SCAN Seismic Data Analysis
Internship report

Fenna Ammerlaan
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Energy Beheer Nederland B.V.

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Energising the transition

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Summary

The SCAN project was set up in order to get a better insight into the geothermal potential of the subsurface of the Netherlands. One component of this project is the acquisition of 2D seismic data along various regional lines in the Netherlands. This internship report is a continuation on work done by previous students, namely analysing the quality of this seismic field shot data. The quality of every shot is quantified, these results can then be analyzed in order to optimize the acquisition phase. Additionally, the quality of the final migrated data is studied.

An increase in data quality will lead to an improvement in the resulting seismic cross-sections of the subsurface. This facilitates the geologists to make an interpretation of this cross-section with a higher level of confidence, thereby further increasing our knowledge of the subsurface.

In this report the data quality of 16 individual lines will be discussed, next to an analysis of the quality of the final cross-sections produced. Finally, an extensive analysis on the data of all the shots collected since 2019 was executed in order to investigate which factors have an influence on the data.

In general higher charge sizes and deeper shot depths lead to better quality data. Noise sources such as windmills, roads and train tracks should be avoided if possible. But most importantly, during the acquisition one should definitely avoid placing shots above the groundwater table. Due to an increase in scattering, this leads to very bad data quality. Push moraines are the most common cause of shots being placed above the water table, therefore future lines should be planned around them.

It should be taken into account that the acquisition of data for geothermal projects is always going to be a compromise. As the proximity of an area with heat demand, the so-called distribution area, is an essential element in the planning of these lines, an increase in proximity to an urban region will decrease the quality but increase the relevance of the data. Therefore, the theoretically optimal acquisition parameters cannot always be realized in the field.

1 Introduction

Energie Beheer Nederland

This internship was completed at Energie Beheer Nederland B.V. (EBN). As an organization, EBN has a unique position in the energy sector of the Netherlands. It is located between the state and the commercial world, being a government-owned company. EBN participates in a large variety of projects, ranging from oil and gas assets to Carbon Capture Utilization and Storage (CCUS). Other sustainable energy resources in which EBN is involved are green gas and geothermal energy.

EBN is subdivided into various teams, each with their own focus. This internship was completed at the GeoTechnical Operations (GTO) team. GTO is responsible for the operational aspects around the execution of geotechnical projects. This includes operations such as seismic data acquisition and processing, re-processing of old seismic data and the drilling of data acquisition wells.

Energy transition

Currently the energy system in the Netherlands is in a phase of transition. Where in the past the gas fields, such as Groningen, have been beneficial for the economy, the sentiment is switching to a more sustainable energy system. The fossils fuel are becoming more and more supplemented by sources of sustainable energy. One of these resources is geothermal energy.

For the production of geothermal energy a doublet is utilized. A doublet exists out of two deep wells which reach a water-containing layer in the subsurface. As the subsurface temperature increases with depth, the water present in these aquifers is warm. The warm water is pumped up and the heat is extracted by a heat exchanger. This is the production well. The other well, the injection well, is used for pumping the cool water back into the ground. This water will be slowly warmed up again by natural processes. The obtained geothermal energy can be used for various industrial processes and the heating of buildings. This decreases the demand of electricity and gas. While geothermal energy has a large potential, the current production in the Netherlands is still limited.

SCAN project

This project was executed within the scope of the SCAN project. This is an abbreviation for "Seismische Campagne Aardwarmte Nederland", translating to Seismic Campaign of Geothermal energy in the Netherlands.

This project is aimed towards obtaining more detailed knowledge about the subsurface of the Netherlands and its potential for geothermal exploration as well as the development of geothermal projects. In some regions of the Netherlands, extensive investigation into the subsurface has already been executed due to the presence of gas fields, for example in northern provinces. In these regions, there is a good 3D seismic coverage, knowledge about the reservoir parameters and well data available. However, there are a lot of areas where the knowledge about the subsurface is lacking, in seismic data as well as the availability of well data. In these regions, the so called "white spots", the aim of the SCAN project is to increase the data available. An overview of the available data showing these white spots is visible in Figure 1.1. Once the SCAN project has produced relevant subsurface data, this data will be made available to the public in order to accelerate the development of geothermal projects in the Netherlands, as it leads to cost reduction and professionalization of the sector.

This will be accomplished by three key components, the reprocessing of old 2D seismic data, the acquisition of new 2D seismic lines and the drilling of data acquisition wells. In this report, the focus will be on the data acquired by the new 2D seismic lines. This seismic data is processed at the London office of DownUnder GeoSolutions (DUG), an Australian processing company. The final 2D seismic cross-sections will be analyzed and interpreted by the geologists at EBN in order to analyze the geothermal potential. The quality of these seismic sections is dependent on the quality of the field seismic data.

Within the scope of this project, the purpose of this report is to analyze the quality of the newly acquired 2D seismic data. After quantifying the quality of the data, we will analyze which acquisition parameters influence the quality of the data and how the acquisition design can be optimized in order to obtain the best possible data. This is important as better quality data will eventually lead to better quality cross-sections. This will increase the level of confidence with which the geologists can

Seismic spread	Split-spread
Acquisition type	Roll on (roll off)
Record length	10 s
Sample rate	2 ms
Far offset	6997.5 m
Nominal fold	116.67
Δ Receiver (land)	5 m
Δ Receiver (water)	15 m
Land receiver type	5 Hz geophone
Water receiver type	10 Hz hydrophone
Δ Source (land)	60 m
Δ Source (water)	40 m
Source type	Explosive source
Charge size	120 - 1540 gram
Shot depth	4 - 34 m

Table 1.1: General acquisition parameters for all lines.

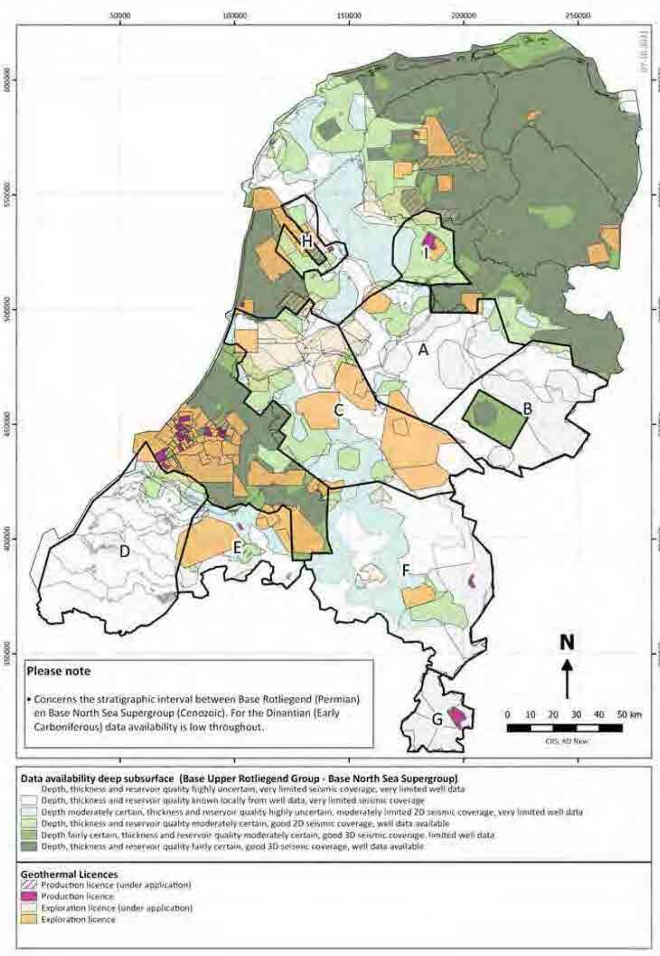


Figure 1.1: Different colours indicating the level of data available for the different regions in the Netherlands. The white spots indicate regions where knowledge about the subsurface is lacking.

make their interpretations, therefore providing a better insight into the geothermal potential of an investigated area.

This data analysis has a fascinating perspective on the workflow of the SCAN operations, as it forms the bridge between the acquisition in the field and the processing performed on computers. While the data is analyzed with the goal of optimizing the acquisition design, in reality the seismic surveys are often dependent on external factors limiting their operations. Issues such as challenging access to private land and urban areas require flexibility in the placement of both shots and receivers. This hinders the ability to stick to the nominal acquisition design.

An interesting contrast exists between seismic surveys for the exploration of oil and gas and the production of geothermal energy. For the extraction of fossil fuels, the proximity of an area of distribution is not relevant as the fuels can be transported over large distances. Contrary, one wants their geothermal doublet to be located close to an area of heat demand. In most cases this is an industrial or urban region, areas not necessarily suitable for the execution of seismic surveys. They are often densely populated, have a large number of buildings and many different landowners, which leads to higher noise levels and more difficulty during the permitting phase. Despite these challenges, geothermal surveys are still executed as the geological information they can provide is so valuable. Data acquisition for geothermal seismic surveys is therefore a compromise between the relevance and the quality of the data.

Acquisition design

At the beginning of the project, a test line was shot in order to optimize the general acquisition parameters for all the lines. This analysis was executed by Janssen (2020) and resulted in the acquisition parameters visible in Table 1.1. These selected parameters were utilized for all the lines. The seismic acquisition of the SCAN project was executed by Rossingh Geophysics.

The setup of the seismic survey can be seen in Figure 1.2. Firstly, a drilling installation is used to drill a hole into the ground using sonic drilling. Ideally, a depth of 20 meters is reached but in reality this varied between 4 - 34 meters. Shot placements shallower than the nominal shot depth were obtained when a consolidated layer was reached. The nominal depth and the placement in a consolidated layer were selected to ensure the coupling of the source, how well the explosive transfers its sound waves into the medium.

The charge size utilized varied between 120 - 1540 grams. The allowed charge size was dependent on the proximity of buildings. The source had to be situated 50 metres away from buildings in order to place a 220 gram charge. The mandated charge size increased moving further away from buildings, where at a distance of 200+ meters the 1540 gram charge could be placed. In the urban region of Amsterdam, exceptional acquisition parameters were selected. Holes as deep as 34 meters were drilled, in which charges of 120 grams were placed. Due to the high concentration of buildings in this urban area, proximity to buildings could not be avoided. By drilling deeper, this increased the absolute distance to buildings allowing the placement of the shots with a very low charge size.

Every 60 meters along the line a shot was drilled. On the surface, every 5 meters a geophone was placed. A geophone is a kind of microphone which can record sound waves. The nominal recorded offset for a shot was 7 kilometers in both directions. Exceptions from this were shots placed within the first or last 7 kilometers of the line. Once all the receivers were in place, the placed charges were detonated. The generated sound waves travel through the subsurface. When there is a medium transition with a significant impedance contrast, some part of the energy will reflect at the boundary and return to the subsurface. The remaining energy will continue to travel downwards.

By stacking and processing all the recorded shots, one can create a cross-section of the subsurface along the line. The better the data quality of the shots, the better the quality of the final subsurface. This report will not go into further detail on the various elements and workflows of seismic data processing, as these are not included in the scope of this work.

While most of the seismic acquisition occurred on land, some lines also crossed bodies of water. These sections had a different acquisition set-up in terms of distance between shots and receivers, as can be seen in Table 1.1. The drilling installation was placed on a pontoon barge which allowed the shots to be drilled underwater. In the waterbed hydrophones were placed rather than geophones. The placement of hydrophones is more time-consuming and expensive. Additionally, the number of available hydrophones was limited. Therefore, the interval between receivers was increased from 5 to 15 meters. In order to keep the fold across the line consistent, the increase in receiver spacing was compensated with a decrease in shot spacing.

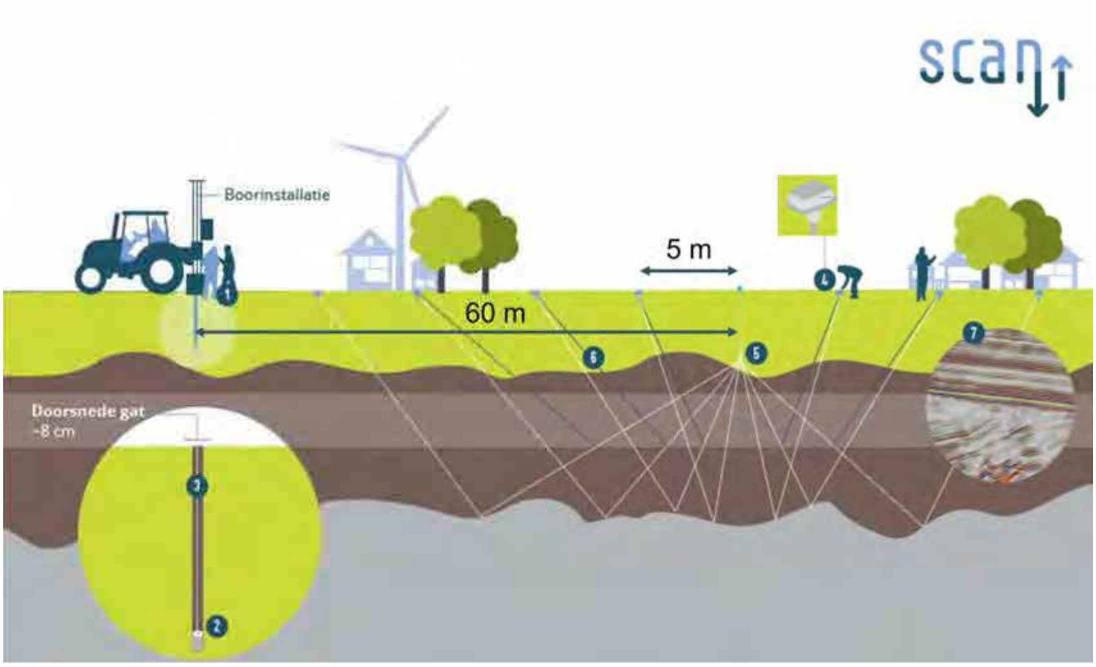


Figure 1.2: Set up of the seismic survey.

Content of this report

This report is a continuation of the previous work executed by Janssen (2020), van der Lucht (2020), van Klaveren (2021) and Gossink (2021). In total, the SEGY field data of 13 newly acquired lines is analyzed. This includes both lines shot for the SCAN project as well as lines shot for the Metropool Regio Amsterdam (MRA). The analyzed lines are SCAN035, MRA036, MRA037, MRA038, MRA039, MRA040, MRA041, SCAN042, SCAN043, SCAN044, SCAN045, SCAN046 and SCAN049.

Furthermore, there are 3 lines for which additional data was shot in 2021 of which the preliminary data was already analyzed in van Klaveren (2021). The complete version of these lines will be analyzed in this report, namely lines SCAN024, SCAN025 and SCAN026. For each individual line, the quality of the data will be quantified, the regional geology is determined and the results are analyzed.

Additionally, there are 21 final processed seismic sections analyzed, namely SCAN019, SCAN020, SCAN024, SCAN025, SCAN026, SCAN030, SCAN031, SCAN032, SCAN033, SCAN034, SCAN035, MRA036, MRA037, MRA038, MRA039, MRA040, MRA041, SCAN042, SCAN043, SCAN044 and SCAN045. A prestack time migration processing sequence was applied on these lines. For these sections the quality is quantified by using cross-correlation. A method that will be explained in the next section.

After the analysis of the individual lines has been completed, both the field and the final processed data, a closer look to data trends taking into consideration the data of all the lines is discussed. Both the acquisition parameters and external factors such as land use, physical-geographical regions and ambient noise sources will be analyzed. Unfortunately, the data of line SCAN046 was acquired significantly later than the rest of the regional lines. Therefore, solely the analysis of the individual line was executed and this data was not included in the data trend analysis on all the lines.

Conclusions drawn in the previous reports

As mentioned before, previous work on the analysis of seismic data was done by Janssen (2020), van der Lucht (2020), van Klaveren (2021) and Gossink (2021). The work of the first student was focused on analyzing the test line data (SCAN001) and optimizing the acquisition parameters. The next 3 students concentrated on analyzing the data of the individual lines and finding larger trends, similar to this report.

The main findings in the previous reports about optimization of the acquisition design are the following. In general, a higher charge will lead to a stronger signal. Additionally, a deeper placement of a charge leads to better coupling of the shot and therefore also to better signal. Gossink (2021) concluded that the amount of time which a charge was in the ground did not have a significant impact on the data quality. This was investigated as large intervals between periods of shooting, caused by holiday periods and the COVID pandemic, led to some sources being placed in the ground for a particularly long time before they were detonated.

The most important conclusion that was drawn was that the placement of a shot relative to the water table is the largest influence on the quality of the data. If the shot is placed above the water table, this leads to very bad data quality. This is most likely because that the coupling of the source is decreased. As the pores of the bedrock are filled with air rather than water, the amount of scattering drastically increases.

The aim of this project is to investigate whether the previous findings still coincide with the trends observed in the newly analyzed data. Additionally, the established analyzing methods will be reviewed to see whether there is room for improvement. Finally, it is examined if there are other trends or parameters influencing the data which were not yet discovered.

2 Method

In this section the different methods for both the acquisition and the analysis of the data will be explained further. The type of seismic survey will be discussed, followed by the different components of a shot and how the quality can be quantified. Some more details will be provided on the usage of hydrophones, after which the analysis method of the final cross-sections will be explained.

2.1 Seismic acquisition method

In total about 1850 kilometer of 2D seismic reflection data was collected for the SCAN project. The main type of spread used is symmetrical split spread. This means that the shot is at the center of the geophones which have a symmetrical geometry. At the beginning and at the end of the lines, end-on spread was used where the maximum offset was only reached at one side of the shot.

In addition to the data acquired from the individual seismic 2D lines, supplemental information about the subsurface was obtained using two different methods. For these methods small lines are shot running parallel or perpendicular to the main regional line. The shots of both lines are then also recorded with the receivers of the other line. By strategically planning and shooting the seismic data, more insight can be obtained for little increase in cost.

The method with the parallel line placement is called wide-line acquisition and can be seen at A in Figure 2.1.1. By also recording the shots of the yellow line on the receivers at the blue line and the other way around, additional information in the form of an extra 2D seismic subsurface line is obtained. This line is indicated with the green dashes. It provides more data without the need of additional shooting and could give more insight into the subsurface geology and the continuity of formations. This method was used for line SCAN048 and SCAN049, which were the short lines for line SCAN046 and SCAN043 respectively.

The other option is called cross-spread seismic acquisition and can be seen at B in Figure 2.1.1. In this case instead of running parallel one or multiple lines are placed perpendicular to each other. This can be two larger regional lines but also one main line with short additional lines. Again the shots of both lines are also recorded on the receivers of the other line. This enables one to extract additional data in the form of a low-fold 3D like image of the subsurface, visualized with the green square. The area of this low-fold region is of the magnitude of a couple of squared kilometers at the intersection of the lines. As no additional shooting is required, cross-spread acquisition is a budget-friendly option for getting more insight. This method was applied for the combination of lines SCAN032 + SCAN033, SCAN044 + SCAN045 and SCAN046 + SCAN047 + SCAN048.

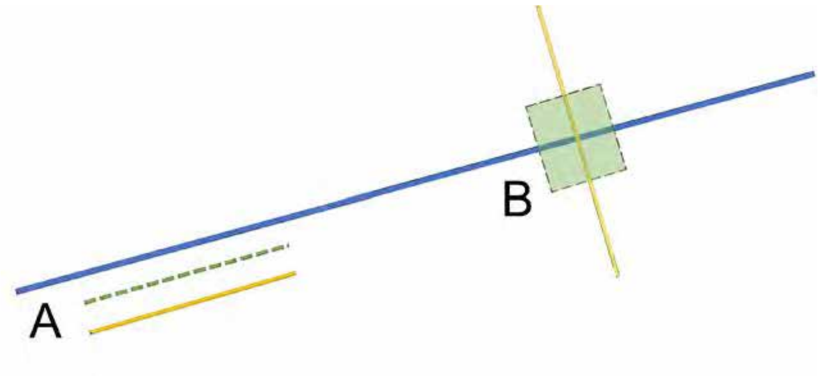


Figure 2.1.1: The set-up at A shows the wide-line acquisition where the green dashed lines indicates the additional subsurface 2D line obtained from this method. The set-up at B shows the cross-spread acquisition method, where the green box indicates the low-fold 3D information obtained from this method.

Hydrophones

Eight of the sixteen lines that will be discussed later in this report contain sections recorded with hydrophones. Due to the mechanism behind hydrophones, the signal they record have a significantly lower amplitude when compared to geophones. For the sake of consistency, all the traces recorded with a hydrophone were multiplied with a factor of 9 before any of the other steps were executed. A factor of 9 was elected as it allowed us to scale the recorded signal of the hydrophones on a similar level to that of the geophones. However, it should be noted that as the noise of the receivers was also affected by this scaling, the noise of the hydrophones is anomalously larger than that of the geophones. In the decision process for the multiplication factor, it was elected to focus on keeping the signal amplitudes on the same magnitude for both geophones and hydrophones. There was no factor which provided a suitable scaling for both the noise and the signal.

2.2 Quantifying seismic shot quality

The seismic data that was collected consists out of seismic traces. For every shot, there were 2800 responding nodes recording the seismic traces. The responding traces for every single shot can be studied as the field SEGY data. The data recorded by a seismic shot consists out of several components which are indicated in Figure 2.2.1. The ambient noise is the noise which is present as background noise and therefore not dependent on any of the acquisition design parameters. The hyperbolic signal indicated with the green lines are the reflections which give us insight into the subsurface geology. The first break is the first arrival of the signal at the receivers and generally have a larger amplitude than the rest of the signal. In yellow the ground roll is indicated which are the high-amplitude low-frequency slow-travelling surface waves, this is shot-generated noise.

When looking at seismic shots, it can be quite simple to judge a shot as good or bad quality based solely on visual characteristics. If a shot has clear reflections and little ambient noise, it is generally of good quality. If a shot has very vague or no reflections and a lot of background noise, it is a bad shot. However, visually inspecting every single individual shot is clearly not a feasible method. Therefore, in order to analyze the data, it is essential to quantify the quality of the shots. This quantification will be done by looking at the signal to noise ratio (SNR) of the shots. In this analysis solely the background noise is considered.

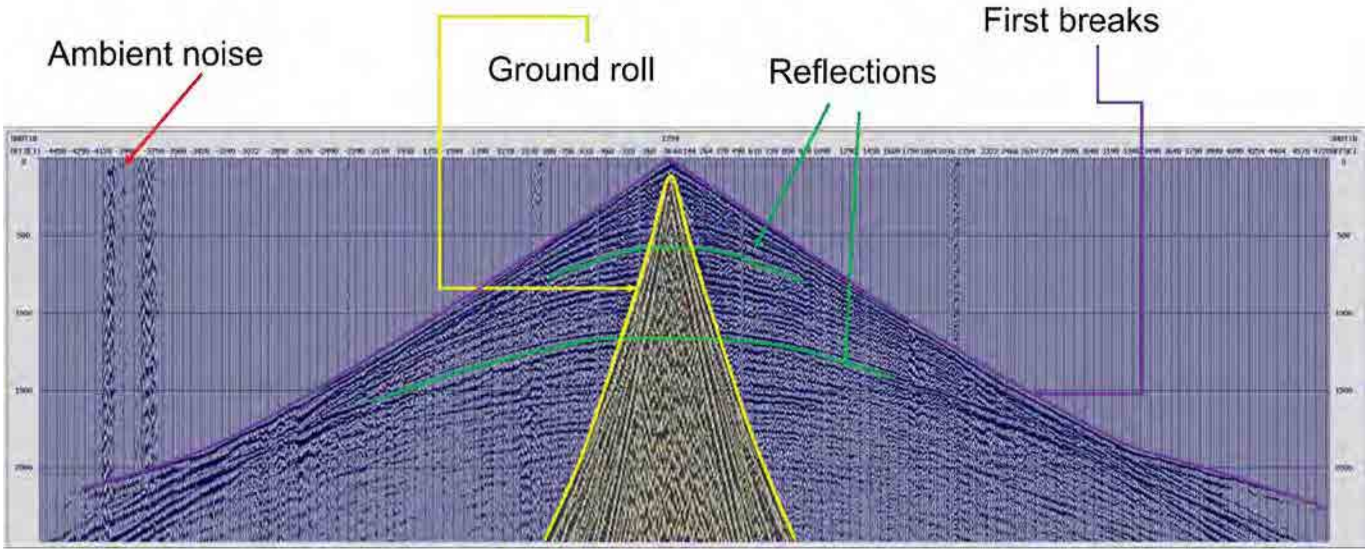


Figure 2.2.1: The different components of a seismic shot indicated.

Noise windows

In order to determine the SNR, windows for analyzing both the signal and the noise must be established. As the SNR is based on background noise, we can determine this value on the seismic shot without any need of muting or filtering. The windows selected for determining the noise are visible in Figure 2.2.2. The windows are selected in such a way that they do not contain any signal generated by the shot. They start at an absolute offset of 900 meters and look at a time period from 0 - 500 ms after detonation.

One of the disadvantages of this method of noise analysis is that the noise which is assigned to a certain shot is not representative of the direct surroundings of that shot. Due to the 900 meters offset which is considered, there is a buffer around the location of the shot in which no noise is measured. This makes it more challenging to link the level of noise per shot to any surrounding variables. Therefore, it is essential that we also study the receiver domain in determining the noise in order to properly link the level of noise created to its environment.

Signal windows

While the noise could be determined solely on the shot data, several alterations must be made to a shot before the signal value of the data can be determined. As mentioned before, the signal of the reflections present in the shot are the main feature of interest. We want to adapt the shot in such a way that we are left with the signal-only data, therefore muting the ambient noise and groundroll. The first step to achieve this is the application of an F-k filter on the data.

An F-k filter stands for frequency and wave number and transfers the data from the time and displacement domain into the F-k domain by applying a Fourier transformation. As we know that groundroll exists out of low frequency and high amplitude data, the next step is to filter out this low-frequency coherent noise. After the application of this filter, the data is transferred back to the time and displacement domain to allow further analysis.

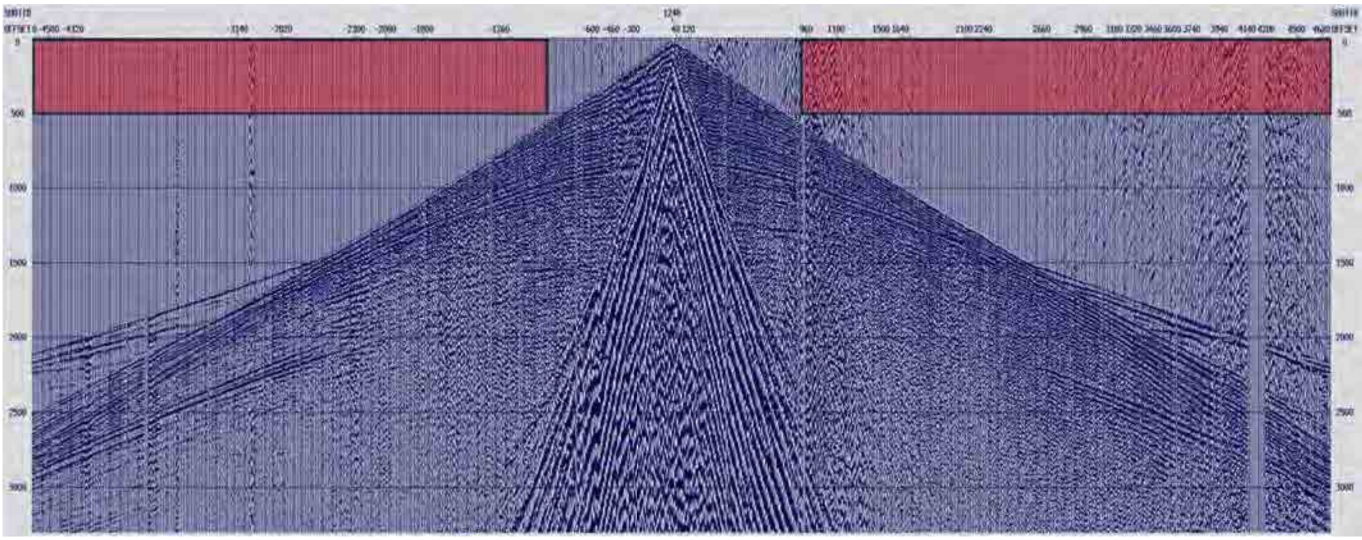


Figure 2.2.2: The windows for determining the noise in a shot indicated in red.

This filter is followed by the muting of the groundroll and the ambient noise plus the first breaks. In this case muting means that the traces in those regions are set to zero. The reason that we first applied a filter on the data is that the muting is not always a 100% perfect. If there is a small discrepancy present in the muting, the magnitude of the signal leaking through will be minimized. The reason the first breaks are included in the muting of the ambient noise is that they generally contain anomalously high amplitude levels.

After altering the shots, we are left with what we consider to be the "signal-only" data. For determining the signal, two windows are selected. For the sake of consistency, identical windows were selected to the ones used in the previous internships. By keeping the windows constant, the results obtained in this analysis can be compared to the previous work.

The windows are visible in Figure 2.2.3. The upper window contains all the signal with a time period of 0-1000ms, with an offset ranging from -1700 to 1700 meters. The deeper window considers a time period of 1000-2000ms with an offset between -3500 to 3500 meters.

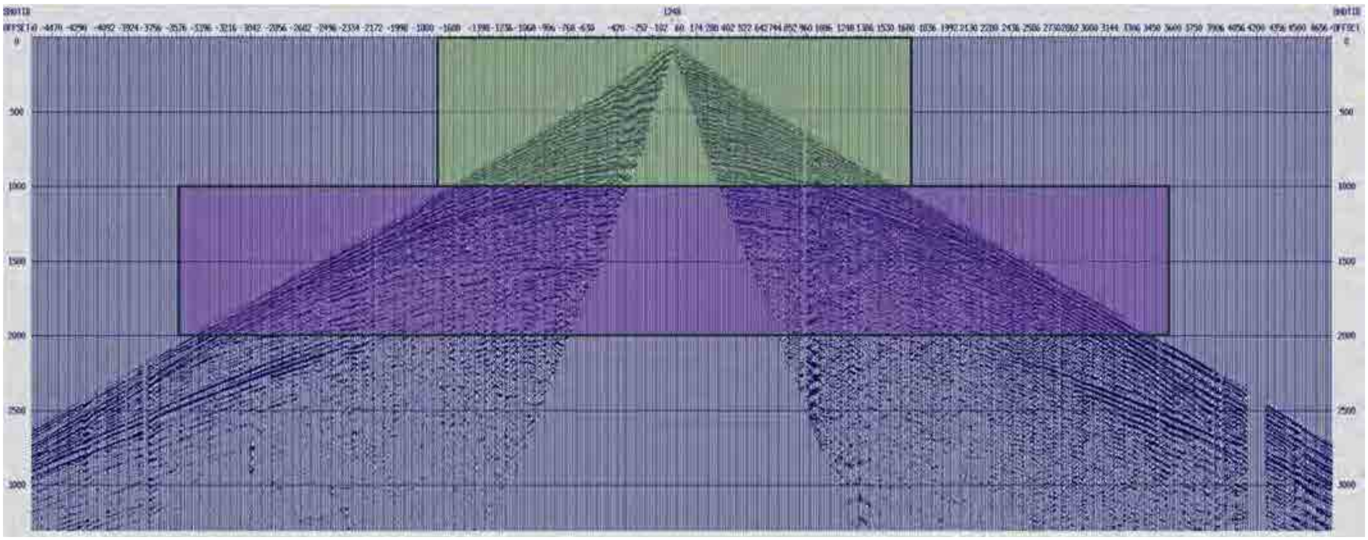


Figure 2.2.3: The windows for determining the signal in a shot indicated in green (0 - 1 s) and purple (1 - 2 s).

SNR calculation

In the previous sections the various windows defined for analyzing the data were introduced. In order to quantify the quality of the shot, we want to look at the ratio between the signal and the noise present. This is also known as the Signal to Noise Ratio (SNR). The higher this ratio, the better the data quality. While it is also possible to take shot generated noise such as groundroll into consideration, for this quantification we only looked at the ambient noise.

The amplitude of the noise and signal is determined by taking the root mean square (RMS) amplitude of all the non-zero traces within the window. The average is determined over these traces. As a wave generally has both positive and negative amplitudes, these values would cancel each other out when taking a general mean of the trace. The magnitude of the signal is therefore based on the signal strength (RMS), rather than positive or negative amplitudes. As there are two signal windows, in the end both a SNR 0-1 and SNR 1-2 value is obtained. These are the quality indicators which will be used for the rest of this study. For reasons on which will be further elaborated on in the discussion, the SNR 1-2 window was found to be a better quality indicator. It was selected to be compared to various parameters influencing the acquisition, in order to investigate their effect on the data quality.

2.3 Seismic cross-section quality

All the data from the seismic shots are used for creating an image of the subsurface. The processing of the shot data is executed by DUG. The first delivery in the processing sequence occurs after two weeks, when the fast-track Pre-Stack Time Migration of the line is produced. A fast-track enables one to get a preliminary insight into the subsurface of the line, both in terms of the quality of the data and the geological structure of the subsurface. This fast-track can be seen as a draft version of the final product, which is often delivered after a couple of months. In the final processing result, most of the issues regarding noise and statics are solved, resulting in a cross-section of a significantly higher quality than the fast-track. This is also the image on which the geologists will base their interpretations.

The quality of the shot data has an impact on the quality of the final section. The better the shot, the better the cross-section. Similarly to the seismic shots, often it is visually quite straightforward to label a region as either good or bad quality. However, for evaluation of the final product it is again important to quantify the quality of the final sections.

In van Klaveren (2021) the method of cross-correlation was introduced which was further enhanced in Gossink (2021). Cross-correlation is a procedure where the similarity between two traces is measured as a function of time. A correlation of 1 indicates that the traces are identical, the closer the value comes to zero, the less similarity there is between the traces. As the expectation is that the geology is relatively consistent over small distances, one would expect values close to 1 for the processed lines. So, the closer the cross-correlation coefficient is to 1, the better the quality of the final section. It should be noted that lower coefficients can also be caused by geological features. For example, the presence of faults in the subsurface disrupt the continuity of traces. This lowers the coefficient, while it does not have to mean that the data quality is worse.

Cross-correlation coefficients can be computed in both the time and the frequency domain. Where the time domain is impacted by the geological features, this effect is decreased in the frequency domain. Unfortunately, the frequency domain coefficient is less suitable for determining the quality of the section. If no clear signal is available, there is little consistency between the traces. This is recognized by the time domain. It could still be the case however, that the traces are inconsistent but do all have a similar frequency. Cross-correlation executed in the frequency domain is less likely to recognize this decrease in quality.

In the work of van Klaveren (2021) the computation of the cross-correlation was based on the comparison of two traces which were located 10 receivers apart from each other, equivalent to 50 meters. Gossink (2021) introduced a more robust method, where a trace was compared to the average of 10 randomly selected traces in the neighboring 20 traces, 10 traces to either side. Using this method, the coefficient was less dependent on local outliers. A time-window of 250-2000 ms was utilized for all the lines, as it limited the dependency on near-surface events.

In this report the results of 21 final sections will be shown which were analyzed for the first time. Additionally, for the lines quantified in van Klaveren (2021) the coefficients were determined again. As a different method was applied for these lines, it was important to run all the lines using the same method for the sake of consistency. This re-running of the lines did not lead to significantly different results.

3 Results

In this section firstly the results of the analysis of every line individually will be discussed. This will be followed by a closer look at the quality of the final processing results. Finally, an extensive analysis of all the data across the lines and the dependence of data trends on various parameters will be considered.

3.1 Analysis of the individual lines

3.1.1 SCAN035

Line SCAN035 runs in Flevoland from Ens in the northeast to Almere in the southwest. Of the 906 shots processed for this analysis, 2 of them were weak shots. While these were included in the analysis, we shall keep the quality of these shots into consideration for any noticeable anomalies during the analysis.

The line SCAN035 is a special line as it includes 3 different kinds of acquisition settings, land/land, water/water and water/land where the former indicates the location of the shots and the latter the location of the receivers. When crossing the Ketelmeer (receiver number 2397-3204) the shots were placed offshore, and hydrophones were used instead of geophones. For these hydrophones the previously mentioned multiplication factor was applied in order to compensate for any discrepancy in signal amplitude between the geophones and hydrophones.

Acquisition length	51.69 km
Number of receivers	9552 (1001-11338)
Of which hydrophones	269
Number of shots	906 (1709.5-10625.5)
Of which in water	482
Skipped shots	1.2%
Skipped receivers	7.6%
Date recorded	15/04/2021 - 10/05/2021

Table 3.1: Acquisition parameters of line SCAN035

Another interesting setting is from station number 6796.5 onward, where the seismic line is parallel to the provincial road N701. As no permission was granted for placing the shots in the dike on which this road is located, the decision was made to place the shots in the water. However, as the usage of hydrophones is more costly and time intensive geophones were used for recording the signal. This led to an average distance of 230 meters between the shots and their nearest receivers.

When we study the quality of the data by looking at Figure 3.1.1.6, we can observe that higher charges lead to a higher signal to noise ratio. Especially around Lelystad, the data quality is found to be low. The shots in this urban region had a relatively low charge size and a shallow depth, both factors which do not aid the coupling of the shot.

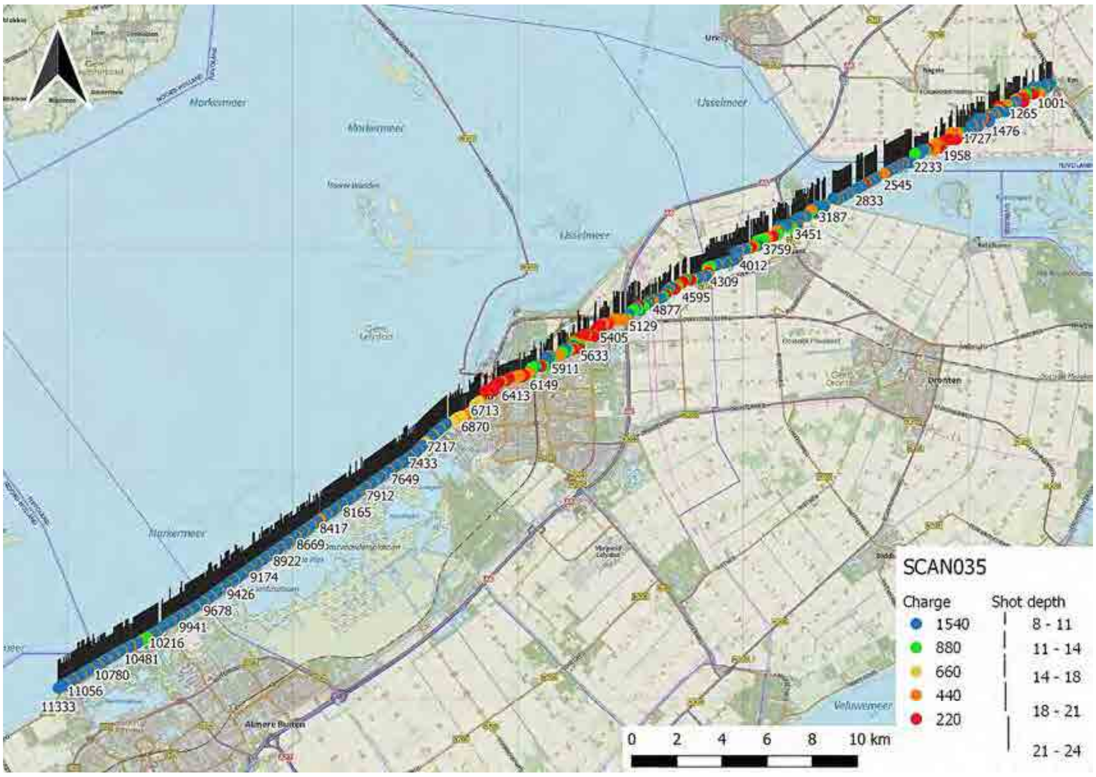


Figure 3.1.1.1: Acquisition parameters of line SCAN035.

General:

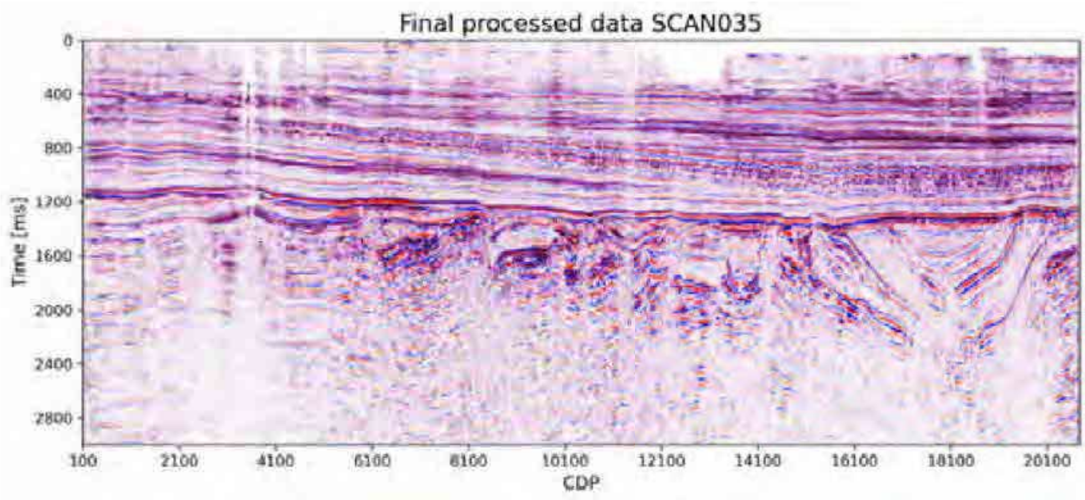


Figure 3.1.1.2: The final full section of line SCAN035.

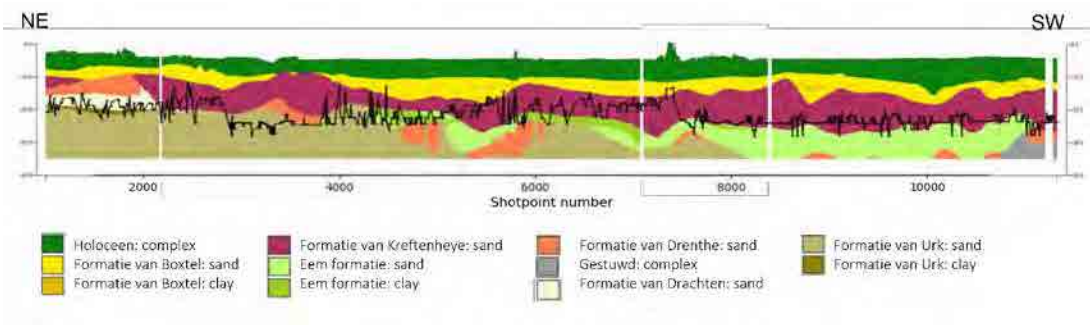


Figure 3.1.1.3: The geological profile of line SCAN035.

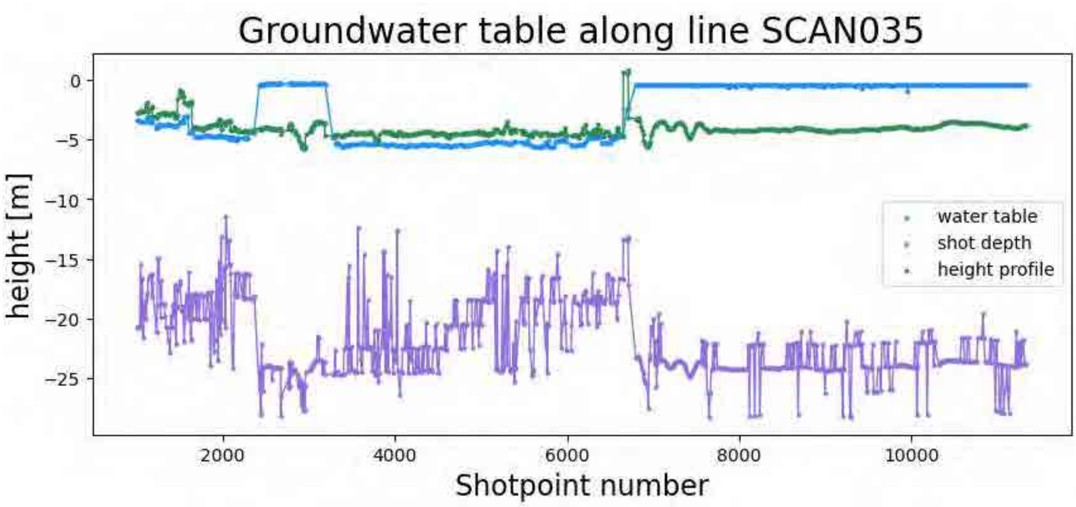


Figure 3.1.1.4: The water table along line SCAN035. All shots are located below the water table.

Shot domain:

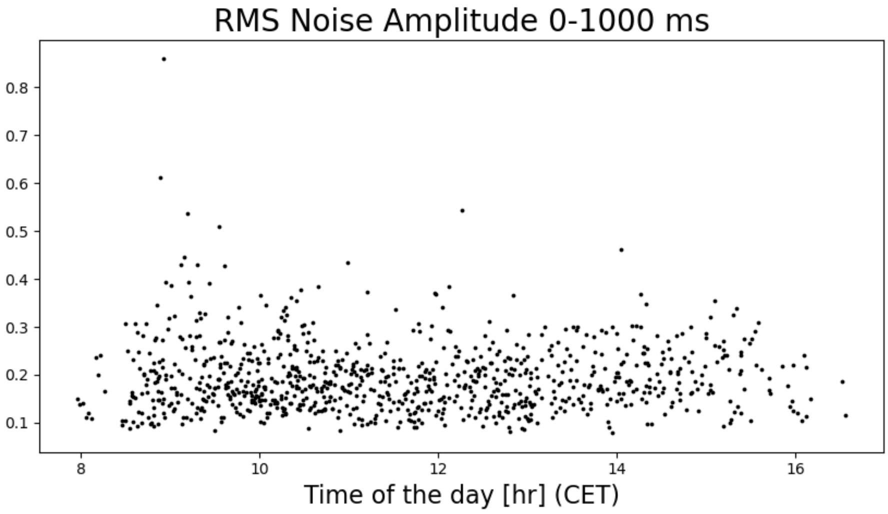


Figure 3.1.1.5: The noise in the shot domain plotted against the time of the day at which the shots were recorded.

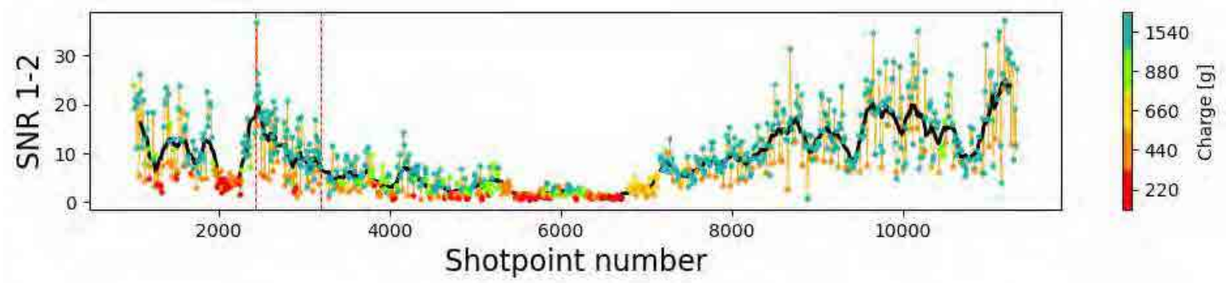


Figure 3.1.1.6: The SNR in the 1-2 second window with a charge size indicator. The black line is the moving average computed with a range of 15 data points. The red dashed lines indicate the hydrophone region.

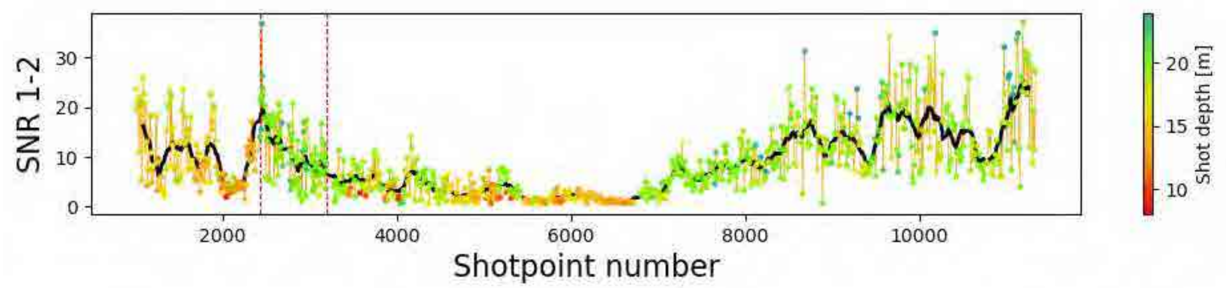


Figure 3.1.1.7: The SNR in the 1-2 second window with a shot depth indicator. The black line is the moving average computed with a range of 15 data points. The red dashed lines indicate the hydrophone region.

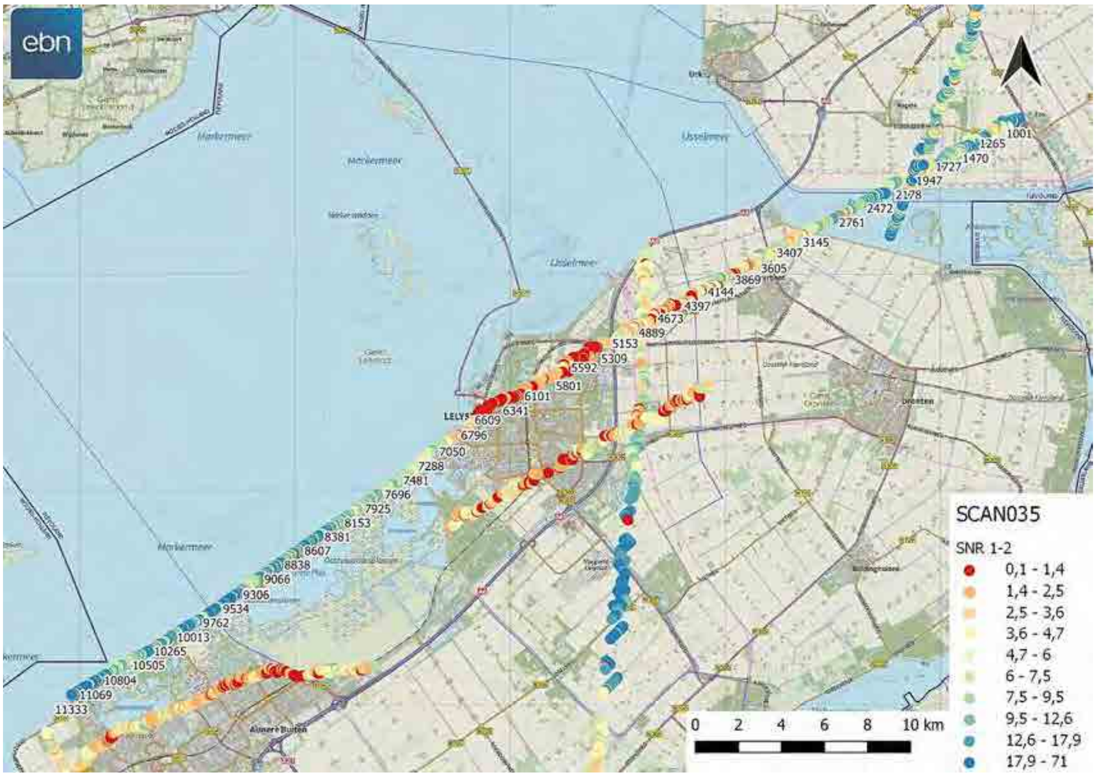


Figure 3.1.1.8: The SNR 1-2 value plotted along the line. The colour of the shot points indicate the quality of the shot, from bad (red) to good (blue). This colour range is divided into 10 segments which are based on the occurrence of the data points along all lines. The red dots therefore indicate that those shots belong to the worst 10 % of all the shots.

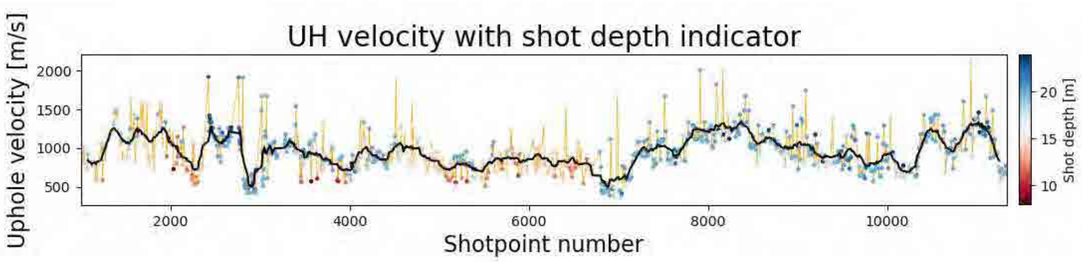


Figure 3.1.1.9: The uphole velocity along the line.

Receiver domain:

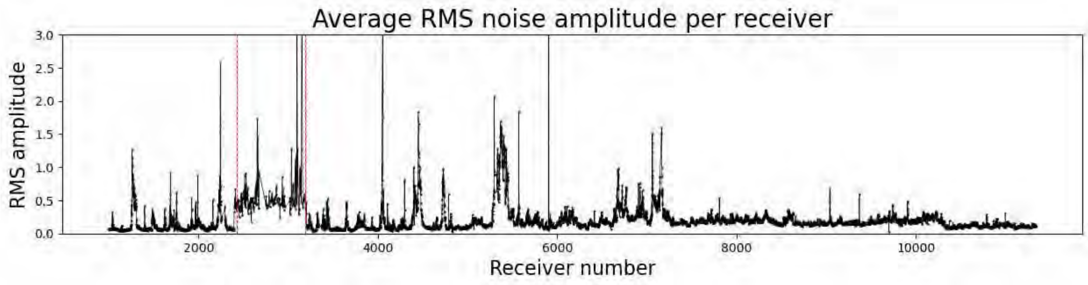


Figure 3.1.1.10: The noise per receiver. The red dashed lines indicate the hydrophone region.

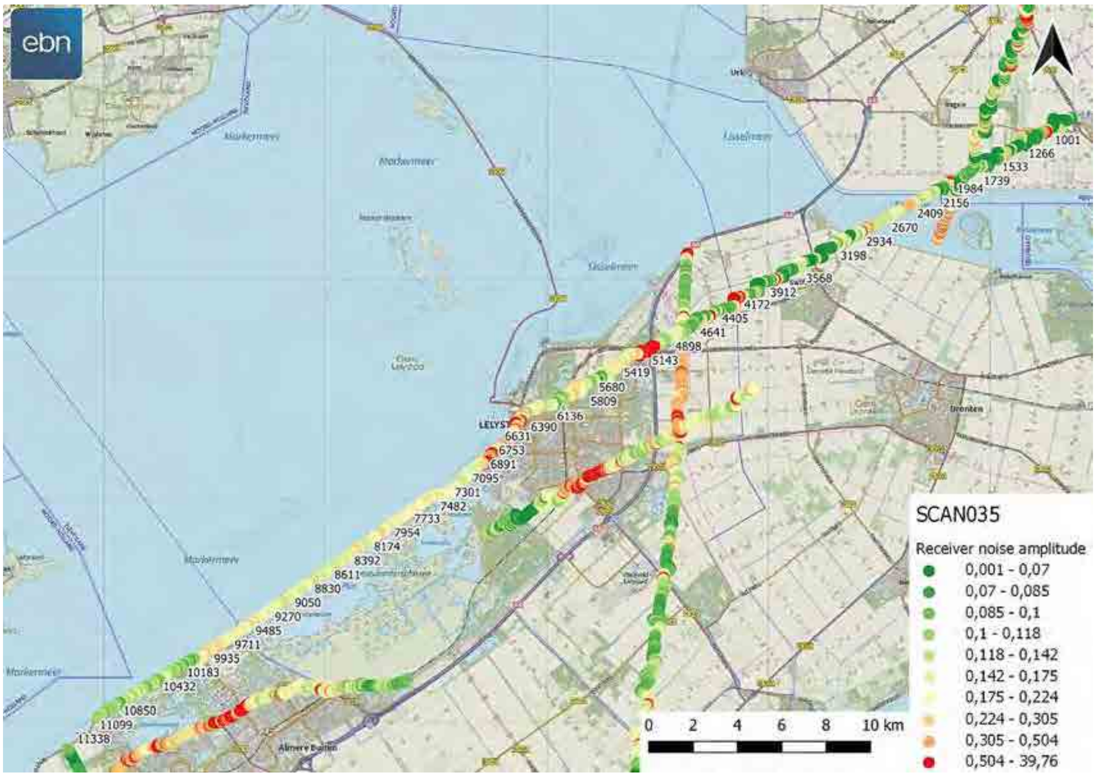


Figure 3.1.1.11: The noise per receiver visualized along the line. The color scale is based on the data of all the receiver data, showing noise relative to the other data points.

3.1.2 MRA036

Line MRA036 is a 2D seismic line which runs from Rijpwetering in the southwest, through Amstelveen and ends in Almere in the northeast. This line contains the largest number of hydrophones of all the lines that will be discussed in this report, namely 498 hydrophones which were placed when crossing the IJmeer. Of the 730 shots, 188 were taken in the water.

The line contained two faulty receivers, namely 5032 and 5070. These were removed from the data before any of the final products were constructed, as they distort the results. On the eastern part of the line, most of the charges were placed in a subdued push moraine, having a complex geology.

Acquisition length	45.90 km
Number of receivers	7744 (1008-10287)
Of which hydrophones	498
Number of shots	730 (1709.5-10625.5)
Of which in water	188
Skipped shots	13.2%
Skipped receivers	15.6%
Date recorded	11/06/2021 - 09/07/2021

Table 3.2: Acquisition parameters of line MRA036

High noise levels are visible along the line around station number 3000 where the line is located parallel to a highway. Additionally, the hydrophones have a large noise amplitude due to the applied multiplication factor. The purple markers in Figure 3.1.2.1 indicate the shots placed in the middle of Amsterdam where very deep drilling with very low charge sizes were utilized. As it was not possible to maintain a distance of 50 meters to buildings, deeper drilling was selected in order to allow the placement of a small charge size.

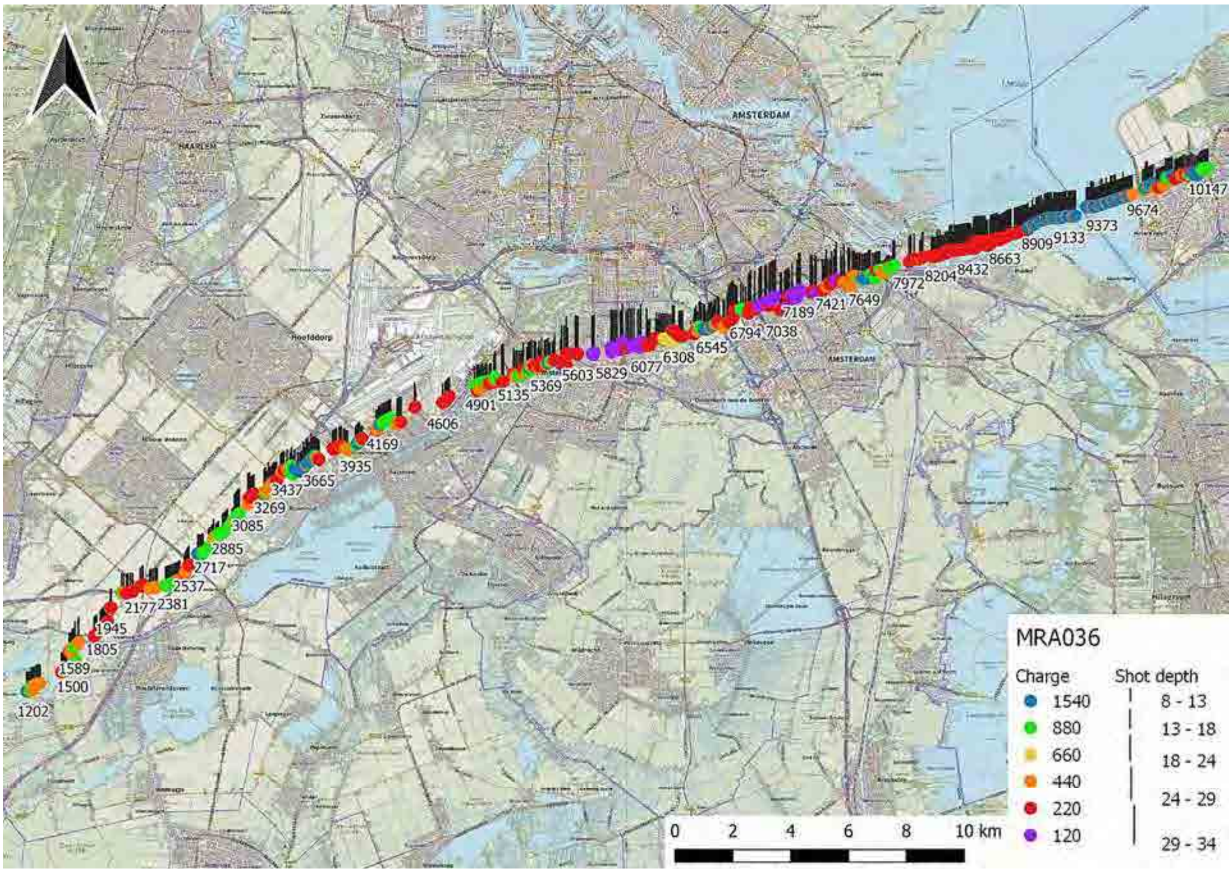


Figure 3.1.2.1: Acquisition parameters of line MRA036

General:

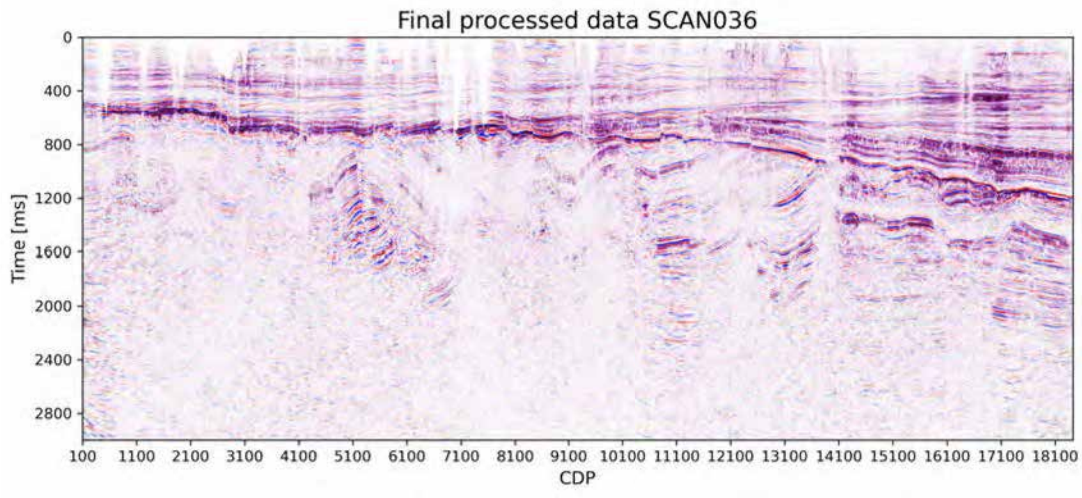


Figure 3.1.2.2: The final full cross-section of line MRA036.

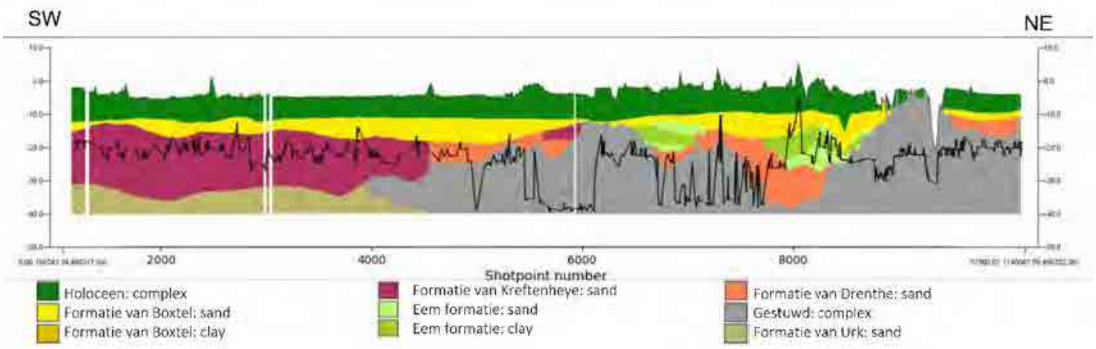


Figure 3.1.2.3: The geological profile of line MRA036.

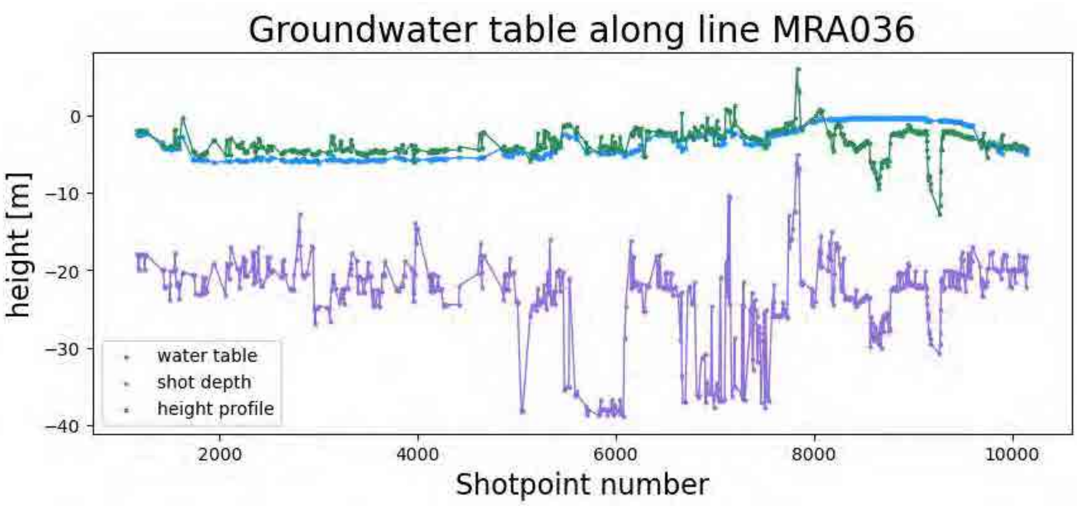


Figure 3.1.2.4: The water table along line MRA036. All shots are located below the water table.

Shot domain:

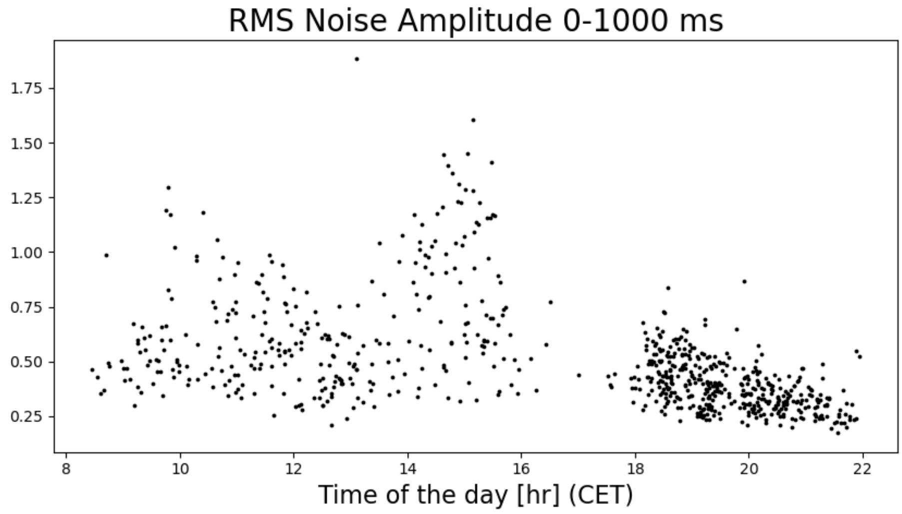


Figure 3.1.2.5: The noise in the shot domain plotted against the time of the day at which the shots were recorded.

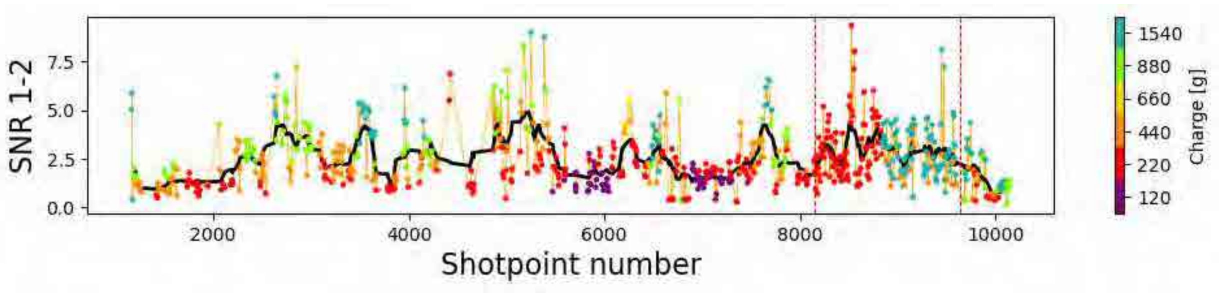


Figure 3.1.2.6: The SNR in the 1-2 second window with a charge size indicator. The black line is the moving average computed with a range of 15 data points. The red dashed lines indicate the hydrophone region. Charge sizes as low as 120 grams were used.

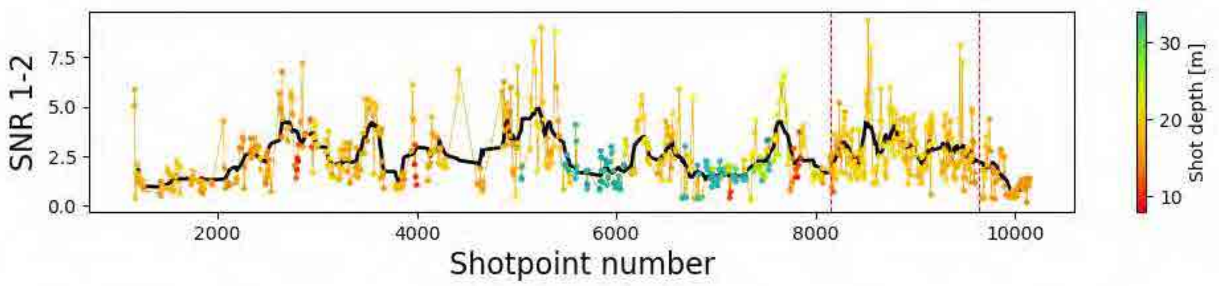


Figure 3.1.2.7: The SNR in the 1-2 second window with a shot depth indicator. The black line is the moving average computed with a range of 15 data points. The red dashed lines indicate the hydrophone region. Shot depths as deep as 34 meters were drilled.

