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für Geräusche und Erschütterungen

Akkreditiertes Prüflaboratorium nach
DIN EN ISO 17025

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# Offshore Wind Farm *Eneco Luchterduinen*

# Ecological monitoring of underwater noise during piling at Offshore Wind Farm *Eneco Luchterduinen*

Version 6

Project Number: 2322-14-bel

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## List of changes

| Version | Date | Changes |
|---|---|---|
| Version 1 | 12.12.2014 | draft |
| Version 2 | 06.02.2015 | Integrated change requests by the client |
| Version 3 | 01.06.2015 | Integrated change requests by Rijkswaterstaat Zee & Delta |
| Version 4 | 15.06.2015 | Integrated change requests by the client |
| Version 5 | 09.07.2015 | Integrated minor change requests by the client |
| Version 6 | 29.10.2015 | Integrated change requests by Rijkswaterstaat Zee & Delta |

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# 1. Abstract

*Clusius C.V.*, as a subsidiary of *Eneco Luchterduinen*, conducted pile driving works for the offshore wind farm (OWF) *Eneco Luchterduinen* in the Northern Sea (Dutch area). One of the requirements for the construction and operation of windpark Eneco Luchterduinen (Q10) in the permit[1] is the conduction of a monitoring and evaluation Program (MEP). One part of this MEP is the measurement of underwater noise during piling.

In accordance to the requirements, underwater noise during pile driving was measured at two different monopiles, at four distances (750 m to several kilometers) from the source. The technical differences between the two monopiles are listed in Table 1.The measurements during pile driving were used to determine the underwater noise of piling at large distances. Also, a comparison between the underwater noise of a 'standard monopile'(EL 39) and an innovative monopile (EL42) has been made. Additionally, the ambient noise before and after piling was measured. The obtained data will be used for the validation of the TNO models (Aquarius and Zampoli). This validation is outside the scope of this report.

***Table 1:*** *Pile and foundation conditions for the monopiles EL39 and EL42.*

| Foundation | EL39 | EL42 |
|---|---|---|
| Diameter [m] | 5.00 | 5.00 |
| Scour protection | Yes | no |
| Pile length [m] | 68.46 | 75.93 |
| Penetration depth [m] | 29.62 | 38.03 |
| Water depth [m] | 21.80 | 20.50 |
| Total blows | 2,971 | 3,628 |
| Total blow energy [kJ] | 1,966,092 | 3,078,621 |
| Max. blow energy [kJ] | 830 | 1,110 |

[1] Beschikking Besluit inzake aanvraag Wbr-vergunning offshore windturbinepark 'Q10' (WSV/2009-914), 2 November 2009)

The measured Sound Exposure Levels (SEL) and their Standard Deviations (SD) during pile driving activities are listed in the following tables:

***Table 2:*** *Overview of pile driving noise for foundation EL39.*

| EL39 (Monopile with scour protection, Pile length: 68.46 m) | | | | | | | |
|---|---|---|---|---|---|---|---|
| Measurement-height above seabed | Position | Distance [m] | Distribution level of SEL [dB re 1 µPa²s] | | | | |
| | | | minimum | mean | median | max | SD |
| 2 m | $MP1_{EL39}$ | 750 | 170 | 175 | 175 | 178 | 1 |
| | MP2 | 4,724 | 154 | 158 | 158 | 160 | 1 |
| | MP3 | 13,232 | 138 | 143 | 143 | 144 | 1 |
| | MP4 | 46,578 | < 120 | < 120 | < 120 | < 120 | |
| 10 m | $MP1_{EL39}$ | 750 | 169 | 174 | 174 | 176 | 1 |
| | MP2 | 4,724 | 154 | 159 | 159 | 161 | 1 |
| | MP3 | 13,232 | 139 | 145 | 146 | 147 | 1 |
| | MP4 | 46,578 | < 120 | < 120 | < 120 | < 120 | |

***Table 3:*** *Overview of pile driving noise for foundation EL42.*

| EL42 (Monopile without scour protection, Pile length: 75.93 m) | | | | | | | |
|---|---|---|---|---|---|---|---|
| Measurement-height above seabed | Position | Distance [m] | Distribution level of SEL [dB re 1 µPa²s] | | | | |
| | | | minimum | mean | median | max | SD |
| 2 m | $MP1_{EL42}$ | 750 | 168 | 173 | 173 | 175 | 1 |
| | MP2 | 5,245 | 151 | 155 | 155 | 157 | 1 |
| | MP3 | 13,749 | 139 | 143 | 144 | 145 | 1 |
| | MP4 | 47,054 | < 118 | < 118 | < 118 | < 118 | |
| 10 m | $MP1_{EL42}$ | 750 | 167 | 171 | 171 | 173 | 1 |
| | MP2 | 5,245 | not valid* | not valid* | not valid* | not valid* | |
| | MP3 | 13,749 | 141 | 146 | 146 | 147 | 1 |
| | MP4 | 47,054 | < 118 | < 118 | < 118 | < 118 | |

*Hydrophone cable got damaged during deployment.

**Impact of different pile designs**

For the standard monopole (EL39) with scour protection the Sound Exposure Level (SEL) was between 2 dB to 3 dB higher than for the longer innovative monopole EL42. A reason for the higher levels could not be verified. The differences are most likely measurement uncertainties. As expected, the results for the Sound Exposure Level (SEL) at the longer pile showing spectra which are shifted to deeper frequencies which is due to a deeper natural resonance frequency (eigen frequency).

### Attenuation over large distances

When using common propagation models like the geometrical absorption - *15 $log_{10}$(d – distance ratio)* or the semi-empirical attenuation approach of Thiele & Schellstede (1980), the calculated attenuation of the pile driving noise at large distances was much lower than the observed attenuation. The observed attenuation in 2 m above the seabed was slightly higher than in 10 m above the seabed.

Up to a distance of 30 km the median Sound Pressure Level (SPL) was higher than the Sound Pressure Level (SPL) of the ambient noise. Due to a variance in ambient noise this distance in some cases increased to more than 40 km.

### Comparison with other windfarms

The measured Sound Exposure Levels (SEL) of both monopiles was within the range of the Sound Exposure Levels (SEL) of other Offshore Wind Farms (based on measurement data of *itap GmbH)*.

### Ambient noise

The ambient noise measurements before and after pile driving were dominated by underwater noise generated by vessels passing the measurement. The unweighted Sound Pressure Levels ($SPL_{,5s}$) varied at all measuring positions, inside and outside the construction area, between 109 dB and 166 dB, in periods without underwater noise generated by pile driving. The mean values for the ambient noise were between 115 dB and 127 dB re 1 µPa$^2$. Values above 140 dB can be explained by vessel traffic. At the measuring positions MP1 to MP3 the noise level during pile driving was at least 6 dB higher than the ambient noise level measured between the single blows.

Oldenburg, the 29th October 2015

P. Remmers Bellmann

Patrick Remmers, B. Eng. Dr. rer. nat. Michael A. Bellmann

# 2. Assignment of Tasks and Local Conditions

The company *Eneco Luchterduinen* is building the OWF *Eneco Luchterduinen* in the North Sea (Dutch area). This OWF will consist of 43 offshore wind turbines (OWT) fixed into the seabed (sediment) by monopiles which will be founded by using impulse pile driving, see Figure 1 and Figure 2.

The Wind Farm includes a scope for innovation which is the result of a covenant signed with the Dutch government. The innovations include two locations where no scour protection is necessary. The only difference between these foundation methods (piles) is the length of monopiles: those ones without scour protection are longer and need to be driven deeper into the seabed. Both types have the same diameter and the same hammer (IHC S-1400 with maximum blow energy of 1.400 kJ) will be used for all monopiles. No noise mitigation measures during the pile driving activities will be applied.

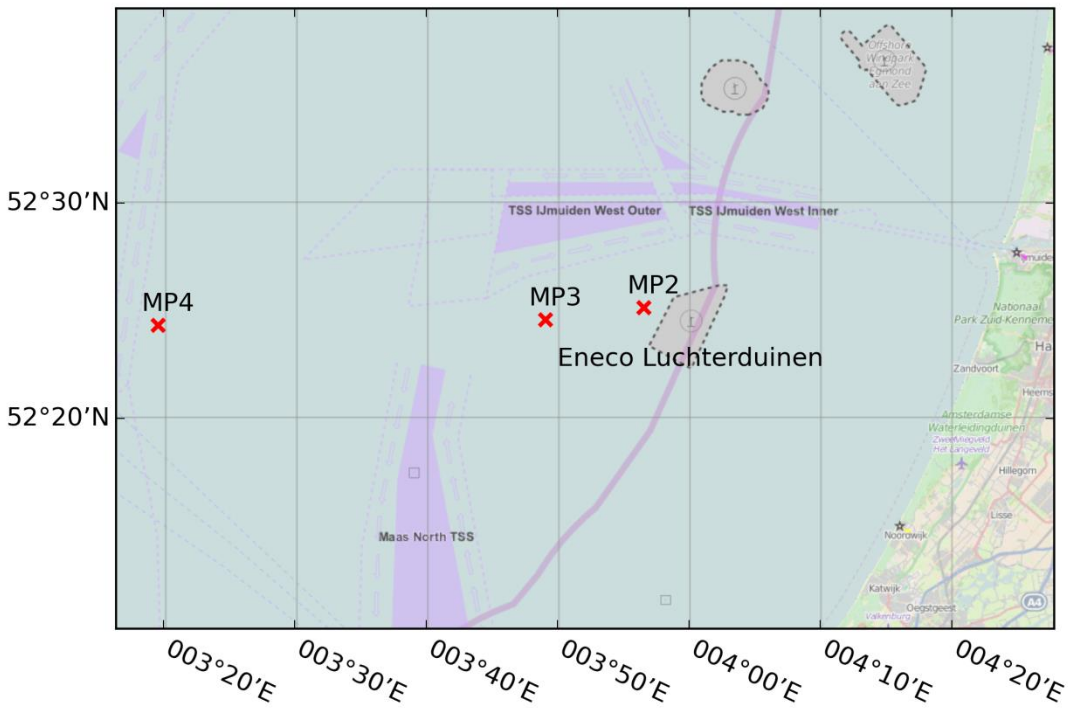



***Figure 1:*** *Overview map from the area around Offshore Wind Farm "Eneco Luchterduinen" and the measurement positions outside the windfarm. The main traffic routes are marked by violet arrows (source: www.Openseamap.org).*

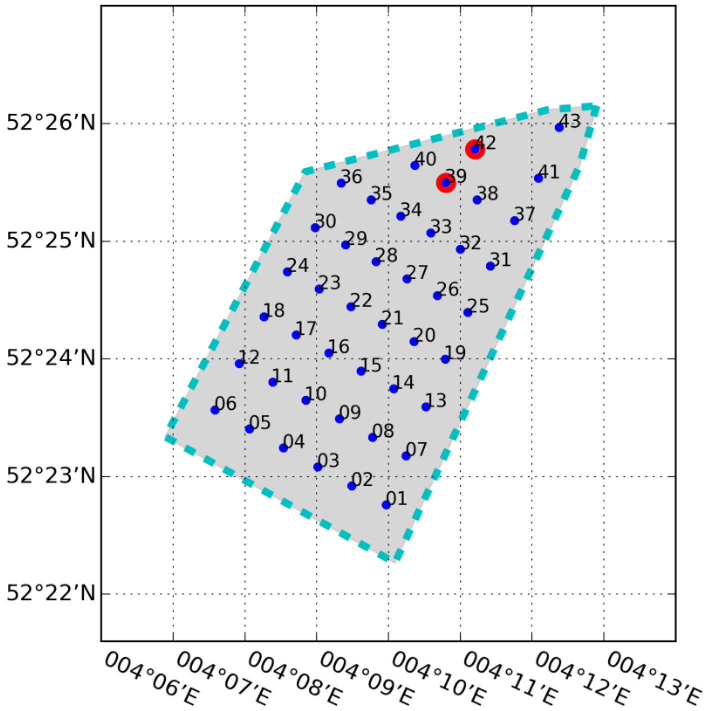



***Figure 2:*** *Overview map from the Offshore Wind Farm "Eneco Luchterduinen". The locations for the hydro sound measurements EL39 and EL42 are marked by red circles.*

The permit (Dutch competent authority: Rijkswaterstaat Zee & Delta) imposed general requirements regarding acoustic measurements (underwater or hydro sound) during these monopile installations:

- The underwater noise of hammering of two monopiles (pile driving activity) – one with and one without scour protection - had to be measured at various distances from the source. These data will be used for validation of the TNO models (Aquarius and Zampoli) and the data should meet the specifications of the TNO standard (TNO report TNO-DV 2011 C251).
- Additionally the ambient noise between the both monopile installations needed to be measured.

