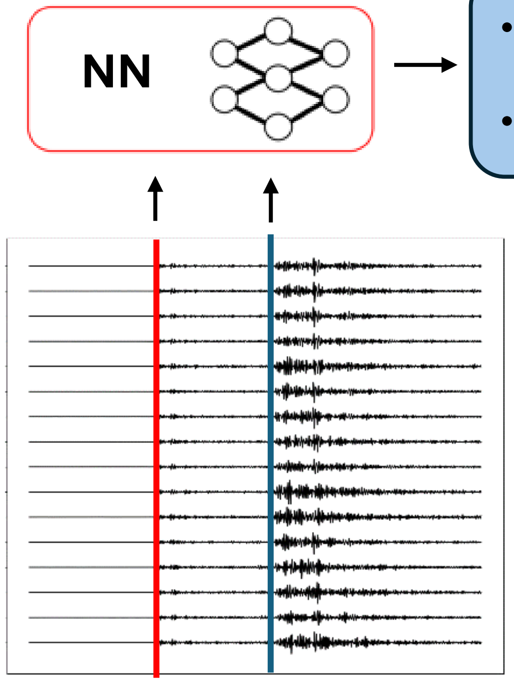
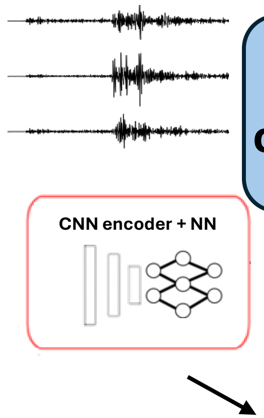




- Back azimuth estimation
- Phase label

4. Event classification



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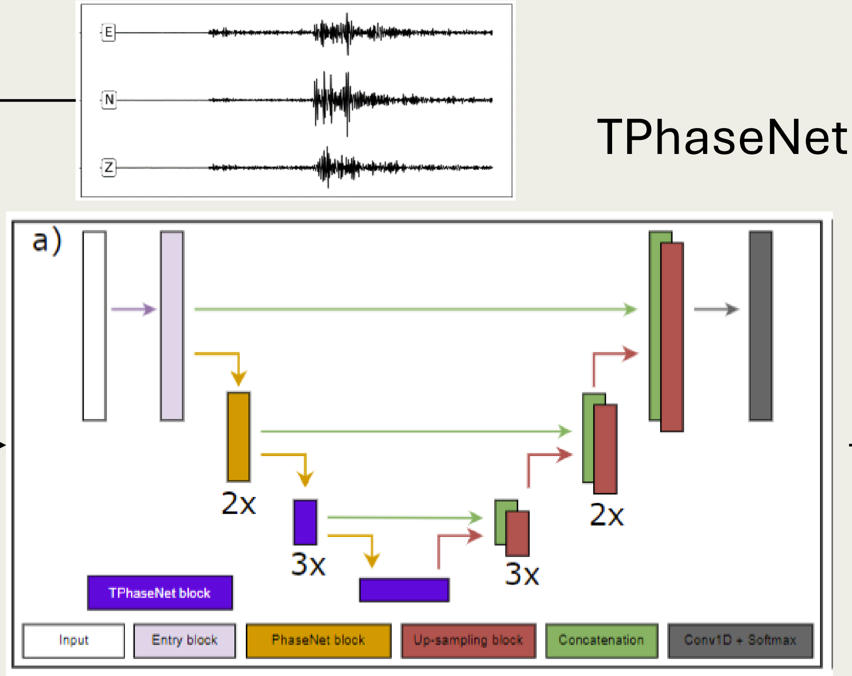
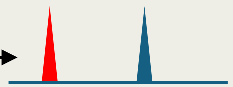
ML-assisted seismic array processing – Our approach

1. Phase detection
Deep CNN architectures

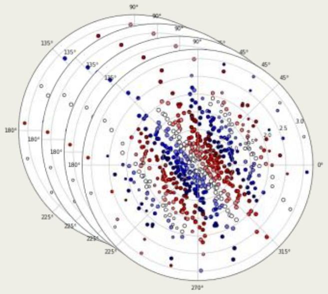
TPhaseNet



Myklebust and Köhler, GJI, 2024



2. Phase classification and back azimuth estimation



Co-array phase shift patterns of detected arrivals in narrow frequency bands

ArrayNet architecture

- Back azimuth
- Noise, P-wave, S-wave, Rg
  - Pg, Pn, P, PKP
  - Sg, Sn

Köhler and Myklebust, BSSA, 2023

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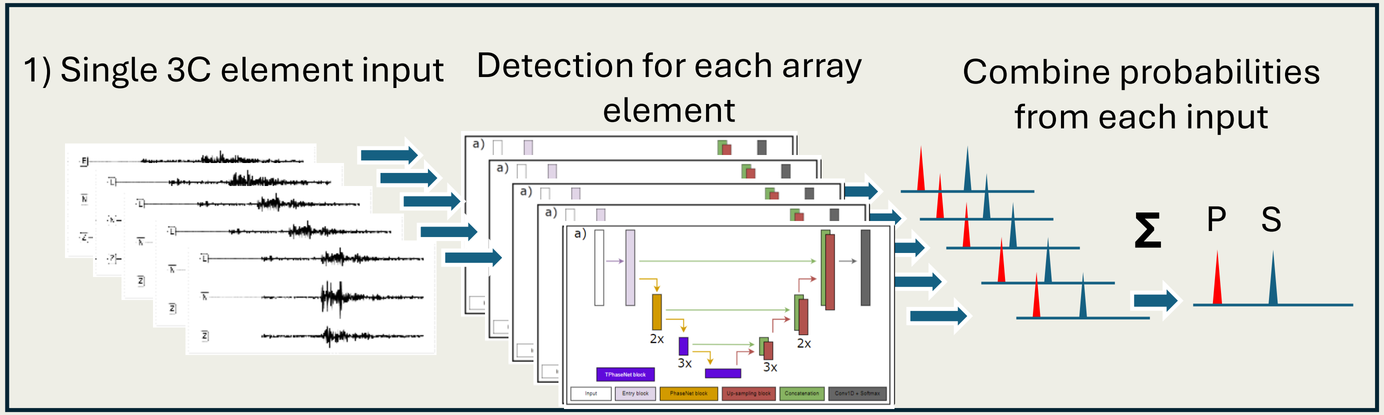
Strategies to apply DNN pickers to seismic array data

1. Single station DNN detection followed by array processing: **Ensemble detection**



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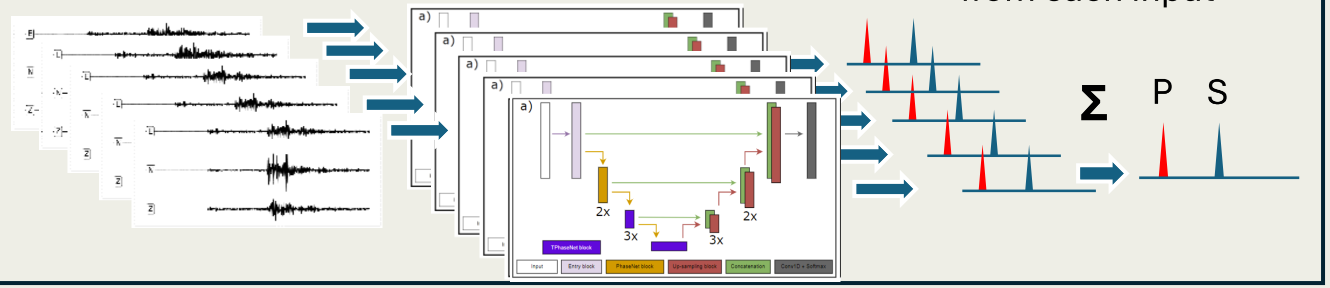
Strategies to apply DNN pickers to seismic array data

1. Single station DNN detection followed by array processing:
Ensemble detection

1) Single 3C element input

Detection for each array element

Combine probabilities from each input

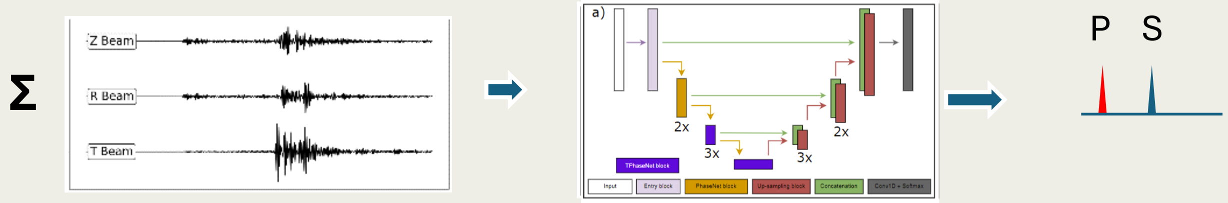


2. Array processing before DNN detections:
Beam detection

2) Beam input (e.g. Z,R,T or Z only)

Single model detection

Phase probability



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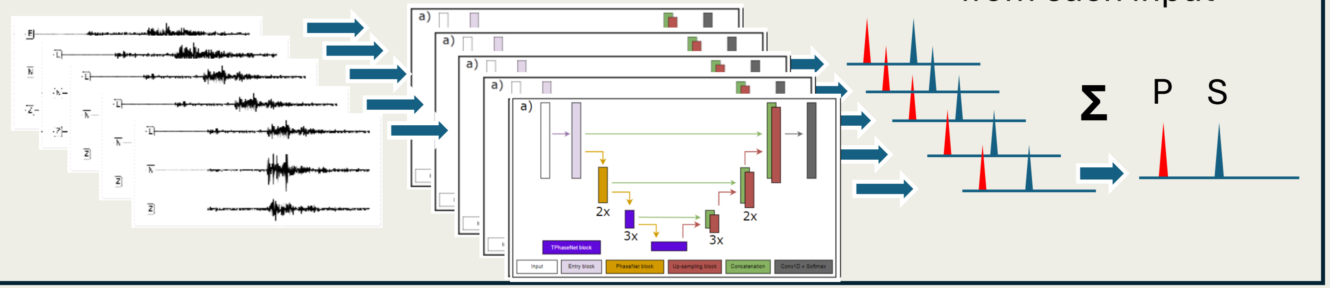
Strategies to apply DNN pickers to seismic array data

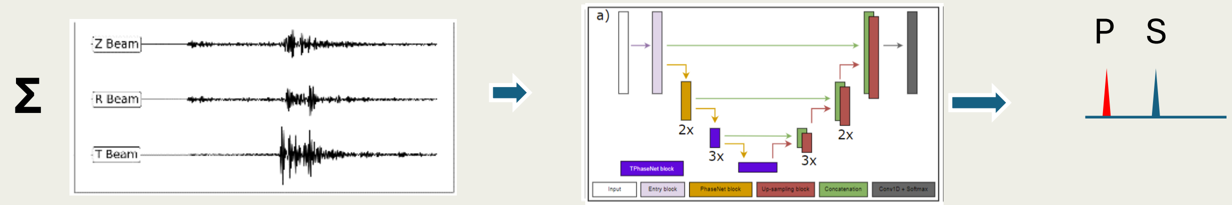
1. Single station DNN detection followed by array processing: **Ensemble detection**

