Seismic noise: A challenge and opportunity for seismological monitoring in densely populated areas

Jörn Groos (1), Joachim Ritter (1)

1) Geophysical Institute, Karlsruhe Institute of Technology, Hertzstr. 16, 76187 Karlsruhe, Germany, joern.groos@kit.edu, joachim.ritter@kit.edu

Abstract

We discuss the ambient seismic noise in densely populated areas which significantly complicates the seismological monitoring of induced seismicity due to geothermal power plants or CO_2 sequestration. We use a statistical time series classification scheme in combination with a spectral time-frequency analysis to demonstrate the most important properties of the urban seismic noise. The analysis focuses on the frequency range above 1 Hz which is important for the seismological monitoring of micro-earthquakes ($M_L < 3$). We select amongst others representative measurements in the vicinity of geothermal power plants in the densely populated south-western part of Germany. Finally we review the promising opportunities to turn seismic noise into a signal for seismological monitoring.

Introduction

Several of the new techniques using the deep underground, such as geothermal power exploitation or CO_2 sequestration, have to be installed in densely populated areas to be economically successful. Geothermal power plants need access to the district heating network to efficiently use the low-temperature heat remaining after electric power production. Therefore, even weak and non-destructive induced micro earthquakes became a serious problem for operators of geothermal power plants as such events are felt by many residents (Giardini, 2009). This induced seismicity causes a loss of acceptance for new technologies in the local population. The potential application of CO_2 sequestration struggles with similar problems as large coal power plants are also installed in densely populated areas. A transparent and comprehensive (seismological) monitoring of new interventions in the underground is crucial to achieve and keep the public acceptance.

Seismological monitoring in cities and densely-populated areas is a challenging task due to the complexity of the man-made seismic noise. Especially the important identification of micro-earthquakes, which are unnoticeable for humans, is made difficult by numerous man-made sources of seismic energy such as traffic and industry. Man-made seismic signals are the dominant source of seismic energy in the frequency range of interest above 1 Hz. A good knowledge and understanding of the seismic noise in densely populated areas is important for the successful planning and operation of seismological monitoring networks. Especially the identification of suitable measuring sites at the surface is important as the installation of entire networks in boreholes is hardly possible for economic and/or practical reasons. Furthermore, the reliable identification of micro-earthquakes requires a good knowledge of the local seismic noise besides other parameters (e.g. seismic velocity structure, etc.).