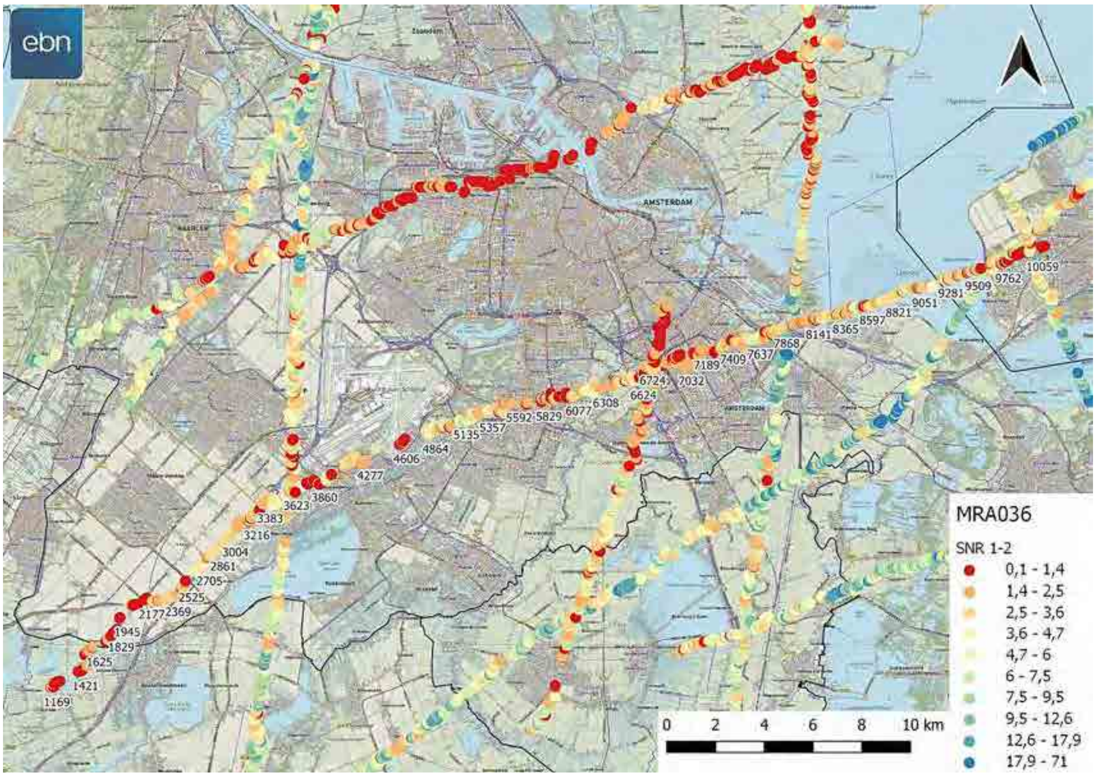


Figure 3.1.2.8: The SNR 1-2 value plotted along the line. The colour of the shot points indicate the quality of the shot, from bad (red) to good (blue). This colour range is divided into 10 segments which are based on the occurrence of the data points along all lines. The red dots therefore indicate that those shots belong to the worst 10 % of all the shots.

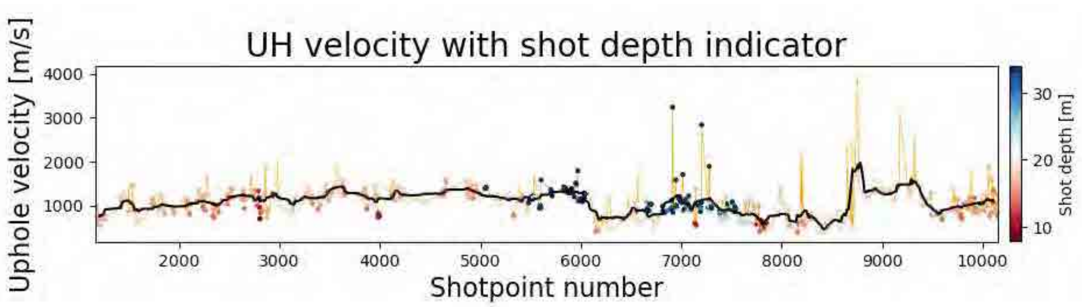


Figure 3.1.2.9: The uphole velocity along the line.

Receiver domain:

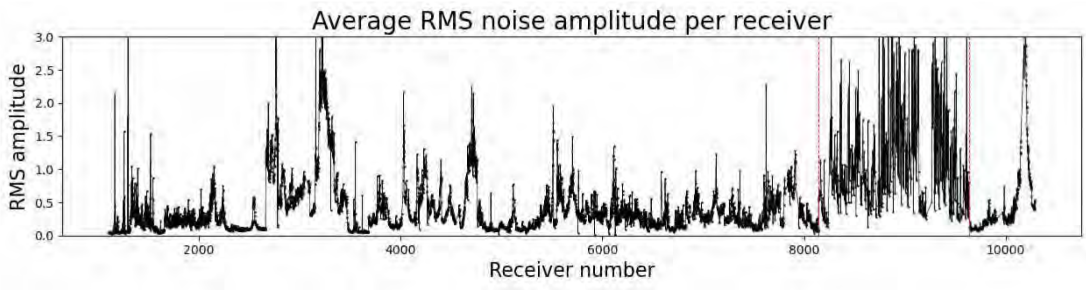


Figure 3.1.2.10: The noise per receiver. The red dashed lines indicate the hydrophone region. The line running parallel to a road explains the high noise levels around station number 3000.

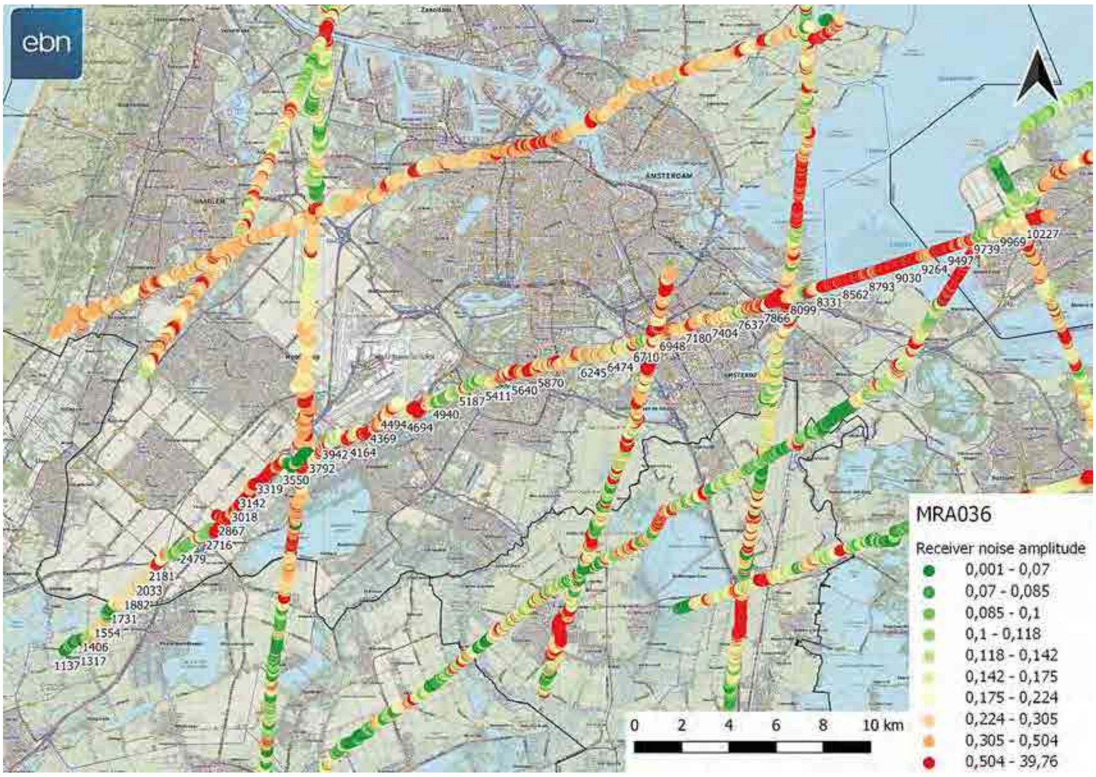


Figure 3.1.2.11: The noise per receiver visualized along the line. The color scale is based on the data of all the receiver data, showing noise relative to the other data points.

3.1.3 MRA037

Line MRA037 is another seismic line of the Metropool Regio Amsterdam project. It runs from Vogelenzang in the southwest, through Amsterdam and ends in the northeast in the vicinity of Monnickendam. The line has a WSW-ENE orientation. While there were no hydrophones deployed for this line, 7 of the 495 shots were placed in water using a piston. These were applied for crossing the river "Het IJ" located in the middle of Amsterdam.

Acquisition length	36.05 km
Number of receivers	6816 (1001-8213)
Number of shots	495 (1001.5-8138.5)
Of which in water	7
Skipped shots	17.6%
Skipped receivers	5.5%
Date recorded	25/08/2021 - 07/09/2021

Table 3.3: Acquisition parameters of line MRA037

Due to the proximity of buildings, in the urban areas sometimes charges as low as 120 grams and holes as deep as 34 meters were used. These acquisition parameters lead to lower quality shots. The impact of the metropolitan area is visible in Figure 3.1.3.6, with the low data quality between station number 3800-6500. As the availability of drilling locations is also more limited in densely populated areas, 17.6 % of the originally planned shots were skipped.

The urban character of this region leads to above average noise levels along the line. Furthermore, the average charge size of 491 grams is one of the lowest of all the lines, while an average depth of 20.3 meters is one of the highest. The combination of high noise levels and low charge sizes causes line MRA037 to be one of the worst lines in terms of field data quality.

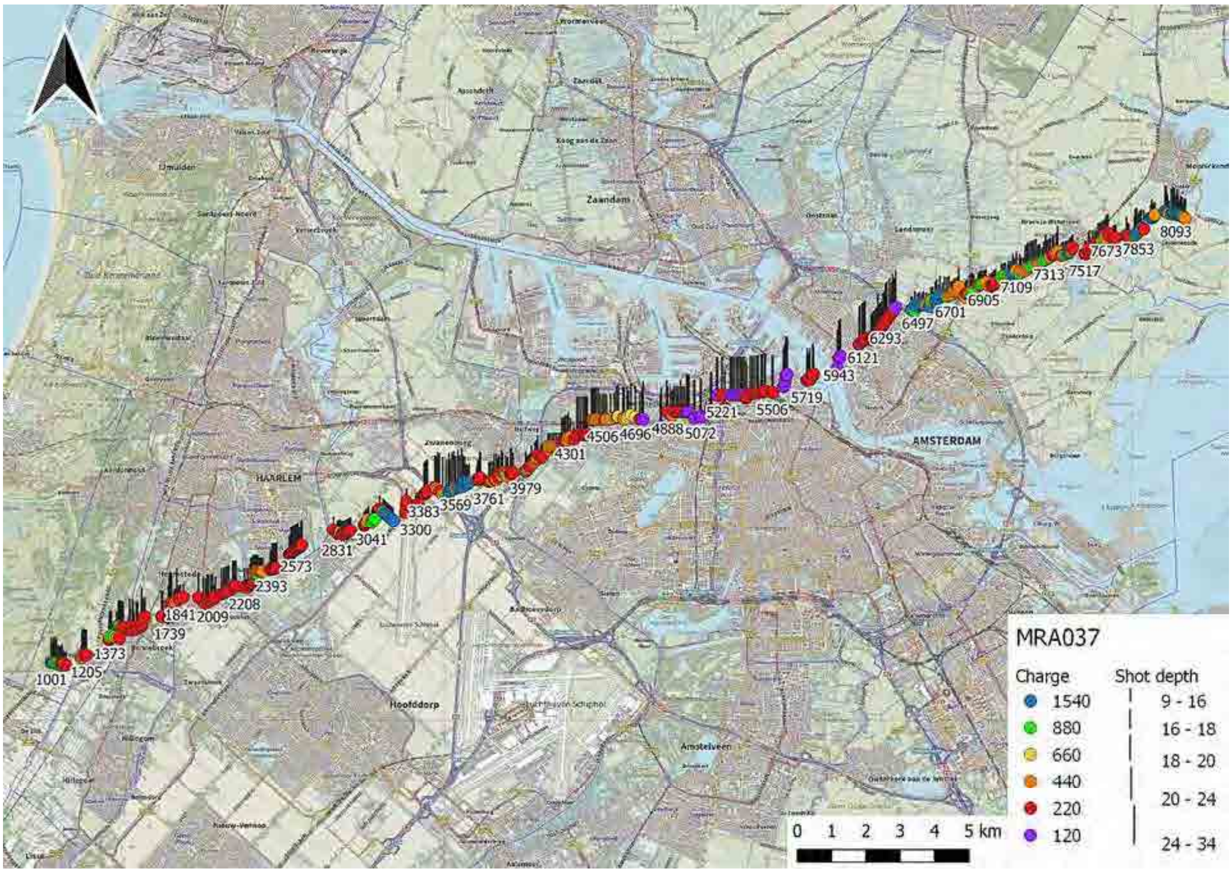


Figure 3.1.3.1: Acquisition parameters of line MRA037.

General:

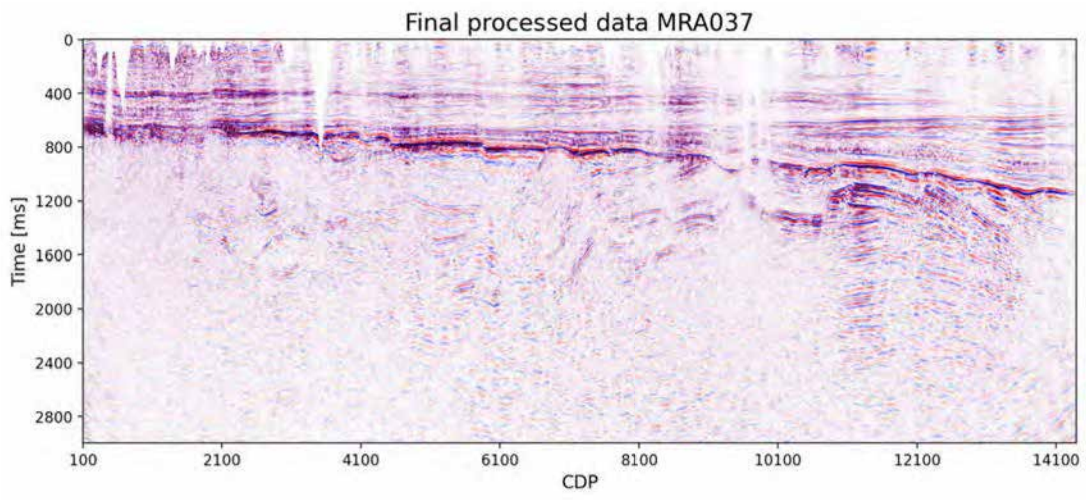


Figure 3.1.3.2: The final full cross-section of line MRA037.

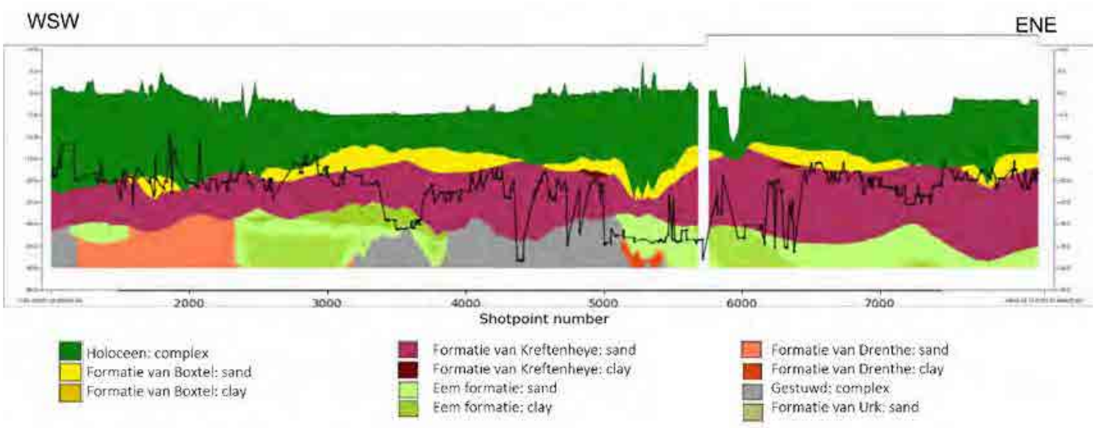


Figure 3.1.3.3: The geological profile of line MRA037.

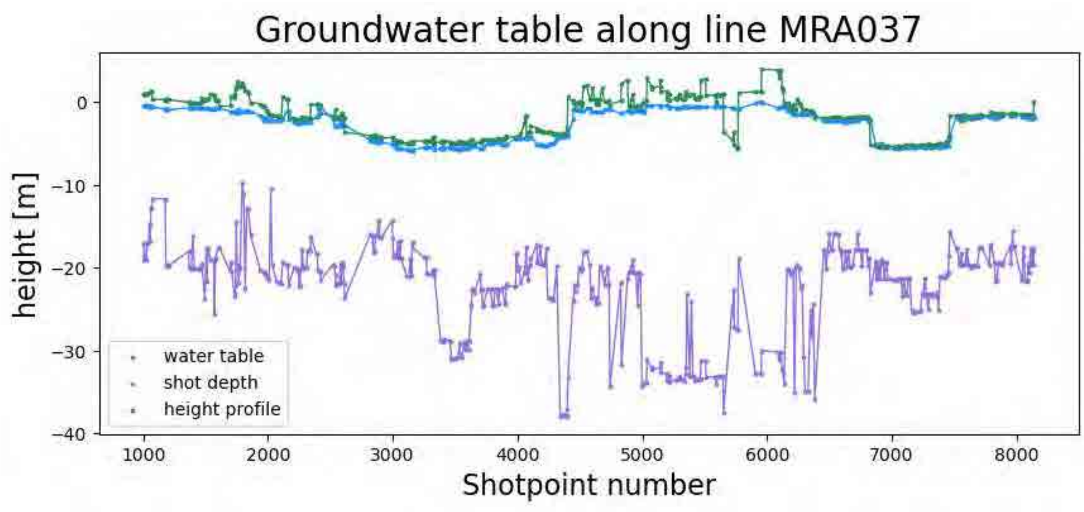


Figure 3.1.3.4: The water table along line MRA037. All shots are located below the water table.

Shot domain:

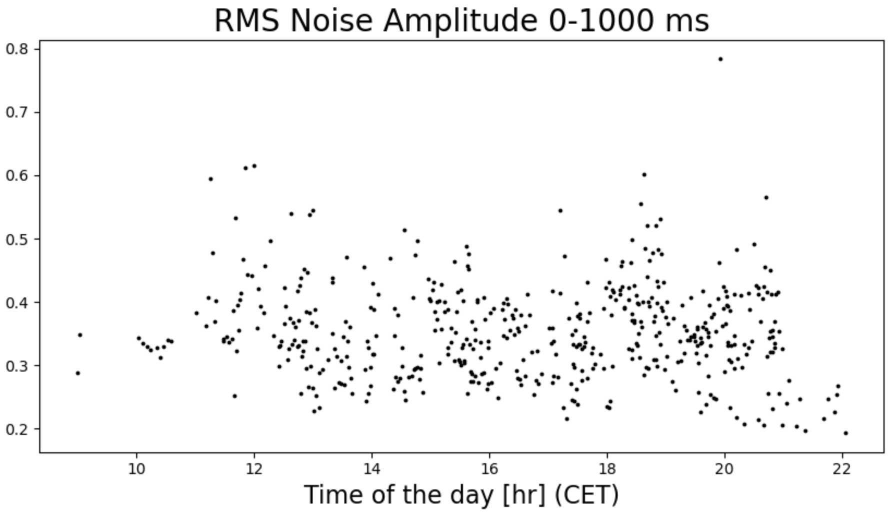


Figure 3.1.3.5: The noise in the shot domain plotted against the time of the day at which the shots were recorded.

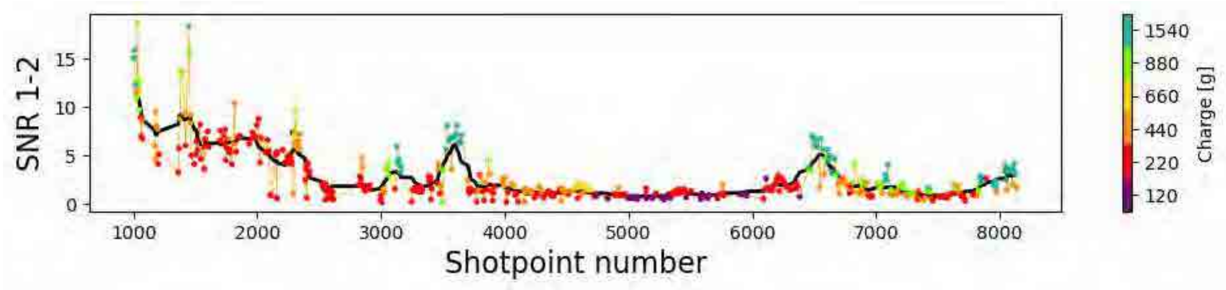


Figure 3.1.3.6: The SNR in the 1-2 second window with a charge size indicator. The black line is the moving average computed with a range of 15 data points. Charge sizes as low as 120 grams were used for this line.

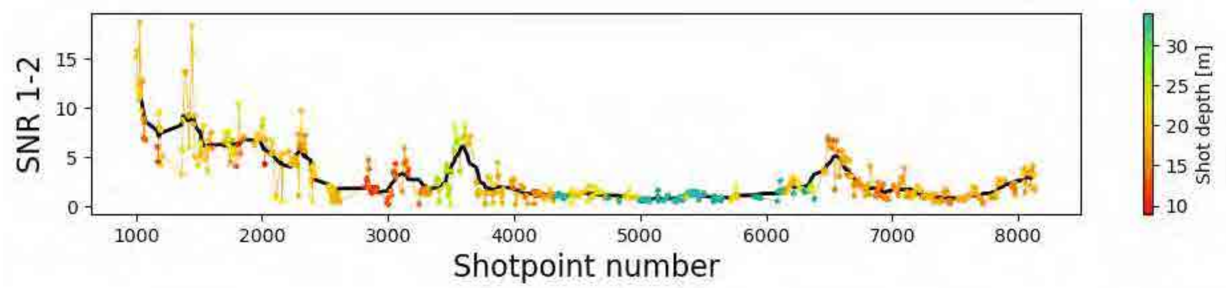


Figure 3.1.3.7: The SNR in the 1-2 second window with a shot depth indicator. The black line is the moving average computed with a range of 15 data points. Shot depths as large as 34 metres were drilled for this line.

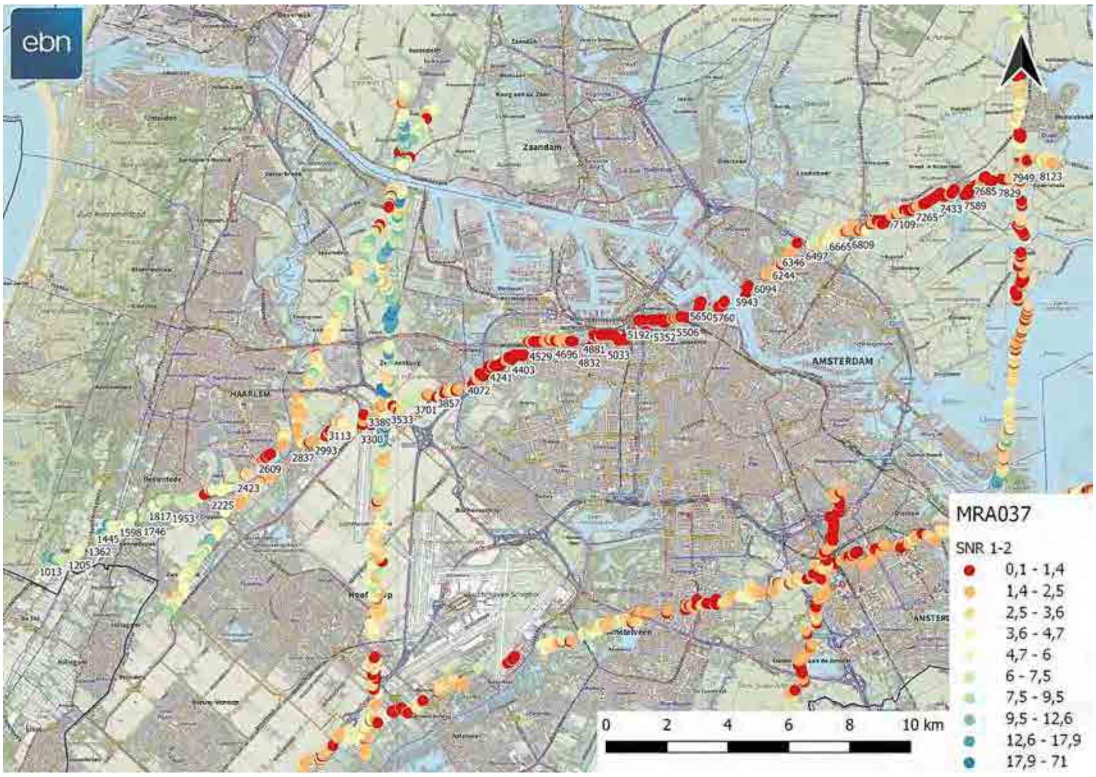


Figure 3.1.3.8: The SNR 1-2 value plotted along the line. The colour of the shot points indicate the quality of the shot, from bad (red) to good (blue). This colour range is divided into 10 segments which are based on the occurrence of the data points along all lines. The red dots therefore indicate that those shots belong to the worst 10 % of all the shots.

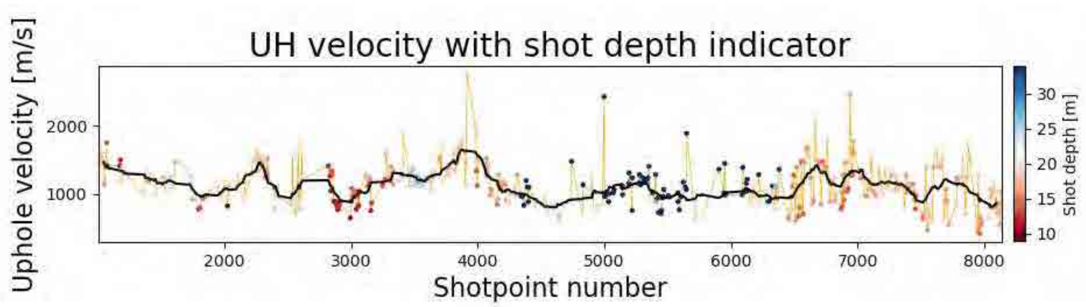


Figure 3.1.3.9: The uphole velocity along the line.

Receiver domain:

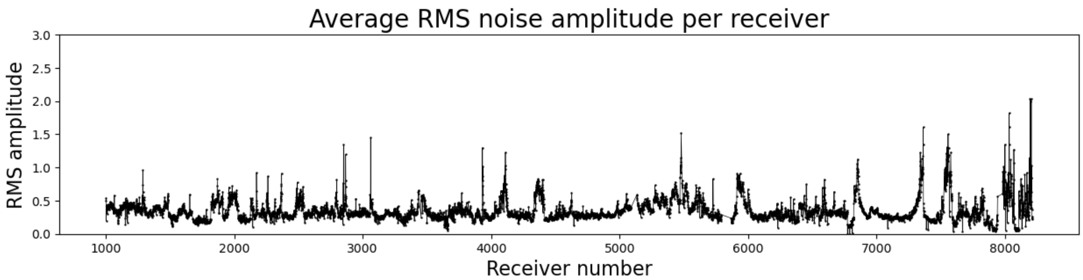


Figure 3.1.3.10: The noise per receiver.

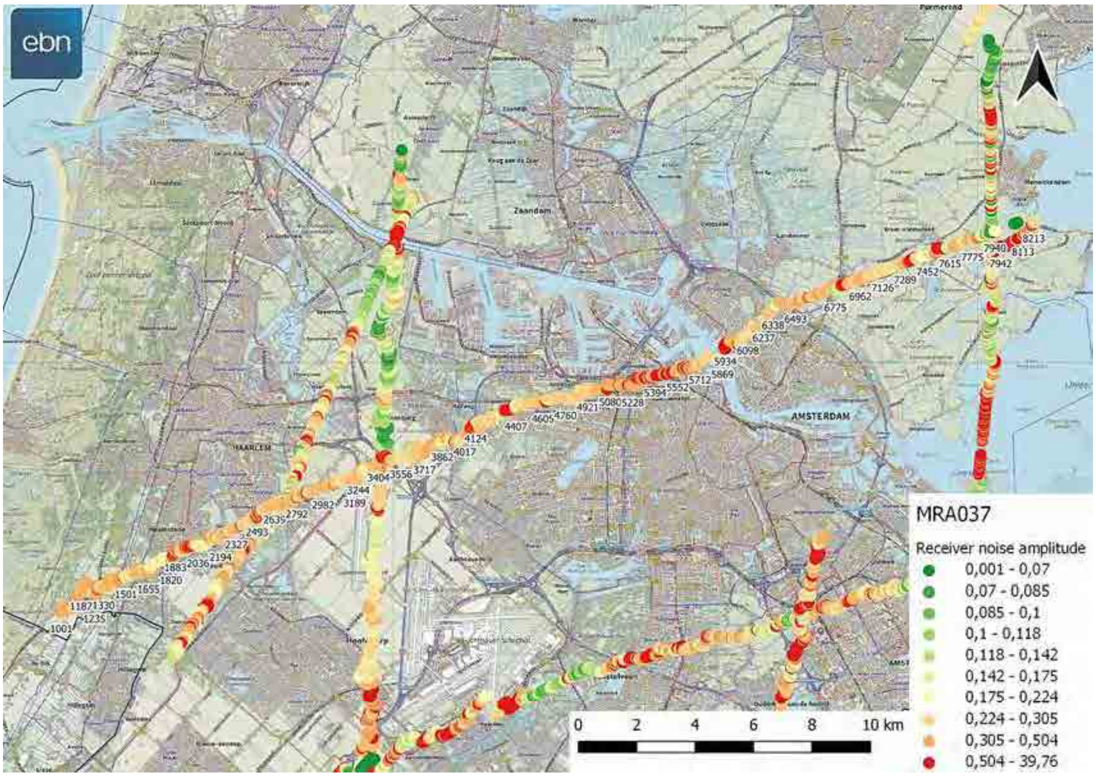


Figure 3.1.3.11: The noise per receiver visualized along the line. The color scale is based on the data of all the receiver data, showing noise relative to the other data points.

3.1.4 MRA038

As part of the Metropool Regio Amsterdam project another line which was shot was line MRA038, running from "De Ronde Venen" to "Blaricum". The line has a WSW-ENE orientation and finishes close to the island "Dode hond" which is located on the Eemmeer. Hydrophones were used on the Eemmeer, apart from a small patch of geophones placed on the previously mentioned island. The recording of this line took place at two different periods, causing a lot of receivers to be redeployed.

Acquisition length	27.75 km
Number of receivers	6604 (1001-8213)
Of which hydrophones	153
Number of shots	470 (1001.5-8138.5)
Of which in water	65
Skipped shots	4.9%
Skipped receivers	6.9%
Date recorded	01/06/2021 - 02/06/2021 13/09/2021 - 20/09/2021

Table 3.4: Acquisition parameters of line MRA038

With an average SNR of 6.1 the line is of decent quality. The noise recorded along the line is above average, possibly due to the impact of hydrophone high noise levels. Regarding the acquisition parameters, the charge size and the shot depth are both around the average for all the lines.

The most noticeable geological feature in the line is the presence of a push moraine in the vicinity of Laren. The combination of a sudden increase in elevation and a more challenging subsurface for drilling causes the shots in this region to be located above the groundwater level. These shots all have very low SNR values, indicating the lack of quality. This patch of low-quality data is also evident in the final cross-section, see Figure 3.1.4.2.

When studying the depth profile, there is one more anomaly visible when we compare it with the geological profile, namely the peak to the ENE of the Larenberg. After inspecting the location more closely using Google Maps, it was found that this anomaly was caused by the fact that the shots were taken on a hill on the side of a viaduct, therefore man-made additional elevation was added.

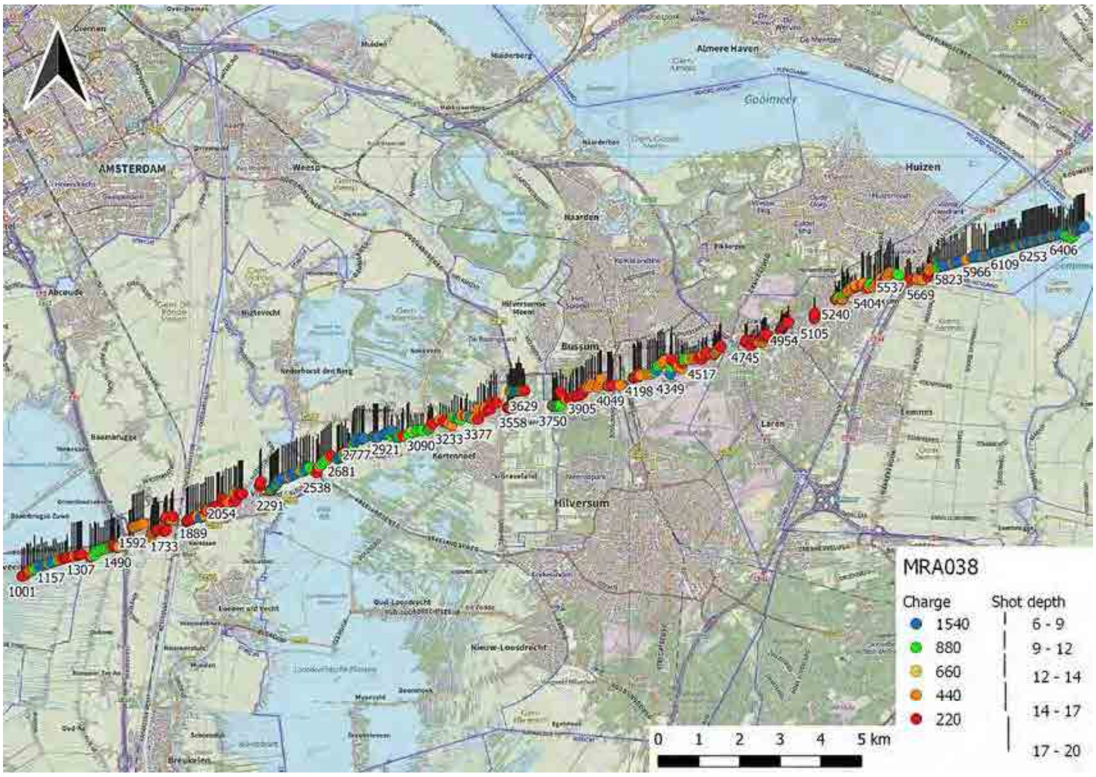


Figure 3.1.4.1: Acquisition parameters of line MRA038.

General:

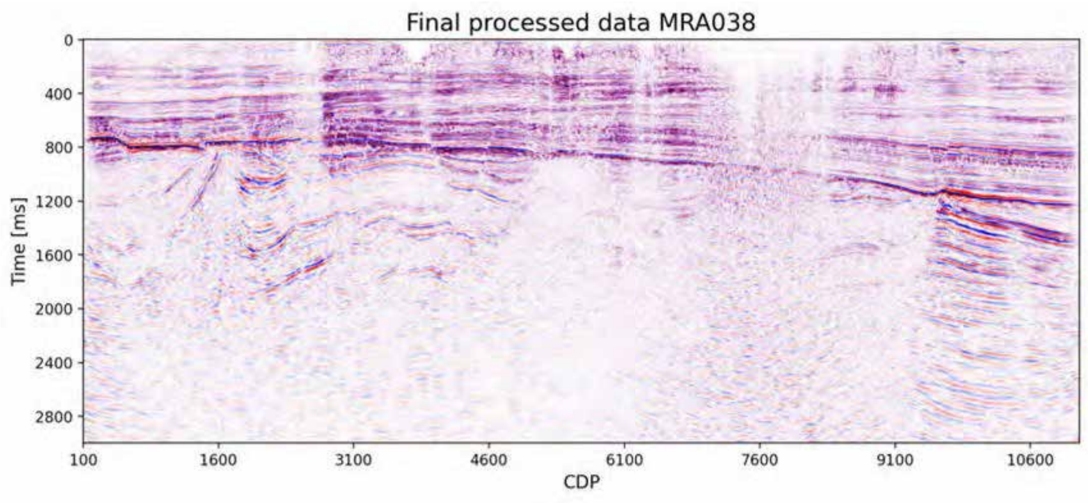


Figure 3.1.4.2: The final full cross-section of line MRA038.

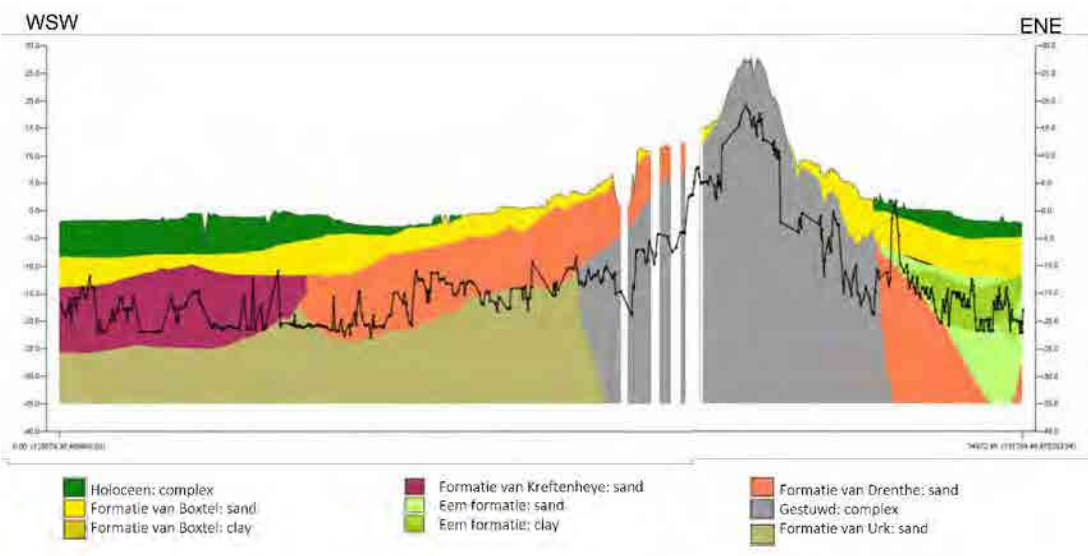


Figure 3.1.4.3: The geological profile of line MRA038.

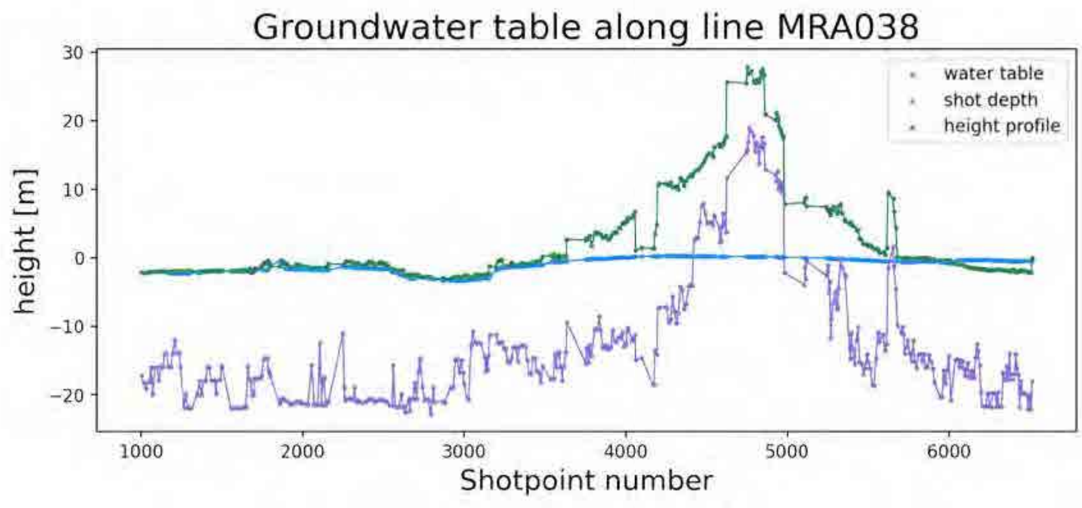


Figure 3.1.4.4: The water table along line MRA038. The shots between 4200-5000 are situated above the water table, as well as a few shots around 5600.

Shot domain:

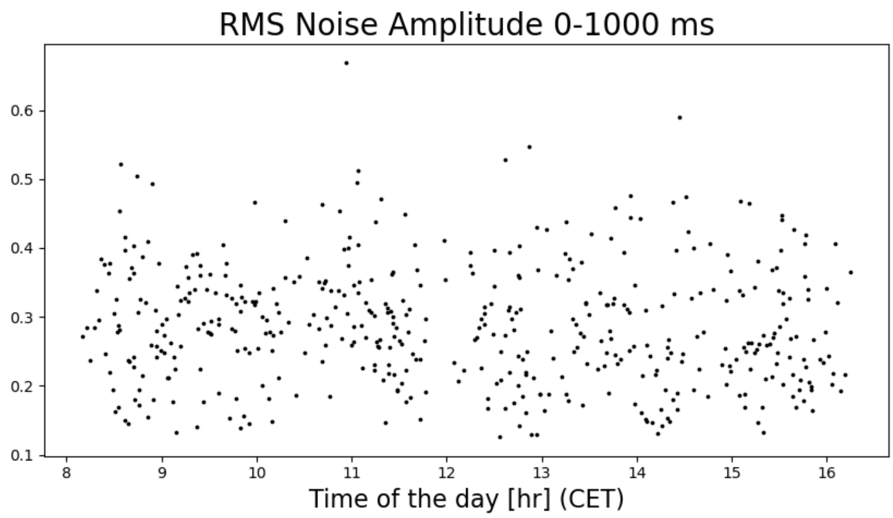


Figure 3.1.4.5: The noise in the shot domain plotted against the time of the day at which the shots were recorded.

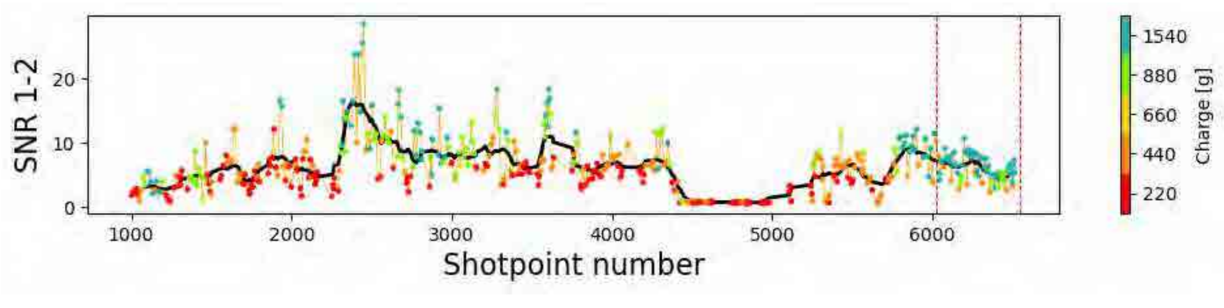


Figure 3.1.4.6: The SNR in the 1-2 second window with a charge size indicator. The black line is the moving average computed with a range of 15 data points. The red dashed lines indicate the hydrophone region.

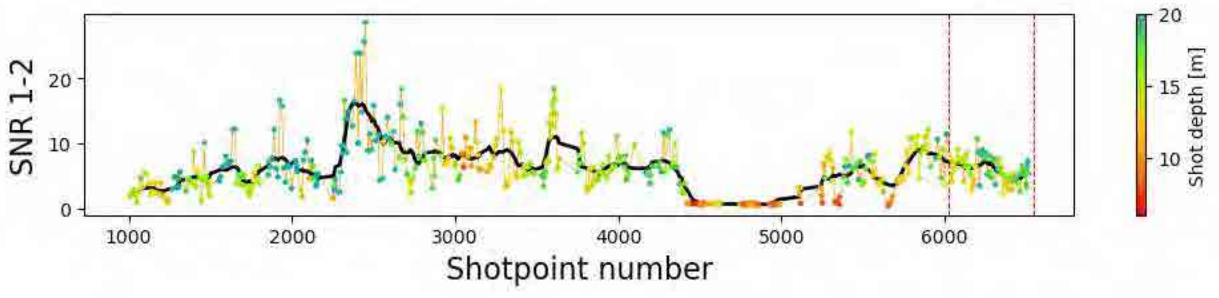


Figure 3.1.4.7: The SNR in the 1-2 second window with a shot depth indicator. The black line is the moving average computed with a range of 15 data points. The red dashed lines indicate the hydrophone region.

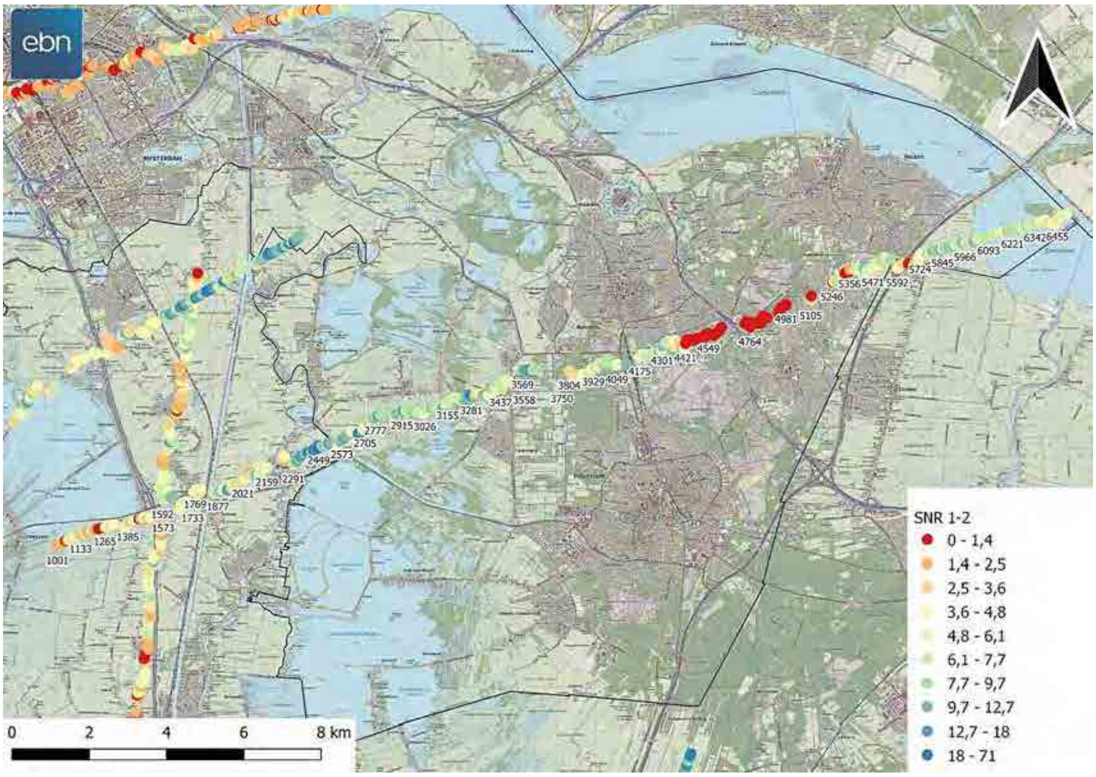


Figure 3.1.4.8: The SNR 1-2 value plotted along the line. The colour of the shot points indicate the quality of the shot, from bad (red) to good (blue). This colour range is divided into 10 segments which are based on the occurrence of the data points along all lines. The red dots therefore indicate that those shots belong to the worst 10 % of all the shots.

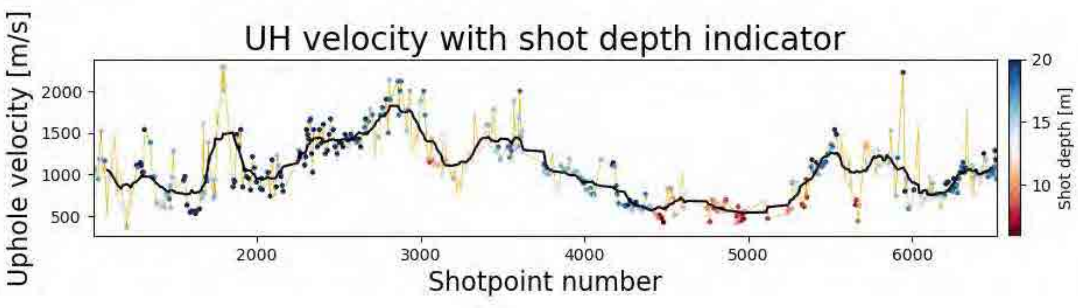


Figure 3.1.4.9: The uphole velocity along the line.

Receiver domain:

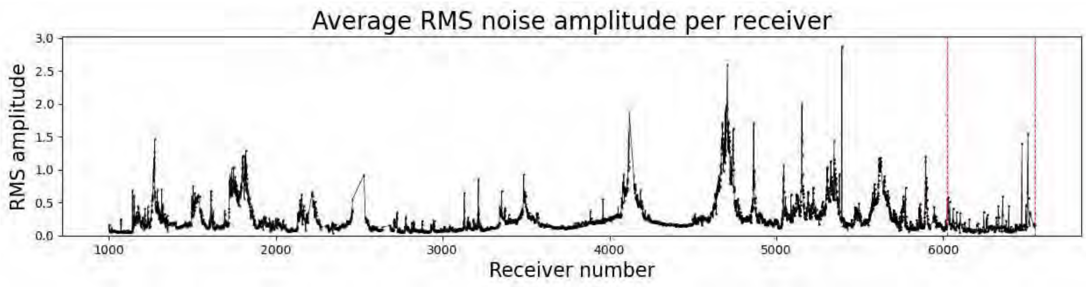


Figure 3.1.4.10: The noise per receiver. The red dashed lines indicate the hydrophone region.

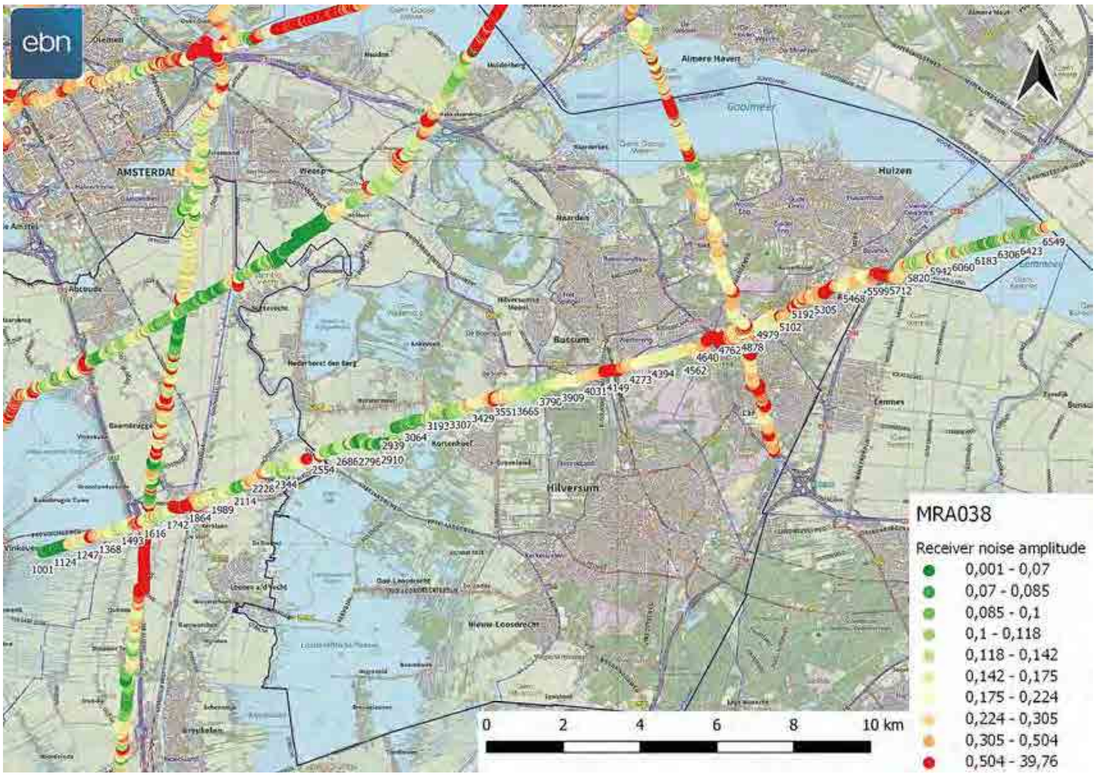


Figure 3.1.4.11: The noise per receiver visualized along the line. The color scale is based on the data of all the receiver data, showing noise relative to the other data points.

3.1.5 MRA039

Line MRA039 runs from Laren to Almere in a NNW-SSE direction. With its 17 kilometers it is one of the shortest lines of the Metropool Regio Amsterdam project. As the shots were recorded in two different periods, a large number of receivers needed to get redeployed. Like line MRA038, this line also crosses the push moraine of Laren.

It is again apparent that the placement of shots above the groundwater table leads to low data quality. While almost all shots are located in a partly subdued push moraine with complex geology, only the shots above the groundwater table have the extremely low SNR values. The shots with the highest SNR values are located in the Gooimeer. As on water no presence of buildings has to be considered, high charges can be used. Both the acquisition parameters and the resulting values are around average for all the lines.

Acquisition length	17.35 km
Number of receivers	5121 (1001-4469)
Of which hydrophones	182
Number of shots	308 (1001.5-4452.5)
Of which in water	63
Skipped shots	7.2%
Skipped receivers	9.2%
Date recorded	25/05/2021 - 26/05/2021 08/09/2021 - 10/09/2021

Table 3.5: Acquisition parameters of line MRA039

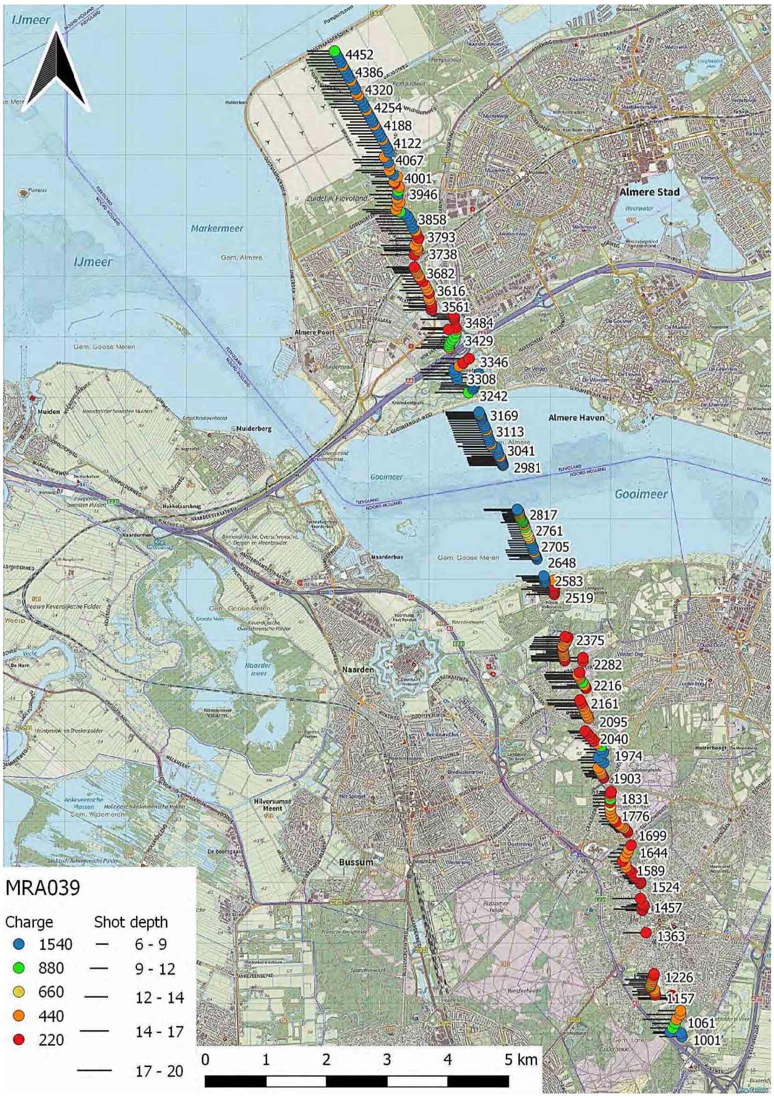


Figure 3.1.5.1: Acquisition parameters of line MRA039.

General:

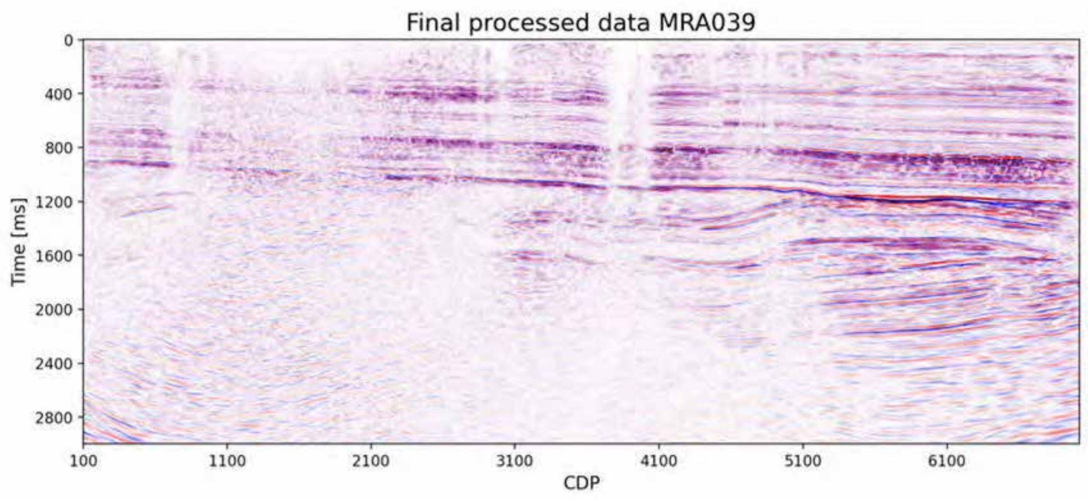


Figure 3.1.5.2: The final full cross-section of line MRA039.

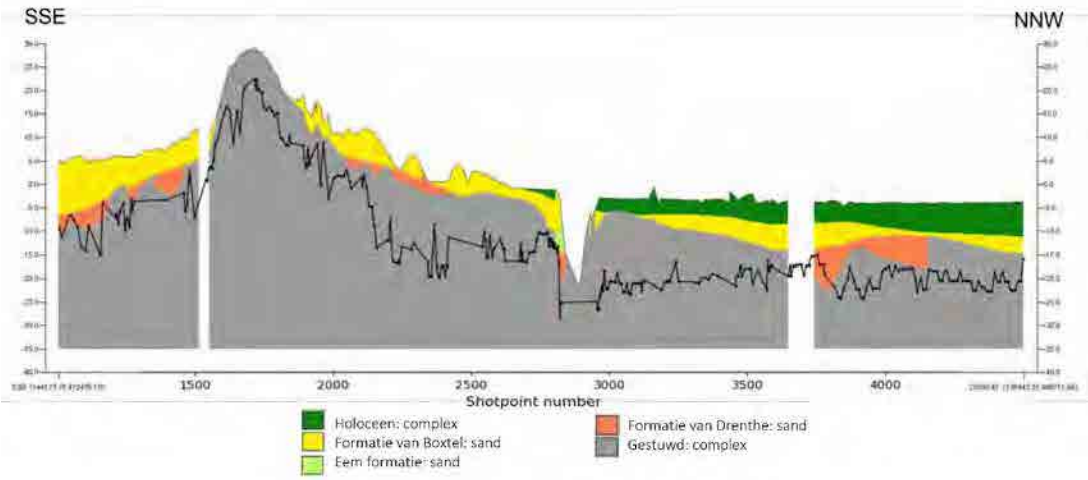


Figure 3.1.5.3: The geological profile of line MRA039.

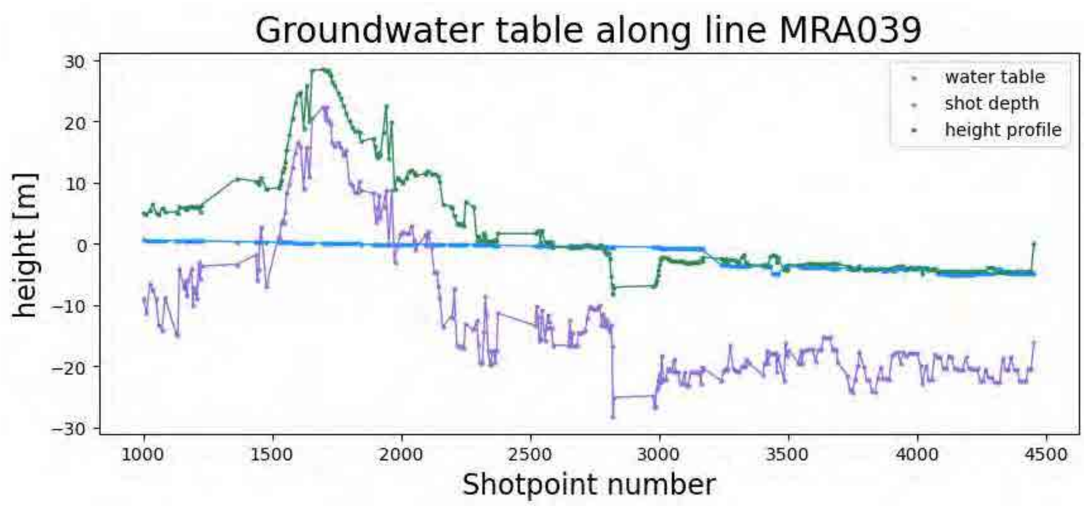


Figure 3.1.5.4: The water table along line MRA039. The shots around 1500-2000 are situated above the water table.

Shot domain:

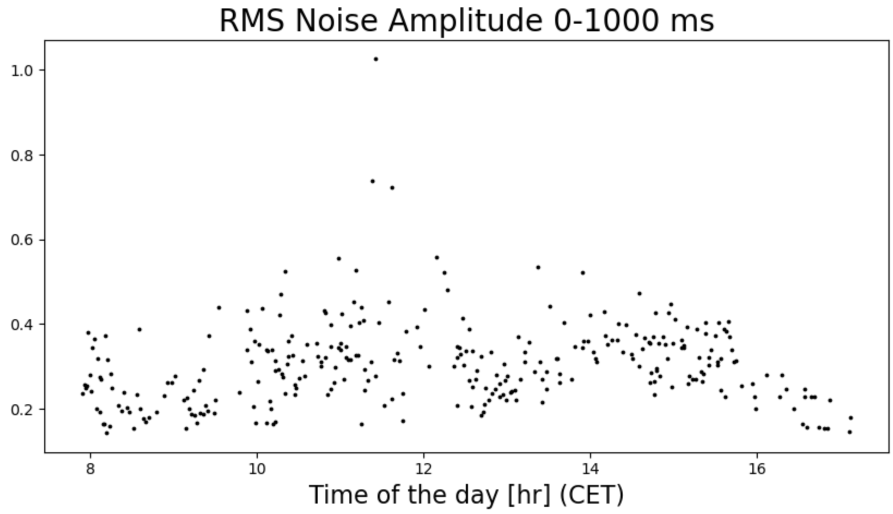


Figure 3.1.5.5: The noise in the shot domain plotted against the time of the day at which the shots were recorded.

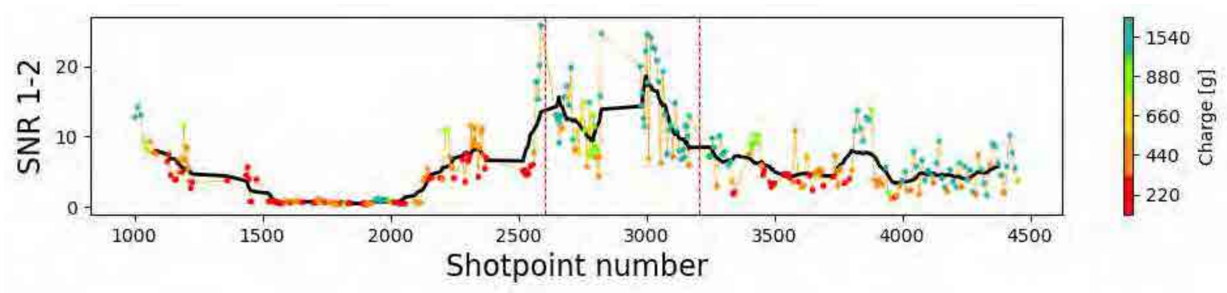


Figure 3.1.5.6: The SNR in the 1-2 second window with a charge size indicator. The black line is the moving average computed with a range of 15 data points. The red dashed lines indicate the hydrophone region.

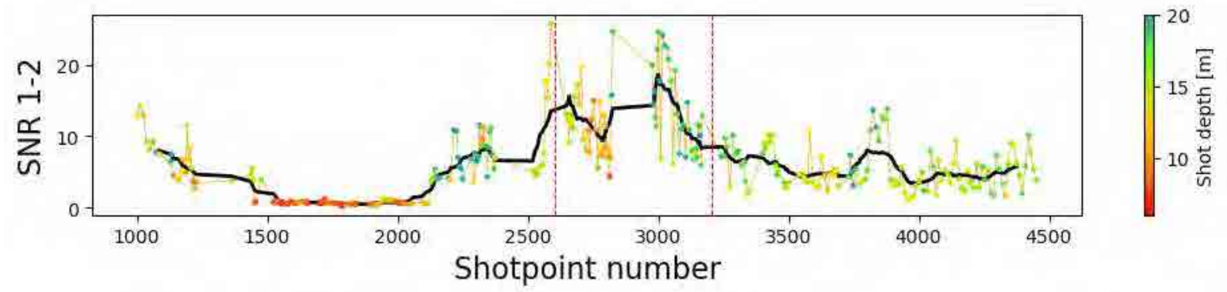


Figure 3.1.5.7: The SNR in the 1-2 second window with a shot depth indicator. The black line is the moving average computed with a range of 15 data points. The red dashed lines indicate the hydrophone region.

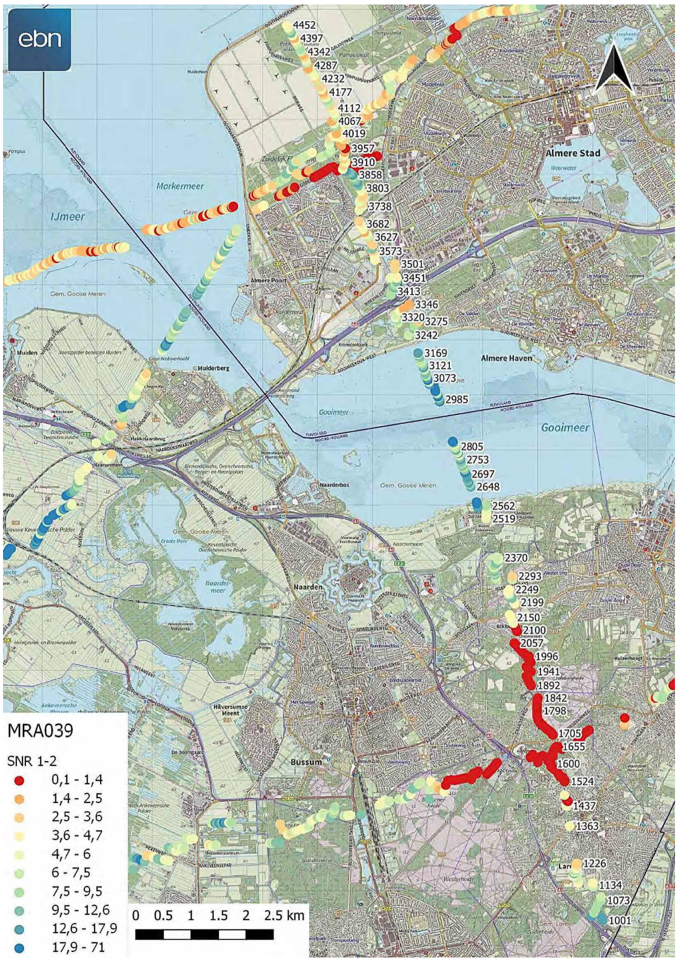


Figure 3.1.5.8: The SNR 1-2 value plotted along the line. The colour of the shot points indicate the quality of the shot, from bad (red) to good (blue). This colour range is divided into 10 segments which are based on the occurrence of the data points along all lines. The red dots therefore indicate that those shots belong to the worst 10 % of all the shots.

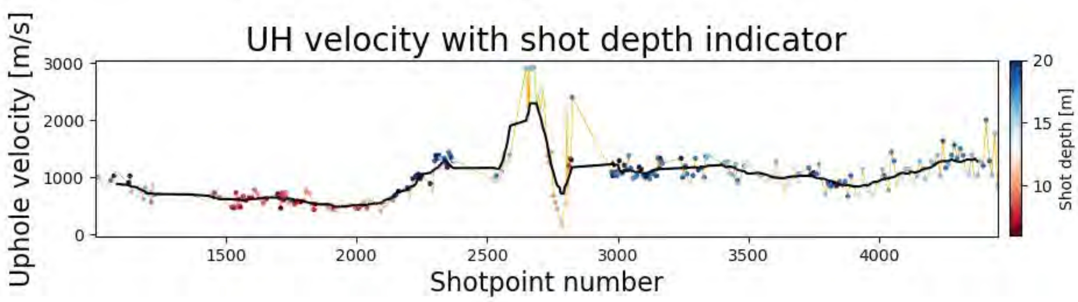


Figure 3.1.5.9: The uphole velocity along the line.

Receiver domain:

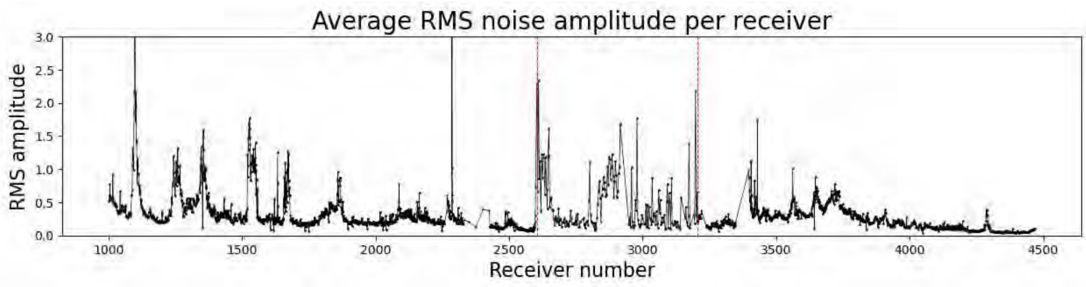


Figure 3.1.5.10: The noise per receiver. The red dashed lines indicate the hydrophone region.

