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Incoherent Seismic Array Processing Using Kurtosis: A Case Study from the Grane Oilfield

A. Jerkins, A. Köhler, and V. Oye

NORSAR, Kjeller, Norway

INTRODUCTION AND MAIN RESULTS

This study tests the stacking of a kurtosis function to improve incoherent (envelope-based) seismic array processing. Data from the Grane Oilfield seabed array (Norway) produced reliable slowness and back-azimuth estimates for events using frequency–wavenumber analysis with kurtosis functions. The method shows promise for IMS arrays with low inter-sensor coherence, such as MJAR in Japan.

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Introduction

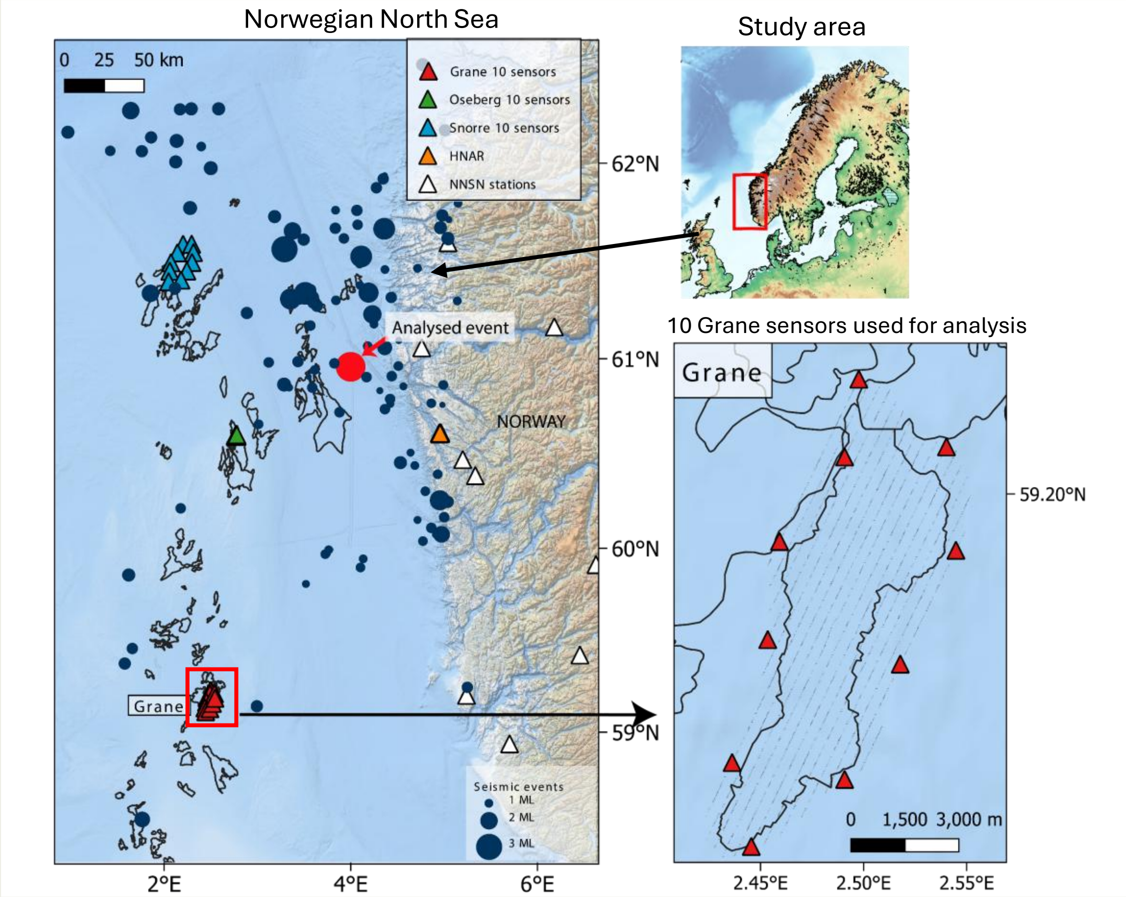
The North Sea is a key region for oil, gas, offshore wind, and future CO_2 storage. Seismic monitoring supports safe operations. While land-based networks offer good coverage, offshore monitoring is limited.