The *itap – Institute for technical and applied Physics GmbH* was commissioned by the future operator *Eneco Luchterduinen* to perform appropriate hydro sound measurements inside and outside the construction site according to the TNO Standard (TNO report TNO-DV 2011 C251). In this report all hydro sound measurements are summarized and discussed.

# 3. Hydro Sound Measurements

## 3.1 Measuring Concept

The purpose of measuring underwater noise during piling was to gather information about the (propagation of) underwater noise generated by pile driving and more specific to gather data for validation of the TNO underwater sound propagation model. Two questions need to be answered by this monitoring program at OWF *Eneco Luchterduinen*:

1) What are the differences in underwater noise between the "standard monopile" (with scour protection) and the innovative monopile (without scour protection)?
2) What were the underwater noise levels caused by piling at larger distances (> 20 km range)?

For this reason the hydro sound were measured at four positions during pile driving of two different piles, EL39 with scour protection and EL42 without scour protection. The measurement positions MP2 to MP4 were fixed outside the OWF area; measurement MP1 were inside the OWF area and individual for each piling activity in a fixed distance of 750 m. At each measurement position four hydrophones in two different heights were used, 2 m and 10 m above the seabed, one hydrophone for ambient noise and one for pilling noise. Table 4 gives an overview of relevant pile parameter. The measurement positions are listed in Table 5 and Figure 3. All measurement positions inside and outside the OWF construction area were selected in cooperation with *Eneco*, the construction company (*Van Oord*) and the competent authority.

***Table 4:*** Pile parameter of the locations EL39 and EL42.

| Parameter | Foundation | |
|---|---|---|
| | EL39 | EL42 |
| Position [WGS 84] | 52° 25.385′ N<br>004° 10.716′ E | 52° 25.671′ N<br>004° 11.119′ E |
| Foundation Type | monopile | monopile |
| Scour protection | yes | no |
| Diameter [m] | 5.00 | 5.00 |
| Pile length [m] | 68.46 | 75.93 |
| Pile mass [t] | 472.44 | 610.79 |
| Penetration depth [m] | 29.66 | 38.03 |
| Water depth [m] | 21.50 | 20.60 |

***Table 5:*** *Measurement positions and distances*

| Position | Location [WGS84] | | Distance [km] | |
|---|---|---|---|---|
| | Lat | Lon | to EL39 | to EL42 |
| $MP1_{EL39}$ | 52° 25.417′ N | 004° 10.055′ E | 0.750 | -- |
| $MP1_{EL42}$ | 52° 25.577′ N | 004° 10.474′ E | -- | 0.750 |
| MP2 | 52° 25.166′ N | 004° 06.551′ E | 4.738 | 5.260 |
| MP3 | 52° 24.603′ N | 003° 59.081′ E | 13.269 | 13.788 |
| MP4 | 52° 24.342′ N | 003° 29.547′ E | 46.711 | 47.189 |

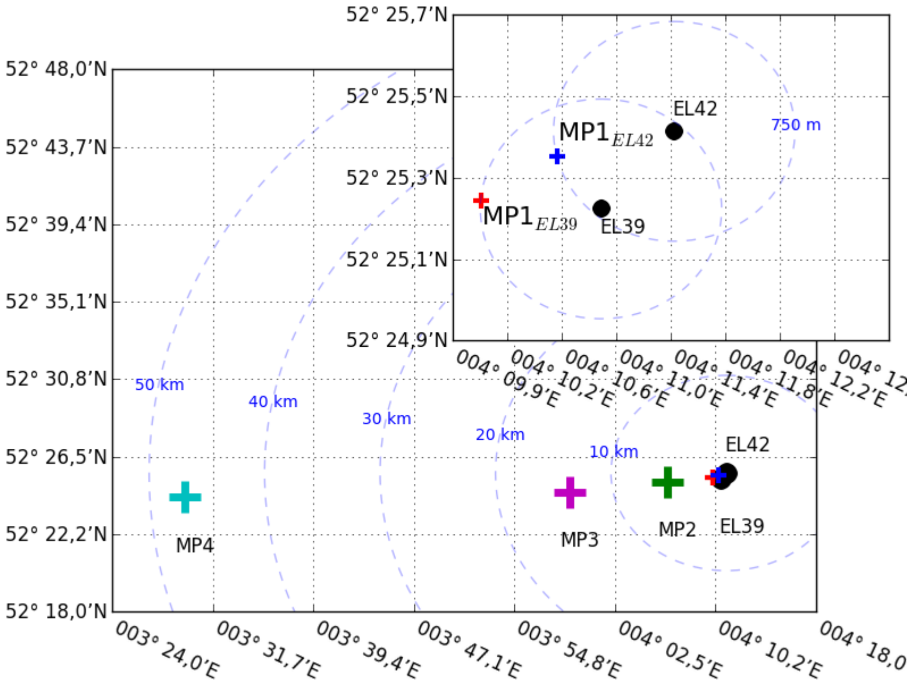



***Figure 3:*** *Measurement positions inside and outside the OWF construction area.*

## 3.2 Hydro Sound Measurement Device and CTD-Device

### 3.2.1 General

For all measurement locations the same type of measuring device were used with different set-ups: different hydrophones for ambient noise or pile driving noise, different hydrophone heights on each measuring device and different file formats for different measurement positions, which leads to different recording times. The applied measurement systems for recording hydro sound are stand-alone (deployed) measuring systems that were developed and built by *itap GmbH*. Figure 4 shows a photographical picture of a hydro sound measuring system incl. “light weighted” anchoring (mooring system, see details in chapter 3.2.2).

The measurement device consists of an anchor (mooring system), a box including all electronically devices and batteries, a rope including lifting bodies and a marker buoy (on the sea surface). Within this arrangement two hydrophones in heights of around 2 m and 10 m above seabed records the actual hydro sound (time recording). For pile driving and ambient noise different devices with different hydrophones were used.

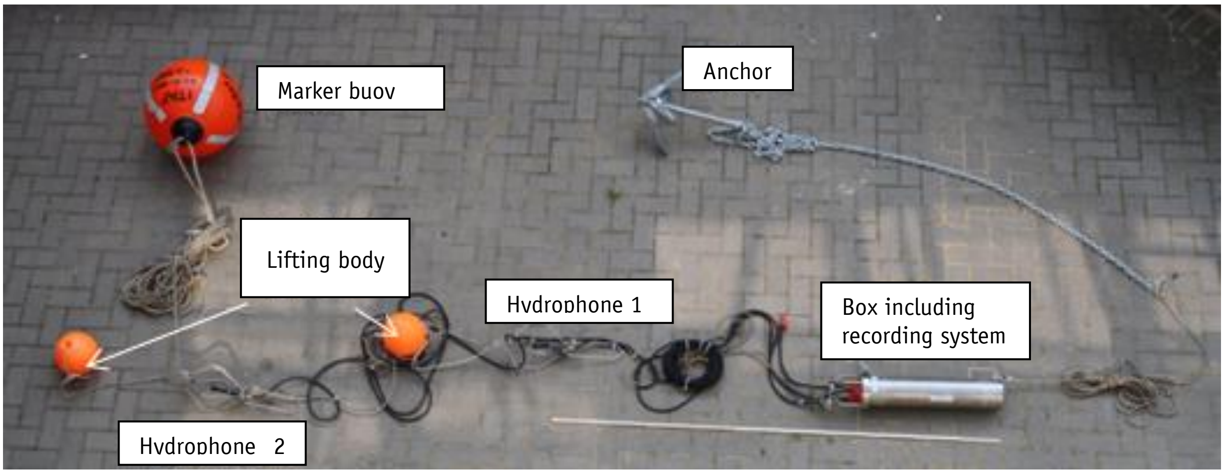



***Figure 4:*** *Stand-alone deployed hydro sound measurement device with “light weighted” anchorage and marking in a two-channel hydrophone design by itap GmbH. For the measurements two of these systems were used for one measuring position, one device for ambient noise and one device for pilling noise.*

### 3.2.2 Mooring system

The hydro sound measurement devices at the locations outside the OWF area (MP2, MP3 and MP4) were attached to a heavy “large” mooring system (Figure 5). On every location two hydro sound measurement devices were attached to the sediment rope from the large anchor stone (#1) to the small anchor stone (#2). The device for ambient noise measurements was fixed at 50 m distance and the device for pilling noise measurements at 90 m distance to the large anchor (anchor #1 in Figure 5) of the 100 m long “sediment rope”.

The hydro sound measurement devices inside the construction area (MP1) were attached to a “light-weighted” mooring system consisting of a marker buoy (marker ball) with a small anchor system (Figure 6). Both devices were fixed on one mooring system (the two devices were fixed together by a special mechanical clamp; all hydrophones were attached on the same rope).