Data set and analysis

In the following the properties of seismic noise in densely populated urban areas are demonstrated with the help of seismological measurements in the Upper Rhine Graben (URG) in Southwest Germany. From December 2004 until May 2006 the TIMO network (Ritter et al., 2008) was operated and since July 2009 the second phase TIMO2 is under way (Figure 1). The URG is interesting for the installation of geothermal power plants due to heat flow anomalies (Hurtig et al., 1991). The first geothermal power plants are already in operation, some 20 plants are in the planning phase. Since historical times, the URG is densely populated and of high economical importance due to the mild weather conditions, the good farmland (sediments) and the vicinity of the river Rhine.
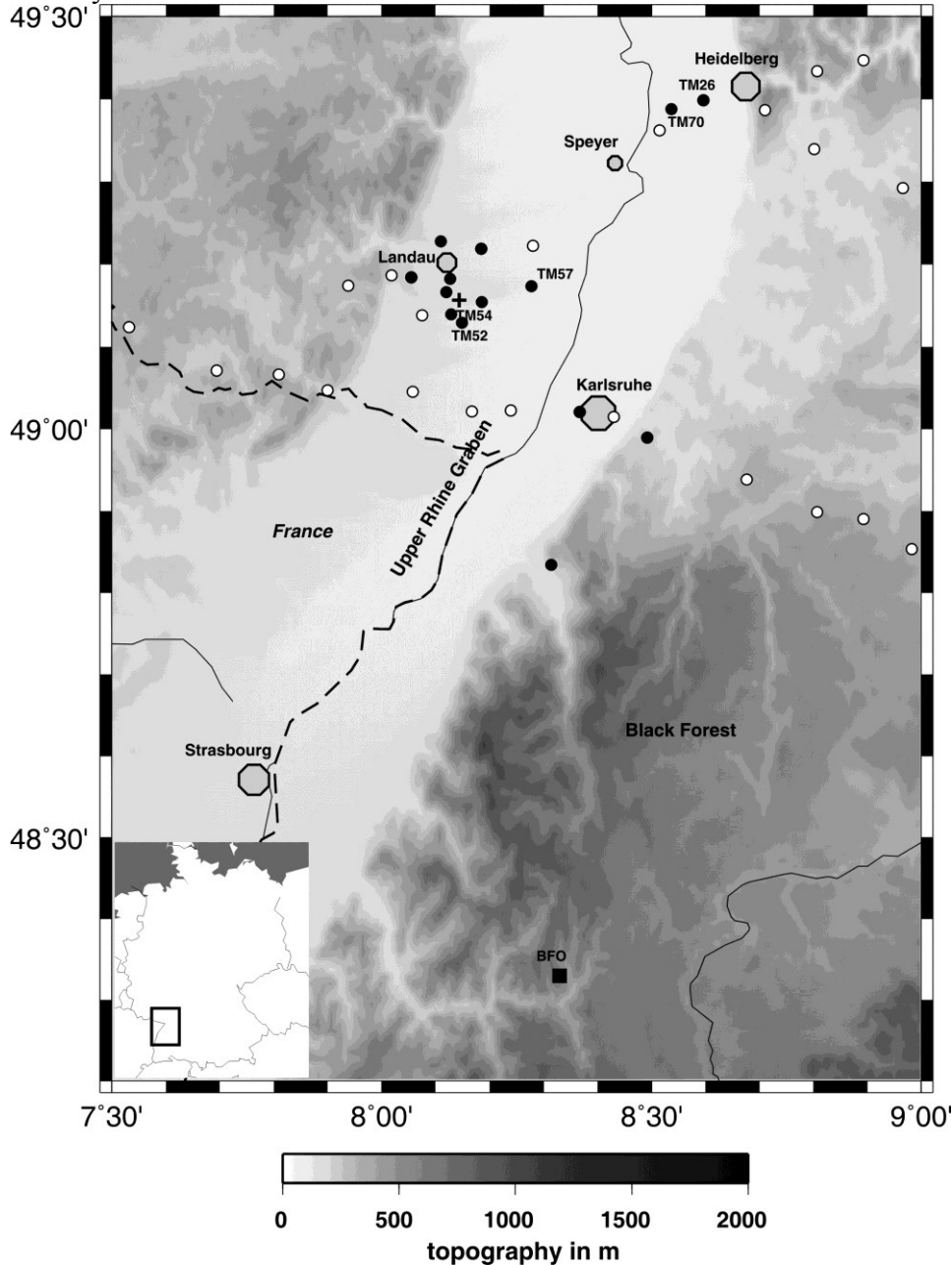
Figure 1: Recent seismological broadband experiments in the region of the Upper Rhine Graben: TIMO experiment (white circles) and TIMO2 experiment (black circles). The approximate epicentre area of 2 events on 9. Apr. 2010 is given by the cross.

Seismic noise is high in the URG due to major traffic lines (railway, highways), industry and unconsolidated sediments. Numerous of the important urban areas worldwide have developed in such sedimentary settings near rivers comparable to the URG. The map in Figure 1 displays the station locations. TIMO2 stations TMO26, TMO54 and TMO70 are located on cemeteries at the outskirts of small towns. TMO52 is inside a former mill which now is used as a residential building outside a village. TMO57 is situated on a farm. For comparison also seismological measurements outside the URG are included in the following. We demonstrate the significant influence of the dense population and the sedimentary setting on seismic noise by a comparison with seismological measurements at the Black Forest Observatory (BFO). The BFO is located in a remote old mine in a hard-rock setting. The BFO is known for high-quality measurements with low noise conditions even on a global scale.