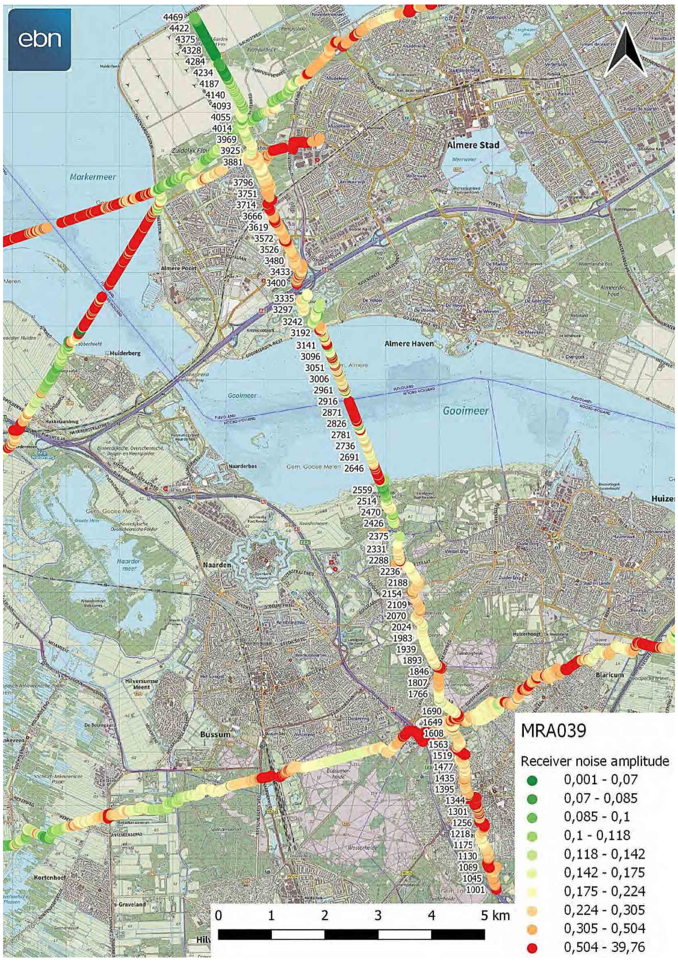


Figure 3.1.5.11: The noise per receiver visualized along the line. The color scale is based on the data of all the receiver data, showing noise relative to the other data points.

3.1.6 MRA040

Acquisition length	18.63 km
Number of receivers	3573 (601-4325)
Number of shots	267 (641.5-4295.5)
Retaken shots	18
Skipped shots	13.9%
Skipped receivers	4.1%
Date recorded	21/09/2021 - 28/09/2021

Table 3.6: Acquisition parameters of line MRA040

Line MRA040 is about 19 kilometers long and runs from Mijdrecht to Amsterdam Zuidoost with a SSW-NNE orientation. The magnitude of the charges placed ranges from 120 to 1540 grams, the shot depth ranges from 12-34 meters. A proximity to buildings could not be avoided due to the highly urban area through which the line was planned. This was mitigated by drilling deeper shot holes (34 meters) which still allowed a placement of small charge sizes (120 grams).

A faulty receiver at station number 1300 was removed before further analysis on the data was performed. When looking at Figure 3.1.6.8, it is evident that the shots placed in the region of Amsterdam have a significantly lower quality. This is due to a combination of low charges and high noise levels.

Interestingly, for this line 18 shots between station number 3500-4300 were drilled and detonated twice. The first round of shots was accidentally taken around 4 PM, while the planning was to shoot them later in the evening. Following the theory that the amount of noise present during the day is higher than in the evening, these shots were drilled again and re-shot. This provided an excellent opportunity to evaluate the impact of the shooting time on the noise levels. This will be further expanded on in the discussion section.

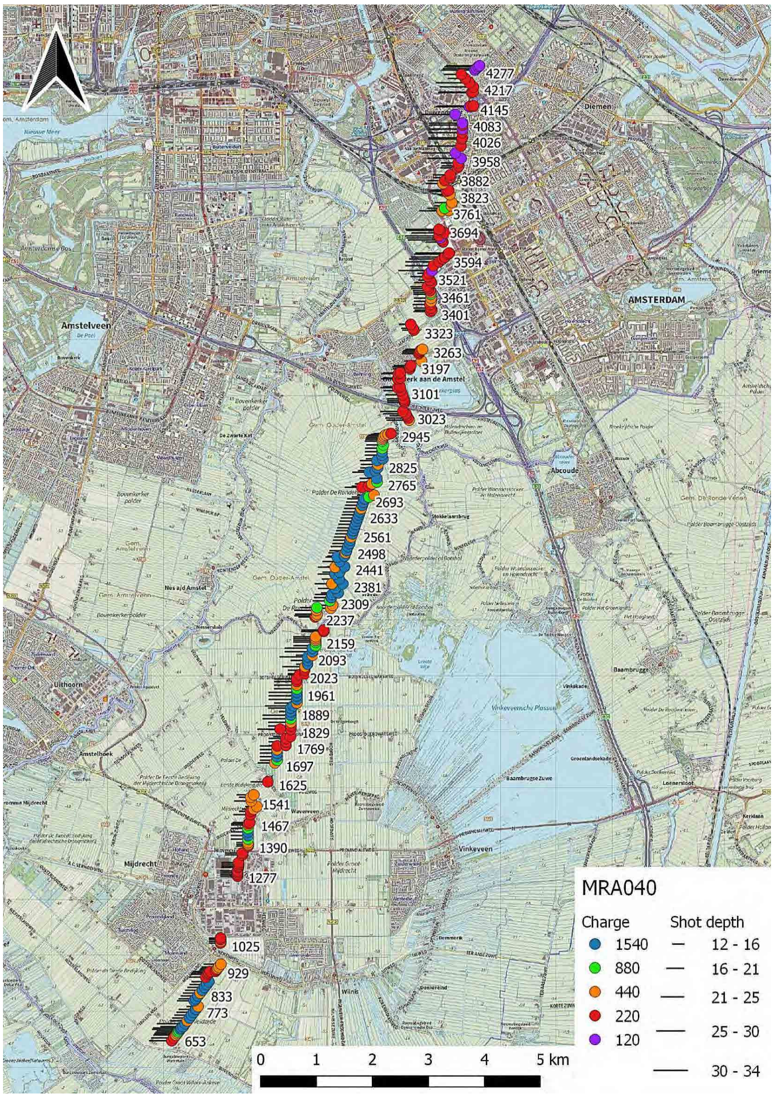


Figure 3.1.6.1: Acquisition parameters of line MRA040.

General:

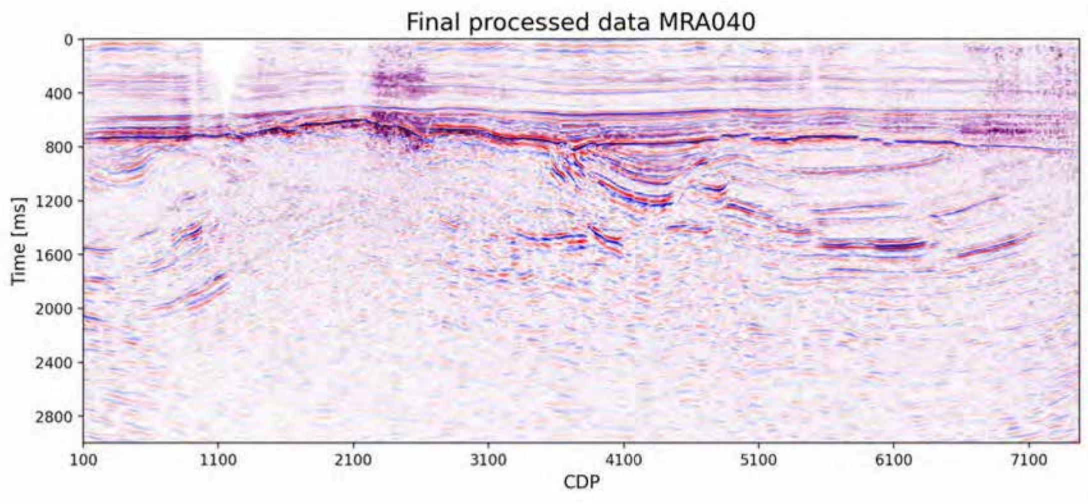


Figure 3.1.6.2: The final full cross-section of line MRA040.

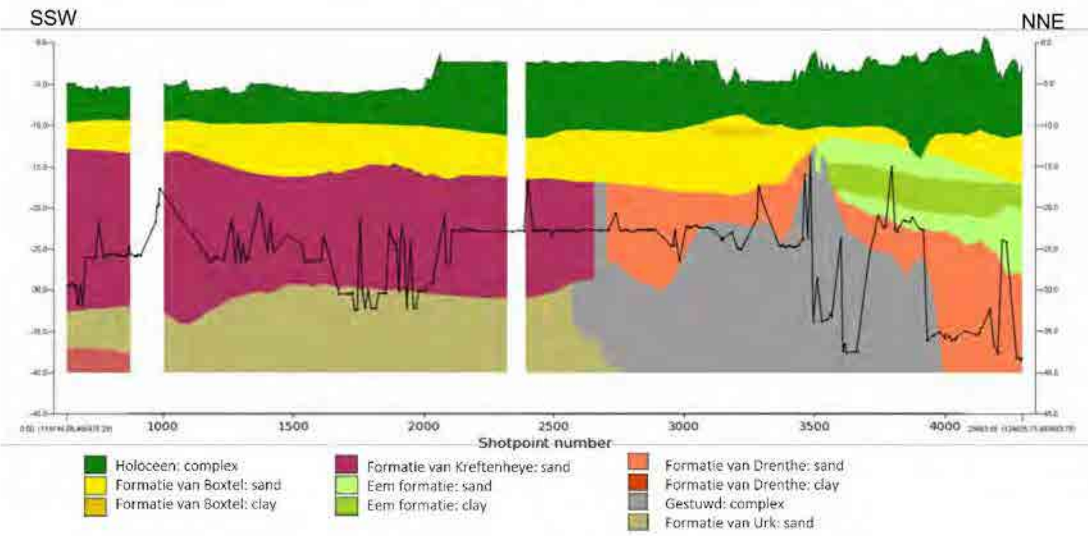


Figure 3.1.6.3: The geological profile of line MRA040.

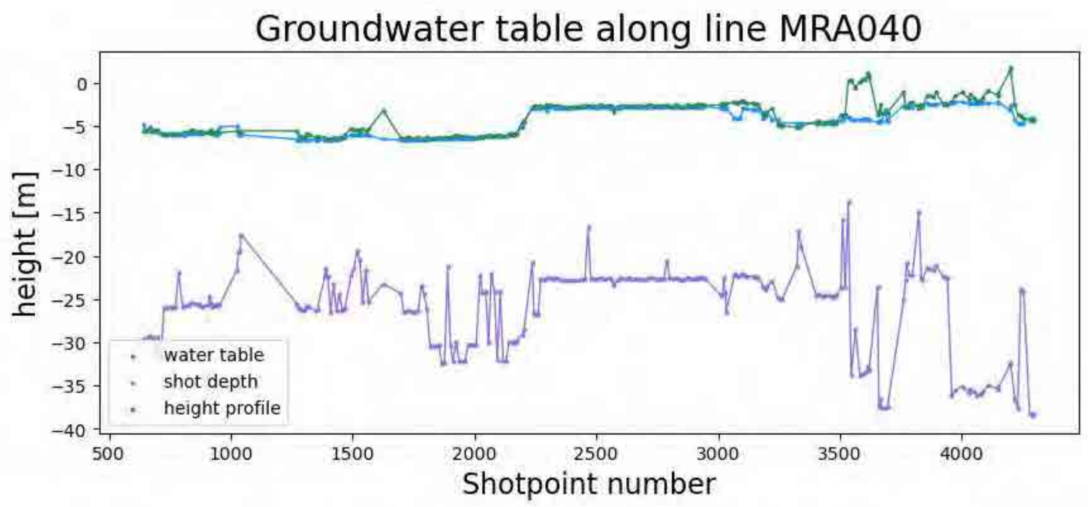


Figure 3.1.6.4: The water table along line MRA040. All shots are located below the water table.

Shot domain:

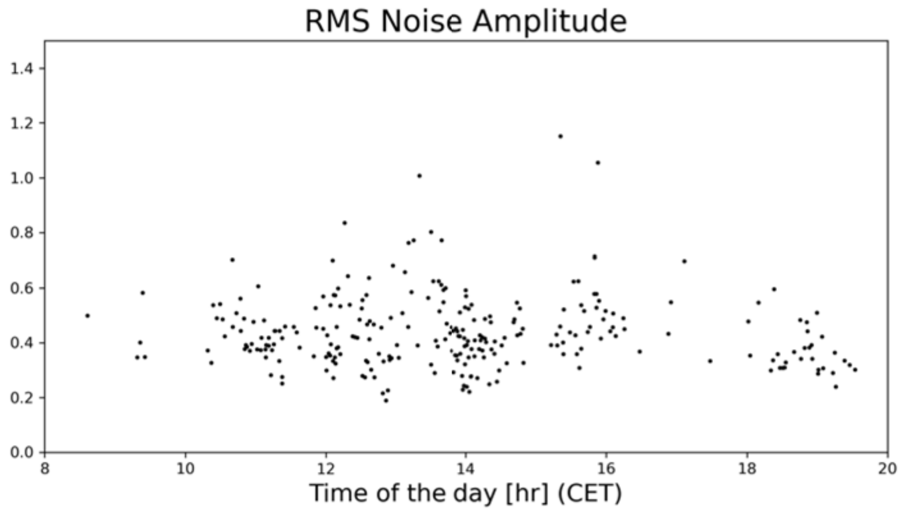


Figure 3.1.6.5: The noise in the shot domain plotted against the time of the day at which the shots were recorded.

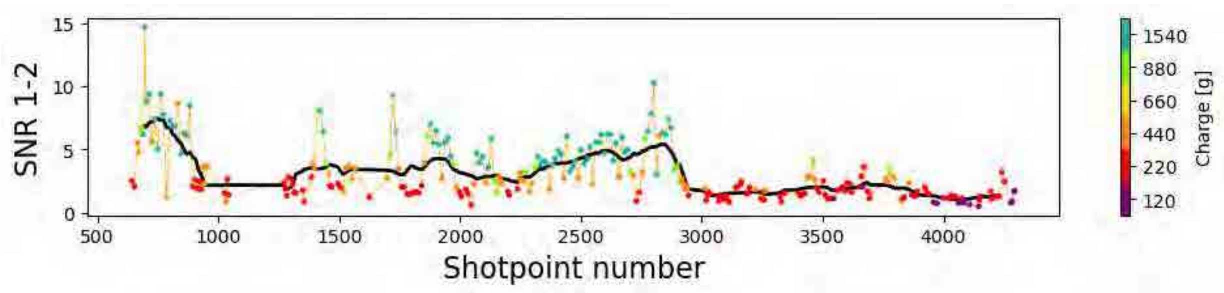


Figure 3.1.6.6: The SNR in the 1-2 second window with a charge size indicator. The black line is the moving average computed with a range of 15 data points. Charge sizes as low as 120 grams were used in Amsterdam.

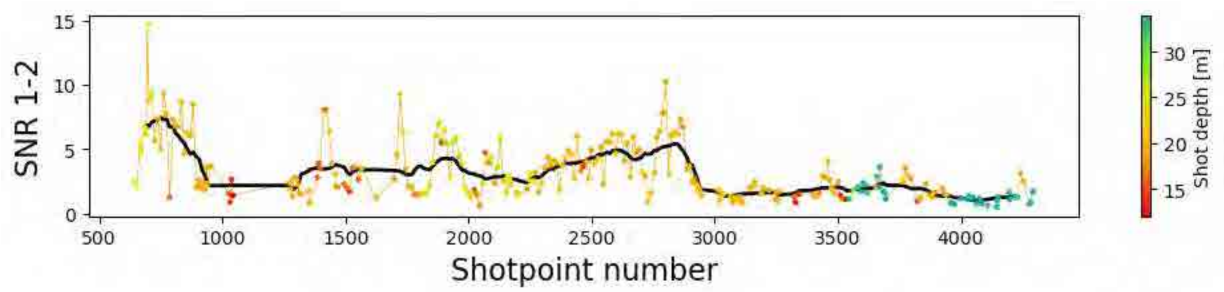


Figure 3.1.6.7: The SNR in the 1-2 second window with a shot depth indicator. The black line is the moving average computed with a range of 15 data points. Shot depths as deep as 34 metres were drilled in Amsterdam.

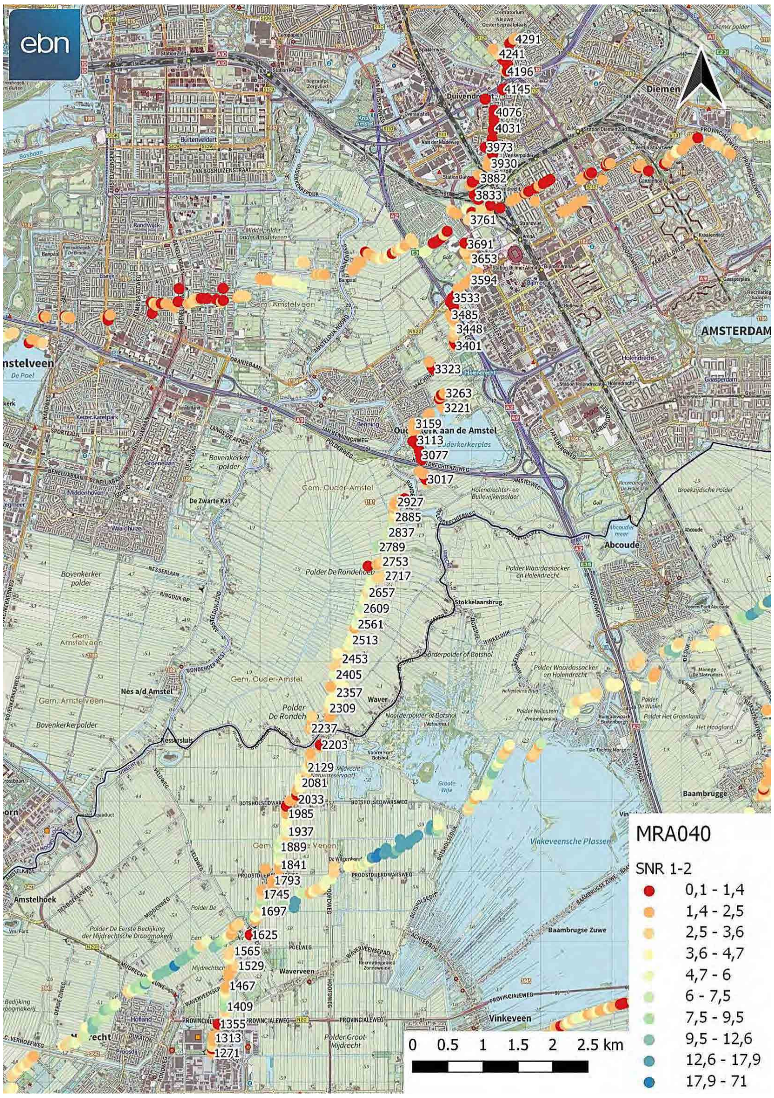


Figure 3.1.6.8: The SNR 1-2 value plotted along the line. The colour of the shot points indicate the quality of the shot, from bad (red) to good (blue). This colour range is divided into 10 segments which are based on the occurrence of the data points along all lines. The red dots therefore indicate that those shots belong to the worst 10 % of all the shots.

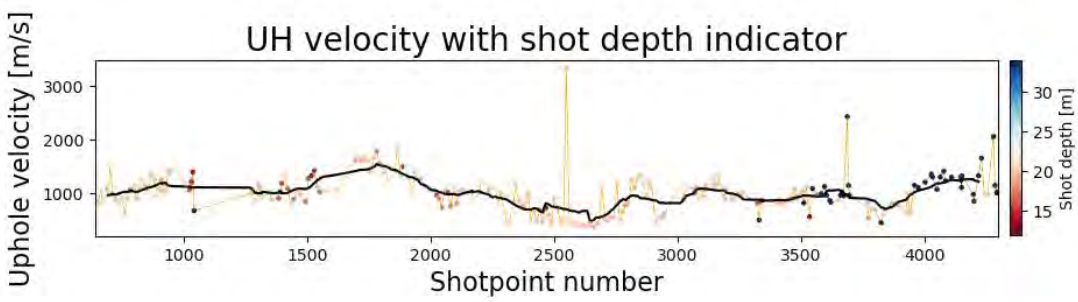


Figure 3.1.6.9: The uphole velocity along the line.

Receiver domain:

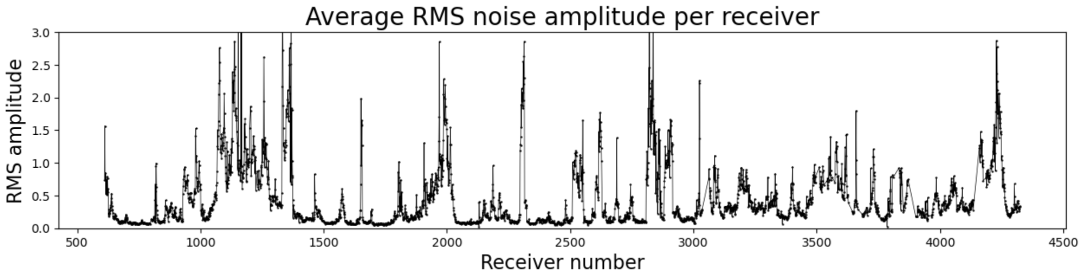


Figure 3.1.6.10: The noise per receiver.

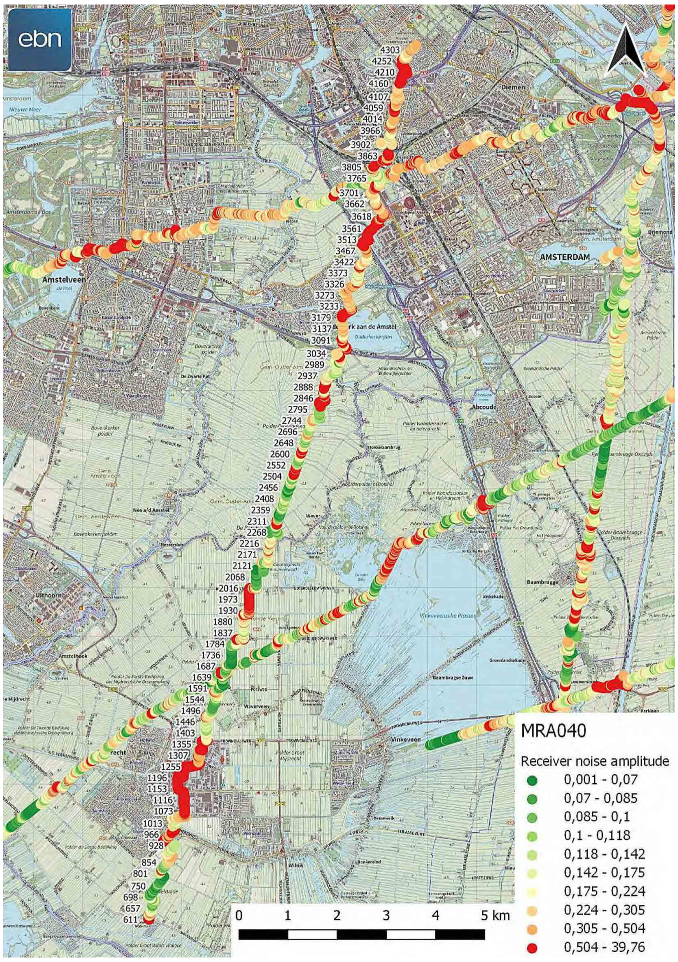


Figure 3.1.6.11: The noise per receiver visualized along the line. The color scale is based on the data of all the receiver data, showing noise relative to the other data points.

3.1.7 MRA041

Line MRA041 is the shortest and last line of the Metropool Regio Amsterdam project. It runs south of Lelystad with a NE-SW orientation. When crossing Lelystad, low charges were used resulting in a low signal. The link between the charge size and the SNR values is especially evident in this line. Next to the city, another source of noise is the presence of windmills along the line. The receivers placed close to a windmill show anomalously high noise levels. Unfortunately, in some regions the density of the windmills is so high that avoiding them during the acquisition phase is nearly impossible.

Acquisition length	13.89 km
Number of receivers	2740 (1001-3777)
Number of shots	216 (1003.5-3737.5)
Skipped shots	6.9%
Skipped receivers	1.3%
Date recorded	27/09/2021 - 30/09/2021

Table 3.7: Acquisition parameters of line MRA041

The line belongs to the group of lines with some of the lowest quality of the whole project. This is due to low signal values and relatively high noise levels. The most noticeable element of line MRA041 is the appearance of strong reverberations in the eastern section of the line, when the shots are located in the meadow. These reverberations, also known as guided waves, have no straightforward explanation for their local presence. Both the subsurface and the land usage did not hint at anything that could explain their appearance.

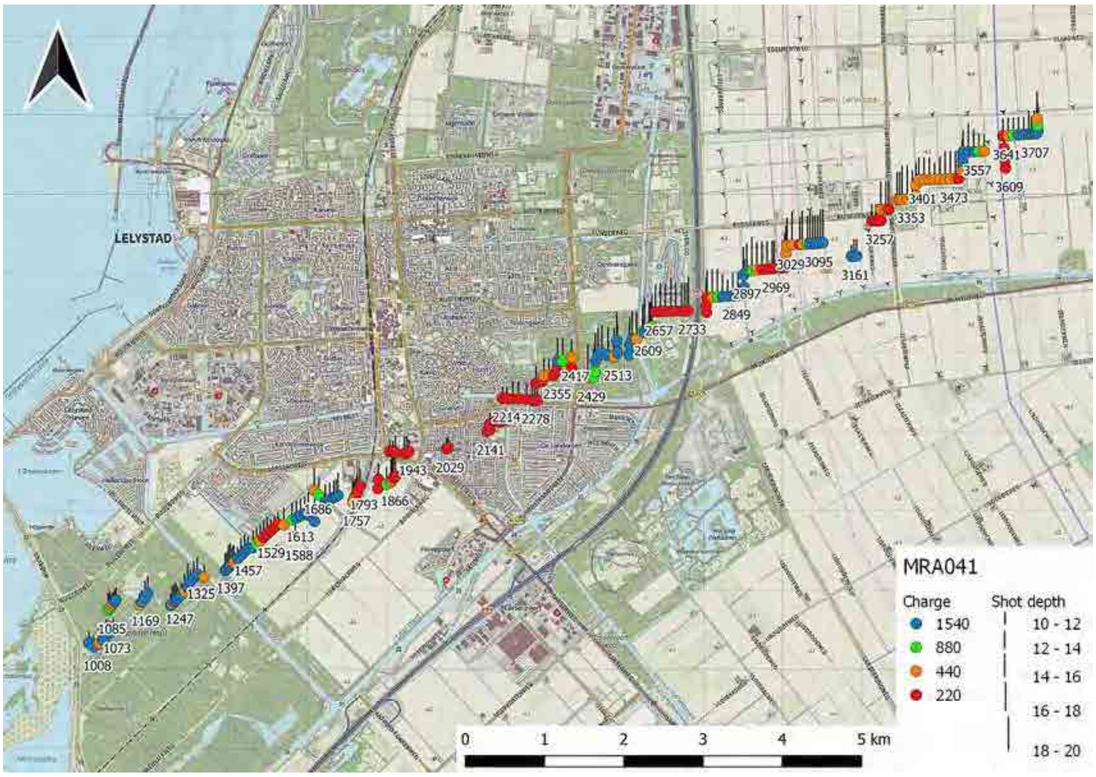


Figure 3.1.7.1: Acquisition parameters of line MRA041.

General:

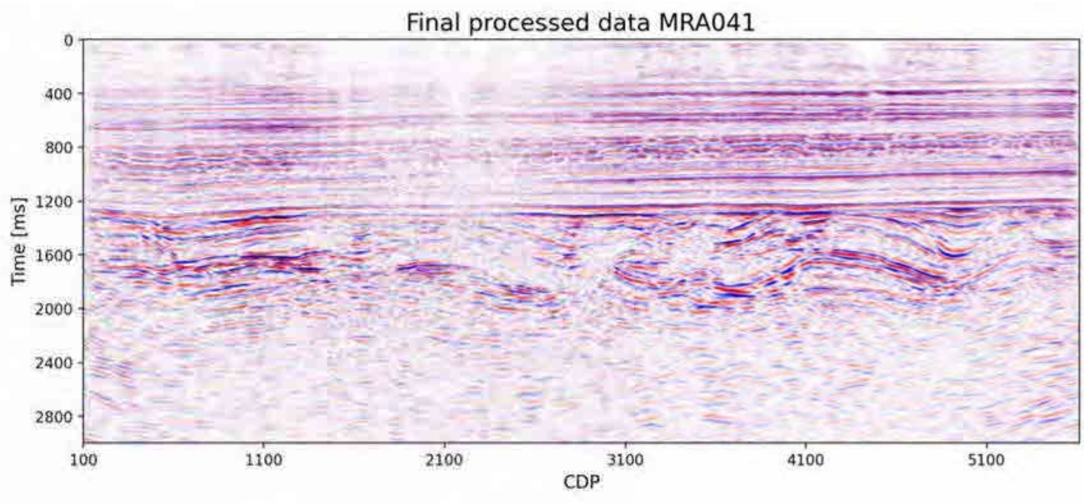


Figure 3.1.7.2: The final full cross-section of line MRA041.

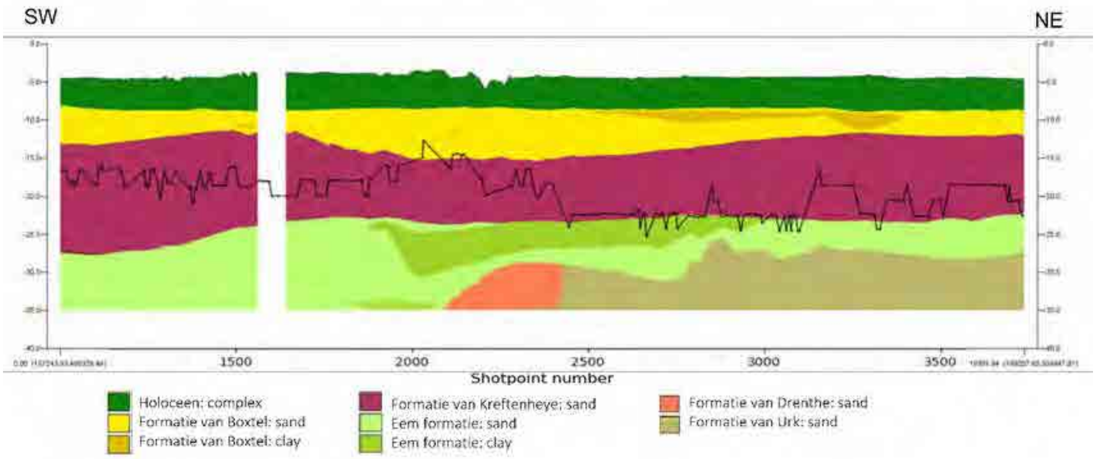


Figure 3.1.7.3: The geological profile of line MRA041.

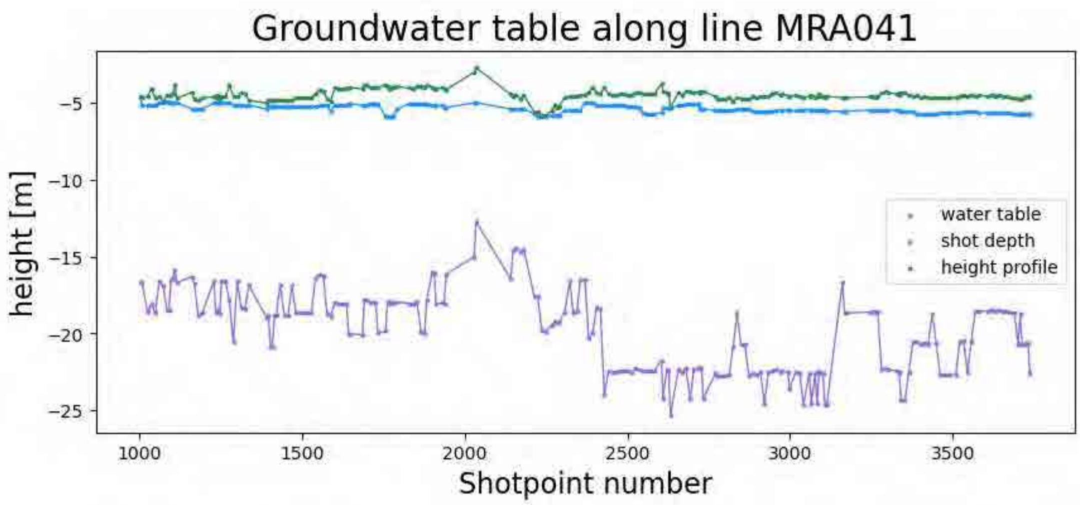


Figure 3.1.7.4: The water table along line MRA041. All shots are located below the water table.

Shot domain:

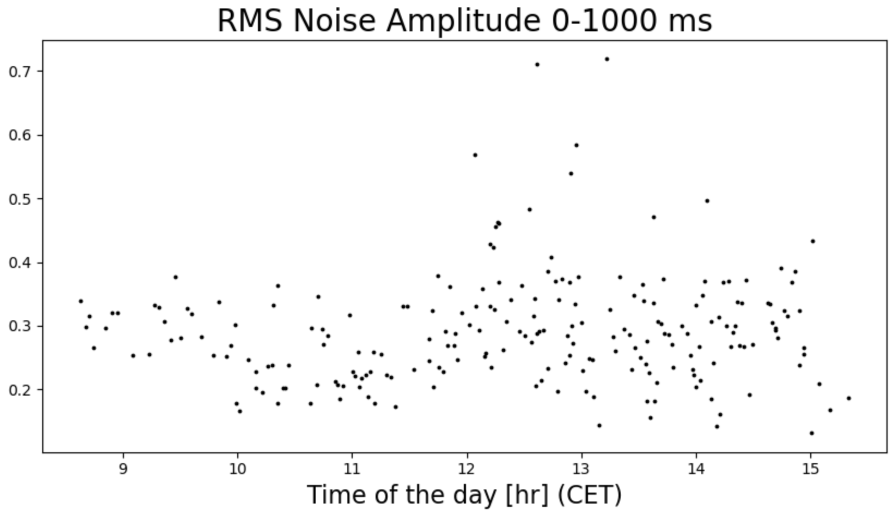


Figure 3.1.7.5: The noise in the shot domain plotted against the time of the day at which the shots were recorded.

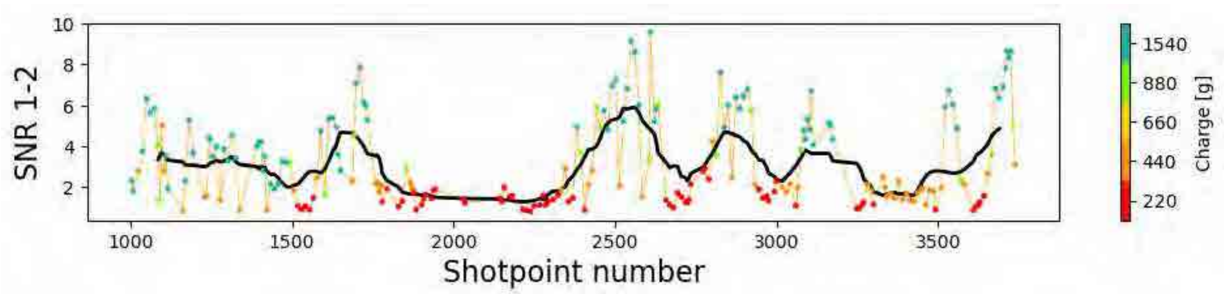


Figure 3.1.7.6: The SNR in the 1-2 second window with a charge size indicator. The black line is the moving average computed with a range of 15 data points.

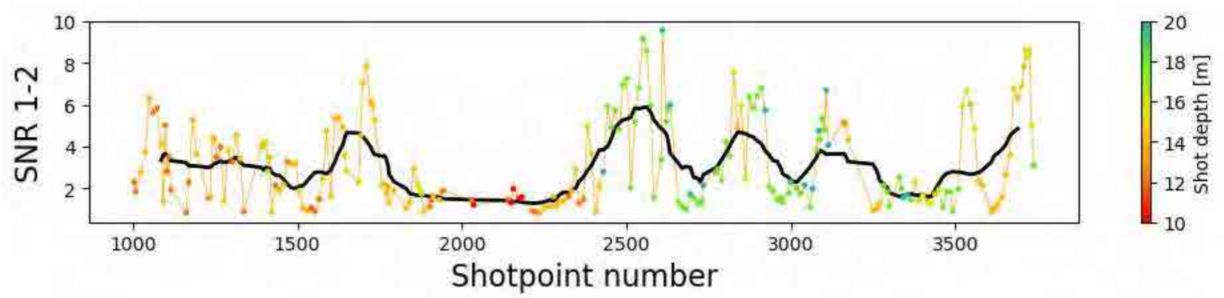


Figure 3.1.7.7: The SNR in the 1-2 second window with a shot depth indicator. The black line is the moving average computed with a range of 15 data points.

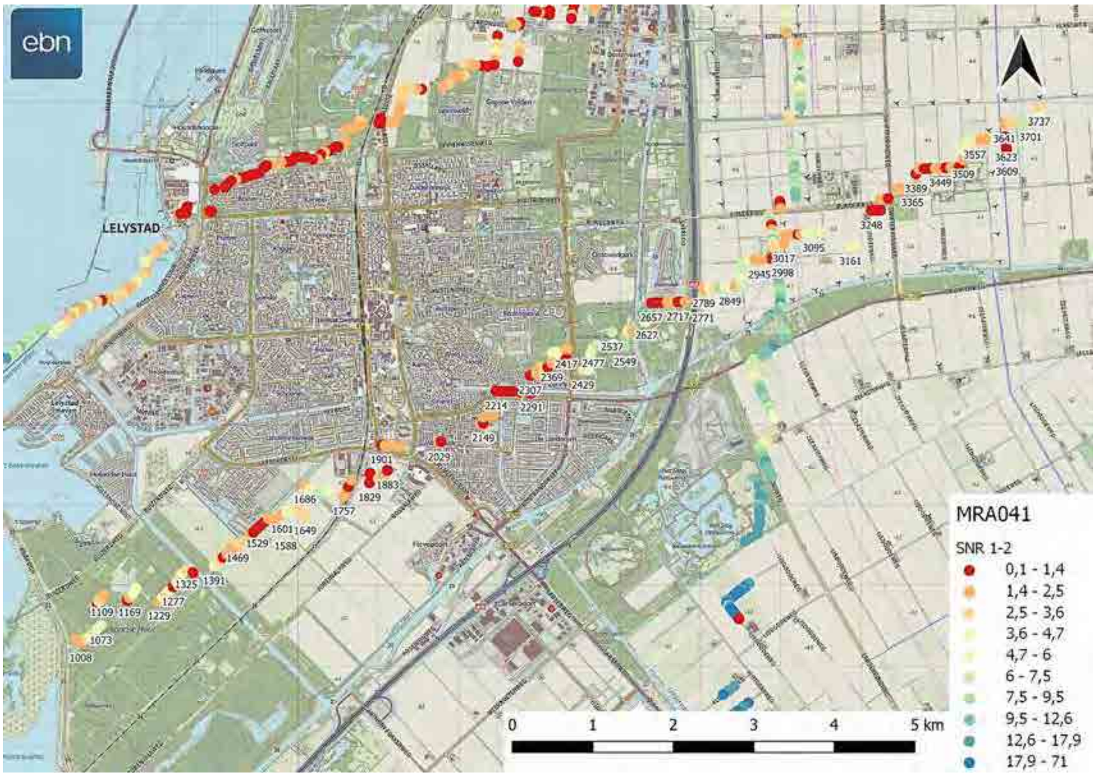


Figure 3.1.7.8: The SNR 1-2 value plotted along the line. The colour of the shot points indicate the quality of the shot, from bad (red) to good (blue). This colour range is divided into 10 segments which are based on the occurrence of the data points along all lines. The red dots therefore indicate that those shots belong to the worst 10 % of all the shots.

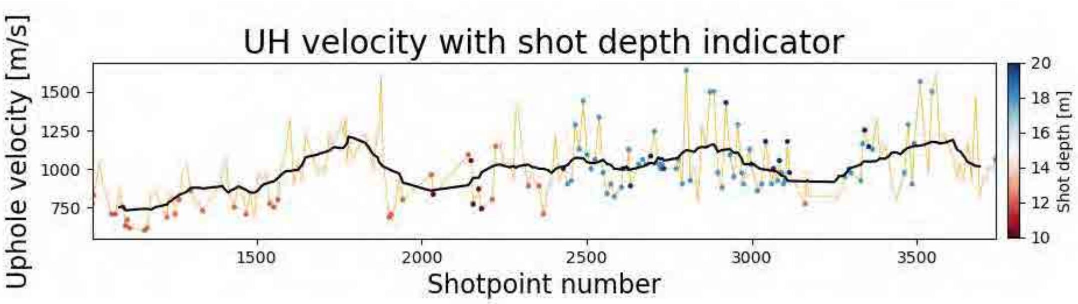


Figure 3.1.7.9: The uphole velocity along the line.

Receiver domain:

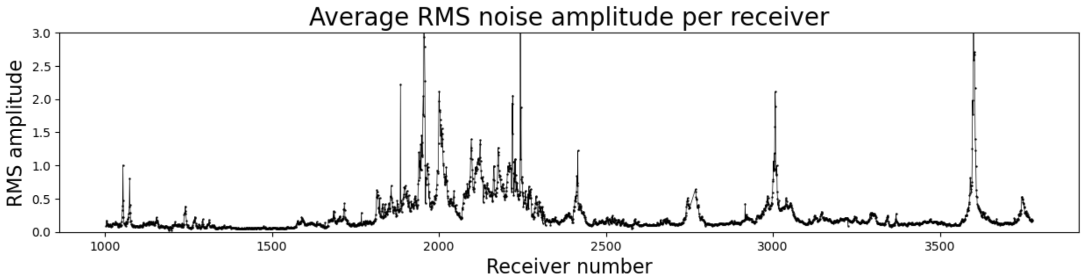


Figure 3.1.7.10: The noise per receiver.

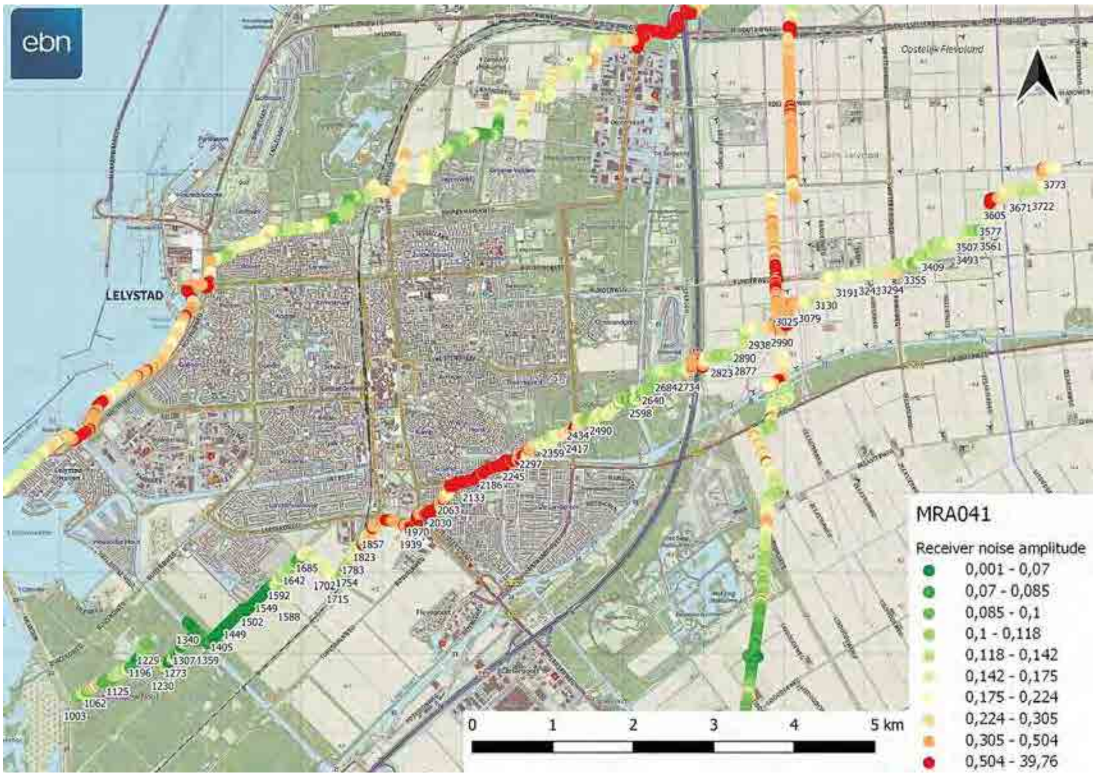


Figure 3.1.7.11: The noise per receiver visualized along the line. The color scale is based on the data of all the receiver data, showing noise relative to the other data points.

3.1.8 SCAN042

Line SCAN042 starts in the Eemmeer and runs with a NNE-SSW orientation through the Noordoostpolder. As a significant part of this region is used for agriculture, the concentration of buildings is low allowing the placement of high charges. With an average charge size of 1067 grams per shot, SCAN042 is far above the average charge size used for all the lines. In combination with the lack of ambient noise present due to the relatively uninhabited area, this led to line SCAN042 to have the highest quality data of all the lines.

Acquisition length	22.96 km
Number of receivers	4225 (1001-5593)
Of which hydrophones	146
Number of shots	395 (1009.5-5585.5)
Of which in water	59
Skipped shots	4.1%
Skipped receivers	8.0%
Date recorded	08/06/2021 - 14/06/2021

Table 3.8: Acquisition parameters of line SCAN042

Interestingly, the guided waves which were visible on the end of line MRA041 are mostly absent in this line. Possible factors influencing this could be the precipitation levels in the period before and during the shooting. This line was shot during dry and sunny weather, where during the acquisition of line MRA041 there was a lot of rainfall.

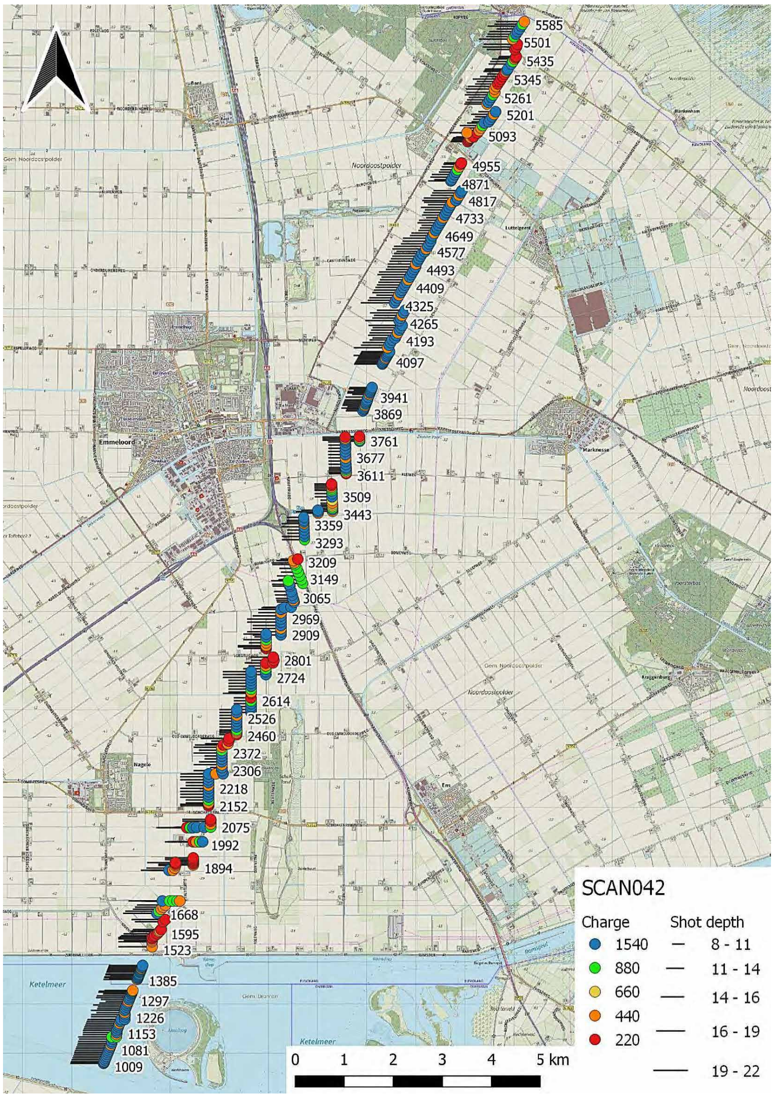


Figure 3.1.8.1: Acquisition parameters of line SCAN042.

General:

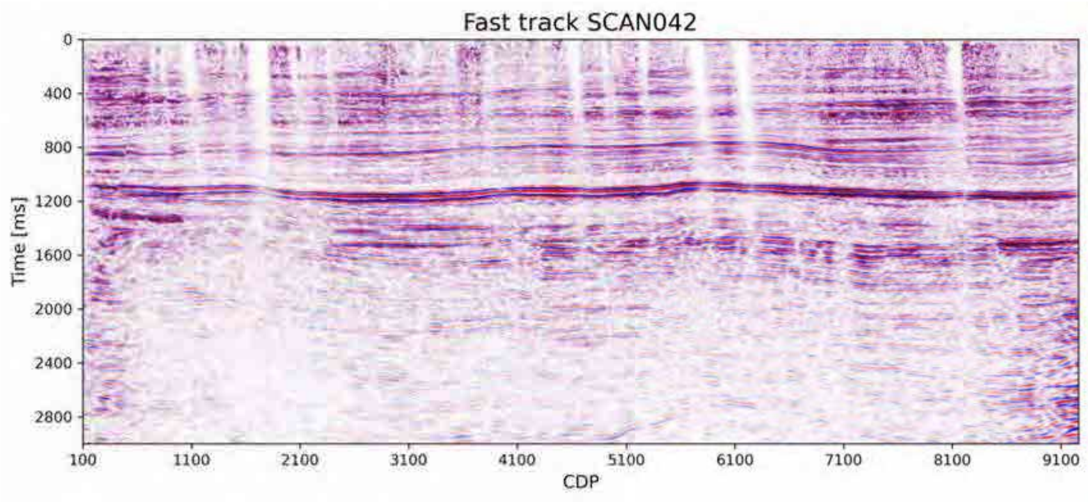


Figure 3.1.8.2: The fast track of line SCAN042.

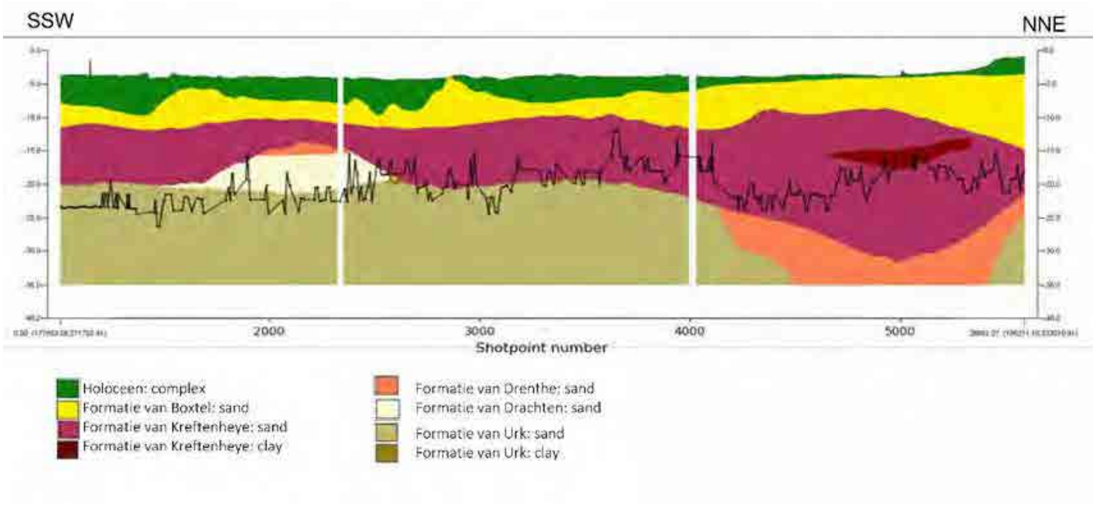


Figure 3.1.8.3: The geological profile of line SCAN042.

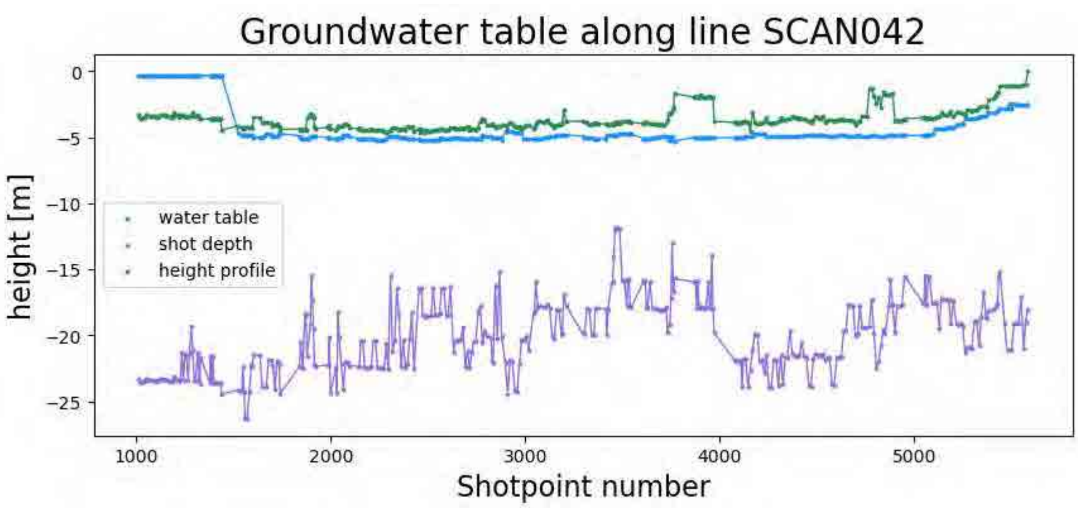


Figure 3.1.8.4: The water table along line SCAN042. All shots are located below the water table.

Shot domain:

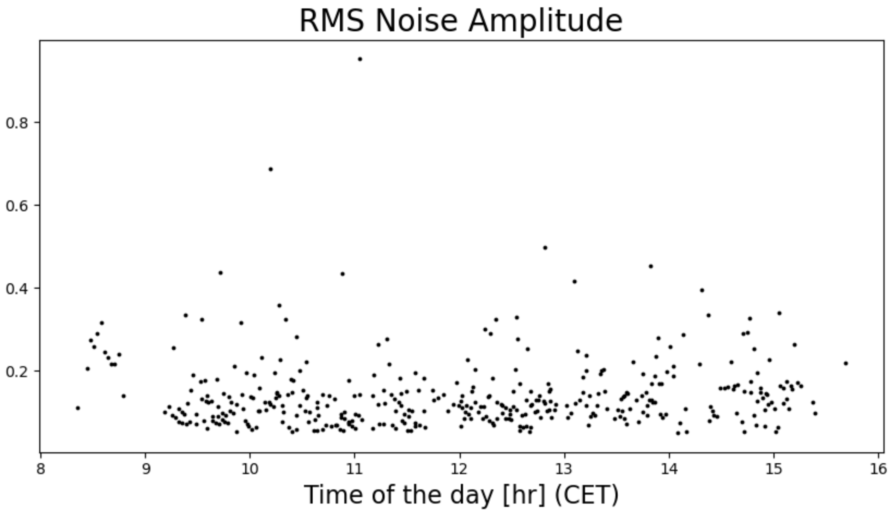


Figure 3.1.8.5: The noise in the shot domain plotted against the time of the day at which the shots were recorded.

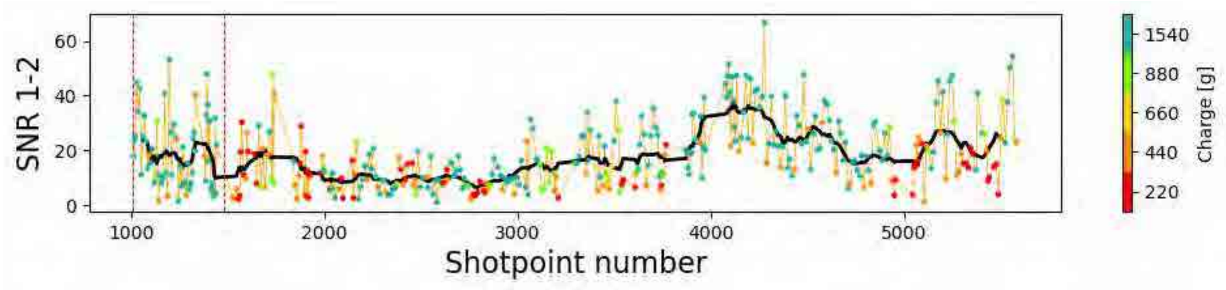


Figure 3.1.8.6: The SNR in the 1-2 second window with a charge size indicator. The black line is the moving average computed with a range of 15 data points. The red dashed lines indicate the hydrophone region.

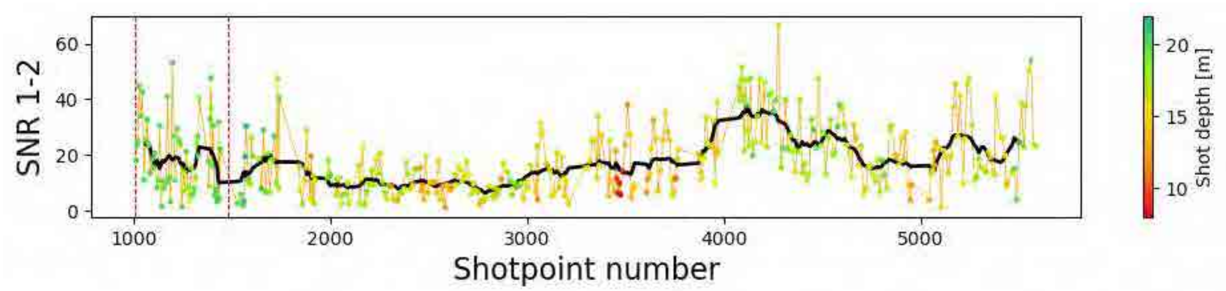


Figure 3.1.8.7: The SNR in the 1-2 second window with a shot depth indicator. The black line is the moving average computed with a range of 15 data points. The red dashed lines indicate the hydrophone region.

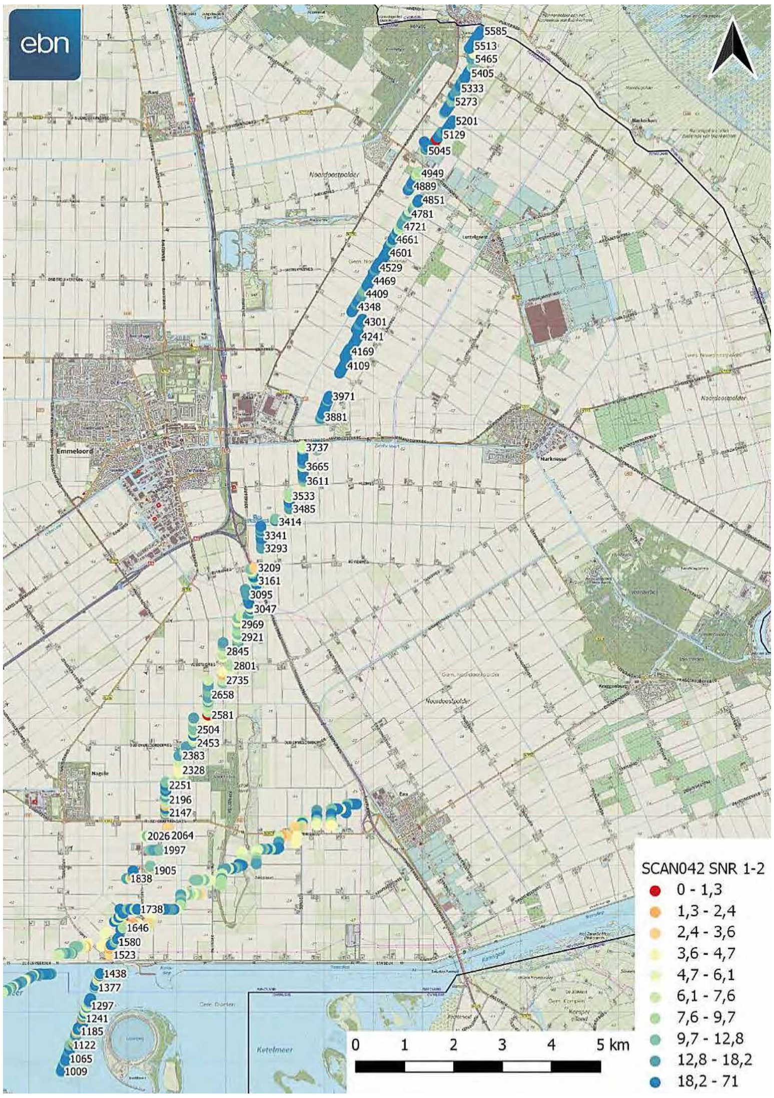


Figure 3.1.8.8: The SNR 1-2 value plotted along the line. The colour of the shot points indicate the quality of the shot, from bad (red) to good (blue). This colour range is divided into 10 segments which are based on the occurrence of the data points along all lines. The red dots therefore indicate that those shots belong to the worst 10 % of all the shots.

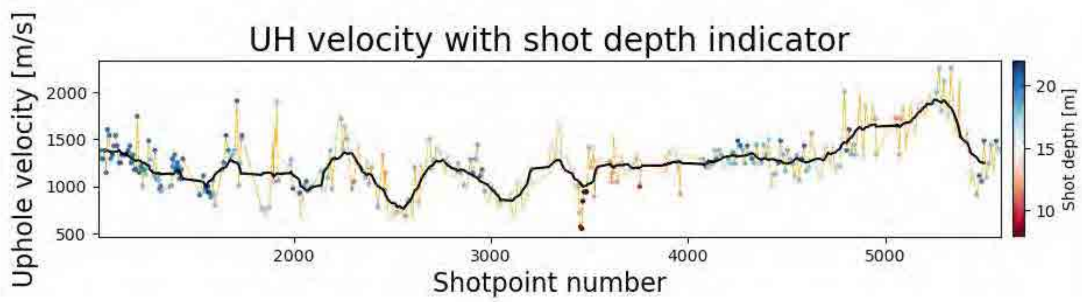


Figure 3.1.8.9: The uphole velocity along the line.

Receiver domain:

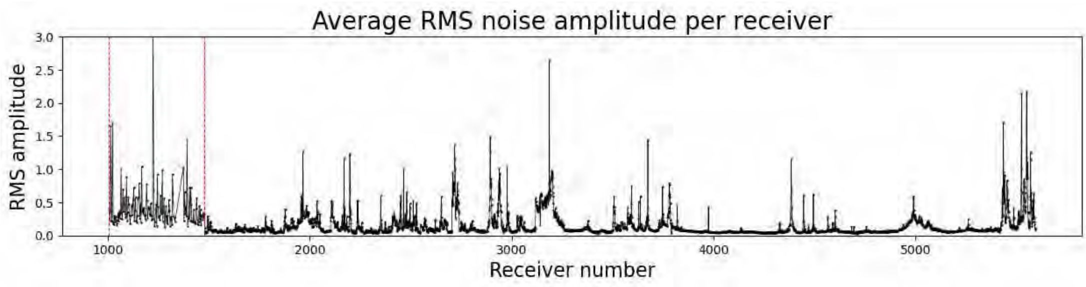


Figure 3.1.8.10: The noise per receiver. The red dashed lines indicate the hydrophone region.

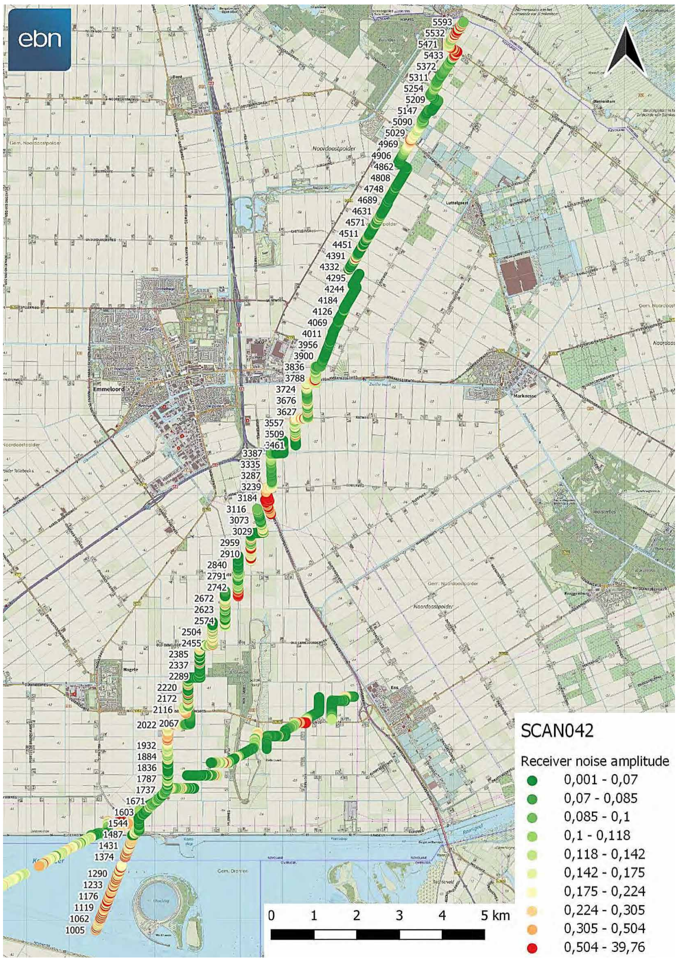


Figure 3.1.8.11: The noise per receiver visualized along the line. The color scale is based on the data of all the receiver data, showing noise relative to the other data points.

3.1.9 SCAN043

Line SCAN043 runs in Brabant from Velddriel, through Oss and finished around Malden with an E-W orientation. All shots were placed on land and below the water table. The line contained a faulty receiver, which was removed before further processing. The average shot depth was above average, while the average charge placed was a bit below average.

The data quality of the line is quite decent. There is one patch where the receivers were placed parallel to the highway which is responsible for the peak in receiver noise as seen in Figure 3.1.9.10. Line SCAN043 was shot in combination with line SCAN049. The method of wide-line acquisition, as previously touched upon in the method section, was applied to gain an additional subsurface line in between the 2D lines.

Acquisition length	37.98 km
Number of receivers	7405 (1001-8596)
Number of shots	611 (1013.5-8585.5)
Skipped shots	3.5%
Skipped receivers	2.5%
Date recorded	07/10/2021 - 26/10/2021

Table 3.9: Acquisition parameters of line SCAN043

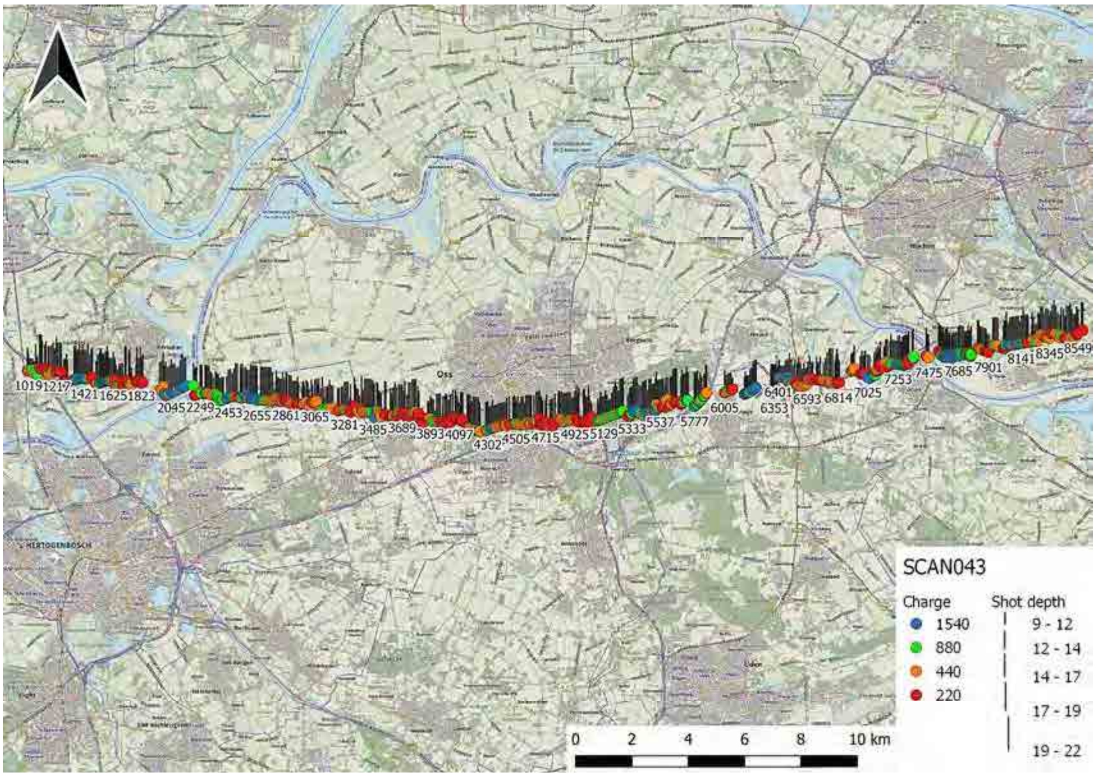


Figure 3.1.9.1: Acquisition parameters of line SCAN043.