1) Single 3C element input — Detection for each array element — Combine probabilities from each input



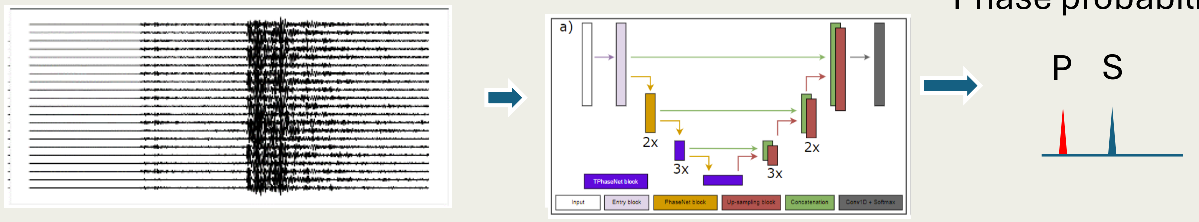
2. Array processing before DNN detections: **Beam detection**

2) Beam input (e.g. Z,R,T or Z only) — Single model detection — Phase probability



3. Array processing learned by DNN detector: **Array detection**

3) Full array input — Single model detection — Phase probability



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Strategies to apply DNN pickers to seismic array data

Array processing

1. Single station DNN detection followed by array processing: **Ensemble detection**

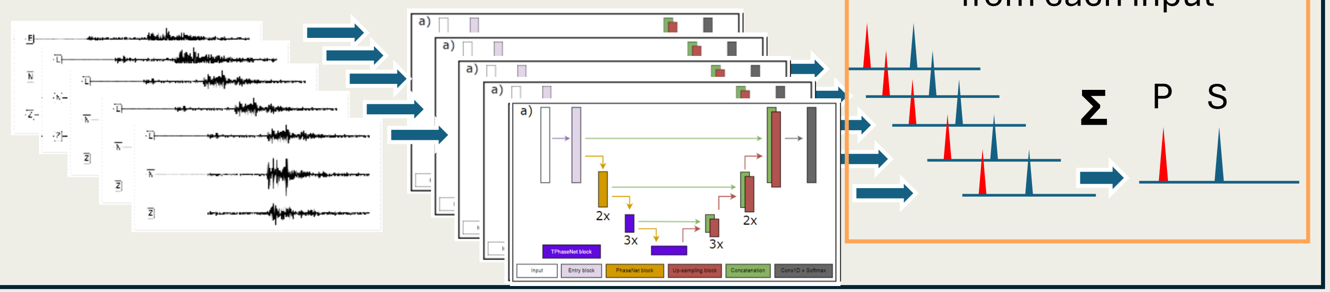
2. Array processing before DNN detections: **Beam detection**

3. Array processing learned by DNN detector: **Array detection**

1) Single 3C element input

Detection for each array element

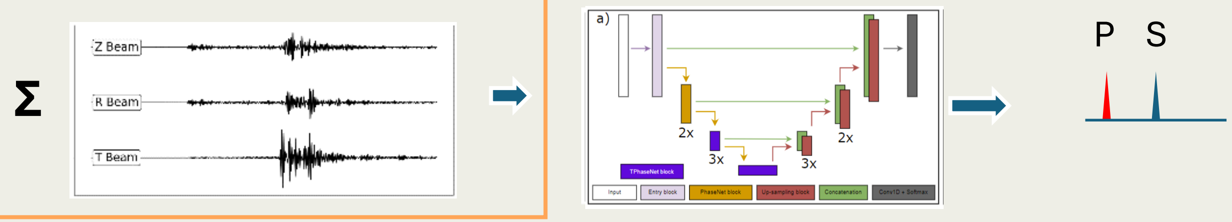
Combine probabilities from each input



2) Beam input (e.g. Z,R,T or Z only)

Single model detection

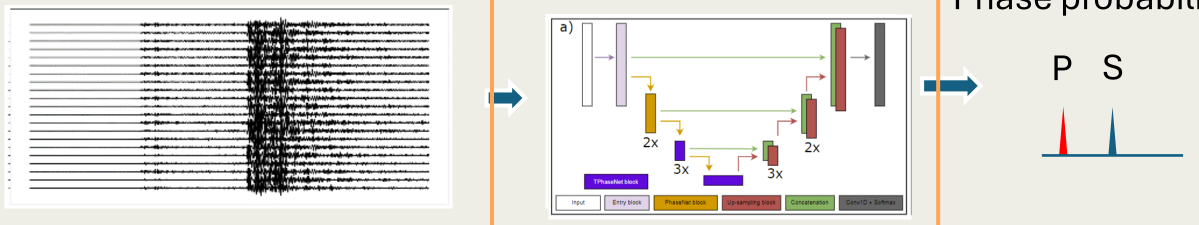
Phase probability



3) Full array input

Single model detection

Phase probability



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Strategies to apply DNN pickers to seismic array data

Array processing

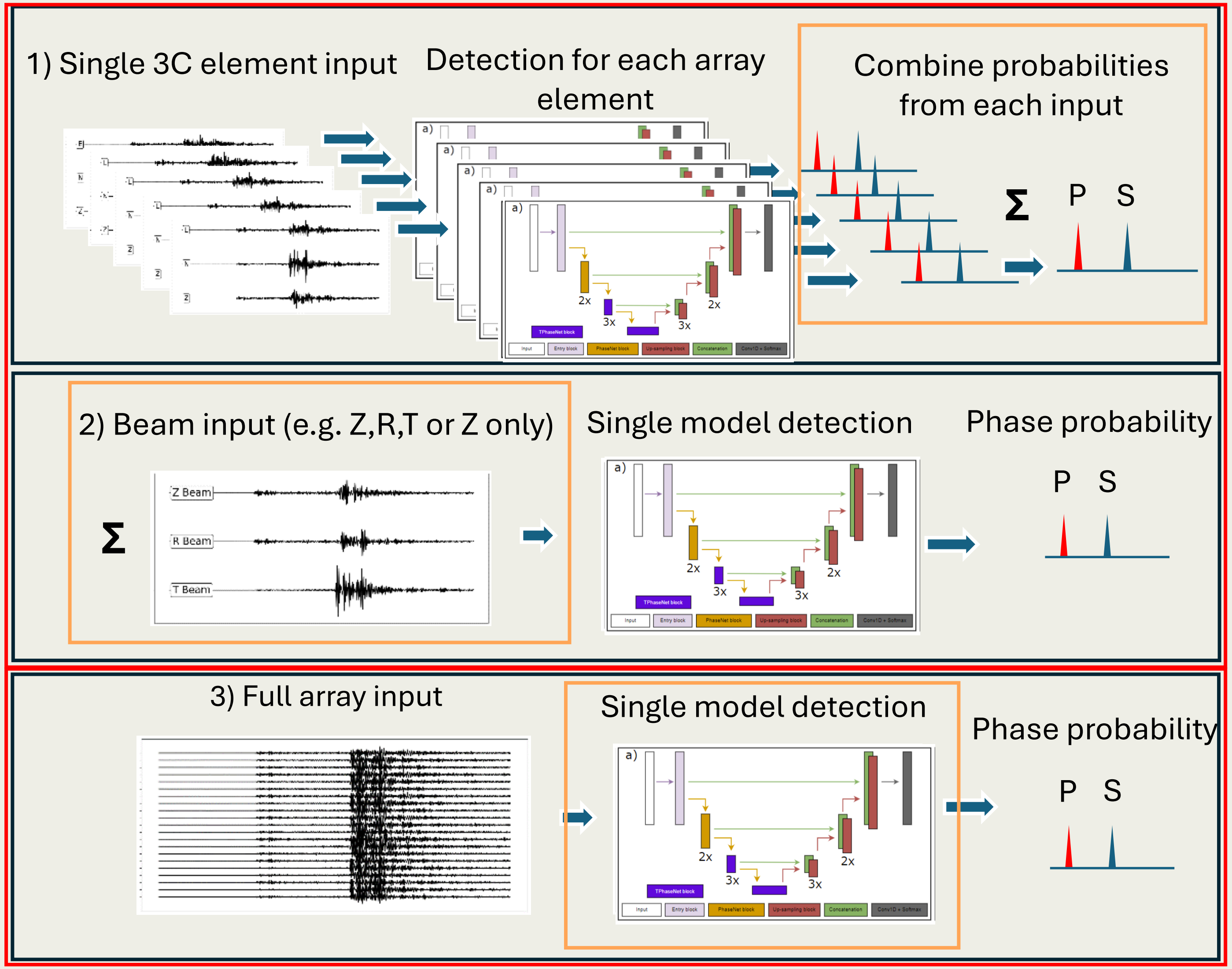
1. Single station DNN detection followed by array processing:
Ensemble detection

Trained for multiple arrays / slow

2. Array processing before DNN detections:
Beam detection

Trained for specific array / fast

3. Array processing learned by DNN detector:
Array detection



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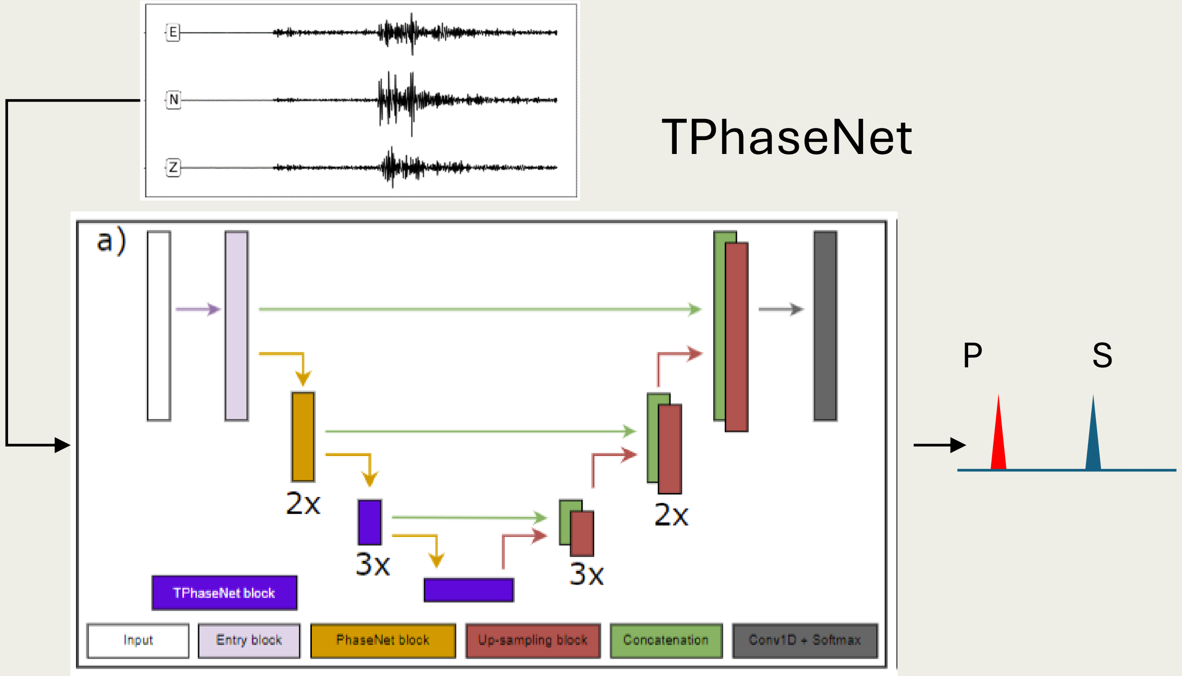
ML-assisted seismic array processing – Our approach

