Supplementary Material for "Improving seismicity monitoring to prepare for CO_2 storage in the Horda platform, Norwegian North Sea"

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Summary This supplementary material contains descriptions of time and orientation corrections applied for the continuous OBS data (Text S1 and S2). The supplementary material also includes Supplementary Figures and Tables. Figure S1 shows the seasonal Noise Power Spectral Density. Figures S2, S3 and S4 show the timing verification using the ambient noise correlation. Figure S5 displays the location of seismic shots used to determine the OBS orientations. Figure S6 illustrates the coordinate system for horizontal channels of the OBSs. Figures S7, S8 and S9 shows the process to determine the orientation of HNO3. Figures S10 shows the distribution of travel-time and arrival time error parameters from Bayesian Hierarchical Earthquake Location (Bayesloc). Figures S11 shows comparison of earthquake locations and location errors from Bayesloc determined using the land stations and the combination of land and OBS stations. Table S1 lists the duration of the continuous OBS records. Table S2 shows list of seismic shots used to determined the OBS orientations. Table S3 provides combination of polarities to resolve the orientation ambiguity. Table S4 shows clockwise rotation angle for horizontal channels. Table S5 shows horizontal component azimuths.

Text S1: Time Correction

Accurate timing is critical for seismic monitoring, as the precise synchronization of the OBS clocks is necessary to ensure the validity of seismic measurements. The internal clocks of the three deployed OBS units (HNO1, HNO2, HNO3) were initially synchronized to GPS time before and after deployment, with clock drift measurements (skew measurements) recorded (Table S1).

To verify the timing correction, we used the EGF_td_toolbox (Loviknes, 2018; Loviknes et al., 2020) to extract the daily empirical Green's functions (EGFs) by cross-correlating the vertical channels of the OBS units.

The data were preprocessed before the cross-correlation step, including:

- Downsampling to 10 samples per second
- Trend removal (detrending the signal)
- Tapering (to reduce edge effects)
- Instrument response removal

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- Bandpass filtering in the frequency range of 0.1–4.9 Hz

Once the preprocessing was complete, the daily continuous waveforms from six combinations of station pairs (HNO1-HNO2, HNO2-HNO3, HNO1-HNO3) were cross-correlated with a window length of 12 hours. The first measurement used the skew-corrected traces to check if the timing correction was accurate. We analyzed the daily cross-correlation functions (CCFs) by stacking signals when necessary, adjusting the filter ranges, and measuring the time shifts.

We have applied the ambient noise cross-correlation between the OBS, and created daily EGFs. To enhance the signal-to-noise ratio (SNR) of the EGFS, we stacked the daily EGFs every seven days. Longer stack time windows can increase the SNR, but we also lose details of variability in the EGFs. We used the stacked EGFs from the first seven days as the reference trace used for time reference. Figure S2 shows the reference trace for HNO1-HNO2 pair filtered with different frequency bands. The band-pass filter of 0.1 - 0.5 Hz produces the clearest stacked EGF signals for the HNO1-HNO2 pair. Therefore, we selected this filter band for further analysis. Since stacked EGFs are only clear for nearby pairs (less than 25 km separation), we decided to use the nearby pairs (HNO1-HNO2 and HNO2-HNO3) for further analysis.

The weekly stacks of EGFs of corrected traces for HNO1-HNO2 pair are shown in Figures S3. The plot shows that the EGFs are asymmetric and complicated. To analyze the timing, we separated the acausal and causal part of the EGFs, and normalized the amplitudes (Figure S3.b and c). Both visual inspection and maximum cross-correlation value measurement show that there is no obvious time shift for the HNO1-HNO2 and HNO2-HNO3 pairs. We notice that the normalized EGFs (Figure S4. b and c) are slightly curved from week 15 to 30 (early January 2022 - late April 2022). The reason for this is not clear and could be related to the data processing.

The weekly stacks of EGFs between uncorrected HNO1 and corrected HNO2 are shown in Figure S4. A clear linear time shift is observed from the EGFs plot. If we assume the HNO2 time correction is accurate, then the time difference measured here is total time shift for the HNO1 raw traces. The time difference between the first and the last traces of daily and weekly EGFs are -29.4 seconds and -28.9 seconds, which are close to the skew measurement for HNO1 (-29.446 seconds). We applied the same approach for the other pairs to estimate the time drift for HNO2 and HNO3. After this quick verification, we measured the time delay by measuring daily time shifts relative to the reference traces and then obtained the time shift by linearly fit the daily time delay. We observe that the values obtained from the EGFs are similar to the skew measurement, and no further time correction is required.

Text S2: Sensor Orientation

Typically OBS are deployed using free-fall, which means the horizontal channel orientation is unknown. Obviously, the horizontal orientation is needed for many seismological analysis, including single station location, seismic anisotropy, receiver function and moment tensor inversion. One can determine the orientation using active sources (e.g, air gun) or passive sources (e.g., ambient noise and earthquakes). In this report, we used seismic airgun shots that were 20-40 km from the OBS (Figure S5). These shots (Table S2) were done at Smeaheia for seismic imaging outside our project, but provided suitable seismic signals for our purpose. The location and time of each shot was provided by Equinor. Previously, we tried to use surface waves from teleseismic earthquakes and body waves from regional earthquakes. However, due to low signal-to-noise ratio we could not obtain reliable results.