General:

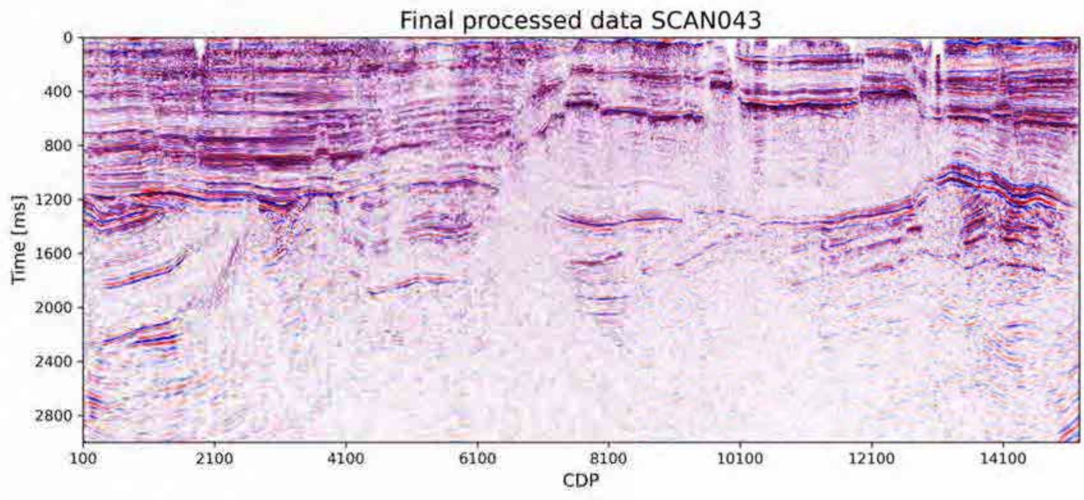


Figure 3.1.9.2: The final full section of line SCAN043.

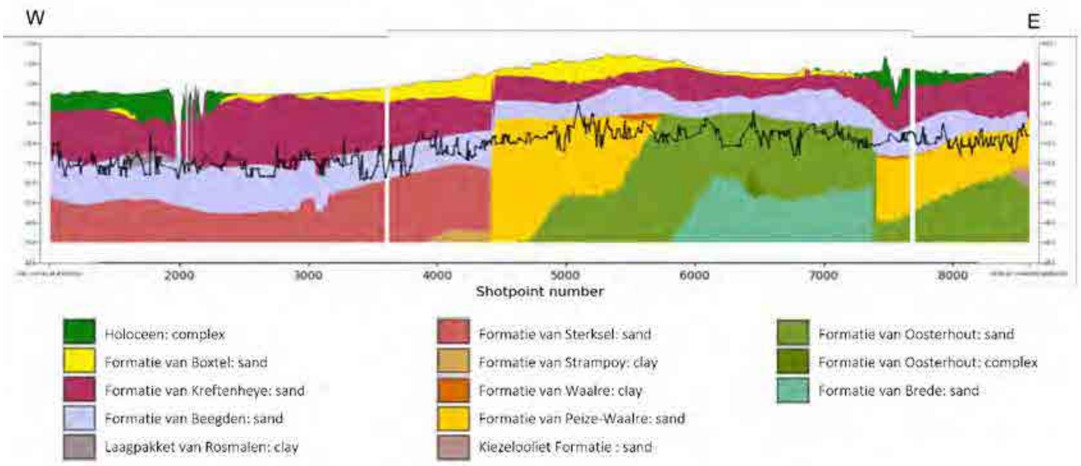


Figure 3.1.9.3: The geological profile of line SCAN043. The left side is in the west and the right in the east.

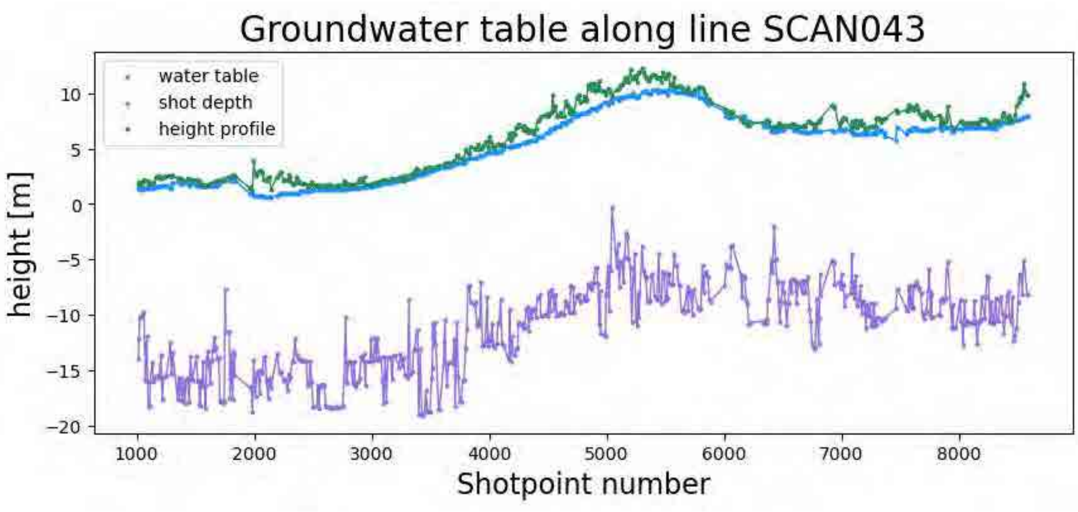


Figure 3.1.9.4: The water table along line SCAN043. All shots are located below the water table.

Shot domain:

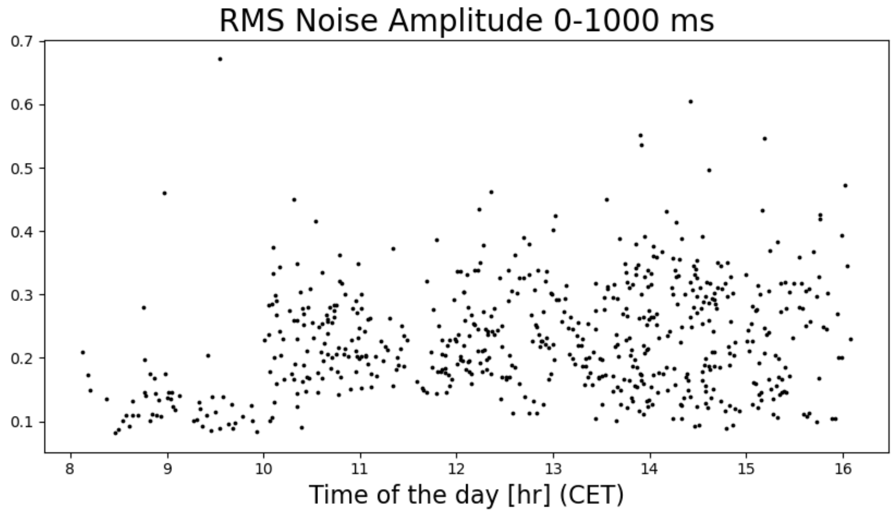


Figure 3.1.9.5: The noise in the shot domain plotted against the time of the day at which the shots were recorded.

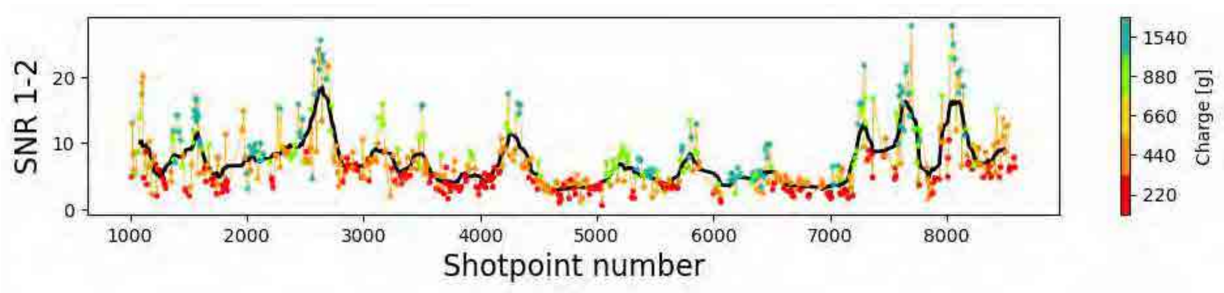


Figure 3.1.9.6: The SNR in the 1-2 second window with a charge size indicator. The black line is the moving average computed with a range of 15 data points.

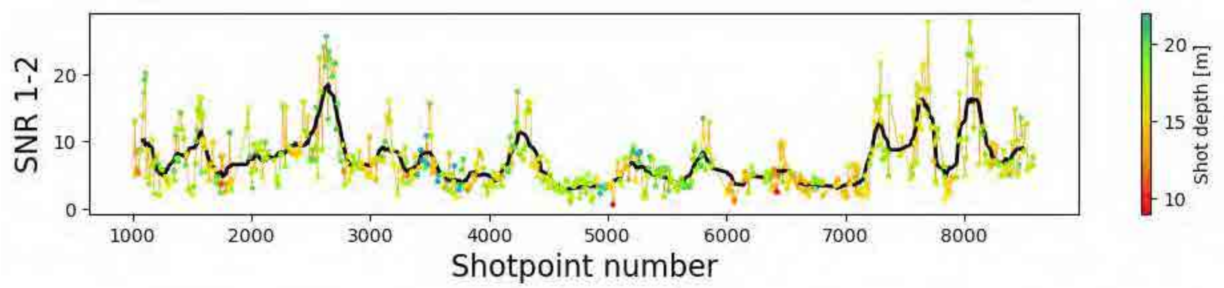


Figure 3.1.9.7: The SNR in the 1-2 second window with a shot depth indicator. The black line is the moving average computed with a range of 15 data points.

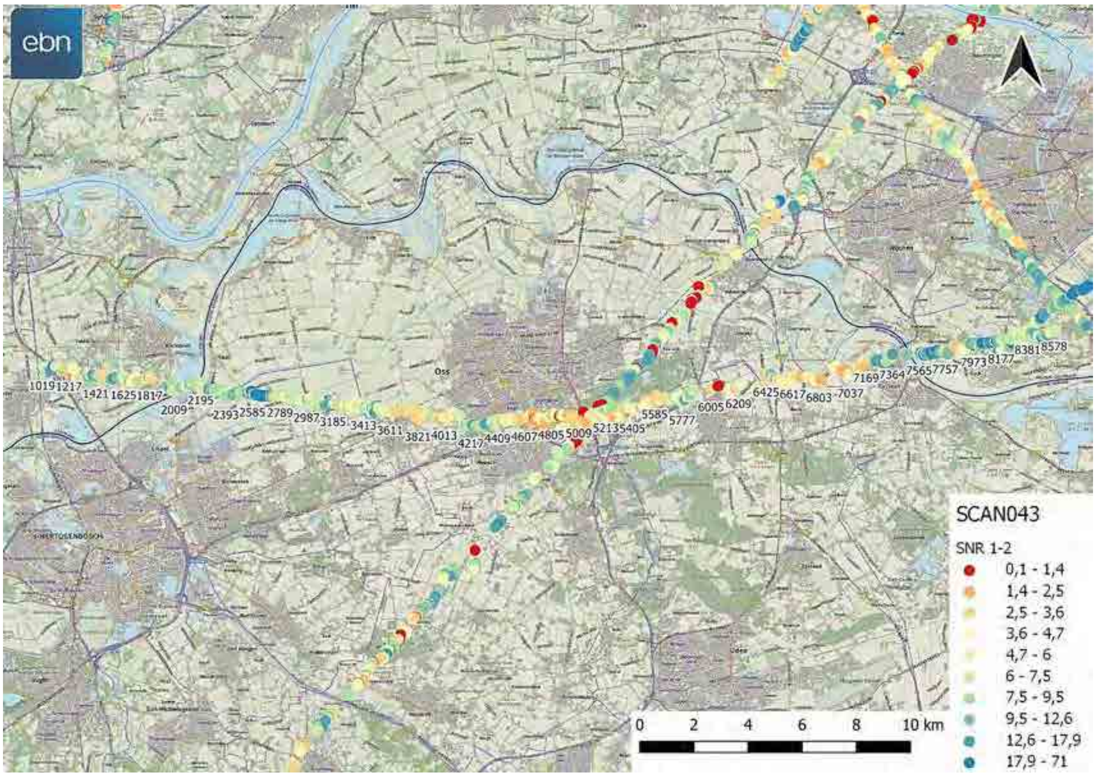


Figure 3.1.9.8: The SNR 1-2 value plotted along the line. The colour of the shot points indicate the quality of the shot, from bad (red) to good (blue). This colour range is divided into 10 segments which are based on the occurrence of the data points along all lines. The red dots therefore indicate that those shots belong to the worst 10 % of all the shots.

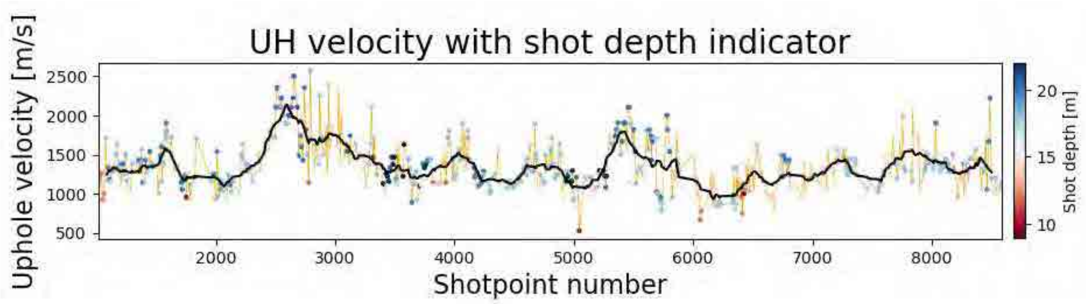


Figure 3.1.9.9: The uphole velocity along the line.

Receiver domain:

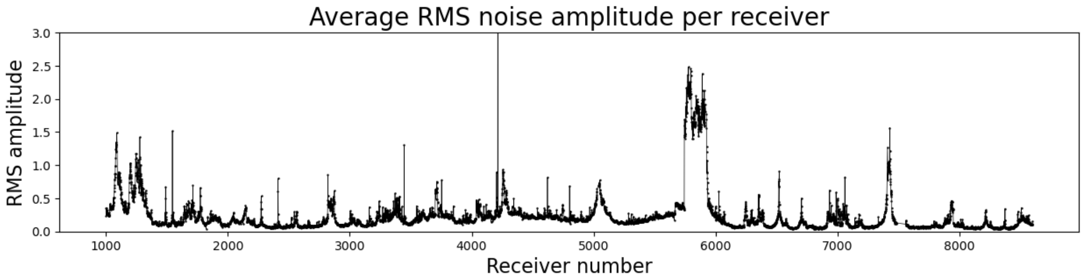


Figure 3.1.9.10: The noise per receiver. The peak around 5800 is caused by the presence of a road.

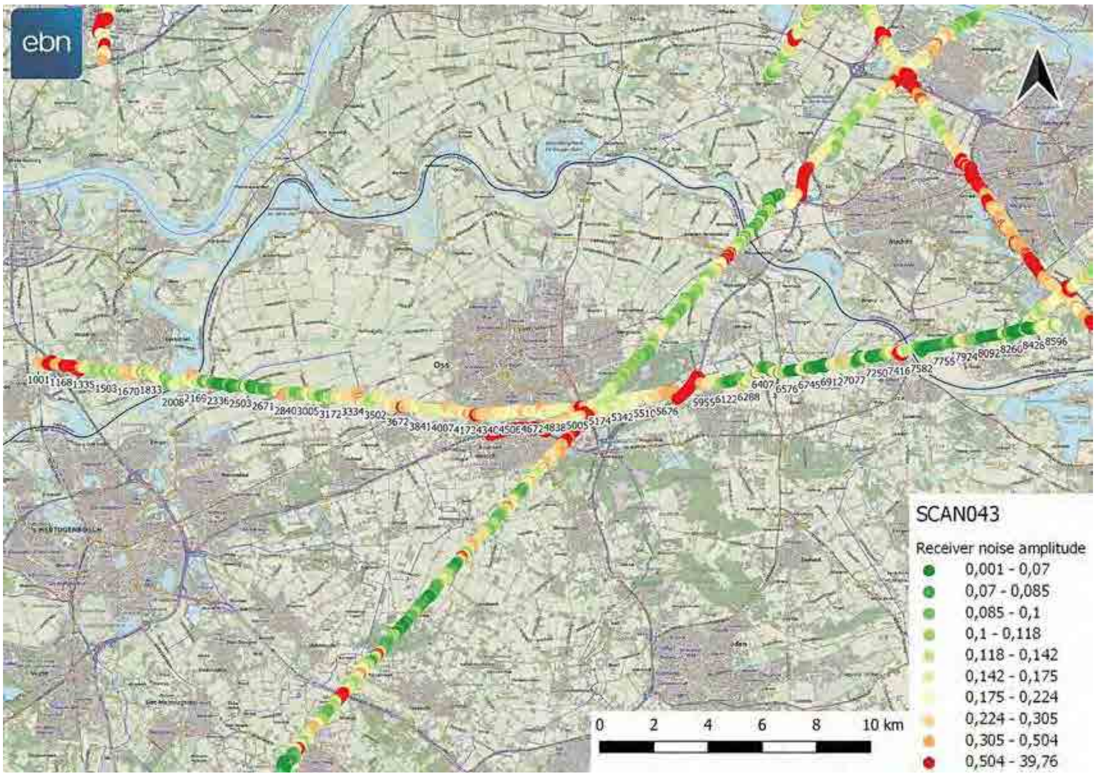


Figure 3.1.9.11: The noise per receiver visualized along the line. The color scale is based on the data of all the receiver data, showing noise relative to the other data points.

3.1.10 SCAN049

Line SCAN049 was shot in combination with line SCAN043 for wide-line acquisition and runs slightly south of it. While the placed shots were relatively deep, the average charge size used was quite low. All the shots were placed well below the water table. In the western part of the line, the receivers were placed parallel to the highway A59 and before that the line crosses the provincial road of the N239. These external factors were responsible for high noise levels along the line, the fifth highest of all the analyzed lines. This has led to a general low quality of the field data of the line.

Acquisition length	5.42 km
Number of receivers	1083 (1001-2083)
Number of shots	61 (1109.5-1937.5)
Skipped shots	14.1%
Skipped receivers	1.5 %
Date recorded	27/10/2021

Table 3.10: Acquisition parameters of line SCAN049

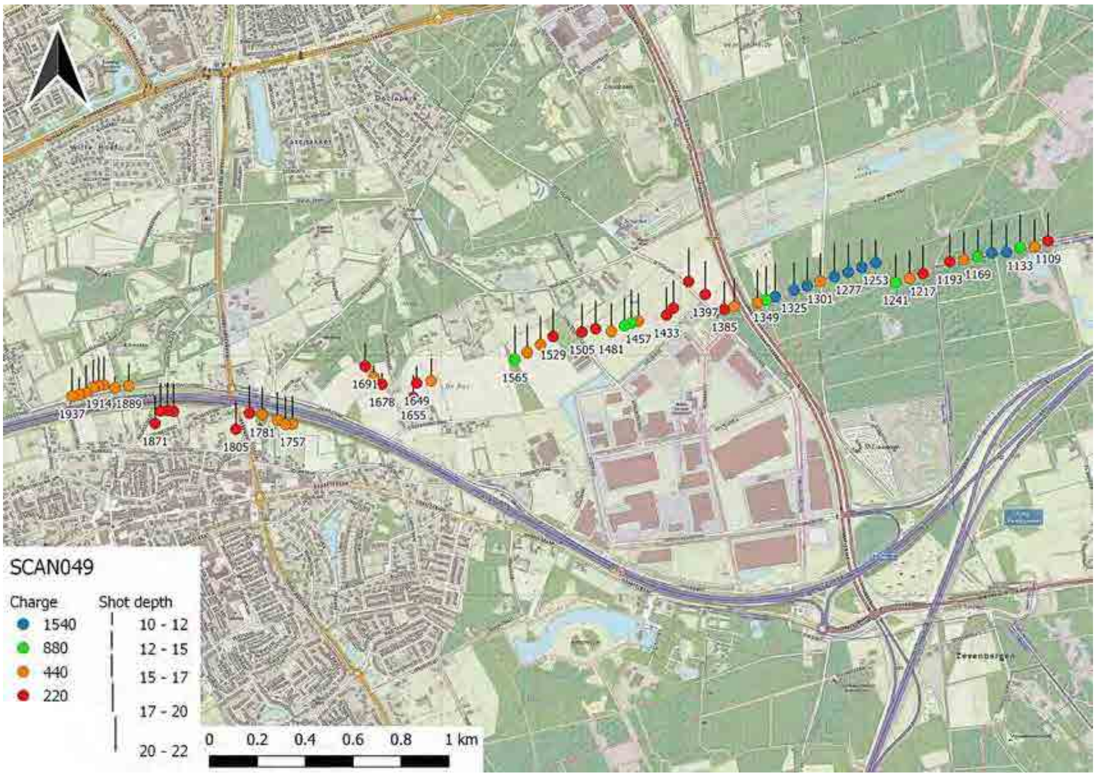


Figure 3.1.10.1: Acquisition parameters of line SCAN049.

General:

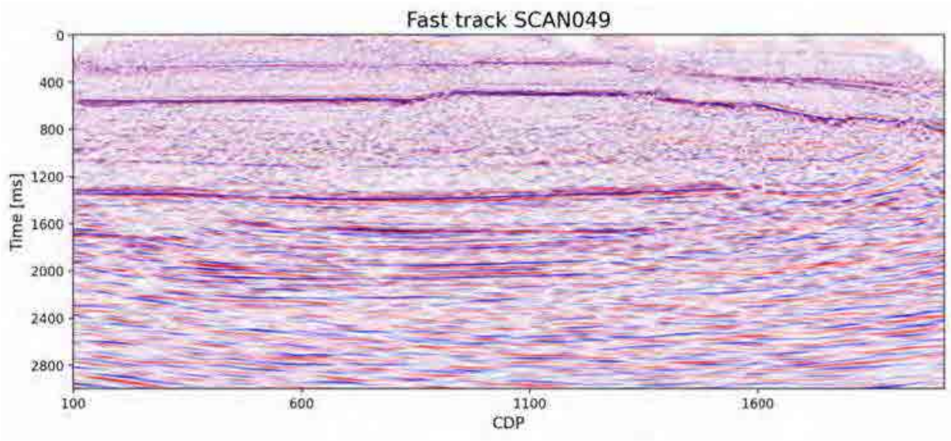


Figure 3.1.10.2: The fast track of line SCAN049.

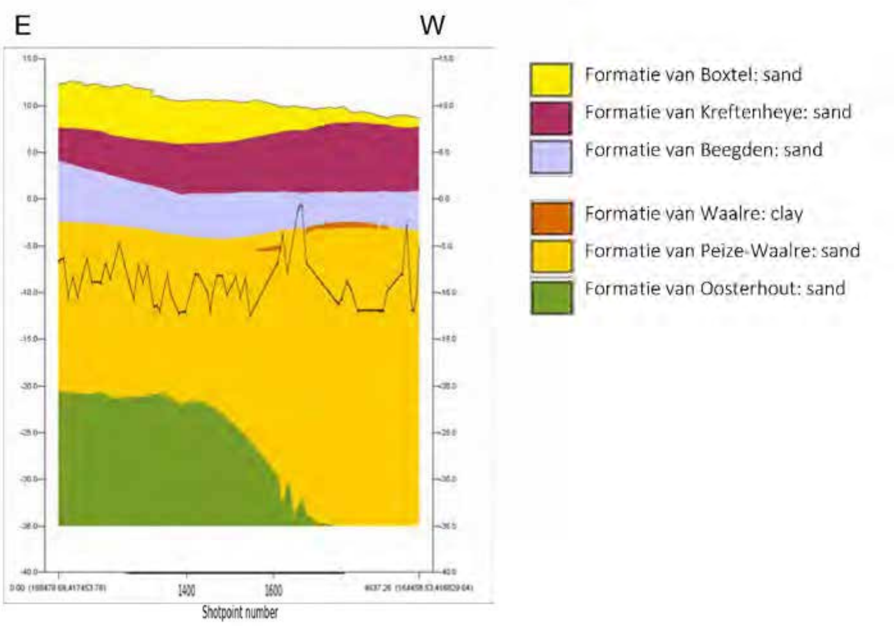


Figure 3.1.10.3: The geological profile of line SCAN049. The left is the east and right the west.

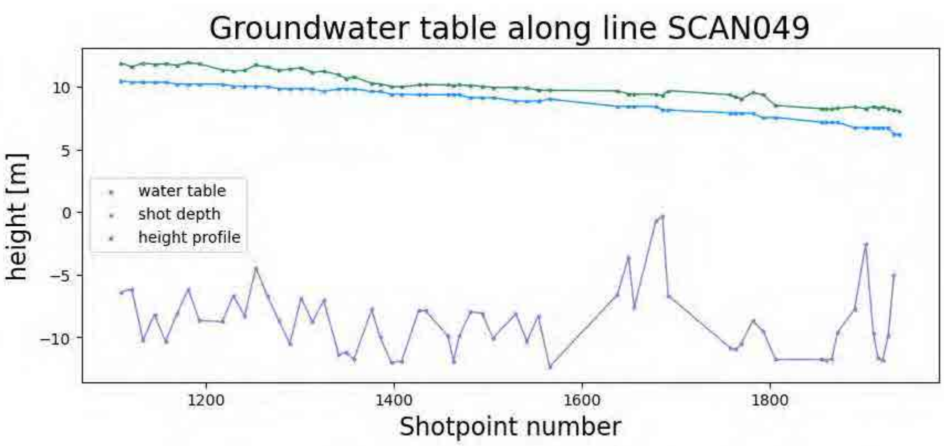


Figure 3.1.10.4: The water table along line SCAN049.

Shot domain:

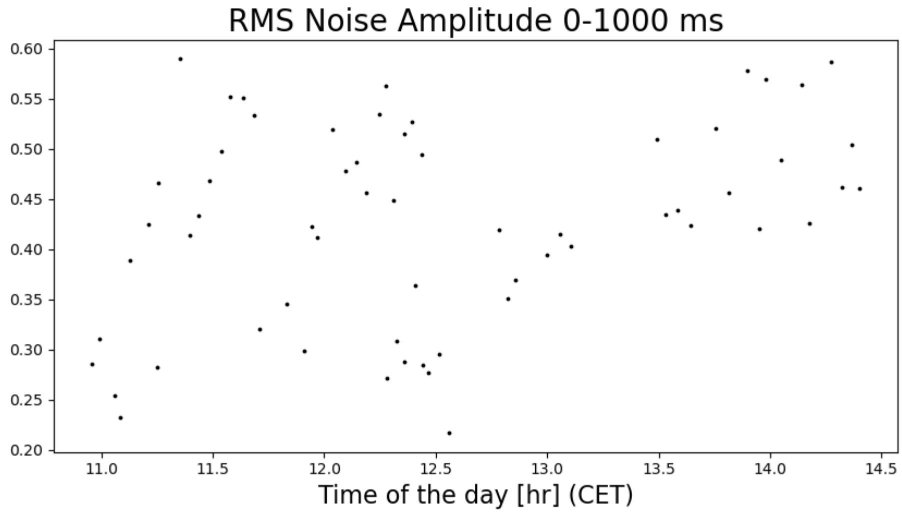


Figure 3.1.10.5: The noise in the shot domain plotted against the time of the day at which the shots were recorded.

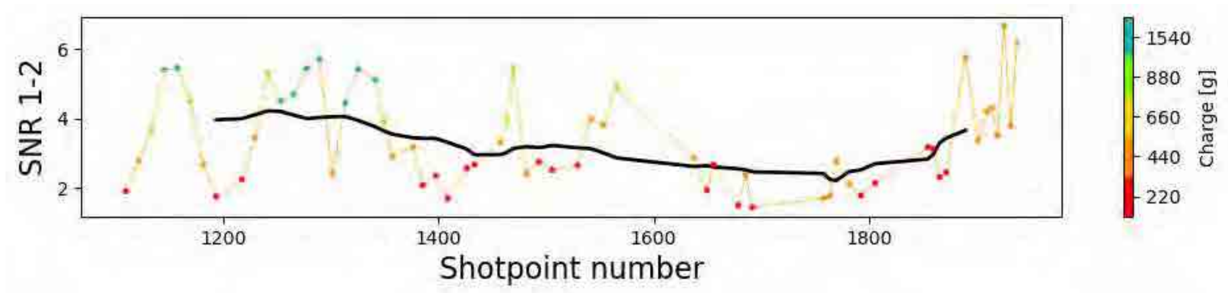


Figure 3.1.10.6: The SNR in the 1-2 second window with a charge size indicator. The black line is the moving average computed with a range of 15 data points.

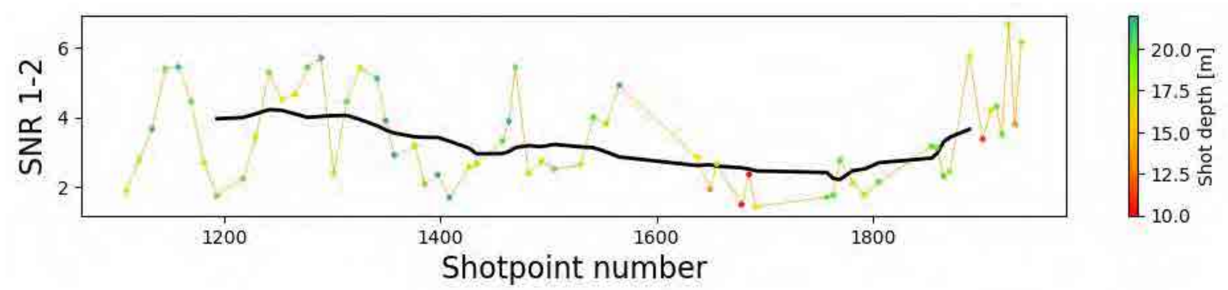


Figure 3.1.10.7: The SNR in the 1-2 second window with a shot depth indicator. The black line is the moving average computed with a range of 15 data points.

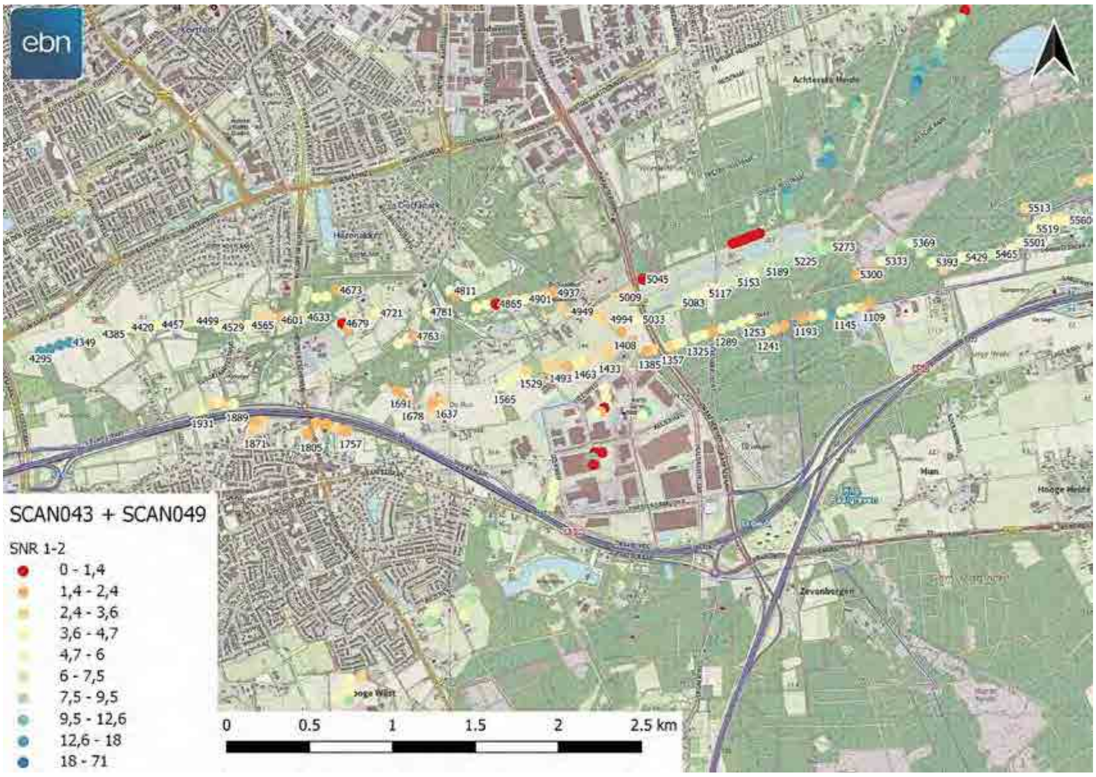


Figure 3.1.10.8: The SNR 1-2 value plotted along the line. The figure also includes line SCAN043. The colour of the shot points indicate the quality of the shot, from bad (red) to good (blue). This colour range is divided into 10 segments which are based on the occurrence of the data points along all lines. The red dots therefore indicate that those shots belong to the worst 10 % of all the shots.

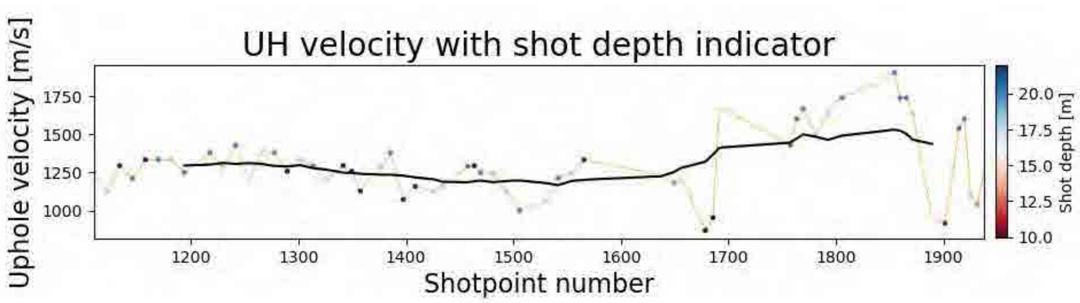


Figure 3.1.10.9: The uphole velocity along the line.

Receiver domain:

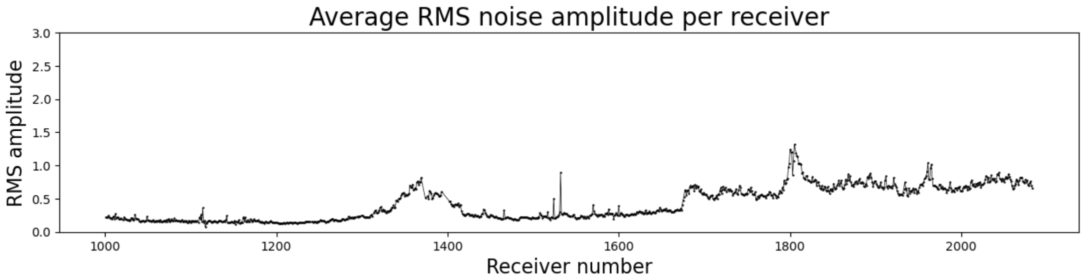


Figure 3.1.10.10: The noise per receiver. Note that the orientation of the station numbers is switched when compared to the map below.

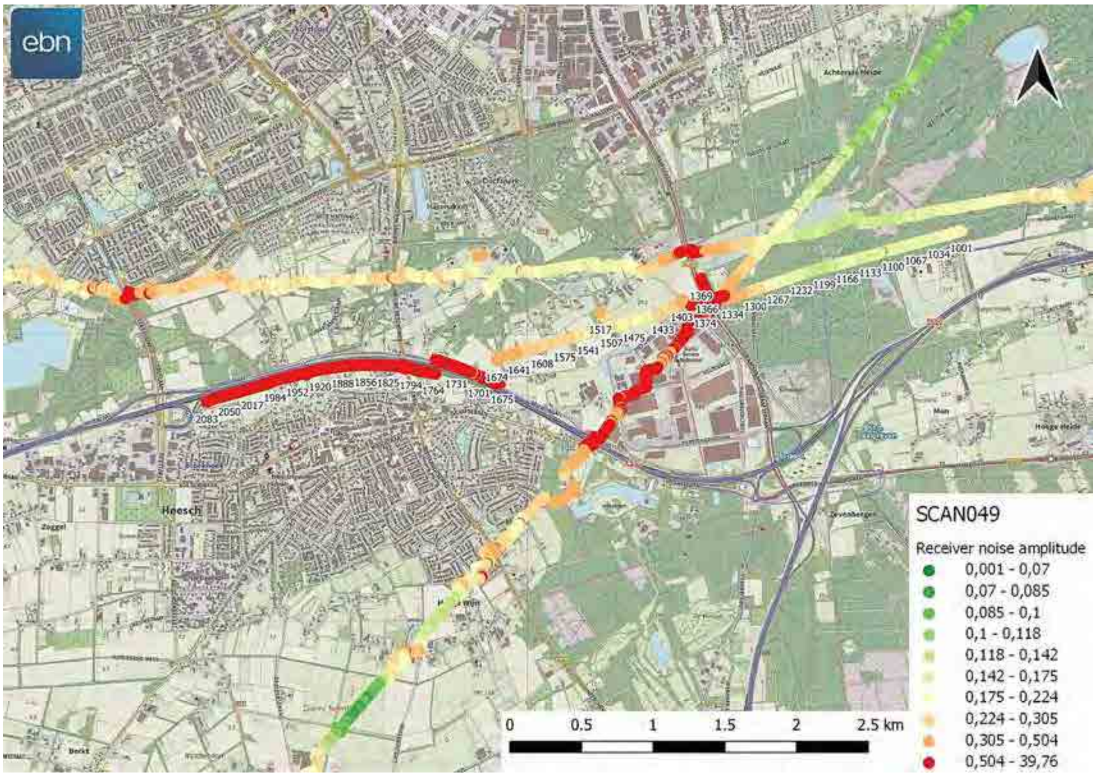


Figure 3.1.10.11: The noise per receiver visualized along the line. The color scale is based on the data of all the receiver data, showing noise relative to the other data points. Note that the station numbering is from right to left, unlike the other lines.

3.1.11 SCAN044

Line SCAN044 was shot in combination with line SCAN045 for the construction of a cross-spread acquisition. This allows one to generate a 3D image of the region where the two lines intersect based on data of 2D lines. It runs from Veenendaal to Wolfheze with an E-W orientation. Between station number 2400-2900 the line crosses a push moraine, causing the shots to be located above the water table.

Acquisition length	14.69 km
Number of receivers	2728 (1001-3928)
Number of shots	251 (1006.5-3892.5)
Of which valid	237
Skipped shots	2.4%
Skipped receivers	3.6%
Date recorded	27/09/2021 - 07/10/2021

Table 3.11: Acquisition parameters of line SCAN044

It is worth noting that there were 14 shots for which the boombox was not calibrated well. This resulted in signals from different shots to overlap. For the last shots on the line, these shots were drilled again and retaken. However, there were two shots located in the middle of the line where this was not done. All the shots containing overlap were not considered in our analysis as they would not coincide with the windows used for analyzing the data.

In general, the data quality of the line can be considered to be low. There is a lot of noise, especially between station numbers 1900 - 2600 where the receivers are placed next to the A12 and around 3300 where the receivers are in the vicinity of a train track. Furthermore, the impact of the placement of shots above the water table is immediately evident when studying Figure 3.1.11.6.

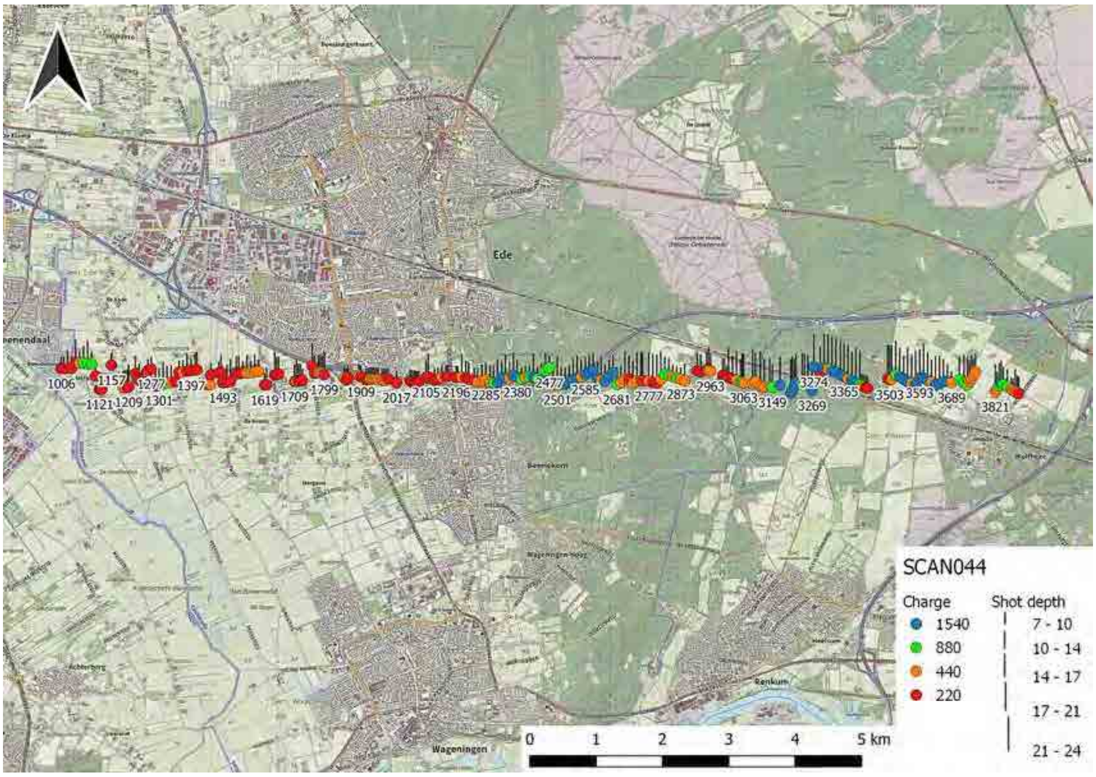


Figure 3.1.11.1: Acquisition parameters of line SCAN044.

General:

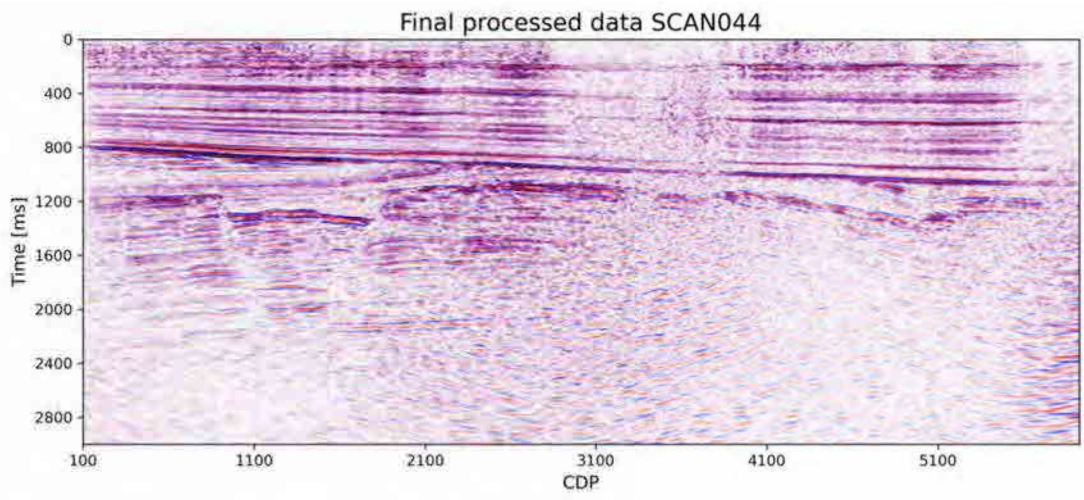


Figure 3.1.11.2: The final full section of line SCAN044.

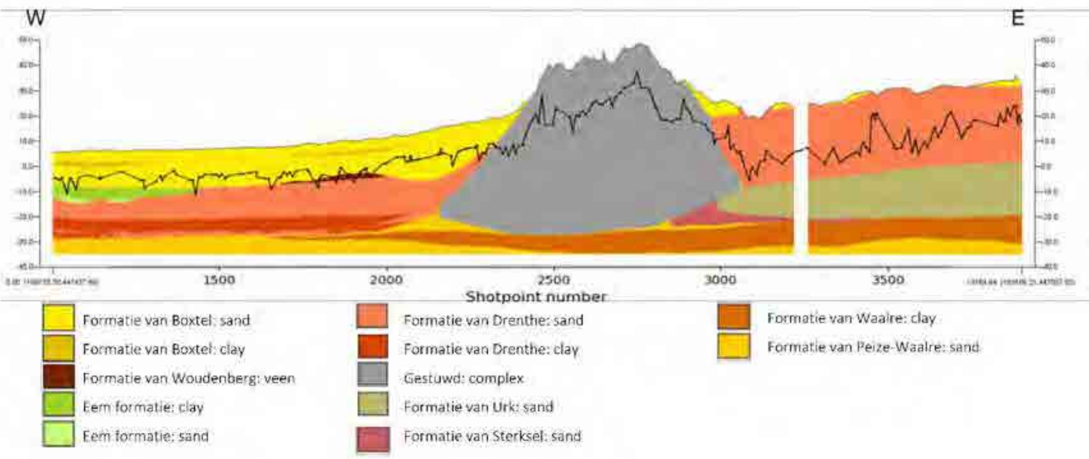


Figure 3.1.11.3: The geological profile of line SCAN044. Left is west, right is east.

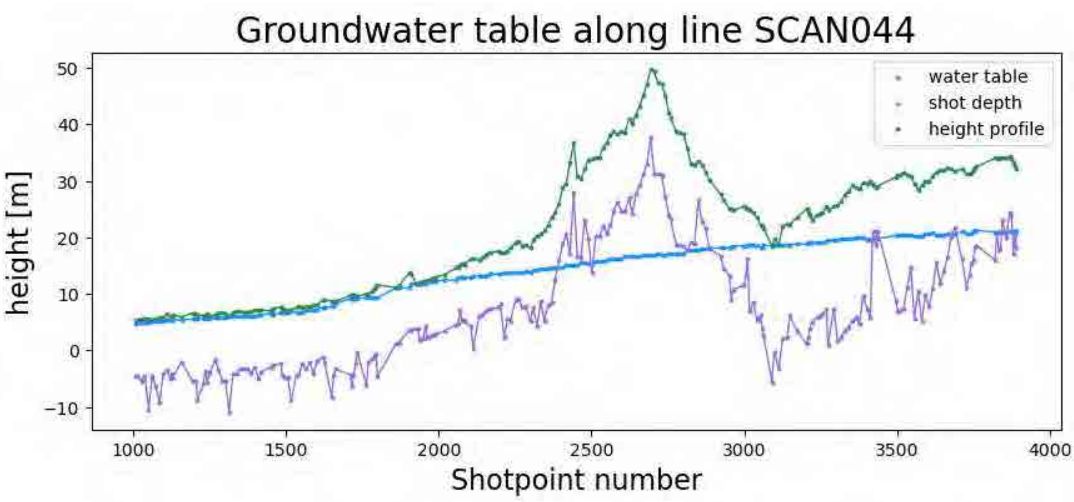


Figure 3.1.11.4: The water table along line SCAN044. Shots in the middle and at the end of the line are located above the water table.

Shot domain:

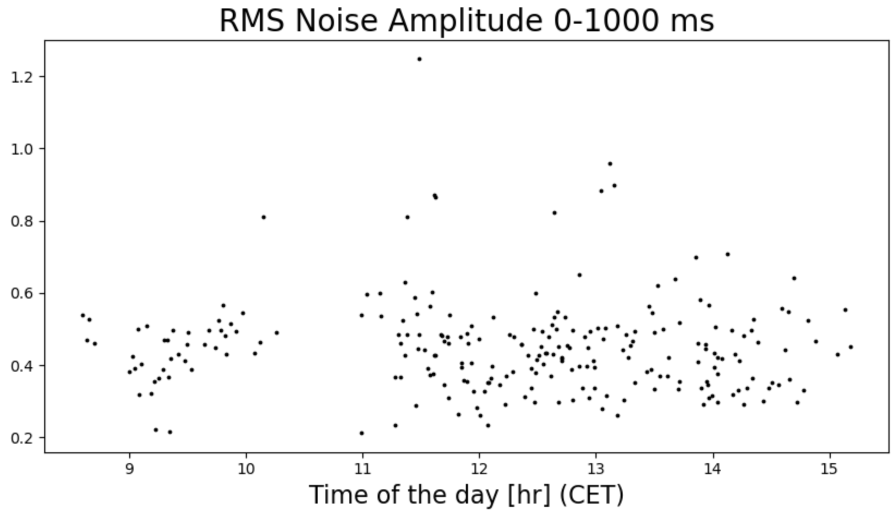


Figure 3.1.11.5: The noise in the shot domain plotted against the time of the day at which the shots were recorded.

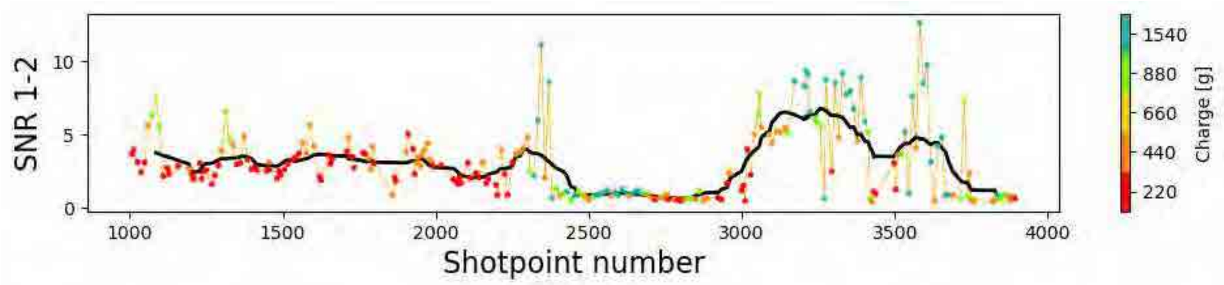


Figure 3.1.11.6: The SNR in the 1-2 second window with a charge size indicator. The black line is the moving average computed with a range of 15 data points.

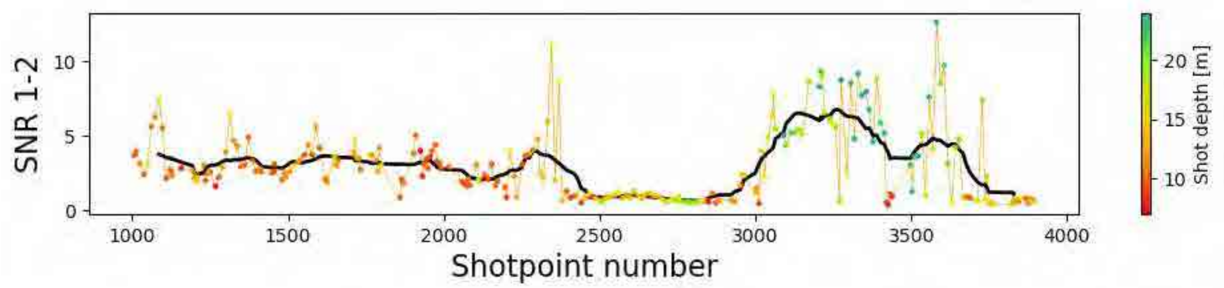


Figure 3.1.11.7: The SNR in the 1-2 second window with a shot depth indicator. The black line is the moving average computed with a range of 15 data points.

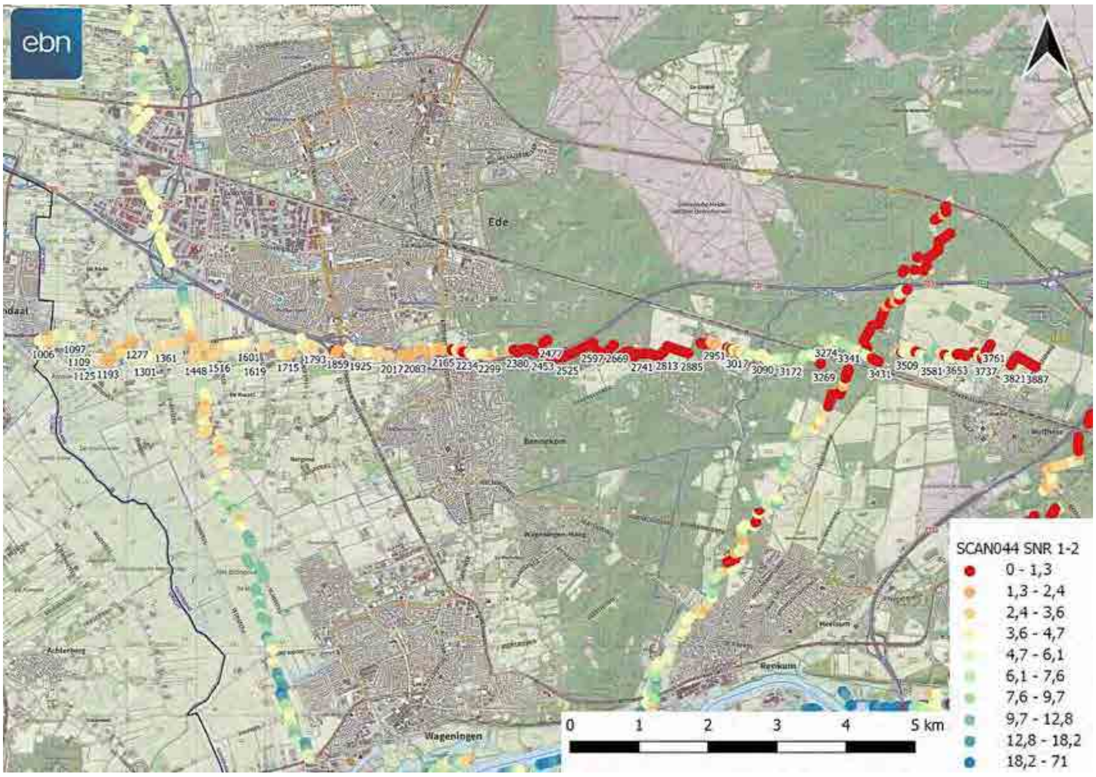


Figure 3.1.11.8: The SNR 1-2 value plotted along the line. The colour of the shot points indicate the quality of the shot, from bad (red) to good (blue). This colour range is divided into 10 segments which are based on the occurrence of the data points along all lines. The red dots therefore indicate that those shots belong to the worst 10 % of all the shots.

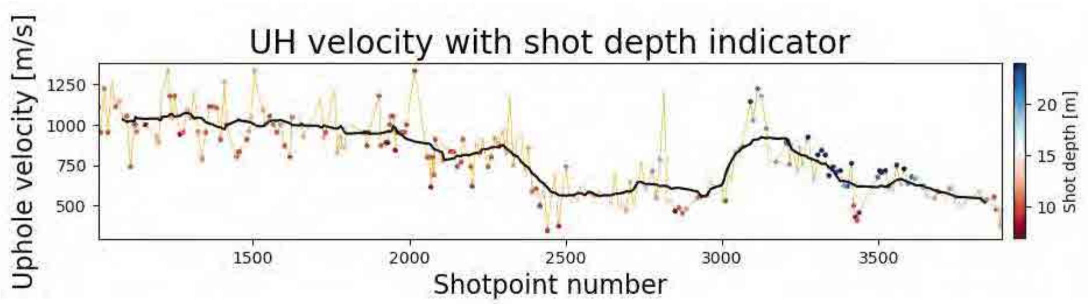


Figure 3.1.11.9: The uphole velocity along the line.

Receiver domain:

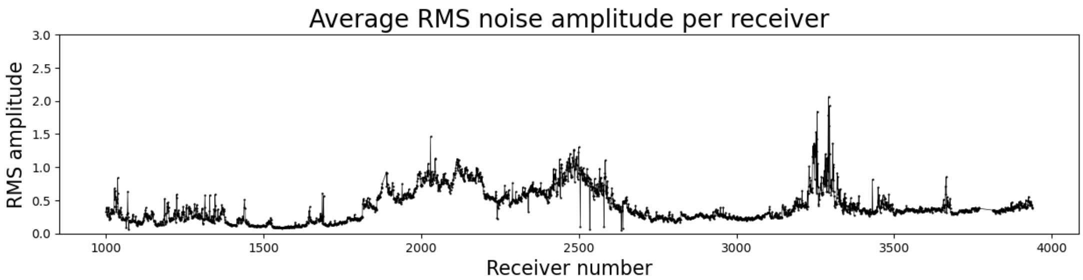


Figure 3.1.11.10: The noise per receiver.

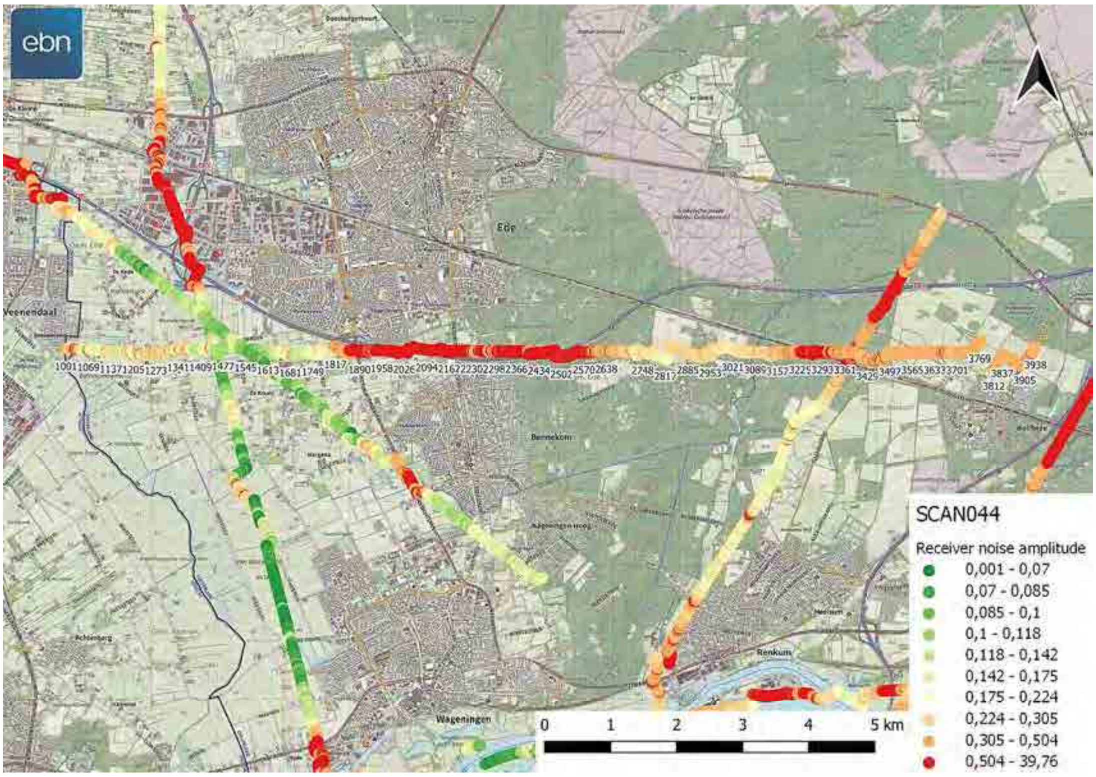


Figure 3.1.11.11: The noise per receiver visualized along the line. The color scale is based on the data of all the receiver data, showing noise relative to the other data points. The A12 is responsible for high noise levels around 2000-2500.

3.1.12 SCAN045

Line SCAN045 was shot in combination with line SCAN044 for the construction of a cross-spread acquisition. This allows one to generate a 3D image of the region based on data of 2D lines. The line runs between Woudenberg and Renkum with an NW-SE orientation. The southeast section of the line is in the vicinity of a push moraine. This causes the last few shots to be located above the water table, see Figure 3.1.12.4. The effect of their placement above the water table is apparent in the SNR value.

Acquisition length	25.42 km
Number of receivers	4996 (1001-6083)
Number of shots	380 (1001.5-6077.5)
Skipped shots	10.4%
Skipped receivers	1.7%
Date recorded	07/10/2021 - 14/10/2021

Table 3.12: Acquisition parameters of line SCAN045

The line has the lowest average charge size of all the lines in addition to one of the shallowest average depths. However, as the noise levels are generally quite low the quality of the line can still be considered to be average. The noisiest part of the line is situated above Veenendaal, when the receivers are placed parallel to the A12 highway.

Another thing which is noticeable about this line is the presence of a big gap in the data between station number 2765 and 3175. The line crossed several properties for which no agreement on land access could be reached, hence it was not possible to place any receivers or shots. A line of receivers was set at an offset parallel to the line, but a gap of about 2 kilometers between shot points was unavoidable. The effect of this data absence is visible in the final processing result (Figure 3.1.12.2), as a large gap in the section.

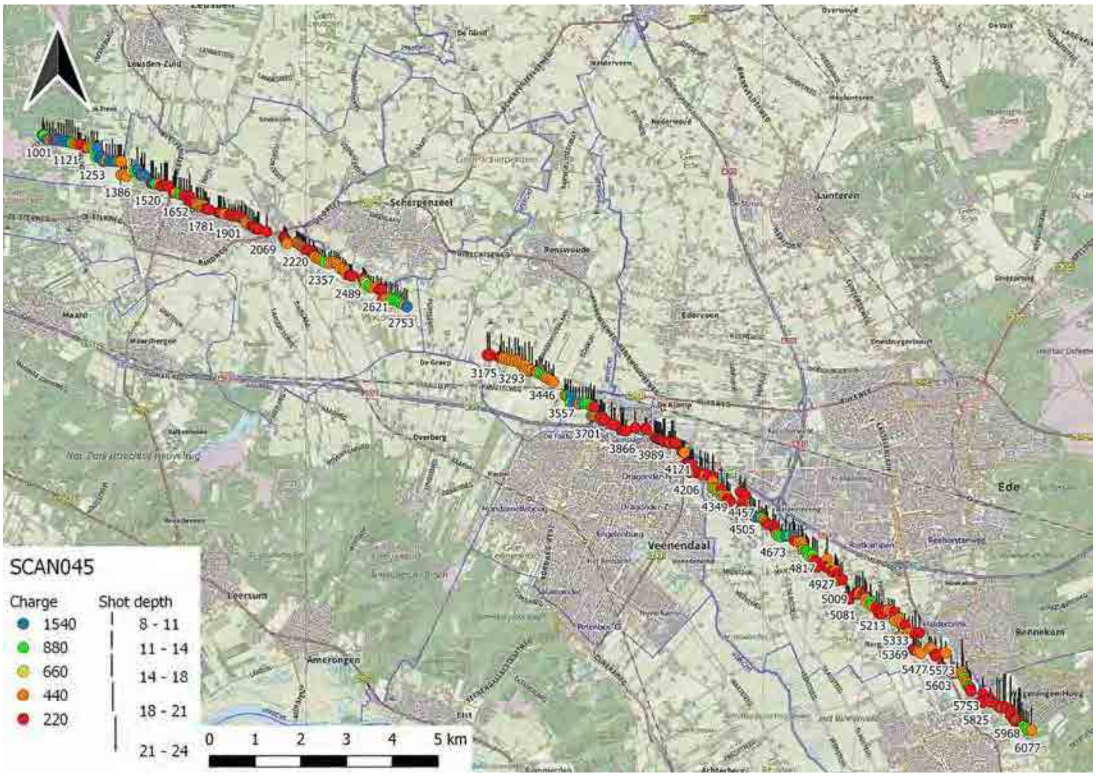


Figure 3.1.12.1: Acquisition parameters of line SCAN045.

General:

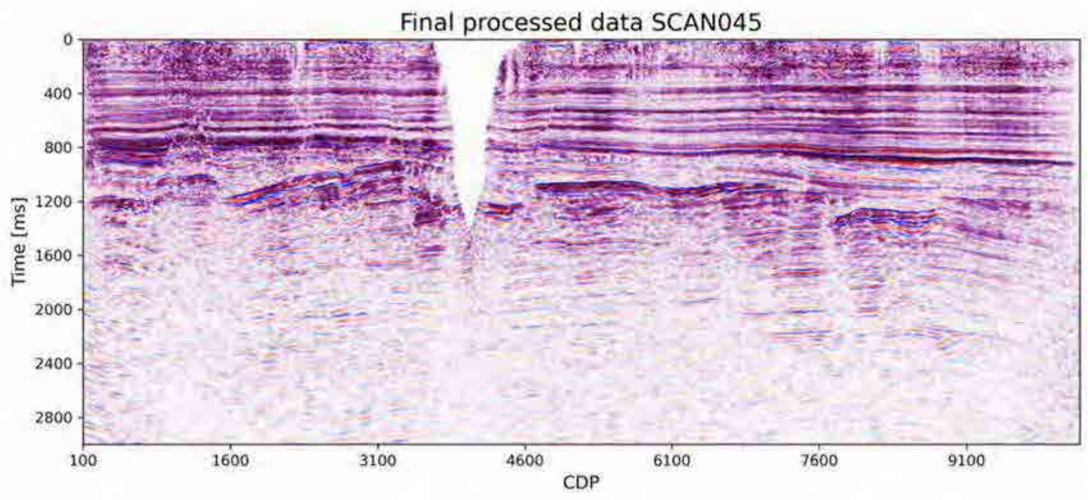


Figure 3.1.12.2: The final full section of line SCAN045.

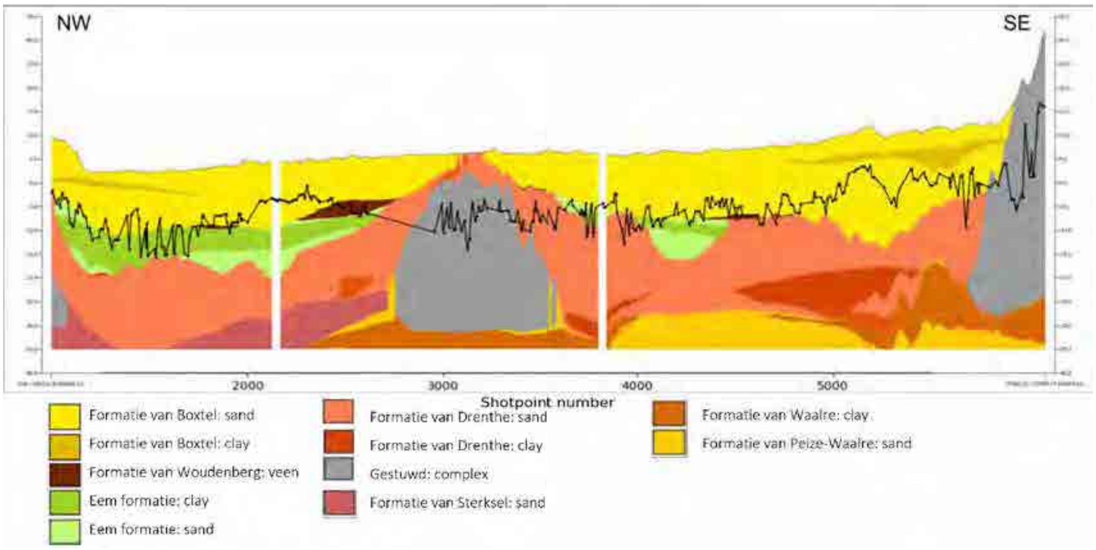


Figure 3.1.12.3: The geological profile of line SCAN045.

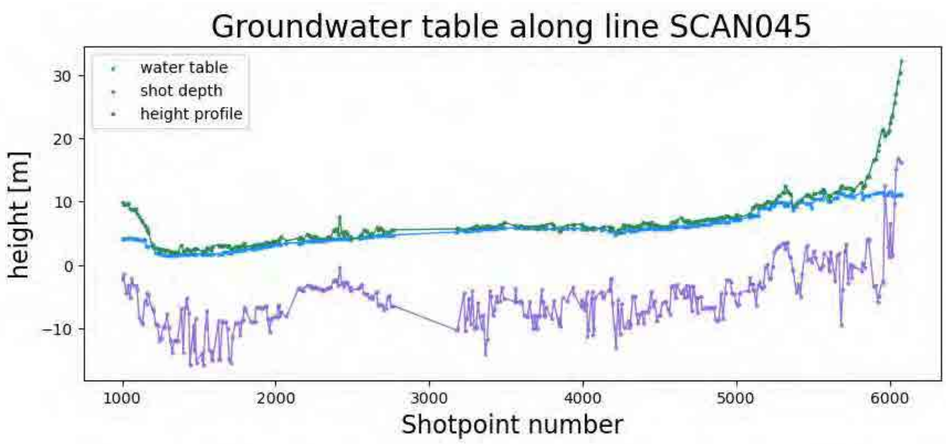


Figure 3.1.12.4: The water table along line SCAN045. A few shots at the end of the line are located above the water table.

Shot domain:

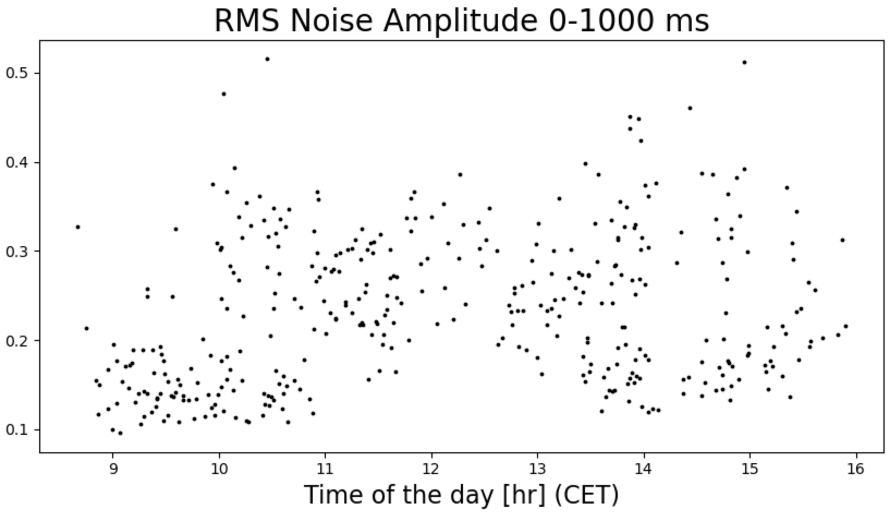


Figure 3.1.12.5: The noise in the shot domain plotted against the time of the day at which the shots were recorded.

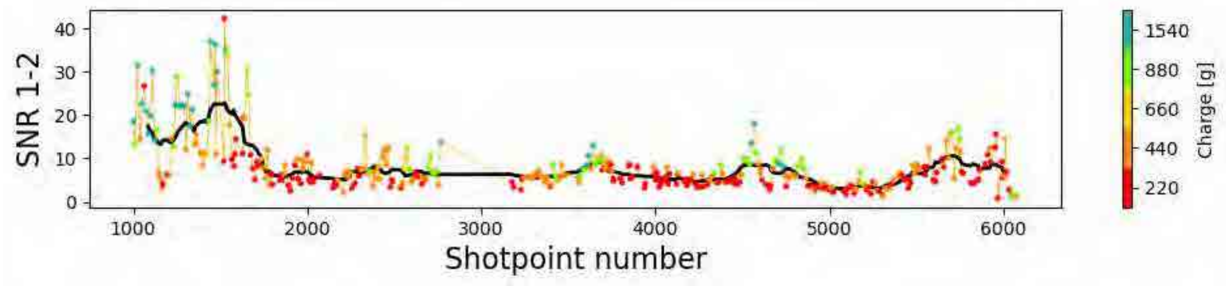


Figure 3.1.12.6: The SNR in the 1-2 second window with a charge size indicator. The black line is the moving average computed with a range of 15 data points.