At some oil/gas fields, reservoir monitoring systems are installed to provide monitoring of reservoir changes during production. We analysed data from 10 ocean-bottom sensors at the Grane oil field (Norwegian sector) to test whether array processing could improve earthquake locations.

Conventional array methods like frequency-wavenumber (FK) analysis depend on coherent wavefields, which are disrupted at Grane due to large sensor spacing. To address this, we combined FK analysis with stacking of a kurtosis-based characteristic function to help recover coherence. This enabled slowness and backazimuth estimation for 8 of 10 events, improving earthquake locations.

This kurtosis method is applicable to similar installations (e.g., Snorre) and to global arrays like IMS station MJAR in Japan, where lack of coherence among the sensors challenges standard processing techniques.

Norwegian North Sea: Grane sensors and location of the analysed M_L 3.4 event



Top right: Regional map of the study area off Norway.
Left: Seismic events and sensor subsets at Grane, Oseberg, and Snorre oil fields. Analysed M_L 3.4 event using kurtosis in red. Land-based stations of the Norwegian National Seismic Network (NNSN), the HNAR seismic array, and oil fields (black lines) are shown.
Bottom right: Close-up of the Grane field sensor layout. We have access to data from 10 sensors shown by the red triangles.

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FK-analysis with kurtosis traces using data from Grane

Reservoir monitoring system at Grane: The system consists of 3,400 sensors in total.

We had access to only a subset: 10 sensors, spaced an average of 6 km apart → incoherent wavefield due to large sensor spacing (numerous side lobes in the array response).

Enhancing signal coherence before FK analysis: We estimated kurtosis characteristic functions to increase coherence. Other characteristic functions could potentially also work.

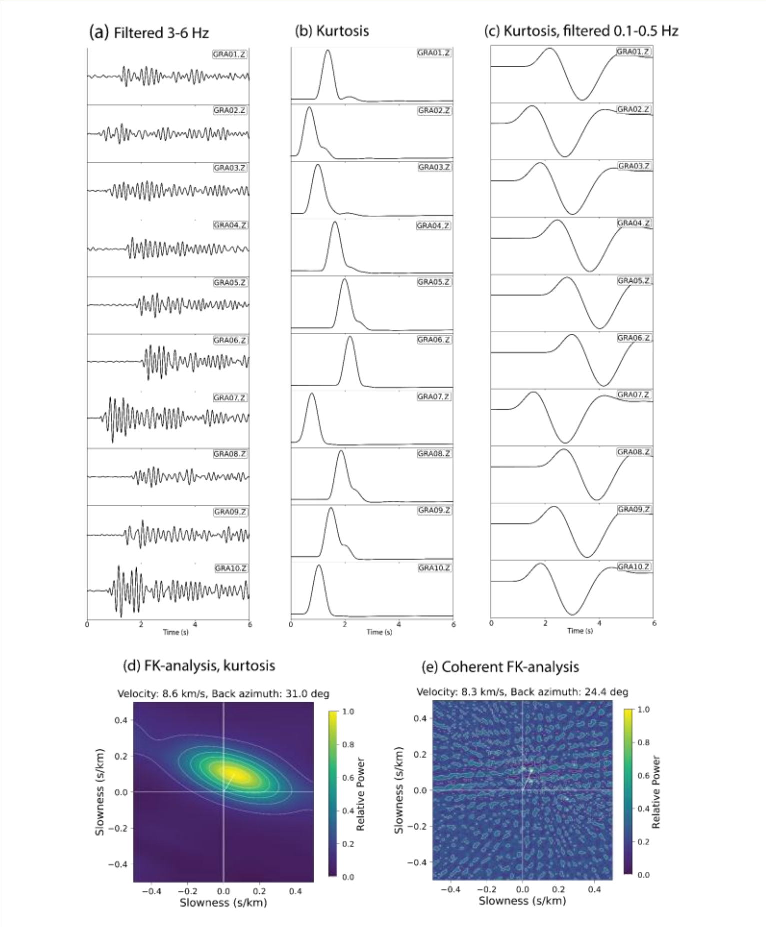
Kurtosis: The kurtosis is the fourth-order statistical moment of a distribution.