The properties of the urban seismic noise are discussed with the help of a statistical time series classification and a spectral time-frequency analysis. The time series classification (Groos & Ritter, 2009) uses ratios of amplitude intervals (I) and percentiles (P) to identify and quantify the deviations of the time series histogram from the Gaussian distribution. In the case of a zero mean Gaussian distribution, 68% of the measurements lie within an interval of one standard deviation away from zero (I68). 95.45% of the measurements are within two times the standard deviation (I95) and 99.73% of the measurements are within three times the standard deviation (I99). This is also known as the 2-σ and 3-σ, or the 'empirical', rule.

We introduce the ratio between I99 and I95 as the new quantity peakfactor (pf) to determine the "peakedness" of the histogram. The peakfactor of a Gaussian distributed time series equals 1.5. Furthermore, the ratios of the lower and upper boundaries of the intervals (e.g. the 16-percentile (P16) and the 84-percentile (P84) for I68) can reveal a possible asymmetry of the histogram. The peakedness and the asymmetry of a time series histogram, especially in comparison to the Gaussian distribution, are commonly described by the statistical measures kurtosis and skewness of a time series. Unfortunately, the common statistical estimators for the kurtosis and skewness are not suitable for broadband seismic noise time series with more than 1 million samples (Groos & Ritter, 2009). Therefore, the ratios between the amplitude intervals (e.g. the peakfactor) and the amplitude percentiles (e.g. P84/|P16|) of the time series are used to classify the seismic noise time series (see Table 1 and below). The ranges of the amplitude intervals are used for quantification.

We introduce six noise classes to classify the typically observed deviations of seismic noise time series from the Gaussian distribution (Groos & Ritter, 2009). Time series are assumed to be Gaussian distributed if the interval ratios exhibit only very small deviations from the empirical rule and the histograms are symmetric (Table 1). Gaussian distributed time series are classified as noise class 1 (NC1). Non-Gaussian but symmetric time series are classified as NC2-NC5 depending on the observed deviation properties (Table 1). Time series which exhibit determinable but rather small and unspecific deviations from the Gaussian distribution (pf 1.5±0.1) are classified as noise class 2 (NC2). Time series with a gentle peaked histogram in comparison to the Gaussian distribution (1.6<pf≤2) due to few transient signals are classified as noise class 3 (NC3). A more pronounced peakedness of the histogram (pf>2) results in a classification of the time series as noise class 4 (NC4). Symmetric time series with a flattened histogram in comparison to the Gaussian distribution (pf<1.4) are classified as noise class 5 (NC5). All time series which are not identified as symmetric time series (see criteria for the ratios P84/|P16| and P97.5/|P2.5| in Table 1) are classified as noise class 6.

Noise class	I95/I68	I99/I68	Peakfactor			P84/|P16|	P97.5/|P2.5|
1	2±0.05	3±0.15				1±0.015	1±0.015
2			1.4≤	pf	≤1.6	1±0.030	1±0.047
3			1.6<	pf	≤2	1±0.030	1±0.047
4			2.0<	pf		1±0.030	1±0.047
5				pf	<1.4	1±0.030	1±0.047

Table 1: Criteria for the interval and percentile ratios to classify symmetric time series as noise classes NC1-NC5.

Only the four noise classes NC1 to NC4 are relevant for the following discussion of the seismic noise in the URG. Time series of seismic noise classified as NC5 or NC6 are in general seldom observed (Groos & Ritter, 2009).

Naturally, the detection of seismic waves excited by micro-earthquakes is less complicated, if the seismic noise itself exhibits only few transient signals. Therefore, the noise classification is a valuable tool for the selection of measuring sites. Next to the seismic noise amplitudes (e.g. the I68 and I95 amplitudes) also the frequency of occurrence of transient signals can be considered for site selection. Assuming the same noise amplitudes, a station site with a lower noise class should be preferred.

The urban seismic noise

A comprehensive and complete literature review of the current knowledge about the seismic noise wave field in general is given by Bonnefoy-Claudet et al. (2006). A detailed discussion of the Urban Seismic Noise (USN) in the frequency range from 8 mHz to 45 Hz is given by Groos & Ritter (2009). In the following, we discuss briefly the USN above 1 Hz which is dominated by man-made signals.