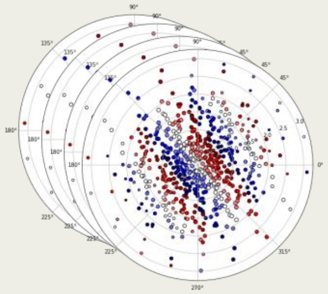
1. Phase detection
Deep CNN architectures



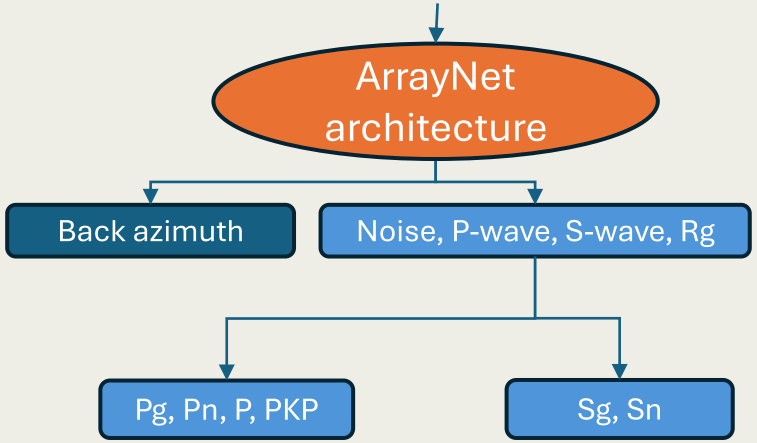
TPhaseNet

Myklebust and Köhler, GJI, 2024

2. Phase classification and back azimuth estimation



Co-array phase shift patterns of detected arrivals in narrow frequency bands



Köhler and Myklebust, BSSA, 2023

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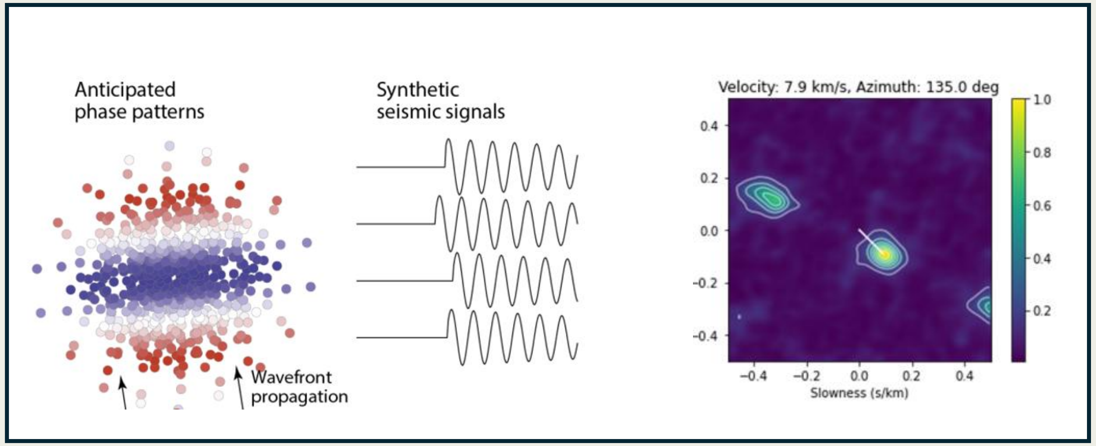
Seismic phase classification and back-azimuth from arrays

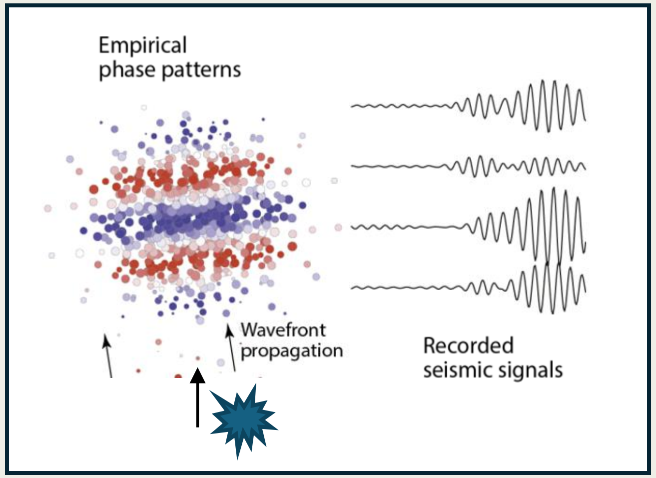
Conventional approach:

- Assumptions: Plane wave and back-azimuth identical to source direction
- Find slowness of best fitting plane wave through grid search (*f-k* analysis) or other methods (e.g., PMCC)
- Use fixed apparent velocity thresholds to classify regional/teleseismic phase arrivals



Limitations:

- Deviation from plane wave due to local inhomogeneities below array
- Back-azimuth deviations due to geology between source and array
- Systematic lack of waveform coherency
- Velocity thresholds for phases differ from site to site and must be defined manually



Solutions:

- Empirical slowness corrections
- Empirical matched field processing

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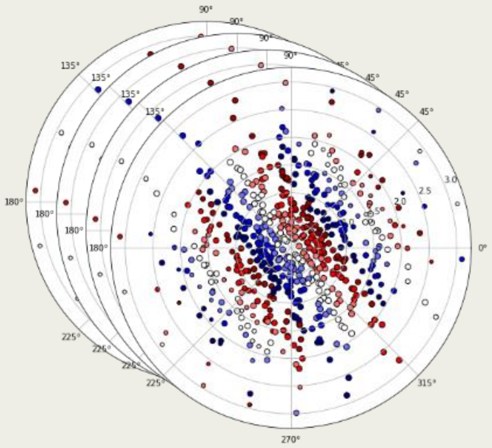
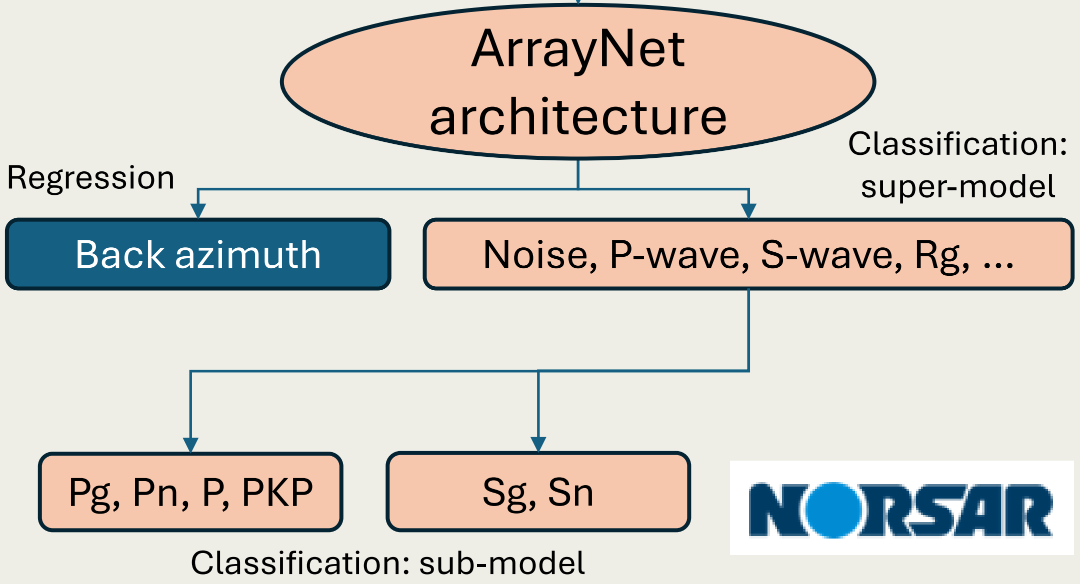
ArrayNet: A Neural Network for phase classification and back azimuth estimation

- NN learns to identify phase types and back-azimuth from measured phase shifts on the co-array
- Advantages:
  - Does not require a plane-wave assumption
  - No need for empirical slowness corrections
  - No hard velocity limits for phase classification
  - Includes a noise class representing array-specific background noise
  - Faster than *f-k* once trained
  - Can include custom signal or synthetic (augmented) arrival classes
  - Recently included uncertainty estimates (MC DropOut & NN calibration)

BSSA, Köhler & Myklebust, 2023



Co-array phase shift patterns in narrow frequency bands for a given seismic arrival = “phase fingerprint”



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Results of performance evaluation

1. Phase detection
TPhaseNet on arrays with:
- Single-station Detection
- Ensemble Detection
- Beam Detection
- Array Detection

→

2. Phase classification and back azimuth estimation: ArrayNet

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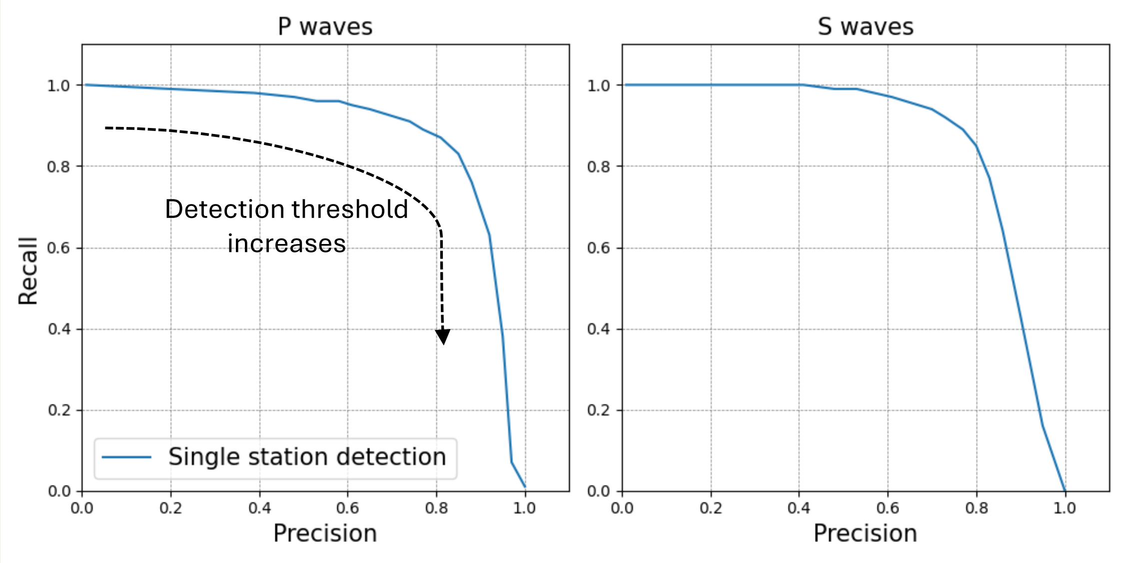
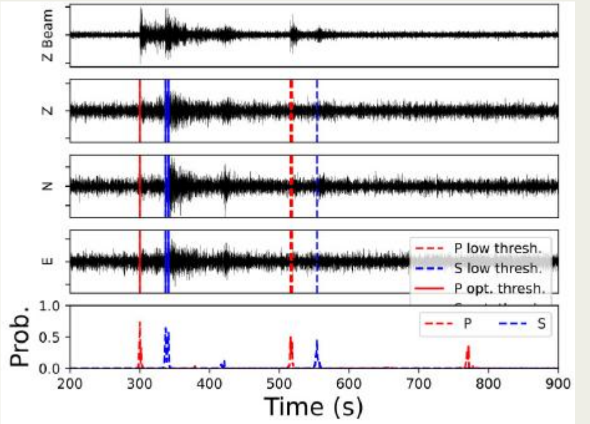
Results Step 1: Phase detection

