# Peer Review of Submitted Manuscript

## Introduction

Thank you for the opportunity to peer review the manuscript “High Spatial and temporal 3D Sea Ice Thickness Reconstruction using Seismic Waveform Inversion and Tomography” by Zandi et al. (2016).

This manuscript presents a novel method of capturing and monitoring the small-scale heterogeneities of sea ice thickness using seismic methods. Utilizing that the frequency of flexural waves in sea ice is highly dependent on the ice thickness, an inversion algorithm is used to derive the ice thickness from vibrations measured with geophone arrays. The novelty is two-part. Firstly, the Spectral Element Method (SEM) is used to compute theoretical waveforms for a range of source-receiver distances and ice thicknesses, thereby building up a matchup-database for quicker computations. Secondly, multiple source-receiver paths are combined to form a high resolution ice thickness map using tomography. The method is applied on two different field campaigns, one with active/controlled sources and another with passive sources, e.g., icequakes. The results show thicknesses that are consistent with drillhole measurements, although negatively biased due layering in the ice, and an example of how this method could be used for autonomous monitoring of a selected area.

I do not have a background within seismology, so my review focuses on the field setup and sea ice properties rather than the theoretical wave equations. The review is structured in 4 major parts. The first part is related to validating the results, the second part is on potential biases in the experiment setup, and the third part discusses potential up-scaling. The fourth part is a list of minor comments before the conclusion.

## Validation of results

### Ice thicknesses

From line 110, the average ice thickness from the two ice types in the controlled-source setup are provided from drillhole measurements, 50±5 cm and 70±5 cm, respectively. Here I suggest stating how many drillholes the estimates are based on and what the uncertainties indicate. Are they uncertainties in the tape reading or the spread of a thickness distribution? Later on in Figure 8a, there are shown 9 drillhole measurements within the area of interest, but only 6 of them are shown in Figure 8b, and with only one measurement in the thickest ice.

Kuchly et al. (2026), another submitted manuscript on the same field campaign, describes the thick ice as “a rough jumble of ice fragments with irregularities about 20 cm high” and with an average thickness of 72 cm. Their thin ice has an average thickness of 54 cm. Furthermore, their colorbar in Figure 1b is cropped at 0.9 m, showing more variability in the thick ice thickness than in Figure 8b mentioned before. I am wondering why there are such discrepancies between the two descriptions given the significant overlap of co-authors.

While I do understand that fieldwork/time constraints might have limited the survey to a single transect, I would have wished for a larger spatial coverage of ice thickness validation given the aim of estimating a 2D map. With the given data, I suggest a more detailed and transparent description of the ice conditions.

### Source positions

I like the stepwise fine-tuning of inverted positions in the 5 step inversion method which shows clear improvements in Figure 9. For the controlled-source setup, it is stated on line 308 that these steps are skipped due to the source positions being known. In the data description, I suggest a description of how these positions were measured in the field.

Also, I see this as a great opportunity to validate step 2 and 3 in Algorithm 1, and I suggest doing a comparison between estimated and actual source positions to assess the uncertainties of the triangulation (or “quintangulation”).

# Potential sources of bias

## The impact of ice variations along source-receiver paths

In line 317 it is stated that 44% of the data at the controlled-source site is filtered away due to a too high misfit with waveforms in the generated database. According to line 311, one of the most common sources for these misfits are large cracks in the ice. How about ridges or deformed ice in general? The research by Xie & Farmers (1994) is mentioned in the introduction, but the influence of deformed ice is not discussed. And given that the waveforms are based on constant ice thicknesses, what effect does the thickness gradient in the field have on the misfits?

44% is a very significant amount of data, so I suggest making a figure that shows which source-receiver paths were discarded. Are they randomly distributed or are they primarily paths that cross the transition between the two ice regions? As a follow-up question: In the current setup, the geophone grid is placed directly at the interface between the two ice regions, ensuring a handful of “pure paths” in each region. If the geophone grid instead were placed fully within one of the two regions, would it then have been possible to derive the thicknesses in the opposite region?

## Sensitivity to temperature changes

During the duration of the time series in Vallunden, the air temperature rose from around -25°C to around -5°C according to line 125. Or below -30°C to close to 0°C according to line 375. I suggest that these descriptions are aligned.