The typical temporal variations of the vertical component USN (1-40 Hz) are demonstrated with the help of the noise amplitudes (ranges of the amplitude intervals I68 and I95) determined with a sliding 4 hour time window (step length 1 hour). The noise amplitudes (ground motion velocity) over 14 days in April 2010 are plotted in Figure 2 for several sites located in the URG. A distinct daily pattern at all sites demonstrates the dominant influence of human activity on the USN in the frequency range 1-40 Hz. The nightly amplitude lows of ~5 hours are much shorter than the daily highs of ~19 hours. Besides this daily pattern, the USN also contains a distinct weekly pattern at most sites (see the weekends at days 5 and 6 as well as 12 and 13).
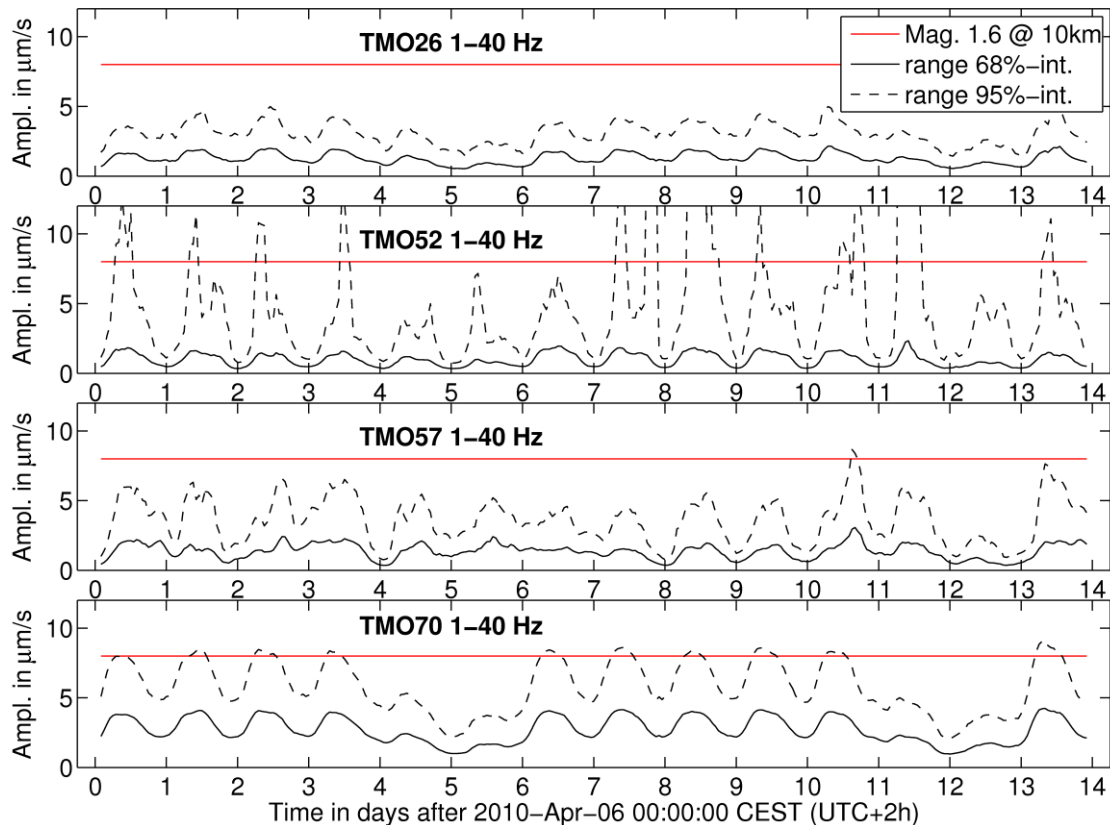
Figure 2: The seismic noise amplitudes (ranges of amplitude intervals I68 and I95) determined in a sliding 4 hour time window (step length 1 hour) in the frequency range 1-40 Hz at TMO stations 26, 52, 57 and 70. All sites are located in the URG. The red lines indicate exemplary the direct P-wave double amplitude of a M_L 1.6 earthquake near Landau (2010-04-07 09:04:04) observed in the URG at a distance of 10 km to the epicentre. The first day (2010-04-06) was a Tuesday.

