Review comments on: "'Locating the Nordstream explosions without a velocity models using polarization analysis' by S.C. Stähler, G. Zenhäusern, J. Clinton, D. Giardini"

Kiran K. S. Thingbaijam

Dated: October 17, 2022

Stähler *et al*. provided critical insights into the explosions that preceded recently reported catastrophic leaks in the Nordstream pipelines. Based on polarization analysis, they demonstrated that the explosions were located close to the leaks. They further reported that the emitted seismic energy lasted over 10 minutes, indicative of resonances in either the water column or the depressurizing pipeline.

The manuscript is an excellent fit for the Fast Reports section of Seismica. The scientific results are relevant for current international affairs and warrants urgent reporting. They would be of interest to not only seismologists but also the general public.

In the following, I list a few comments and believe that these are minor and can be quickly addressed by the authors. Of course, the authors can improve their writing if they think it would be useful. For examples; in Line 15: removing "can", and in Line 30: replacing "accompanied" by "preceded".

Comment 1. It will be a good idea to include a line in the abstract informing the time-sensitive nature of this study. I'd like to suggest that the following sentence or a one on the same line be inserted after the first sentence of the abstract.

"As it pertains to current international affairs, there is an urgent need to obtain reliable information about these explosions.**"**

Comment 2. May I suggest that the title can be shortened as follows:

"Locating the Nordstream explosions using polarization analysis"

Comment 3. Abstract, Line 14-15: perhaps, "with the uncertainties in elliptical bounds of 30km and 10x60km, respectively."

Comment 4. Line 43: "26 October 2022" would be "26 September 2022"

Comment 5. Line 44: "Several hours after the first explosion shortly after 02:00 local time …". Who noticed the pressure drop? Also, perhaps, this sentence can be broken up into two.

Comment 6. Line 49-53: As there have been reports confirming the locations of these events, the authors need to clarify what is new in their report.

Comment 7. Line 64: "Via observation of differential arrival time of seismic phases, …". Perhaps, "Based on differential arrival time of seismic phases, …"

Comment 8: LIne 68: The abbreviation CTBTO is not mentioned again and is not required.

Comment 9. Line 76: Perhaps, ..which we developed to locate seismic events on Mars." Also, a reference is required here.

Comment 10. Line 90-91: "This method is based on the work of (Samson, 1983) and was first applied to seismic data by Schimmel and Gallart (2003); Schimmel et al. (2011)."

Perhaps, "This method is based on Samson (1983) and was first applied to seismic data by Schimmel and Gallart (2003) and Schimmel et al. (2011)."

Is Schimmel et al. (2011) a necessary reference here?

Comment 11. Line 93: "and correct the data to displacement."
What do the authors mean by correcting the data to displacement? How did they do it? Are the analyses (in Figure 2 and in the supplement) based on displacement time series, instead of velocity time series?

Comment 12. Does the information presented in Table 1 need a reference? Latitude, Longitude and Magnitude seems to have been taken from a previous study or a report.

Comment 13. Line 109-111 (also, Line 144): Do we have sufficient information to strongly negate the possibility of these events being earthquakes (instead of explosions)?

Comment 14. Line 139: "identify" .. or is it "associate"?

Comment 15. Figure 2 is quite a busy one. While I like the applied colormaps, it will be nice to have each panel explained (in the caption). Additionally, it might be helpful if x-axis are labeled. The first column obviously has time in the x-axis. Is the xtick labeled correctly?

Comment 16. Figure 2 caption: "After the P-wave, polarization in the same direction is seen at 3.5 and 15 Hz, estimated as a continued pulsation at the source location." I am not able to correlate this observation with the subplots.

Comment 17. It would be a good idea to have the supplement as a single .pdf file containing the plots, with the figures numbered (perhaps, S1, S2….) and appropriately captioned.

Comment 18. Acknowledgements. What the authors provided in Line 150-155 are not appropriate. In fact, a guide for this section is already included in their text - "Thank all relevant parties and acknowledge funding sources, if any."

Comment 19. Data and Code availability. Please refer to the author guidelines on Data & code availability and reproducibility (https://seismica.library.mcgill.ca/author-guidelines). Perhaps, references to python packages - NumPy, SciPy and Matplotlib may not be required as these packages are well recognized and widely used. Also, I'd request that the processed data, and if possible, the codes can be shared on Zenodo (https://zenodo.org/) or similar long-term platform as mentioned in the author guidelines. Of course, if the data are not available, the data availability statement should explain why.

Review comments from Handling Editor (Dr. Ryo Okuwaki)

The submitted manuscript; "Locating the Nordstream explosions without a velocity model using polarization analysis" authored by S. C. Stähler, G. Zenhäusern, J. Clinton, and D. Giardini, is presenting a series of seismic analyses for the very recent seismic events around the Nordstream natural gas pipelines in Baltic Sea. The authors conduct a seismic event location based on a polarization method that was originally developed for locating Marsquakes. The authors successfully identify and locate a series of seismic events using only 4 or 5 nearby seismic stations, which are not likely regular earthquakes.

The technical advancement over the routine seismic event location algorithm is clear, that is, the authors' approach does not need travel times that are hugely affected by the local velocity structure, which is often unknown or uncertain especially in the seismically inactive region. The location uncertainty is well evaluated and visualized to adequately discuss a possible link to the explosive event at the Nordstream pipeline. I agree with the authors that such a successful event location should be applicable to the other non-tectonic seismic events where only a limited number of seismic stations and/or an unknown velocity structure are available.

I only have minor concerns about how uniquely the Nordstream explosive seismic signals are understood compared with other non-tectonic events (e.g., submarine volcano eruptions, submarine landslides or nuclear explosions). I see the associated seismic signals are lacking shear rupture elements (e.g., S-wave) and dominant in isotropic components, but how could the seismic signatures tell us about the physical cause (detonation) of the explosion or possibly the source processes at the very beginning of the explosion? Also, to my best understanding, one of the highlights of the authors' location algorithm is that it requires very few assumptions about the source type and velocity structures, and it can be applied to continuous records. Given that advantage (or in order to strengthen that advantage), would it be possible to conduct a further scan of continuous waveform data at stations considered in this study, for example, in one-day time period (2022-09-26) to identify any other non-tectonic seismic events, which are possibly missed by routine analyses by SNSN or other agencies (other than Event 1 and Event 2A,2B)? Perhaps the authors might already have done that, but any further comments or discussion about such advanced monitoring would be appreciated.

Also, I would like to suggest the authors showing waveforms (possibly in a separate figure), so that the seismic signals from Event 1 and 2(A,B) can be recognized and evaluated by the readers, and also compared with the associated spectrograms.