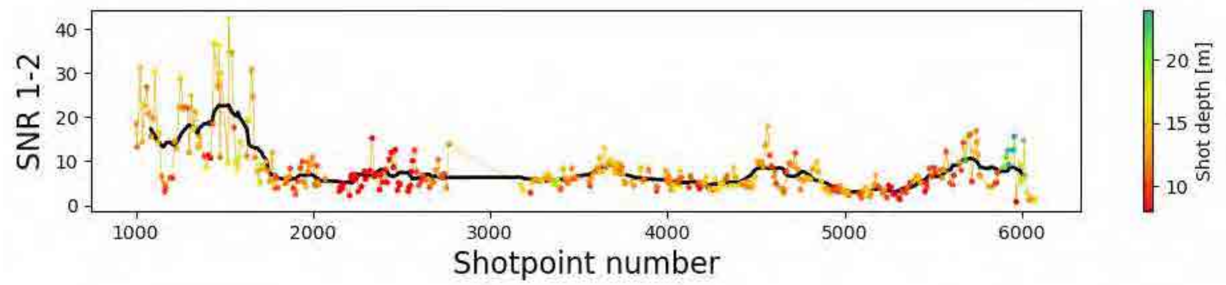


Figure 3.1.12.7: The SNR in the 1-2 second window with a shot depth indicator. The black line is the moving average computed with a range of 15 data points.

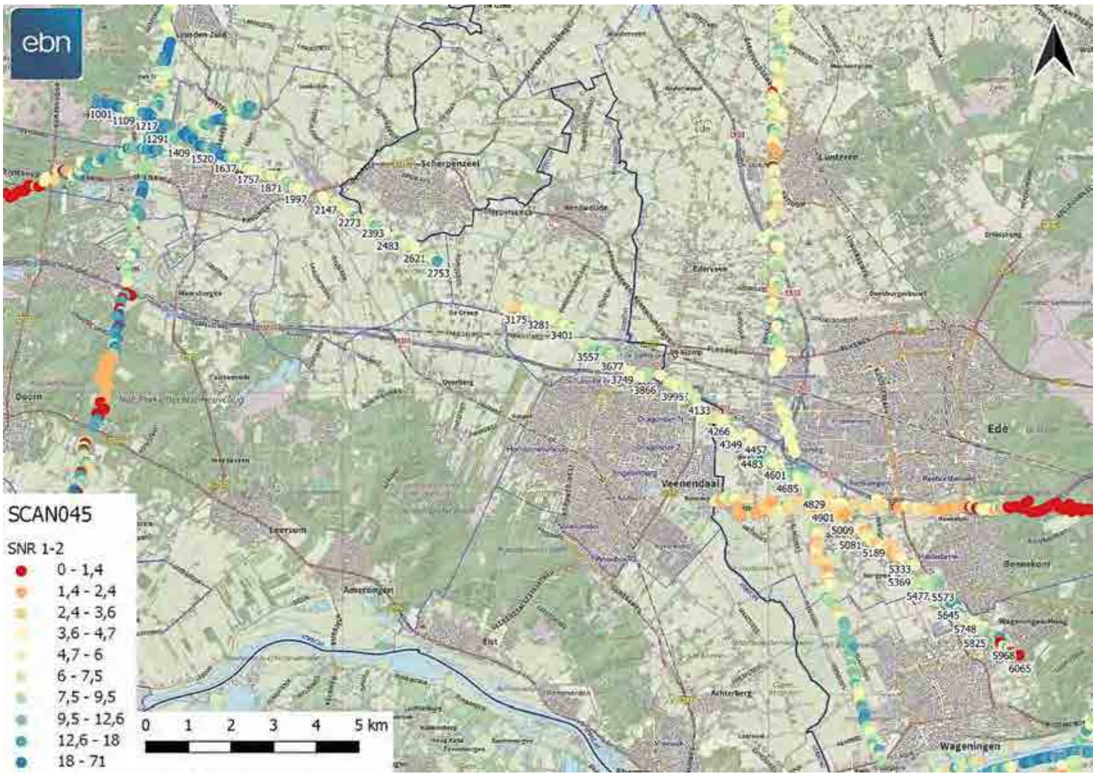


Figure 3.1.12.8: The SNR 1-2 value plotted along the line. The colour of the shot points indicate the quality of the shot, from bad (red) to good (blue). This colour range is divided into 10 segments which are based on the occurrence of the data points along all lines. The red dots therefore indicate that those shots belong to the worst 10 % of all the shots.

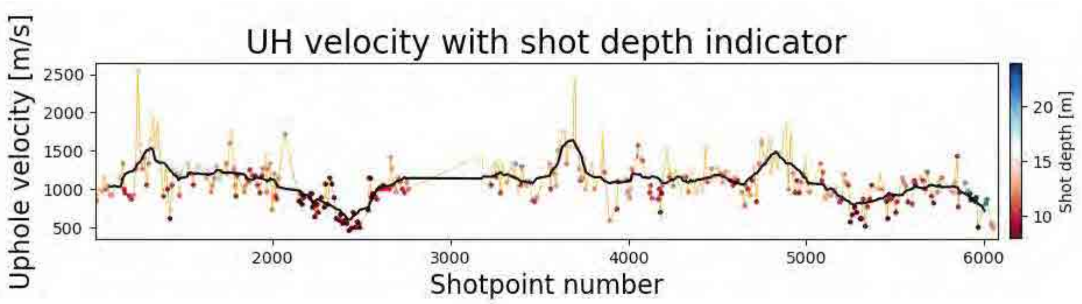


Figure 3.1.12.9: The uphole velocity along the line.

Receiver domain:

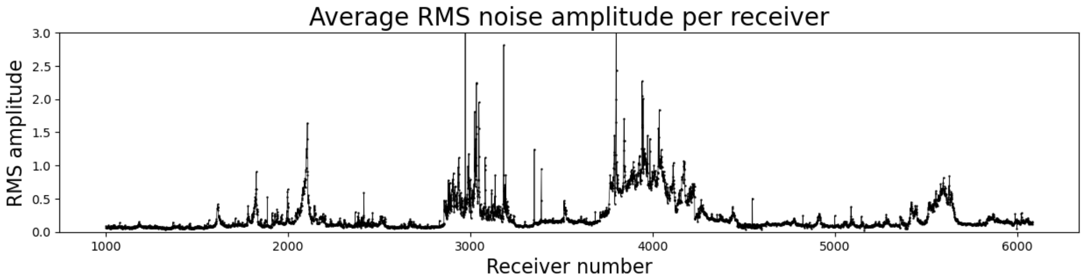


Figure 3.1.12.10: The noise per receiver.

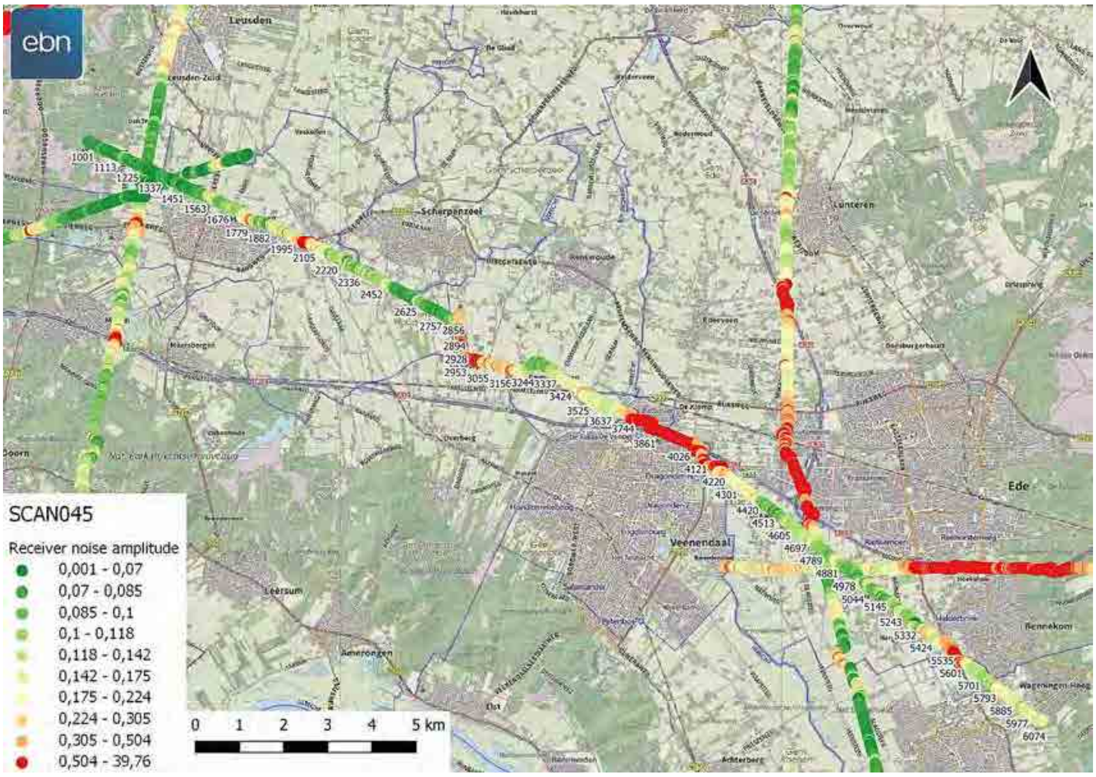


Figure 3.1.12.11: The noise per receiver visualized along the line. The color scale is based on the data of all the receiver data, showing noise relative to the other data points.

3.1.13 SCAN046

Line SCAN046 is the final regional line which was shot in the scope of the SCAN project. It mainly runs in northern Limburg, from Deurne to the German border. The line has a WSW-ENE orientation. Due to the late shooting date, the data of this line could not be included in the analysis of all the lines and will therefore solely be discussed in this section.

Acquisition length	30.46 km
Number of receivers	5901 (1001-7090)
Number of shots	469 (1001.5-6729.5)
Skipped shots	7.7%
Skipped receivers	3.1%
Date recorded	13/01/2022 - 24/01/2022

Table 3.13: Acquisition parameters of line SCAN046

A low average charge size led to low signal values around Venray. This is enhanced by the fact that the line runs parallel to a provincial road, responsible for relatively high noise levels. With an average charge size of 497 grams and an average depth of 11.95 meters, these acquisition parameters were below average for all the lines. All shots were located below the water table.

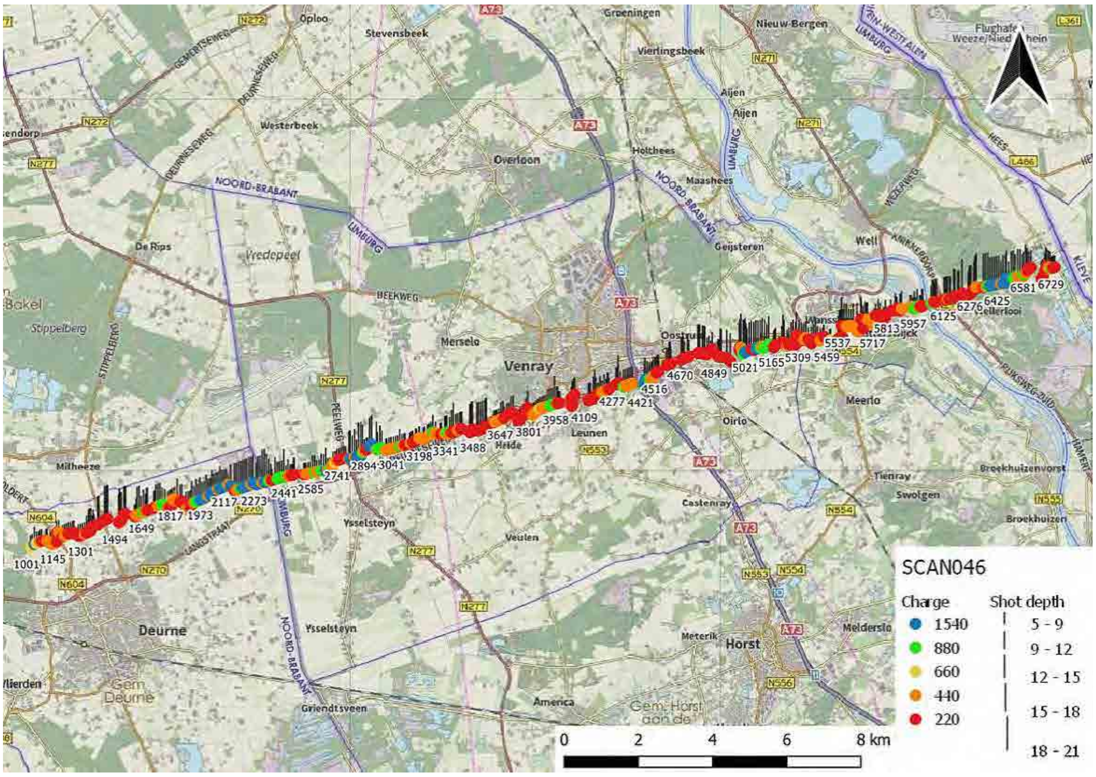


Figure 3.1.13.1: Acquisition parameters of line SCAN046.

General:

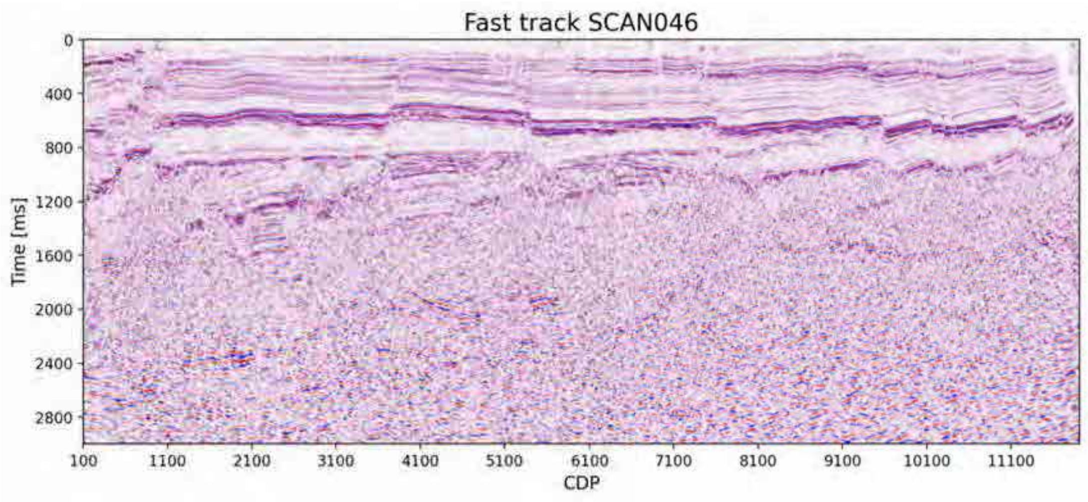


Figure 3.1.13.2: The fast track of line SCAN046.

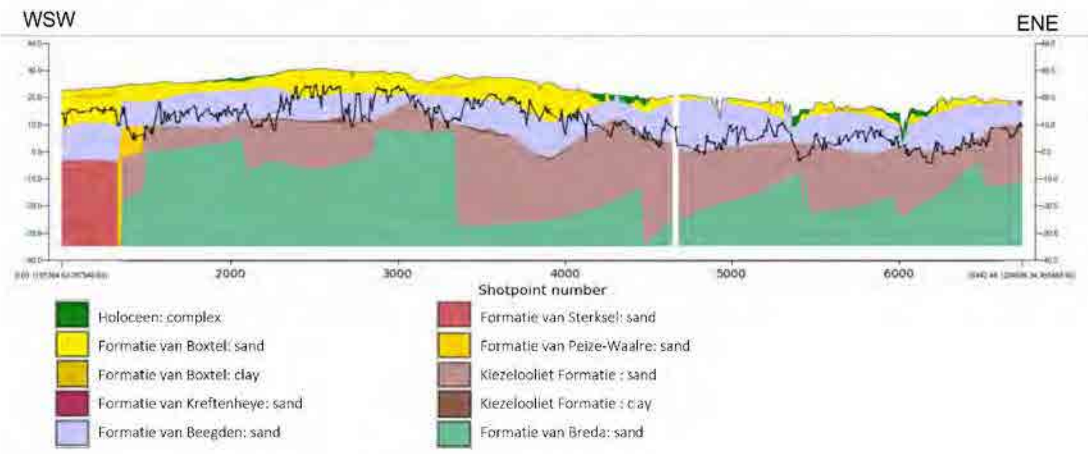


Figure 3.1.13.3: The geological profile of line SCAN046.

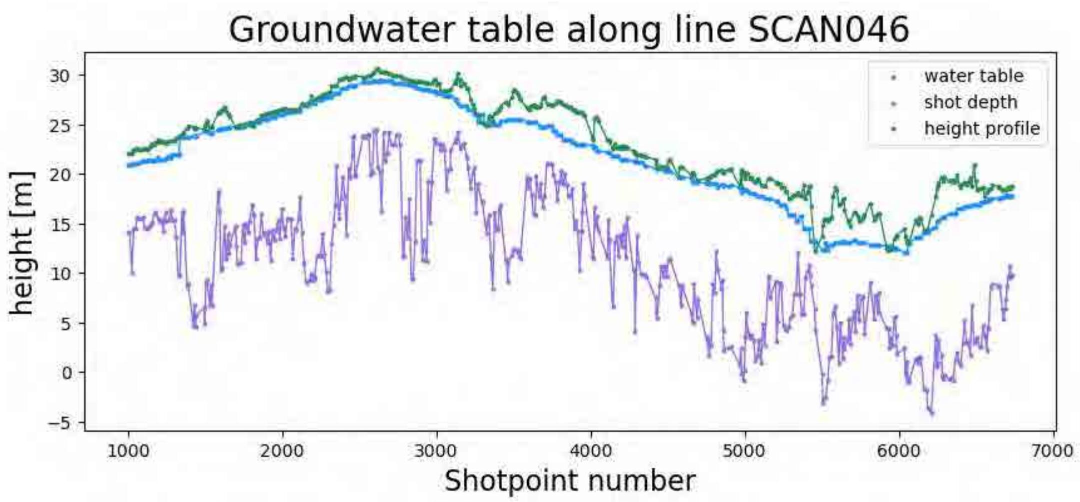


Figure 3.1.13.4: The water table along line SCAN046. All shots are located below the water table.

Shot domain:

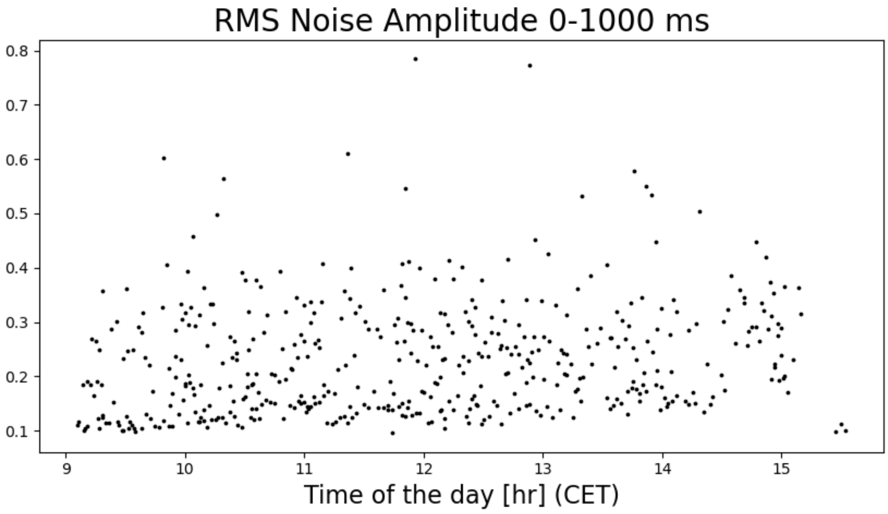


Figure 3.1.13.5: The noise in the shot domain plotted against the time of the day at which the shots were recorded.

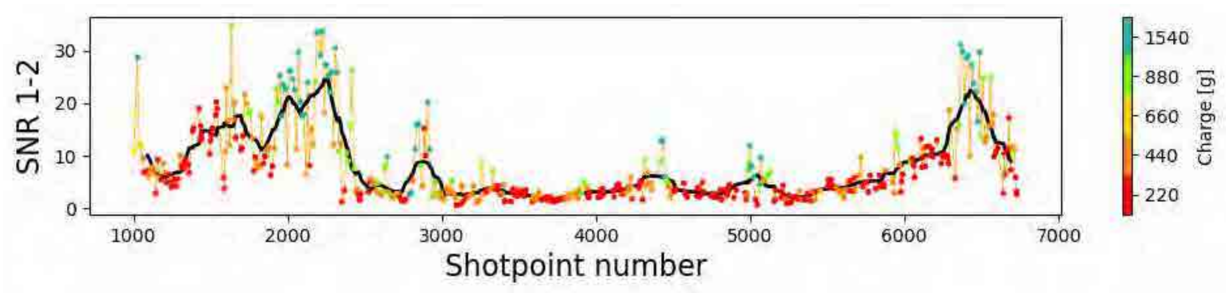


Figure 3.1.13.6: The SNR in the 1-2 second window with a charge size indicator. The black line is the moving average computed with a range of 15 data points.

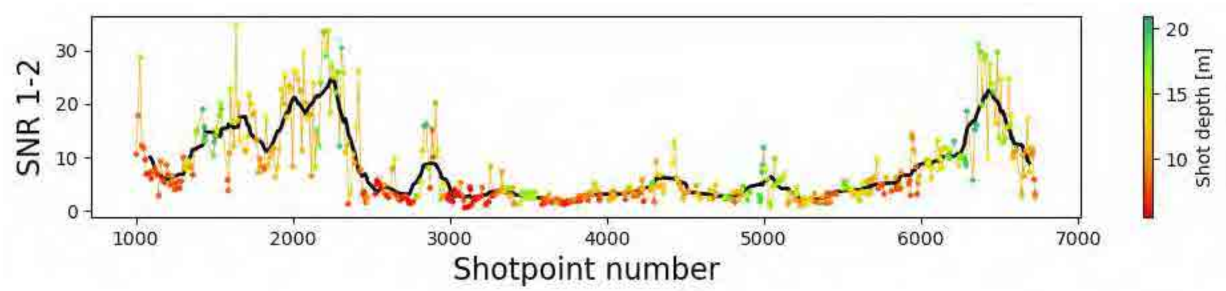


Figure 3.1.13.7: The SNR in the 1-2 second window with a shot depth indicator. The black line is the moving average computed with a range of 15 data points.

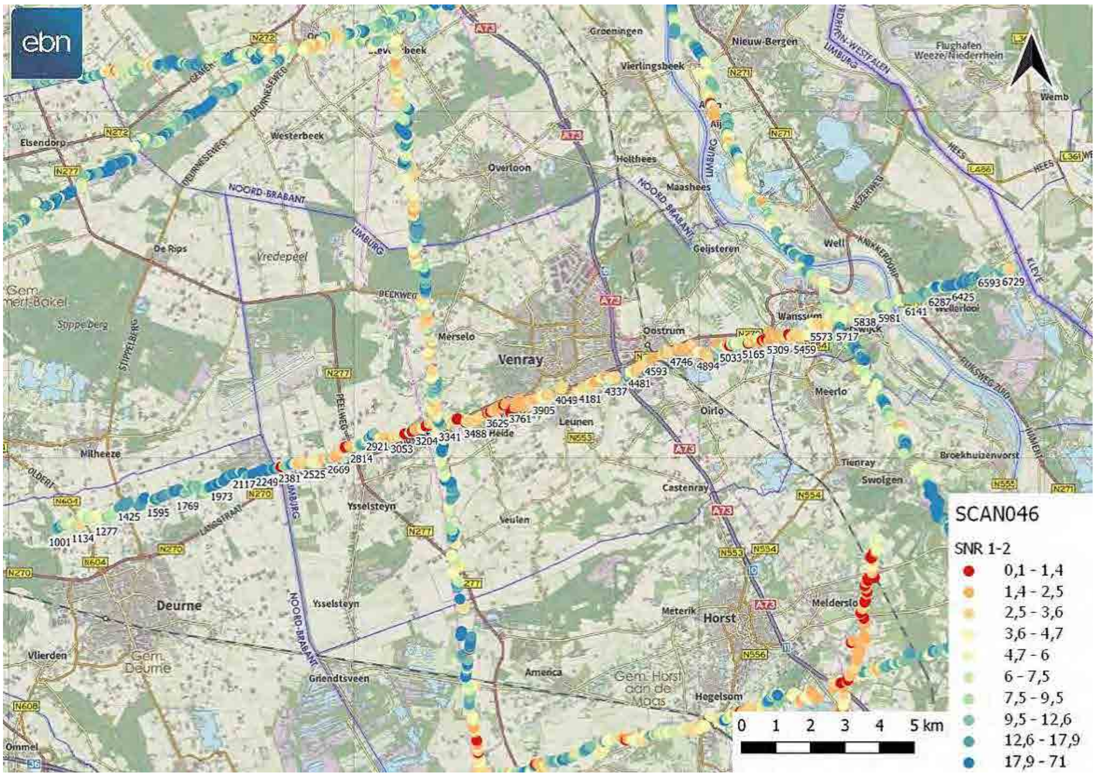


Figure 3.1.13.8: The SNR 1-2 value plotted along the line. The colour of the shot points indicate the quality of the shot, from bad (red) to good (blue). This colour range is divided into 10 segments which are based on the occurrence of the data points along all lines. The red dots therefore indicate that those shots belong to the worst 10 % of all the shots.

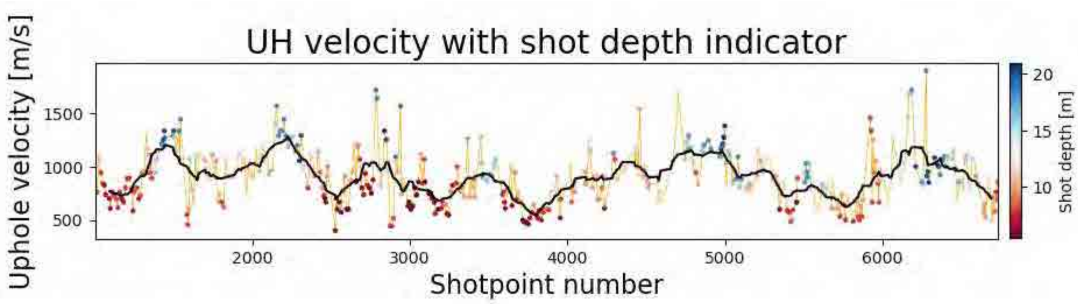


Figure 3.1.13.9: The uphole velocity along the line.

Receiver domain:

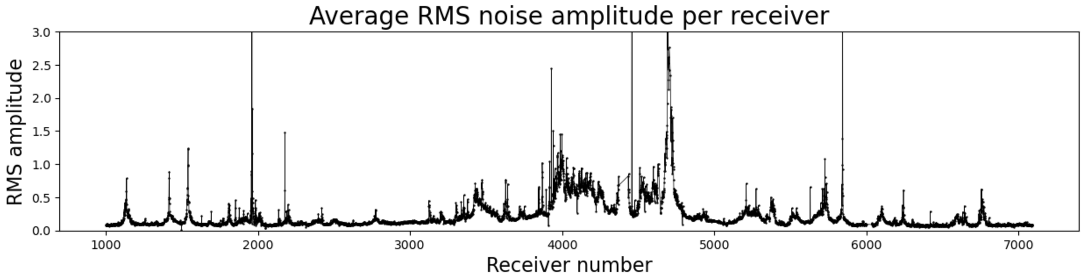


Figure 3.1.13.10: The noise per receiver.

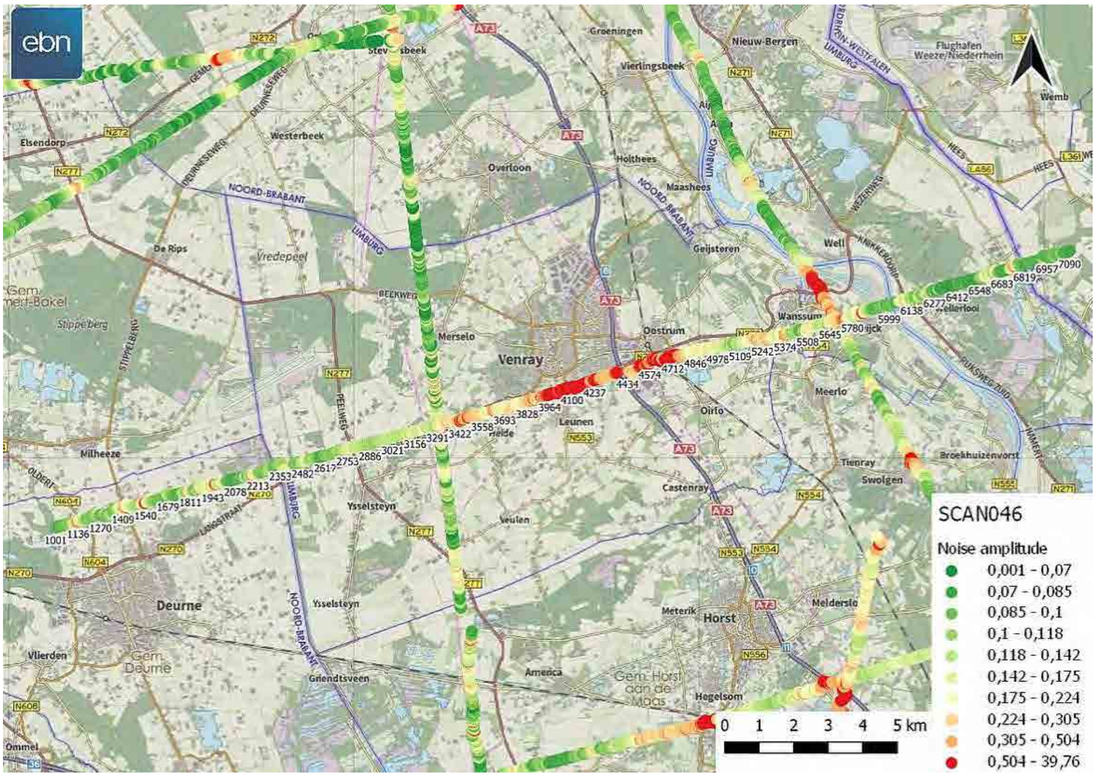


Figure 3.1.13.11: The noise per receiver visualized along the line. The color scale is based on the data of all the receiver data, showing noise relative to the other data points.

3.1.14 SCAN024

SCAN024 is one of the two lines of which the first 478 shots were recorded in 2020 (1001.5 - 6784.5) and the second part was shot in 2021. This second part existed of 496 shots with station numbers 6870.5 - 12629.5. The first section was previously analyzed in van Klaveren (2021), but for the sake of consistency the line is analyzed again as a whole.

The line has a N-S orientation and runs from Montfoort in the south to Edam-Volendam in the north. On 3 different patches where the line crossed a body of water hydrophones were placed. These were again multiplied with the appropriate multiplication factor. All shots are placed below the water table.

Acquisition length	58.20 km
Number of receivers	10409 (1001-12639)
Of which hydrophones	229
Number of shots	983 (1001.5-12629.5)
Of which in water	117
Skipped shots	5.1%
Skipped receivers	10.6 %
Date recorded	04/09/2020 - 15/09/2020 13/07/2021 - 21/07/2021

Table 3.14: Acquisition parameters of line SCAN024.

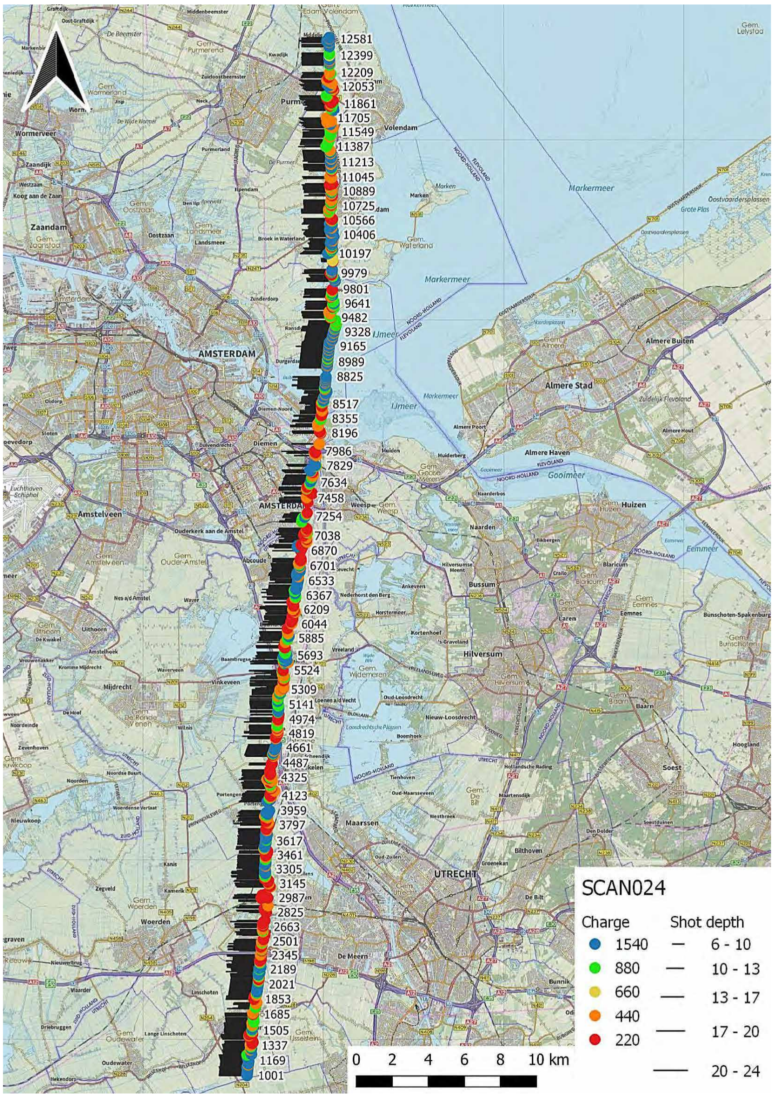


Figure 3.1.14.1: Acquisition parameters of line SCAN024.

General:

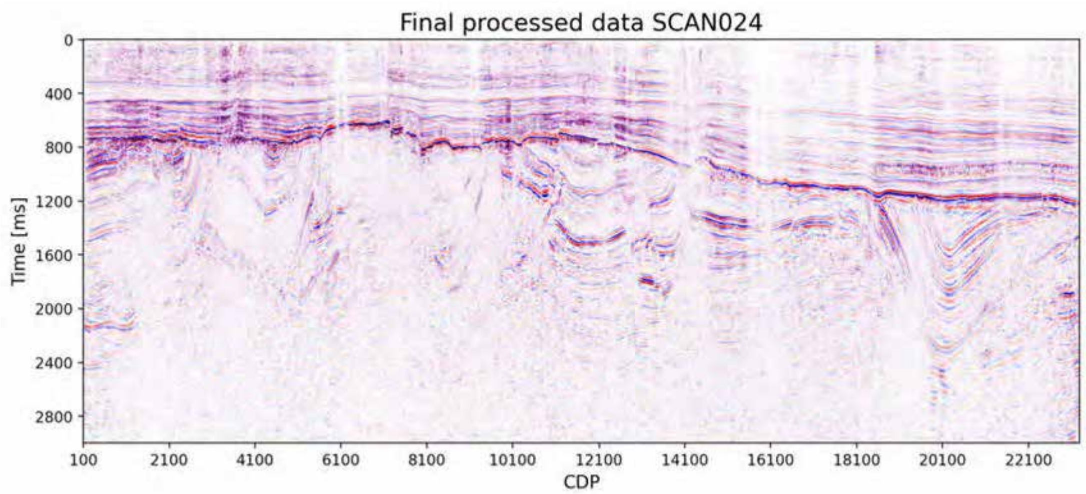


Figure 3.1.14.2: The final cross-section of line SCAN024.

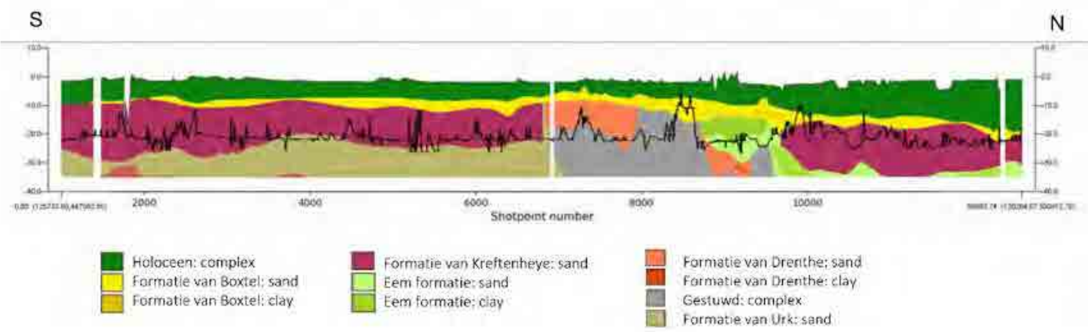


Figure 3.1.14.3: The geological profile of line SCAN024.

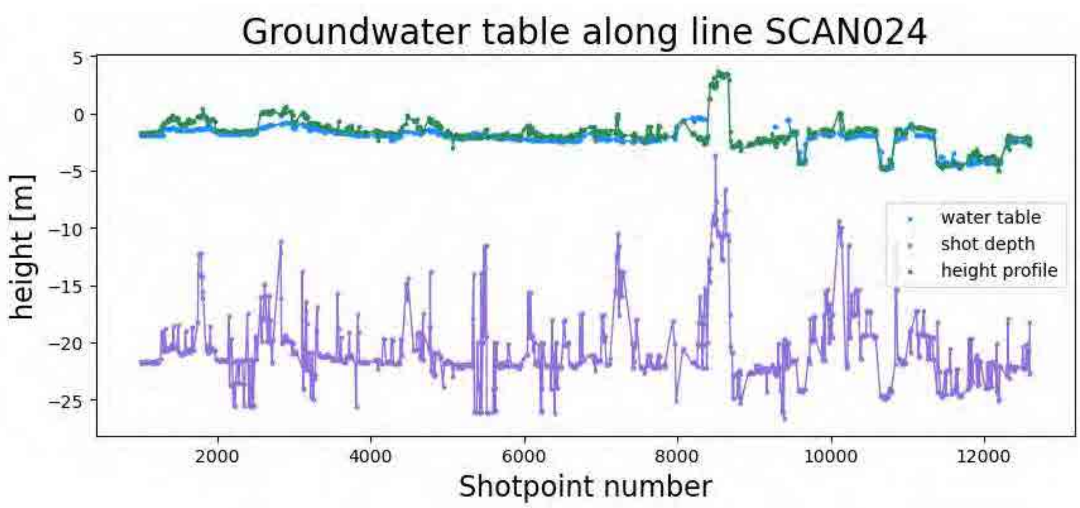


Figure 3.1.14.4: The water table along line SCAN024. All shots are located below the water table.

Shot domain:

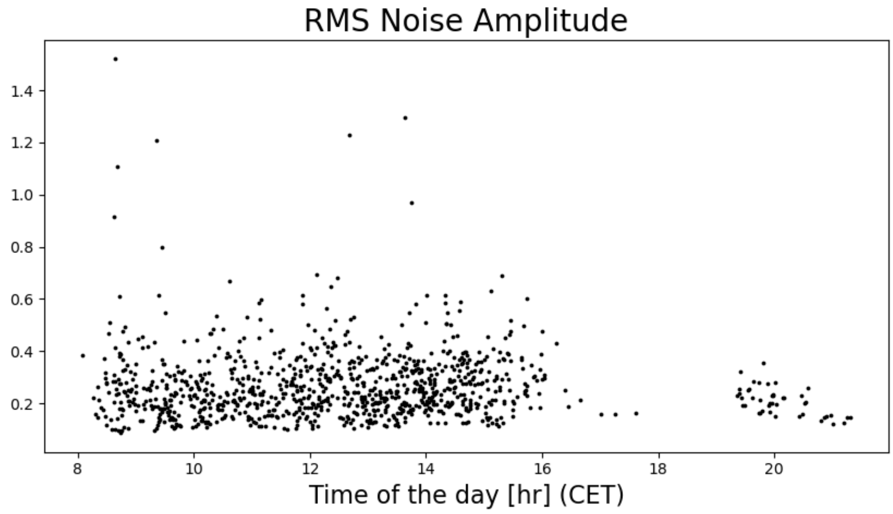


Figure 3.1.14.5: The noise in the shot domain plotted against the time of the day at which the shots were recorded.

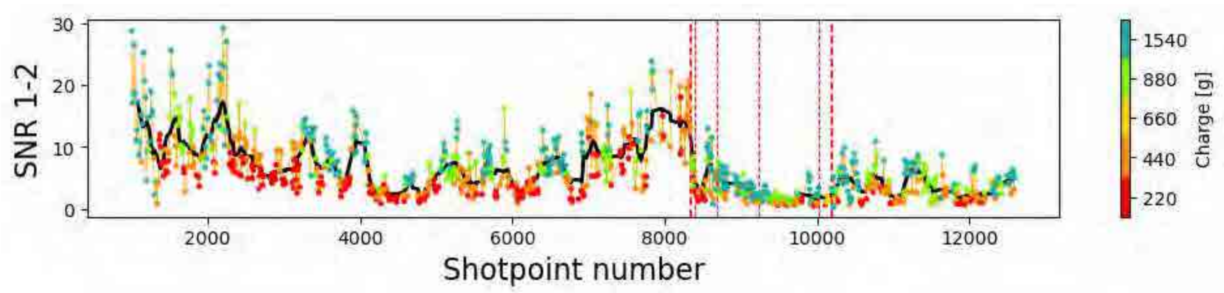


Figure 3.1.14.6: The SNR in the 1-2 second window with a charge size indicator. The black line is the moving average computed with a range of 15 data points. The red dashed lines indicate the hydrophone regions.

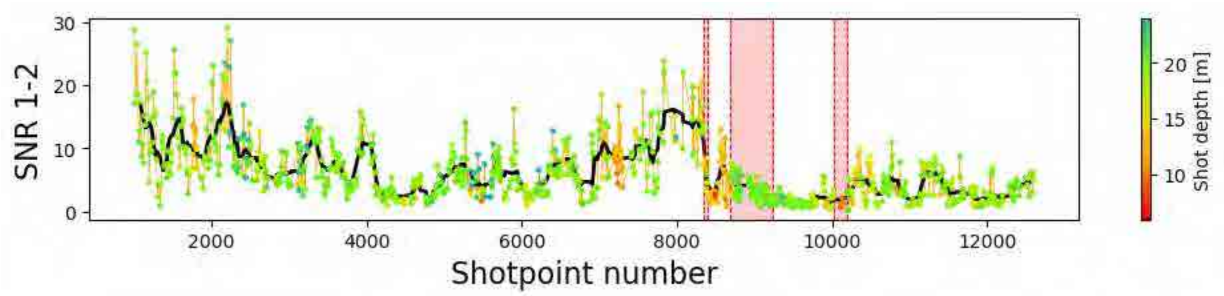


Figure 3.1.14.7: The SNR in the 1-2 second window with a shot depth indicator. The black line is the moving average computed with a range of 15 data points. The red dashed lines indicate the hydrophone regions.

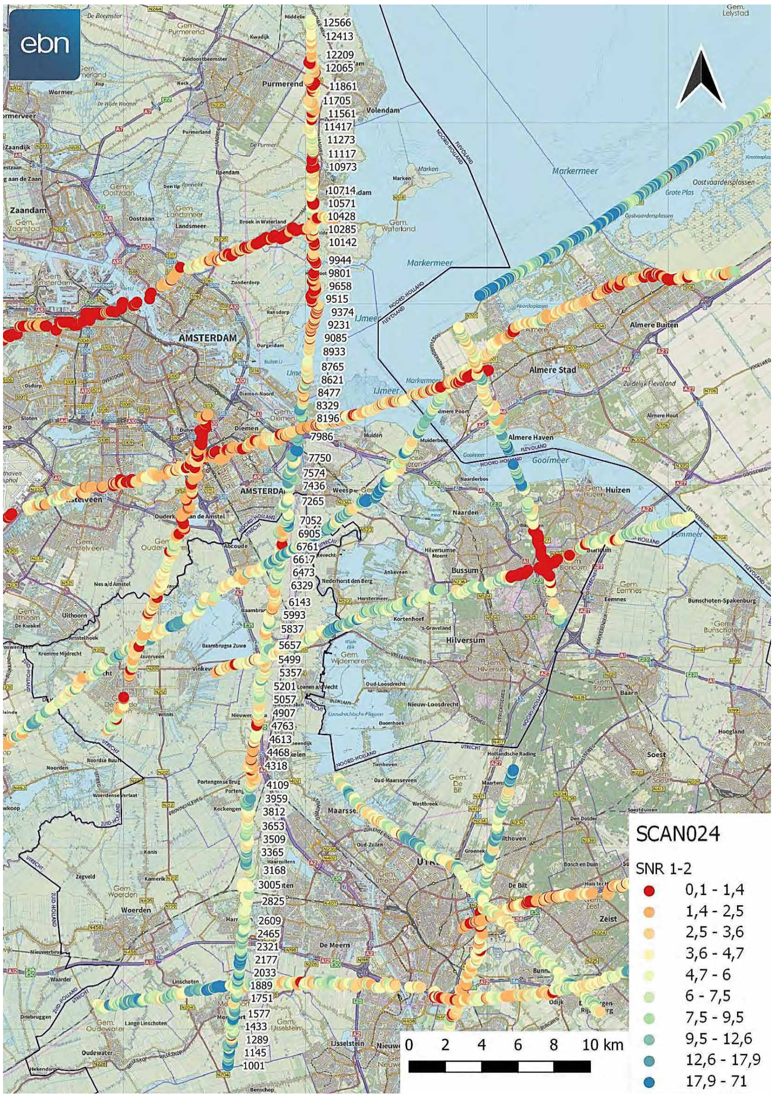


Figure 3.1.14.8: The SNR 1-2 value plotted along the line. The colour of the shot points indicate the quality of the shot, from bad (red) to good (blue). This colour range is divided into 10 segments which are based on the occurrence of the data points along all lines. The red dots therefore indicate that those shots belong to the worst 10 % of all the shots.

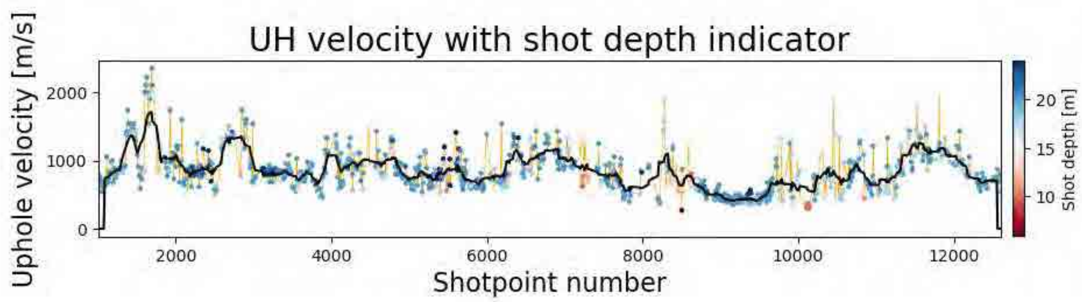


Figure 3.1.14.9: The uphole velocity along the line.

Receiver domain:

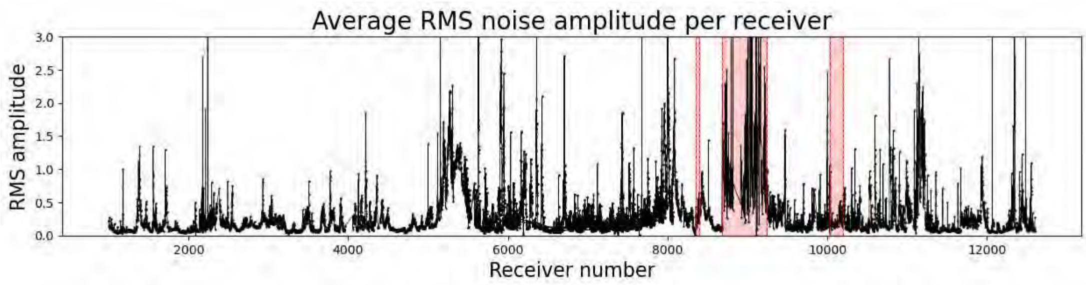


Figure 3.1.14.10: The noise per receiver. The red dashed lines indicate the hydrophone regions.

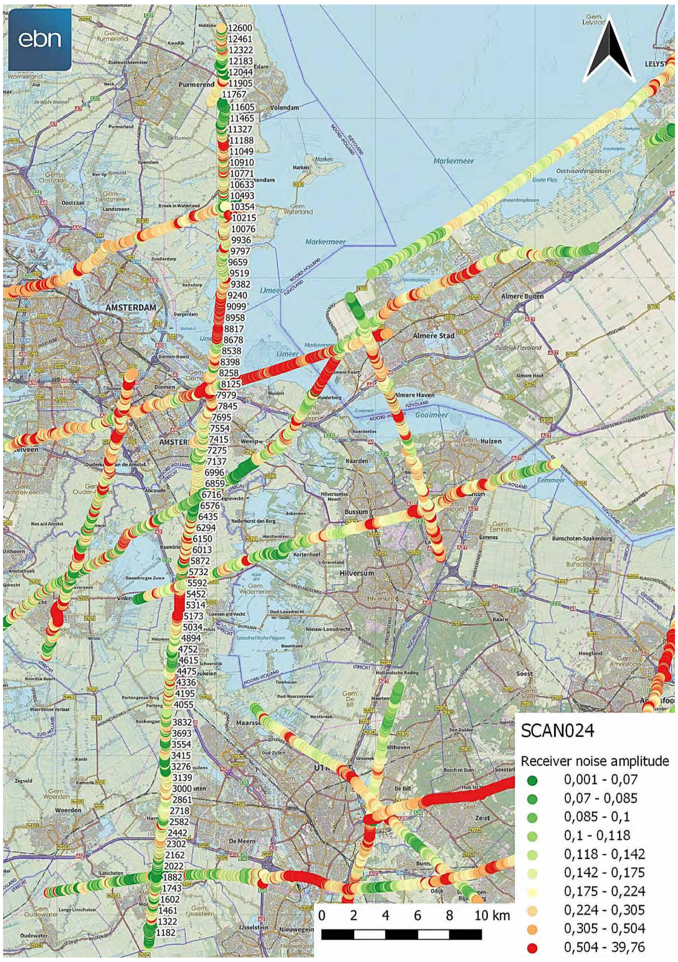


Figure 3.1.14.11: The noise per receiver visualized along the line. The color scale is based on the data of all the receiver data, showing noise relative to the other data points.

3.1.15 SCAN025

SCAN025 is the other line which was recorded in two different parts. Again, an analysis of the first 582 shots ranging from station number 1114.5-8537.5 was previously executed by van Klaveren (2021). Another 478 shots were added to this line in 2021, from 8550.5 - 13997.5.

The line runs from Boskoop in the southwest to the Oostvaardersplassen in the northeast. This includes the crossing of the IJmeer for which hydrophones were deployed. Next to hydrophones, SCAN025 also consists out of 26 marshphones. Like SCAN024, the line is analyzed again taking both parts into consideration to make sure the all the data is comparable. All shots were placed below the water table and in general the quality of the line is quite decent.

Acquisition length	65.04 km
Number of receivers	14620 (1001-14007)
Of which hydrophones	156
Number of shots	1060 (1114.5-13997.5)
Of which in water	???
Skipped shots	6.1%
Skipped receivers	7.4 %
Date recorded	17/09/2020 - 29/09/2020 10/05/2021-20/05/2021

Table 3.15: Acquisition parameters of line SCAN025

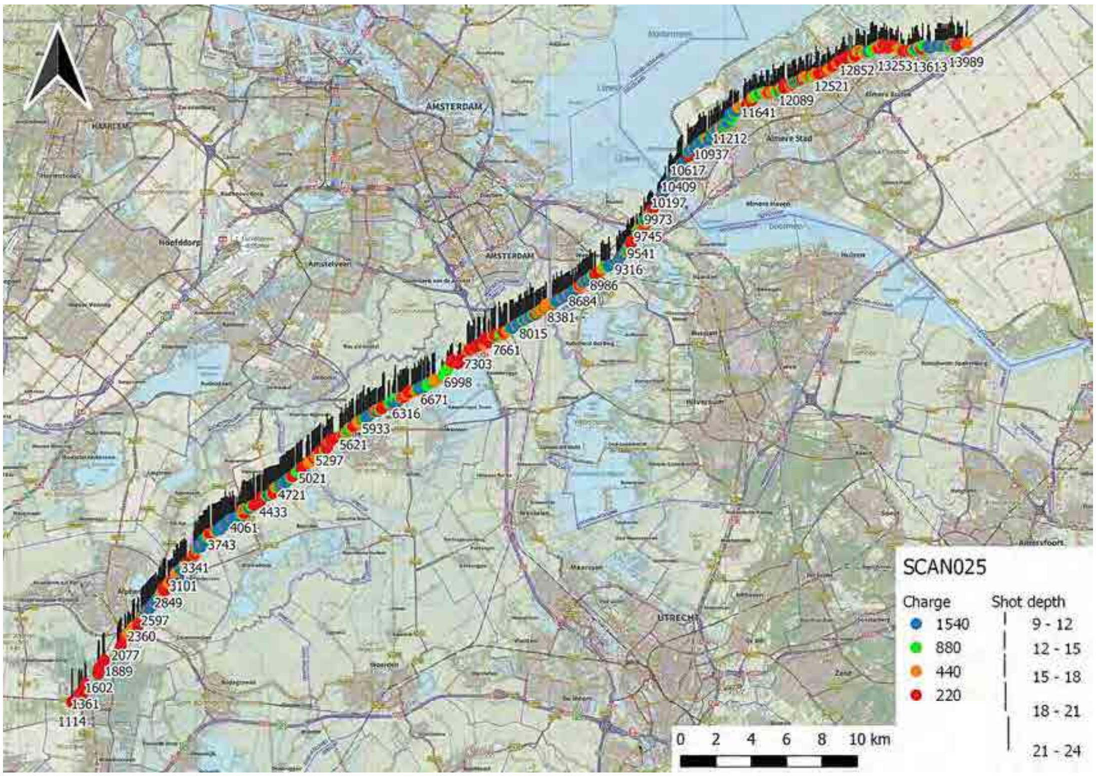


Figure 3.1.15.1: Acquisition parameters of line SCAN025.

General:

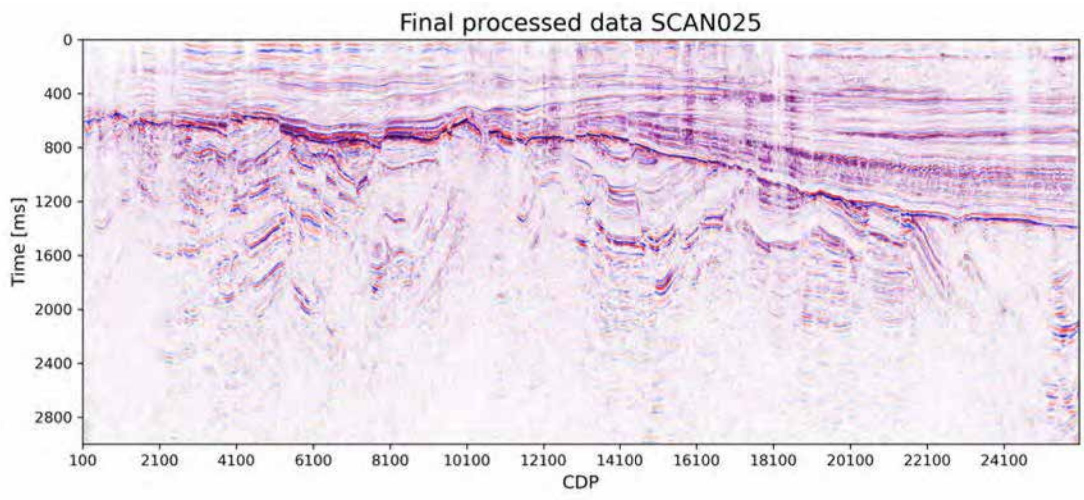


Figure 3.1.15.2: The final full cross section of line SCAN025.

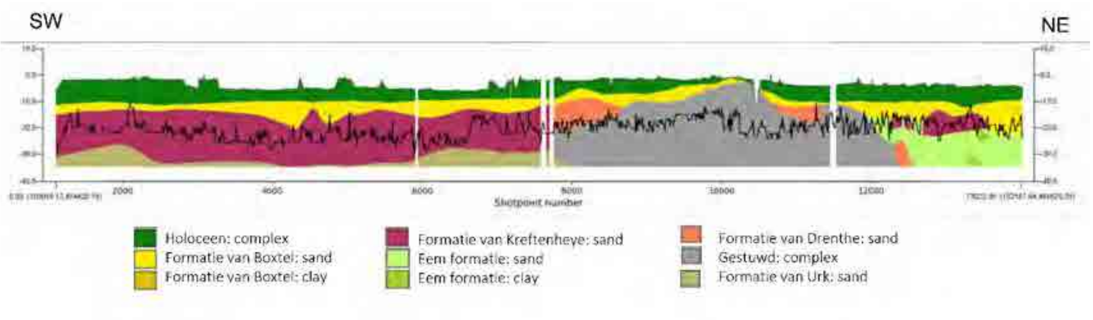


Figure 3.1.15.3: The geological profile of line SCAN025.

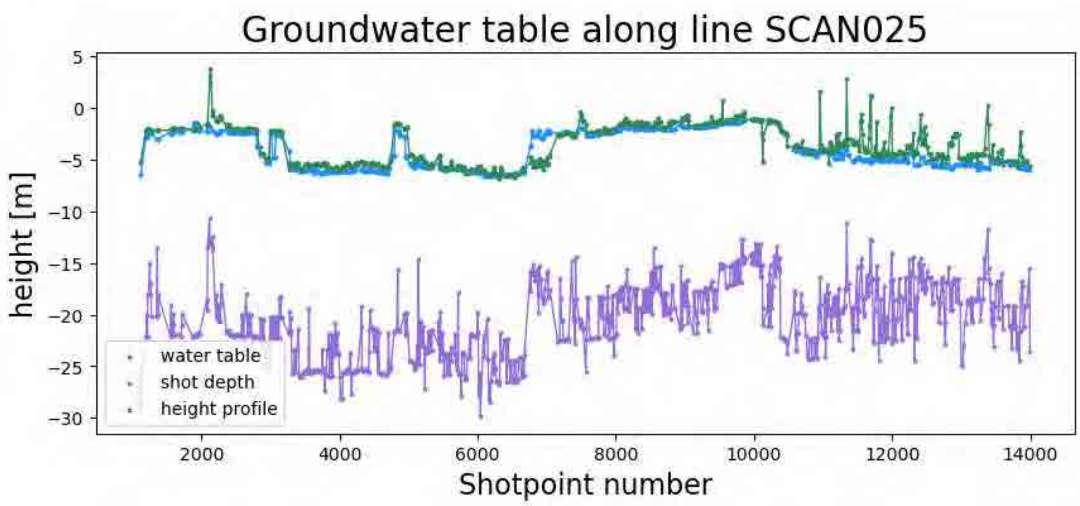


Figure 3.1.15.4: The water table along line SCAN025. All shots are located below the water table.

Shot domain:

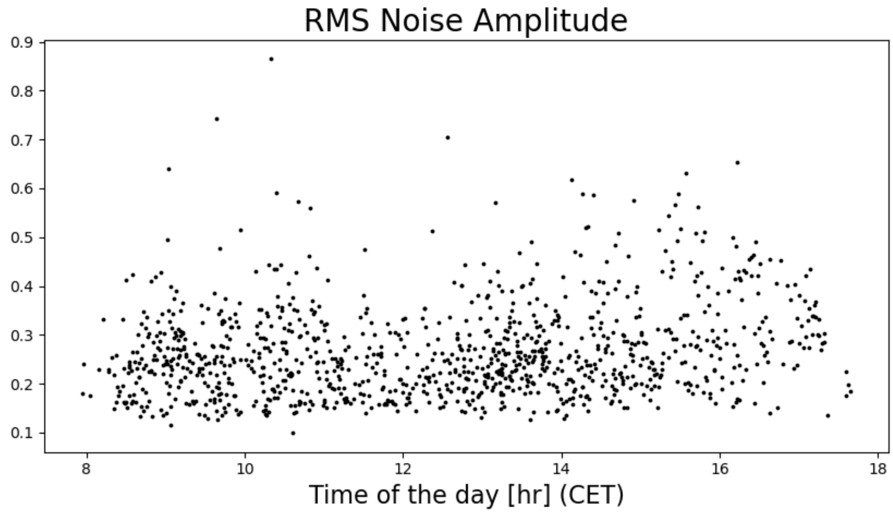


Figure 3.1.15.5: The noise in the shot domain plotted against the time of the day at which the shots were recorded.

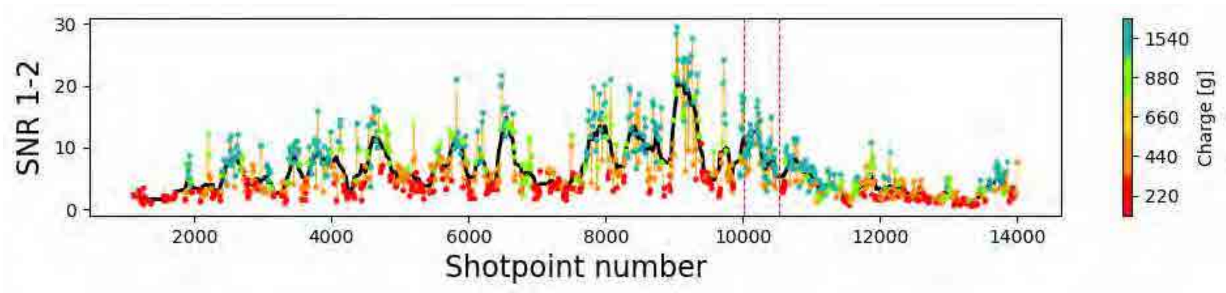


Figure 3.1.15.6: The SNR in the 1-2 second window with a charge size indicator. The black line is the moving average computed with a range of 15 data points. The red dashed lines indicate the hydrophone region.

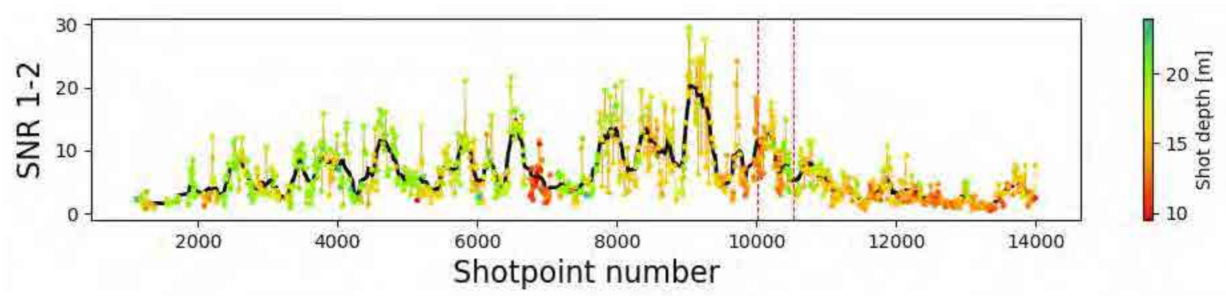


Figure 3.1.15.7: The SNR in the 1-2 second window with a shot depth indicator. The black line is the moving average computed with a range of 15 data points. The red dashed lines indicate the hydrophone region.

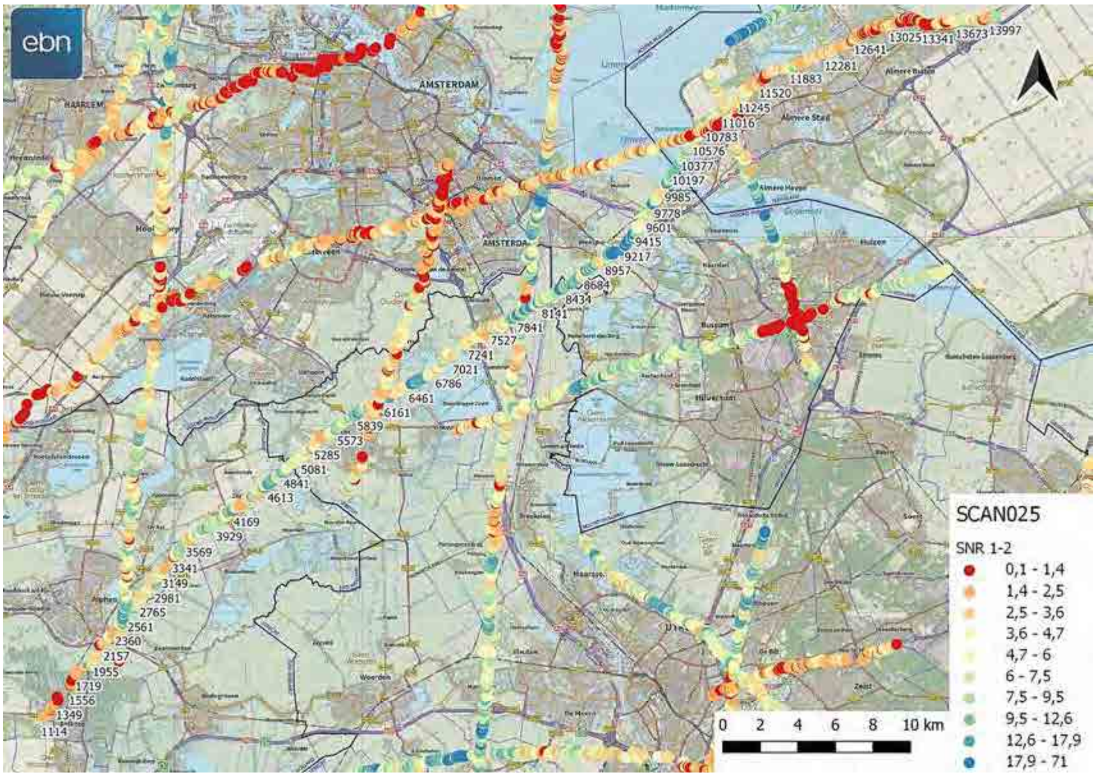


Figure 3.1.15.8: The SNR 1-2 value plotted along the line. The colour of the shot points indicate the quality of the shot, from bad (red) to good (blue). This colour range is divided into 10 segments which are based on the occurrence of the data points along all lines. The red dots therefore indicate that those shots belong to the worst 10 % of all the shots.

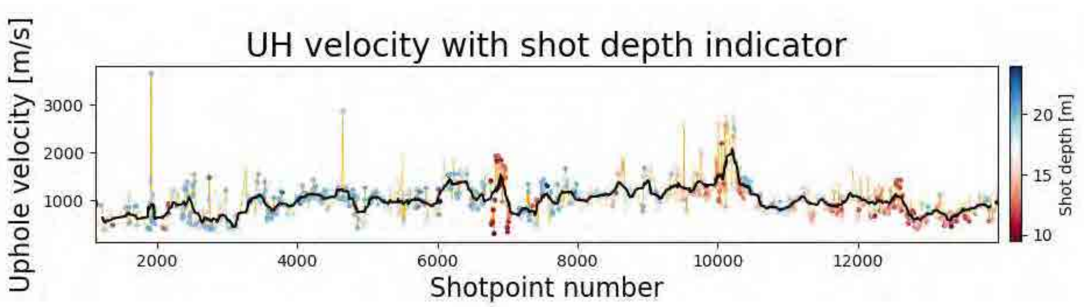


Figure 3.1.15.9: The uphole velocity along the line.

Receiver domain:

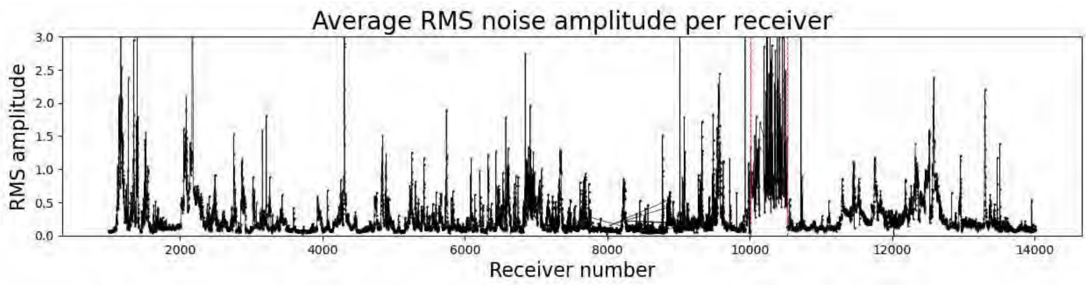


Figure 3.1.15.10: The noise per receiver. The red dashed lines indicate the hydrophone region.

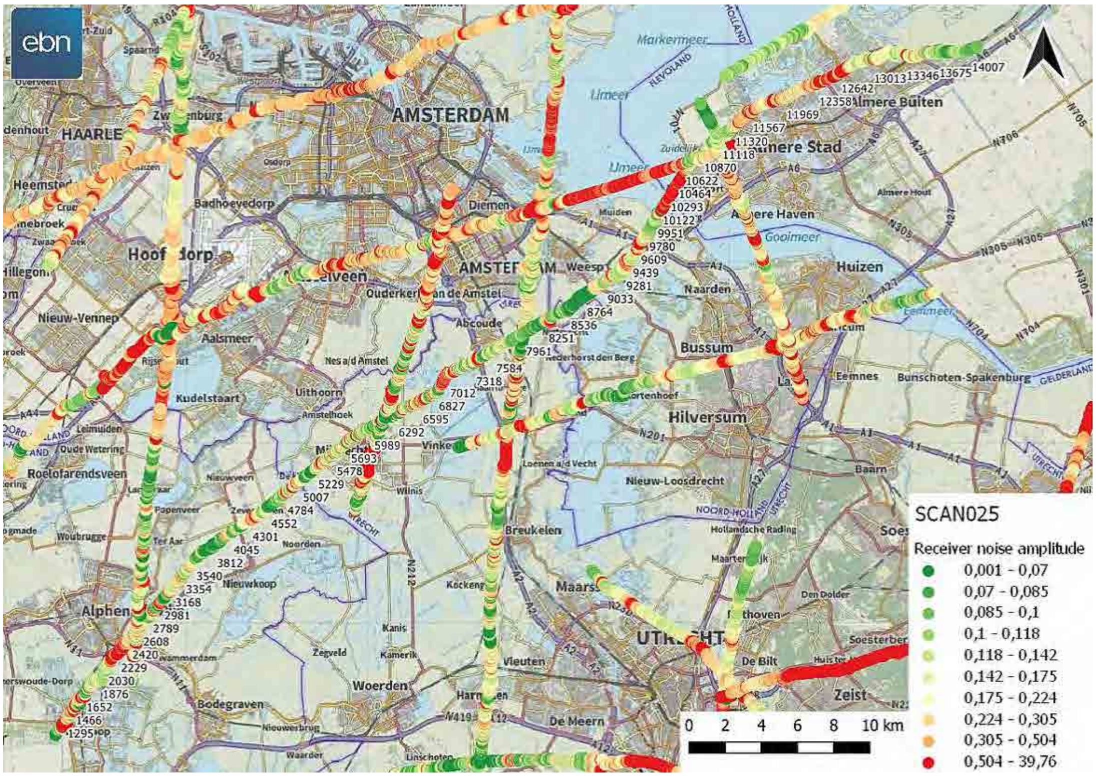


Figure 3.1.15.11: The noise per receiver visualized along the line. The color scale is based on the data of all the receiver data, showing noise relative to the other data points.