The red lines in Figure 2 indicate exemplary the p-onset double amplitude measured at a distance of 10 km to the epicentre of a M_L 1.6 earthquake which occurred in the URG near the city of Landau. It is a rule of thumb that a transient signal should be larger as two to three times the 95% interval of the time series to emerge clearly from the background signals. The examples in Figure 2 illustrate that a P-wave with a double amplitude of ~8 μm/s emerges not clearly from the seismic noise at several typical surface sites in the URG. For example, such a p-onset is only one transient signal amongst many others at sites such as TMO52 or TMO70 because the P-wave double amplitude is even smaller than the 95% amplitude interval at daytimes. Therefore, a dense and sensitive seismological network is necessary in such a setting to ensure the observation and identification of micro-earthquakes at several stations for localisation. The examples illustrate furthermore, that the seismic noise amplitudes exhibit a significant spatial variation (compare for example TMO26 with TMO52) which are further discussed in the next section about station site characterisation. A spectral time-frequency analysis as shown in Figure 3 gives a more detailed insight into the character of the urban seismic noise.
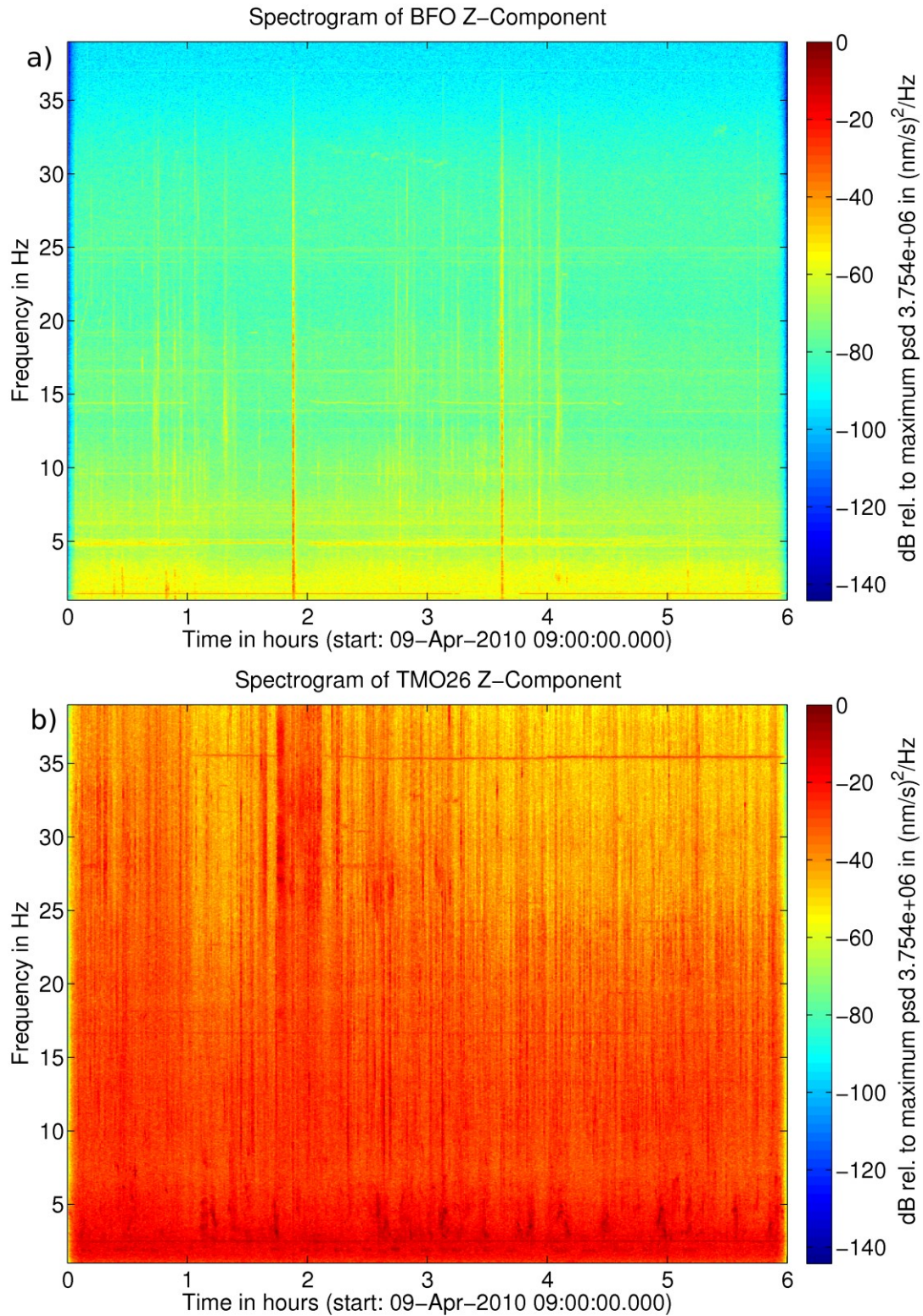
Figure 3: Spectral time-frequency analysis (power spectral density in dB by colour) of the vertical component seismic noise between 1 Hz and 40 Hz at station (a) BFO and (b) TMO26. The colour bars are normalised identically to the largest power spectral density observed at site TMO26 for comparison.