Evaluation on test data

Event time windows, all stations, year 2022





Single station detection

Recall: computed using clear P and S arrivals

Precision: computed from all coherent arrivals

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Results Step 1: Phase detection

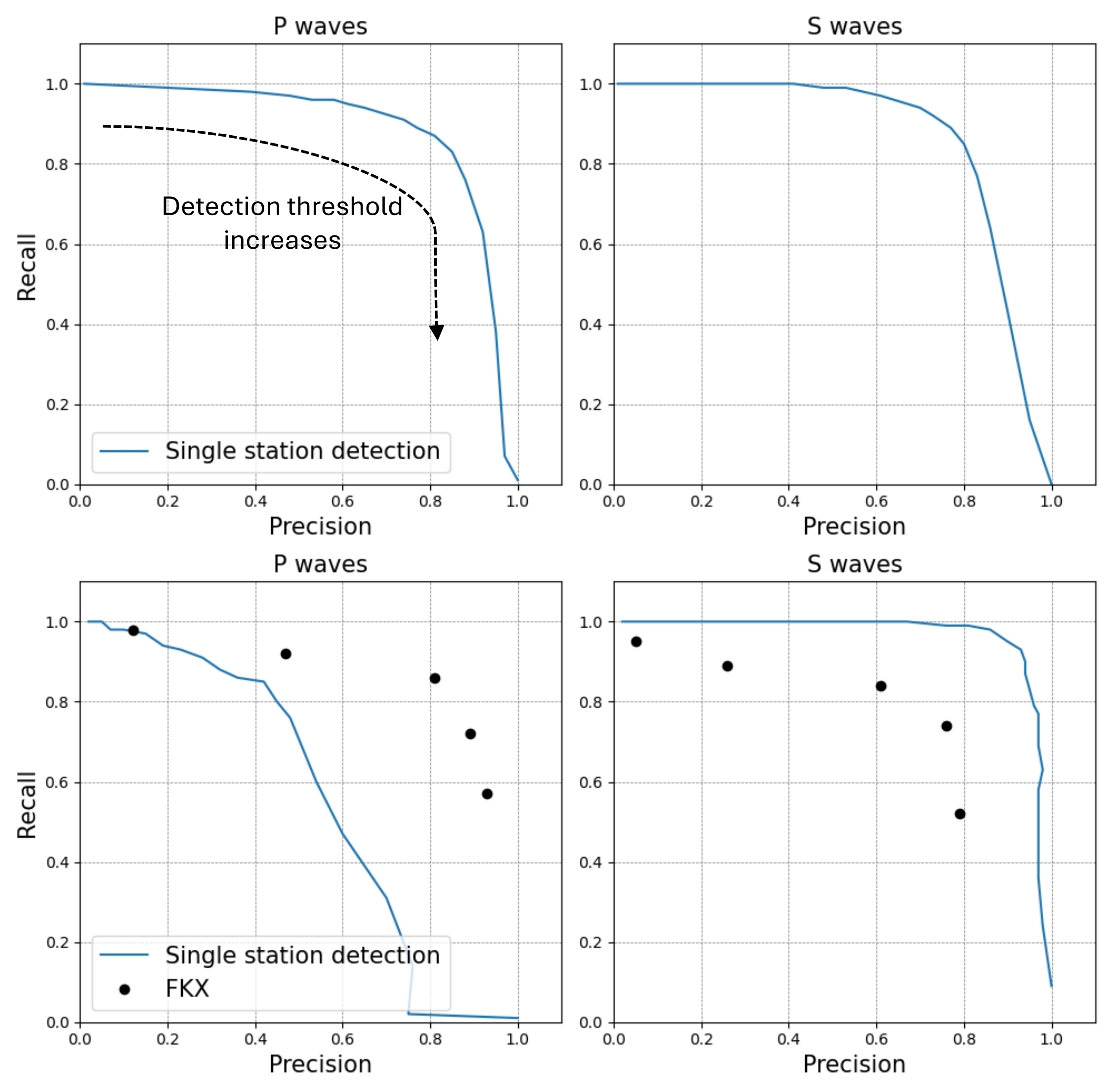
Evaluation on test data

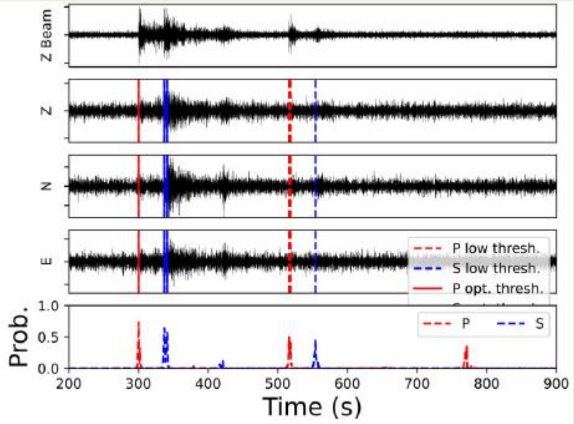
Event time windows, all stations, year 2022

Evaluation on continuous data

Four days of 920 hand-picked arrivals at ARCES (486 clear P & S waves)

Operational NORSAR STA/LTA-based detector for comparison (FKX) ●





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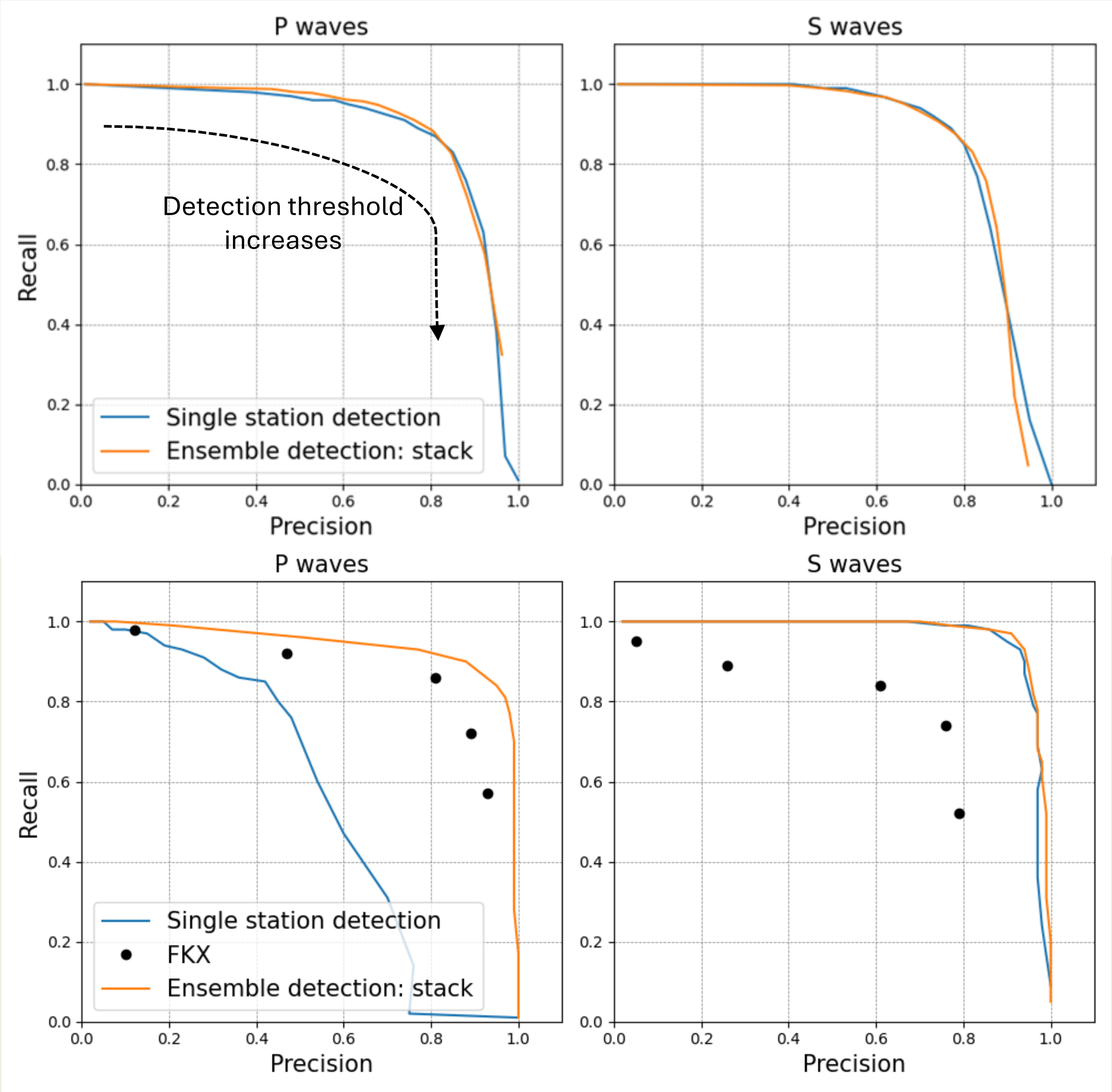
Results Step 1: Phase detection

Evaluation on test data

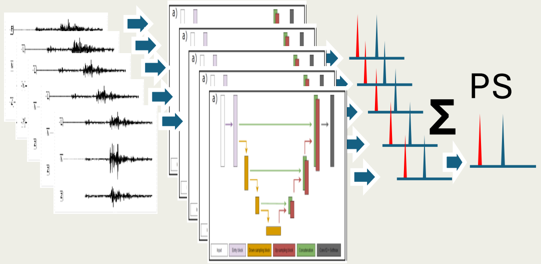
Evaluation on continuous data



Single station

vs.