One other thing that I would like to note here is that some of the sentences or discussion seems to have been missing necessary references to support the authors' arguments. I understand the necessity of being concise for Fast Reports articles, but I would like the manuscript to present a logic supported by necessary references, which I believe the authors' work will easily be followed by the readers from a broad seismological background and even stimulate further detailed research on this topic.

The other very minor comments are also itemized below, which I hope might be helpful for authors' revision.

Dr. Ryo Okuwaki

L10: ", most likely man-made"
I agree with the authors that, after reading the whole manuscript, the seismic events should not likely be the regular earthquakes, but at the same time, I am thinking that it might also be able to leave any judgments about the cause at this specific line. I am suggesting this also because the authors' work is mostly dedicated to illustrate how the polarization location method is efficient to locate the unknown seismic events that are often missed by routine location algorithms, but not in detail to evaluate an exact cause of the explosion (in other words, how or by whom the explosion is detonated). It is totally up to the authors' decision, but I would omit the relevant expression like ", most likely man-made" at least in the abstract.

L15: "30km and 10x60km"
Are these the dimensions for an uncertainty ellipse for each event? If so, would it be able to show longer and shorter axes for each uncertainty ellipse?

Additional language abstract
Thank you very much for your efforts to provide an additional language abstract. I would like to note that the additional language abstract has not undergone review so far, but I will ask our Editorial Board member to review the additional language abstract at the final round of review before the production stage. Thanks again.

L43: "26 October 2022"
26 September 2022?

L45 and L47: "02:00 local time" and "19:00 local time"
Are these the origin times of the events determined by someone? For example, this report says 2:03.
https://www.geus.dk/om-geus/nyheder/nyhedsarkiv/2022/sep/seismologi

L47: "Despite the fact"
Is it natural to expect the gas pipe to be pressurized when it is not transporting anything, or is it usually not pressurized when the pipe is not operated? Do the authors have any references to show what kind of contents (methane?) was filling the pipe before the event?

L49: "methane were released after the leak"
Show reference (perhaps the report from Danish military intelligence?)

L52: "SNSN as ML = 3.1"
Do the authors have any ideas of why the second event has a larger magnitude (ML 3.1) than the first one (ML 2.7), based on the authors' own analyses? If the first event contributed to decompression of the pipe by leaking, the second one might have a lower potential for decompression and hence the lower emitted seismic energy? I would appreciate it if the authors could extend the discussion about this.

L53–54: "a region of very low seismicity", "most likely deliberate"

Are there any possibilities of submarine landslides that cause damages to the pipeline in this region?

L53: "it is plausible to identify these seismic events with the leaks and attribute them to an explosion, most likely deliberate"
I guess it might be better to keep the seismic source unknown at this particular section before the authors untangle the associated seismic signatures in the subsequent sections.

L57: "NORSAR"
Norwegian Seismic Array (NORSAR)

L57: "Nordstream quake"
Nordstream seismic events considered in this study

L57: "precisely for this task"
Show reference.

L60: "10-100 km"
Use double hyphens "--" for the range of values; $10--100$~km.

L60:
Are there any specific reasons to mention those arrays other than the NORSAR array here? If not, I would omit these lines about those arrays.

L66: "its magnitude estimated to obtain the yield of a nuclear test"
Have the authors determined magnitudes of this kind for the 2022 Nordstream events?

L72: 4-5
Use double hyphens for a range of values; $4--5$ mm/y.

L70–72:
Show reference for the tectonic setting of Baltic Sea or the associated glacial movements introduced here.

L81: "P-wave is not sufficient"
Clarify the meaning of "not sufficient". Does this mean that the number of P-wave traces are not sufficient to constrain the location?

L93: "HH?"
I understand the practical meaning of "?", but please show specific channels considered in this study, for example, HHZ, HHN and HHE.

L94: "i.e. the 2 days before the leaks"
Perhaps this is "1 day before the leaks"? if the leak is reported on 2022-09-26.

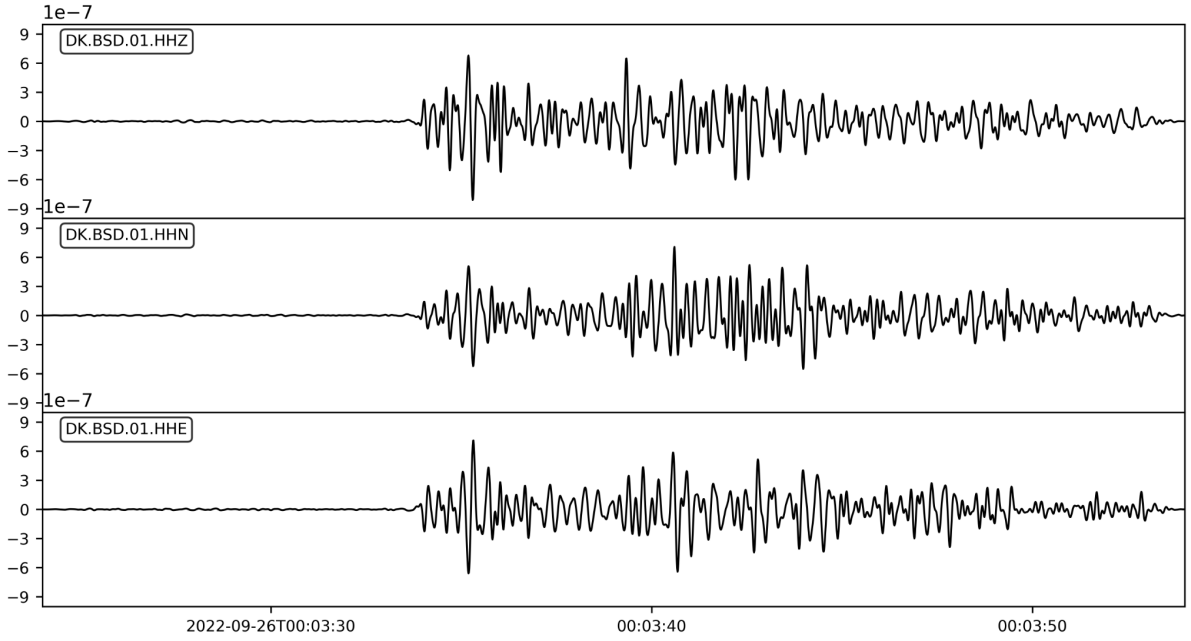
L95: "high-frequency seismic events"
Please clarify the range of frequency if possible. Also, are these "high-frequency seismic events" the 2022 Nordstream events?