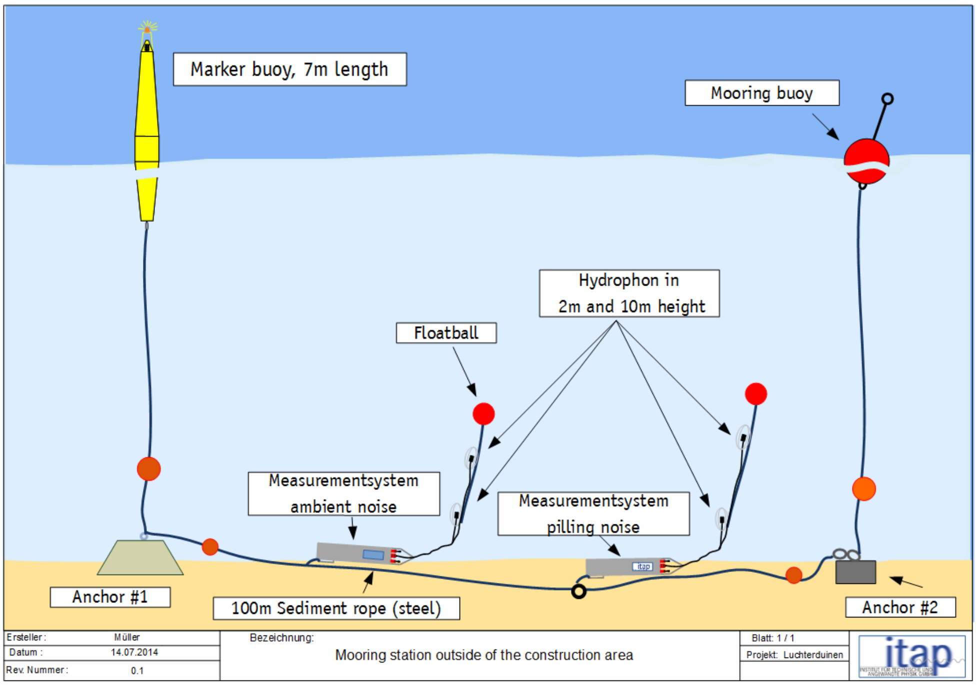



**Figure 5:** *Schematic depiction of a long-term hydro sound recording for the measurement locations outside the OWF area (MP2 to MP4) with two devices (not to scale). In case of this measurement the two devices will be fixed to the sediment rope and each system will have two hydrophones in two different heights: 2 m and 10 m above seabed.*

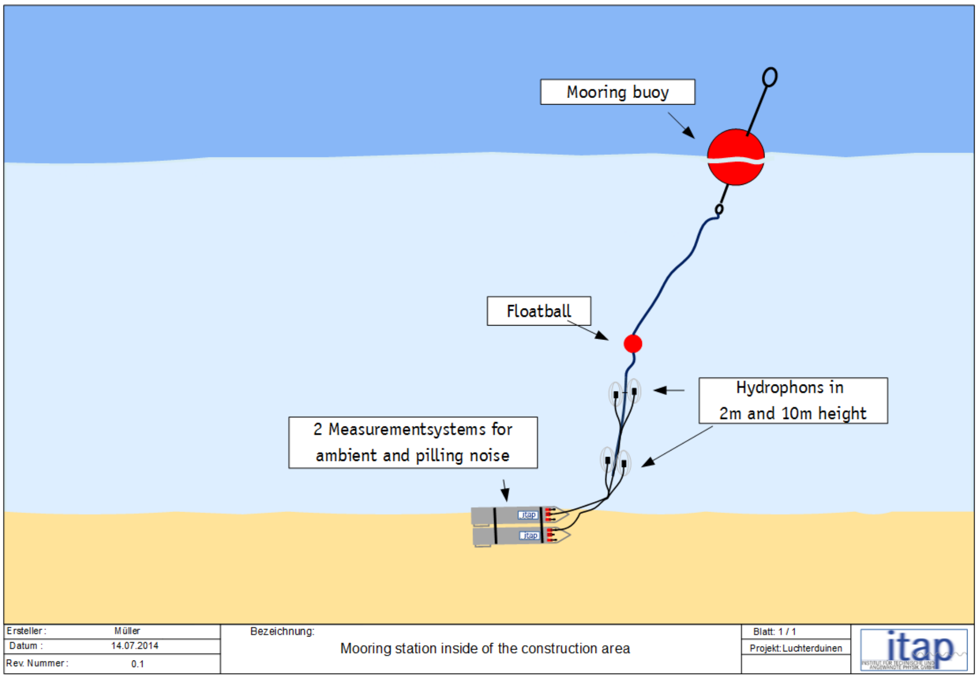



**Figure 6:** *Schematic diagram of a hydro sound measuring system incl. "lighted weighted" anchorage (for the measurement location inside the OWF area – MP1). (not to scale)*

### 3.2.3 Hydrophones

For the ambient noise measurements *Bruel & Kjær 8106* hydrophones (sensitivity of 2 mV/Pa) and *Reson TC4033* hydrophones (sensitivity of 0,5 pC/Pa) were used (depending on the distance of the measurement locations to the pile-driving activity). For the pile driving noise measurements *RESON TC4033* (sensitivity of 0,5 pC/Pa) or *Bruel & Kjær 8106* (sensitivity of 2 mV/Pa) hydrophones were used depending on the distance to the source of sound. Table 6 and Table 7 give an overview of all used devices and hydrophones. A detailed overview is listed in the Annex A2.1.

### 3.2.4 File formats (signal specifications)

The hydro sound measurement devices are able to record the time signal of the measured hydro sound at the hydrophone(s) in different recording or file formats by using different set-ups. According to the TNO measurement standard different options for the hydro sound recording formats and recording times (operational time offshore for each device) are possible. In the following subsection the selected and by the competent Dutch authority agreed file format, including device set-up, is summarized.

All measurement devices measured with a sampling frequency of 48 kHz. With this sampling frequency it is possible to record frequencies up to 24 kHz. In the following text all data is presented in 1/3-Octave bands with center frequencies between 20 Hz and 20 kHz. The 20 kHz Octave band is the complete Octave band below 24 kHz. The lower cut off frequency of 20 Hz is determined by the technical components of the measuring system.

Measurements were conducted with stand-alone underwater measuring systems for each foundation and location separately. Each system for measuring pile-driving activities or ambient noise was connected with two hydrophones in a determined water depth (2 m and 10 m above ground). Both signals per measurement device are fully synchronized per location.

**Lossless file format (MP1 to MP3):** The measuring systems recorded the hydro sound signals lossless (uncompressed) and in compliance with the actual available test code of the TNO-report (24 Bit resolution, PCM WAVE file format, 48 kHz sampling-rate). The used measurement devices were able to measure the hydro sound max. 36 h (storage / operational time is limited).

**Compressed file format (MP4):** The measuring systems recorded the hydro sound signals in a compressed file format (MPEG1[1], 48 kHz sampling-rate). In this recording mode the hydro sound could be stored (operational time) for a period of four weeks.

The raw data of all measurements are stored on an external medium and will be provided by *itap GmbH* for further applications.

### 3.2.5 Overview of used devices

The main components used for the hydro sound measurements are listed in Table 6. Table 7 gives an overview for the different set-ups used on every position. All measuring devices applied are in accordance with the measuring instruction for underwater sound measurements from the German approval authority (Müller & Zerbst, 2011) and will also fulfill the requirements of the WD ISO 18406 (2014) + TNO report (2011).

***Table 6:*** *Devices applied for hydro sound measurements.*

| Device | Producer | Important technical data/number of entities |
|---|---|---|
| Stand-alone underwater sound measuring system | Itap GmbH | Frequency range: 10 Hz-20 kHz |
| Hydrophone TC 4033 | RESON | sensitivity:<br>about 0.5 pC/Pa<br>number: 4 pieces |
| Hydrophone B&K 8106 | Bruel & Kjær | sensitivity: ca. 2 mV/Pa<br>number: 1 piece |
| Charge amplifier | Itap GmbH | 0.1 mV/pC (only for TC4033) |

[1] MPEG1 Audio Layer 3 to ISO IEC 11172 3 (Codingrates 32, 64 oder 96 kps per channel)

***Table 7:*** *Hydrophones and File Formats applied on every Position.*

| Position | Hydrophone height [m] | Hydrophone | | File Format | | Mooring system |
|---|---|---|---|---|---|---|
| | | pilling | ambient | Pilling | ambient | |
| MP1 | 2 | TC4033 | TC4033 | lossless | lossless | small |
| | 10 | TC4033 | TC4033 | lossless | lossless | |
| MP2 | 2 | TC4033 | TC4033 | lossless | lossless | large |
| | 10 | TC4033 | TC4033 | lossless | lossless | |
| MP3 | 2 | TC4033 | B&K 8106 | lossless | lossless | large |
| | 10 | TC4033 | B&K 8106 | lossless | lossless | |
| MP4 | 2 | TC4033 | B&K 8106 | compressed | compressed | large |
| | 10 | TC4033 | B&K 8106 | compressed | compressed | |

### 3.2.6 CTD Multiparameter probe

A multiparameter probe “CTD48” from Sun & Sun Marine Tech was used to measure the temperature, the static pressure and the salinity in the water column. On basis of these parameters it is possible to determine the sound velocity profile over the water column.

The mooring system of this device consisted of a rope (max. length 100 m) with an anchor weight of 2 kg at one end of the rope.

The sound velocity profile was recorded on every measuring position before deployment and after recovery. Even though the control light on the probe reported no error and a system check signalized that all data was successfully stored on the probe, it was impossible to read out the collected data. The CTD-probe got a storage error and also an emergency read out by the manufacturer was without success. Therefore no measured data for the sound velocity during these measurements is available. For this reason the sound velocity has to be calculated. For the calculation of a sound velocity profile different models are available. In this case the sound velocity profile was calculated by two different models due to Mackenzie (Mackenzie KV, 1981) and to Medwin (Medwin H, 1975).

Both calculations are empirical models in dependence of temperature, salinity and water depth. Figure 7 shows an example for calculated sound profiles compared with measured data in the North Sea. The blue line shows a sound velocity profile measured at the 13th June 2014 in the North Sea. The temperature was 15.6°C and the salinity 33.5 ppt over the whole water depth, except the last cm close to the sea bed and the surface. The green line shows the sound velocity due to Mackenzie (Mackenzie, 1981) and the red line due to Medwin (Medwin, 1975). The difference between both models is less than 1 m/s and the measured data fits between these calculations. For both models changes in temperature of 1°C leads to changes in sound velocity of 3.1 m/s and changes in salinity of 1 ppt to changes of 1.2 m/s.

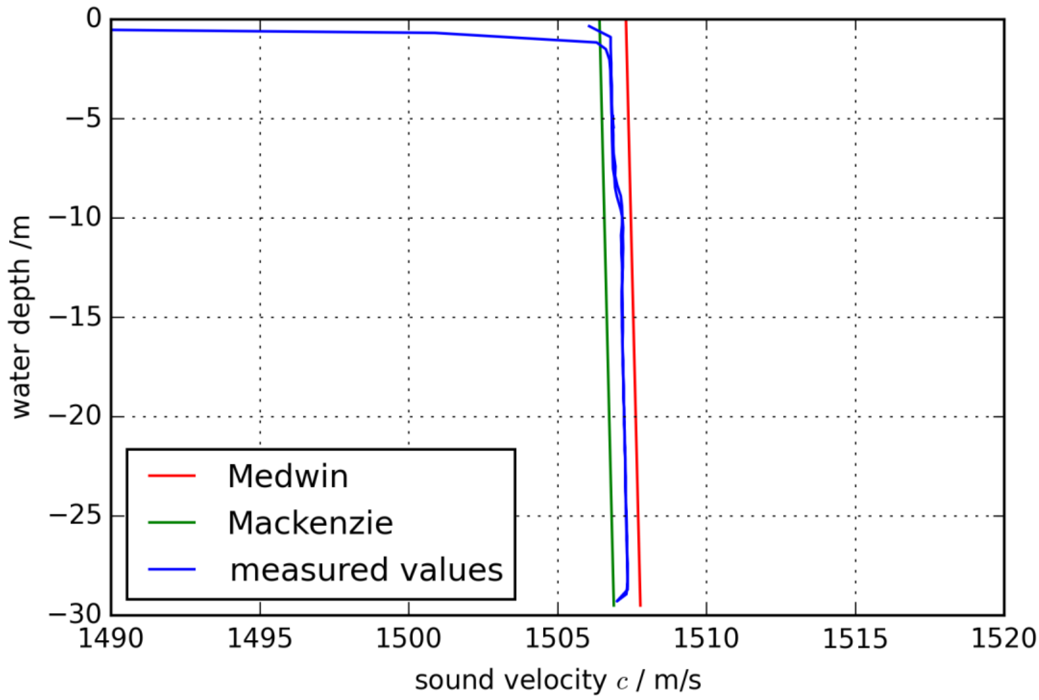



***Figure 7:*** *Calculated sound velocity profiles (red and green) compared with measured data (blue line).*

By knowing the temperature and salinity in the area it is possible to calculate a sound profile with a sufficient accuracy. The temperature was measured by a weather buoy in the construction field at the position: 52° 25.320′ N, 004° 10.020′ E in 824 m distance to location EL39 and 1,395 m distance to location EL42. During the pilling activities on EL39 between 17:00 and 19:00 at the 23th September the temperature was 18.0°C. During the pilling of EL42 between 02:00 and 04:00 at the 26th September the temperature was 17.6°C. The National Oceanographic Data Center (NODC, United States Department of Commerce) published a salinity database for the North Sea. The closest salinity data measured in autumn is available from two measurements in 2011. One measured at the 22nd August in approx. 65 km distance north west from the location EL39 and one at the 23rd August in approx. 59 km distance north east. On both measurement positions the salinity was constant over the whole water depth. At the first position (North West) 34.4 ppt and 33.6 ppt at the second position (North East). For the calculation a salinity of 34.0 ppt is assumed. The calculated profiles are shown in Figure 8.