In Figure 3 the spectrograms of 6 hours duration of the vertical component seismic noise (1-40 Hz) are plotted for the stations BFO (Figure 3a) in a mine (solid rock) and TMO26 (Figure 3b) at the outskirts of a small town (sediments). In this time window

two earthquakes of M_L 2.4 (2010-04-09 10:52 UTC) and M_L 2.2 (2010-04-09 12:36 UTC) occurred in the URG at the same epicentre near the village of Insheim. Both earthquakes are clearly visible in the recordings at site BFO at a distance of ~90 km to the epicentre due to the very low noise conditions at BFO. The broadband transient signals of the earthquakes are visible in the spectrogram (Figure 3a) as vertical lines of increased power spectral density (red colours). Due to the high noise conditions in the URG the signals of both earthquakes are not identifiable at site TMO26 located at a distance of only 38 km to the epicentre (Figure 3b). The colour scales of both spectrograms are normalised identically to the largest power spectral density (psd) observed at site TMO26 to visualise the tremendous difference of the noise amplitudes between BFO and TMO26.

The most important sources of the observed man-made seismic signals are traffic and industry. In the frequency range above 1 Hz traffic-induced seismic waves are excited by road traffic and trains or can be generated by traffic induced bridge oscillations. These contribute significantly to USN in a broad frequency range from ~1 Hz to more than 45 Hz with maximum amplitudes at 1-10 Hz. Long lasting and very narrow-band signals above 1 Hz, recognised as horizontal lines of increased psd in the spectrograms (e.g. ~2 Hz and ~5 Hz in Figure 3a as well as 16.7 Hz and ~35 Hz in Figure 3b) are sinusoidal-type seismic waves most probably excited by rotating machinery at sharp frequencies. Examples are electrical motors and gear boxes of industrial machinery, power generators and building services machinery. Due to gear boxes and frequency converters such sinusoidal signals can be observed in the whole frequency range from 1 Hz up to the electrical power frequency (50 Hz) but predominantly at frequencies around 2.08 Hz (48 poles; generators and engines), 12.5 Hz (8 poles; engines), 16.7 Hz (6 poles; engines), 25 Hz (4 poles; engines) and 50 Hz (2 poles; engines). A significant drop of psd by up to 20 dB can be observed above 25 Hz towards higher frequencies at most sites in urban areas (Figure 3b).

Site characterisation
The ranges of the amplitude intervals I68, I95 and I99 in combination with the derived noise classification provide a useful tool for site characterization and therefore site selection. It is illustrated by the examples in Figure 2 that not only the noise amplitudes quantified by the amplitude intervals but also the ratios between the amplitude intervals exhibit distinct spatial variations. The ratio between I95 and I68 is increasing with increasing deviations from the Gaussian distribution due to transient signals. As an example, significantly more transient signals are observed at station site TMO52 than at site TMO26 (Figure 2) resulting in an increased ratio I95/I68 at site TMO52. The capability to identify seismic waves excited by a micro-earthquake is therefore significantly limited at site TMO52 in comparison to site TMO26.