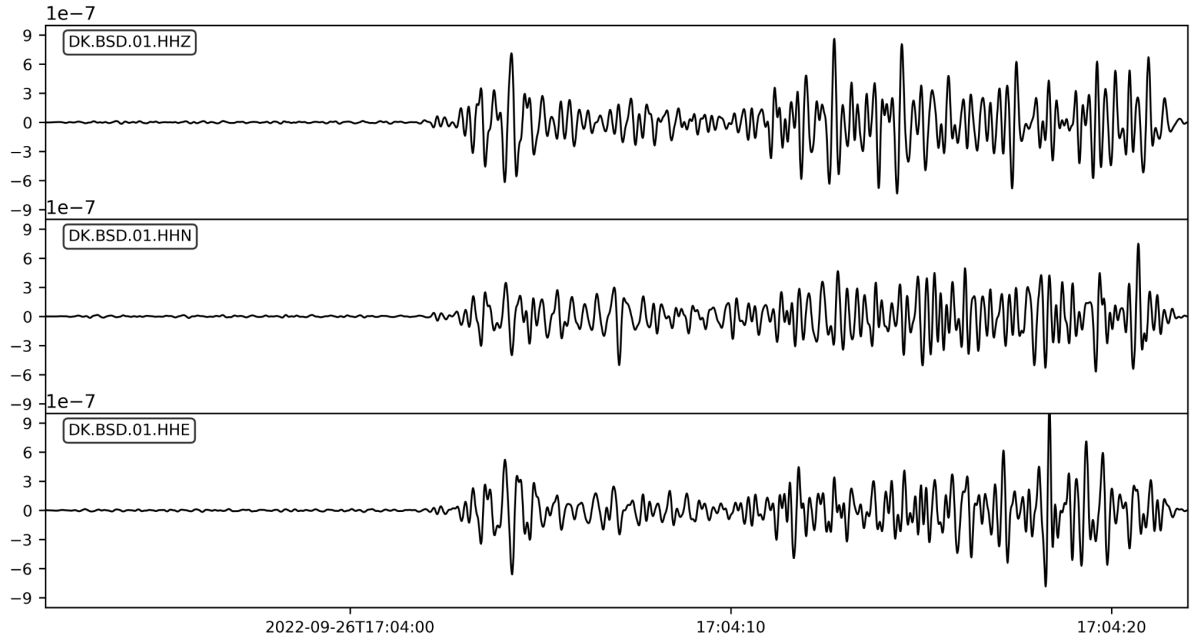
L96:" 2022-09-26 17:03:50 UTC and a second event around 2022-09-26 00:03:24 UTC"
It seems the timeline is contrary to the ones displayed in Table 1. Please check the timeline again.

L97: "were clearly detectable."
How can the readers find the signals? It would be great if the authors show data (waveforms) somewhere in Figure 2 or in a new figure, so that the readers could evaluate the authors' own observation. (I did check the data by myself and I agree with the authors that the signals are clearly visible anyways.)

Total three figures are allowed, so would it be possible to show waveform data at, for example, BSD station, so that it illuminates how the associated signals of Event 1 and 2 are different from or similar to each other.

Related to this point, for Event 2, it is intriguing to see some high-frequency signals at the very beginning or preceding the larger amplitude of signals (please see example waveform traces below), which may look different from Event 1. I would be very curious how the authors could see this difference and how this may perhaps differentiate the source processes of Event A and B?





Bandpass filtered (2–8 Hz) velocity waveforms at DK.BSD.

Event 2A and 2B
How are the two minor events A and B recognized (or seperated) in the waveform data? Please show the example figure in the main text.

L100:
Explain \alpha briefly.

eq(1):
What does `tot` represent?

Table 1 : "00:03:24.5"
In L96, the authors write "00:03:24". I think it might be helpful to be consistent about the precision throughout the manuscript.

Table 1:
Use parenthesis "()" or different symbols for uncertainty range, because the brackets are already used for units; e.g., [deg] in a header of the table.

Table 1:
Origin time is determined by authors? If not please show references for the origin times in the table caption (SNSN?).

Table 1:
Could it be possible to use ± for the uncertainty range in the same way as the main text?
111–139 --> 125 ± 14

L105: "clearly polarized P-waves"
Could you please clarify what this "clearly polarized" means in the authors' context?

Does this mean that both the P- and coda-waves have a single peak in its density in a certain range of frequency (the right-most azimuth-density plot in Figure 2)?

L107: "(see table 1."
(table 1).

L109: "an identification of the explosions would already be possible"
We might still have some possibilities that the seismic location just coincides with the infrastructure, before the authors discuss the signal properties in the subsequent lines. I would omit this line if possible.

L110: "a clear P-wave but no obvious S-wave"
A lack of clear S-wave should be nice evidence of an explosive seismic event. Showing waveforms would be helpful.

L112: "overall duration of at least 10 minutes before falling to pre-event noise levels"
This is a very interesting observation. Is this 10-min duration common for other seismic stations? Have the authors observed the similar duration for Event 2 as well?

L112: "A signal is visible on several other openly accessible stations in Germany, Denmark, and Sweden"
Is it possible to show these station codes and channels, so that the readers could conduct some further analyses following the authors' work.

L113: "Swedish National Seismic Network"
SNSN

L115: "KQ.PEEM in Peenemünde, Germany, in 100 (event 1) and 150 km (event 2) distance has clearly visible signals as well"
What kind of "signals" is discussed here? Is it the waveform signal or spectrogram?
Again, showing the waveform would be helpful to evaluate this argument.

L117: "80°for"
Add a space; "80° for".

L126: The actual leak
Show reference for the location of "the actual leak".

L129: "sustained polarization"
Does this mean that the back azimuth is the same among the P- and coda-waves? Please clarify the meaning of "sustained".

L133: "1450 m/s (typical for 15°C)"
Show reference.

L136: "Minnaert resonance of rising gas bubbles"
Show reference.

Figure 1:
It seems Figure 1 has enough space, so please add network code along with the station code (e.g., UP.DEL).

Figure 1 Legend:
"combined location" looks a bit unclear. Please clarify what these contours represent. Also, explain the meaning of dashed and solid contours in the caption.

"Gas leaks": Are these the locations determined by Danish military intelligence? Please indicate the agencies as well, in the same manner as for "SNSN location" for yellow squares.

It should be nice to make time precision for the origin times of Event 1 and 2 consistent with those shown in Table 1.

Show reference for bathymetry. Also clarify the data source and its availability in Data and code availability if possible.

Show reference for pipeline location (blue lines). I would expect those lines to be openly available so that the readers could reproduce the figure.

Figure 1 caption:
"We could obtain clear back-azimuths from 5 stations for event 1 (generally marked by reddish colors) and 4 for event 2 (marked by greenish colors)."
It seems it is inconsistent with Table 1. Table 1 shows 4 stations for Event 1 and 5 stations for Event 2.