Steps to process kurtosis traces for FK-analysis:

a) Bandpass filter seismic traces.
b) Compute kurtosis.
c) Bandpass filter in low frequency band (0.1-0.5 Hz) and normalise.
d) Apply FK-analysis for P-wave arrival.

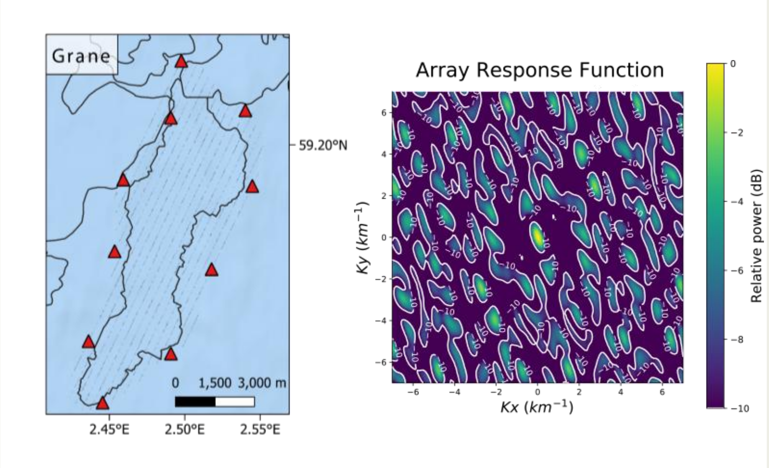
FK analysis shows improved sensitivity when using kurtosis traces compared to regular traces.

Steps for estimating kurtosis traces and FK analysis. Compare sensitivity using kurtosis vs. regular array processing.



Example: M_L 3.4 earthquake analysed using our kurtosis processing approach. The event (red circle on previous map) was processed using outlined steps. Bottom panel: kurtosis vs. coherent processing – note the number of sidelobes when using regular array processing.

Location and array response of the 10 Grane sensors



Left: Entire monitoring system shown by dots (3,400 sensors). The red triangles are the 10 sensors for which we had data access.
Right: Array response for the 10 red sensors shows numerous sidelobes.