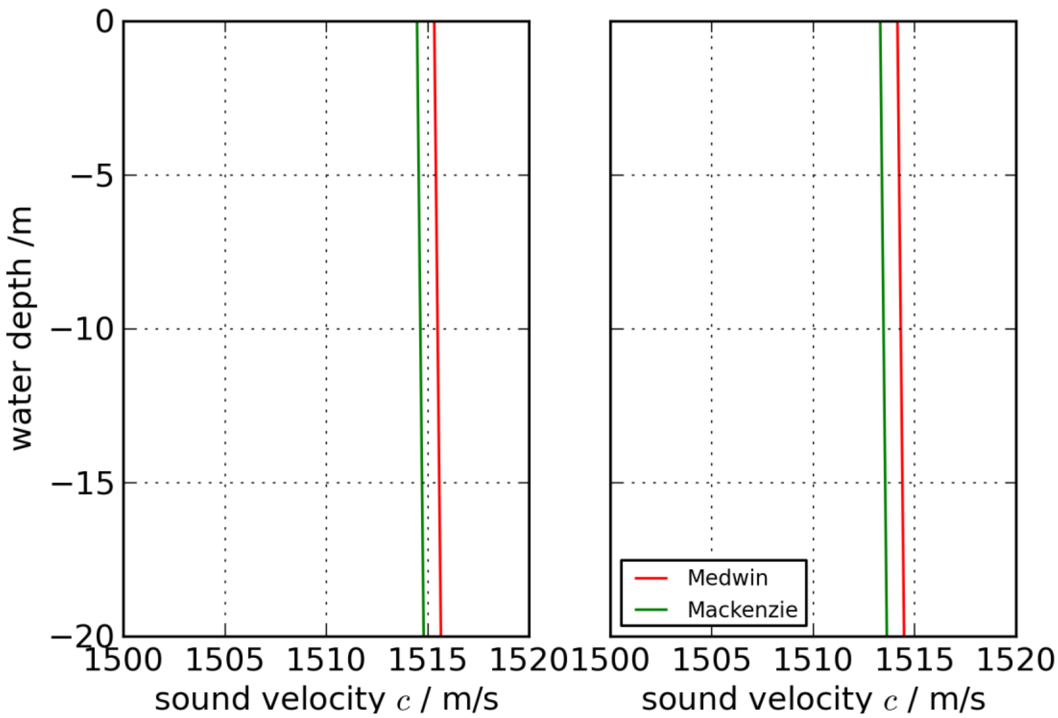



***Figure 8:*** *Calculated sound velocity profiles. The left axis shows the sound velocity for EL39 and the right axis for EL42.*

## 3.3 Practical implementation

All hydro sound measuring systems in and outside the construction site were deployed a few hours before the pile driving work started after a coordinated procedure. According to the used file formats (see chapter 3.2.4) the devices at MP1, MP2 and MP3 were deployed and retrieved twice prior to and immediately after the end of pile driving for each pile. The measurement device on MP4 was deployed and retrieved only once before and after the end of both pile driving activities. The measurement times and the quality status of these measurements are listed in Table 8 for each position.

All deployment and recovery works were done from the vessel *Reykjanes* by an employee of *itap GmbH* and instructed personal from the *Reykjanes*. All positions were determined by the GPS-system from the *Reykjanes*. Uncertainties of a few meters are possible due to the accuracy of the GPS-system and a possible drifting during the deployment. In relation to the measurement distance a drift of 10 m leads in 750 m distance to an inaccuracy of 1.3 % and in 1,500 m distance of 0.7 %.

***Table 8:*** *Recording times of each measurement position and quality status for each used device.*

| Position | Measurement time [utc] | | Raw data status |
|---|---|---|---|
| | start | end | |
| $MP1_{EL39}$ | 23.09.14 11:58 | 24.09.14 06:23 | No valid ambient noise data for EL39 at 2 m above seabed are available. Rests of the data are valid. |
| $MP1_{EL42}$ | 25.09.14 14:26 | 26.09.14 06:11 | Data of all 4 hydrophones are valid. |
| MP2 | 23.09.14 11:27 | 24.09.14 17:25 | Data of all 4 hydrophones are valid. |
| | 25.09.14 11:20 | 26.09.14 06:43 | No valid pilling noise data for EL42 at 10 m above seabed are available. Rests of the data are valid. |
| MP3 | 23.09.14 10:49 | 24.09.14 16:52 | Data of all 4 hydrophones are valid. |
| | 25.09.14 12:46 | 26.09.14 07:34 | Data of all 4 hydrophones are valid. |
| MP4 | 23.09.14 08:20 | 26.09.14 10:20 | Data of all 4 hydrophones are valid. |

During the measurements of ambient noise on location $MP1_{EL39}$ at 2 m height some rubbing sounds were detected. It can be assumed that prevailing currents drifted flotsam to the hydrophone which caused the sounds. The calculated levels of this measurement are influenced by the rubbing noise, so the measured data for this hydrophone is not valid accordingly.

At the measuring position MP2 the 10 m hydrophone cable for the pile driving noise measurement was damaged during the 2nd deployment mechanically (technical defect of the used hydrophone). The second hydrophone for the ambient noise on this position was too sensitive to record the pilling noise. For this reason no measurement data are available for the pile driving activities at pile EL42.

The CTD-probe got a storage error (chapter 3.2.6). It was not possible to read out the collected data. Therefore no measured data for the sound velocity during these measurements are available.

# 4. Evaluation of Hydro Sound Measurements

## 4.1 General Aspects

All measurements are evaluated according to the TNO report “standard for measurement and monitoring of underwater noise, Part II (2011)”.

Within the framework of this report all measuring positions during pile driving activities of the monopiles were evaluated and the results were summarized, which includes all measuring positions in- and outside the construction site. For this purpose *Eneco Luchterduinen* provided the respective pile driving protocol.

## 4.2 Definitions

For the following evaluation following terms and definitions according to the TNO report apply:

**Unweighted Sound Pressure Level *(SPL)* for continuous sound**

Ten times the logarithm to the base 10 of the square of ratio of a given root-mean-square sound pressure to the reference sound pressure

$$SPL = 10\, log_{10} \frac{1}{T} \int_0^T \frac{p(t)^2}{p_{ref}^2} dt \qquad \text{in dB re 1 µPa}^2$$

in which *p(t)* stands for the instantaneous sound pressure, $p_{ref}$ for the reference sound pressure 1 µPa and *T* for the average time[2].

**Unweighted zero-to-peak acoustic pressure *($p_{peak}$)* for transient sounds**

The maximum absolute value of the unweighted instantaneous sound pressure (p) during a stated time interval.

$$p_{peak} = max(|p(t)|) \qquad \text{in Pa}$$

[2] The SPL is also referred to as the equivalent continuous sound (pressure) level ($L_{eqT}$).

### Unweighted zero-to-peak sound pressure level *($L_{Peak}$)* for transient sounds

Ten times the logarithm to the base 10 of the ratio of the square of the *unweighted zero–to-peak acoustic pressure ($p_{peak}$)* to the square of the reference sound pressure

$$L_{Peak} = 10\ log_{10} \frac{p_{peak}^2}{p_{ref}^2} \qquad \text{in dB re 1 µPa}^2$$

in which $p_{ref}$ is the reference sound pressure 1 µPa.

### Unweighted Sound Exposure Level (SEL) for transient sounds

Ten times the logarithm to the base 10 of the ratio of the unweighted sound exposure *(E)* to the reference sound exposure *($E_{ref}$)* the sound exposure being the time integral of the time-varying square of the unweighted instantaneous sound pressure over a transient sound event[3].

$$SEL = 10\ log_{10}\ \frac{E}{E_{ref}} \qquad \text{in dB re 1 µPa}^2\text{s}$$

With the unweighted sound exposure $E = \int_{-\infty}^{\infty} p(t)^2 dt$ and the reference exposure $E_{ref} = p_{ref}^2 \cdot T_{ref}$ in which $p_{ref}$ is the reference sound pressure 1 µPa and $T_{ref}$ the reference duration 1 s.

### *N* percent exceedance level

The *unweighted Sound Pressure Level* (in dB re 1 µPa$^2$) or *sound exposure level* (in dB re 1 µPa$^2$s) for continuous sound that is exceeded for *N* % of the time interval considered.

### Signal duration *($\tau_x$)* for transient sounds

The time during which a specified percentage x of unweighted sound exposure occurs (e. g. $\tau_{90}$ is the time window during which 90 % of the energy arrives), expressed in milliseconds (ms).

[3] The sound exposure level is also referred to as $L_E$, or $L_{ET}$ when the exposure is defined over a specified time interval *T*.

## 4.3 Evaluation Concept

All hydrophone signals are available as time signals (MPEG1[1] or PCM-WAV-files). The sampling frequency of the stand-alone deployed measuring systems at all positions was $f_S$ = 48 kHz.

Initially the typical low frequency signals of the hydrophone signals generated by wind or pounding of the waves, were reduced by high pass filtering (limit frequency 20 Hz, Butterworth-Filter 6$^{th}$ order).

Determining the *unweighted Sound Pressure Level (SPL)* for continuous sound over a period of 5 s and the *Sound Exposure Level (SEL)* were conducted by using a bandpass filterbank according to IEC 1260:1995 standard. Third octave spectra are limited to the frequency range >12.5 Hz $\leq$ 20 kHz for any further depiction of results.

Following parameters, based on measuring instructions of the TNO report, are specified for documentation:

- the maximum SEL
- the median (50 % exceedance) SEL
- the mean and the standard deviation (SD) of the SEL
- the minimum SEL

All of the mathematical operations were carried out by a program developed by *itap GmbH* for Python (in combination with SciPy). The program was verified with the aid of a spectrum analyzer (HP35670a Dynamic Signal Analyzer). Determination (calculation) of SPL is based on DIN 45641. Depicted percentile parameters are determined analogously to the described procedure in VDI 3723, sheet 1.