Ensemble detection



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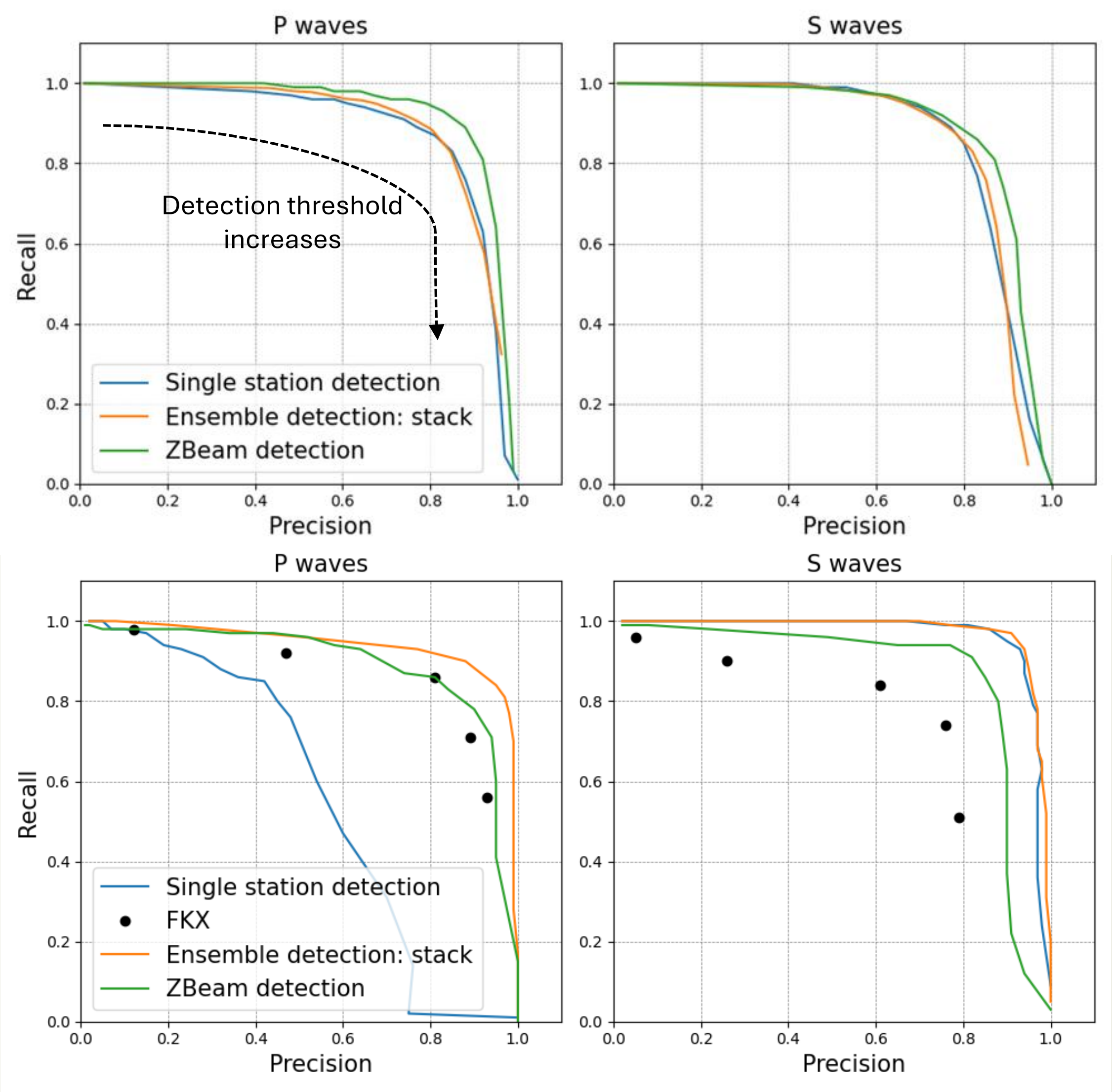
Results Step 1: Phase detection

Evaluation on test data

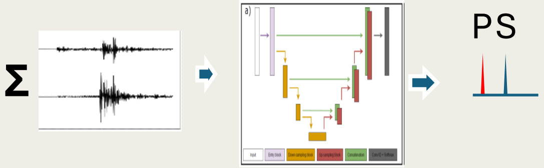
Evaluation on continuous data



Single station, ensemble

vs.

Z Beam detection



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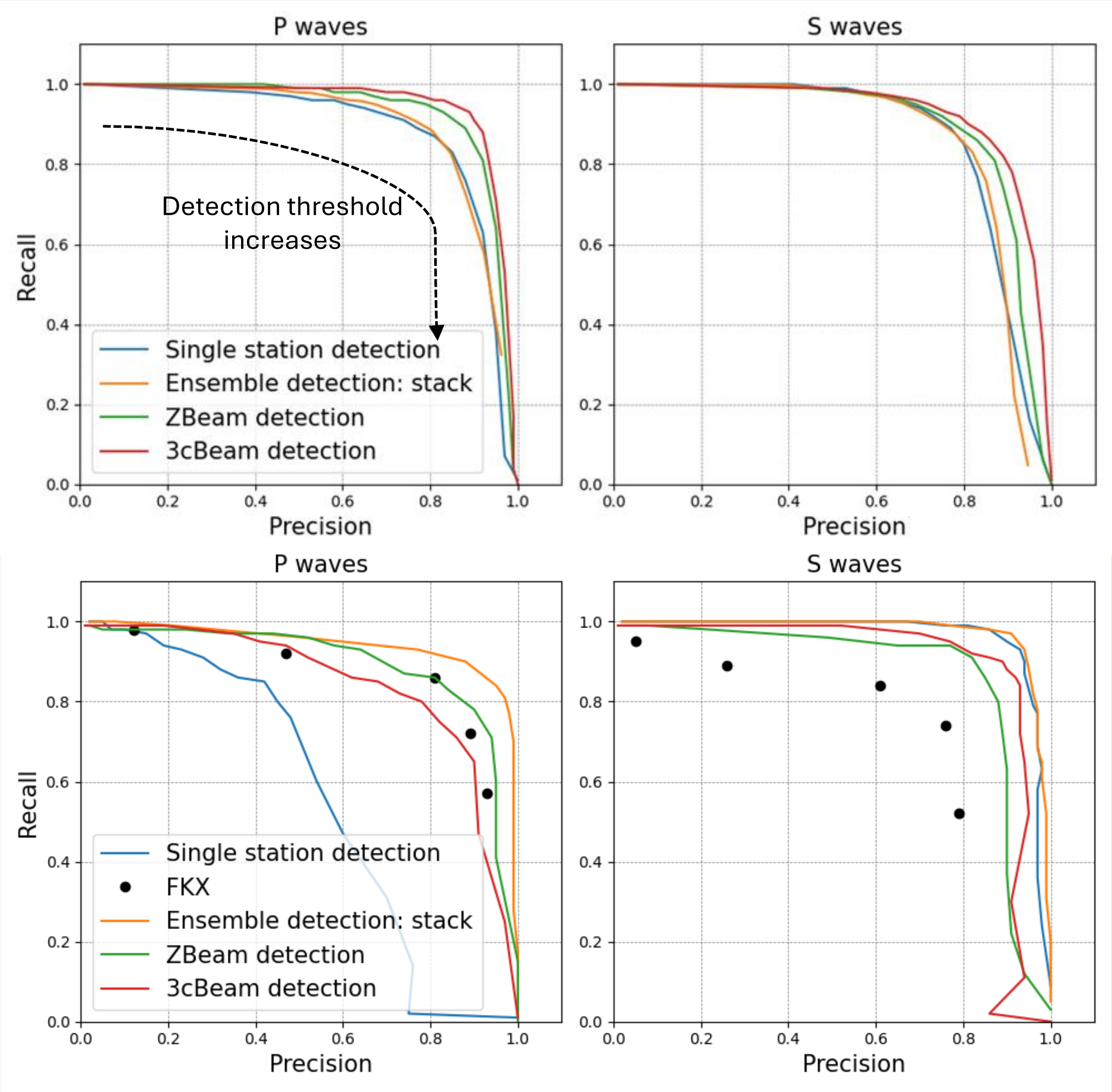
Results Step 1: Phase detection

Evaluation on test data

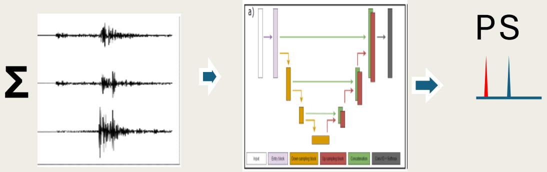
Evaluation on continuous data



Single station, ensemble

vs.

3c Beam detection



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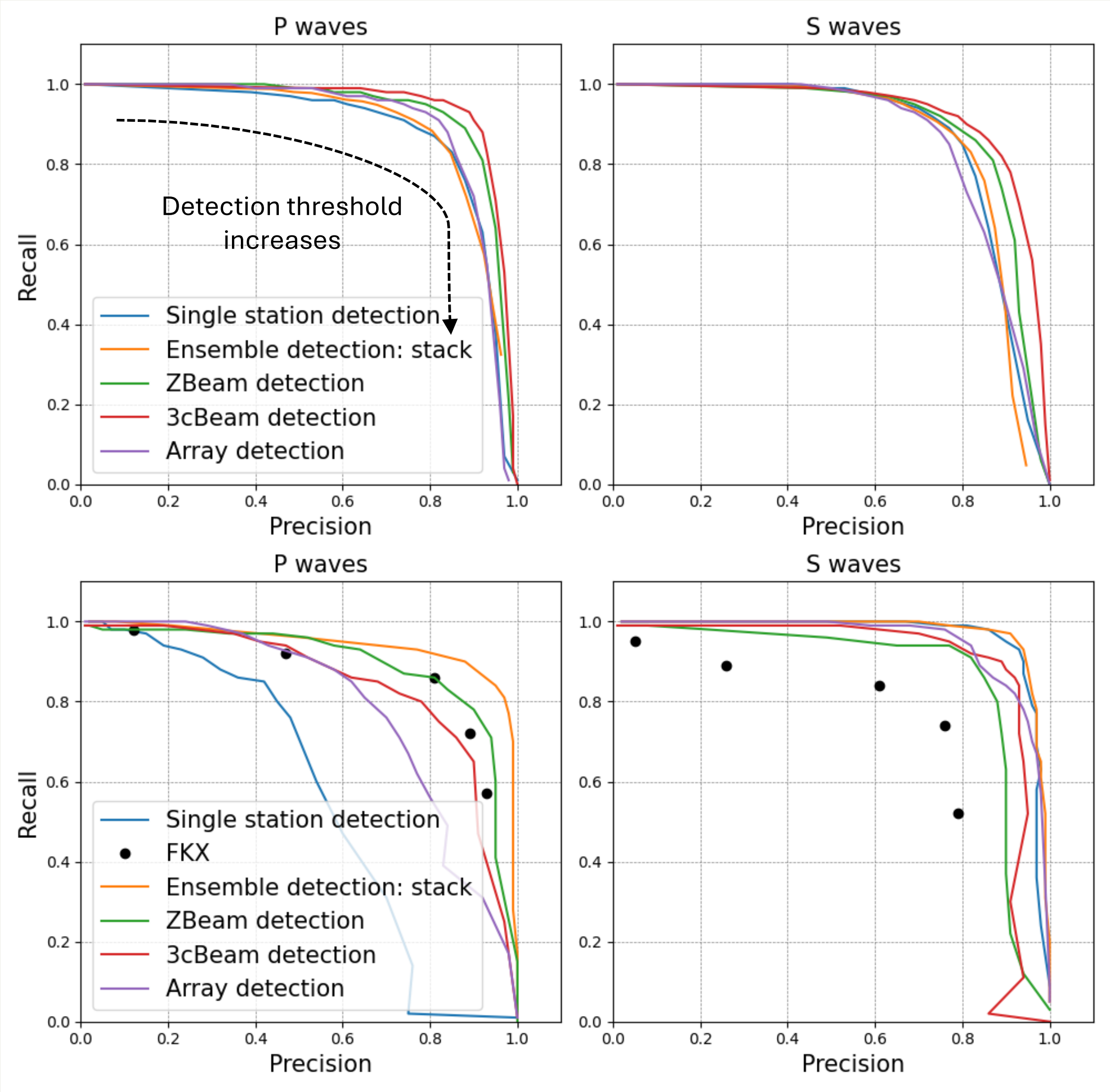
Evaluation on test data

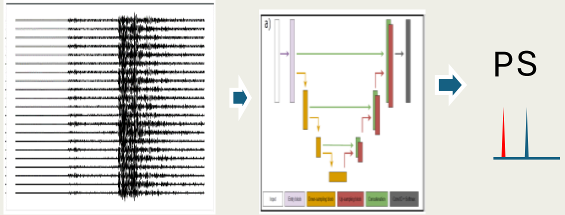
Evaluation on continuous data



Single station, ensemble, beam

vs.