3.1.16 SCAN026

The recording of line SCAN026 has also occurred in two parts. However, it differs from the previous two lines in the sense that the second recording was not an addition to the first section but rather an attempt to fill-in some of the gaps of the previous data acquisition. There were a few large gaps with a kilometer-scale size which were attempted to be filled in. Additional shots were placed in 3 patches: between 5112.5-5657.5 in the vicinity of Hoofddorp, between 6299.5-6365.5 next to the Polderbaan of Schiphol Airport and between 7055.5 - 7199.5 in a meadow. This sums up to an additional 3.3 kilometer with shot points.

The line has a N-S orientation and runs from Boskoop to Zaanstad, east of Amsterdam. All shots are located below the water table and two patches of hydrophones were deployed during the crossing of lakes. The peak in noise levels around station number 5000 is due to the proximity of the A4 highway.

Acquisition length	40.65 km
Number of receivers	11688 (1001-9130)
Of which hydrophones	123
Number of shots	639 (1001.5-9113.5)
Of which in water	38
Skipped shots	18.9%
Skipped receivers	10.2 %
Date recorded	30/09/2020 - 13/10/2020 03/06/2021

Table 3.16: Acquisition parameters of line SCAN026

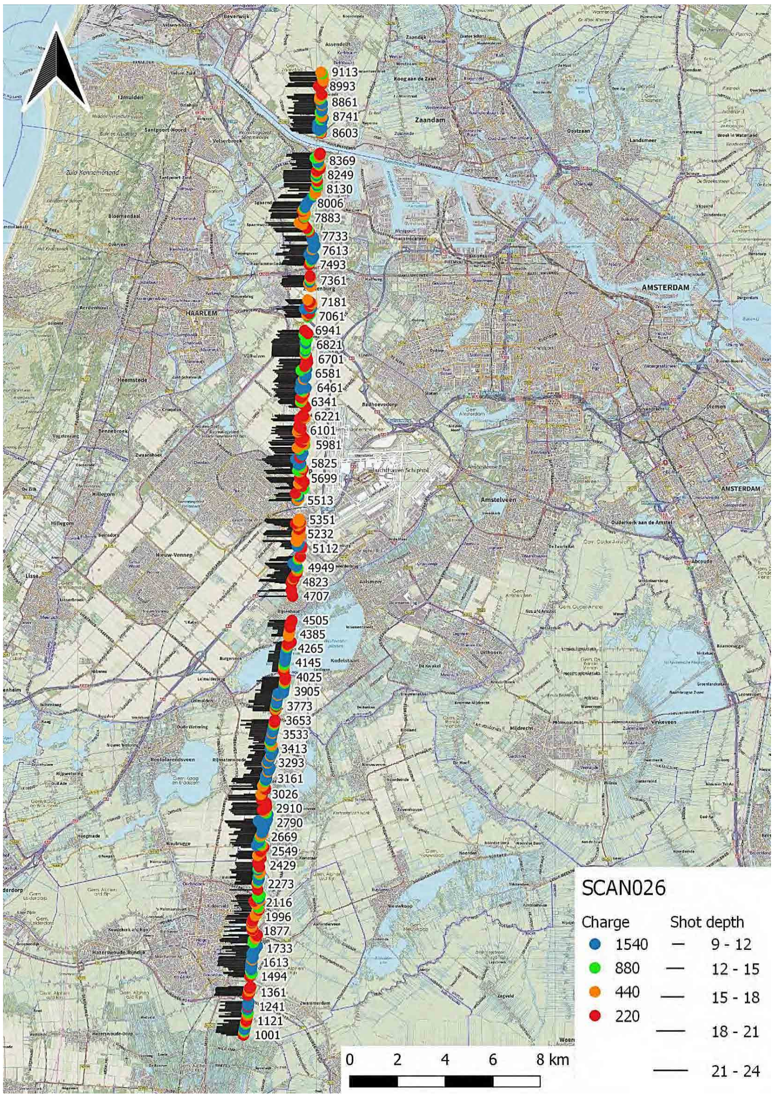


Figure 3.1.16.1: Acquisition parameters of line SCAN026.

General:

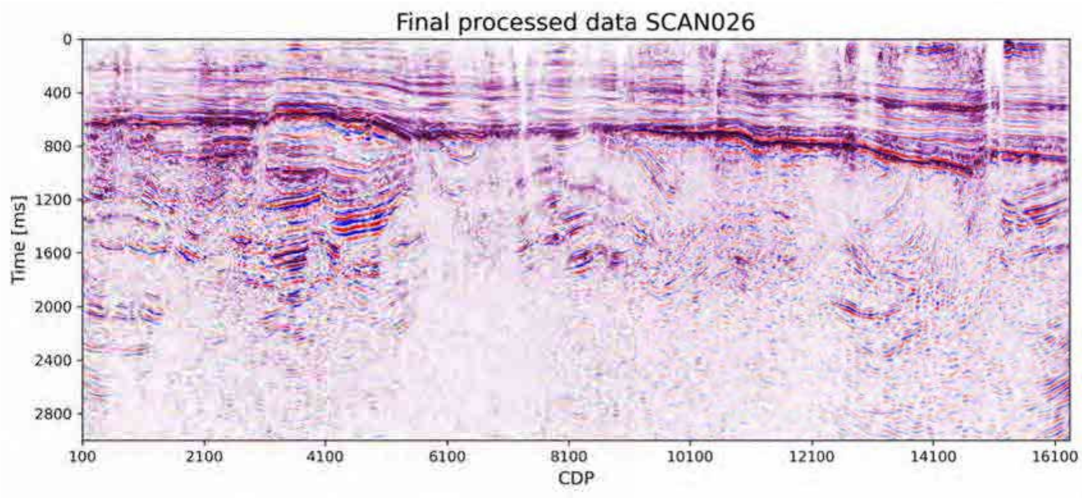


Figure 3.1.16.2: The final full cross-section of line SCAN026.

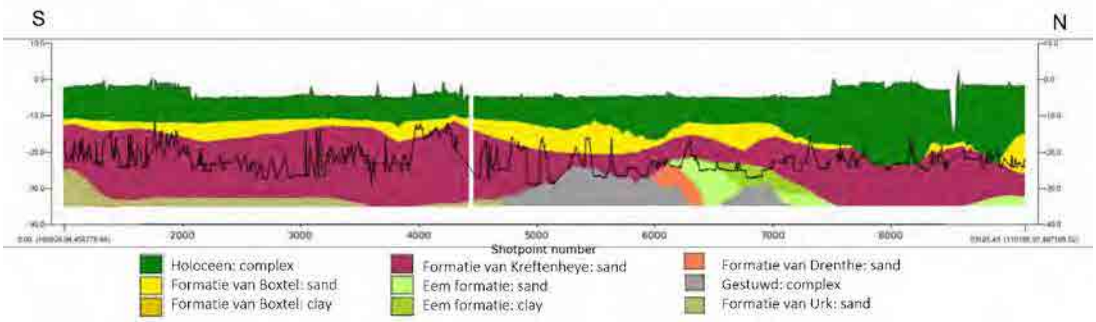


Figure 3.1.16.3: The geological profile of line SCAN026.

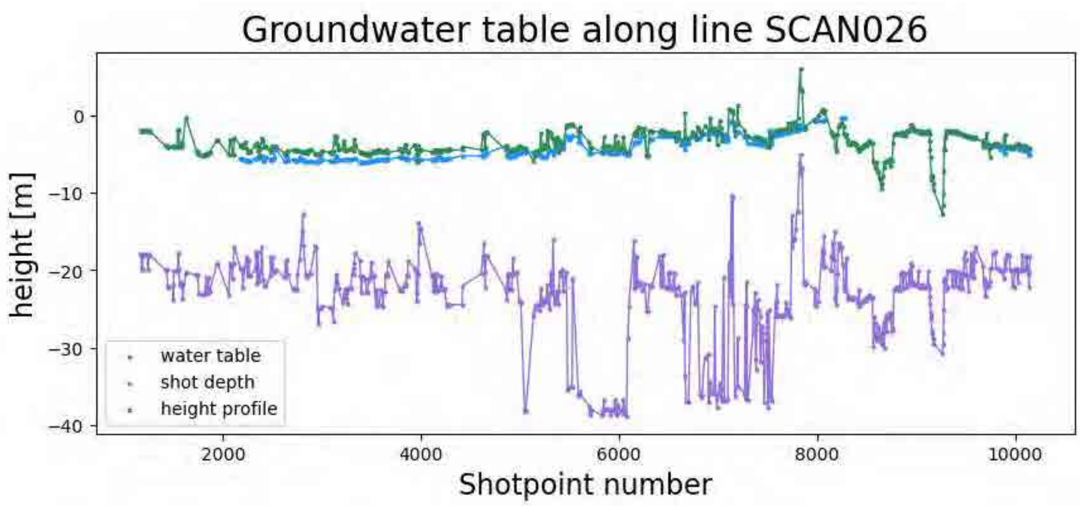


Figure 3.1.16.4: The water table along line SCAN026. All shots are located below the water table.

Shot domain:

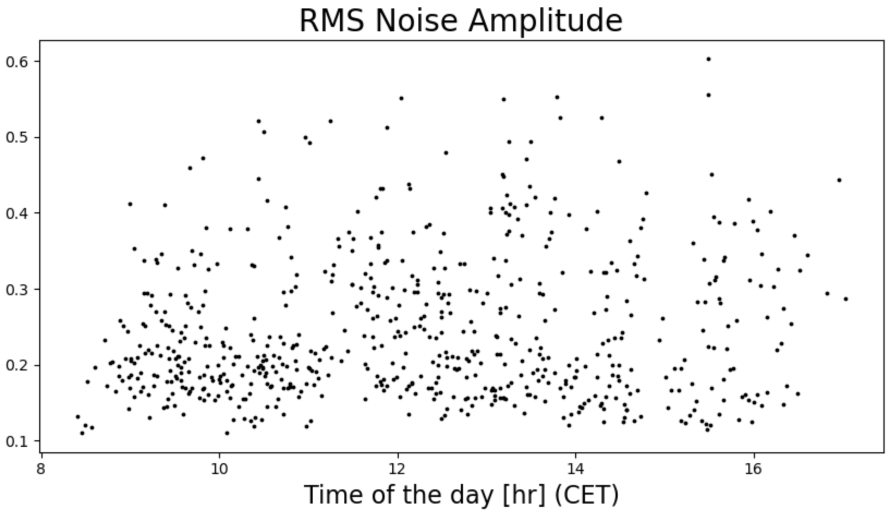


Figure 3.1.16.5: The noise in the shot domain plotted against the time of the day at which the shots were recorded.

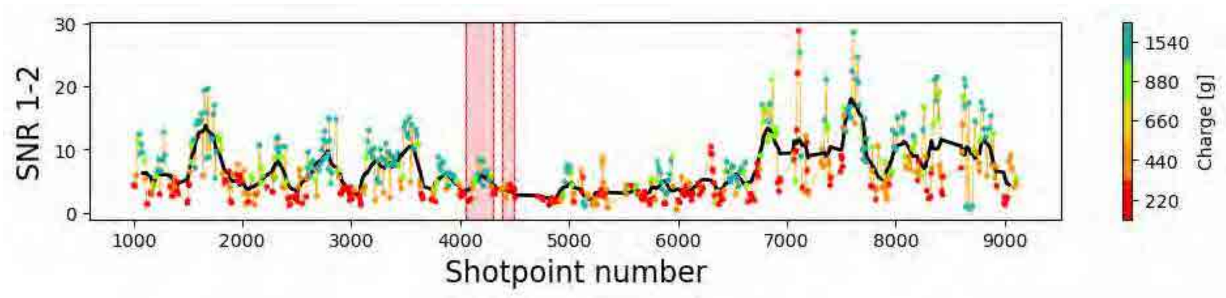


Figure 3.1.16.6: The SNR in the 1-2 second window with a charge size indicator. The black line is the moving average computed with a range of 15 data points. The red dashed lines indicate the hydrophone region.

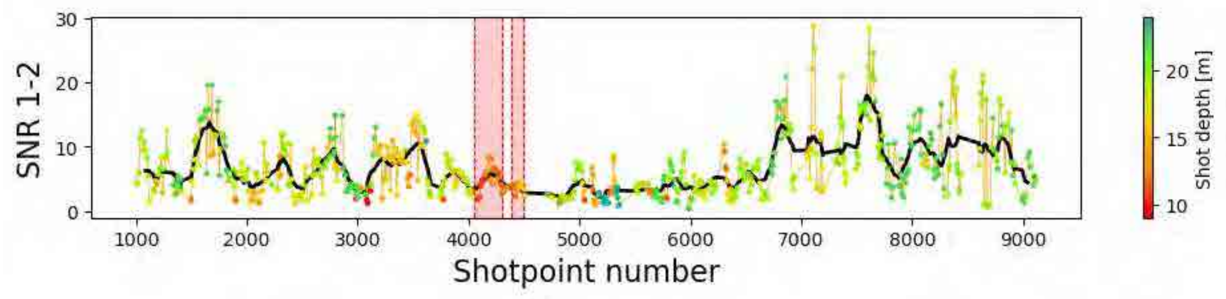


Figure 3.1.16.7: The SNR in the 1-2 second window with a shot depth indicator. The black line is the moving average computed with a range of 15 data points. The red dashed lines indicate the hydrophone region.

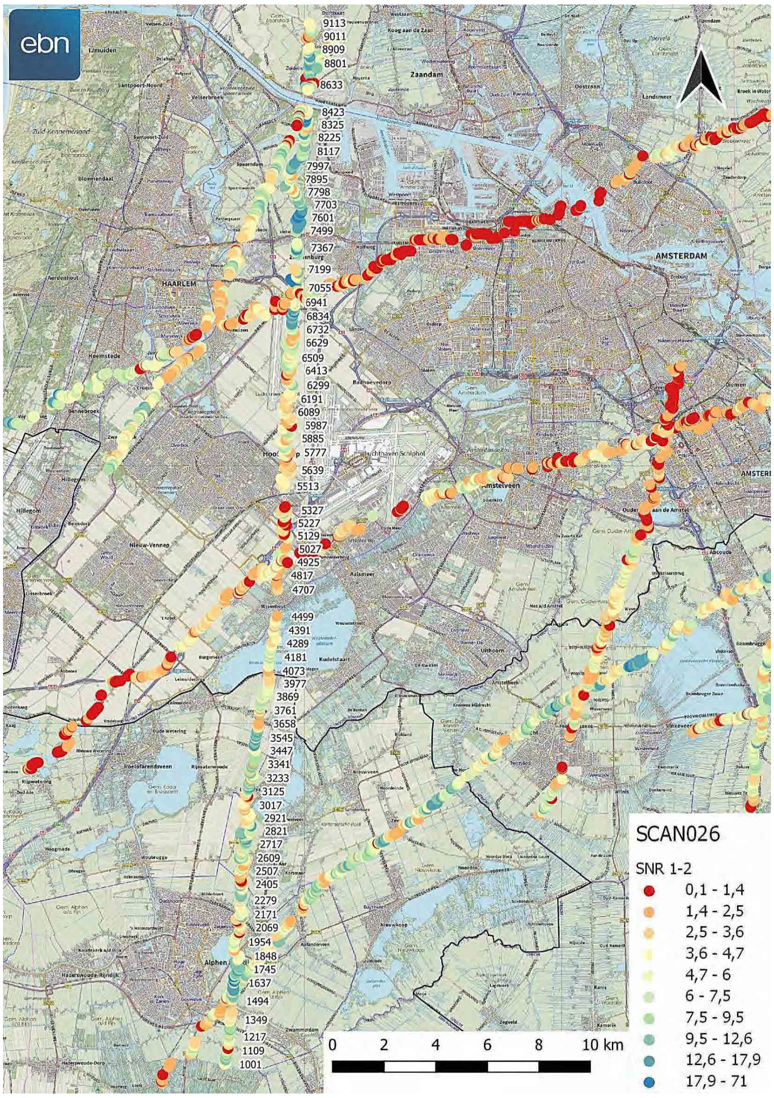


Figure 3.1.16.8: The SNR 1-2 value plotted along the line. The colour of the shot points indicate the quality of the shot, from bad (red) to good (blue). This colour range is divided into 10 segments which are based on the occurrence of the data points along all lines. The red dots therefore indicate that those shots belong to the worst 10 % of all the shots.

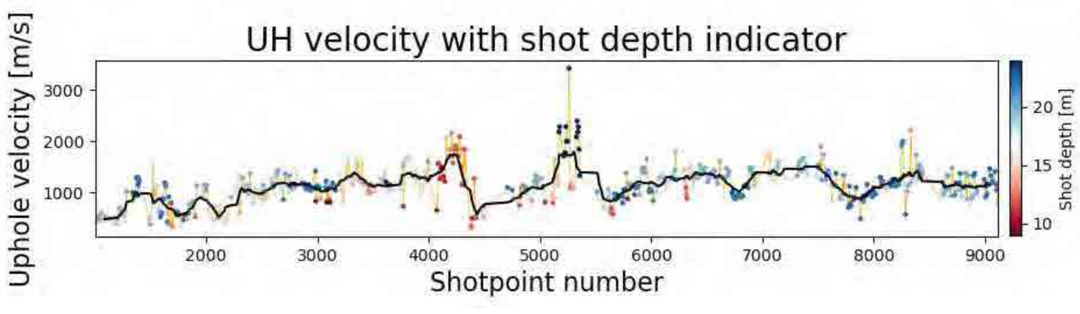


Figure 3.1.16.9: The uphole velocity along the line.

Receiver domain:

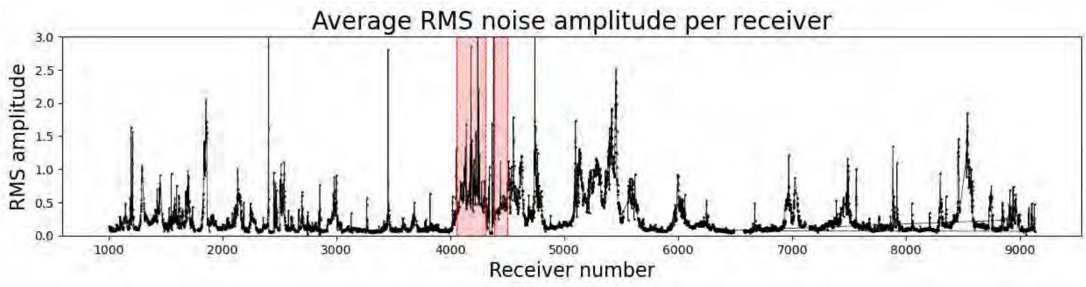


Figure 3.1.16.10: The noise per receiver. The red dashed lines indicate the hydrophone region.

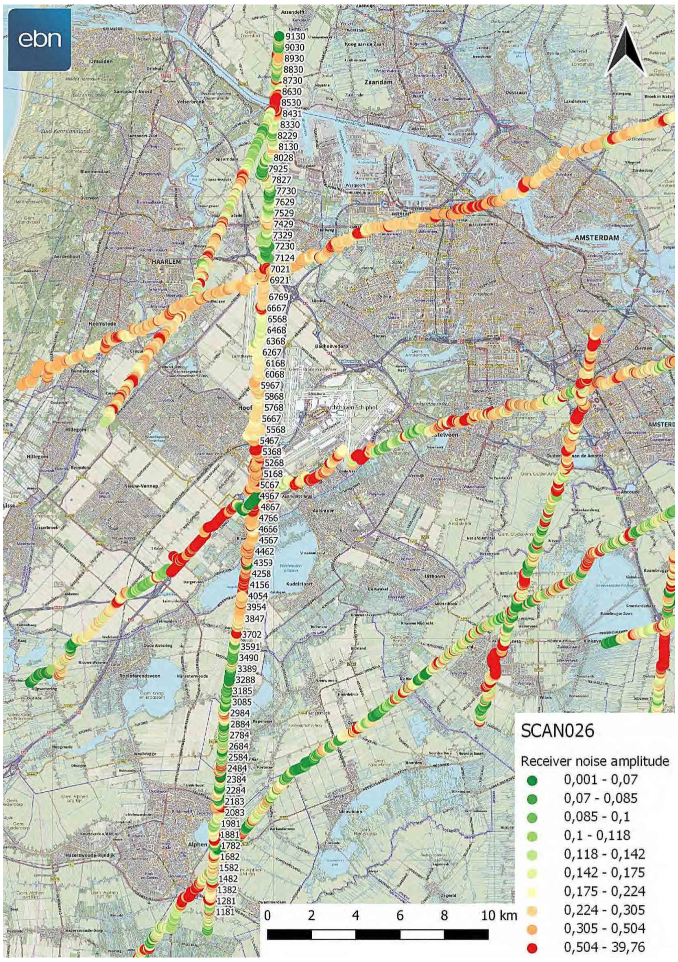


Figure 3.1.16.11: The noise per receiver visualized along the line. The color scale is based on the data of all the receiver data, showing noise relative to the other data points.

3.2 Processed data

As touched upon in the method section, cross-correlation coefficients were computed for the final sections of 21 different lines. Both the coefficient in the time and in the frequency domain was determined. This was done in order to quantify the quality of the different sections. By doing so, a possible correlation between the quality of the shot data and the final sections could be investigated.

In Table 3.17 the different computed coefficients are shown. SCAN042 has the best values and line SCAN031 is found to be of the lowest quality.

It should be noted that this analysis was performed on the true amplitude (TA) shot data. For every final deliverable both a TA and an Automatic Gain Control (AGC) version of the data is available. AGC controls the amplitude of the signal, enabling it to amplify the output and therefore the visibility of late-arriving events. Amplitude decay occurred at these events due to divergence or attenuation. This makes the AGC version suitable for investigating deeper events. However, the TA version is more applicable for the cross-correlation analysis. This is due to the fact that it is a less altered version of the data.

As previously mentioned, the cross-correlation was based on the 10 neighbouring traces to either side on a time window of 250-2000 ms. In this section, the individual analysis for all 21 lines will be shown. This includes the final seismic cross-section, the time and frequency cross-correlation coefficient trend and the SNR 1-2 value along the line. The SNR is plotted in order to allow a visual comparison between the trends in the shot data quality and those in the final sections. The SNR data from some of the lines is retrieved from Gossink (2021).

Line	Time	Frequency	Average
SCAN019	0.904	0.957	0.931
SCAN020	0.914	0.955	0.935
SCAN024	0.870	0.933	0.902
SCAN025	0.869	0.932	0.901
SCAN026	0.865	0.927	0.896
SCAN030	0.915	0.962	0.939
SCAN031	0.801	0.910	0.856
SCAN032	0.931	0.974	0.953
SCAN033	0.921	0.954	0.938
SCAN034	0.930	0.970	0.950
SCAN035	0.932	0.971	0.952
MRA036	0.871	0.927	0.899
MRA037	0.846	0.918	0.882
MRA038	0.839	0.915	0.877
MRA039	0.839	0.927	0.883
MRA040	0.839	0.913	0.876
MRA041	0.900	0.952	0.926
SCAN042	0.947	0.983	0.965
SCAN043	0.841	0.910	0.876
SCAN044	0.886	0.949	0.918
SCAN045	0.907	0.956	0.932
Average	0.860	0.932	0.897

Table 3.17: Cross-correlation coefficients of 21 lines.

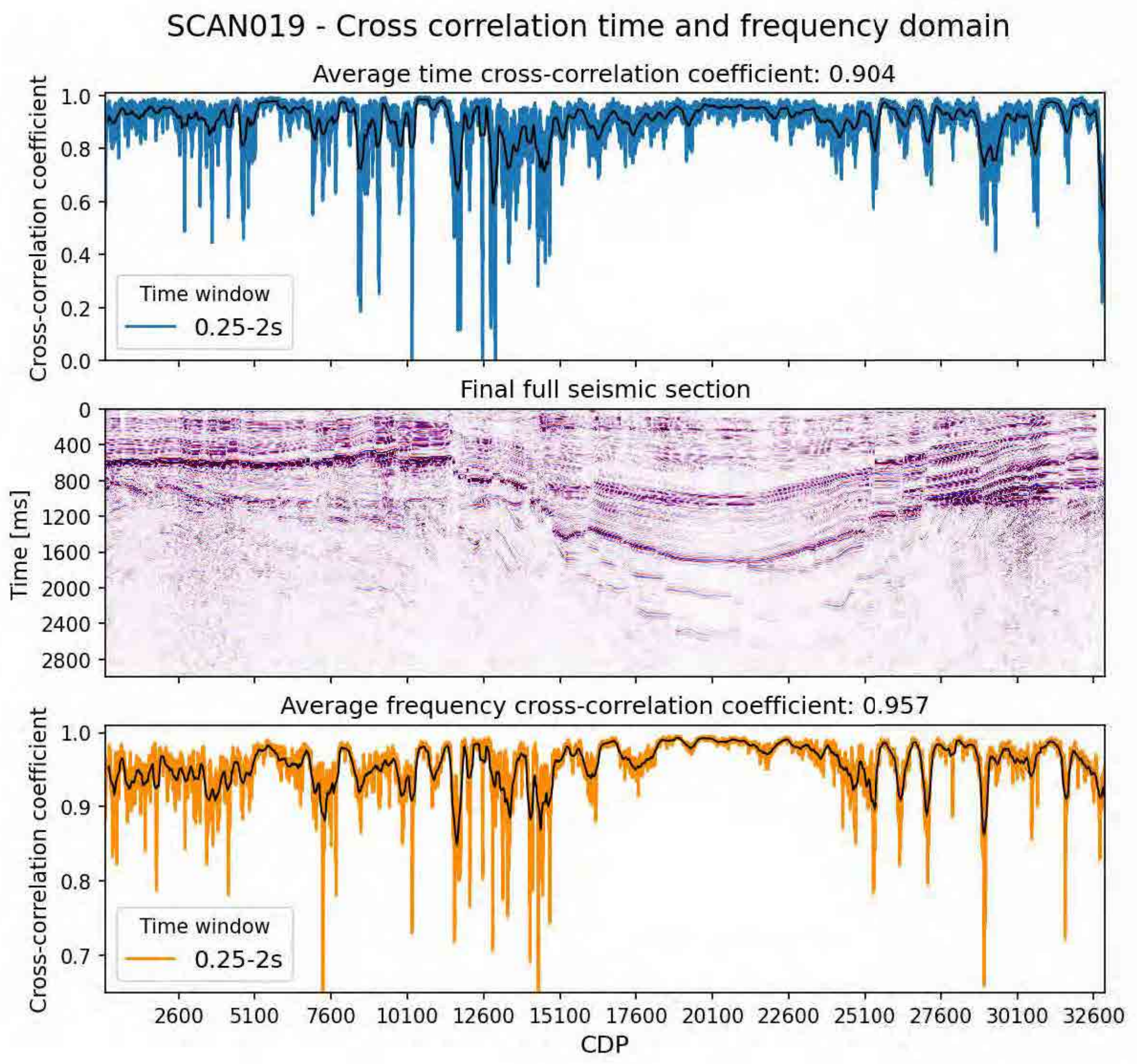


Figure 3.2.1: The cross-correlation in the time domain (blue), the frequency domain (orange) and in the middle the final seismic section is visible. Left is northeast, right is southwest.

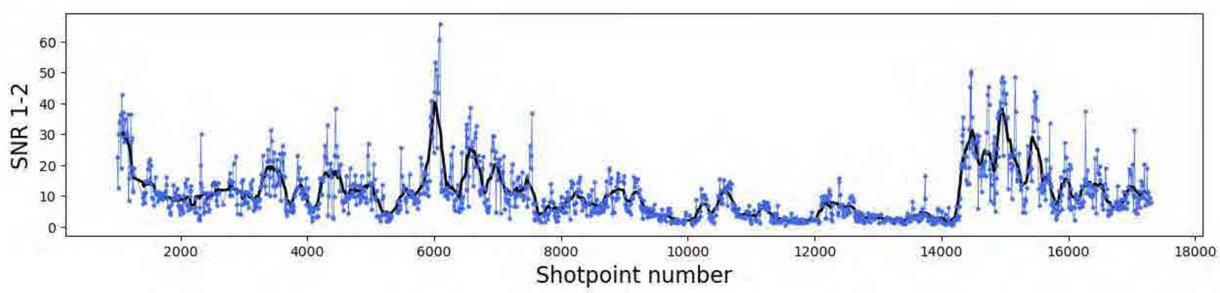


Figure 3.2.2: The SNR 1-2 values for line SCAN019. Data from Gossink (2021).

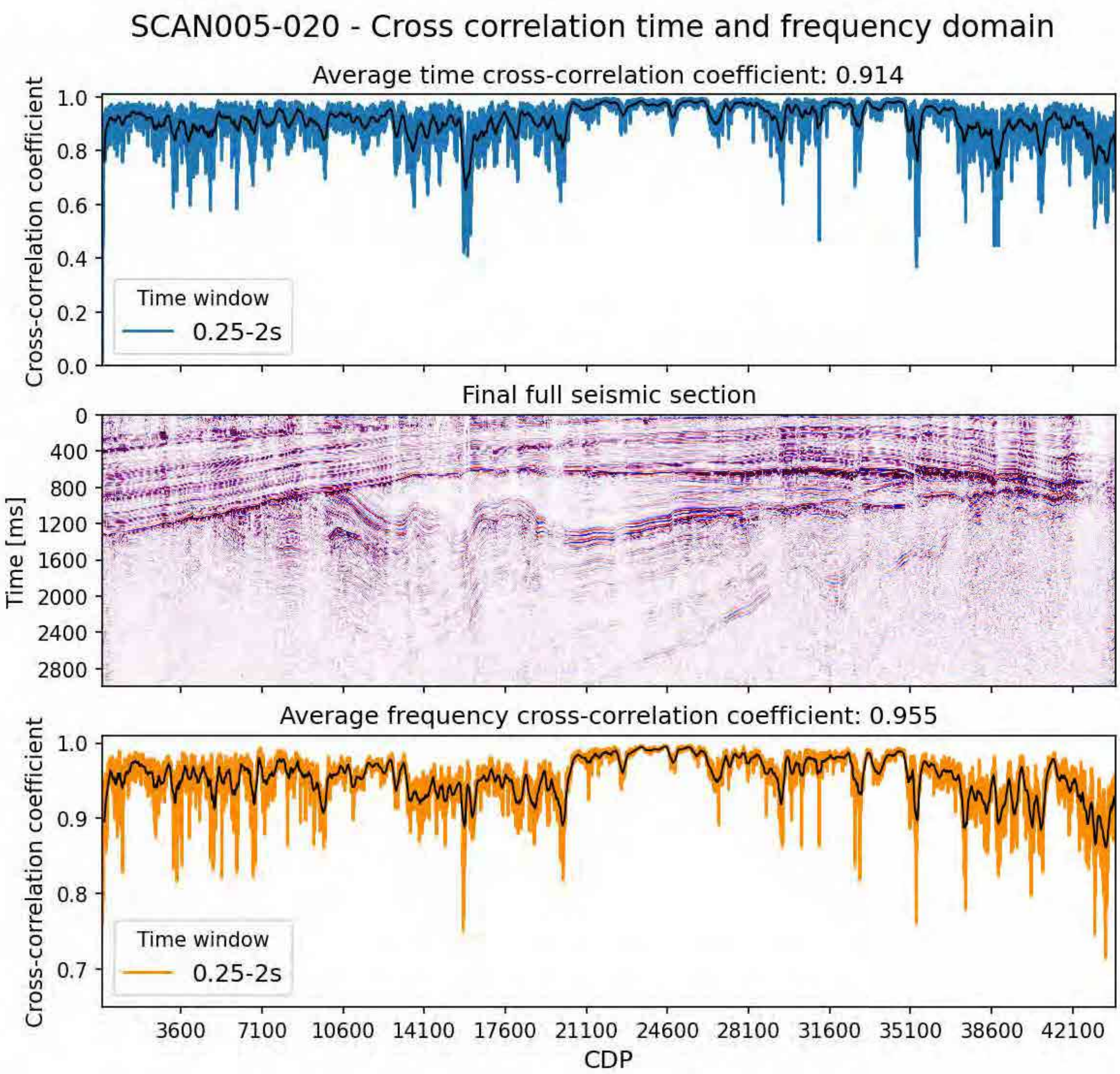


Figure 3.2.3: The cross-correlation in the time domain (blue), the frequency domain (orange) and in the middle the final seismic section is visible. Left is northwest, right is southeast.

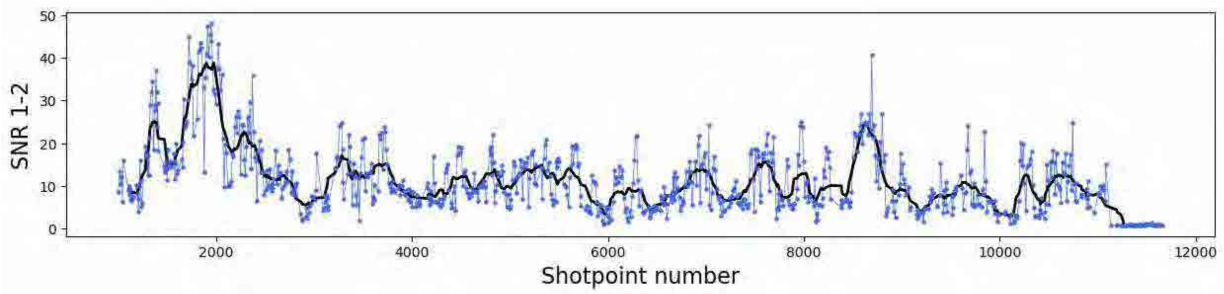


Figure 3.2.4: The SNR 1-2 values for line SCAN020. Data from Gossink (2021).

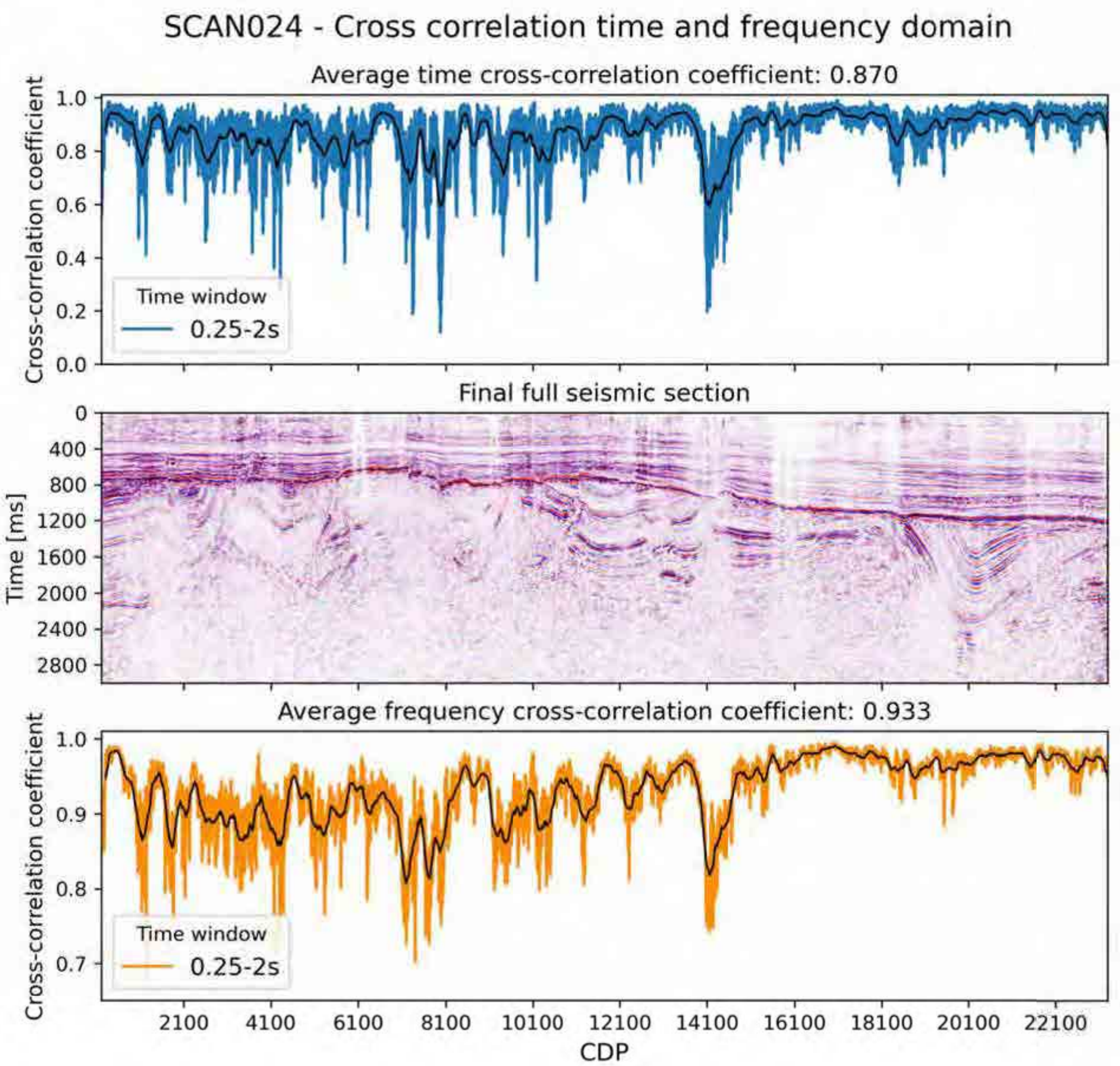


Figure 3.2.5: The cross-correlation in the time domain (blue), the frequency domain (orange) and in the middle the final seismic section is visible. Left is south, right is north.

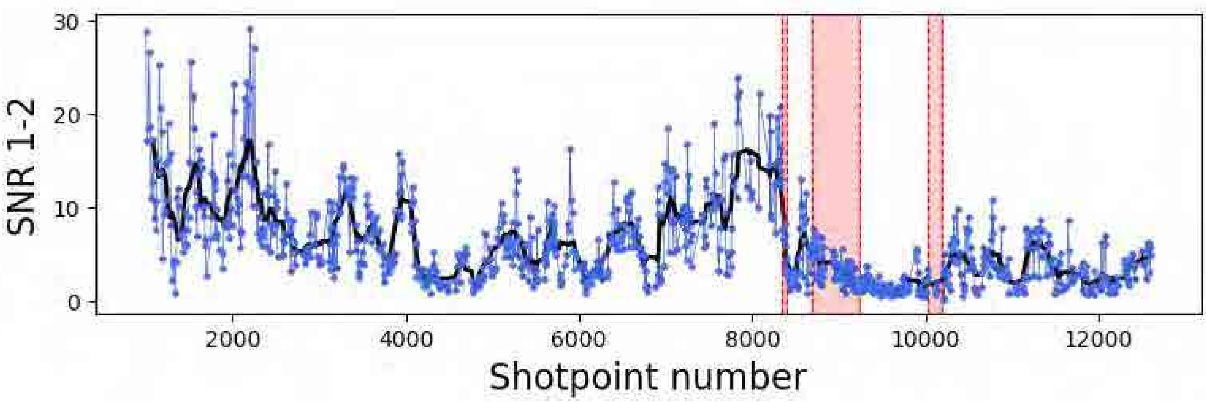


Figure 3.2.6: The SNR 1-2 values for line SCAN024. The red dashed lines enclose the hydrophone regions.

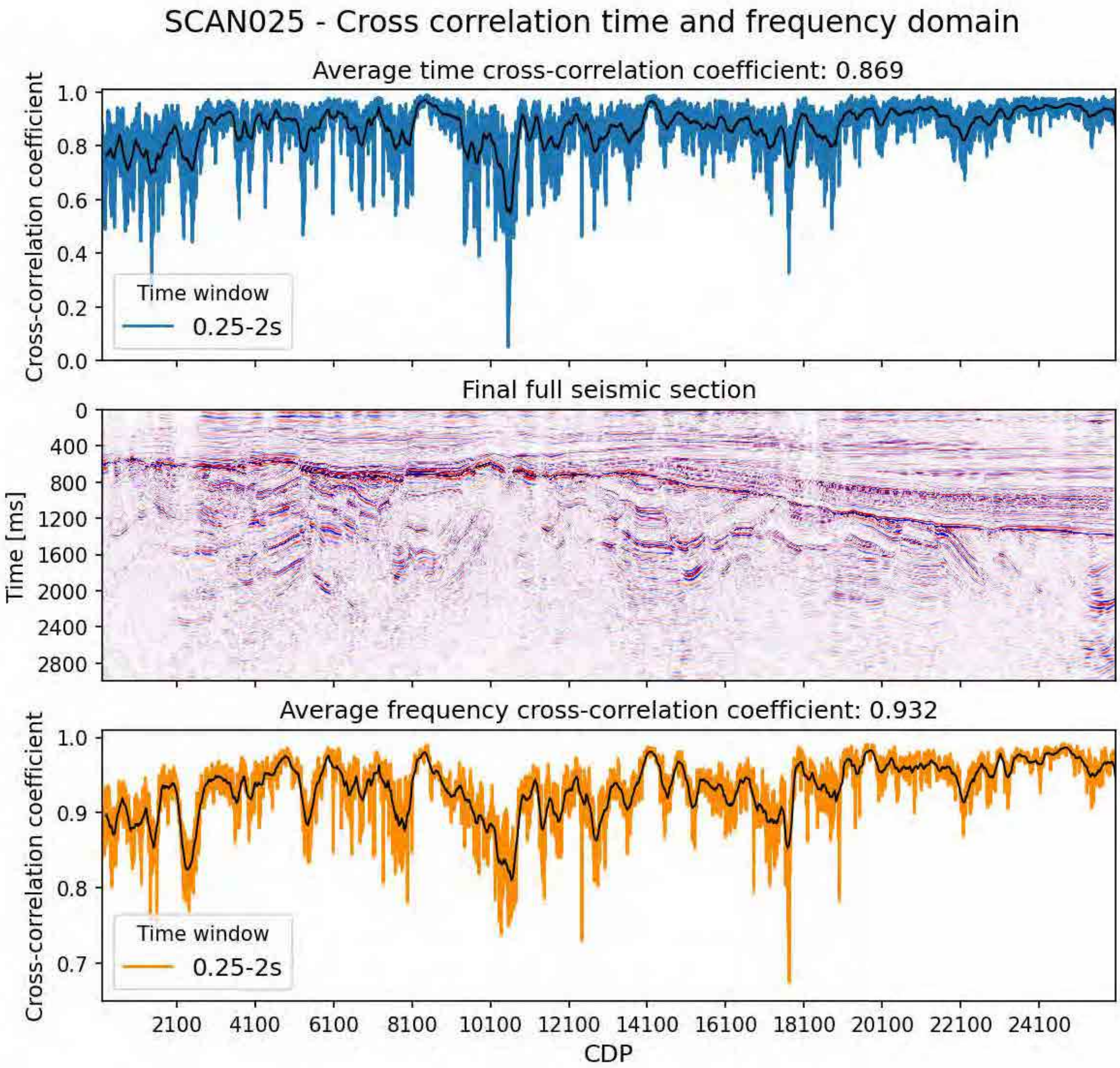


Figure 3.2.7: The cross-correlation in the time domain (blue), the frequency domain (orange) and in the middle the final seismic section is visible. Left is southwest, right is northeast.

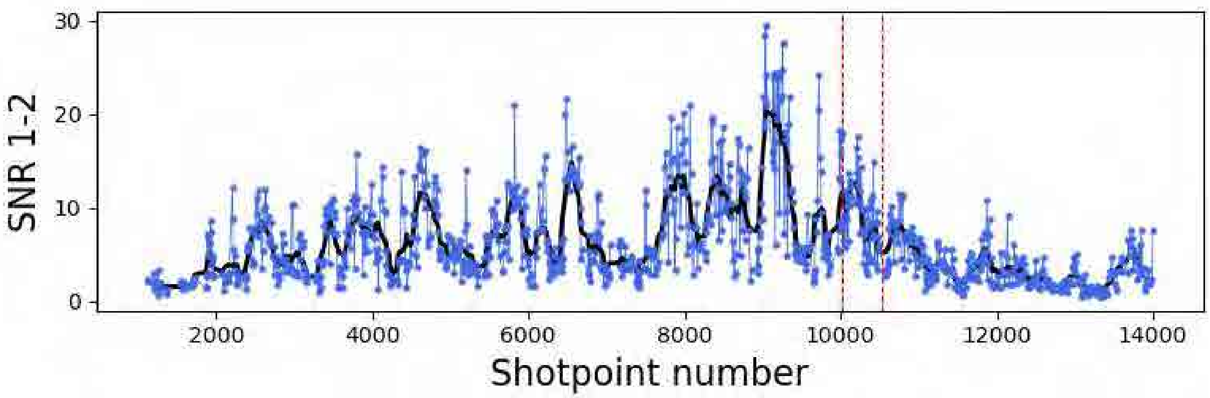


Figure 3.2.8: The SNR 1-2 values for line SCAN025. The red dashed lines indicate the hydrophone region.

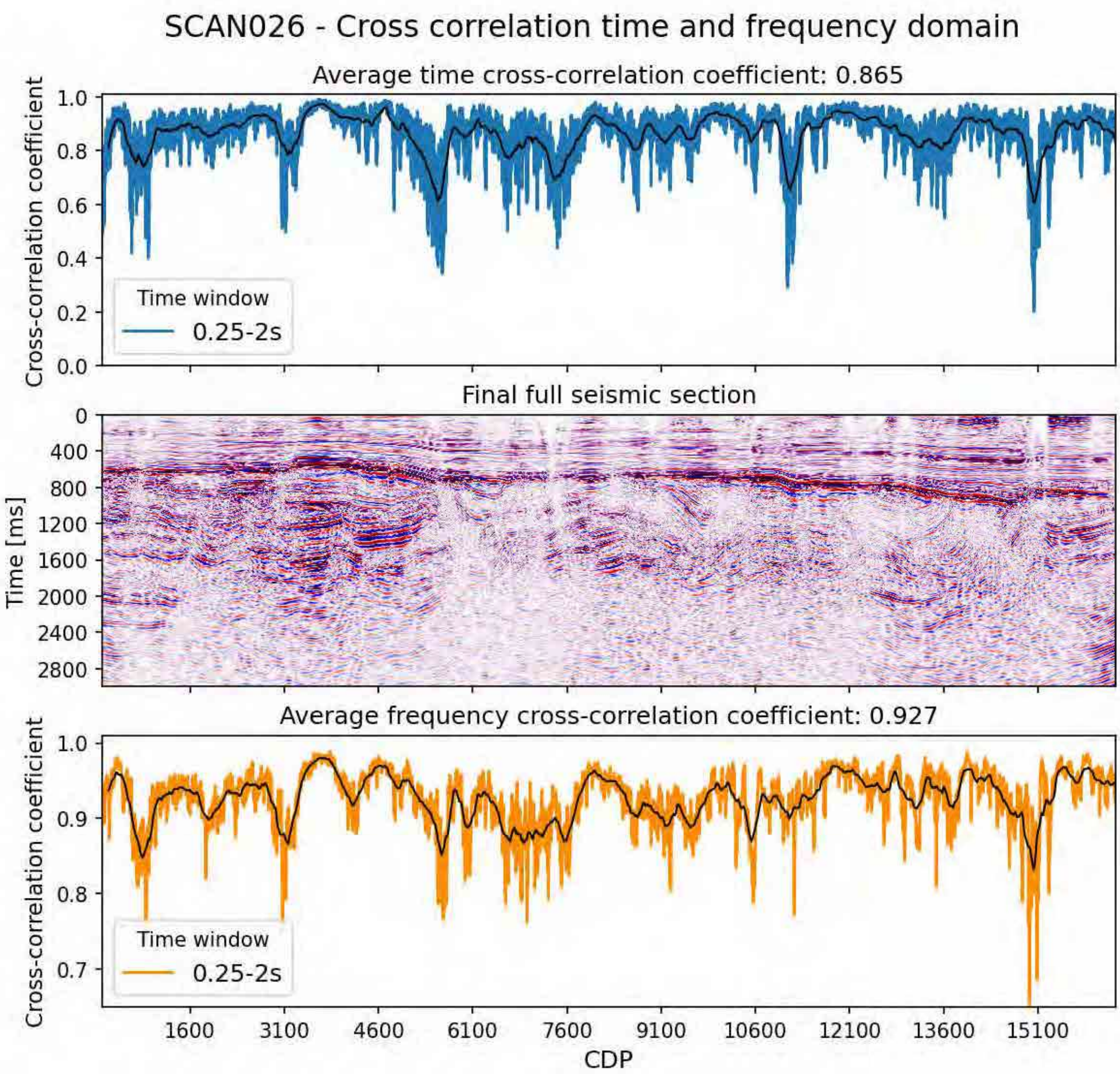


Figure 3.2.9: The cross-correlation in the time domain (blue), the frequency domain (orange) and in the middle the final seismic section is visible. Left is south, right is north.

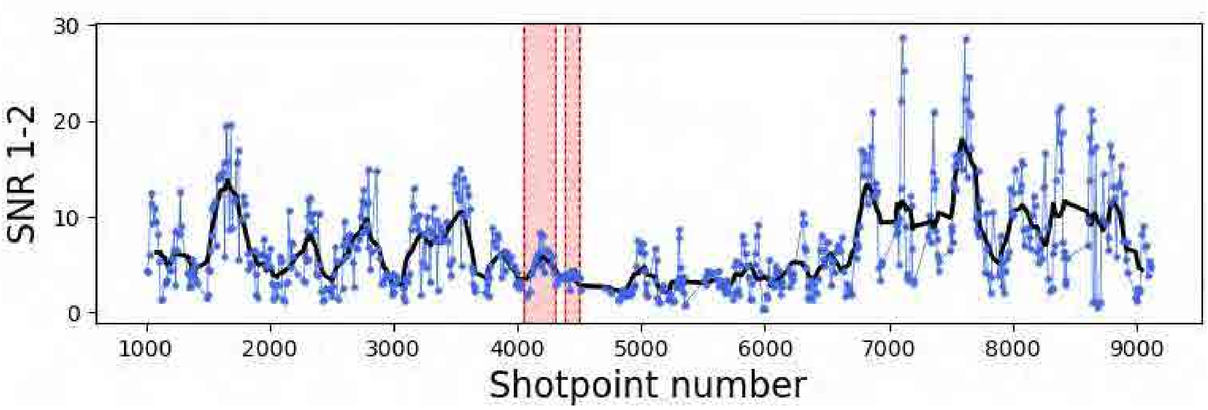


Figure 3.2.10: The SNR 1-2 values for line SCAN026. The red dashed lines indicate the hydrophone regions.

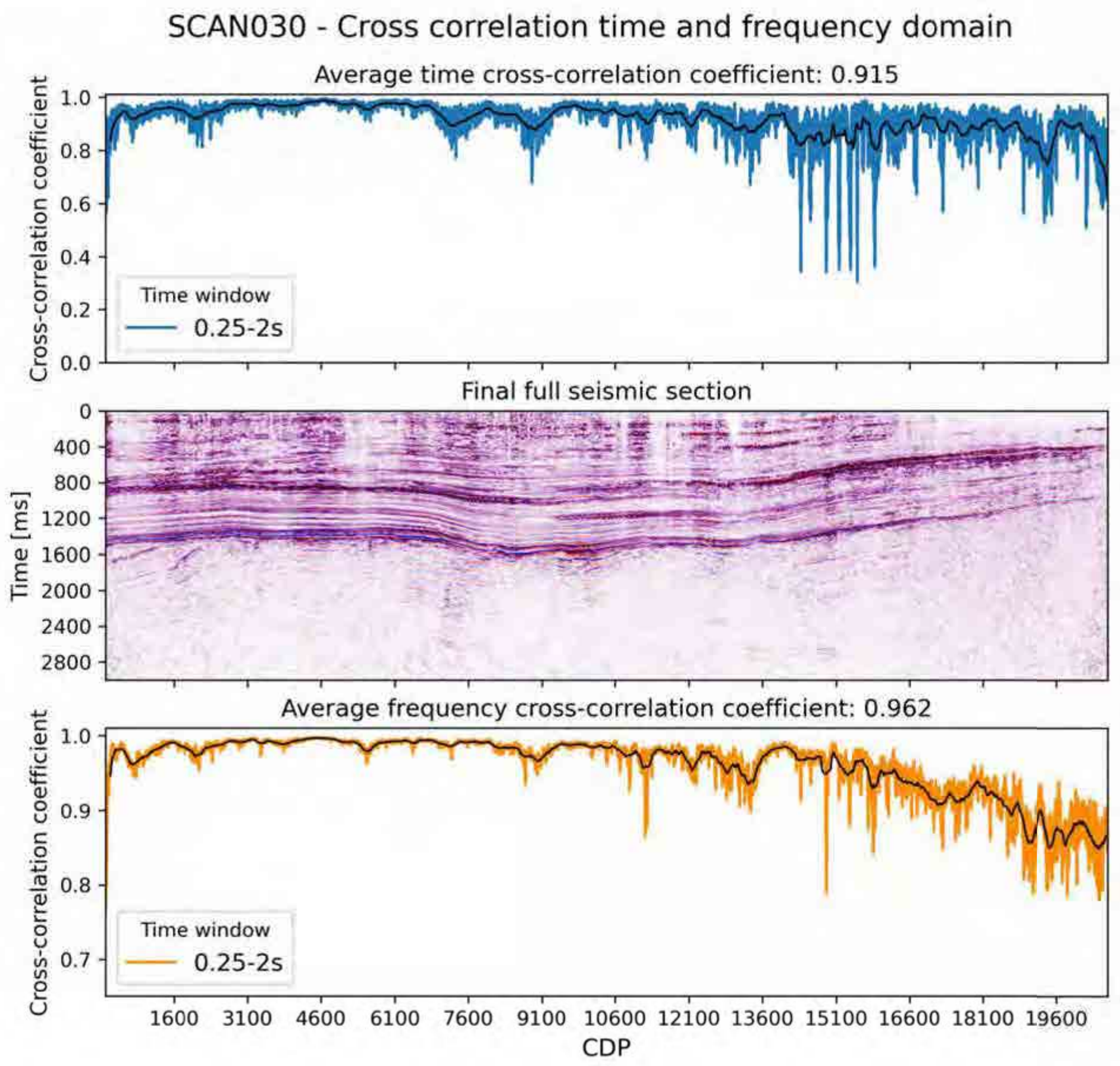


Figure 3.2.11: The cross-correlation in the time domain (blue), the frequency domain (orange) and in the middle the final seismic section is visible. Left is northwest, right is southeast.

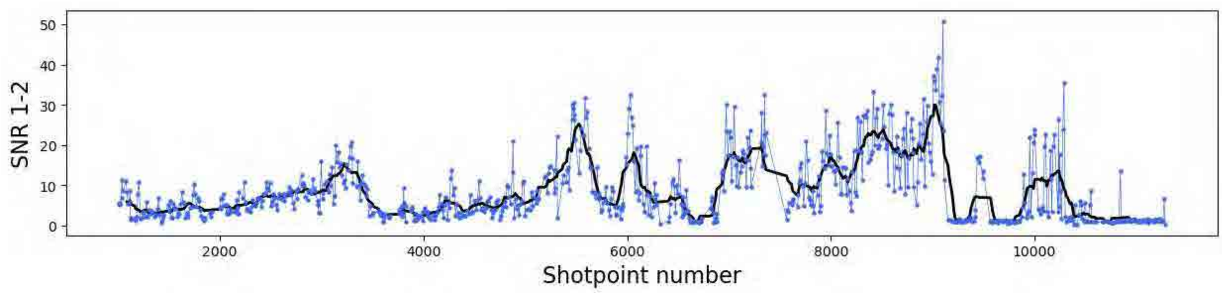


Figure 3.2.12: The SNR 1-2 values for line SCAN030. Data from Gossink (2021).

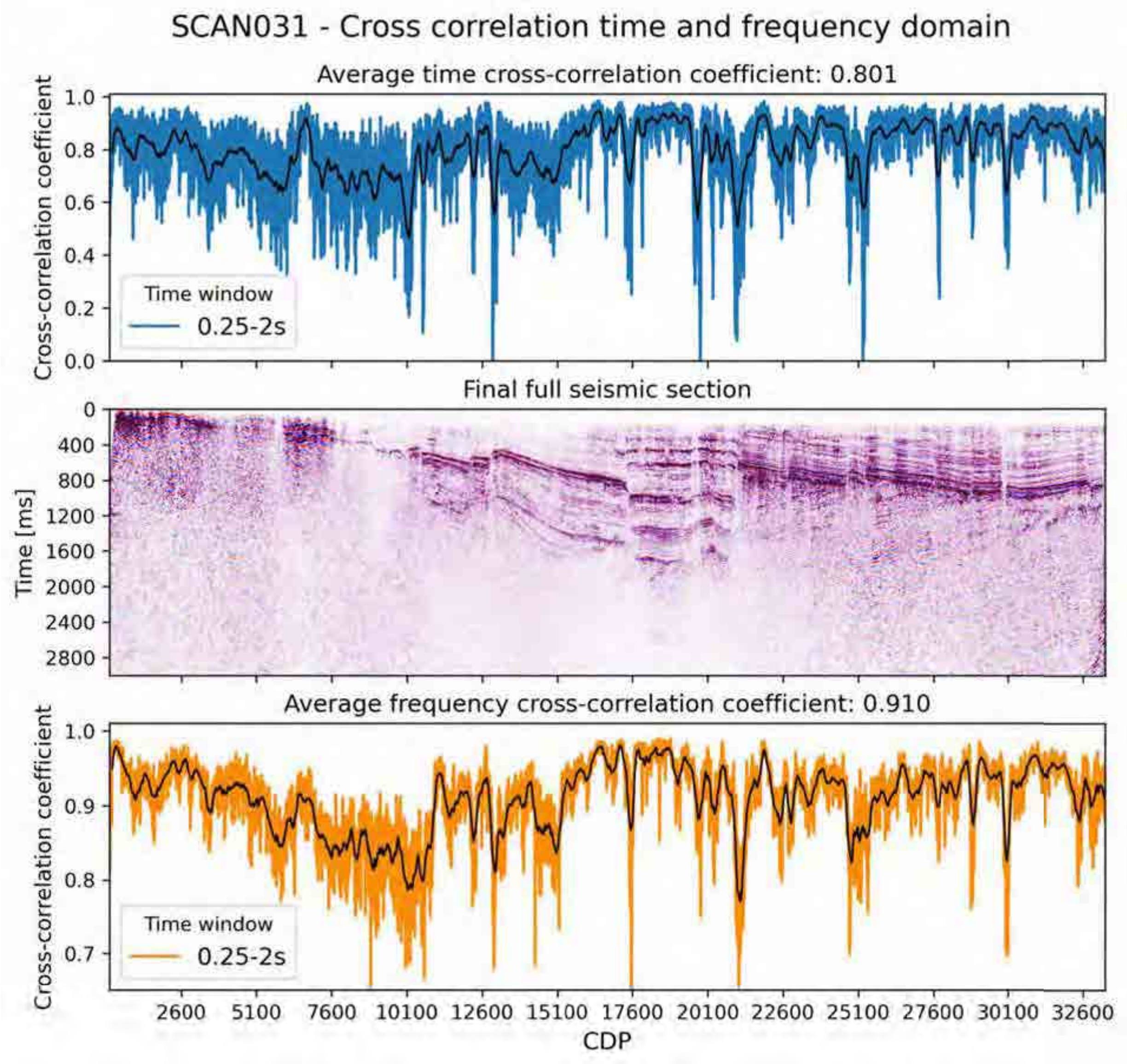


Figure 3.2.13: The cross-correlation in the time domain (blue), the frequency domain (orange) and in the middle the final seismic section is visible. Left is north, right is south.

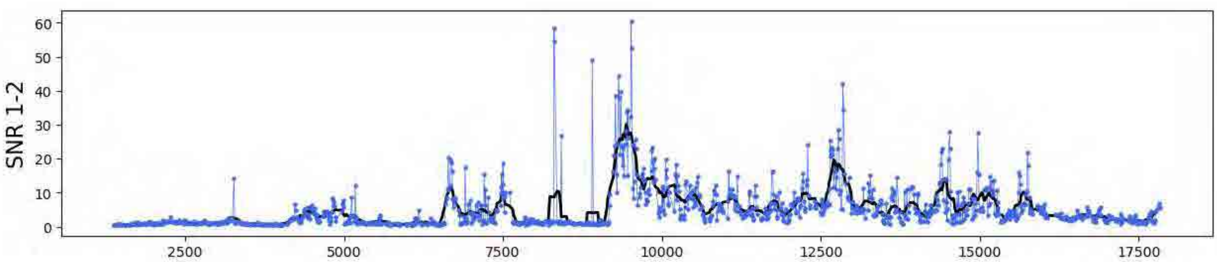


Figure 3.2.14: The SNR 1-2 values for line SCAN031. Data from Gossink (2021).

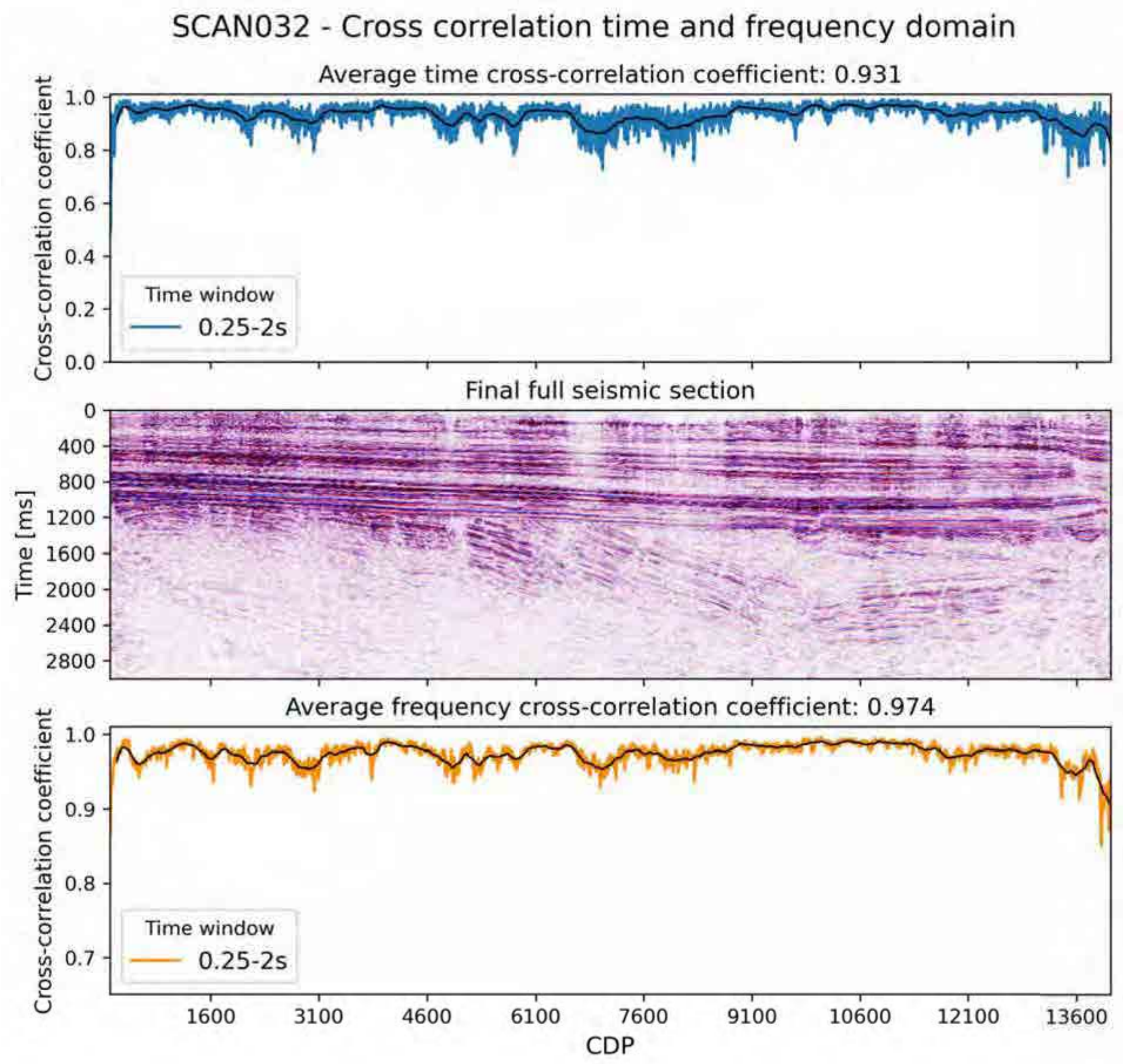


Figure 3.2.15: The cross-correlation in the time domain (blue), the frequency domain (orange) and in the middle the final seismic section is visible. Left is southwest, right is northeast.

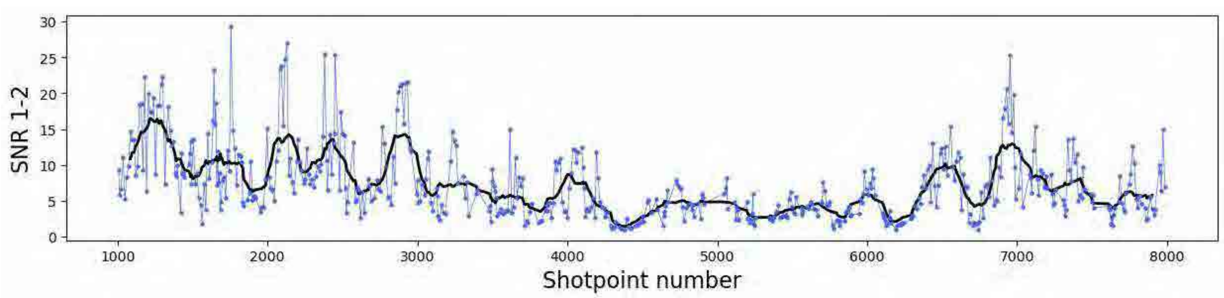


Figure 3.2.16: The SNR 1-2 values for line SCAN032. Data from Gossink (2021).

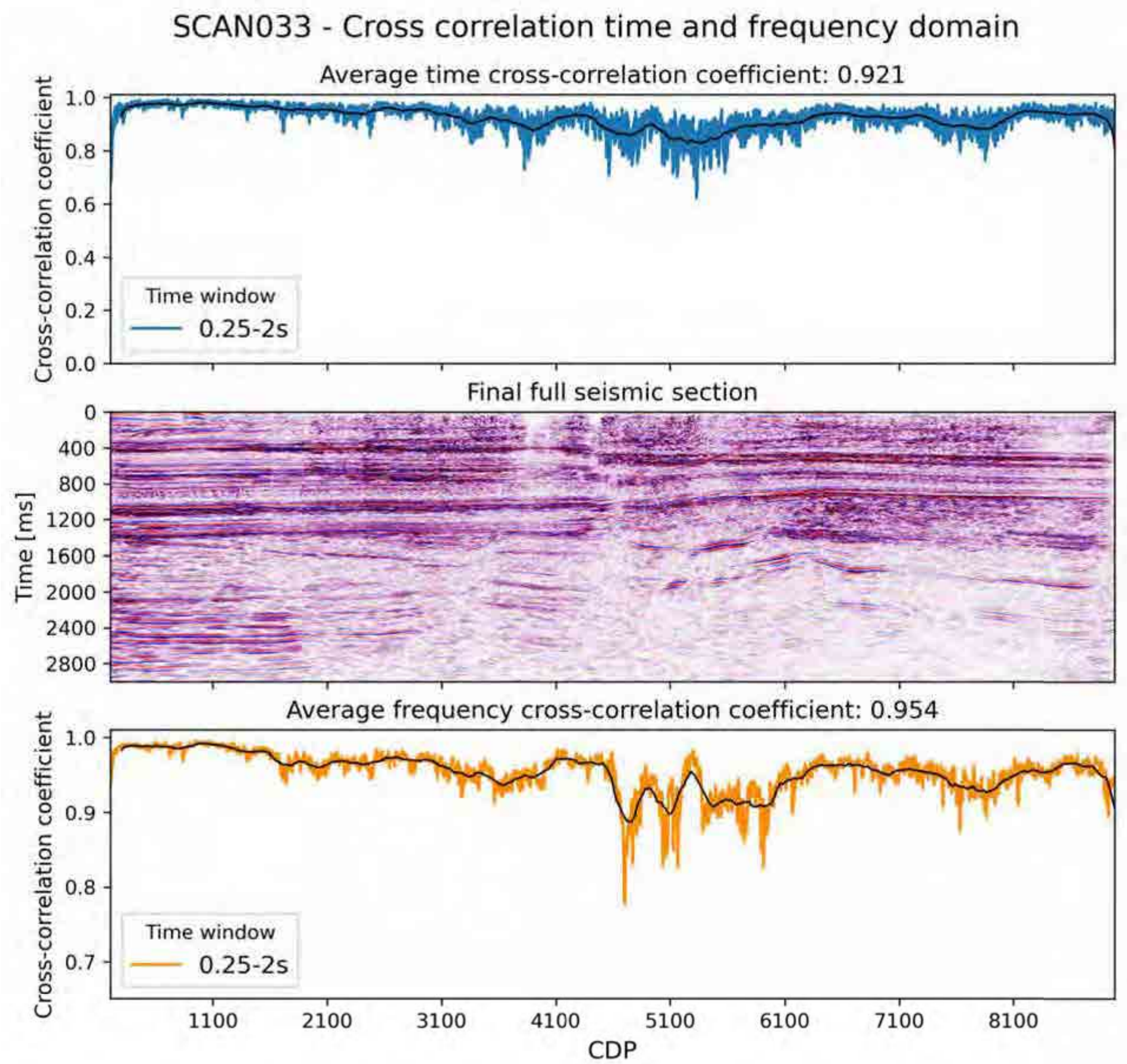


Figure 3.2.17: The cross-correlation in the time domain (blue), the frequency domain (orange) and in the middle the final seismic section is visible. Left is northwest, right is southeast.