## 4.4 Measuring Uncertainty and Measuring Variance

### 4.4.1 Measuring Uncertainty

According to the measuring concept for underwater sound measurements by the German approval authority BSH (Müller & Zerbst, 2011), only measuring systems whose entire measurement chain has a deviation with sensitivity of < 2 dB and ± 1 dB may be applied. Measuring systems developed by *itap GmbH* fulfil these requirements and have a high reproducibility of ≤ ± 1 dB concerning hydrophones and electric measuring chain (full measurement device). Moreover all used hydrophones are calibrated by the manufacturer regularly (full spectrum calibration each 2 years) and by *itap GmbH* regularly (point source calibration). Additionally, each measurement device (recorder) will be calibrated by a defined electrical point source before and after each offshore application. The used measurement devices fulfil also the requirements of the WD ISO 18406 (2015).

Due to fluctuations in water depth, wave height and temperature etc., an unsystematic measurement uncertainty in repeated measurements in the range of ≥ 2 dB was often observed during field measurements under offshore conditions, even with calm sea. A systematic study on this issue is currently not available.

### 4.4.2 Measuring Variance

In the following chapters it becomes apparent that Sound Exposure Levels measured during pile driving of one pile differ significantly to some extent (≥ 6 dB). These differences are not due to systematic or unsystematic measuring uncertainties but can partly be explained by the applied used blow energy (for example, maximum energy and soft start) and/or by the sound reflecting pile skin surface (a large sound radiating surface in water will lead to higher noise level than a small surface).

Recent measurement results from the construction monitoring of other offshore wind farms (confidential studies of *itap GmbH* within OWF construction phases in Europe) show that not only the used blow energy but also layers and components of the sediment can have a considerable impact on emitted hydro sound (ground coupling effects). Whether and to what extent further parameters have an impact is currently studied in other research projects, for instance German research project BORA (project ID 0325421A/B/C funded by BMU, BMWi and PTJ).

Therefore, those differences of the measuring results have to be regarded as measuring variance and not measuring uncertainty. They are used for characterization of all pile driving activities qualitatively and quantitatively by indicating the 5%, 50% and 90% percentile of the Sound Exposure Level (SEL).

# 5. Measurement Results

The measured hydro sound pollutions (immissions) during the installation phase of the two selected monopiles EL39 and EL42 are separated in two different kinds of noises, (i) transient and (ii) continuous noise. (i) The transient noise immissions (impulse like) are radiated from the pile driving activities on both monopiles (pile driving noise). (ii) All other underwater sound measurements are defined as ambient noise which contains not only the natural background noise inside the water but also vessel noise.

## 5.1 Pile Driving Noise

### 5.1.1 Introduction

During pile driving activities each blow is producing a bending wave in the pile which is moving from the head of the pile downwards and is reflecting on the bottom of the pile. This moving wave produces local deformations in the pile which radiates short pressure fluctuations in water. These pressure fluctuations in water can be measured by hydrophones and can be interpreted as pile driving noise or radiated noise from percussive pile driving (see Figure 9). The complete acoustical energy transmitted into the water can be described with the following three acoustic metrics:

(i) the Sound Exposure Level (SEL),

(ii) the maximum zero-to-peak Level ($L_{Peak}$) and

(iii) the signal duration of each noise impulse ($\tau_{90}$), see chapter 4.3.

(i) The Sound Exposure Level (SEL) for one blow is the value of the whole energy transmitted by one single blow expressed as a level. In order to compare the energy of one blow with the energy of other blows the energy is normalized to a time of one second.

(ii) The maximum zero-to-peak Level ($L_{Peak}$) expressed the value of the maximal sound pressure during one blow as a level (red arrow in Figure 9).

(iii) The signal duration ($\tau_{90}$) describes the time window during which 90 % of the energy arrives (grey shaded area in Figure 9). This value is a good indicator for the quality of a measurement. If the signal to noise ratio is poor, the energy of background noise can account on more than 10 %. In this case the signal duration ($\tau_{90}$) is increasing rapidly. Smaller variances (< 100 ms for distances < 10 km) could be caused in dependence of the distance by dispersion (see Chapter 6.2.2).

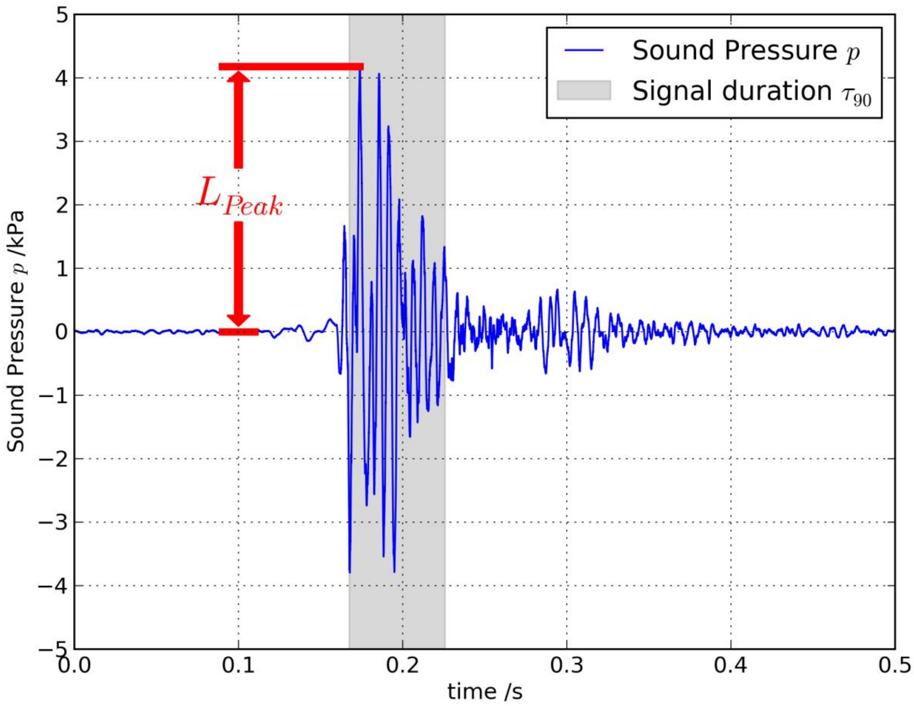



***Figure 9:*** *Sample of pile driving noise (transient noise) measured in 750 m distance. Blue: time signal of 0.5 seconds (1 blow) during pile driving of monopile EL39. Grey: Signal duration $\tau_{90}$.*

## 5.1.2 Underwater noise during pile driving

The distribution of the Sound Exposure Levels (SEL) separated for each measurement positions during the pile driving activities on the foundations EL39 and EL42 are summarized in Table 9 (EL39) and Table 10 (EL42). On position MP4 it was not possible to determine any pilling noise. For this reason the lowest unweighted Sound Pressure Level

($SPL_{5s}$) during pilling is listed as the maximal possible value for the Sound Exposure Levels (SEL).

***Table 9:*** *Sound Exposure Level (SEL) measured at different measurement locations during the installation of the monopile at foundation EL39.*

| EL39 (Monopile with scour protection, pile length: 68.46 m) | | | | | | | |
|---|---|---|---|---|---|---|---|
| Hydrophone-height | Position | Distance [m] | Sound Exposure level (SEL) [dB re 1 µPa²s] | | | | |
| | | | minimum | mean | median | max | SD |
| 2 m | $MP1_{EL39}$ | 750 | 170 | 175 | 175 | 178 | 1 |
| | MP2 | 4,724 | 154 | 158 | 158 | 160 | 1 |
| | MP3 | 13,232 | 138 | 143 | 143 | 144 | 1 |
| | MP4 | 46,578 | < 120 | < 120 | < 120 | < 120 | |
| 10 m | $MP1_{EL39}$ | 750 | 169 | 174 | 174 | 176 | 1 |
| | MP2 | 4,724 | 154 | 159 | 159 | 161 | 1 |
| | MP3 | 13,232 | 139 | 145 | 146 | 147 | 1 |
| | MP4 | 46,578 | < 120 | < 120 | < 120 | < 120 | |

***Table 10:*** *Sound Exposure Level (SEL) measured at different measurement locations during the installation of the monopile at foundation EL42.*

| EL42 (Monopile without scour protection, pile length: 75.93 m) | | | | | | | |
|---|---|---|---|---|---|---|---|
| Hydrophone-height | Position | Distance [m] | Sound Exposure Level SEL [dB re 1 µPa²s] | | | | |
| | | | minimum | mean | median | max | SD |
| 2 m | $MP1_{EL42}$ | 750 | 168 | 173 | 173 | 175 | 1 |
| | MP2 | 5,245 | 151 | 155 | 155 | 157 | 1 |
| | MP3 | 13,749 | 139 | 143 | 144 | 145 | 1 |
| | MP4 | 47,054 | < 118 | < 118 | < 118 | < 118 | |
| 10 m | $MP1_{EL42}$ | 750 | 167 | 171 | 171 | 173 | 1 |
| | MP2 | 5,245 | n.v.[4] | n.v.[4] | n.v.[4] | n.v.[4] | |
| | MP3 | 13,749 | 141 | 146 | 146 | 147 | 1 |

[4] The cable for the pile driving noise measurement device was damaged during the 2nd deployment mechanically (technical defect of the used hydrophone).

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | MP4 | 47,054 | < 118 | < 118 | < 118 | < 118 | |

A detailed overview of all results for all measurement positions and both foundations (monopile EL39 and EL42) is summarized in Appendix A1. As an example Figure 10 to Figure 12 shows the measurement results for $MP1_{EL39}$ in 750 m for the hydrophone height of 2 m. The relevant chronical sequence of the Sound Exposure Level (SEL) and zero-to-peak Level ($L_{Peak}$) are presented in Figure 10 as time dependent single value distribution as well as time and frequency dependent spectrogram (first two plots). The first plot shows the Sound Exposure Level (SEL) and the zero-to-peak Level ($L_{Peak}$) for every single blow and the unweighted Sound Pressure Level (SPL) in 5 second intervals. The distribution of the Sound Exposure Level (SEL) is within the range shown in Table 9. The unweighted Sound Pressure Level (SPL) is nearly similar to the Sound Exposure Level (SEL) which is always the case when 5 blows are within a 5 second interval. The unweighted Sound Pressure Level (SPL) is also shown in the second plot as a spectrogram. The difference between the first plot is that the unweighted Sound Pressure Level (SPL) is split in 1/3 octave components. The frequency is listed on the y-axis and the time on the x-axis. The value of the unweighted Sound Pressure Level (SPL) in every 1/3 octave band is marked by different colors, red for high levels and blue for low levels. The frequency composition of the unweighted Sound Pressure Level (SPL) is similar to the Sound Exposure Level (SEL).

The Sound Exposure Level (SEL) and the used blow energy are presented in the same figure as a function of time to illustrate the impact of used blow energy on the radiated pile driving noise (third plot of Figure 10). The last plot of Figure 10 shows the time depending signal duration $\tau_{90}$ each single blow.

Figure 11 shows the Sound Exposure Level (SEL) distribution as 1/3-octave spectra for the pile installation EL39 at the measurement position $MP1_{EL39}$ in 750 m distance as an example of the results of Table 10. In the histogram in Figure 12 the distribution of the Sound Exposure Level (SEL) at this measurement position is depicted. On this position all measured Sound Exposure Level (SEL) were within a range between 171 dB and 177 dB. During this measurement 44 % of all blows had a Sound Exposure Level (SEL) of 174 dB.