Array detection (ARCES only)



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Results of performance evaluation

1. Phase detection
TPhaseNet on arrays with:

- Single-station Detection
- Ensemble Detection
- Beam Detection
- Array Detection

→

2. Phase classification and back azimuth estimation: ArrayNet

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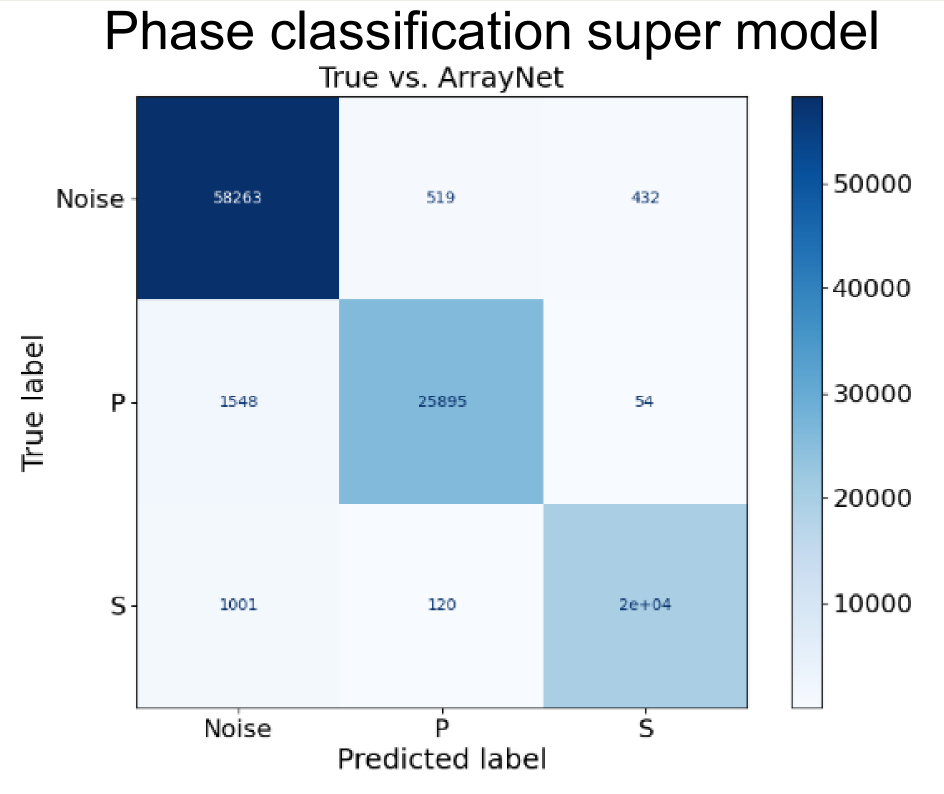
Results Step 2: ArrayNet applied to ARCES array



Better performance compared to classic *f-k*-based phase classification (NORSAR FKX)

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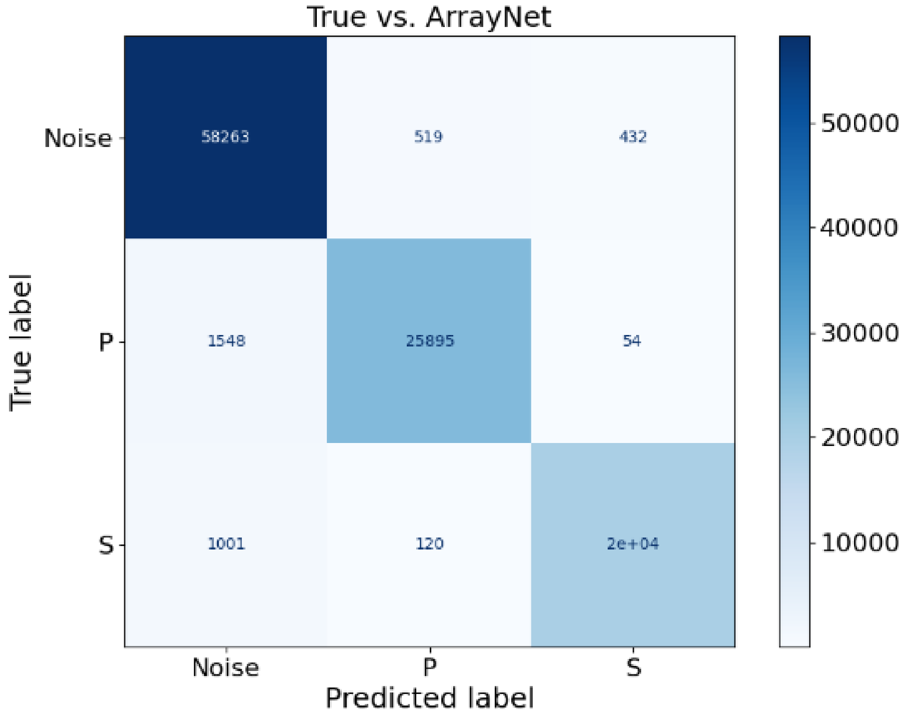
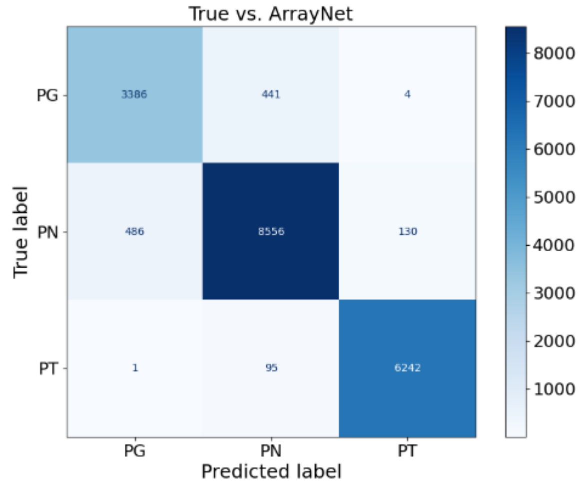
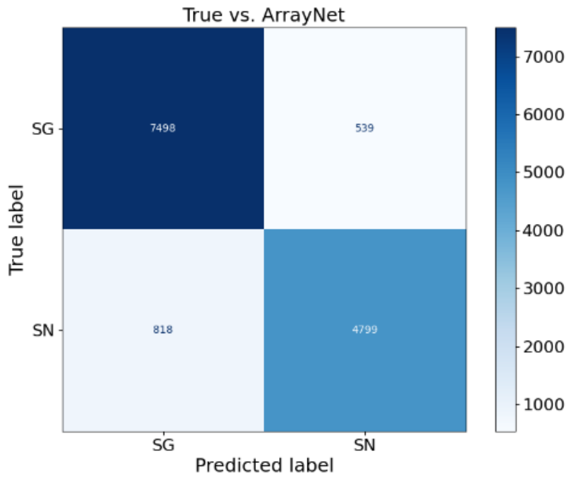
Results Step 2: ArrayNet applied to ARCES array

Phase classification super model



Classification sub model





Better performance compared to classic *f-k*-based phase classification (NORSAR FKX)