The OBS contain two horizontal channels, labelled HHY and HHX. An Illustration for the coordinate system for the horizontal channels is shown in Figure S6. To determine the OBS orientation within the geographic coordinate system, we used the early part of the seismic signals and then analyzed the polarisation of the horizontal channels (HHY-HHX) to measured the apparent back-azimuth. If the horizontal channels are well oriented to north-south and east-west directions, the measured back-azimuth will be similar to the back-azimuth between receiver and source, with 180° ambiguity. With this assumption, we can estimate the deviation between the HHY-HHX and HHN-HHE channels by calculating the difference between back-azimuth from polarisation analysis and the receiver-to-source back-azimuth (α). Then we rotate the HHY-HHX channels clockwise by α, using the following relation:

$$\begin{aligned} HHN(t) &= cos\alpha.HHY(t) + sin\alpha.HHX(t) \\ HHE(t) &= -sin\alpha.HHY(t) + cos\alpha.HHX(t) \end{aligned} \tag{1}$$

To resolve the 180° ambiguity, we use two approaches: 1) using polarity combination between horizontal channels, HHN and HHE, and the vertical channel, HHZ, following Havskov and Ottemöller (2010) (see table S3), 2) Comparing the polarities of radial and vertical channels, radial and transverse channels are rotated clockwise by azimuth ϕ), using the following relation:

$$\begin{aligned} Radial &= -cos\phi.HHN - sin\phi.HHE \\ Transverse &= sin\phi.HHN - cos\phi.HHE \end{aligned} \tag{2}$$

The radial and vertical channels should be correlated and have the same polarities. If the polarities of the radial and vertical channels are in the opposite direction, we add 180° to the rotation angle α.

Before we performed the orientation analysis, we selected several seismic shots to cover different source-to-receiver back-azimuths (see Figure S7.a as an example for OBS HNO3). We extract the seismograms from the continuous records and applied a high-pass filter of 10 Hz (see Figure S7.b for OBS HNO3). Then we manually picked the first arrivals and cut the seismograms with the SAC software (Goldstein et al., 2003).

We begin determining the orientation of HNO3, which is the closest OBS to the seismic shots (between 20 - 26 km away, shot1-shot6) and the recorded seismic signals have less complicated signal compared to other OBS. To perform the polarisation analysis, we used the first two seconds of the signal (Figure S7.b). The polarisation analysis shows that HNO3 deviates 305.6° ± 1.8°, with 180° ambiguity (Figure S8). To resolve the ambiguity, we used shot2 as an example (Figure S9.a), which is southeast from HNO3. Channels HHN, HHE and HHZ show the same polarities, which indicates that we need to add 180° to the rotation angle. To verify this result we generated two sets of horizontal channels: 1) HHN-HHE rotated by 305.6° then rotated to R-T channels (HHR-HHT), 2) HHN-HHE rotated by 305.6° + 180° (125.6°) then rotated to R-T channels (HHR+180°-HHT+180°). Figure S9.b shows that the vertical HHZ channel is correlated with HHR+180 deg channel indicating that the correct rotation angle for HNO3 is 125.6° ± 1.8°.

We proceed to determine the orientations of HNO1 and HNO2 with the same approach. The results are summarized in Table S4. The corresponding component azimuth angles (degrees clockwise from north) are given in Table S5.

Supplemental Figures

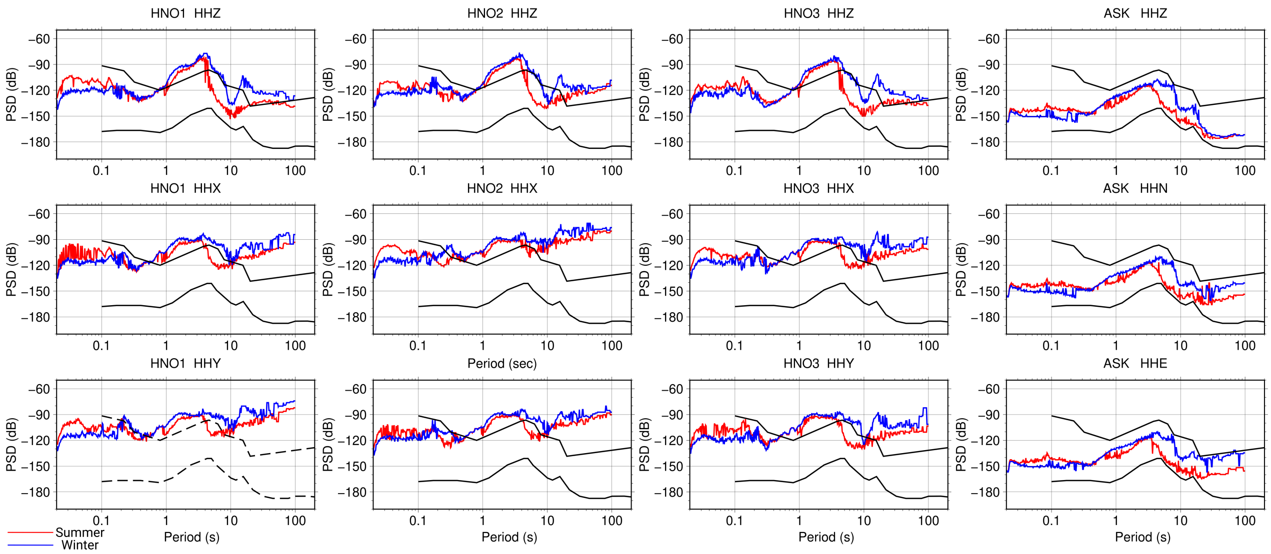

Figure S1 Seasonal Noise Power Spectral Density between winter (21 December 2021 - 20 March 2022) and summer (21 June 2022 - September 2022) for the three OBSs (HNO1, HNO2 and HNO3) and reference land station ASK.