"Additional stations like GE.RGN on the Rügen island (Germany) or DK.COP near Kopenhagen were tried, but had poorer azimuth constraints than neighbouring stations. We thus did not include them in this analysis and figure."
I think this is an important statement and it should be written in the main text, not in the caption.

"The SNSN operates several more stations in Southern Sweden that might give additional constraints, but data from these was not publicly available at the time of writing."
This is important information. I would suggest writing in the main text, not in the cation.

Figure 1 color bar:
"Negative Depth" should mean positive elevation (e.g., above the sea level). If the color of the matplotlib.pyplot.contourf represents depth, the ticklabels of the color bar should be positive.

Why does the color bar involve different intensity for one value? For example, if we see the color at `-50 m` on the color bar, the color seems to change from dark to light from left to right (please see attached screen capture).

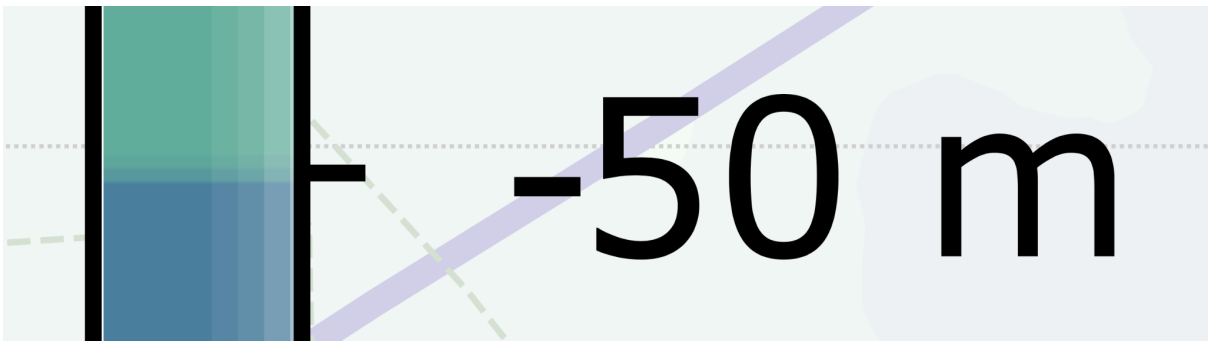


Figure 2
Is it possible to draw "Noise" section (window) in the spectrogram panel?

What does the pale red rectangle represent (matplotlib.pyplot.axhspan)? It seems it highlights 2–4 Hz, but why? (I guess this should be a range used for calculating histograms in the right-most panels, but please clarify in the caption).

The authors may need to thoroughly explain the middle panels. What is the abscissa (X axis)? (I guess that should be, for example, amplitude [dB] for the upper panels, but please explain or add labels on panels).

"After the P-wave, polarization in the same direction is seen at 3.5 and 15 Hz"
Could you highlight that corresponding portion in Figure 2, so that anyone could evaluate this? Please indicate any marks or highlights on the panel.

"pulsation"
Is this corresponding to "resonance of rising gas bubbles"?

Acknowledgements:
"Thank all relevant parties and acknowledge funding sources,"
Please delete this template line.

"The polarization code is available on github"
Could I ask where I can access the code? As the authors clearly say "The polarization code is available on github" in the code availability, I need to evaluate the code and make sure of its reproducibility before making any judgments about final publication of this manuscript.

References:
L194: "page Approximately 65 active permanent stations"
Please check if the reference is nicely formatted. According to the SNSN website http://www.snsn.se/network/ , it seems it is advised to cite as follows:
SNSN (1904): Swedish National Seismic Network. Uppsala University, Uppsala, Sweden. Other/Seismic network. doi:10.18159/SNSN

Dear Ryo Okuwaki,

Thanks a lot for the rapid handling of this manuscript and the very helpful comments, which we tried to incorporate and which should improve the stringency of the article.

We are a bit uncertain about the suggestion of changing the title, as proposed by reviewer 1. “Locating the Nordstream explosions using polarization analysis” (without the velocity model reference) is certainly more catchy, although the reference to the velocity models is important in our view.

Please find a detailed reply below.

Regards,

Simon Stähler, Géraldine Zenhäusern and coauthors

Other Changes

Table 1: Added information on origin time in local time, in addition to UTC.

Reviewer 1

Kiran K. S. Thingbaijam
Dated: October 17, 2022

Stähler et al. provided critical insights into the explosions that preceded recently reported catastrophic leaks in the Nordstream pipelines. Based on polarization analysis, they demonstrated that the explosions were located close to the leaks. They further reported that the emitted seismic energy lasted over 10 minutes, indicative of resonances in either the water column or the depressurizing pipeline.

The manuscript is an excellent fit for the Fast Reports section of Seismica. The scientific results are relevant for current international affairs and warrants urgent reporting. They would be of interest to not only seismologists but also the general public.

In the following, I list a few comments and believe that these are minor and can be quickly addressed by the authors. Of course, the authors can improve their writing if they think it would be useful. For examples; in Line 15: removing “can”, and in Line 30: replacing “accompanied” by “preceded”.

Specific Comments:

Comment 1. It will be a good idea to include a line in the abstract informing the time-sensitive nature of this study. I’d like to suggest that the following sentence or a one on the same line be inserted after the first sentence of the abstract. “As it pertains to current international affairs, there is an urgent need to obtain reliable information about these explosions.”

In accordance with the comments of the second reviewer (and editor), we prefer to tone down the political implications a bit.

Comment 2. May I suggest that the title can be shortened as follows:

“Locating the Nordstream explosions using polarization analysis”

Comment 3. Abstract, Line 14-15: perhaps, “with the uncertainties in elliptical bounds of 30km and 10x60km, respectively.”

Changed, thank you

Comment 4. Line 43: “26 October 2022” would be “26 September 2022”
Changed, thank you.

Comment 5. Line 44: “Several hours after the first explosion shortly after 02:00 local time …”. Who noticed the pressure drop? Also, perhaps, this sentence can be broken up into two.
Split up and added “by the pipeline operators”

Comment 6. Line 49-53: As there have been reports confirming the locations of these events, the authors need to clarify what is new in their report.
Added: The identification was facilitated by the relatively high amplitude the signal, so that its arrival time could be observed on tens of stations. We present an approach that uses a minimum number of stations and does not require a prior velocity model.

Comment 7. Line 64: “Via observation of differential arrival time of seismic phases, …”. Perhaps, “Based on differential arrival time of seismic phases, …”
Changed as suggested.

Comment 8: LIne 68: The abbreviation CTBTO is not mentioned again and is not required.
Removed, thank you.