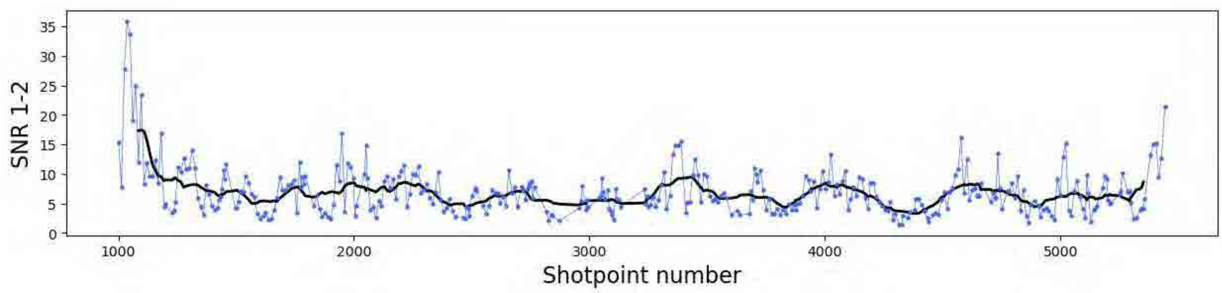


Figure 3.2.18: The SNR 1-2 values for line SCAN033. Data from Gossink (2021).

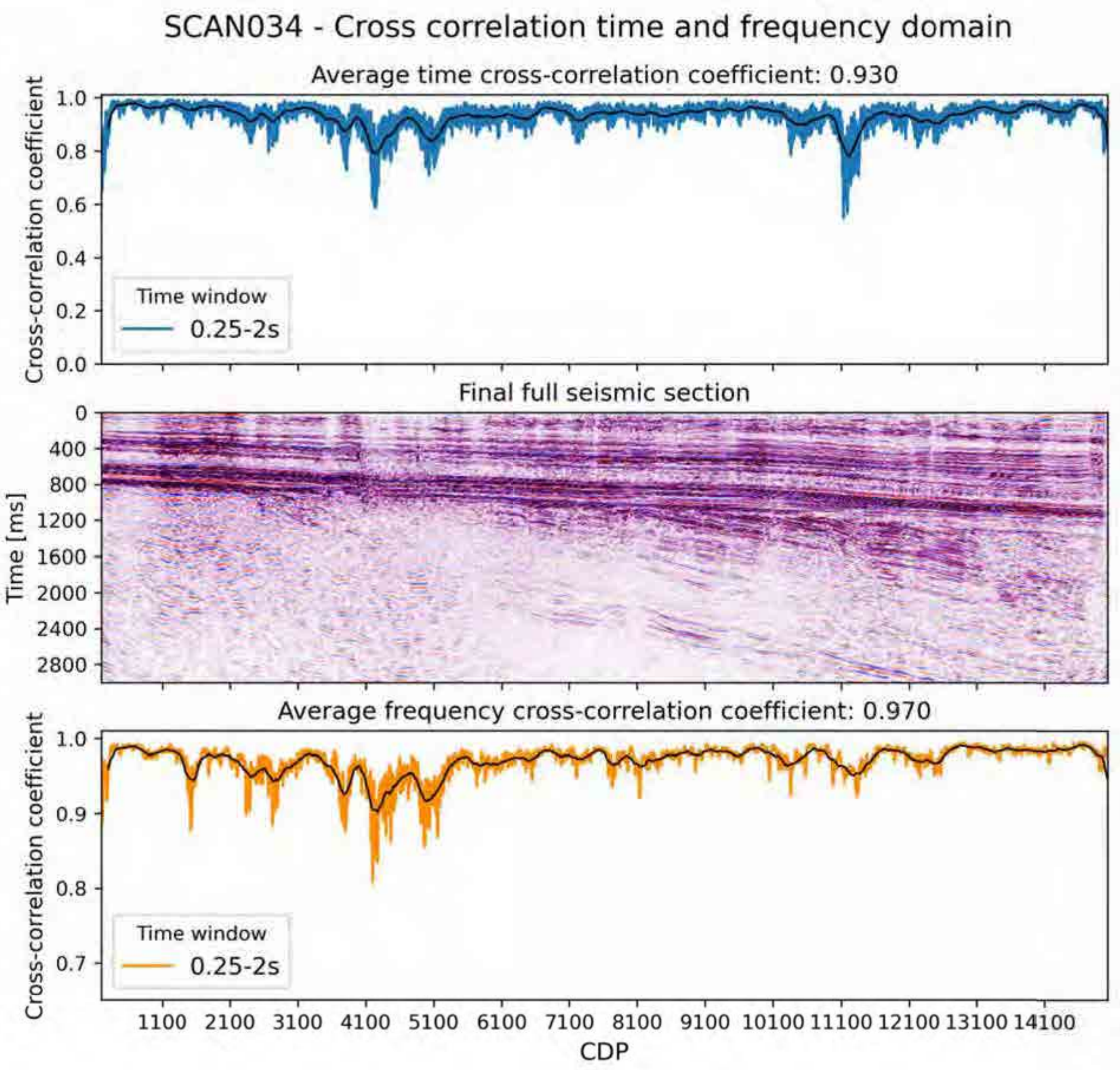


Figure 3.2.19: The cross-correlation in the time domain (blue), the frequency domain (orange) and in the middle the final seismic section is visible. Left is south, right is north.

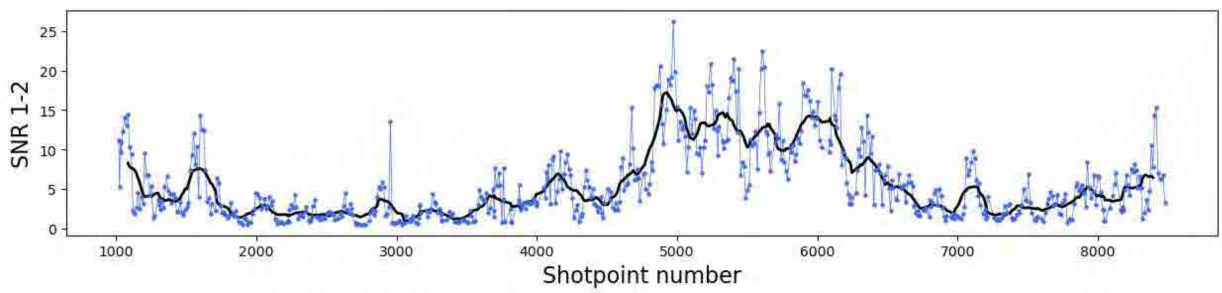


Figure 3.2.20: The SNR 1-2 values for line SCAN034. Data from Gossink (2021).

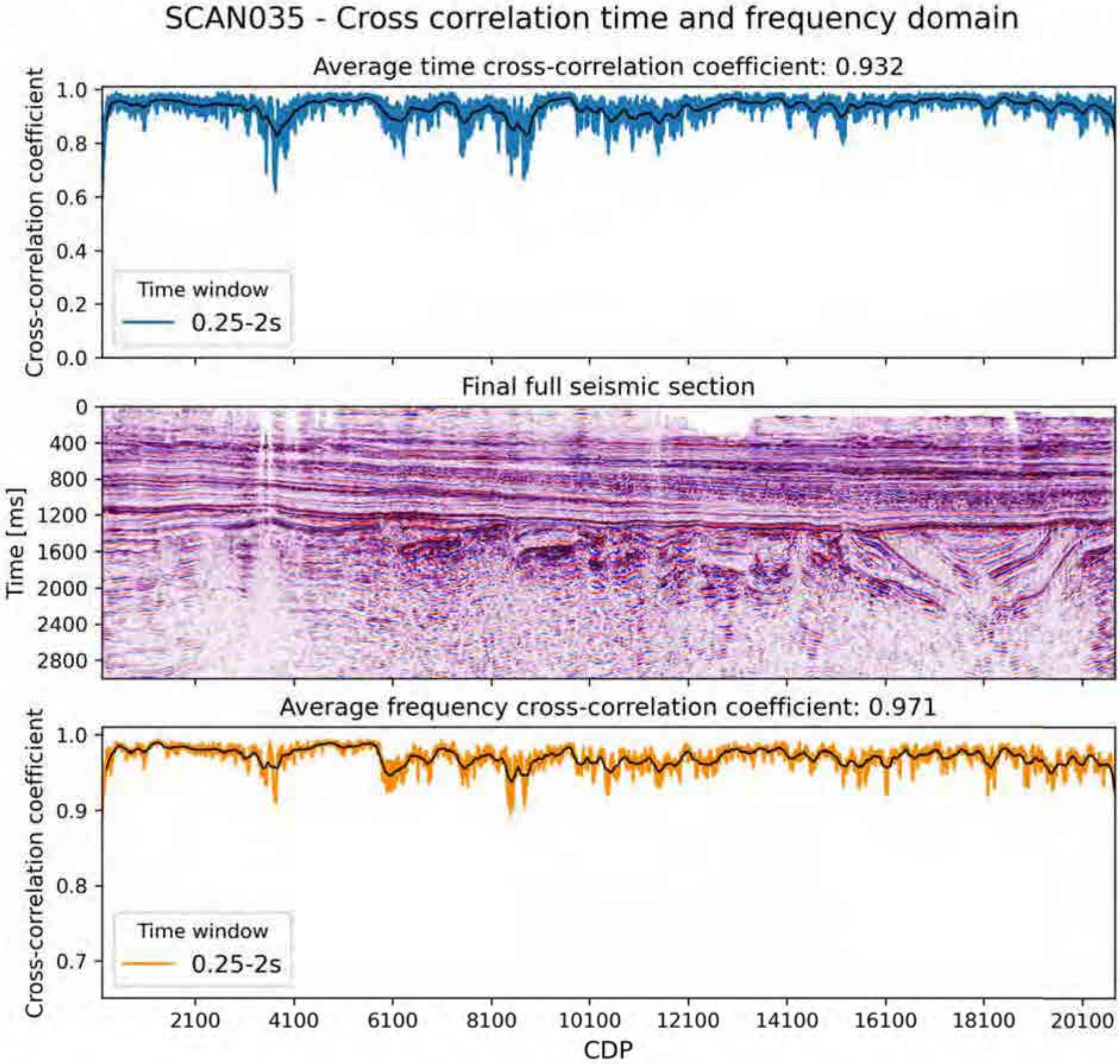


Figure 3.2.21: The cross-correlation in the time domain (blue), the frequency domain (orange) and in the middle the final seismic section is visible. Left is northeast, right is southwest.

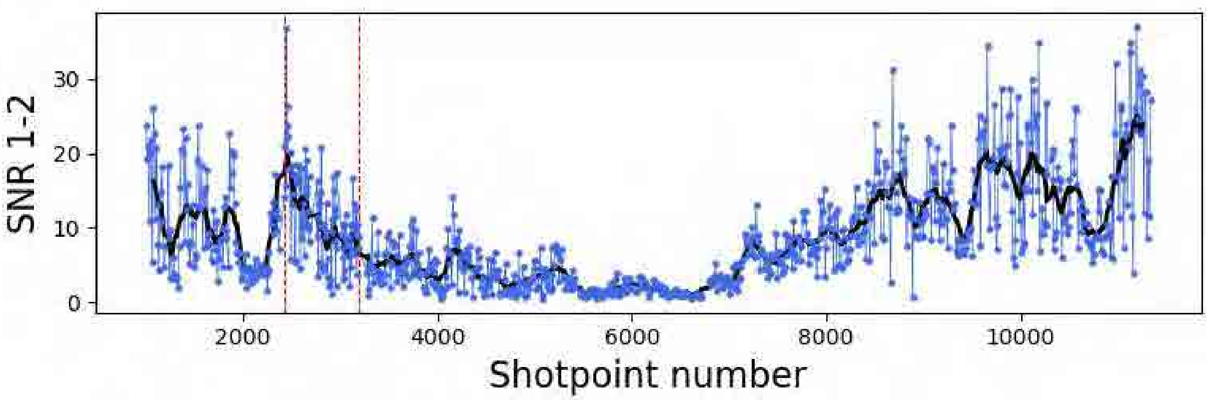


Figure 3.2.22: The SNR 1-2 values for line SCAN035. The red dashed lines indicate the hydrophone region.

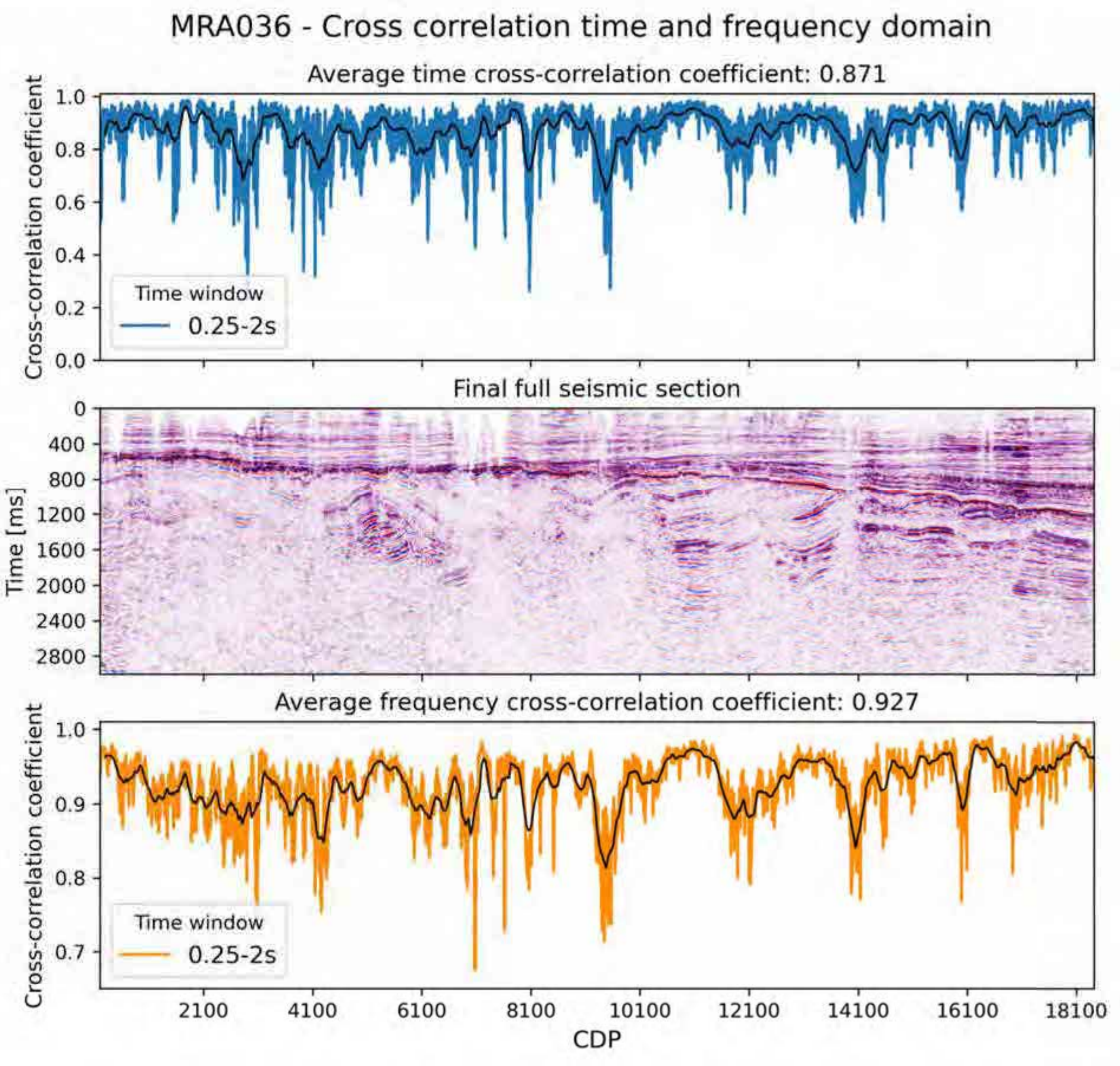


Figure 3.2.23: The cross-correlation in the time domain (blue), the frequency domain (orange) and in the middle the final seismic section is visible. Left is southwest, right is northeast.

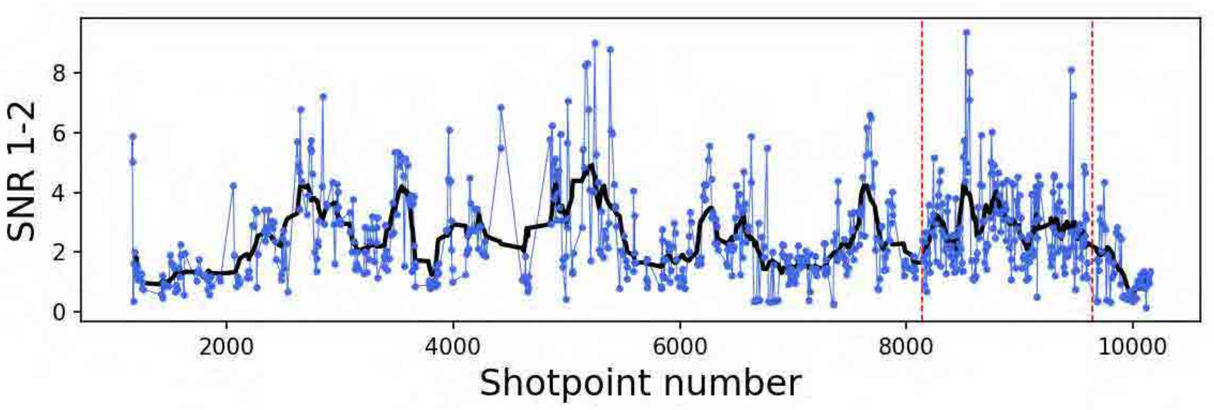


Figure 3.2.24: The SNR 1-2 values for line MRA036. The red dashed lines indicate the hydrophone region.

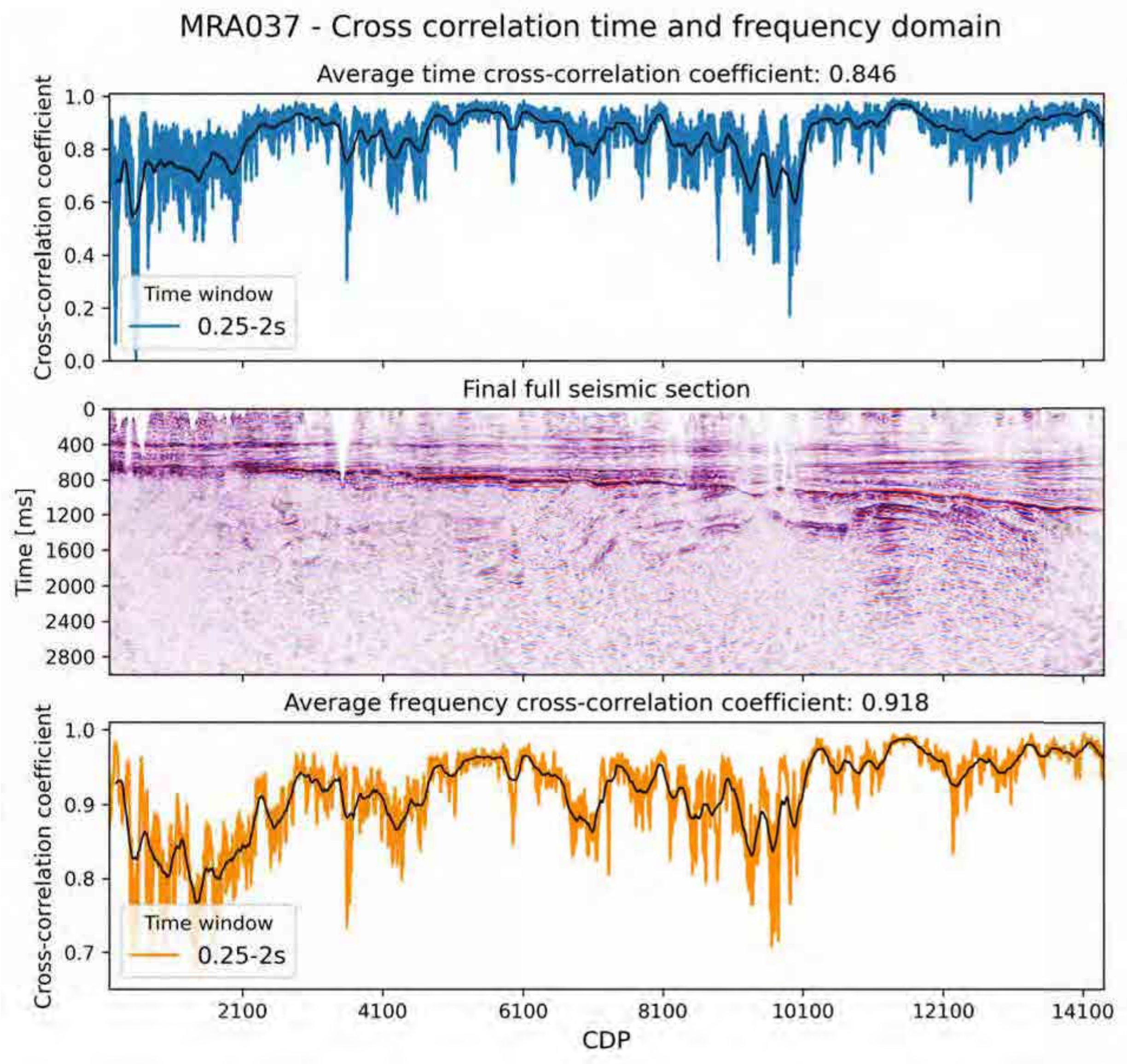


Figure 3.2.25: The cross-correlation in the time domain (blue), the frequency domain (orange) and in the middle the final seismic section is visible. Left is southwest, right is northeast.

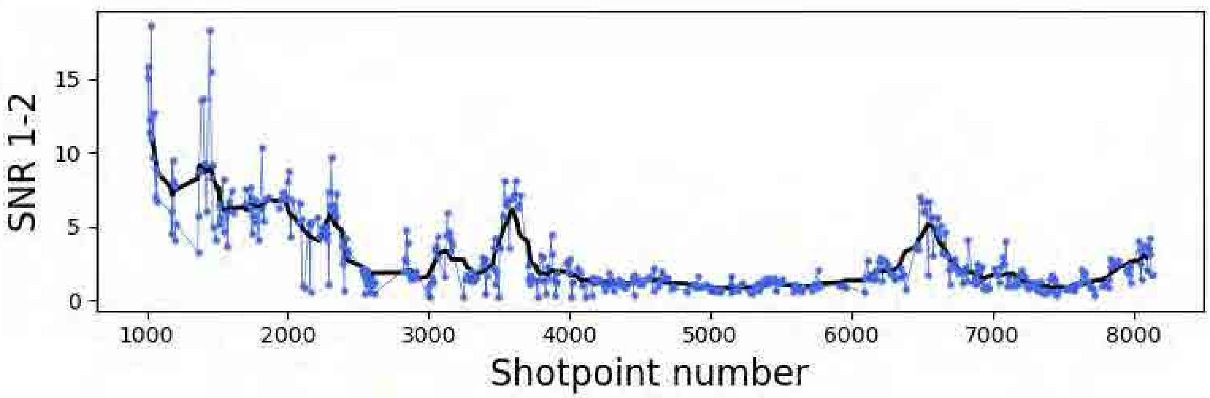


Figure 3.2.26: The SNR 1-2 values for line MRA037.

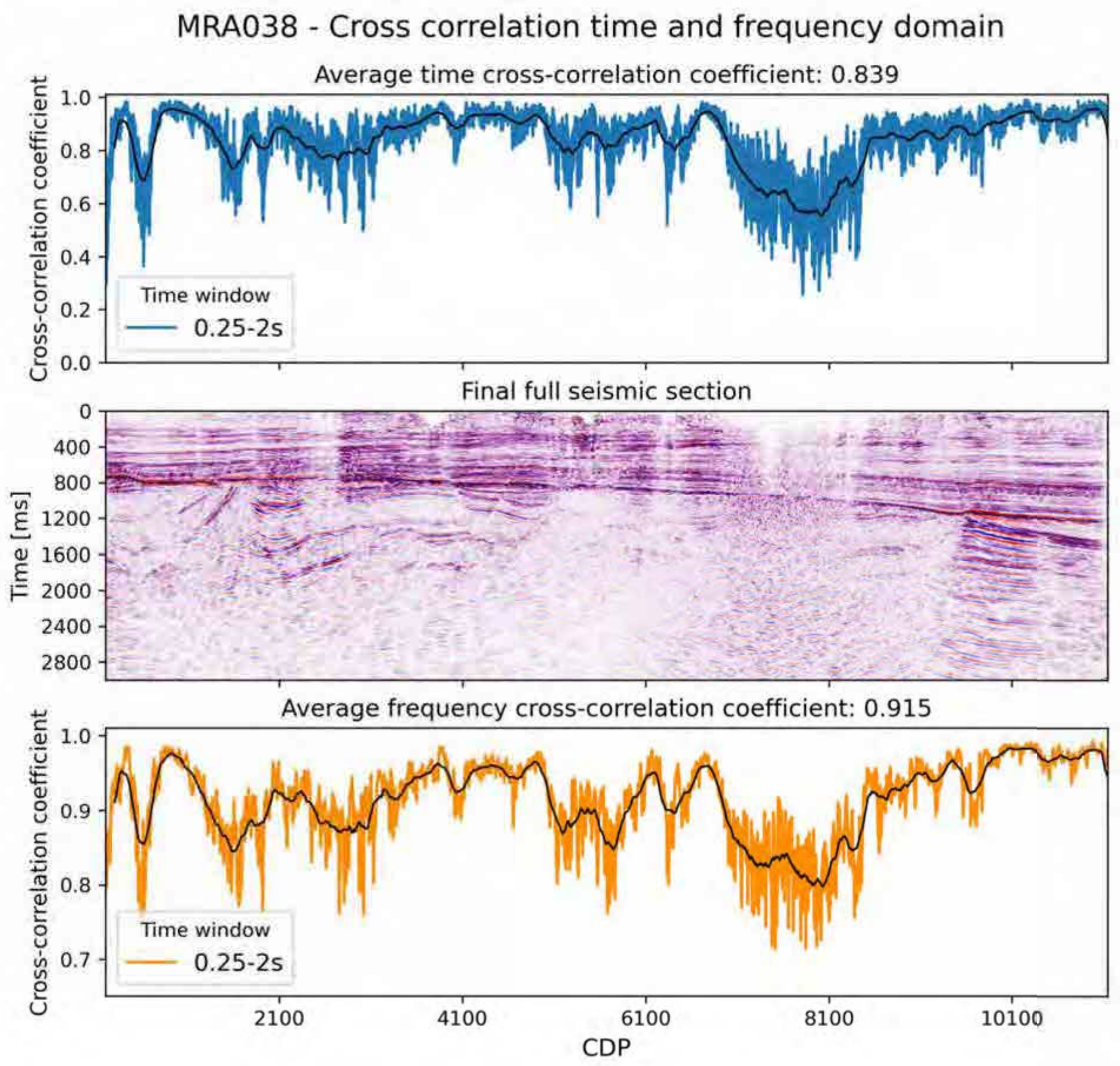


Figure 3.2.27: The cross-correlation in the time domain (blue), the frequency domain (orange) and in the middle the final seismic section is visible. Left is southwest, right is northeast.

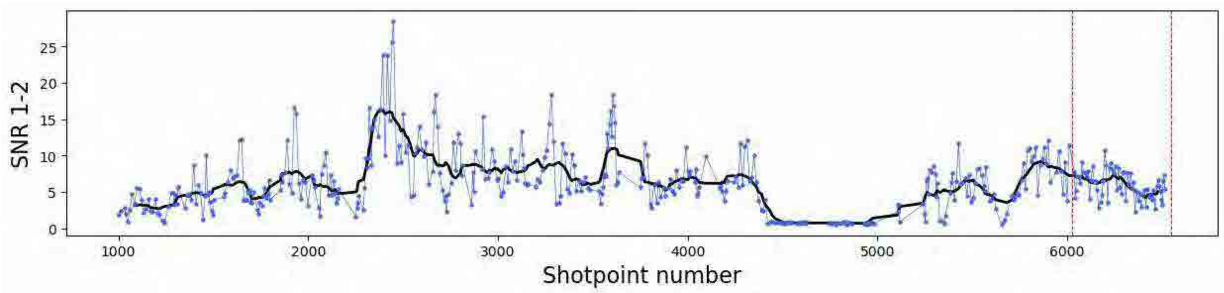


Figure 3.2.28: The SNR 1-2 values for line MRA038. The red dashed lines indicate the hydrophone region.

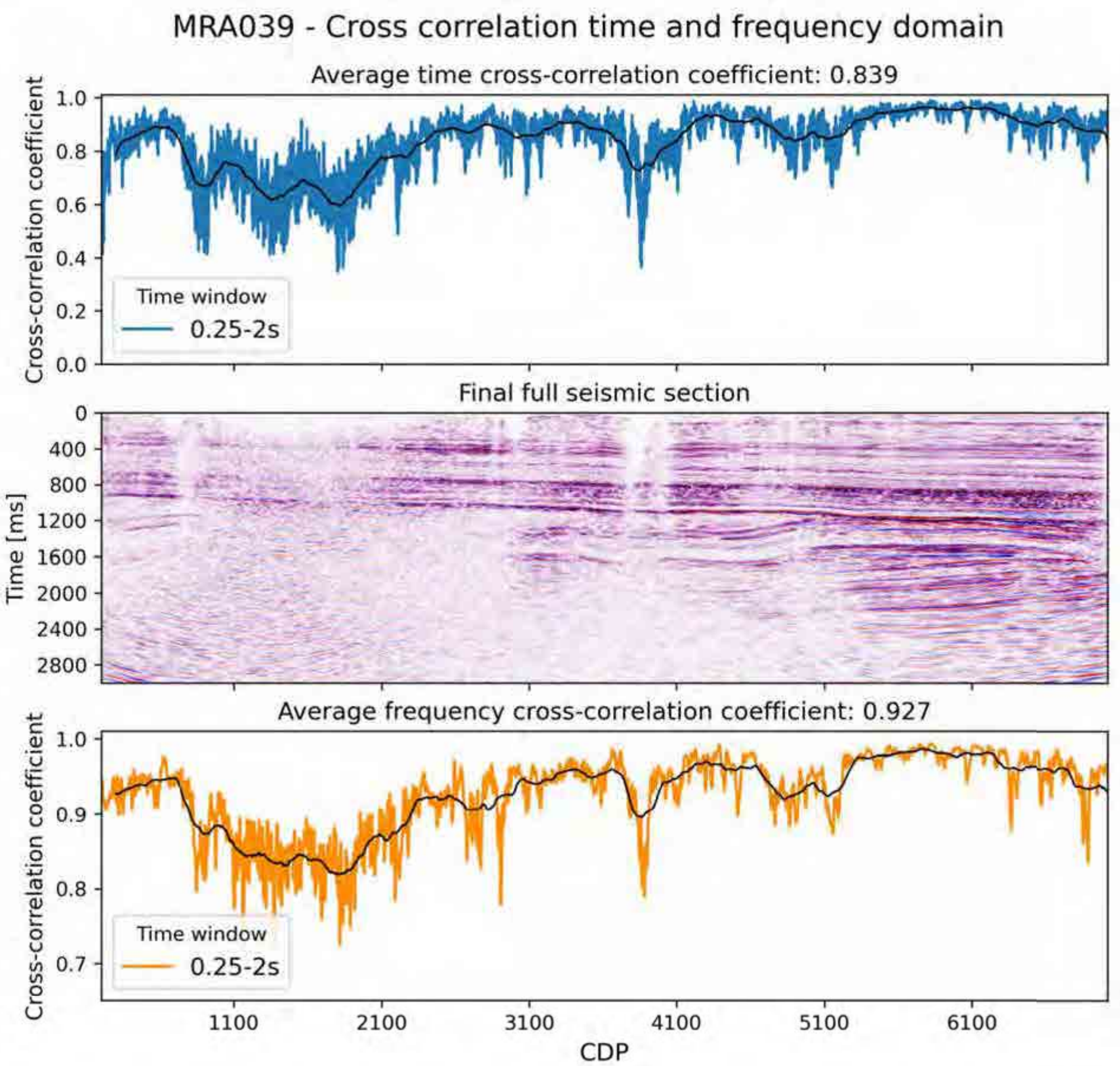


Figure 3.2.29: The cross-correlation in the time domain (blue), the frequency domain (orange) and in the middle the final seismic section is visible. Left is southeast, right is northwest.

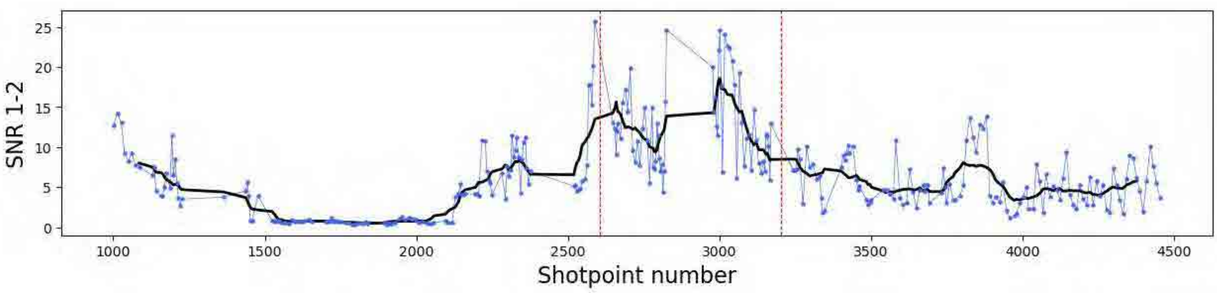


Figure 3.2.30: The SNR 1-2 values for line MRA039. The red dashed lines indicate the hydrophone region.

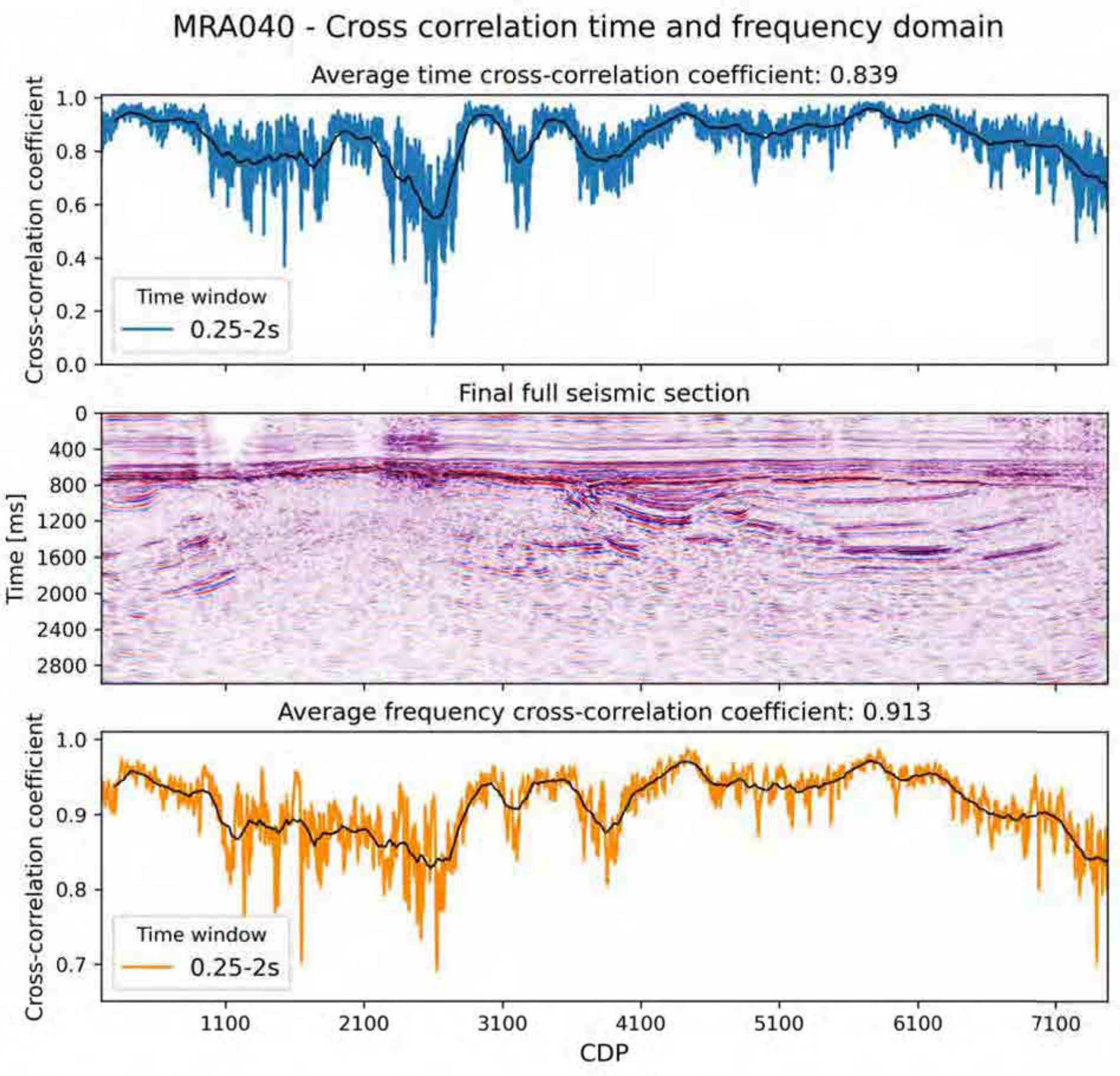


Figure 3.2.31: The cross-correlation in the time domain (blue), the frequency domain (orange) and in the middle the final seismic section is visible. Left is south, right is north.

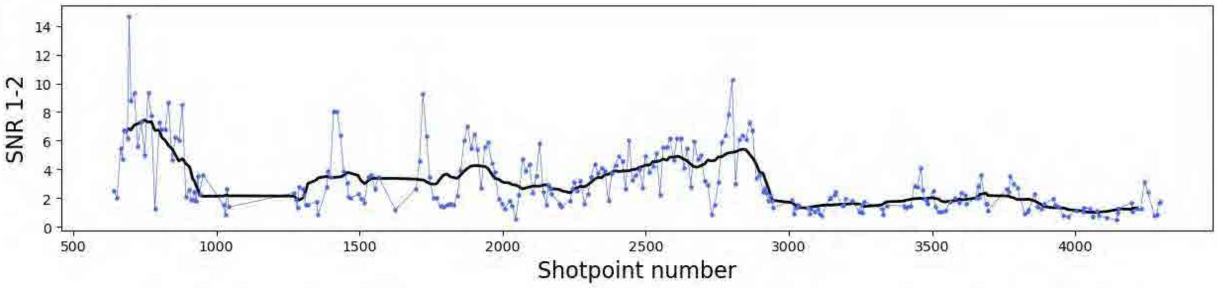


Figure 3.2.32: The SNR 1-2 values for line MRA040.

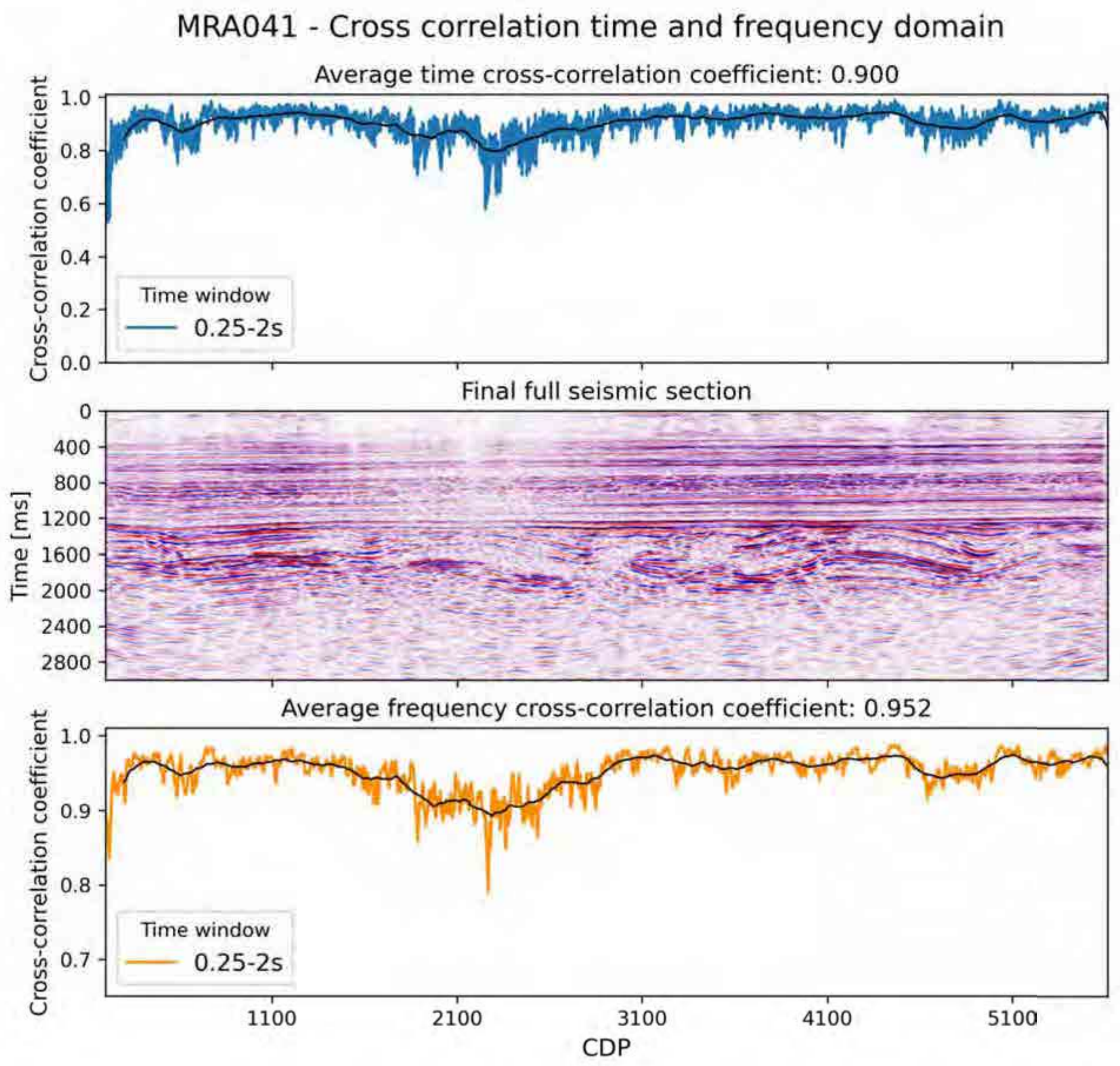


Figure 3.2.33: The cross-correlation in the time domain (blue), the frequency domain (orange) and in the middle the final seismic section is visible. Left is southwest, right is northeast.

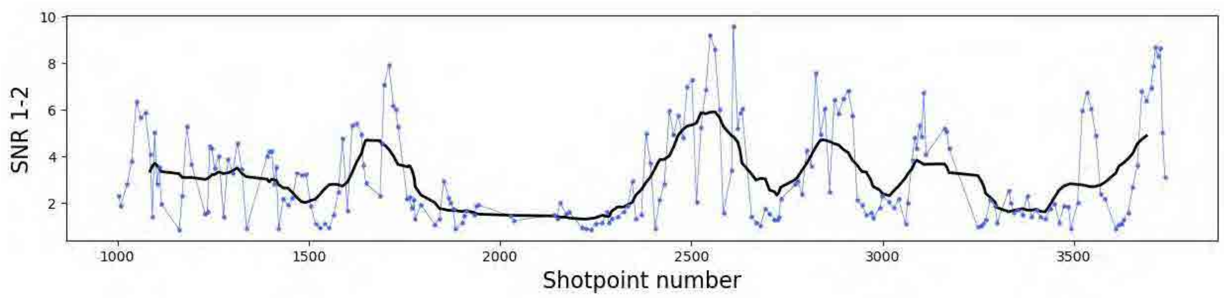


Figure 3.2.34: The SNR 1-2 values for line MRA041.

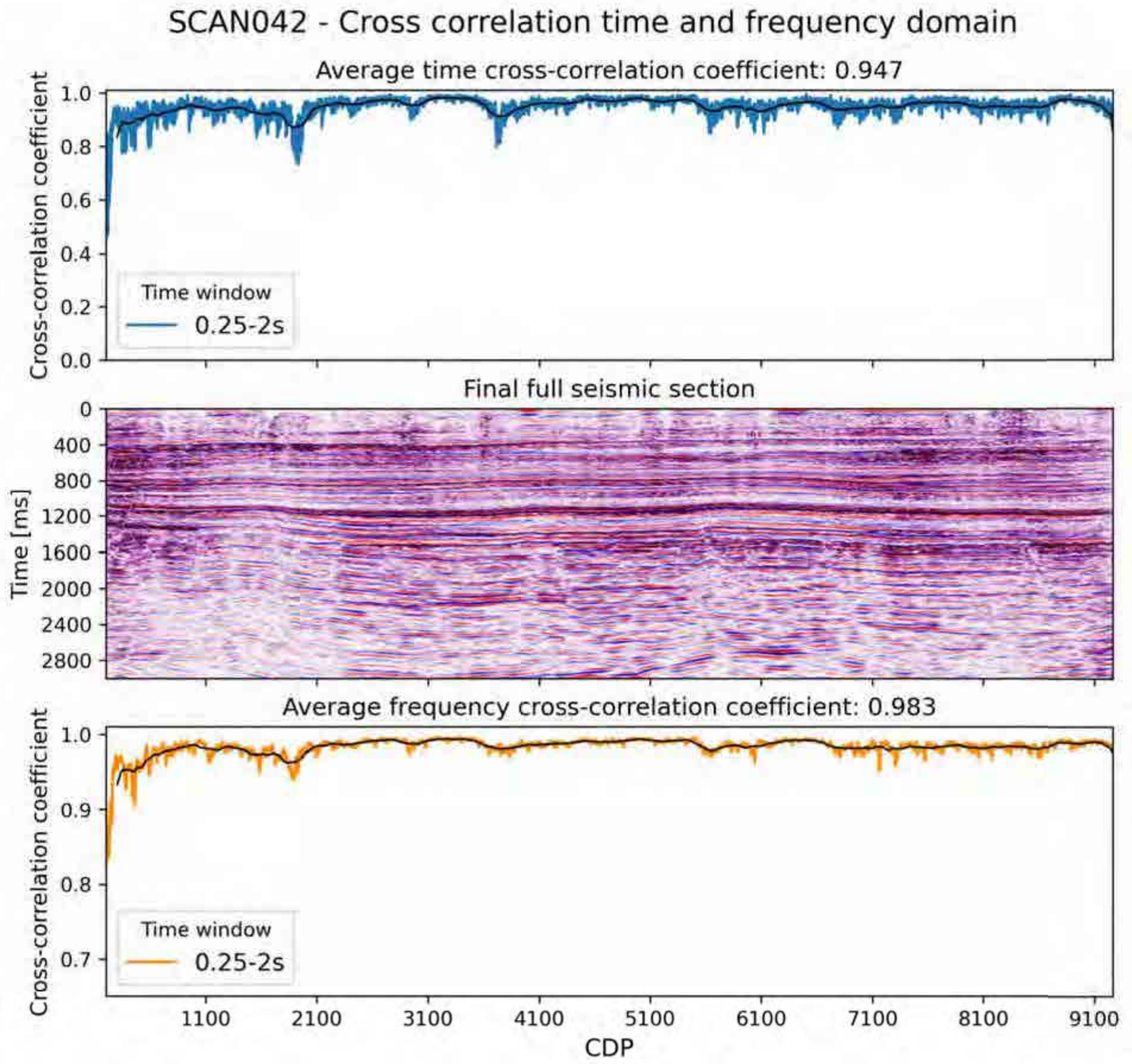


Figure 3.2.35: The cross-correlation in the time domain (blue), the frequency domain (orange) and in the middle the final seismic section is visible. Left is southwest, right is northeast.

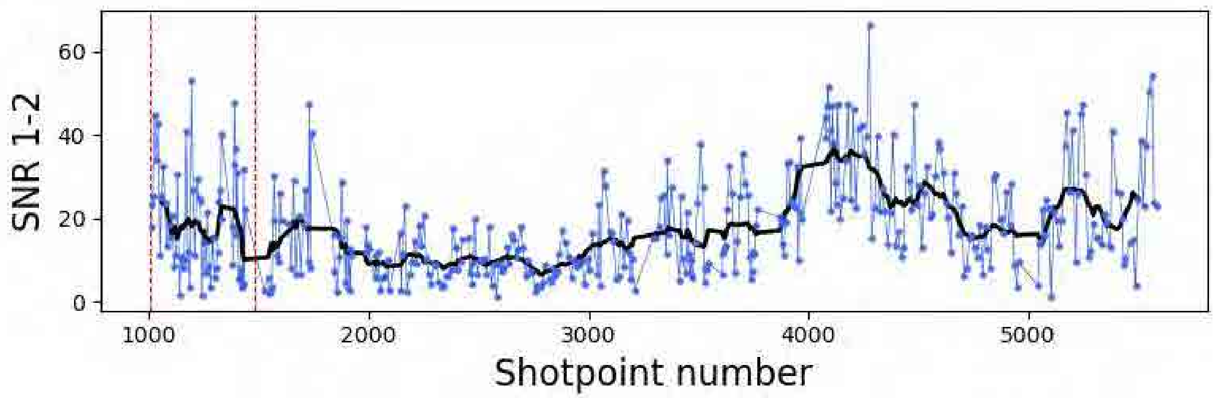


Figure 3.2.36: The SNR 1-2 values for line SCAN042. The red dashed lines indicate the hydrophone region.

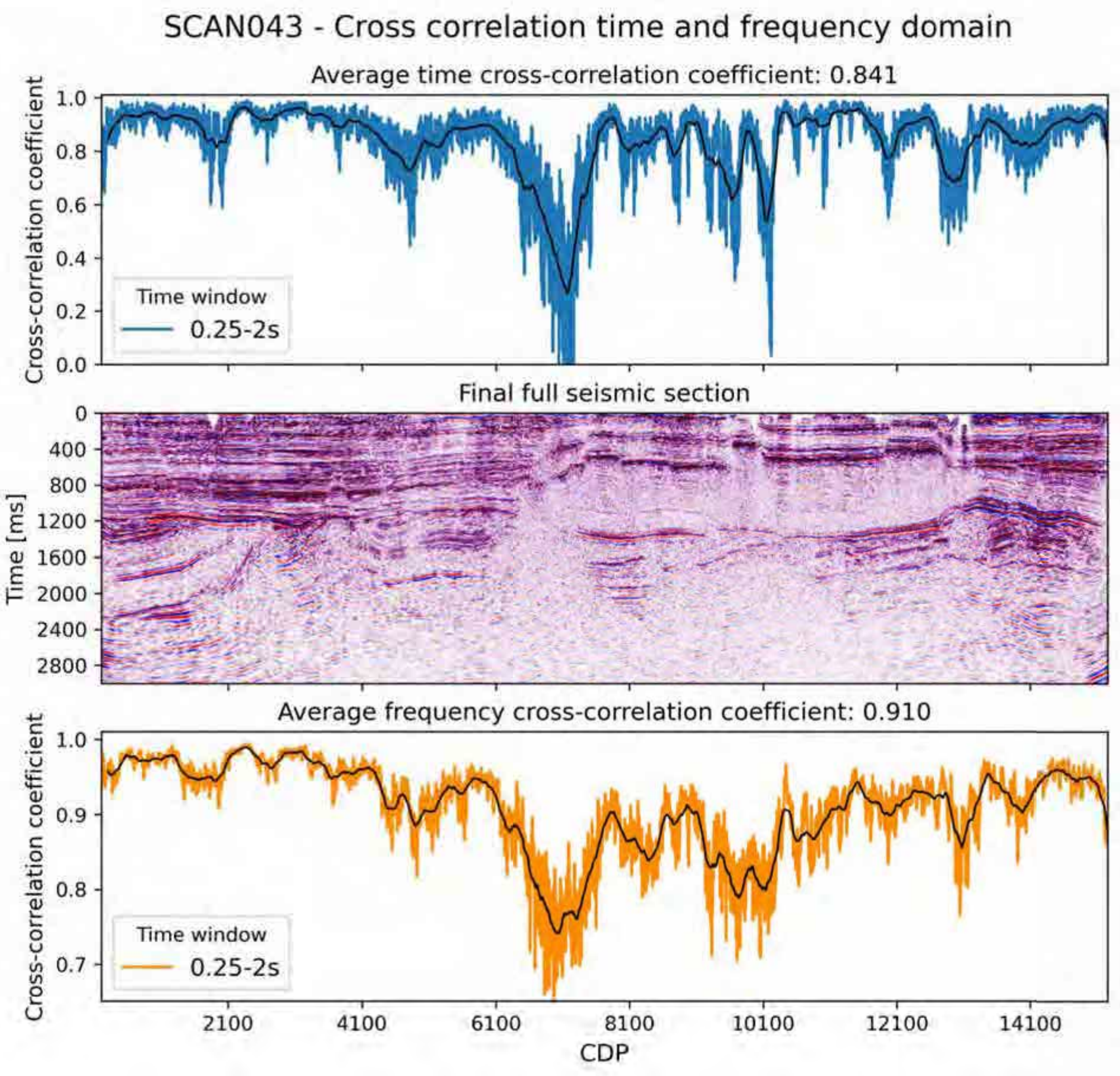


Figure 3.2.37: The cross-correlation in the time domain (blue), the frequency domain (orange) and in the middle the final seismic section is visible. Left is west, right is east.

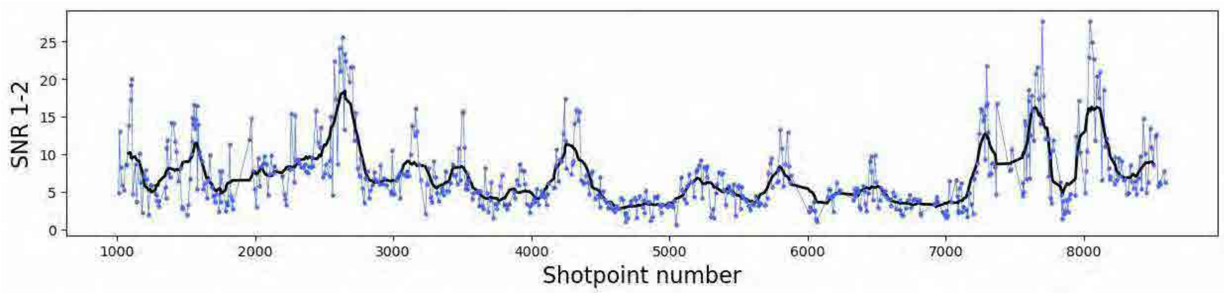


Figure 3.2.38: The SNR 1-2 values for line SCAN043.

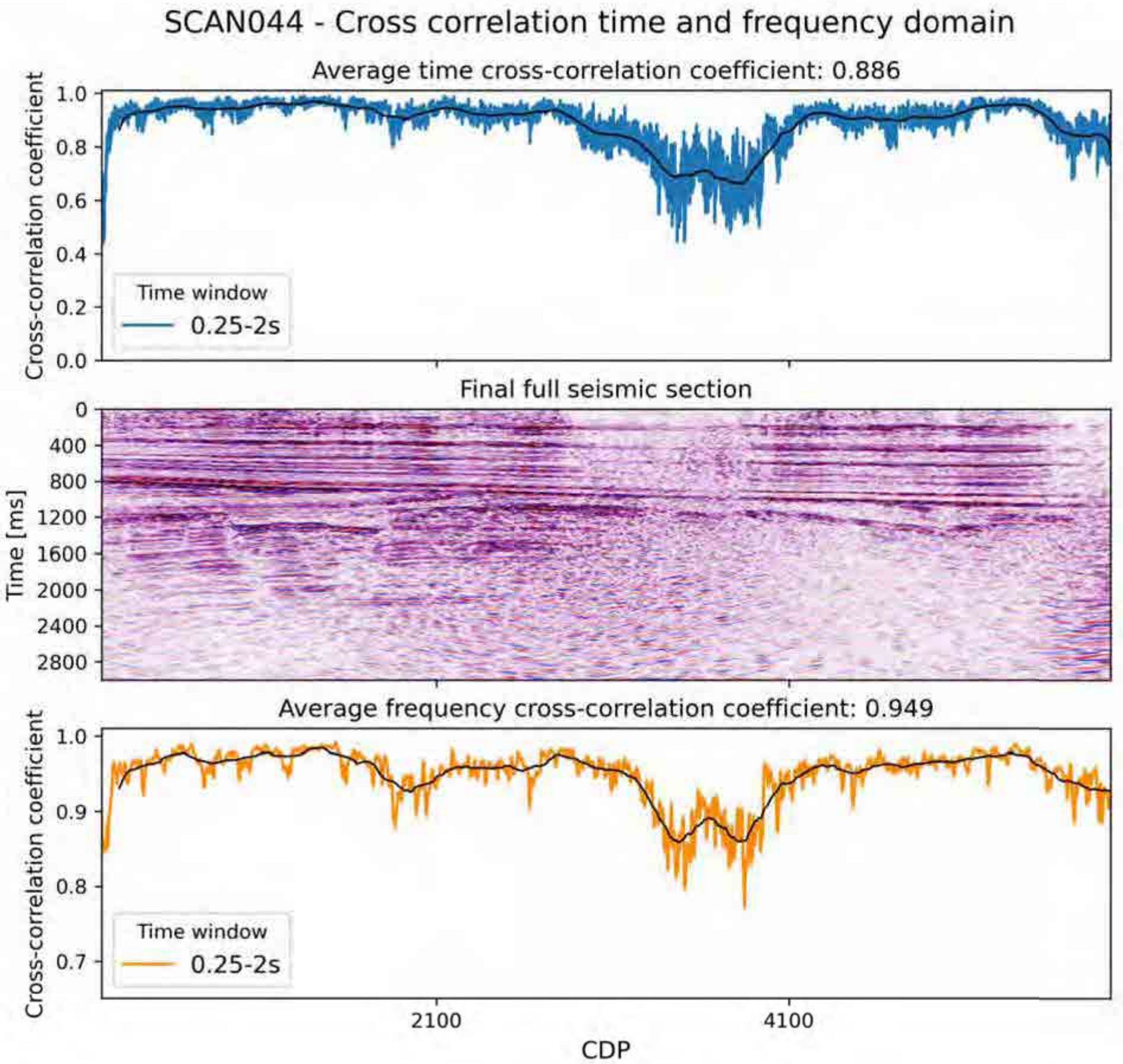


Figure 3.2.39: The cross-correlation in the time domain (blue), the frequency domain (orange) and in the middle the final seismic section is visible. Left is west, right is east.

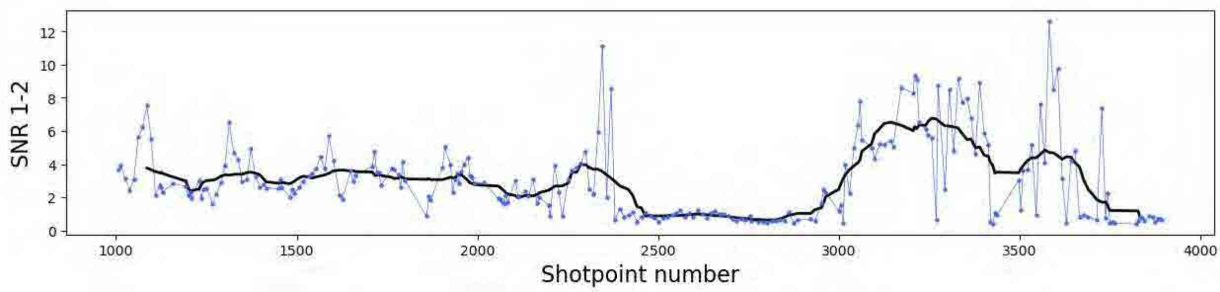


Figure 3.2.40: The SNR 1-2 values for line SCAN044.

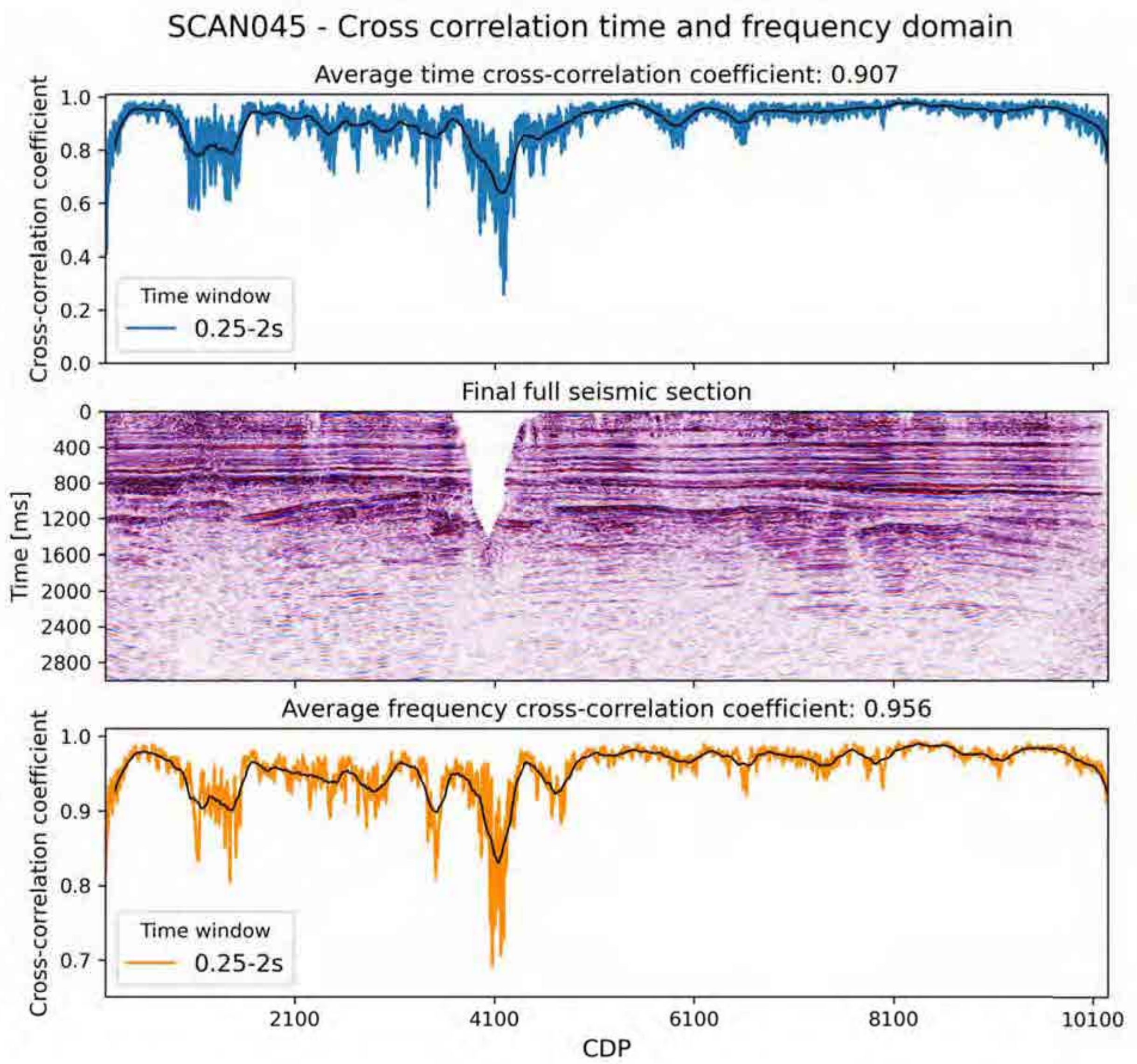


Figure 3.2.41: The cross-correlation in the time domain (blue), the frequency domain (orange) and in the middle the final seismic section is visible. Left is northwest, right is southeast.

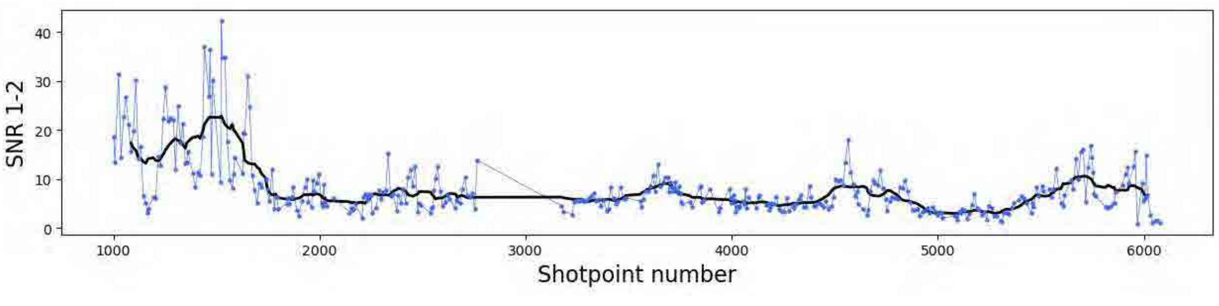


Figure 3.2.42: The SNR 1-2 values for line SCAN045.

3.3 Between lines

In total 27,741 shots recorded with 372,618 receivers resulted in 1793 kilometers of acquisition length and 431 km of shot depth. The first shot, not including the test line, was recorded on the 6th of September 2019 and the last one on the 5th of February 2022. This finalized a period of 2.5 years of data acquisition for the SCAN project. The data for almost all the analyzed lines is included in this final encompassing section. It is worth noting that the data from line SCAN046 is absent, due to the late timing of the shooting. Likewise, the additional data of lines SCAN024, SCAN025 and SCAN026 is only included in the heat maps as the individual analysis was executed after the main data analysis.

This section will be started off by discussing the impact of the various acquisition parameters on the quality of the data. This will be followed by looking at the impact of external factors on the data. Three heat maps showing the regional trends of the signal, noise and SNR values in the shot domain are considered. Finally, the relation between the seismic data quality and the quality of the post-processing cross-sections will be investigated. The average charge size, shot depth, signal, noise and SNR value for all the lines can be found in Appendix A.

3.3.1 Acquisition parameters

During the acquisition of the seismic data, a variety of charge sizes and shot depths were used for the shots. The magnitude of the used explosive was dependent on the vicinity of buildings and the depth of the shots, as regulated by SodM. The depth of drilling was dependent on the subsurface. As the decision was made to use relatively small but mobile drilling rigs, the drillers were not always able to breach hard subsurface layers. This occasionally resulted in shallower shot depths than expected in some regions. The effect of this irregularity in acquisition parameters on both the signal and SNR values can be seen when evaluating all the data.

Charge

The total range of charge sizes used for the SCAN project is from 120 grams to 2100 grams. However, most of the shots had either 220, 440, 660, 880 or 1540 grams. The exceptionally low charges were solely used when shooting lines for the Metropool Regio Amsterdam project, as it was impossible to avoid a close vicinity to buildings on occasions.

As the charge size has no impact on the recorded noise amplitude, the signal value was selected to analyze the effect of the magnitude of charge used. The signal from the 1-2 second window was used, as this was found to be more reliable. In Figure 3.3.1.1, it is apparent that the signal value increases as the charge size increases. This relation is best shown by the dark blue trend line. This correlation follows the expectations, as an increase in charge size leads to a larger release of energy, therefore creating higher signal amplitude values. The R-sq value of the trend line is an indication of how well the data distribution is explained by this linear trend line. The closer the value is to either 1 or -1, the better the data is explained.

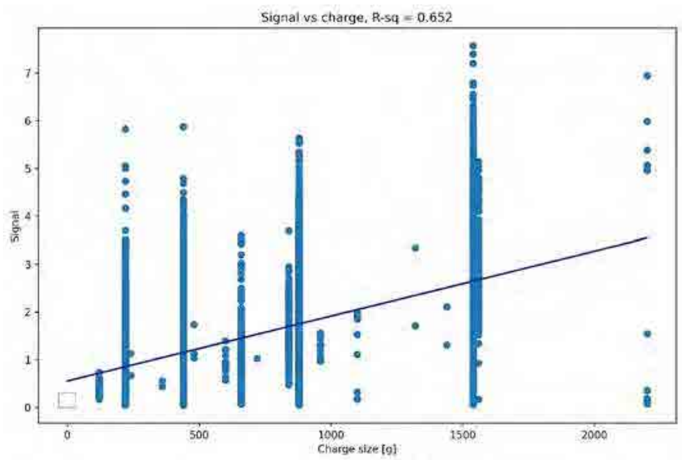


Figure 3.3.1.1: The effect of the used charge size on the signal of the shot. The trend line shows an increase in signal value for an increase in charge size.

Shot depth

The total range of shot depths drilled for the SCAN project is from 4 to 34 meters. Most of the shots are situated between the 10-26 meter window. In general, the aim was to drill to a depth of around 20 meters. Similar to the extremely low charge sizes, a depth of 34 meters was drilled in the urban areas around Amsterdam to compensate for the proximity of buildings.

In general, the hypothesis is that the deeper the drilling, the higher the data quality. This relation is confirmed in Figure 3.3.1.2a, where a correlation between deeper shots and higher signal values is visible. Noticeable is the cluster of data points with a low signal amplitude and a shot depth of 34 meters. These are the previously mentioned urban shots recorded in Amsterdam. If these would have been excluded in the analysis, the correlation between the signal amplitude and the shot depth would have been even more obvious.

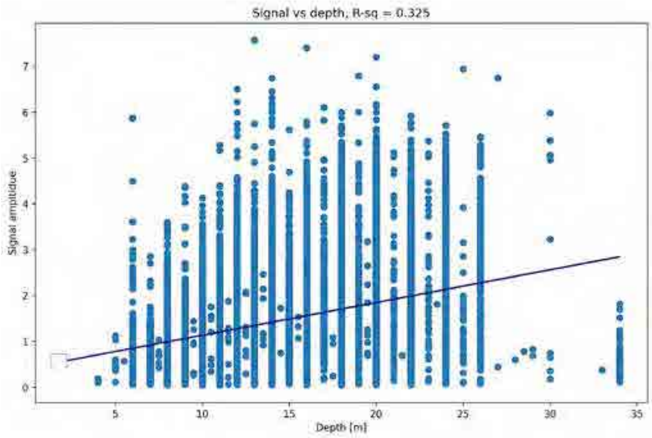
In order to exclude any influence of the relation between the charge size and the signal, the shots were grouped based on their charge size. The same signal vs depth plot could now be created, without possible data distortion due to the variance in charge size. This can be seen in Figure 3.3.1.2b, for all the shots with a charge of 880 grams.

This plot was also created for the other charge magnitudes, of which the results can be seen in Table 3.18. N indicates the number of shots which had that charge size and the R-sq value indicates how well the trend in the data was described. The 880 gram group had the clearest correlation between shot depth and signal value.