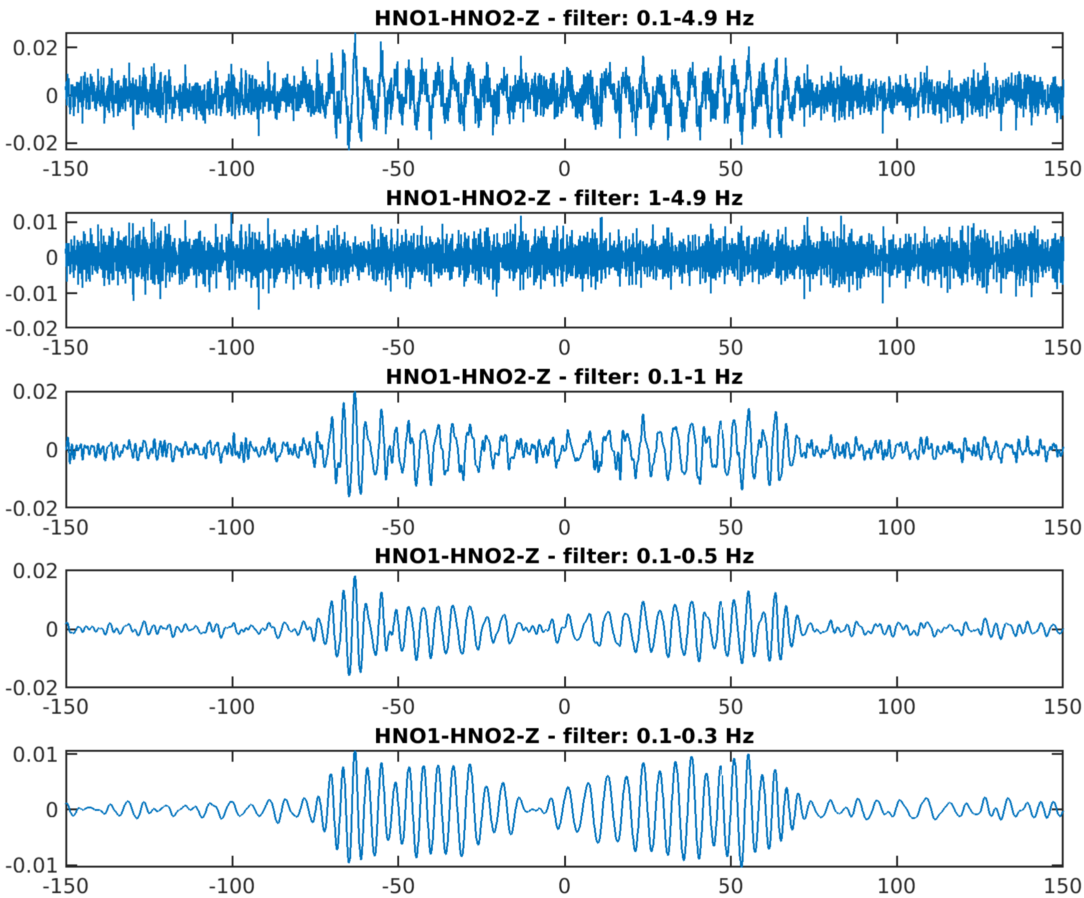

Figure S2 Stack of the first 7 days EGFs used as the timing reference. The stacks are shown with different filter ranges (0.1 - 4.9 Hz, 1 - 4.9 Hz, 0.1 - 1 Hz, 0.1 - 0.5 Hz and 0.1-0.3 Hz). For further analysis, we used filter range of 0.1 - 0.5 Hz, which shows clear EGFs.

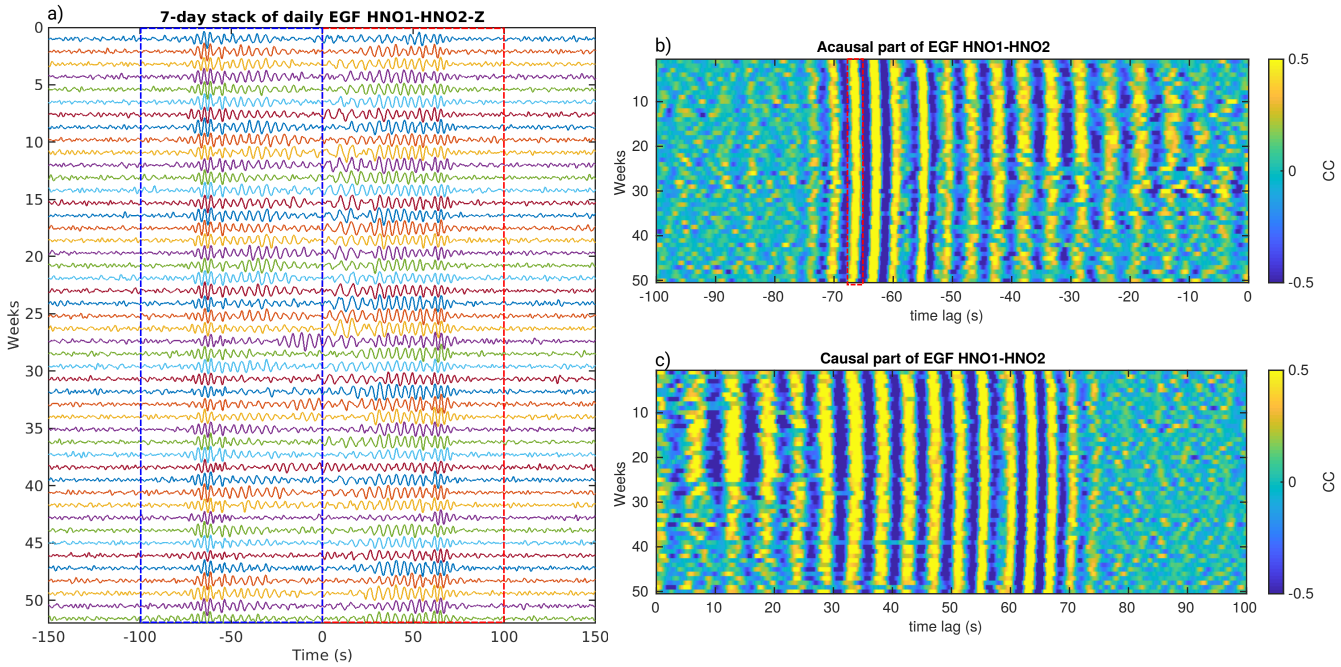

Figure S3 a) Weekly stack of EGFs of HNO1-HNO2 pair extracted from the skew corrected traces. The traces are divided into two parts: causal (red dashed box) and acausal (blue dashed box). Normalized amplitude of acausal and causal part of the EGFs are shown in b) and c). Dashed red box in b) shows a slight bend in the EGFs.