The classification results of the 14 days of USN with the sliding 4 hour time window are shown for several TMO sites and site BFO in Figure 4. For this analysis the frequency range 1-10 Hz is selected which is predominantly affected by transient traffic induced signals. Far most 4 hour time windows of seismic noise recorded at TMO stations in the URG are classified as NC3 and NC4. They are therefore identified to exhibit a significant number of transient signals complicating the detection of earthquake waves. In contrast, up to 40 % of the 4 hour time windows of the seismic noise recorded at the BFO are Gaussian (NC1) or nearly Gaussian (NC2) distributed. The detection of micro-earthquakes at BFO is enhanced not only by the significantly lower noise amplitudes but also by the more suitable statistical characteristics of the seismic noise in terms of less transient signals.

The seismic noise in the URG above 1 Hz is dominated in general by transient signals but differences between the sites are revealed by the noise classification. The seismic noise at site TMO52 exhibits numerous transient signals which is illustrated not only by the high I95 amplitudes (Figure 2) but also by the classification of nearly 80 % of the 4 hour time windows as NC4 (Figure 4, upper right corner). As indicated by the I95/I68 ratio, the recording conditions are better at site TMO26 with less time windows classified as NC4 (Figure 4, upper left corner). From the statistical point of view, the seismic noise at site TMO70, a cemetery at the outskirts of a town, is most suitable to detect transient signals excited by micro-earthquakes as apparently less man-made transient signals exist. This is indicated by the lower amount of time windows classified as NC4 (below 20 %) and the observation of some nearly Gaussian distributed noise time windows (NC2). Nevertheless, the seismic noise amplitudes at site TMO70 are higher than at the other sites. Especially the comparably high I68 amplitudes even at nighttimes inhibit the detection of small transient signals at this site. Based on the combined analysis of the noise amplitudes and the noise classification sites such as TMO26 and TMO57 should be preferred in comparison to sites such as TMO52 or TMO70.

Concluding, a careful site selection including a statistical noise analysis is capable and necessary to improve seismological monitoring in densely populated areas.
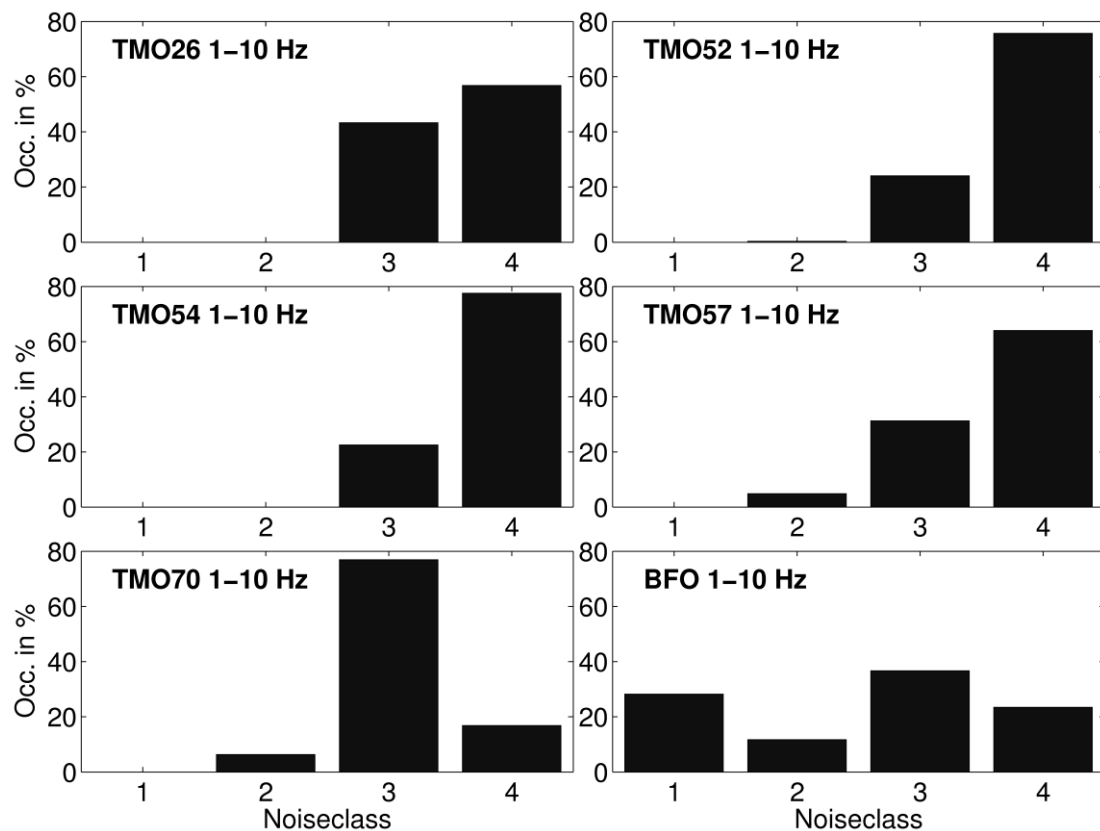