Comment 9. Line 76: Perhaps, ..which we developed to locate seismic events on Mars.” Also, a reference is required here.
Added

Comment 10. Line 90-91: “This method is based on the work of (Samson, 1983) and was first applied to seismic data by Schimmel and Gallart (2003); Schimmel et al. (2011).” Perhaps, “This method is based on Samson (1983) and was first applied to seismic data by Schimmel and Gallart (2003) and Schimmel et al. (2011).”
Is Schimmel et al. (2011) a necessary reference here?
Changed as suggested.

Comment 11. Line 93: “and correct the data to displacement.” What do the authors mean by correcting the data to displacement? How did they do it? Are the analyses (in Figure 2 and in the supplement) based on displacement time series, instead of velocity time series?

Added “using EVALRESP as implemented in ObsPy”.

Comment 12. Does the information presented in Table 1 need a reference? Latitude, Longitude and Magnitude seems to have been taken from a previous study or a report.
This information is from the SNSN catalog, added to the caption

Comment 13. Line 109-111 (also, Line 144): Do we have sufficient information to strongly negate the possibility of these events being earthquakes (instead of explosions)?
Added “The lack of a Love wave or transversally polarized S-waves (SH) supports an isotropic source, such as an explosion.”

Comment 14. Line 139: “identify” .. or is it “associate”?
Changed as proposed.

Comment 15. Figure 2 is quite a busy one. While I like the applied colormaps, it will be nice to have each panel explained (in the caption). Additionally, it might be helpful if x-axis are labeled. The first column obviously has time in the x-axis. Is the xtick labeled correctly?
We have added some clarification on the subplots in the caption. The time ticks are correct, though there might be some confusion as e.g. 00:03:30 is only marked by ‘30’ after the ‘00:03’ timestamp.

Comment 16. Figure 2 caption: “After the P-wave, polarization in the same direction is seen at 3.5 and 15 Hz, estimated as a continued pulsation at the source location.” I am not able to correlate this observation with the subplots.
We have added some clarification in the caption. This is referring to the histogram clusters marked with ‘Reverberations’.

Comment 17. It would be a good idea to have the supplement as a single .pdf file containing the plots, with the figures numbered (perhaps, S1, S2….) and appropriately captioned.

Comment 18. Acknowledgements. What the authors provided in Line 150-155 are not appropriate. In fact, a guide for this section is already included in their text - “Thank all relevant parties and acknowledge funding sources, if any.”
We have removed the placeholder statement and added the correct acknowledgement.

Comment 19. Data and Code availability. Please refer to the author guidelines on Data & code availability and reproducibility (https://seismica.library.mcgill.ca/author-guidelines).Perhaps, references to python packages - NumPy, SciPy and Matplotlib may not be required as these packages are well recognized and widely used. Also, I‘d request that the processed data, and if possible, the codes can be shared on Zenodo (https://zenodo.org/) or similar long-term platform as mentioned in the author guidelines. Of course, if the data are not available, the data availability statement should explain why.
We have moved the code package acknowledgements to the appropriate section and added the link to the polarization package. While the Python packages are widely used, we feel that it is appropriate to reference them.

Handling Editor

Review comments from Handling Editor (Dr. Ryo Okuwaki)

The submitted manuscript; "Locating the Nordstream explosions without a velocity model using polarization analysis" authored by S. C. Stähler, G. Zenhäusern, J. Clinton, and D. Giardini, is presenting a series of seismic analyses for the very recent seismic events around the Nordstream natural gas pipelines in Baltic Sea. The authors conduct a seismic event location based on a polarization method that was originally developed for locating Marsquakes. The authors successfully identify and locate a series of seismic events using only 4 or 5 nearby seismic stations, which are not likely regular earthquakes.

The technical advancement over the routine seismic event location algorithm is clear, that is, the authors' approach does not need travel times that are hugely affected by the local velocity structure, which is often unknown or uncertain especially in the seismically inactive region. The location uncertainty is well evaluated and visualized to adequately discuss a possible link to the explosive event at the Nordstream pipeline. I agree with the authors that such a successful event location should be applicable to the other non-tectonic seismic events where only a limited number of seismic stations and/or an unknown velocity structure are available.

I only have minor concerns about how uniquely the Nordstream explosive seismic signals are understood compared with other non-tectonic events (e.g., submarine volcano eruptions, submarine landslides or nuclear explosions). I see the associated seismic signals are lacking shear rupture elements (e.g., S-wave) and dominant in isotropic components, but how could the seismic signatures tell us about the physical cause (detonation) of the explosion or possibly the source processes at the very beginning of the explosion?

On Mars, we specifically use the S-wave polarization to support the backazimuth determined from P or to resolve ambiguities. Here, due to the lack of an S-wave, we are not able to do so. We use only a short time window after the P-arrival of 10s, so that even the strong S-wave of a tectonic event would not affect our analysis.

Also, to my best understanding, one of the highlights of the authors' location algorithm is that it requires very few assumptions about the source type and velocity structures, and it can be applied to continuous records. Given that advantage (or in order to strengthen that advantage), would it be possible to conduct a further scan of continuous waveform data at stations considered in this study, for example, in one-day time period (2022-09-26) to identify any other non-tectonic seismic events, which are possibly missed by routine analyses by SNSN or other agencies (other than Event 1 and Event 2A,2B)? Perhaps the authors might already have done that, but any further comments or discussion about such advanced monitoring would be appreciated.

Such a continuous polarization monitoring is an intriguing idea, however, in practice, there are a few difficulties: Strongly polarized signals typically only last a few seconds and integration over longer time windows is needed to find polarization in noise. So this is an active area of research for us, but not yet good enough to be presented here.

Also, I would like to suggest the authors showing waveforms (possibly in a separate figure), so that the seismic signals from Event 1 and 2(A,B) can be recognized and evaluated by the

readers, and also compared with the associated spectrograms.
One other thing that I would like to note here is that some of the sentences or discussion seems to have been missing necessary references to support the authors' arguments. I understand the necessity of being concise for Fast Reports articles, but I would like the manuscript to present a logic supported by necessary references, which I believe the authors' work will easily be followed by the readers from a broad seismological background and even stimulate further detailed research on this topic.
The other very minor comments are also itemized below, which I hope might be helpful for authors' revision.
Dr. Ryo Okuwaki

Specific Comments:
L10: ", most likely man-made"
I agree with the authors that, after reading the whole manuscript, the seismic events should not likely be the regular earthquakes, but at the same time, I am thinking that it might also be able to leave any judgments about the cause at this specific line. I am suggesting this also because the authors' work is mostly dedicated to illustrate how the polarization location method is efficient to locate the unknown seismic events that are often missed by routine location algorithms, but not in detail to evaluate an exact cause of the explosion (in other words, how or by whom the explosion is detonated). It is totally up to the authors' decision, but I would omit the relevant expression like ", most likely man-made" at least in the abstract.
We agree with this. The other reviewer proposed strengthening the political implications, but we prefer to keep it toned down and stick to the seismological observation.