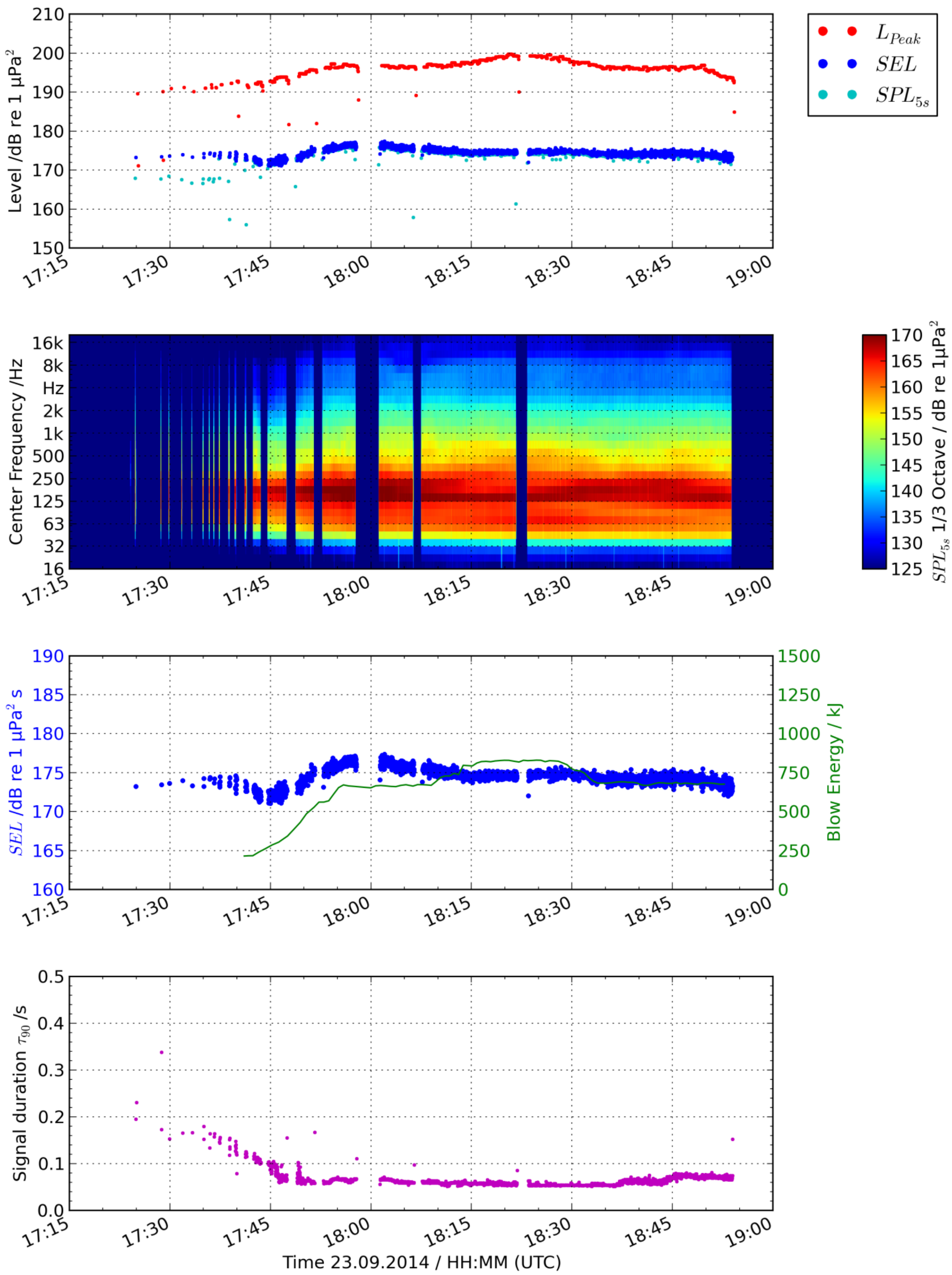



***Figure 10:*** *Results of the pile driving noise on foundation EL39 (monopile with scour protection) in 750 m distance (MP1$_{39}$; hydrophone height: 2 m above seabed). Plot on top: Time depending Sound Exposure Level (SEL), Sound Pressure Level (SPL$_{5s}$) and Peak Level (L$_{Peak}$). 2$^{nd}$ plot: 1/3-octave spectrogram of the SEL (depending on time and frequency) The Y-axis is conform DIN 461. Hz between 8 k and 2k should be read as 4k. This is the case in all figures in the report.,, 3$^{rd}$ plot: SEL as well as used blow energy as function of time, bottom: measured signal duration ($\tau_{90}$).*

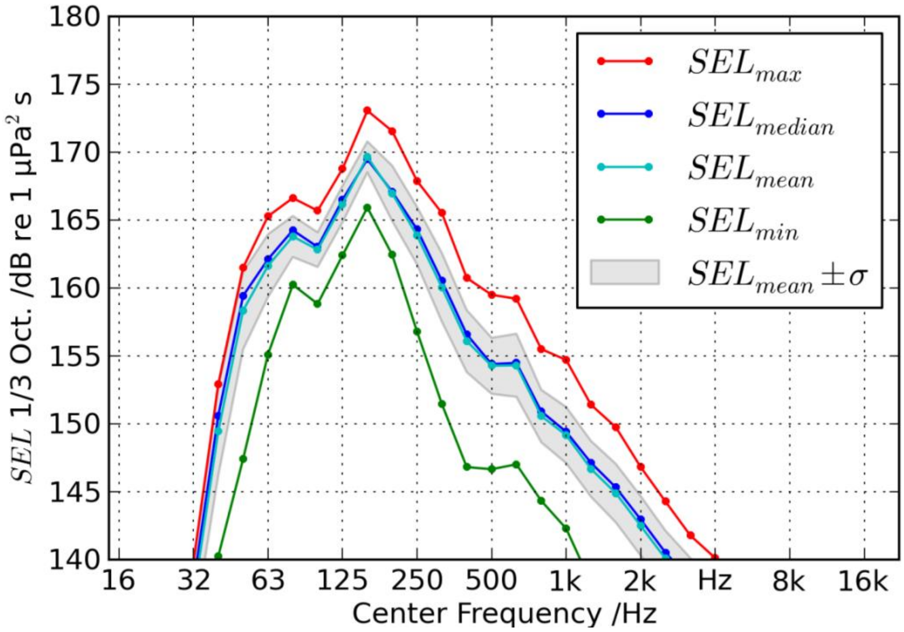



***Figure 11:*** *1/3-Octave spectra of the Sound Exposure Level (SEL) measured at MP1$_{EL39}$ (hydrophone height: 2 m above seabed).*

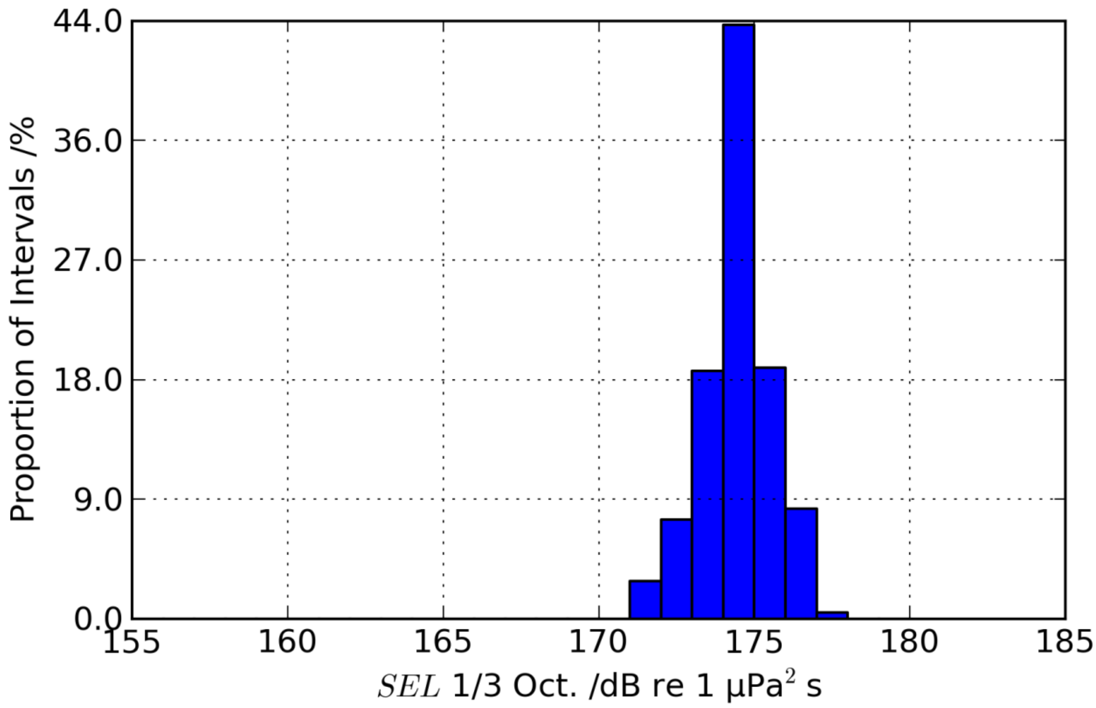



***Figure 12:*** *Histogram of the Sound Exposure Level (SEL) measured in 750 m distance (MP1$_{EL39}$) during the installation of the monopile at EL39 (hydrophone height: 2 m above seabed).*

## 5.2 Ambient Noise

The continuous ambient noise is analyzed in averaged unweighted Sound Pressure Levels (SPL) for a period of five seconds ($SPL_{5s}$). For the evaluation of the ambient noise for each monopile two time windows per foundation are chosen before and directly after the pile driving activity of each foundation took place. The chosen time windows are listed in Table 11 for each foundation. The piling activities took place during the time between the first and the second time window.

***Table 11:*** *Evaluation periods for each foundation for ambient noise.*

| Foundation | Time window [utc] | | |
|---|---|---|---|
| | Date | Start- time | End-time |
| EL39 | 2014-09-23 | 15:00 | 17:24 |
| | 2014-09-23/24 | 18:53 | 06:00 |
| EL42 | 2014-09-25/26 | 18:00 | 01:35 |
| | 2014-09-26 | 03:20 | 06:00 |

The distribution of the measured Sound Pressure Level ($SPL_{5s}$) for all measurement positions before and after each pile driving activity is expressed in different percentiles and summarized in Table 12 and Table 13. Similar to the figures of the pilling noise the time dependent $SPL_{5s}$ behavior as broadband value and frequency dependent analysis (spectrogram), a presentation of the above mentioned distribution levels as a function of frequency and the distribution are shown in Appendix A.1. The recorded ambient noise is dominated by noise emissions from vessels. The next shipping lanes are in a distance 2 km to MP4, 4 km to MP3 and 5 km to MP2 and MP1 (see Annex 4). Figure 13 to Figure 15 give an example for the measurement position MP1 in 750 m distance to the monopile EL39 at a hydrophone height of 2 m. Between 00:00 and 01:00 on September 24$^{th}$ the sound pressure level was increasing to more than 160 dB. This steadily increase and decrease is typical for passing vessels. By hearing the recorded sound files this assumption was confirmed. It was possible to hear an engine and the cavitation noise from a vessel propeller. To determine the distance of this vessel the contactor *Eneco Luchterduinen* provided the AIS-Data for this duration but it was not possible to assign this event to a recorded vessel track (see Annex 4).