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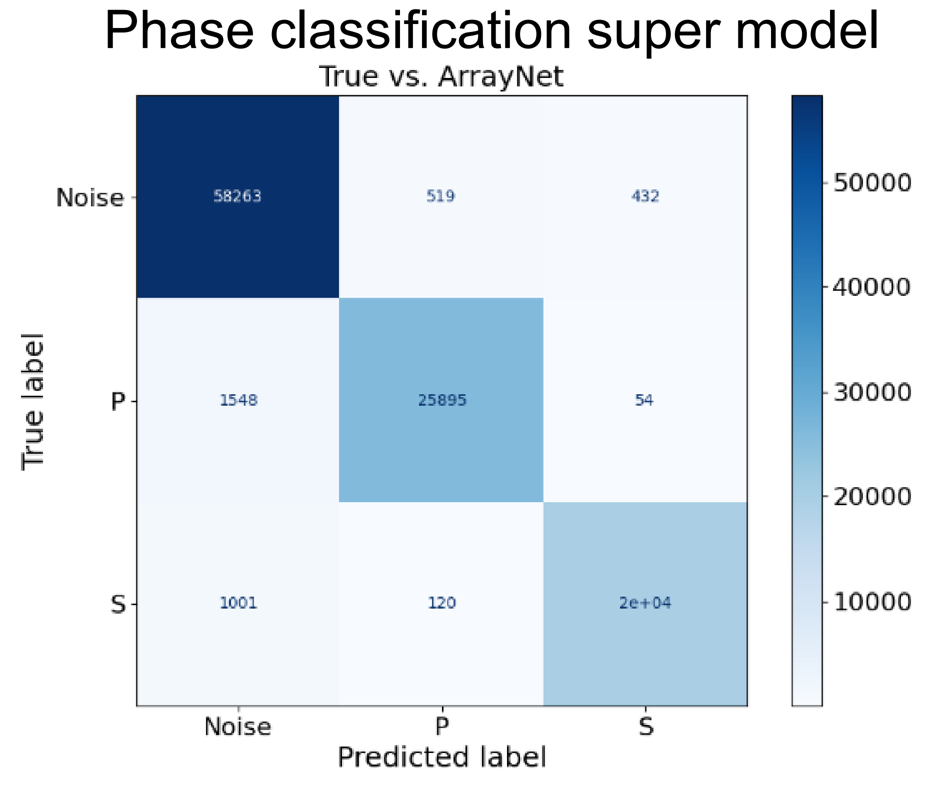
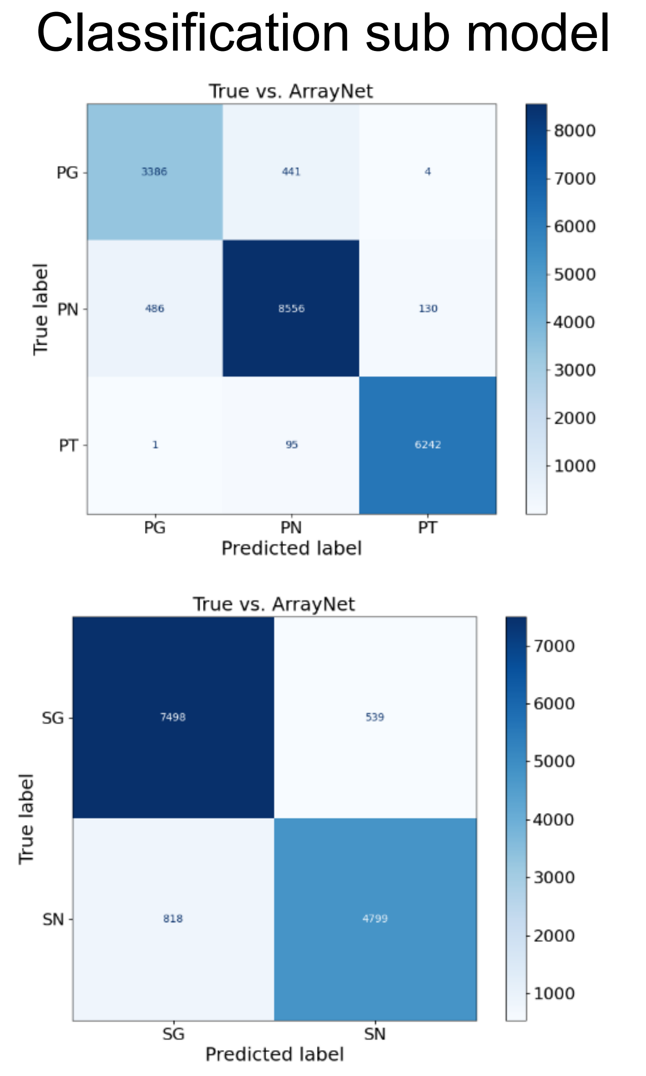
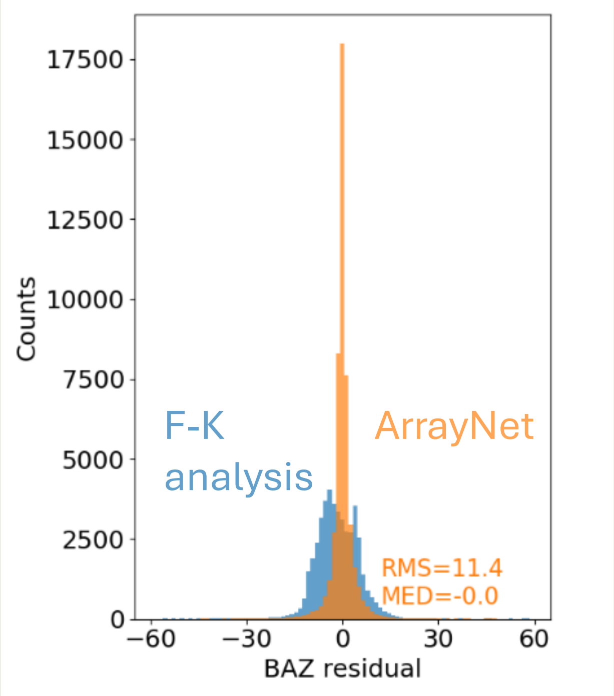
Results Step 2: ArrayNet applied to ARCES array







Back-azimuth regression

Better performance compared to classic *f*-*k*-based phase classification (NORSAR FKX)

BSSA, Köhler & Myklebust, 2023

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Conclusions

- NORSAR has developed the usage of ML for seismic array processing
- Evaluation of three strategies to leverage DNN pickers (TPhaseNet) with array data:
  - All tested strategies outperform single-station detection
  - Application to continuous data with ensemble and beam detection outperforms classic array processing but is computational expensive
  - Array detection model without pre- or post-beamforming is much faster - currently outperforms S wave detection using classic array processing
- ArrayNet is a successful ML method for phase classification and back-azimuth estimation.
- Ongoing and future work: Pipeline processing & integration of Graph Neural Network

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Acknowledgements & References

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- Thank you to both AFRL and ARA

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ArrayNet: A Combined Seismic Phase Classification and Back-Azimuth Regression Neural Network for Array Processing Pipelines

Andreas Köhler ; Erik B. Myklebust

+ Author and Article Information

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Geophysical Journal International

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Advance Access publication 2024 August 23
GJI Seismology

Deep learning models for regional phase detection on seismic stations in Northern Europe and the European Arctic

Erik B. Myklebust [1] and Andreas Köhler [1,2]

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[2] UiT - The Arctic University of Norway, Department of Geosciences, 9037 Tromsø, Norway

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Additional back-up slides

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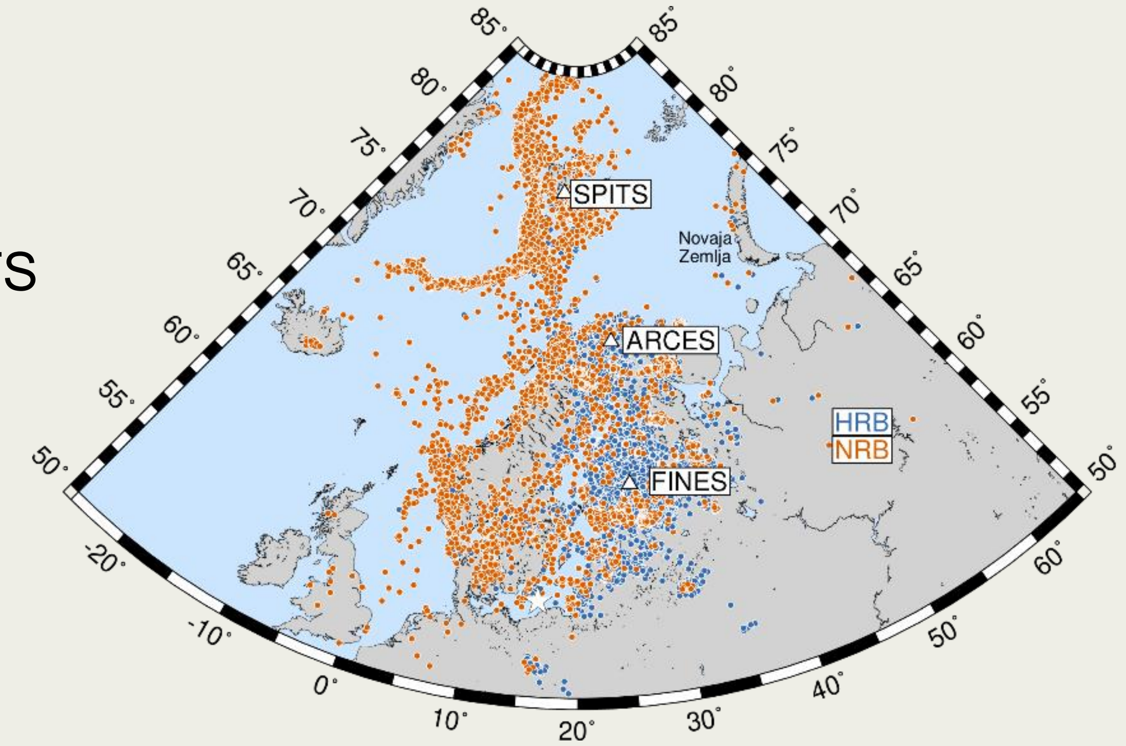
Training data for all methods

- Regional seismic events since 1994 obtained from reviewed bulletins:
  - NORSAR (NRB)
  - University of Helsinki (HRB)
  - LEB
  - EURARC: European Arctic Bulletin
- Waveforms: ARCES, FINES, NORES, NOA & SPITS
- For DNN pickers:
  - Labels: P and S picks
  - About 300,000 waveforms
  - Pre-filtering 2-8 Hz
  - 1994-2020 used for training; 2021 for validation (during training); 2022 for testing (after training)
  - Various augmentation of training data
  - Training one model: 4-24 hours on GPU



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Assessing deep learning for seismic array processing pipelines

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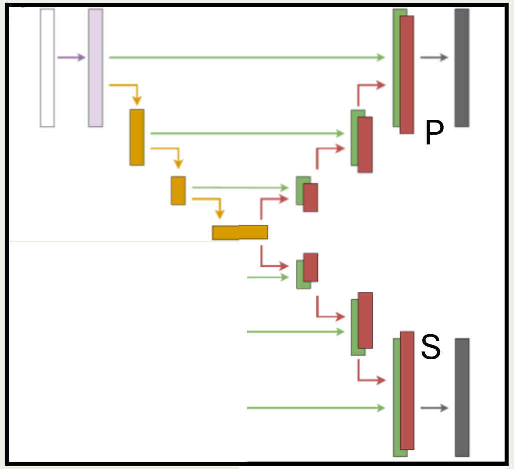
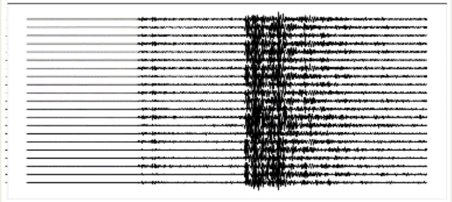
Implemented modifications for array detection approach

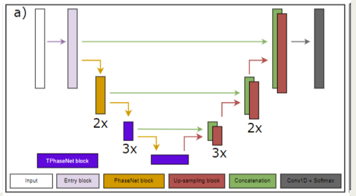
- Use TPhaseNet with depth-wise convolution layers
- Use separate decoder branches for P and S waves (as EQ transformer)



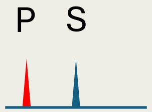
3) Full array input



Single model prediction

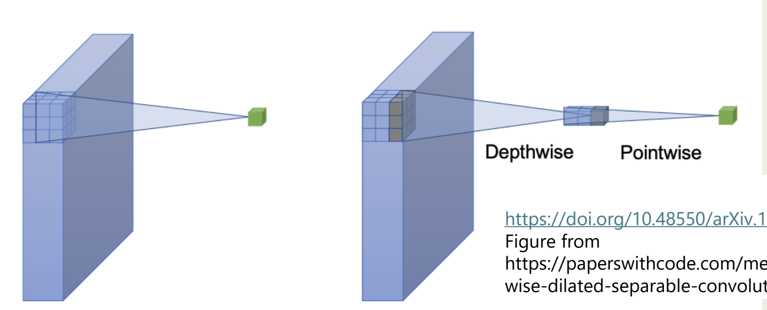


Phase probability



Normal convolution

Depth-wise convolution



https://doi.org/10.48550/arXiv.1811.11431
Figure from https://paperswithcode.com/method/depthwise-dilated-separable-convolution

- Applies filters across all channels at once
- Channels mix during convolution

- Applies filters separately to each channel
- Channels mix later (with point-wise convolution)