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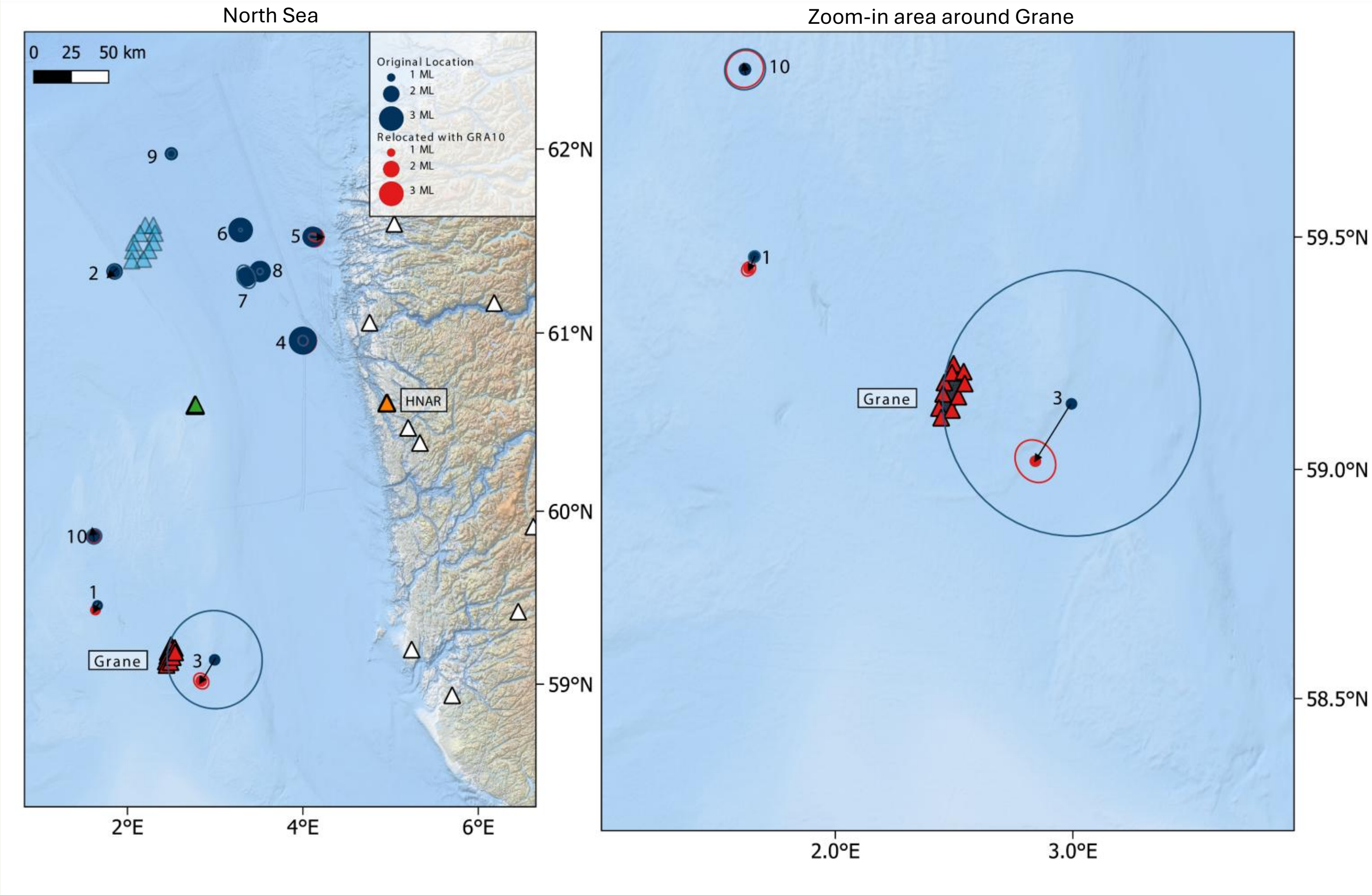
Relocating seismic events

- Tested our method on 10 events with known locations.
- 8 events showed azimuth residuals <15° using kurtosis-stack FK analysis.
- Incorporated slowness and back-azimuth results from incoherent analysis to improve locations (originally just located using the onshore sensors).
- Largest shifts observed for events near the array.
- Reduced size of uncertainty ellipses.

Events near the Grane array show significant shift in location and smaller uncertainty ellipses



Relocated seismic events. Blue: Original location (only using onshore sensors) with uncertainty ellipse. Red: Relocated using array-derived parameters from Grane. Arrows indicate location shifts. The size of the uncertainty ellipse is significantly reduced close to the sensors.

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Example MJAR array, Japan

We further tested our incoherent array processing method on a 4.7 Mb earthquake from 2009* using the MJAR array in Japan, which is affected by lack of coherent signals among sensors for higher frequencies due to complex subsurface geology.