L15: "30km and 10x60km"
Are these the dimensions for an uncertainty ellipse for each event? If so, would it be able to show longer and shorter axes for each uncertainty ellipse?
We would rather not add this to fig 2 (now 3) to keep the figure simple.

Additional language abstract
Thank you very much for your efforts to provide an additional language abstract. I would like to note that the additional language abstract has not undergone review so far, but I will ask our Editorial Board member to review the additional language abstract at the final round of review before the production stage. Thanks again.
This abstract was written in German, which is the first language of the two main authors and is a bit less technical than the English language abstract, so that it is aimed at a general public. We welcome an editorial review, if a German-speaking editor is available (I know there are…).

L43: "26 October 2022"
26 September 2022?
Changed, thank you.

L45 and L47: "02:00 local time" and "19:00 local time"
Are these the origin times of the events determined by someone? For example, this report says 2:03.
https://www.geus.dk/om-geus/nyheder/nyhedsarkiv/2022/sep/seismologi

We used the origin times and locations and magnitudes of SNSN, reference added.

L47: "Despite the fact"
Is it natural to expect the gas pipe to be pressurized when it is not transporting anything, or is it usually not pressurized when the pipe is not operated? Do the authors have any references to show what kind of contents (methane?) was filling the pipe before the event?

As we learned after this event, it is normal that gas pipelines are pressurized, even when not transporting, which increases the lifetime of valves and other systems. However, this goes a bit beyond this article.

L49: "methane were released after the leak"
Show reference (perhaps the report from Danish military intelligence?)

Reference to Danish Maritime Office added

L52: "SNSN as ML = 3.1"
Do the authors have any ideas of why the second event has a larger magnitude (ML 3.1) than the first one (ML 2.7), based on the authors' own analyses? If the first event contributed to decompression of the pipe by leaking, the second one might have a lower potential for decompression and hence the lower emitted seismic energy? I would appreciate it if the authors could extend the discussion about this.

The second event happened on a completely separate pipeline. But given the complex combination of (likely) explosives, rupture and methane release, many things can affect the magnitude.

L53–54: "a region of very low seismicity", "most likely deliberate"Are there any possibilities of submarine landslides that cause damages to the pipeline in this region?

The bathymetry in this region is very flat and landslides have so far not been reported to my knowledge. This has been confirmed to me by oceanographic researchers.

L53: "it is plausible to identify these seismic events with the leaks and attribute them to an explosion, most likely deliberate"
I guess it might be better to keep the seismic source unknown at this particular section before the authors untangle the associated seismic signatures in the subsequent sections.

Done

L57: "NORSAR"
Norwegian Seismic Array (NORSAR)
Changed as suggested.

L57: "Nordstream quake"
Nordstream seismic events considered in this study
Changed as suggested.

L57: "precisely for this task"
Show reference.
Changed as suggested

L60: "10-100 km"
Use double hyphens "--" for the range of values; $10--100$~km.
Changed, thank you.

L60:
Are there any specific reasons to mention those arrays other than the NORSAR array here? If not, I would omit these lines about those arrays.
Changed as suggested

L66: "its magnitude estimated to obtain the yield of a nuclear test"
Have the authors determined magnitudes of this kind for the 2022 Nordstream events?

Since magnitude determination usually requires a velocity model, we think that it goes beyond our analysis. Also, we do not think that we could add anything to the reported magnitude from SNSN.

L72: 4-5
Use double hyphens for a range of values; $4--5$ mm/y.
Changed, thank you.

L70–72:
Show reference for the tectonic setting of Baltic Sea or the associated glacial movements introduced here.
Added

L81: "P-wave is not sufficient"
Clarify the meaning of "not sufficient". Does this mean that the number of P-wave traces are not sufficient to constrain the location?
We have added some clarification. There is only a single station on Mars, so any analysis must be made from its three components. Marsquakes have a very low amplitude and are generally located far from the station, resulting in very low signal to noise ratios. It is often difficult to discern between seismic signal and wind contamination, so the additional information in the S-wave helps with the back azimuth determination.

L93: "HH?"
I understand the practical meaning of "?", but please show specific channels considered in this study, for example, HHZ, HHN and HHE.
Changed “HH?” to “HHZ, HHN, and HHE”.

L94: "i.e. the 2 days before the leaks"
Perhaps this is "1 day before the leaks"? if the leak is reported on 2022-09-26.
Thank you, we have changed it to “i.e. including the day before the leaks were reported”.

L95: "high-frequency seismic events"

Please clarify the range of frequency if possible. Also, are these "high-frequency seismic events" the 2022 Nordstream events?

L96:" 2022-09-26 17:03:50 UTC and a second event around 2022-09-26 00:03:24 UTC"
It seems the timeline is contrary to the ones displayed in Table 1. Please check the timeline again.
We have clarified the sentence so that it is consistent with the labelling of the events.

L97: "were clearly detectable."
How can the readers find the signals? It would be great if the authors show data (waveforms) somewhere in Figure 2 or in a new figure, so that the readers could evaluate the authors' own observation. (I did check the data by myself and I agree with the authors that the signals are clearly visible anyways.)
Total three figures are allowed, so would it be possible to show waveform data at, for example, BSD station, so that it illuminates how the associated signals of Event 1 and 2 are different from or similar to each other.
Related to this point, for Event 2, it is intriguing to see some high-frequency signals at the very beginning or preceding the larger amplitude of signals (please see example waveform traces below), which may look different from Event 1. I would be very curious how the authors could see this difference and how this may perhaps differentiate the source processes of Event A and B?Bandpass filtered (2–8 Hz) velocity waveforms at DK.BSD. Event 2A and 2B
How are the two minor events A and B recognized (or seperated) in the waveform data? Please show the example figure in the main text.
We added a combined spectrogram/seismogram as figure 1. These are big figures, but they thus contain a lot of information, including about the spectral character. We therefore added a discussion of spectral peaks as well.

L100:
Explain \alpha briefly.
Changed

eq(1):
What does `tot` represent?
Changed to “total”

Table 1 : "00:03:24.5"
In L96, the authors write "00:03:24". I think it might be helpful to be consistent about the precision throughout the manuscript.
We have changed the table to be consistent with the text.

Table 1:
Use parenthesis "()" or different symbols for uncertainty range, because the brackets are already used for units; e.g., [deg] in a header of the table.
Changed to parentheses.

Table 1:
Origin time is determined by authors? If not please show references for the origin times in

the table caption (SNSN?).
Changed

Table 1:
Could it be possible to use ± for the uncertainty range in the same way as the main text?
111–139 --> 125 ± 14
The uncertainties are not necessarily symmetric, therefore we provide the range in this way.