This was just a minor comment, and I wanted to bring focus on the significant temperature increase during the time series. In the discussion, line 420, the large uncertainty of Young’s modulus is mentioned. It ranges from 1 GPa to 9GPa, but is assumed constant in the analysis. Young’s modulus depends on the brine volume fraction of the ice which increases with rising temperatures. Thereby, the Young’s modulus would decrease over time as the ice gets more compliant, leading to a negative thickness bias. I do not know if the magnitude of this bias is significant, but I would have liked to read about it in the discussion given that the results are in general underestimated.

## Optimal geophone setup for up-scaling

As one of the goals is to present a scalable solution for ice monitoring, as mentioned on line 11, I suggest discussing the potential up-scaling. I am especially interested in your thoughts on the optimal geophone setup. If you could re-do the experiments, would you change anything?

The two field experiments have very different geophone grids, of which the first one is already reviewed in the part about potential biases. Looking at the generated time series maps, I cannot help but wonder why all the sensors were placed in the middle with such a high density (about 250 geophones in total with about 1 geophone pr. 10 $m^2$). Would it not improve the triangulation, result in a more constrained waveform matching, and lead to a higher spatial resolution (instead of radial rays) if the geophones were more spread out? At line 404 it is mentioned that “denser ray distributions, as well as broader and more uniform spatial coverage, result in more accurate thickness estimates”.

Just a suggestion after having read the manuscript: Would it make sense to have many clusters of geophones with at least 3 geophones in each cluster, such that each cluster can do an effective triangulation? Besides increasing the spatial coverage, it could reduce the mismatches from changing ice conditions because the ice could be measured from multiple sides with different clusters. And the lower density would make the up-scaling more feasible.

## List of minor points

Title: “Temporal” should be capitalized for consistency.

Line 276: … zero of *the* misfit function …

Figure 8: There is an extra “a)” in the beginning of the caption.

Figure 8: If (0212) and (0206) are dates, 12 Feb and 6 Feb is clearer without context.

Figure 9: “b),c)” error in the caption.

Line 360: Besides the faster cooling at shallower water depths, could the thicker ice also be due to dynamical thickening from tides?

Figure 14: A legend would suit this figure.

Line 413: Random question mark mid-sentence.

Line 449: The end of the conclusion focuses on future developments regarding extending the framework to include heterogeneity, anisotropy, and snow cover. This needs to be mentioned in the discussion as well.

2.3.1 Construction of a SEM database:
I understand that for each discrete source-receiver distance, the database has a range of derived waveforms corresponding to a range of discrete ice thicknesses. Thereby the number of waveforms would equal the product of distance steps and thickness steps.

The formulation explaining this, line 221, is confusing. The variables x and y are defined as the respective intervals, i.e., step sizes, together with xx and yy as the maximum distance and thickness, respectively. This results in z waveforms. Besides being confusing, these variables are not used later on, and both x and y are redefined in section 2.3.3 for the tomography computation. Are they needed? I think it would be more informative to know the actual number of waveforms in the database and the actual used ranges - together with a justification of chosen limits.

## Conclusion

The manuscript covers a novel and fascinating way of monitoring the sea ice thickness of a local area with high spatial resolution. Unfortunately, the analysis does not demonstrate that the approach is robust across different environments as stated in the conclusion - and it does not demonstrate the opposite either.

About 44% of the data in the controlled-source experiment is filtered away without a detailed description of given data, and there is no discussion on the influence of deformed ice or varying ice thicknesses on the waveform matchings.

I suggest being more clear about potential limitations of the method and a discussion on how to mitigate them. That would include thoughts on how to place the geophones most optimally for future experiments, and if there are hypothetical cases where this method cannot be applied.

Based on these two points specifically, but also with a smaller emphasis on the other points mentioned in this review, a major revision is suggested.

## References

Kuchly, S., Moreau, L., Zanchi, V., Mokus, N., Dansereau, V., Smith, M. M., Dumont, D., Perrard, S., and Eddi, A.: High-Resolution Measurement of Sea Ice Mechanical Characteristics Using Distributed Acoustic Sensing, Seismological Research Letters, (under review), 2026.

Xie, Y. and Farmer, D. M.: Seismic-acoustic sensing of sea ice wave mechanical properties, J. Geophys. Res. Oceans, 99, 7771–7786, https://doi.org/https://doi.org/10.1029/93JC03483, 1994.