Figure 4: Histograms of the noise classification of 14 days of seismic noise in the frequency range 1-10 Hz with a sliding 4 hour time window (time step one hour) for the station sites TMO 26, 52, 54, 57 and 70 in the Upper Rhine Graben as well as site BFO in a remote mine in the Black Forest.

Identification of earthquake signals

As demonstrated above, the discrimination of earthquake signals from other disturbing transient signals present in the ambient seismic noise is the major challenge for seismological monitoring above 1 Hz in densely populated areas such as the URG. Traditional tools such as trigger algorithms for the detection of transient signals alone are not suitable for this task as far most of the numerous transient signals are not related to seismic events. A successful automatic detection system for earthquake waves has to include further characteristics of the signals such as frequency content, waveform or duration. Furthermore it has to be capable to recognise similar and/or reoccurring signals and to provide some kind of signal classification to support and simplify a following manual analysis. A promising aspect is the application of machine learning and pattern recognition techniques to this seismological problem.

One suitable unsupervised pattern recognition technique is the Self-Organising Map (SOM) technique which was already applied successfully to seismological signal detection problems (Köhler et al., 2010). This technique is also used for an ongoing analysis of an urban seismic noise data set recorded in the URG in the town of Staufen im Breisgau about 20 km south of Freiburg (Baumann et al., 2010). The inner city area of Staufen ($\sim$200x200 m^2) started to lift up after the drilling of boreholes (140 m) for shallow geothermal heat pumps next to the old town hall in September 2007. The still ongoing uplift is taking place with local uplift rates up to 8 mm/month (www.staufen.de). Between May 2009 and August 2010, up to 9 Karlsruhe BroadBand Array (KABBA) stations were operated with the objective of finding possible seismic signals related to the uplift. Although no seismic signals related to the uplift could be identified up to now, the SOM approach proofed to be successful to identify reoccurring transient signals caused by traffic and other sources in the town. The automated discrimination of different types of reoccurring transient signals by machine learning techniques is a promising approach to improve seismological monitoring in complicated settings.

Future opportunities and outlook

The continuously recorded seismic noise, precisely the ambient vibrations of the ground, provides also opportunities for seismological monitoring. Promising in this context is the application of seismic interferometry (Snieder & Wapenaar, 2010). Seismic interferometry denotes the approach to retrieve Green's functions of the underground from cross-correlations of seismic signals. Green's functions retrieved from seismic noise cross-correlations are successfully used for seismic tomography. Furthermore, subtle changes of the retrieved Green's functions with time can be used to obtain changes of the propagation velocity of seismic waves in the underground of 0.1% or even less (e.g. Sens-Schönfelder & Wegler, 2006). Both approaches are promising applications for the characterisation and monitoring of all kind of underground reservoirs. First tests of this noise based monitoring of reservoirs are taking place for example at the CO_2-sequestration site near Ketzin, Germany (Mündel et al., 2009) and at hydrocarbon reservoirs (Bussat & Kugler, 2009). Concluding, seismic interferometry can be expected to improve and extend the capabilities of seismological monitoring tremendously in the near future.

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