L105: "clearly polarized P-waves"
Could you please clarify what this "clearly polarized" means in the authors' context?Does this mean that both the P- and coda-waves have a single peak in its density in a certain range of frequency (the right-most azimuth-density plot in Figure 2)?
done

L107: "(see table 1."
(table 1).
Changed as proposed, added missing parenthesis.

L109: "an identification of the explosions would already be possible"
We might still have some possibilities that the seismic location just coincides with the infrastructure, before the authors discuss the signal properties in the subsequent lines. I would omit this line if possible.
Good point! Done

L110: "a clear P-wave but no obvious S-wave"
A lack of clear S-wave should be nice evidence of an explosive seismic event. Showing waveforms would be helpful.
Done, see figure 1

L112: "overall duration of at least 10 minutes before falling to pre-event noise levels"
This is a very interesting observation. Is this 10-min duration common for other seismic stations? Have the authors observed the similar duration for Event 2 as well?
Yes, see new figure 1

L112: "A signal is visible on several other openly accessible stations in Germany, Denmark, and Sweden"
Is it possible to show these station codes and channels, so that the readers could conduct some further analyses following the authors' work.
done

L113: "Swedish National Seismic Network"
SNSN
Changed as proposed.

L115: "KQ.PEEM in Peenemünde, Germany, in 100 (event 1) and 150 km (event 2) distance has clearly visible signals as well"
What kind of "signals" is discussed here? Is it the waveform signal or spectrogram?
Again, showing the waveform would be helpful to evaluate this argument.

We present polarisation plots in the supplement. Showing a full seismic section of all stations goes against the flow of this paper, which is more focused on in-depth analysis of a few stations.

L117: "80°for"
Add a space; "80° for".
done

L126: The actual leak
Show reference for the location of "the actual leak".
Added the reference to the navigational warnings

L129: "sustained polarization"
Does this mean that the back azimuth is the same among the P- and coda-waves? Please clarify the meaning of "sustained".
Yes, clarified

L133: "1450 m/s (typical for 15°C)"
Show reference.
Added a more specific reference to the region (the Baltic sea has a very low salt content, which affects the sound speed.

L136: "Minnaert resonance of rising gas bubbles"
Show reference.Figure 1:
It seems Figure 1 has enough space, so please add network code along with the station code (e.g., UP.DEL).
done

Figure 1 Legend:
"combined location" looks a bit unclear. Please clarify what these contours represent. Also, explain the meaning of dashed and solid contours in the caption.
Done

"Gas leaks": Are these the locations determined by Danish military intelligence? Please indicate the agencies as well, in the same manner as for "SNSN location" for yellow squares.
Done

It should be nice to make time precision for the origin times of Event 1 and 2 consistent with those shown in Table 1.
Done

Show reference for bathymetry. Also clarify the data source and its availability in Data and code availability if possible.
SRTM30_PLUS dataset, reference added

Show reference for pipeline location (blue lines). I would expect those lines to be openly available so that the readers could reproduce the figure.
added.

Figure 1 caption:
"We could obtain clear back-azimuths from 5 stations for event 1 (generally marked by reddish colors) and 4 for event 2 (marked by greenish colors)."
It seems it is inconsistent with Table 1. Table 1 shows 4 stations for Event 1 and 5 stations for Event 2.
fixed

"Additional stations like GE.RGN on the Rügen island (Germany) or DK.COP near Kopenhagen were tried, but had poorer azimuth constraints than neighbouring stations. We thus did not include them in this analysis and figure."
I think this is an important statement and it should be written in the main text, not in the caption.
Done

"The SNSN operates several more stations in Southern Sweden that might give additional constraints, but data from these was not publicly available at the time of writing."
This is important information. I would suggest writing in the main text, not in the cation.
done

Figure 1 color bar:
"Negative Depth" should mean positive elevation (e.g., above the sea level). If the color of the matplotlib.pyplot.contourf represents depth, the ticklabels of the color bar should be Positive.
Done, thanks!

Why does the color bar involve different intensity for one value? For example, if we see the color at `-50 m` on the color bar, the color seems to change from dark to light from left to right (please see attached screen capture).
Good spot! This was an error during PDF conversion. It should be fixed now

Figure 2
Is it possible to draw "Noise" section (window) in the spectrogram panel?
What does the pale red rectangle represent (matplotlib.pyplot.axhspan)? It seems it highlights 2–4 Hz, but why? (I guess this should be a range used for calculating histograms in the right-most panels, but please clarify in the caption).
The shaded area indeed marks the frequency band for the Kernel density estimate in the rightmost column - we have added a more in-depth figure caption to make the different subplots more clear.
We have decided to focus on the event signal, including the coda. Unfortunately the time resolution gets poorer if we extend the time axis to include the noise window. However, the 30 seconds before the event (00:03:00 to 00:03:30) should give an indication of how the noise looks like.

The authors may need to thoroughly explain the middle panels. What is the abscissa (X axis)? (I guess that should be, for example, amplitude [dB] for the upper panels, but please explain or add labels on panels).
We have extended the figure caption.

"After the P-wave, polarization in the same direction is seen at 3.5 and 15 Hz"
Could you highlight that corresponding portion in Figure 2, so that anyone could evaluate this? Please indicate any marks or highlights on the panel.
We have added some clarification in the caption. This is referring to the two histogram clusters marked with ‘Reverberations’ on the plot.

"pulsation"
Is this corresponding to "resonance of rising gas bubbles"?
Yes, for the reverberation at 3.5 Hz (described in the text as a possible Minnaert resonance).

Acknowledgements:
"Thank all relevant parties and acknowledge funding sources,"
Please delete this template line.
We have deleted it.

"The polarization code is available on github"
Could I ask where I can access the code? As the authors clearly say "The polarization code is available on github" in the code availability, I need to evaluate the code and make sure of its reproducibility before making any judgments about final publication of this manuscript.
We have added the GitHub/Zenodo repository reference.

References:
L194: "page Approximately 65 active permanent stations"
Please check if the reference is nicely formatted. According to the SNSN website http://www.snsn.se/network/ , it seems it is advised to cite as follows:
SNSN (1904): Swedish National Seismic Network. Uppsala University, Uppsala, Sweden. Other/Seismic network. doi:10.18159/SNSN
Thank you, we have adjusted the reference.

Comments from Handling Editor (Dr Ryo Okuwaki)

*Below, I marked ">>" for the previous comments from Reviewer 1 or Handling Editor and ">" for the authors' reply.

>> Comment 17. It would be a good idea to have the supplement as a single .pdf file containing the plots, with the figures numbered (perhaps, S1, S2....) and appropriately captioned.