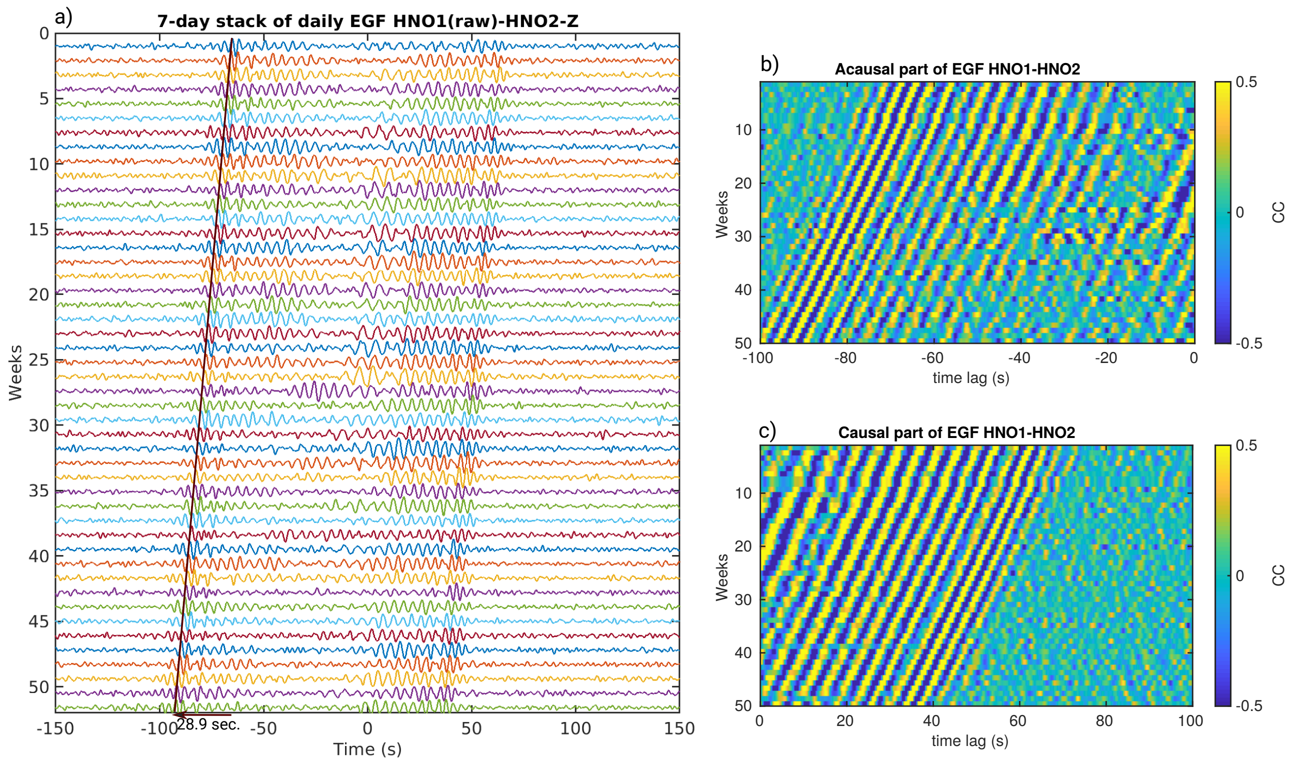

Figure S4 a) Weekly EGFs for HNO1(uncorrected/raw)-HNO2 (corrected). Black line shows the time shift of 28.9 second over the recording period for the pair. Normalized amplitude of acausal and causal part of the EGFs are shown in b) and c).