***Table 12:*** *Evaluation of the measured ambient noise by showing the Sound Pressure Level ($SPL_{5s}$) distribution before (2.5 hours) and after (7.0 hours) the installation of the monopile EL39.*

| EL39 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Hydrophone-height | Position | Distance [m] | Sound Pressure Level $SPL_{5s}$ [dB re 1 µPa$^2$] | | | | | | |
| | | | minimum | 95 % exceedance | mean | median | 5 % exceedance | max | SD |
| 2 m | $MP1_{EL39}$ | 750 | n.v.[5] | n.v. | n.v. | n.v. | n.v. | n.v. | n.v. |
| | MP2 | 4,724 | 111 | 112 | 118 | 116 | 132 | 156 | 6 |
| | MP3 | 13,232 | 109 | 111 | 117 | 117 | 125 | 135 | 4 |
| | MP4 | 46,578 | 114 | 117 | 126 | 126 | 135 | 148 | 5 |
| 10 m | $MP1_{EL39}$ | 750 | 121 | 122 | 128 | 126 | 142 | 166 | 6 |
| | MP2 | 4,724 | 111 | 112 | 118 | 116 | 132 | 156 | 6 |
| | MP3 | 13,232 | 108 | 110 | 116 | 115 | 124 | 134 | 4 |
| | MP4 | 46,578 | 114 | 117 | 126 | 125 | 135 | 147 | 5 |

***Table 13:*** *Evaluation of the measured ambient noise by showing the Sound Pressure Level ($SPL_{5s}$) distribution before (7.5 hours) and after (2.5 hours) the installation of the monopile EL42.*

| EL42 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Hydrophone-height | Position | Distance [m] | Sound Pressure Level $SPL_{5s}$ [dB re 1 µPa$^2$] | | | | | | |
| | | | minimum | 95% exceed-ance | mean | median | 5 % exceed-ance | max | SD |
| 2 m | $MP1_{EL42}$ | 750 | 113 | 118 | 126 | 126 | 133 | 139 | 4 |
| | MP2 | 5,245 | 109 | 112 | 121 | 120 | 136 | 156 | 7 |
| | MP3 | 13,749 | 110 | 112 | 119 | 119 | 128 | 139 | 5 |
| | MP4 | 47,054 | 116 | 119 | 127 | 127 | 136 | 144 | 5 |
| 10 m | $MP1_{EL42}$ | 750 | 113 | 118 | 126 | 126 | 133 | 139 | 4 |
| | MP2 | 5,245 | 109 | 112 | 121 | 120 | 136 | 156 | 7 |
| | MP3 | 13,749 | 110 | 112 | 119 | 119 | 128 | 139 | 5 |
| | MP4 | 47,054 | 116 | 119 | 127 | 127 | 136 | 144 | 5 |

[5] During the measurements of ambient noise on location $MP1_{EL39}$ at 2 m height some rubbing sounds were detected. It can be assumed that prevailing currents drifted flotsam to the hydrophone which caused the sounds. The calculated levels of this measurement are influenced by the rubbing noise, so the measured data for this hydrophone is not valid accordingly (SNR < 6 dB).

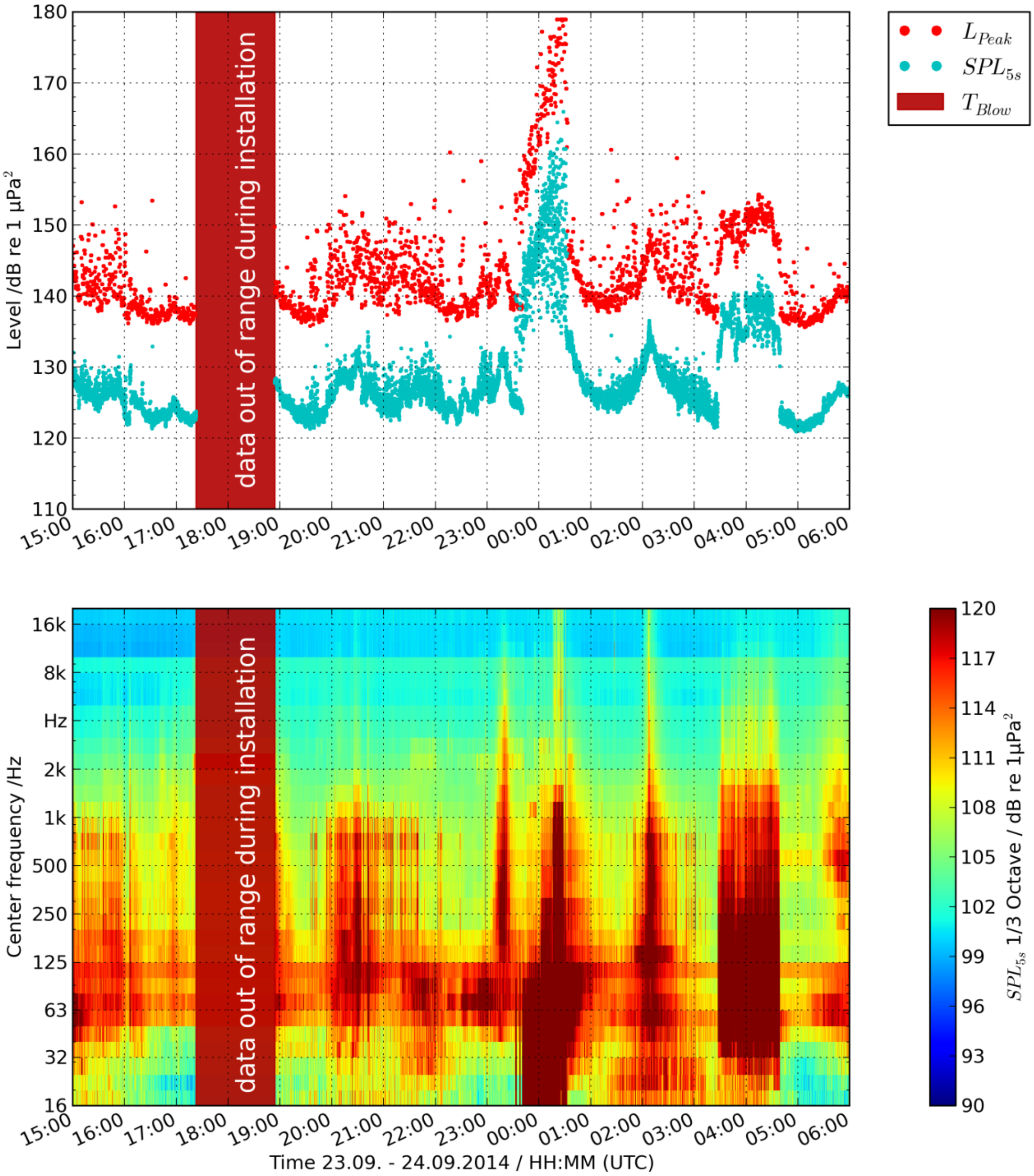



***Figure 13:*** *Time dependent zero-to-peak ($L_{Peak}$) and Sound Pressure Level ($SPL_{5s}$) distribution of the ambient noise measurements at the measurement position $MP1_{EL39}$ before and after the installation of the monopile EL39 (hydrophone height 2 m above seabed). Top: $SPL_{5s}$ and $L_{Peak}$ values versus time. Bottom: Spectrogram of $SPL_{5s}$ (frequency resolution in 1/3 Octaves).*

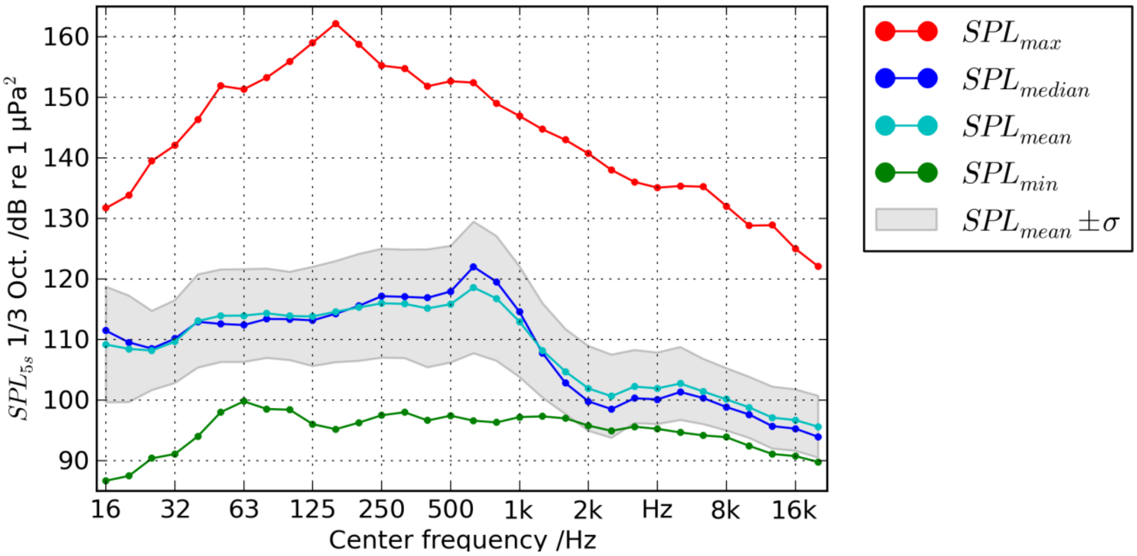



***Figure 14:*** *Measured Sound Pressure Level ($SPL_{5s}$) in 1/3 Octave bands at $MP1_{EL39}$ before and after the installation of the monopile EL39 (hydrophone height: 2 m above seabed).*

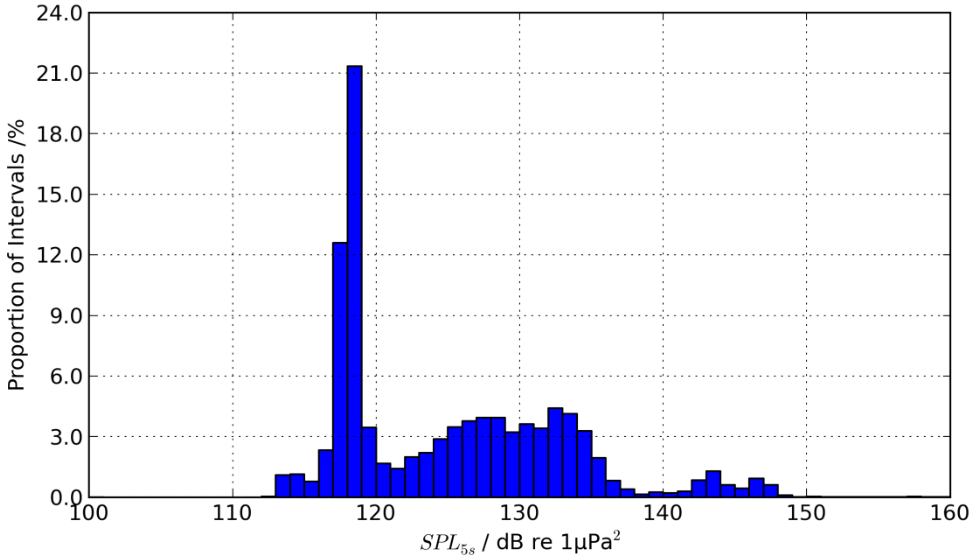



***Figure 15:*** *Histogram of the Sound Pressure Level ($SPL_{5s}$) measured at $MP1_{EL39}$ before and after the installation of the monopile EL39 (hydrophone height: 2 m above seabed). Sound Pressure Level ($SPL_{5s}$) ≥ 140 dB were always caused by passing vessels und could be subjective identified by listening sound samples.*

## 5.3 Underwater noise from deterrence devices (*Faunaguard*)

In order to protect harbor porpoises against hearing impairments caused by noise pollution during pile driving, a deterrence device (*Faunaguard, harbor porpoise module*) was used to scare away the animals from the construction area before piling. The *Faunaguard* device was switched on approx. 15 minutes before the first blows and switched off after piling. On location EL39 the *Faunaguard* device was in use between 16:30 and 18:55 UTC time and on location EL42 between 01:10 and 03:20 UTC time.