This comment by Reviewer 1 is not resolved. Please submit the revised Supplementary Material by combining the supplementary figures into one single PDF file.

>> L15: "30km and 10x60km"

>> Are these the dimensions for an uncertainty ellipse for each event? If so, would it be able to show longer and shorter axes for each uncertainty ellipse?

> We would rather not add this to fig 2 (now 3) to keep the figure simple.

Yes, I agree with the authors that it is not needed to add anything to Fig. 3, but I have meant to ask for clarification in the abstract. Is the dimension "30km" representing an uncertainty ellipse for Event 2? If so, "30×30~km" might be clearer to represent the dimension? Also, "with the uncertainties in elliptical bounds of 10 x 60 km and 30 x 30 km" might be good to align with the timeline of Events 1 and 2?

L53: "high amplitude the signal"

high amplitude signal or high amplitude of the signal

L54: "(event 20220926135_nJ3BWW)"

(SNSN, 1904, event 20220926135_nJ3BWW)

L86: ", is determined"

is determined

>> L95: "high-frequency seismic events"

>> Please clarify the range of frequency if possible. Also, are these "high-frequency seismic events" the 2022 Nordstream events?

This comment is not resolved.

L117: "80°for"

>> Add a space; "80° for".

> done

It seems the space is still missing.

L152: "these two peaks would correspond to wave lengths of about 100 and 420 meter"

1470 [m/s] * (1/15) [s] = 98 [m]

1470 [m/s] * (1/3.5) [s] = 420 [m]

I know the authors are already saying "about" in this sentence, but "98" meters would be appropriate for the estimates for 15 Hz?

L155: "higher wavelength"

longer wavelength

>> Show reference for pipeline location (blue lines). I would expect those lines to be openly available so that the readers could reproduce the figure.

> added.

> the pipeline can be obtained from OpenStreetMap

Please show how exactly one can access the pipeline location in Data and code availability section, so that Fig. 2 can be reproduced. Is the below source the one the authors exactly used to generate Fig. 2?

https://www.openstreetmap.org/relation/2006544

>> Is it possible to draw "Noise" section (window) in the spectrogram panel?

> We have decided to focus on the event signal, including the coda. Unfortunately the time resolution gets poorer if we extend the time axis to include the noise window. However, the 30 seconds before the event (00:03:00 to 00:03:30) should give an indication of how the noise looks like.

I appreciate the authors' reply. I understand. Could you please write so in the figure caption, so that the readers might not be confused?

>> I only have minor concerns about how uniquely the Nordstream explosive seismic signals are understood compared with other non-tectonic events

> On Mars, we specifically use the S-wave polarization to support the backazimuth determined from P or to resolve ambiguities. Here, due to the lack of an S-wave, we are not able to do so. We use only a short time window after the P-arrival of 10s, so that even the strong S-wave of a tectonic event would not affect our analysis.

Yes, I agree with the authors that there is a lack of S-wave in the signals associated with the Nordstream incidents. In my original review report, I was asking about how the overall signals of the Nordstream incidents (mainly P-waves or coda waves) can be differentiated from the other non-tectonic seismic signals, for example, from submarine volcanoes (e.g., Lyons et al., 2019, Nat. Geosci.; Tepp & Dziak, 2021, JGR, 10.1029/2020JB020912) or submarine landslides (e.g., Caplan-Auerbach et al., 2001, GRL, 10.1029/2000GL012545; Fan et al., 2019, GRL, 10.1029/2020GL087213). These tectonic or environmental source signals are not necessarily involving S-waves (or not even clear body waves), and can be compared with the signals of the Nordstream incidents. For example, I'm guessing that the signals associated with the Nordstream incidents are likely lacking longer periods of signals because the source itself is likely spotted (on the pipe, perhaps) with very few or little mass transports (e.g., sediments), unlike the submarine landslides. I thought such a discussion may help differentiate the Nordstream seismic signals from any other environmental or tectonic seismic signals, which can be (briefly) added somewhere in the main text.

> Such a continuous polarization monitoring is an intriguing idea, however, in practice, there are a few difficulties: Strongly polarized signals typically only last a few seconds and integration over longer time windows is needed to find polarization in noise. So this is an active area of research for us, but not yet good enough to be presented here.

Thank you for your reply to the comment. I understand. Please discuss this point (or write as is) in the main text. Because the authors are saying; "We then manually scan the data of days 2022-09-25 and 2022-09-26" at L104, it may be helpful for readers to know why the scan is done manually.

Thank you for adding Fig. 1, which is really helpful to evaluate the signals. I list below the minor requests to improve the figure.

I understand the space is limited, but the label font size seems to be too small to recognize. Please use a bigger font size.

Please delete the label "2022-09-26" in the right top of the longer-period spectrogram panel, which is overlapping with the spectrogram.

It seems the right-most time tick label and left-most PSD tick label are overlapping. Please fix.

Please indicate which linestyle (or symbol) is corresponding to which value (median, 5th, 25th, 75th, 95th, NLNM and NHNM), either in the caption or as a legend.

I asked our Seismica Board Member Dr. Alice-Agnes Gabriel to review the additional language abstract. I have received the comments below. I would appreciate it if the authors could consider the suggestions and make changes to the abstract. Although it should be totally up to the authors' decision, I would be grateful if there happens to be any rooms to acknowledge Dr. Alice-Agnes Gabriel, perhaps in Acknowledgements section.

comments from Dr. Alice-Agnes Gabriel
The German abstract captures the paper’s content very well and resembles the English abstract 1:1. I am aware of the authors excellent German capabilities; however, I offer a few language-specific suggestions and typo corrections below, marked in bold.

Die Lecks in **den Röhren** der beiden **Nord-Stream-Pipelines** wurden von zwei **signifikanten** Seebeben begleitet. Der Charakter dieser Seebeben spricht gegen einen tektonischen Prozess und für eine Explosion, gefolgt von schneller Dekompression des Gases. Wir verwenden eine Polarisationsanalyse, die die Richtung der Bodenbewegung analysiert, um die Beben zu lokalisieren. Diese Methode wurde ursprünglich entwickelt, um **die Epizentren** von Beben auf dem Mars mit einem einzelnen Seismometer zu bestimmen. Wir zeigen, dass mithilfe von 5 Stationen **in der Nähe der** westlichen Ostse**e** die beiden Explosionen sicher den an der Oberfläche beobachteten Methan-**Strudeln** zugeordnet werden können. Darüber hinaus können wir zeigen, dass auf die Explosionen ein mindestens zehnminütiger energie-reicher Dekompressionsprozess folgte. Mehrere Resonanzfrequenzen in **den analysierten** Signal**en** deuten auf Reverberationen in der Wassersäule oder de**n** geplatzten Leitung**en** hin.

Großartig!

Alice Gabriel