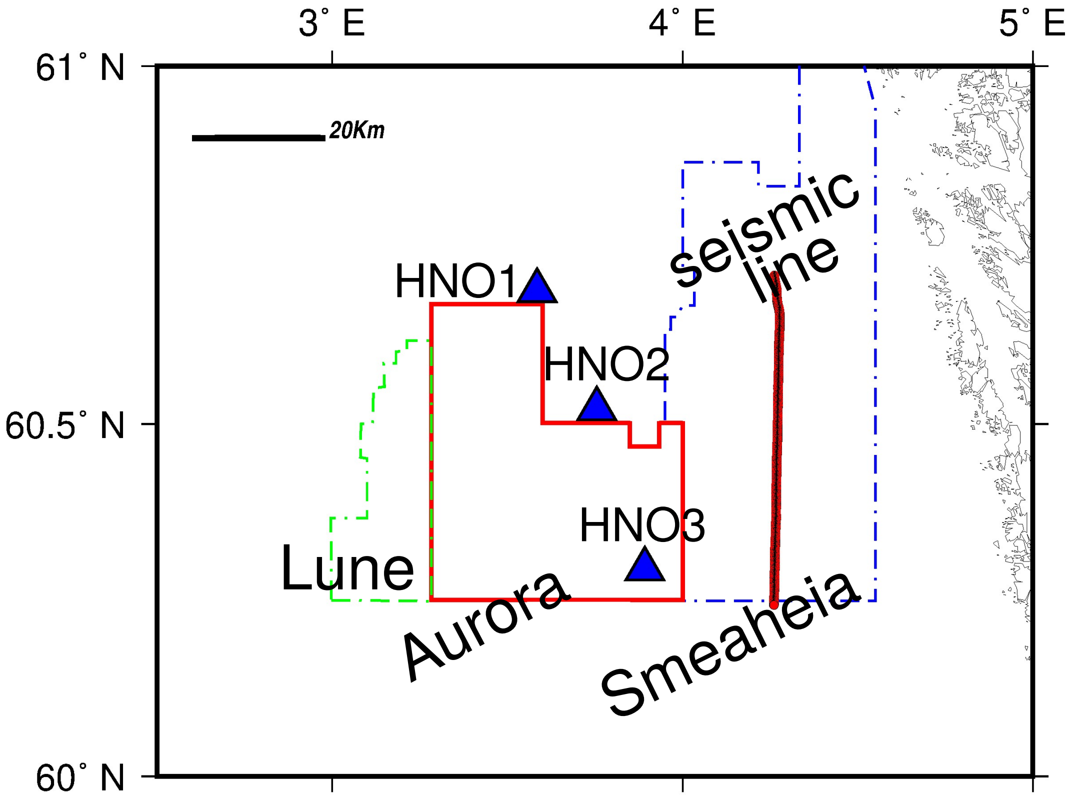

Figure S5 Location of three OBS (HNO1, HNO2 and HNO3) and seismic line used to determined sensor orientation. CO2 storage sites (Lune, Aurora, Smeaheia) are also shown here.

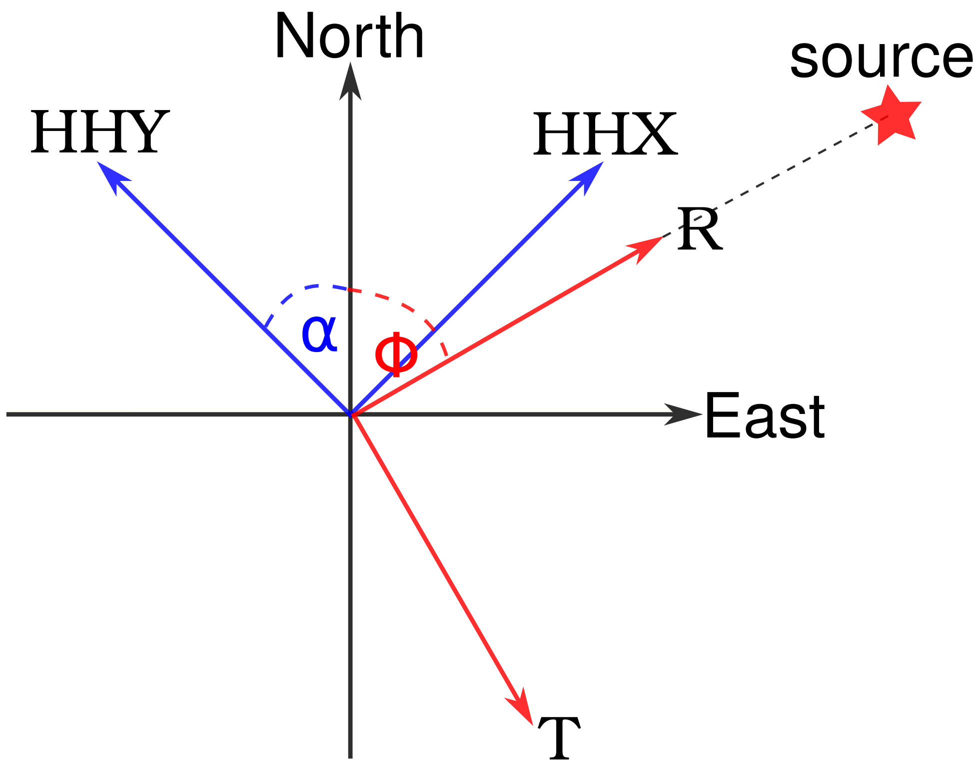

Figure S6 Illustration of coordinate system for horizontal channels of OBS modified after Zha et al. (2013). The horizontal channels of the raw data are labelled as HHY and HHX, and are shown as blue axes. The relative difference between the HHY-HHX and North-East coordinate system in clockwise direction is α. The radial (R) and transverse (R) channels (red axes) rotated clockwise by back-azimuth (ϕ) relative to the location of seismic source (red star).