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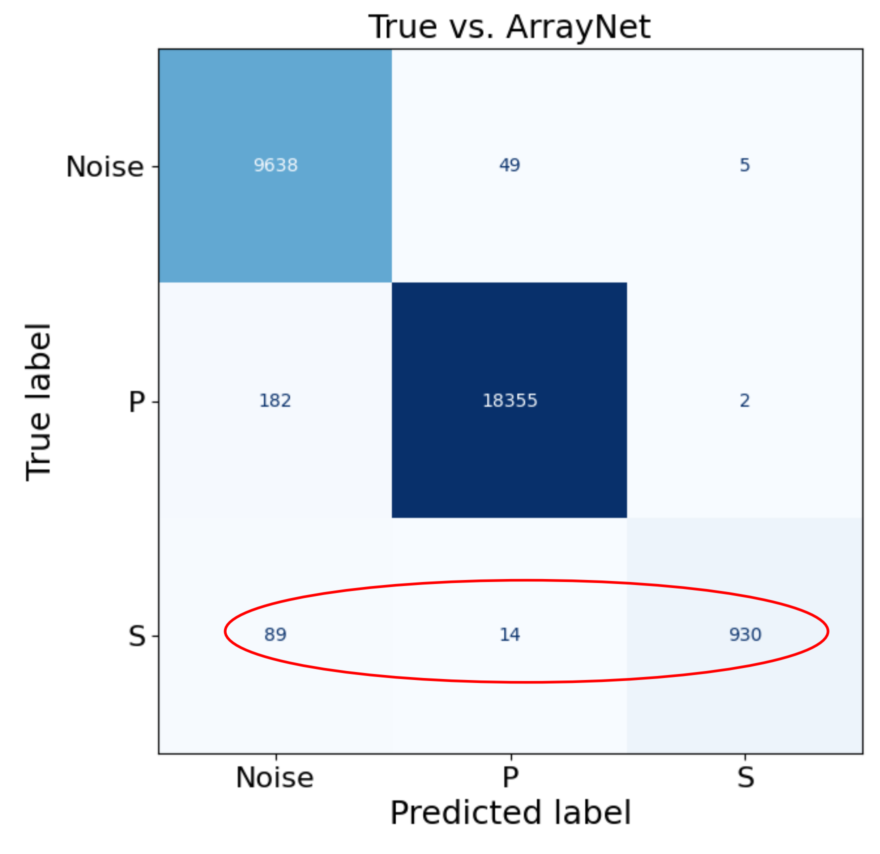
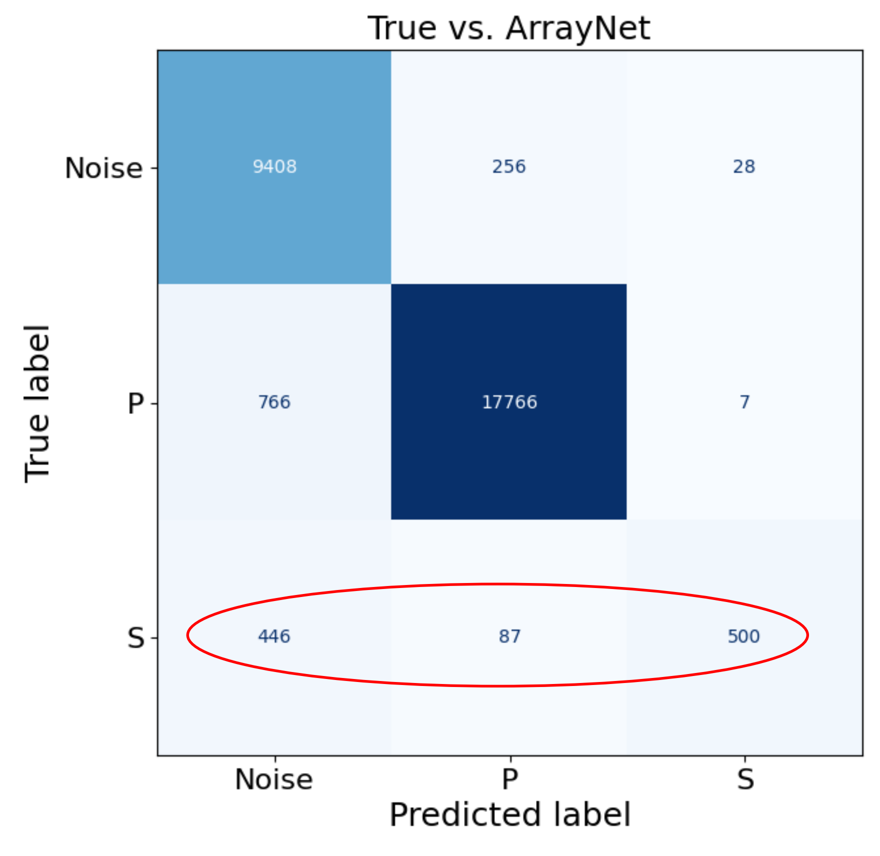
Results: ArrayNet applied to MKAR array

Dataset: LEB events

Problem: class imbalance because of few S wave arrivals

Better performance when augmenting training data with synthetic S wave phase pattern to better balance the classes.





Un-augmented training data

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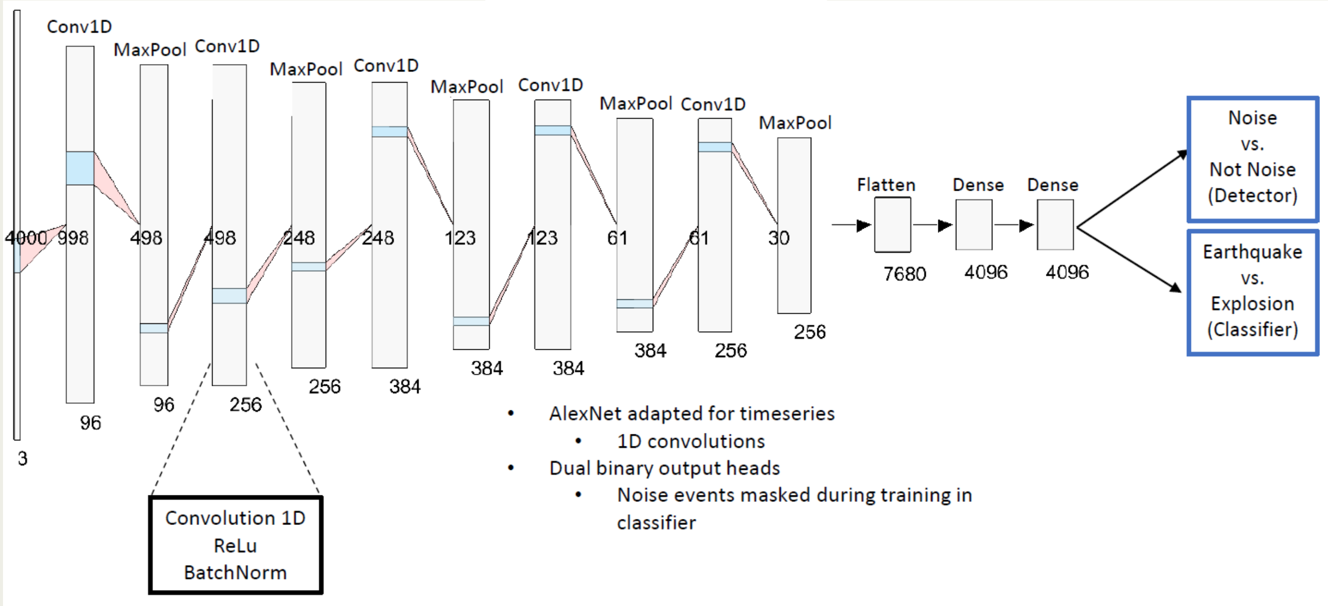
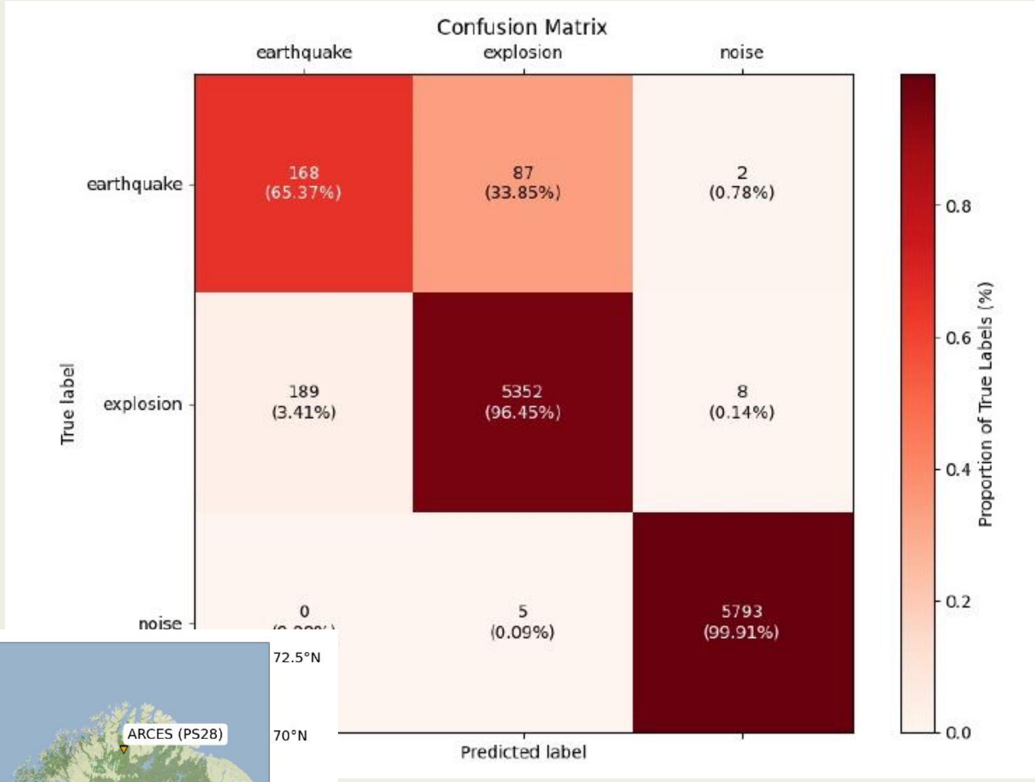
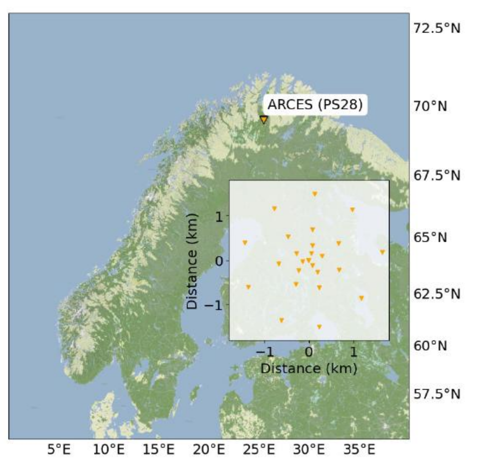
Results Step 3: Event classification at ARCES array





- Sequential classifier:
  - noise vs. events
  - If event: earthquake vs explosion
- Designed for a single array (ARCES) for now
- Trained on regional events 1998-2018
- Input: 100 seconds ZRT beams (2-8 Hz)



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