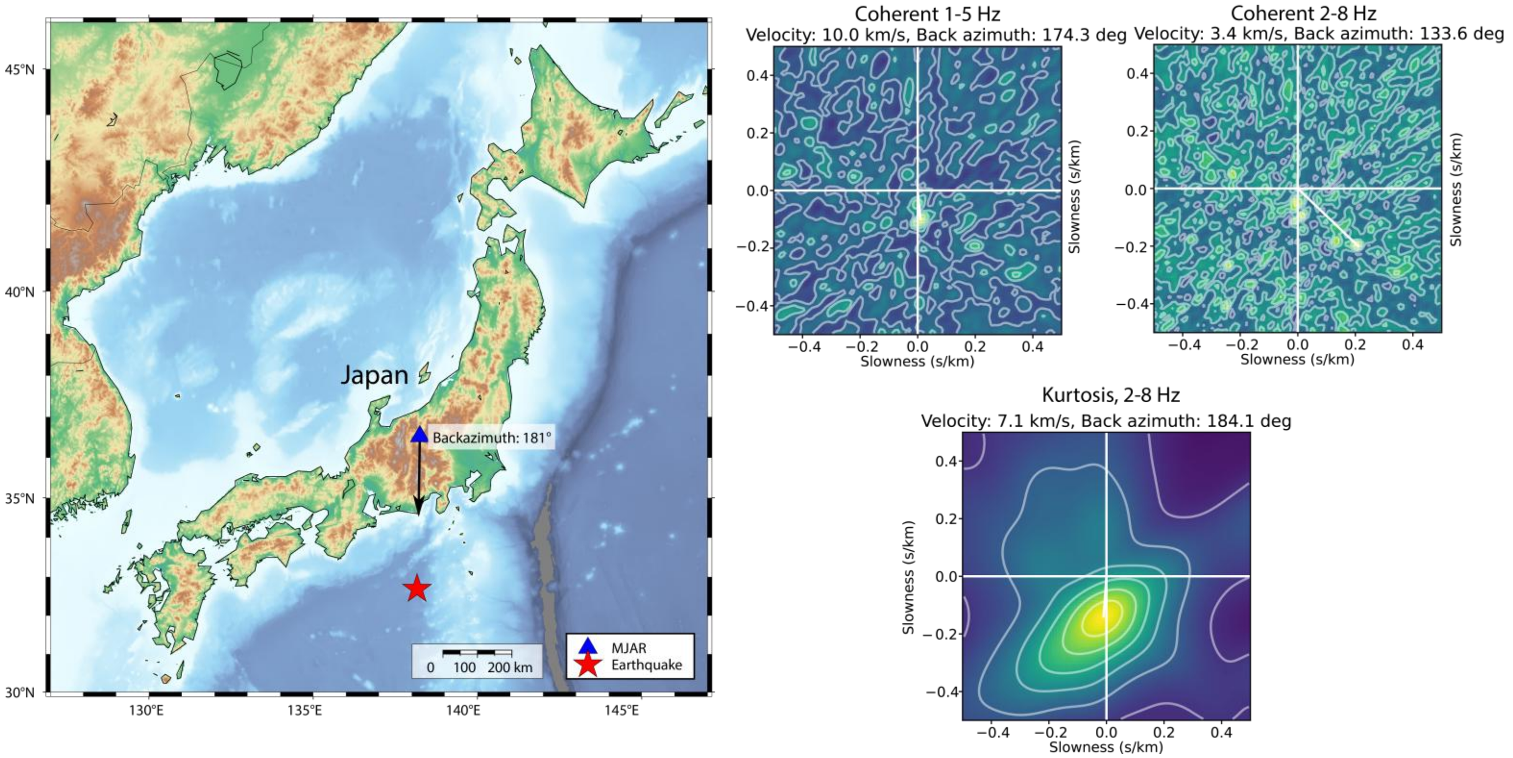
Our estimated back azimuth closely matches the Reviewed Event Bulletin (REB), with a residual of ~3°. Unlike coherent processing (using regular seismic traces), our method yields accurate back-azimuth estimates for higher frequencies, where the coherent approach fails. At lower frequencies, the MJAR array produces a reasonable result with coherent processing, but with limited sensitivity.

Conclusion

We showed that estimating and processing kurtosis traces increases coherency prior to FK analysis for the Grane sensors, and contributes to improved accuracy in event location estimates. The method performed well for most events and shows promise for other arrays. For details, check out our publication:

Jerkins, A. E., Köhler, A., & Oye, V. (2023). On the potential of offshore sensors and array processing for improving seismic event detection and locations in the North Sea. ***Geophysical Journal International***

Kurtosis-based FK analysis at MJAR (Japan) compared with conventional ("coherent") FK-analysis



Left: MJAR array location, earthquake location from the REB, and theoretical back azimuth (181°) based on the REB location. **Right:** Coherent processing (using regular traces) results across different frequency bands. Coherent processing fails in the 2–8 Hz frequency band. In the bottom row, processing using kurtosis traces shows improved back azimuth estimation, even at higher frequencies, with increased sensitivity.

* Using the same event as Kværna, T., Gibbons, S.J. & Näsholm, S.P, (2021). CTBT seismic monitoring using coherent and incoherent array processing, *J. seismology*, 25, 1189-1207

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