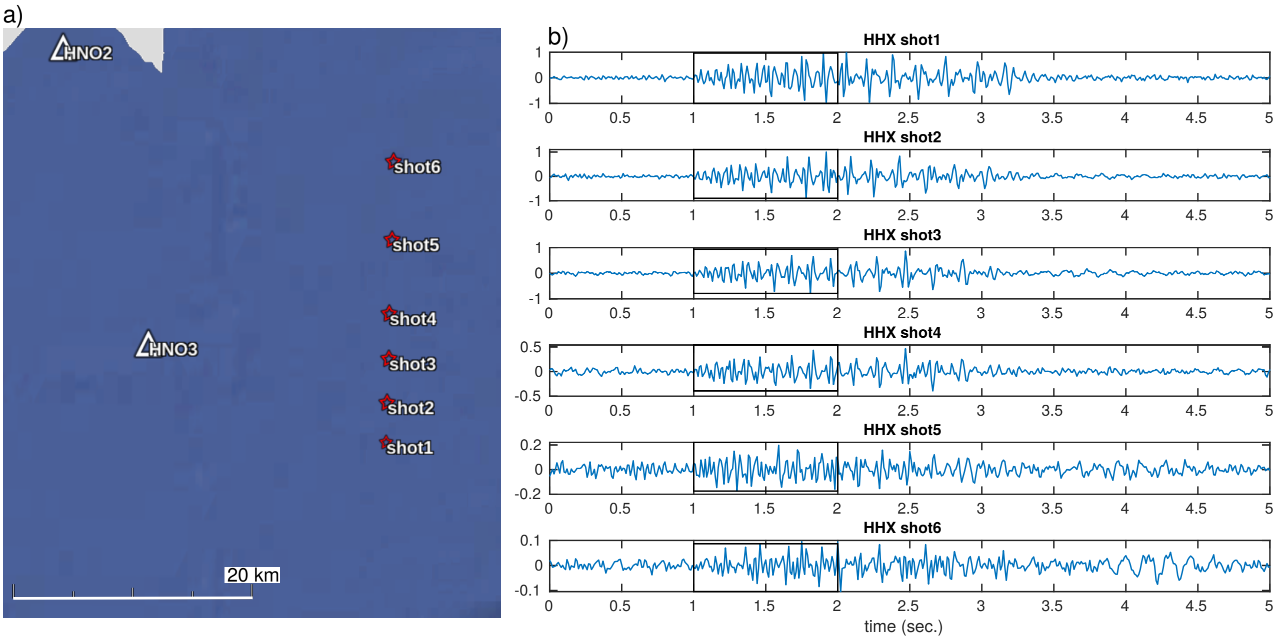

Figure S7 a) Six seismic shots used to determine the orientation for HNO3. b) Seismograms recorded at HHX channel for the six shots. Black boxes marked the part of the signals used for the orientation analysis.

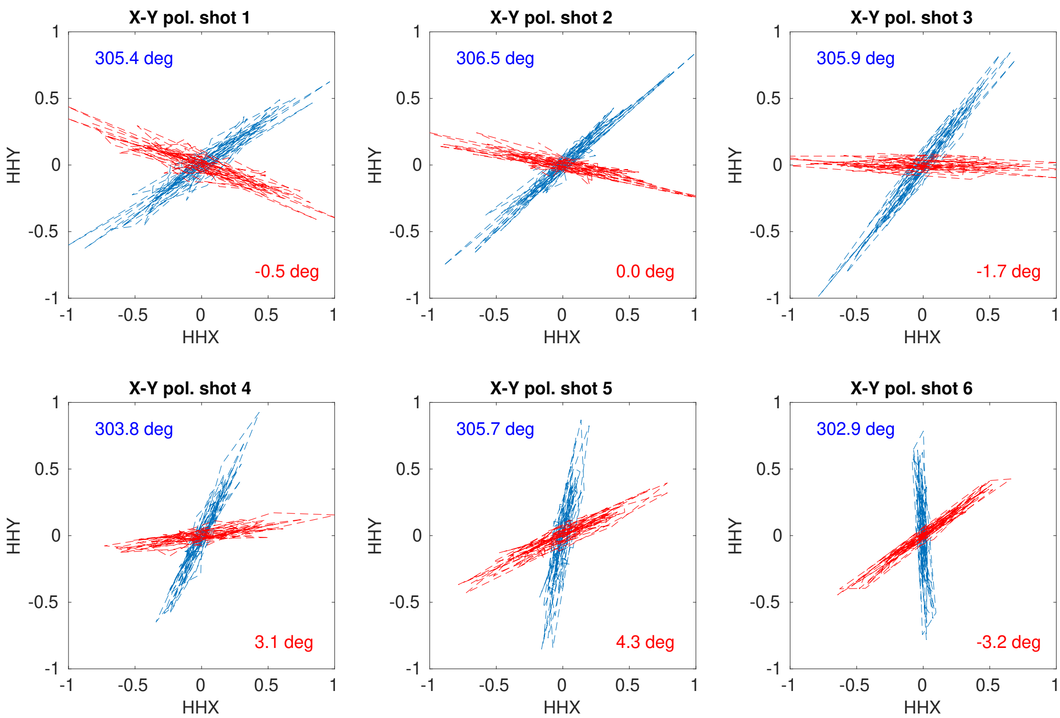

Figure S8 Polarisation analysis for horizontal channels of HNO3: HHX-HHY (blue lines) and rotated channels HHE-HHN (red lines). The difference between back azimuth measured with geographical coordinate and polarisation analysis for HHX-HHY and HHE-HHN channels are shown in blue and red text respectively.