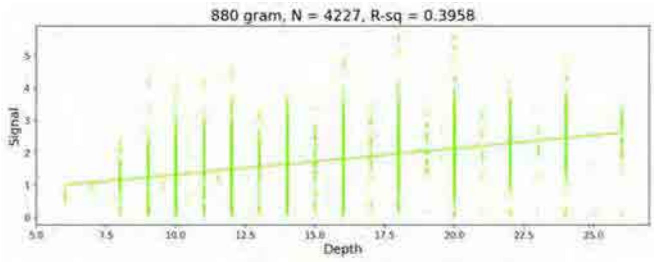
Charge [g]	N	R-sq
120	100	0.20
220	7327	0.26
440	7276	0.38
660	433	-0.02
880	4227	0.40
1540	6606	0.29

Table 3.18: Table showing the number of shots per charge category and their correlation.

An interesting factor to consider is that where for the charge size the impact on the signal is straightforward, this becomes more complex for the shot depth. It is not only a matter of drilling as deep as possible, the subsurface coupling of the source is actually a very relevant factor. Unfortunately, shot depth is the only variable we can use as indicator for the level of coupling, as the coupling itself cannot be measured and evaluated.



(a) The signal vs shot depth for all shots.



(b) The link between the shot depth and signal for shots with a charge size of 880 grams.

Figure 3.3.1.2: The relation between signal values and shot depth.

3.3.2 External factors

While one can influence some of the acquisition parameters in order to optimize the data collection, there are also external factors on which little influence can be had. These factors and their impact on the data quality will be discussed in this section. Firstly, the focus will be on the type of terrain and its use, after which the scope is extended to include objects located on the surface.

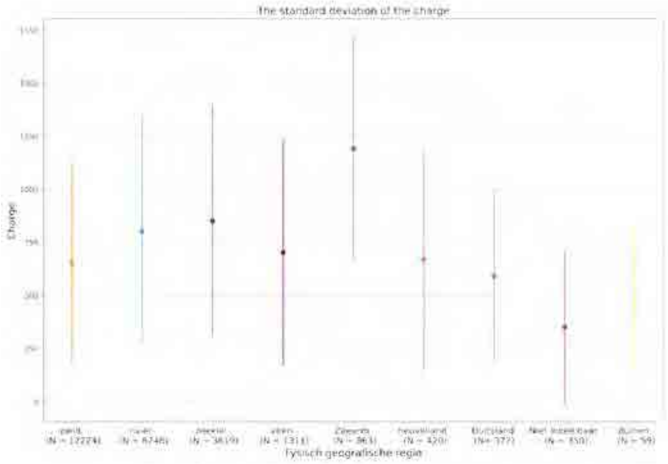
Physical-geographic regions

The surface of the Netherlands exists out of various regions, each with their own characteristics and properties. In this analysis, it is attempted to find a link between the quality of the shot data and the region on which this shot was taken. Data which is labeled as "Niet indeelbaar" (translating to not classifiable) were almost all shots located in urban areas. As solely data from the Netherlands was used in this analysis, all shots located in Germany are grouped separately. In general, these shots were also located on hilly terrain. Please note that this analysis considers the physical-geographic region at the surface level of the shot, not at the drilling depth.

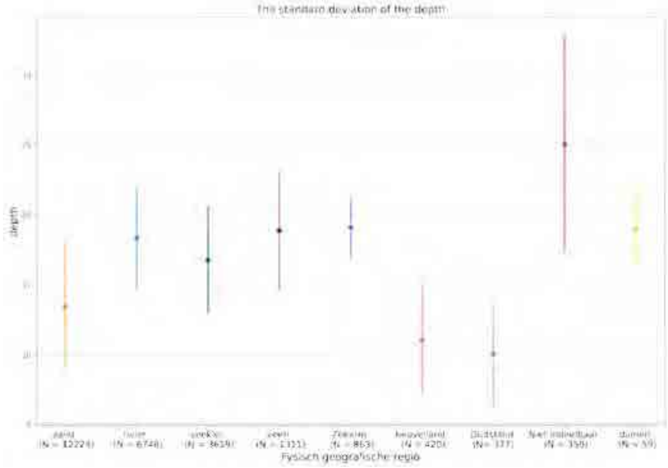
When studying the results seen in Figure 3.3.2.1, several conclusions can be drawn. The shallowest shots were drilled in the "heuvelland" (hills), causing many charges to be placed above the water level. This resulted in low signal amplitudes and therefore also low SNR values. The urban shots were the deepest due to the proximity of buildings. If we look at the general trend of the different regions, we again observe a similar trend in the used charge size and the recorded signal for the different categories.

The best shots were recorded at regions of water, such as "Zeearm" and "Rivier" (translating to bays and rivers). This were often less densely populated places, therefore allowing the placement of higher charge sizes. The worst data comes from the hills and the urban shots. Urban shots had low charge sizes and more noise, while in the hills the combination of shallow shot depths and shots located above the groundwater table had the largest impact.

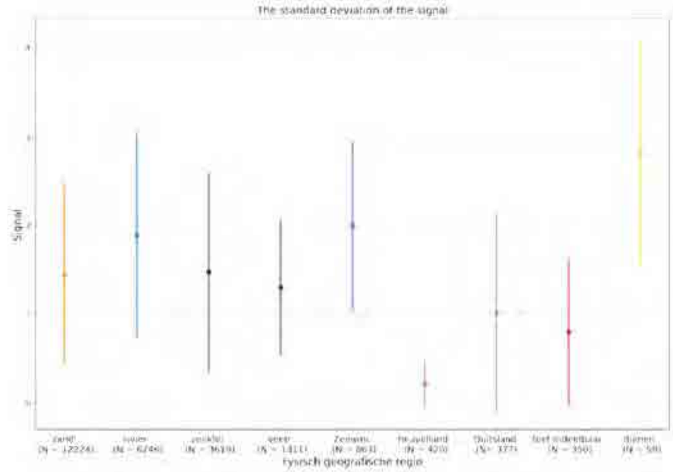
There was little impact visible on the variance in noise levels for most of the physical-geographic regions. This coincides with expectations, as the noise levels generally do not depend on the type of surface. The two exceptions on



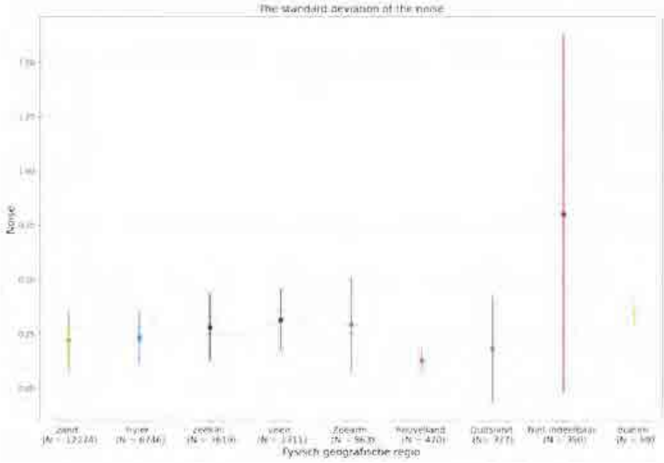
(a) Charge size



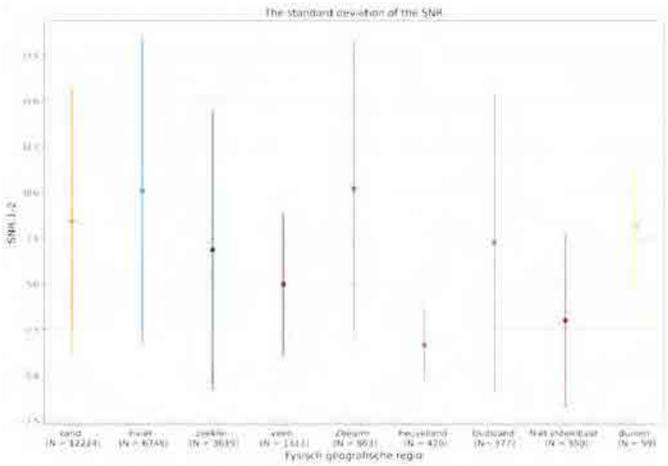
(b) Shot depth



(c) Signal amplitude



(d) Noise



(e) SNR value

Figure 3.3.2.1: The average value and the standard deviations for various parameters based on their physical geographic region.

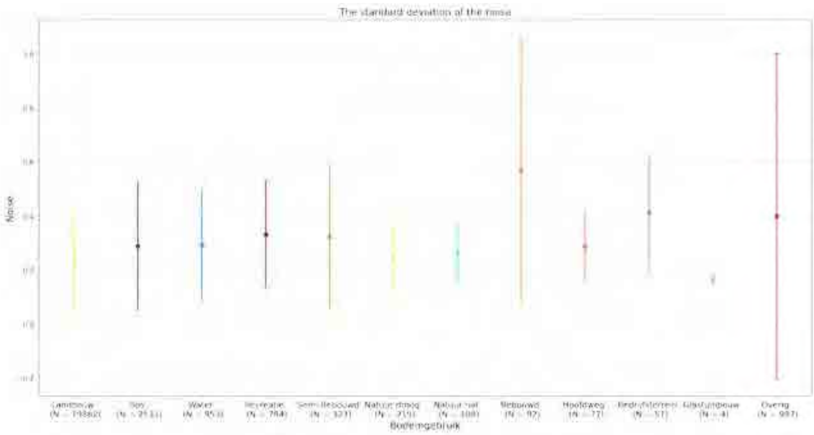
this statement are the shots located in Germany and those in the urban regions. Urban regions are densely populated, therefore more noise sources are present. Contrary, most of the shots in Germany were in quite rural areas. The anomalously high noise levels can be explained by the fact that a period of freezing affected the geophones, resulting in more noise as concluded by Gossink (2021).

Land use

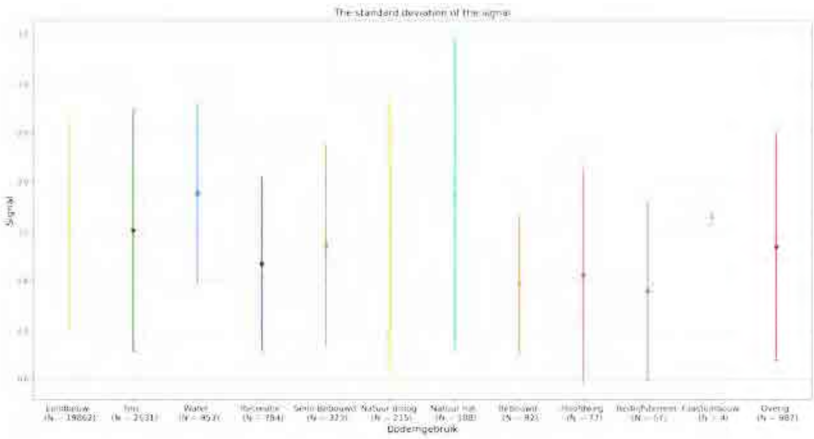
Besides the physical-geographic region, it is also interesting to see how the usage of land impacts the quality of the data. The shots were linked to their land use in QGIS based on the data set: "CBS Bestand Bodemgebruik". The largest share of the shots was recorded in agricultural regions, followed by forests, water and recreational areas. The effect of the land use on the noise, signal and SNR can be seen in Figure 3.3.2.2. The average value for every category is plotted, together with the standard deviation. The "overig" category contains all the shots which could not be labeled.

As expected, the highest noise levels were recorded in the urban areas, followed by the industrial areas. Both nature areas are relatively quiet, while forest have a higher average noise with more deviation. This can be explained by the fact that trees are prone to create a lot of noise on windy days, where windless days produce relatively little noise. Please note that this analysis was performed in the shot domain. Due to the way we determine the noise value, this means that noise sources within 900 meters of the shot are not included. The effect of big areas is still visible, but small scale noise sources such as roads can be less representative.

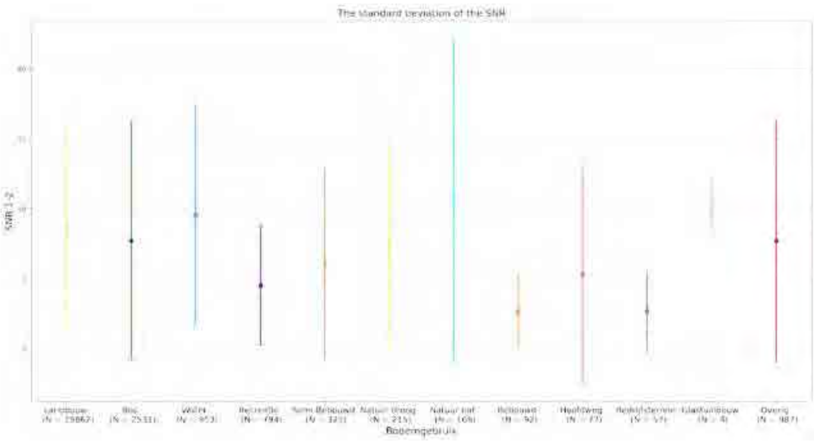
The highest signal amplitudes were recorded in the wet areas. As less buildings are close by, often higher charge sizes could be used. In urban regions and industrial areas the signal is lower due the lower charge magnitude. The general trends observed in both the signal and the noise can be seen in the resulting SNR.



(a) Noise amplitude



(b) Signal amplitude



(c) SNR

Figure 3.3.2.2: The impact of land use on the data quality.

Water level

Of all the data acquired, from 8 lines a significant part of the shots were placed above the groundwater table. These lines are SCAN019, SCAN020, SCAN030, SCAN031, MRA038, MRA039, SCAN044 and SCAN045. In the previous report, the conclusion was already drawn that the position of the shot relative to the groundwater table has a significant effect on the quality of the data. In order to quantify this, this relation was plotted in Figure 3.3.2.3. The blue dashed line indicates the water table level. Shots located left of this line are all situated above the groundwater table, while shots on the right are located below. It is apparent, that as soon as the shots are taken above the water table, the quality of the data severely degrades.

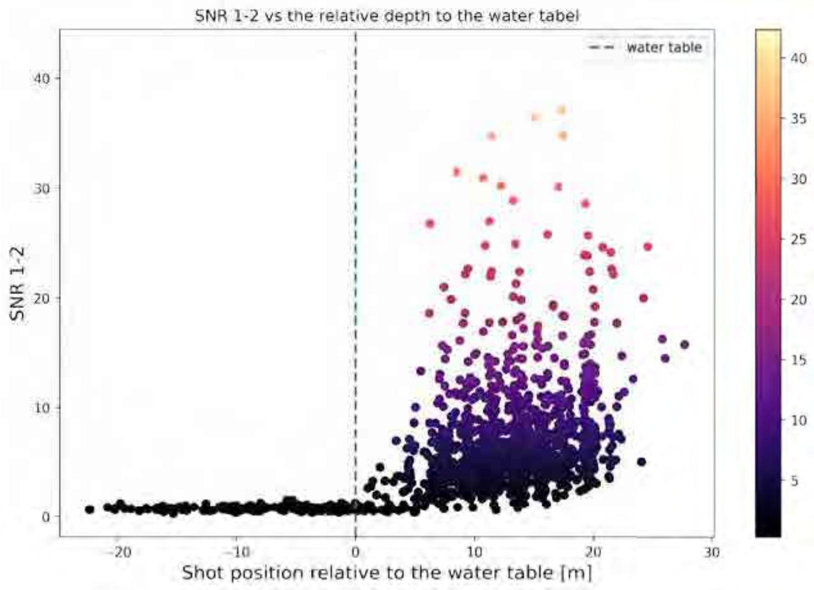


Figure 3.3.2.3: The link between the relative position to the water table and the data quality.

The reason some shots are located above the groundwater table is mainly due to the presence of push moraines in the Netherlands. These moraines are a remainder of the glacial periods. As the name suggests, they have a complex geology existing out of material that has been pushed together. These features are responsible for a sudden increase in elevation. This increase is steep and locally concentrated, such that the water table does not follow the topography. The distance between the surface and the water table therefore increases, requiring a deeper shot depth in order to place shots below the water table. However, drilling in moraines is more challenging due to the tough subsurface. When big boulders are encountered during the drilling, this makes further drilling impossible. Therefore, the drilling depth that can be reached when compared to sand or clay formations is often limited.

3.3.3 Ambient noise sources

One of the determining factors in the quality of the field data is the degree of ambient noise present in the shots. This type of noise is caused by external factors, not the detonation of the charge itself. Such external factors are urban areas, railroads, highways and windmills. Their impact on the recorded noise is discussed in this section.

Shooting time

The timing of the detonation of shots can have an influence on the recorded noise levels. Especially in urban areas, where a proximity to noise sources cannot always be avoided, choosing a relatively quiet time of the day for shooting can reduce noise levels. In order to analyze this, the noise of all the shots was plotted versus the time of shooting, see Figure 3.3.3.1. It is apparent that the moving average of the noise levels peaks around 6 PM, coinciding with the timing of the rush hour. Interestingly, the general noise levels in the evening are higher than during the day. While this would suggest shooting in the evening is noisier, the data has to be viewed with a bit more nuance.

In general, the decision to shoot in the evening was only made in regions where high noise levels were expected. This is also visible in the figure, as after 5 PM there are barely any low noise level shots recorded. Generally, it is expected that the level of noise in the evening is lower. A more focused scope is necessary in order to investigate the validness of this claim.

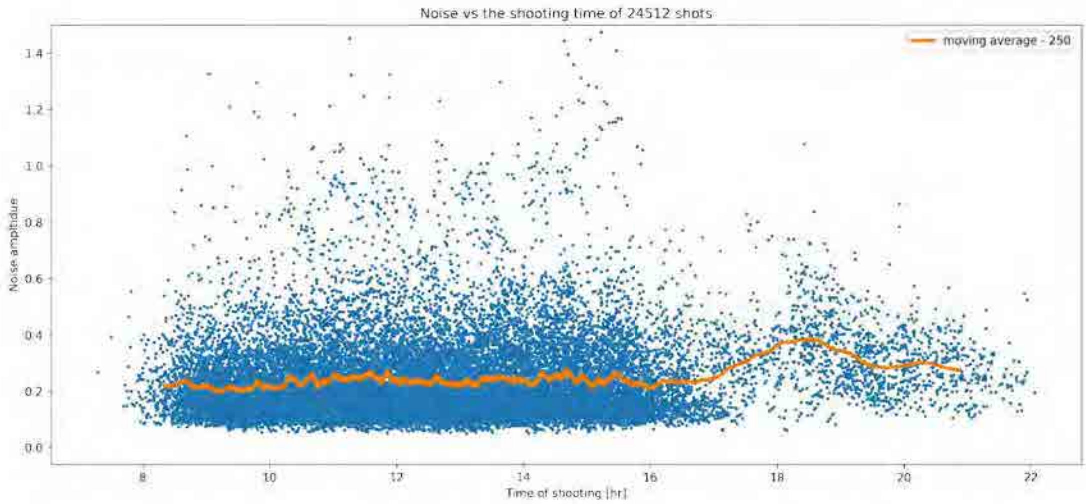
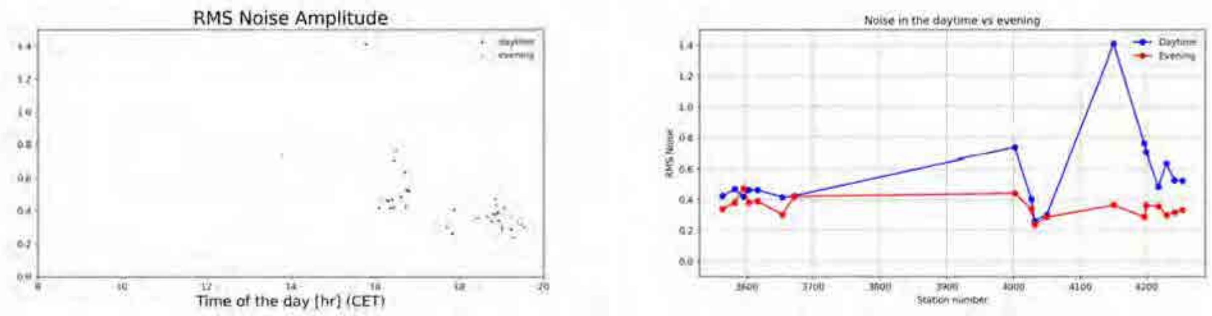


Figure 3.3.3.1: The dependence of noise levels on the timing of detonation. The orange line indicates the moving average of the noise levels, considering a window of 250 data points.

This can be done by looking at the data of line MRA040. On this line, 18 shots were accidentally recorded during the day while the original planning was that they would be detonated in the evening. These shots were re-drilled and shot again, enabling a proper analysis of the difference in noise levels where the timing was the only variable.



(a) Noise levels at the different times.

(b) Difference between the noise levels of the shots.

Figure 3.3.3.2: The general trend of the noise levels at the different timings (a) and the difference in noise level for the individual shots (b).

In Figure 3.3.3.2 it is clear that for almost all shots the ambient noise is lower in the evening than in the daytime. However, the magnitude with which the noise is lowered varies a lot per shot. During a closer investigation, no reason could be found for the difference in noise reduction for the individual shots.

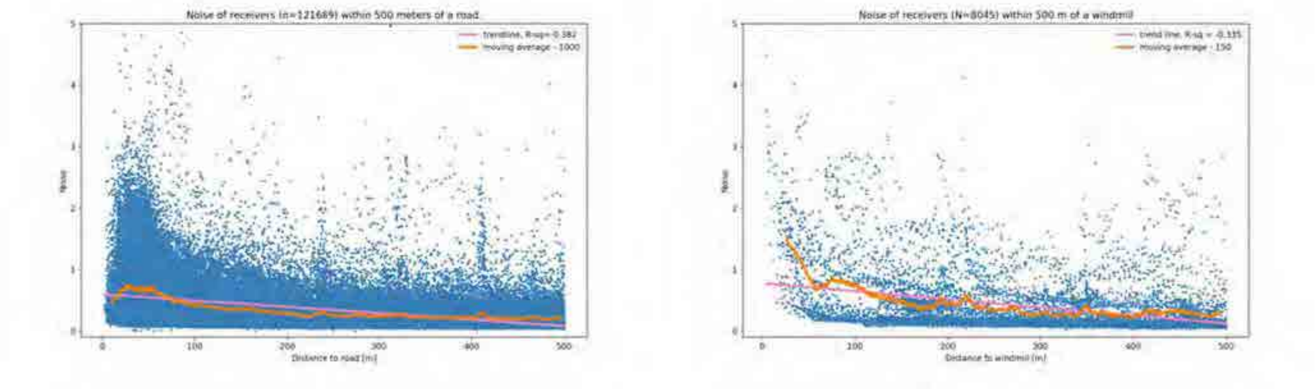
Infrastructure

Both windmills and roads are more avoidable producers of noise. In this section the effects of these on the ambient noise will be discussed. It should be noted that while the previous sections looked at the data from a shot domain perspective, for the noise the receiver domain is more relevant and informative. This is due to the fact that for determining the ambient noise the first 900 meters of offset is not taken into account. For large trends such as geographical regions, this is less of a deal breaker. However, if we want to consider the impact of a noise source on the data it is more important to have an accurate idea of its proximity.

From the "Nationaal Wegenbestand" (NWB) it was possible to extract information about the location of roads in the Netherlands. Next, in order to compress the data and keep it computable, we looked at the location of the highway location markers (in Dutch better known as "hectometerpaal"). In such a way, for every receiver the distance to the nearest location marker was computed. The downside of this method is that the data contains an error margin with a maximum added distance of 50 meters. If a receiver is located directly next to a road but in the middle of two location markers, the resulting distance will be 50 meters rather than the true distance of a few meters.

Figure 3.3.3.3a shows the link between the level of noise present and the proximity to a road. Both the moving average with a window of 1000 data points and a linear trend line are plotted. The trend line shows a general decrease in noise once the receivers are located further away from the road, as expected. When looking at the moving average, a kind of platform of high noise levels is visible within the first 50 meters. This is due to the previously mentioned simplification of the road's location.

Almost all the data points have a smaller distance to a road than shown in Figure 3.3.3.3a, suggesting a shift to the left. However, it is not known how much this shift should be per individual point. For future research, it would be interesting to investigate this with the actual location of the roads. This would allow the analysis of the nearby effect of the road on the noise levels. In general, the conclusion can be drawn that one should stay away from the first 50 meters around a road.



(a) Noise due to roads.

(b) Noise due to windmills.

Figure 3.3.3.3: The effect of roads (a) and windmills (b) on the recorded receiver noise amplitude.

A similar analysis was executed for the windmills, where for every receiver its distance to the nearest windmill was computed. One aspect which was not considered in this analysis was the fact whether the windmill was turned on during the time of shooting. An active windmill is responsible for reverberations travelling into the subsurface due to the spinning of the blades. This causes a large amount of noise. While a windmill which is turned off still produces noise due to the amount of wind it catches, this is of a significantly lower amplitude.

The moving average of the window is computed over 150 data points. This smaller window was selected as the number of receivers within this range is significantly lower than within the range of a road. In Figure 3.3.3.3b it is clear that the noise peaks within the first 50 meters and afterwards the amount degrades, following the trend line.

Like roads, railroad tracks can also cause a significant amount of noise. However, the activity on a railroad track is quite incidental. Where roads have an almost constant flow of traffic and therefore noise, for trains there is an average interval of a couple of minutes without any noise. Accordingly, the effect of railroad generated noise is limited on the data quality. Figure 3.3.3.4 shows how the noise for three different shots varies between the same receivers, this difference is caused due to the passing of a train.

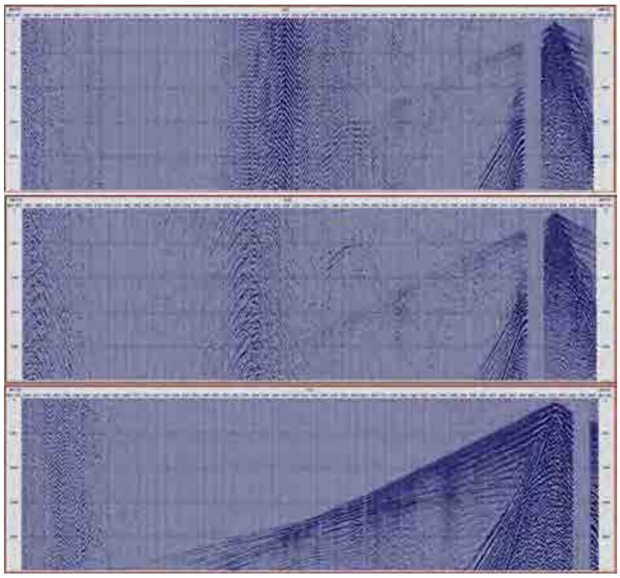


Figure 3.3.3.4: The effect of the passage of trains on shots of line SCAN044. The top picture shows the high noise levels due to the passing of a train, lower levels on the middle shot just after the train passed and no noise visible on the bottom shot.

3.3.4 Regional trends

The previous sections have investigated which parameters have an influence on the data quality. In order to visualize the regional trends of this data, heat maps were created based on Inverse Distance Weighted (IDW) interpolation. This method was selected rather than the Triangular Interpolation Network (TIN) as the TIN method is less suitable when a lot of small scale variations are present.

Firstly, the noise is studied, followed by the signal and finally showing the general SNR trends. The color scale of all maps is based on a quantile division, showing the increase in value with steps of 10%. The red colored dots indicate the worst 10% of the data, where the blue or green dots belong to the best 10% of the data.

Ambient noise

The main trend visible in Figure 3.3.4.1 is the difference in noise amplitude between the urban and rural areas. Both Amsterdam and Utrecht are large concentrations of noise, while more to the east and south the noise levels decrease. In the rural regions there are anomalous concentrations of high noise levels present, for example around Eindhoven. These were due to a seismic line running parallel to a main road for a significant length, a substantial noise source as illustrated in the previous section. Most of the bright red sections are due to this presence of roads. The effect of more local noise sources such as windmills is not represented on this heat map. It is apparent that the high noise levels of the hydrophones (due to the multiplication factor) can also be observed on lines which cross bodies of water.

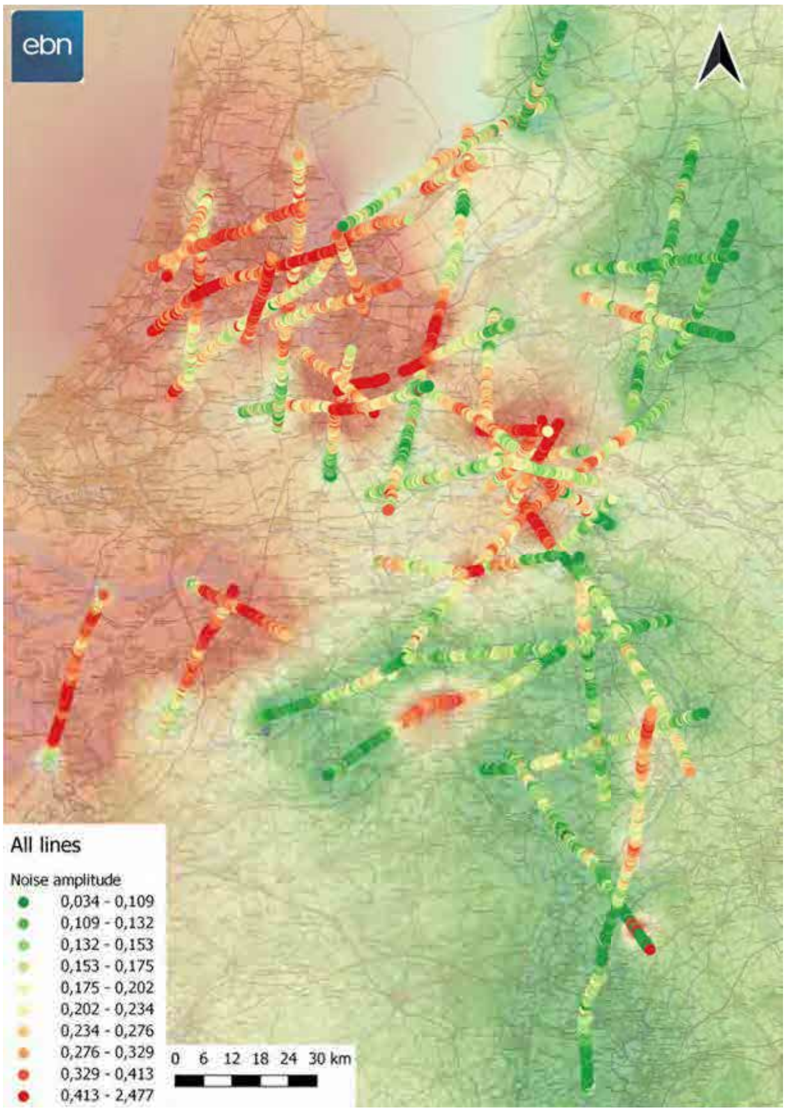
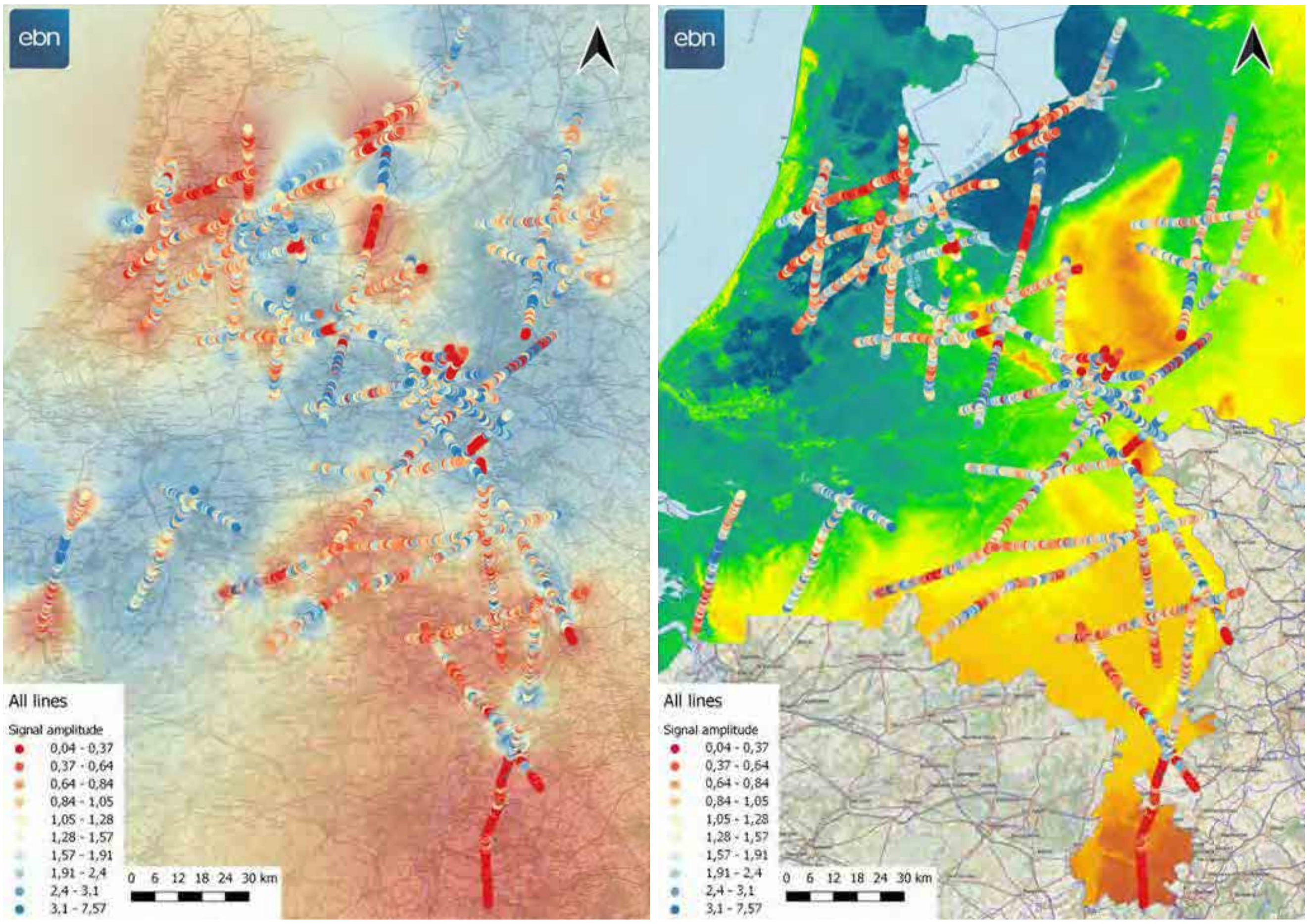


Figure 3.3.4.1: Heat map showing the regional trend of the noise values in the shot domain. Green indicates regions of low noise levels, where the red areas illustrate the high noise levels.

Signal

Figure 3.3.4.2a shows the regional trends of the signal amplitude in the Netherlands. The general trend that can be observed is that the signal values in the south and around Amsterdam are low. The lines running through Amsterdam were shot in the scope of the MRA project and were planned crossing the center of the city. Due to the densely populated location, low charge sizes had to be used. As previously seen, lower charge sizes lead to lower signal amplitudes. In the south of the Netherlands, it was more difficult to obtain deep shot depths due to a more challenging subsurface for drilling. A shallower shot depth leads to both the placement of lower charges and decreases the coupling, factors which both negatively impact the resulting signal amplitude.

Besides these larger regional trends, local concentrations of very low signal data can be seen. These locations coincide with the location of the push moraines, causing the shot to be placed above the groundwater table. This statement can be supported by plotting the signal values on top of the topography of the Netherlands, resulting in Figure 3.3.4.2b. Additionally, in the south of Limburg it is not the presence of a push moraine but the steep gradient of elevation which causes the shots to be placed above the groundwater table. Also in this region, it leads to very low data quality.



(a) Heat map showing the regional trend. **(b)** Elevation.

Figure 3.3.4.2: A heat map of the signal trend in the Netherlands (a) where higher values are an indicator of higher data quality. The signal amplitudes are plotted on top of the topography of the Netherlands (b), showing that the low signal values coincide with regions of local elevation.

Signal-to-Noise Ratio

The trends observed in the heat map of the noise and signal are combined in the heat map of the SNR. The highest quality shots are in the rural regions. In these areas high charge sizes were used and low noise levels were recorded. The presence of push moraines and roads can cause local anomalies of bad data in these rural regions. In general, the data around the urban areas of Utrecht and Amsterdam is of lower quality, due to low charge sizes and high noise levels. However, these are areas with a more relevant geothermal outlook.

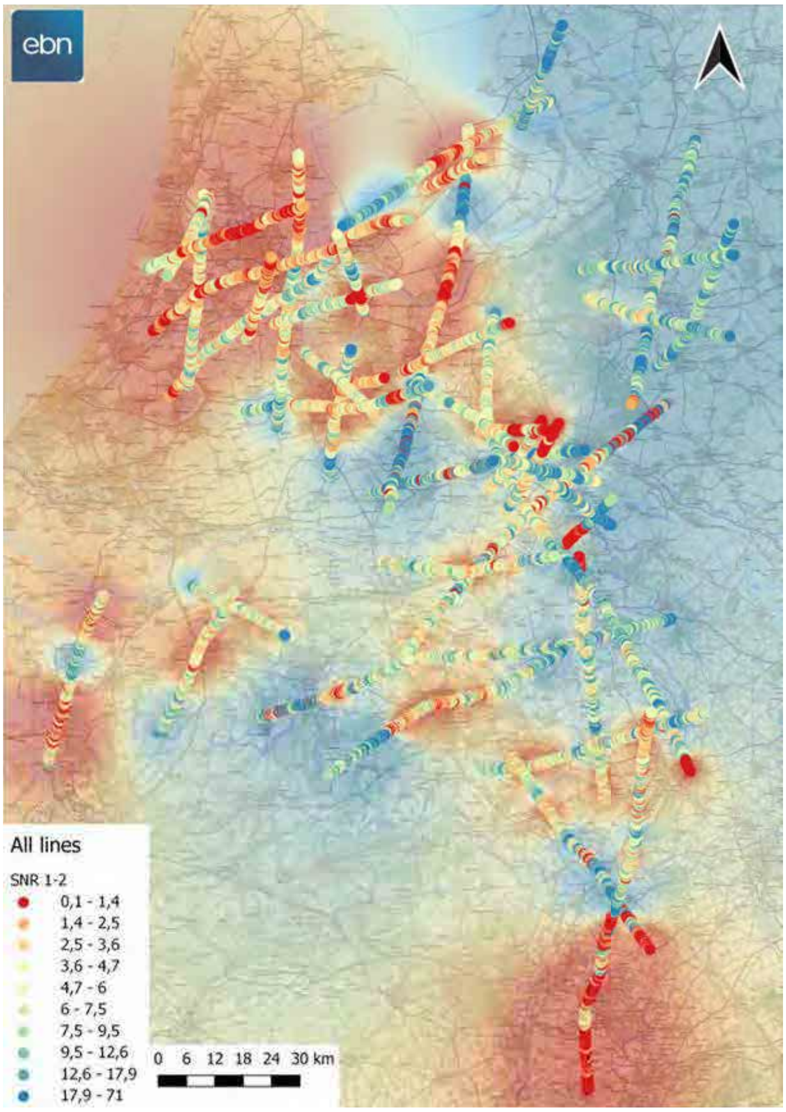


Figure 3.3.4.3: Heat map showing the regional trend of the SNR values where higher values indicate a higher quality.

3.3.5 Final processed seismic data quality

The quality of the final processed seismic cross-sections of the lines was quantified based on cross-correlation. It is possible to compare the results between the quality analysis of the shot data and the cross-section to investigate whether there was a correlation between these two quality indicators. For this the time coefficient was elected, as this was found to be a more robust indicator of the seismic quality.

When solely looking at Figure 3.3.5.1, there is no apparent relationship visible between the SNR value and the post-processing correlation coefficient. However, due to the nature of cross-correlation, sections with a simpler geology are more likely to obtain higher cross-correlation coefficients. The coefficient is an indicator of the continuity of a section but cannot filter between in-continuities due to geological factors such as faults or due to a lower quality section. Therefore, all the analzsed sections were manually labeled with a "simple", "medium" or "complex" geology in order to take this variable into account.

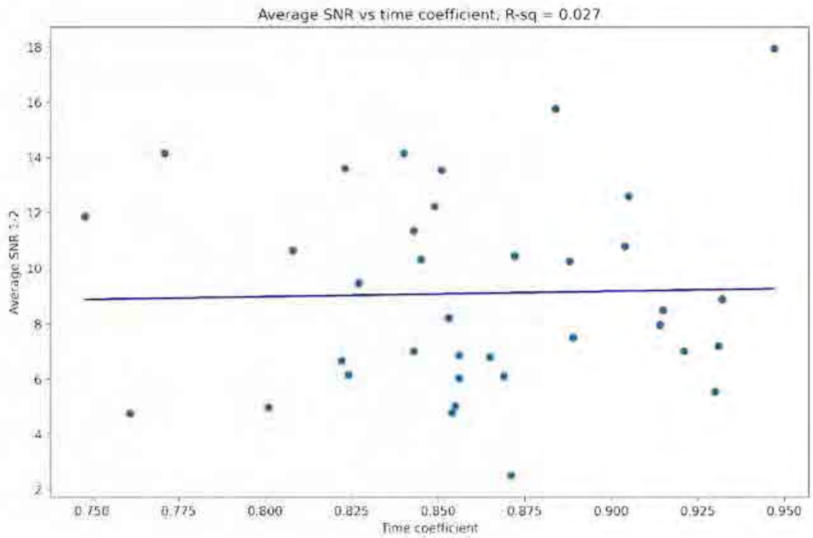


Figure 3.3.5.1: Link between the SNR value in the 1-2 second window of a line and its cross-correlation coefficient in the time domain.

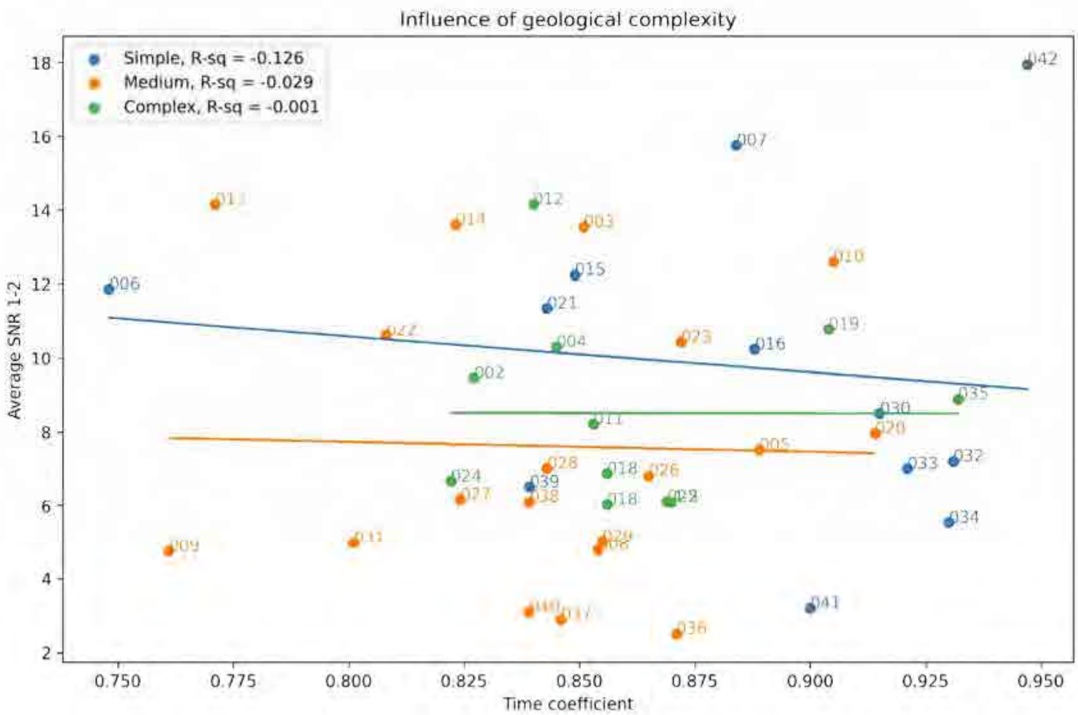


Figure 3.3.5.2: The link between the SNR value and the cross-correlation coefficient in the time domain of the lines. All the lines are grouped based on the complexity of their geology, leading into the resulting trends.

This resulted in Figure 3.3.5.2, where still no apparent link was visible for the different quality indicators. It can be observed that in general the simpler geologies have a higher time cross-correlation coefficient value, but this is not necessarily linked to better SNR data quality.

There are several arguments which could potentially explain this lack of correlation. Firstly, we are looking at averages along the whole line for both the shot data and the post-processed results. It could be possible that for specific sections along the line a better correlation exists, which is averaged out when all data is taken into account. Additionally, low shot data quality can often be compensated for during the processing phase. Therefore, the negative impact on the quality of the final section is reduced. Finally, it could be possible that the way the cross-correlation is executed does not provide us with a very representative quality indicator. For future analysis, it would be interesting to perform another run of the time cross-correlation coefficient computations, but this time to solely look at the North Sea group. The complexity of this formation is relatively consistent for all the regions of the Netherlands, therefore possibly providing a better benchmark for the quality indication of the line.

4 Discussion

In the result section we have looked at the shot data quality for all the individual lines and the general trends that could be found when analyzing the quality of all the lines. In this section we will further enhance on some of the elements, in addition to discussing the largest impact on the quality of the data. These conclusions can be used for optimizing the acquisition phase and therefore the quality of the final processed seismic cross-sections.

4.1 Hub distance

As previously addressed, two different windows were elected for determining the SNR value of a shot. In the previous reports by Janssen (2020), van der Lucht (2020), van Klaveren (2021) and Gossink (2021), both the SNR 0-1 and the SNR 1-2 values were analyzed, in which the emphasis was on the former window. It was argued that the deeper window already had some signal degradation and was therefore less suitable for analyzing the signal amplitude. However, in this section a counter-argument will be provided why the SNR 1-2 window is a more suitable quality indicator.

As sound waves travel further away from their source, their amplitude decays due to a process called spherical divergence. The same energy is spread over a larger volume, decreasing the strength of the signal. Therefore, receivers which are placed the closest will record the highest amplitudes. The process of spherical divergence can be compared with the dropping of a pebble in a body of water, but in this case we are considering body waves rather than surface waves.

Due to external factors such as permitting or terrain conditions, the ideal setup of shots and receivers cannot always be reached. This leads to a non-uniform acquisition setup of the lines. Therefore, there is inconsistency in the distance between a shot and its nearest receiver. This distance will be further on referred to as the hub distance. Figure 4.1.0.1 shows a part on line MRA038 where for every shot the hub distance is shown by a drawn line to the closest receiver. Evidently, for shots where the hub distance is larger, it is not possible to record the near-offset high amplitude waves.

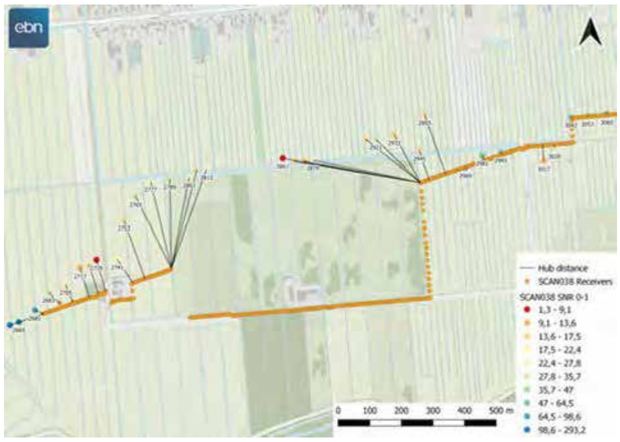
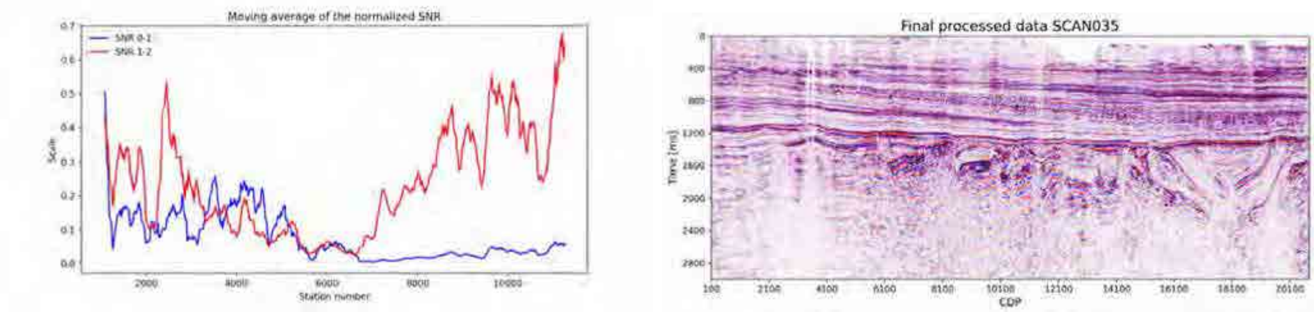


Figure 4.1.0.1: The non-uniform set up of the receivers and shots in the field on line MRA038.

This lack of recording has a significant impact on the signal values retrieved from the 0-1000 ms window. This became evident when a normalization was applied to the SNR 0-1 and SNR 1-2 values along line SCAN035, see Figure 4.1.0.2a. In the first part of the line, both parameters showed a similar trend but the 0-1 window contained more extreme peaks. Interestingly, at the second part of the line the SNR 0-1 value was very low while the seismic data was of decent quality, as apparent in Figure 4.1.0.2b. At first sight these variations could not be explained by any of the acquisition parameters such as the charge size or the shot depth.

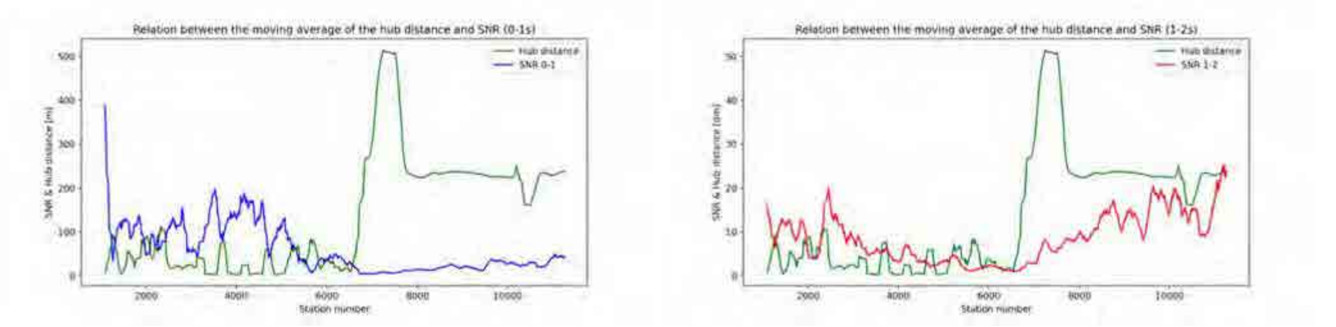


(a) The moving average of the normalized SNR for both the time windows of line SCAN035.

(b) Final full section of line SCAN035.

Figure 4.1.0.2: The right part of the line has anomalously low SNR 0-1 values (a) while the seismic section does contain good seismic data (b).

The reason for these extremer values became evident when we plotted both the hub distance and the SNR values in one plot. As visible in Figure 4.1.0.3, there is an inverse relation visible between the SNR 0-1 and the hub distance. Whenever the hub distance was larger, the SNR value was lower and the other way around. The peaks resulting from this relationship were similar to the anomalies observed when looking at the normalized values. This relation was not visible when we compared the SNR 1-2 value and the hub distance.



(a) An apparent inverse relationship is visible where the SNR 0-1 decreases as the hub distance increases.

(b) No clear relationship between the SNR 1-2 value and hub distance is visible. Note the differently scaled y-axis when compared to Figure (a).

Figure 4.1.0.3: Showing the relationship between the hub distance and the SNR 0-1 (a) or SNR 1-2 (b) value. Plotted are the 15 period moving average.

Both the SNR 0-1 and the SNR 1-2 window were applied on the signal-only shots as mentioned in the method section. In these signal-only shots, both the groundroll and the ambient noise has been removed. This means that for the 1-2 second window all the traces with an offset smaller than 300 meters are already excluded in the analysis. As the hub distance is rarely larger than 300 meters, it is possible to neglect any effect of this on the data.

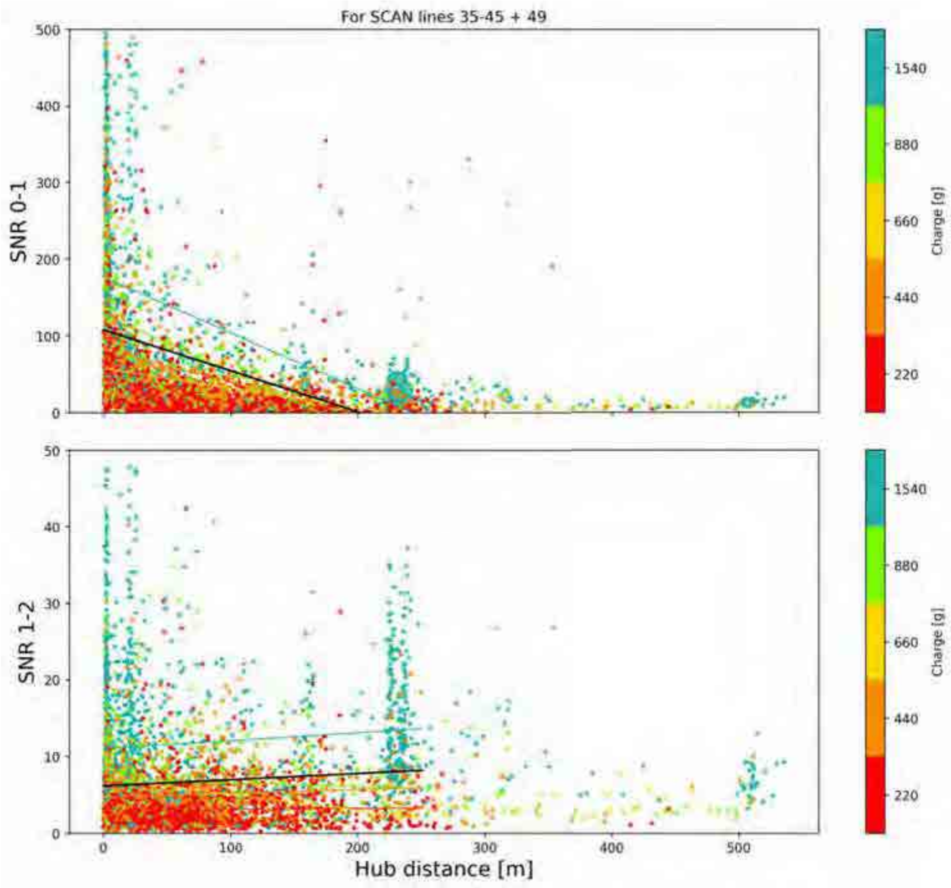


Figure 4.1.0.4: Link between the hub distance and the SNR value for the two different windows. The colours indicate the used charge size. A general trend line is plotted in black, but additionally for every group of charge sizes a trend line is plotted.

However, in the 0-1 second window these nearby traces are included due to the narrowness of the groundroll cone. Therefore, the hub distance has a significant impact on the data. It is possible to tackle this problem in the 0-1 second window if the window is adapted in such a way that for all shots the traces within the first 300 meters of offset are excluded. However, as the previous analysis executed on the lines did not take this into consideration, the decision was made not to re-run every line and to focus on the 1-2 window as the primary quality indicator.

The inverse relationship visible between the hub distance and the SNR 0-1 values shown in Figure 4.1.0.3a can be supported by looking at the data from multiple lines. For 12 of the discussed individual lines the hub distance was computed and this was plotted against the SNR 0-1 and SNR 1-2 values. Figure 4.1.0.4 has linear trend lines plotted based on the data of receivers within the first 250 meter of hub distance. They show that the SNR 0-1 value decreases as the hub distance increases. This correlation is largely absent for the SNR 1-2 value.

The conclusion can be made that the SNR 0-1 value has a stronger dependency on near-offset high amplitude waves while these do not necessarily indicate the actual quality of the shot. SNR 0-1 can therefore be considered as an indicator of the observed strength rather than the quality of the shot. For future research it is advised to look at the SNR 1-2 value in order to get a more trustworthy quality indicator.

4.2 Optimizing the shot data quality

By analyzing the quality of the shots of all the recorded data in the previous section, conclusions can be drawn about optimizing the acquisition design to achieve the highest possible data quality. This means high signal amplitude and low noise levels. Do note that this solely considers optimizing the theoretical side of the data acquisition. The dependence on various factors in the field, such as obtaining permission for land access, regulations and unexpected limitations are not taken into account.

Increasing the signal

From analyzing all the data, it was found that both higher charge sizes and deeper shot depths lead to higher signal values. If possible, one should therefore use the maximum charge size allowed as determined by SodM regulations. Of course, this should be from the previously selected range between 220-1540 grams. By planning the lines in such a way that the distance to buildings is larger, in general higher charge sizes are allowed and data of a higher quality can be acquired.

The shot depth is especially important to ensure proper coupling between the explosive and the subsurface. Additionally, the shot depth also has an impact on the amount of charge that can be used. Therefore, deeper shot depths will lead to better signal.

One thing that should be avoided during the acquisition is the shooting above the groundwater table. As previously mentioned, push moraines are local zones of elevation which cause shots to be placed above the groundwater table. This drastically decreases the retrieved signal, as the air-filled pores cause scattering of the sound waves. The relative position to the groundwater table is the single most important factor in terms of the data quality.

The drilling installations used for the SCAN seismic acquisition are not equipped to drill far enough through the hard subsurface of push moraines to place shots below the water table. Theoretically, it would the possible to use heavier drilling rigs suitable for this job. The downsides of this are that those stations are less mobile, the drilling would be more time-consuming and the financial expenses would increase. This makes it a less feasible solution. Therefore, the advice is to avoid the crossing of push moraines in the planning of future seismic acquisitions.

In general, it would be advised to take the local groundwater level into consideration during the planning of future seismic acquisition. This allows one to determine the minimum drilling depth which should be reached to ensure the placement of shots below the groundwater table. During the planning phase, the decision could then be made to use a heavier drilling station on a select number of locations.

Decreasing the noise

From the heat maps the observation was made that there is a large difference in the general noise between the rural and urban regions. The densely populated areas cause higher noise levels as there is more activity going on. If one wants to acquire cleaner data, urban areas are less suitable.

From the data we have seen that proximity of receivers to roads and windmills is responsible for higher noise levels. Ideally, one would like to keep distance from these structures along the line. However, in reality this is often quite complicated due to permitting and land access limitations. It is sometimes necessary to reach a compromise in order to place any shots or receivers at all.

Where roads and windmills are a constant factor of noise, railroad tracks are more incidental. The noise levels peak at the moment a train passes but are otherwise quite low. Hypothetically, one would be able to take the timing of the trains into account with the shooting of the sources. Realistically speaking however, the exact timing of trains can deviate a lot so this would have to be a manual task for somebody. If you then consider the relatively small benefits versus the additional costs, one can draw the conclusion this is not a worthwhile investment of time and people.

The last factor which can affect the recorded noise is the shooting time. In general, noise levels in the evening are lower than those during the day. However, as seen on the data of line SCAN040, accidental detonations during the day do not have such a significant influence on the quality of the data that it compensates for the costs of re-drilling the shots.

The bigger picture

The previous sections discussed how the acquisition phase can be optimized in order to retrieve the best possible data quality. One important element was not yet discussed in this analysis, namely the geothermal perspective. Both the quality of the data but also the relevance of the data was considered during the SCAN project.

We have seen that in urban areas lower charge sizes are allowed to be used and that there are higher noise levels. However, from a geothermal perspective the geological information close to a city can be very relevant. For a geothermal production location, it is namely essential that it has both suitable geological constraints and a nearby area of heat demand. Urban activity is therefore an inevitable source of noise when planning seismic acquisition for geothermal project developments.

During the project, it is a constant search of the balance between relevance and quality of data. The analysis done in this report attempts to aid this search, by considering aspects of both the acquisition and the processing phase.

4.3 Future research

With the finalizing of this report, a data analysis on all the regional lines shot in the scope of the SCAN project has been completed. The signal to noise ratio of the all the recorded shots was determined, based on the recorded ambient noise. For future studies, it would be interesting to also consider shot generated noise and to see how suitable this would be as a quality indicator. An example of shot generated noise is the previously mentioned groundroll, high-amplitude low-frequency and slow-travelling surface waves caused by the detonation of the charge. The advantage of considering this type of noise is that it could provide some more information about near-surface parameters.

Next to groundroll, another type of shot-generated noise was observed in the data. So called guided waves dominated some of the shots. These are reverberations which can occur if there is a strong velocity contrast present in a superficial layer. This enlarges the super-critical region, trapping the energy. These reverberations are visible in shots as high-amplitude low-frequency but fast-travelling waves. While the groundroll is relatively easily removed during processing due to slower travelling of the waves, guided waves form a bigger problem. Filtering in the frequency domain could namely also remove some of the signal, something one would like to avoid during processing.

As guided waves complicate the processing phase, it would be interesting to study what their origin is and whether these circumstances can be avoided in the acquisition phase. During the data analysis of the individual lines, it was noted that a lot of reverberations were present at the end of line MRA041 in Flevoland. Line SCAN042 ran through the Noordoostpolder, with a similar subsurface, but barely any guided waves were observed. The period in which these lines were shot did vary. Where during the acquisition of line MRA041 it was raining, line SCAN042 was mainly recorded during sunny weather.

The hypothesis is therefore that the occurrence of guided waves could be dependent on the saturation of the subsurface. If after periods of heavy rainfall the ground is saturated with water, this could potentially cause these energy trapping layers. It would therefore be interesting to investigate a method for identifying the presence of guided waves in shots. This information could then be compared with local precipitation levels to see whether there is a correlation.

The ground saturation is an interesting component, but it would also be valuable to look at the bigger picture of the near-surface geology. This analysis could provide insight into other elements potentially causing the reverberations, such as specific formations. During this analysis, it would also be insightful to consider whether guided waves occur at all charge sizes or whether there is a minimum amount of energy necessary for them to come into existence.

Another element on which could be improved is the quality quantification of the final processing results. It would be interesting to run another analysis but this time solely on the North-Sea group. As this formation has relatively constant geology on all the lines, less impact of local geology on the seismic data is expected.

Finally, in order to properly investigate the nearby effect of roads, the data analysis on this element should be performed again. This time the complete length of the roads should be considered, rather than the distance markers. While it was opted for using these markers as it decreased the computation time, it did not allow us to study the exact effect of the proximity of a road on the recorded noise levels.

5 Conclusion

This data analysis was executed within the scope of the SCAN project. By evaluating the quality of the data and its dependence on various parameters, potential enhancements of the seismic acquisition design could be investigated. The goal of this optimization is to increase the retrieved signal, while decreasing the recorded ambient noise.

A reduction in ambient noise can be realized on a regional scale by avoiding more urban regions and locally by keeping distance from windmills, roads and railroad tracks. An increase in signal amplitude can be accomplished by drilling deeper shot depths, placing higher charge sizes but most importantly shooting below the groundwater table. Shots placed above the groundwater table always resulted in very low data. Local zones of elevation, such as moraines, should therefore be avoided in the planning of future seismic acquisition projects. If they cannot be avoided, preliminary research into the groundwater table and local usage of heavier equipment for drilling deeper shot holes could provide a solution.

This analysis has been insightful for the theoretical side of the data acquisition optimization. When we consider the bigger picture however, one should take into account that the main goal of the SCAN project is to accelerate developments in the geothermal sector. For geothermal production both the geological constraints and the proximity of a heat demand area are crucial elements. Therefore, the practical side of the data acquisition is to find the best possible balance between the relevance and quality of the data, while being limited by external factors such a permitting.

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Appendices

A Average parameters of the lines

An overview of the acquisition parameters and analysis results of all the lines is presented in the following figures. The names of some lines were adapted to SCAN, to keep the labels in a clear and consecutive order for the reader. Next to the lines discussed in this report, the corresponding values of 7 local lines shot in the vicinity of northern Limburg and Oost-Utrecht are shown.

Charge size

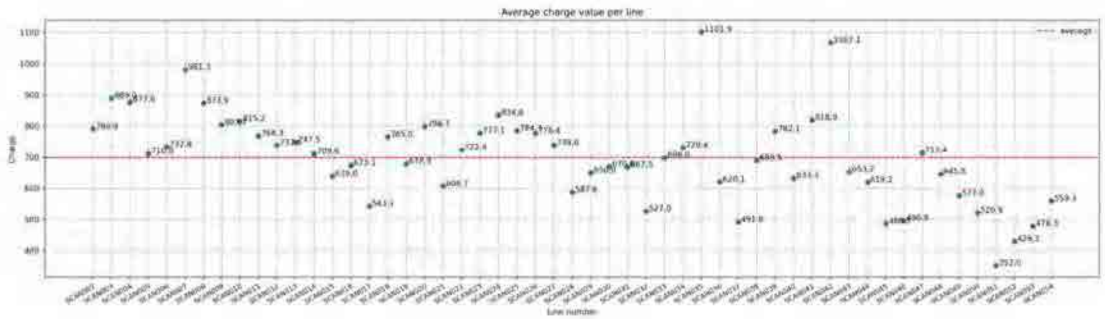

Figure A.1: Average charge size of all the lines.

Shot depth

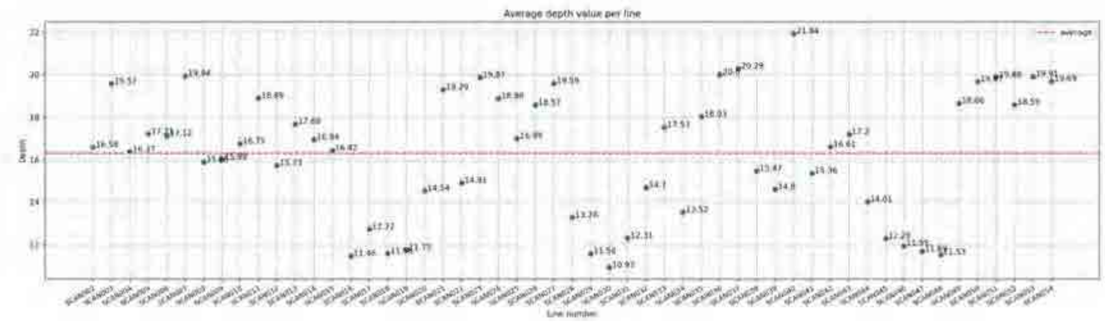

Figure A.2: Average shot depth of all the lines.

Signal

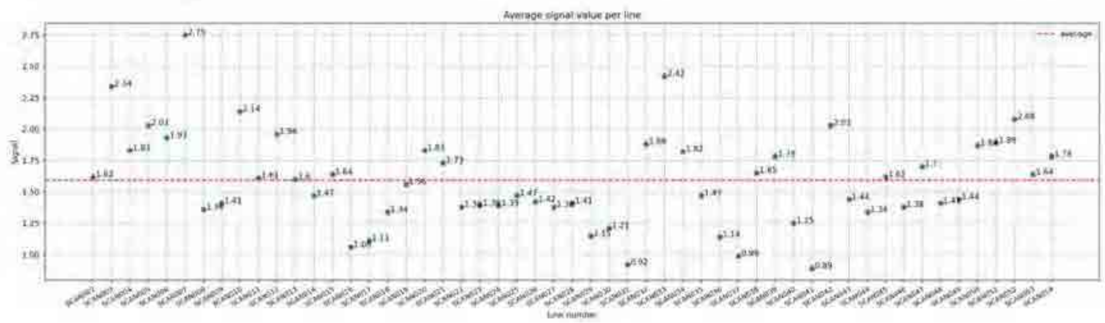

Figure A.3: Average signal of all the lines.

Noise

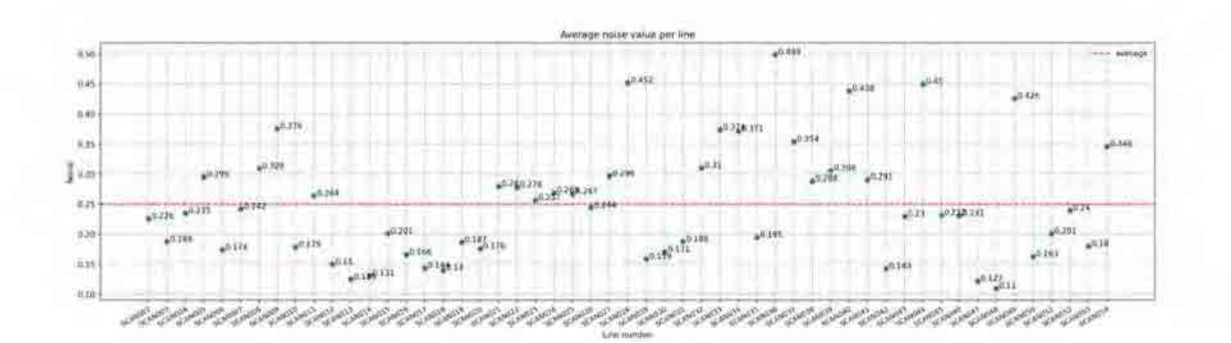

Figure A.4: Average signal of all the lines.

Signal-to-Noise Ratio

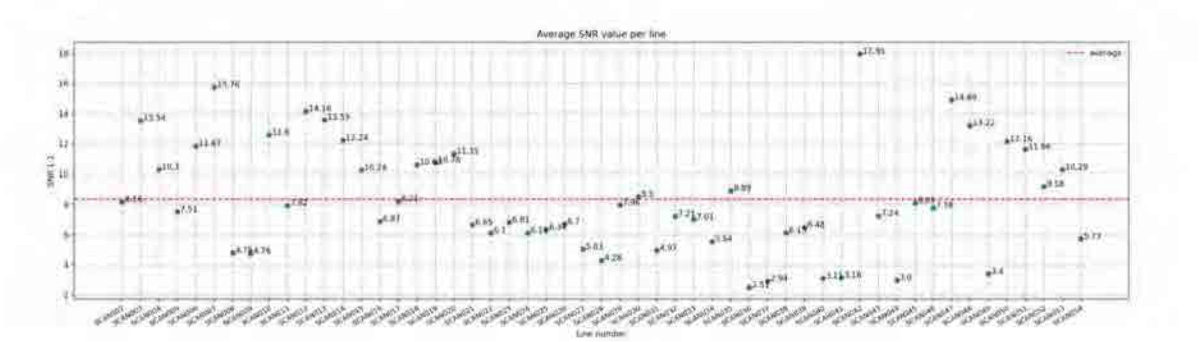

Figure A.5: Average SNR of all the lines.