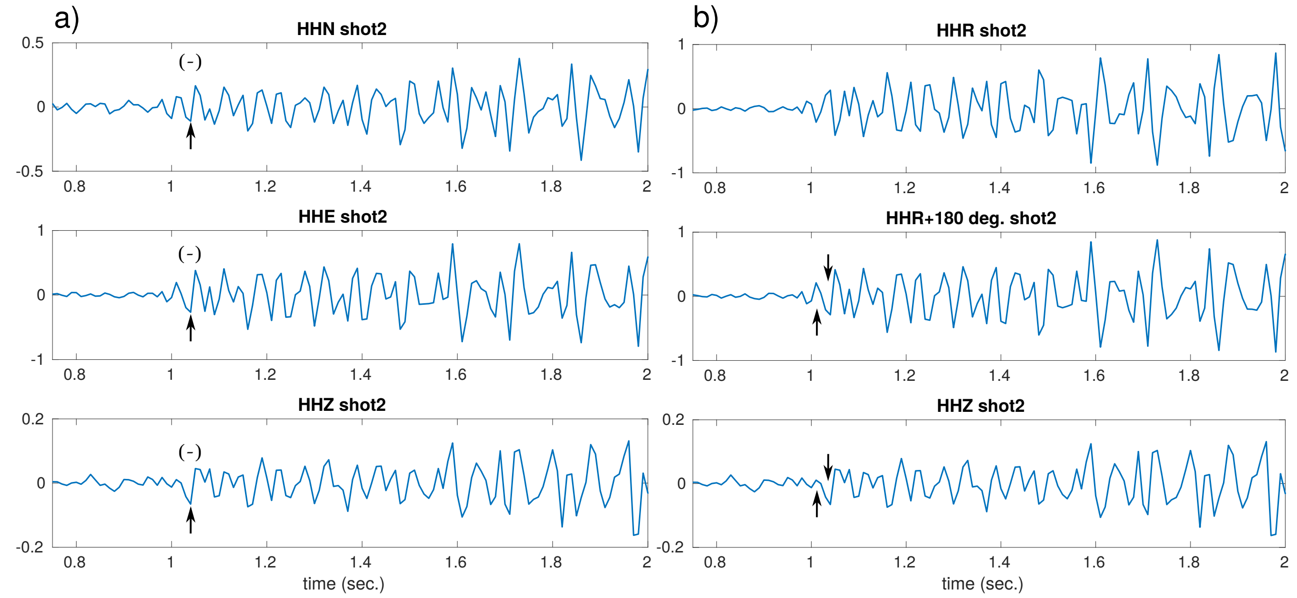

Figure S9 Resolving the 180° ambiguity for HNO3: a) traces for shot2 rotated by 305.6° clockwise. All channels show the same polarities, indicating that 180° needs to be added to the rotation angle. b) traces rotated to R-T channels. The HHR+180° correlates with the vertical HHZ channel, which confirms the finding shown in a).

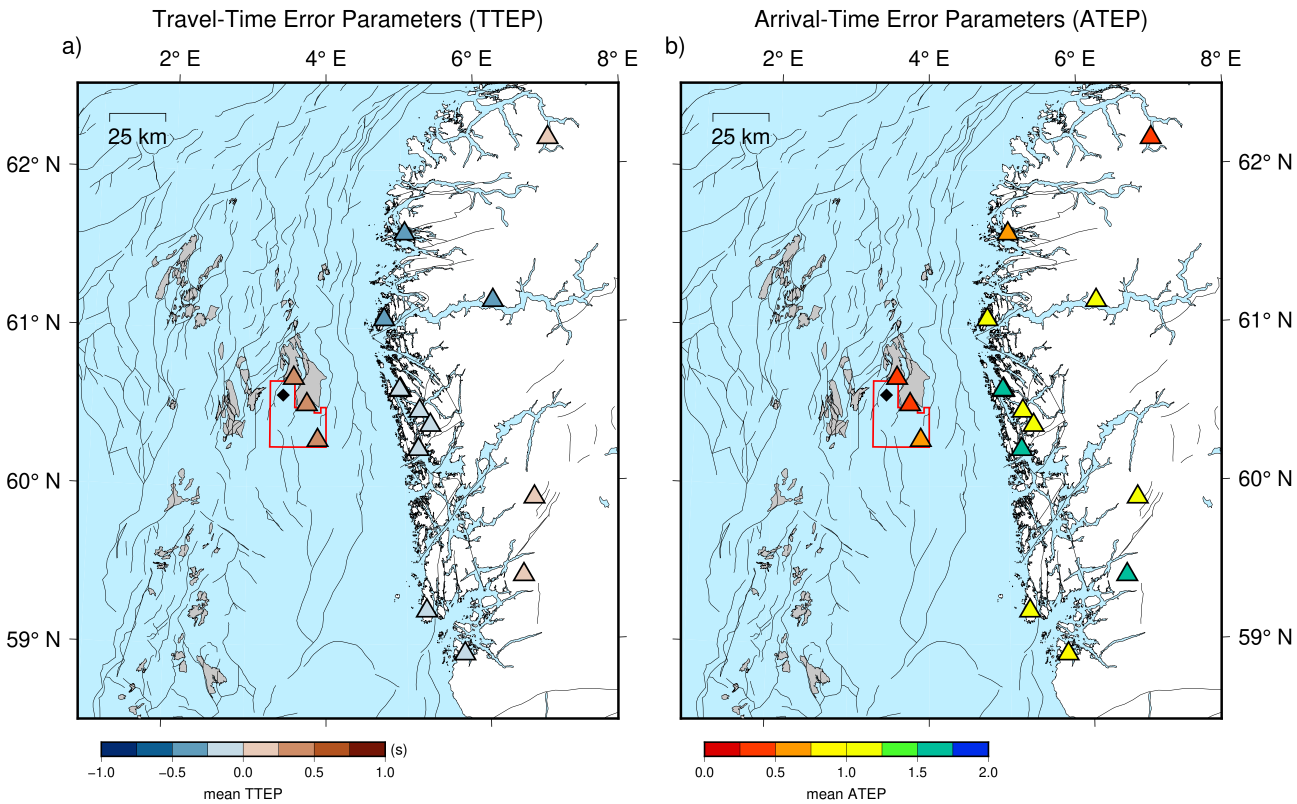

Figure S10 a) Travel-Time Error Parameters for each stations obtained from Bayesloc inversion. b) Arrival Time Error Parameters for each stations obtained from Bayesloc inversion.

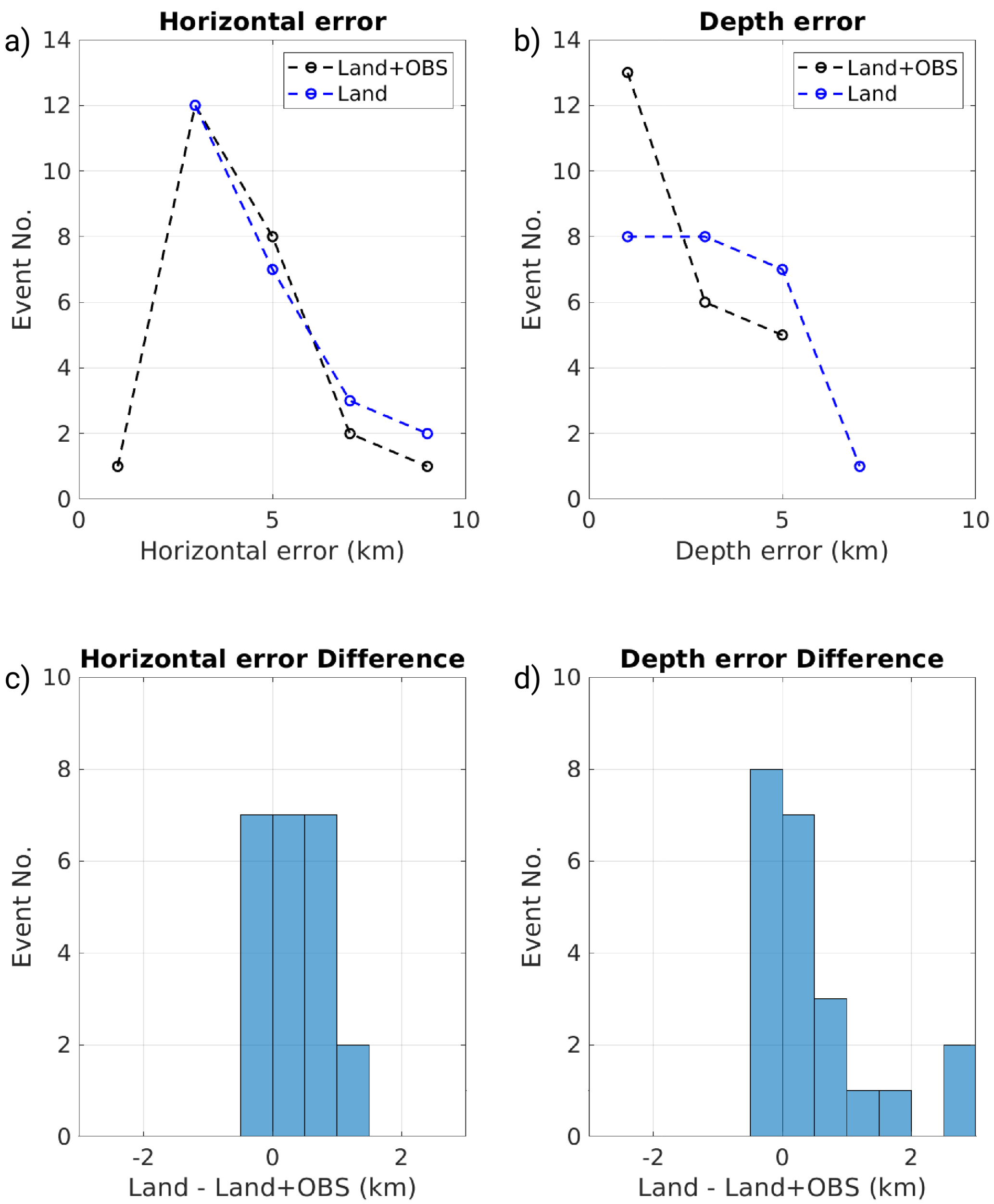

Figure S11 Earthquake location errors comparison for the datasets using the land stations and the combination OBS and land stations for in horizontal (a and depth (b. Differences between location errors between these two type of datasets in horizontal (c and (d depth error.

Supplemental Tables

Table S1 Duration of the continuous OBS data

Station	Start Time (UTC)	End Time (UTC)	Duration (days, hours, minutes)
HNO1	04/10/2021 19:32:08	20/09/2022 12:10:51	350d 23h 7m
HNO2	04/10/2021 16:22:31	20/09/2022 15:29:49	350d 19h 57m
HNO3	04/10/2021 17:58:17	20/09/2022 13:56:07	350d 16h 38m

Table S2 List of seismic shots used in this analysis

Used for OBS	shot	time	latitude	longitude
HNO3	1	2022:08:17:06:39:46.235816	60.22170828	4.25916942
HNO3	2	2022:08:17:04:43:11.383819	60.25200387	4.2604757
HNO3	3	2022:08:17:03:56:49.330816	60.28550963	4.26294691
HNO3	4	2022:08:17:06:17:05.037817	60.31997518	4.26330753
HNO3	5	2022:08:17:05:51:53.286816	60.37638339	4.26710537
HNO3 and HNO2	6	2022:08:17:05:26:03.241816	60.43597338	4.26886147
HNO2	7	2022:08:17:03:29:33.224820	60.47086191	4.27012428
HNO2	8	2022:08:17:03:03:20.386816	60.50408714	4.27091216
HNO2	9	2022:08:17:02:25:37.480816	60.55197817	4.27295436
HNO2 and HNO1	10	2022:08:17:02:02:06.499817	60.58272105	4.27481439
HNO1	11	2022:08:17:01:34:16.633817	60.61921219	4.27526173
HNO1	12	2022:08:17:01:01:24.539816	60.6615548	4.27526653
HNO1	13	2022:08:17:00:46:26.83981	60.68041765	4.26967625
HNO1	14	2022:08:17:00:28:51.646817	60.70226072	4.26378246

Table S3 Combination of polarities three component seismograms to resolve the orientation ambiguity (Havskov and Ottemöller, 2010)

HHZ	+	-	+	-	+	-	+	-
HHN	+	+	-	-	-	-	+	+
HHE	+	+	+	+	-	-	-	-
add	180	0	0	180	0	180	180	0

Table S4 Clockwise rotation angles for horizontal channels of the OBSs

OBS	Rotation Angle	Uncertainty
HNO1	219.2°	± 2.2°
HNO2	116°	± 1.4°
HNO3	125.6°	± 1.8°

Table S5 Component azimuth angles positive in degrees clockwise from north

OBS	HHY azimuth	HHX azimuth
HNO1	140.8°	230.8°
HNO2	244.0°	334.0°
HNO3	234.4°	324.4°

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