All used measurement devices measured with a sampling frequency of 48 kHz, for this reason it only possible to record any frequencies up to 24 kHz. The *Faunaguard* device emits noises in a frequency range between 60 kHz and 150 kHz. So it was not possible to measure the underwater noise of the *Faunaguard* device with the used measurement devices for hydro sound.

# 6. Discussion

Beside the validation of the TNO underwater sound propagation models (not task of this report) two questions need to be answered by this monitoring program:

1) What are the differences in underwater noise between the “standard monopile” (with scour protection) and the innovative monopile (without scour protection)?
2) What are the underwater noise levels caused by piling at larger distances (> 20 km range)?

To answer the first question the differences in source level will be analysed and compared with different installation parameter. Ideally it would be possible to assign a cause to certain sound events. For the second question some effects of the sound propagation during these measurements has to be determined and compared with common propagation models.

## 6.1 Variances of the source level caused by different pile conditions

Generally the source level symbolises the sound power of a source. In the literature it is often called the Sound Pressure Level (SPL) at one meter distance to the pile. This is a virtual value, that cannot be determined by measurements because a pile emits sound over the whole surface not on a single point (moving point source see chapter 5.1). Additionally in the acoustic near field measurements of the sound pressure and the sound velocity are needed to characterize the strength of sound or sound intensity but sound velocity sensors for underwater noise are not available or not accurate. In the following text the measured source level is defined as the level measured at 750 m distance. To reduce the impact parameter for comparison of the source level only the measurements at a height of 2 m above the seabed will be used. The differences between both measuring heights will be discussed in the following chapter 6.2.3.

Responsible for the source level are (i) the strength of the pile vibrations and (ii) the size of the sound radiating surface in the water column. The main differences between the two measured monopiles are the length and the scour protection. On the position of EL39 a scour protection was deployed around the pile location before the installation. On location EL42 a new pile design was tested. By using a longer monopile it is possible to dispense of the scour protection. The main conditions for both piles are compared in Table 14.

***Table 14:*** *Pile and foundation conditions for the monopiles EL39 and EL42.*

| Foundation | EL39 | EL42 |
|---|---|---|
| Diameter [m] | 5.0 | 5.0 |
| Scour protection | Yes | No |
| Pile length [m] | 68.46 | 75.93 |
| Pile mass [t] | 472.44 | 610.79 |
| Penetration depth [m] | 29.62 | 38.03 |
| Water depth [m] | 21.50 | 20.60 |
| Total blows | 2,971 | 3,628 |
| Total blow energy [kJ] | 1,966,092 | 3,078,621 |
| Max. blow energy [kJ] | 830 | 1,110 |

Differences in pile and foundation conditions could be separated in two different classes. The time variant conditions, like the blow energy and the penetration depth, and the time invariant conditions, like the pile geometry.

In Figure 16 the broadband Sound Exposure Level (SEL) is plotted over the blow count for both piles EL39 (cyan) and EL42 (magenta). This figure shows variances of the Sound Exposure Level (SEL) of around 6 dB during the installation time of each pile. This variance of 6 dB can be attributed to the impact of the time variant conditions (used blow energy and penetration depth). This figure shows also that the Sound Exposure Level (SEL) for monopile EL39 is higher than for monopile EL42 and that during the whole installation. Possible reasons could be differences during the installation (e. g. pile design, used blow energy, coupling between pile and hammer, penetration depth, etc.), geological differences like the soil conditions or water depth or simply the measuring variance (see chapter 4.4). The fact that the Sound Exposure Level (SEL) on EL39 is higher over the whole installation leads to the assumption that the reason must be a difference which is continuing over the whole installation. Therefore the next chapters will attempt to separate the impacts in time variant and time invariant impacts.

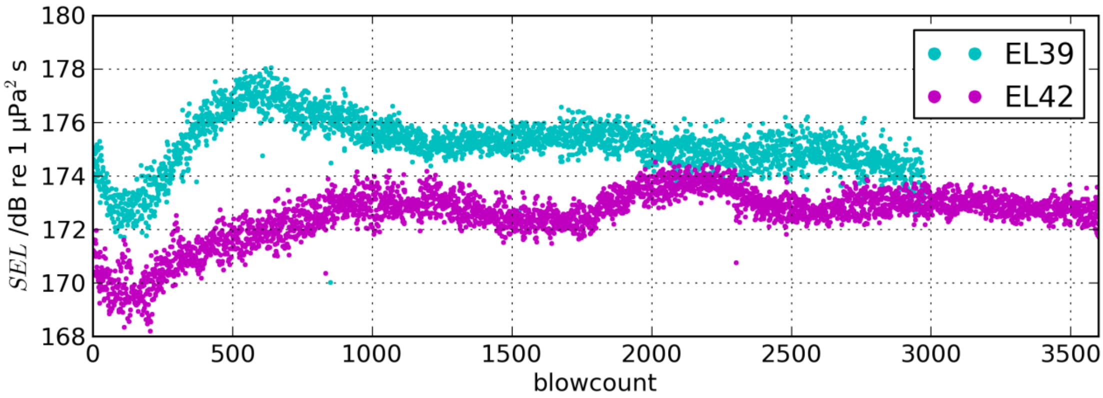



***Figure 16:*** *SEL during the pile driving of EL39 and EL42.*

### 6.1.1 Impact of time variant conditions

During a pile installation the penetration depth is increasing steadily. The penetration per blow is mostly highly correlated with the blow energy. Usually the deeper the pile is intruding in the soil, the more blow energy is necessary to get the pile forward. Deviations could be caused by different soil conditions (sediment resistance).

It is also expected that higher blow energy leads to higher sound energy radiated in the water (Gündert, 2014). In the context of a master thesis at *itap GmbH* the impact of blow energy has been investigated. An increase to twice as much of the blow energy leads in average to an increase of 2.5 dB for the pile driving noise measured in several hundred meter distance (Gündert, 2014). This impact was examined at different kinds of foundations and has been proved by a statistical comparison of the changes in blow energy with the changes in Sound Pressure Level and penetration depth during each installation.

Figure 17 shows the Sound Exposure Level (SEL) and the blow energy (green) for the foundation EL42 on the measuring position $MP1_{EL42}$ in 750 m distance and 2 m hydrophone height. The blue points are the measured Sound Exposure Level (SEL) values. The red line is the rolling mean value of the Sound Exposure Level (SEL) averaged over 50 blows (mean value for every 50 blows) and the grey shaded area is the variance (mean ± SD) over each 50 blows. Moreover the blow energy is plotted in a green line over the same time interval. This figure illustrated that in the most times when the blow energy is increasing significantly the Sound Exposure Level is increasing too (for example 02:30 AM to 02:45 AM), but there are also time intervals with constant blow energy and increasing Sound Exposure Levels (SEL), for example during 02:00 AM and 02:15 AM. It can be concluded that the blow energy has a significant impact of the radiated sound energy but the blow energy is not the only influencing parameter on the Sound Exposure Level (SEL). For instance the penetration depth has also an influence on the Sound Exposure Level (SEL) especially near the final depth since the Sound Exposure Level is usually constant or decrease slightly with increasing penetration also the blow energy is constant close the final depth (Gündert, 2014). This effect is also visible in Figure 15 for the monopile EL42.

To illustrate the impact of blow energy by reducing other impacts for both piles EL39 and EL42 a shorter time window is chosen during the blow energy is increasing significantly. These time intervals are shown in Figure 18 and Figure 19. Both figures show a high correlation between the blow energy and the Sound Exposure Level (SEL) during the increase of the blow energy. In Figure 18 the increase of blow energy from 250 kJ to 500 kJ leads to an increase of Sound Exposure Level (SEL) to 2.5 dB as theoretically expected (EL39). The increase from 300 kJ to 600 kJ leads to an increase of the Sound Exposure Level (SEL) of about 4 dB. During piling of EL42 the increase of blow energy from 780 kJ to 1,030 kJ leads to an increase of the Sound Exposure Level (SEL) of about 1.2 dB. In this case a doubling of blow energy leads to an increase of Sound Exposure Level (SEL) of 3 dB. During these time windows the impact of blow energy was around 2.5 dB to 4 dB at doubled blow energy. This is a bit higher than expected (Gündert, 2014). However, in mean an increase of about 2 dB to 3 dB can be observed and these differences are within the range of the measurement uncertainty (chapter 4.4). For the investigation of other time variant impacts like the soil conditions more measurements – not only underwater noise – are needed. Due to this measuring concept it is not possible to make statements about the impact of the soil.

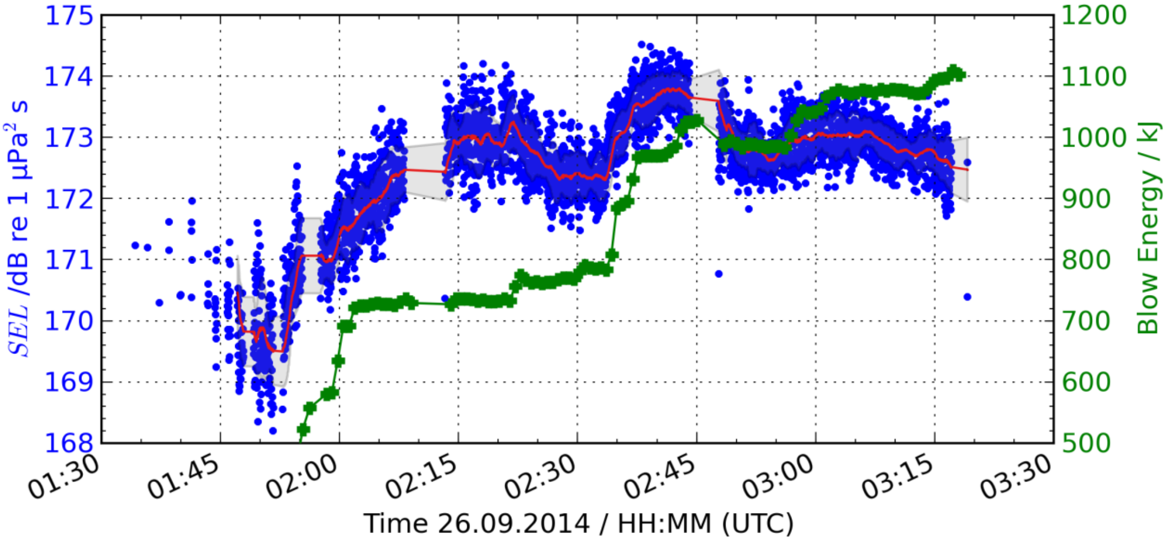



***Figure 17:*** *Sound Exposure Level (SEL, blue) and blow energy (green) on MP1$_{EL42}$ at 2 m hydrophone height during the installation. Red: median of the SEL over 50 blows. Grey: median ± SD.*

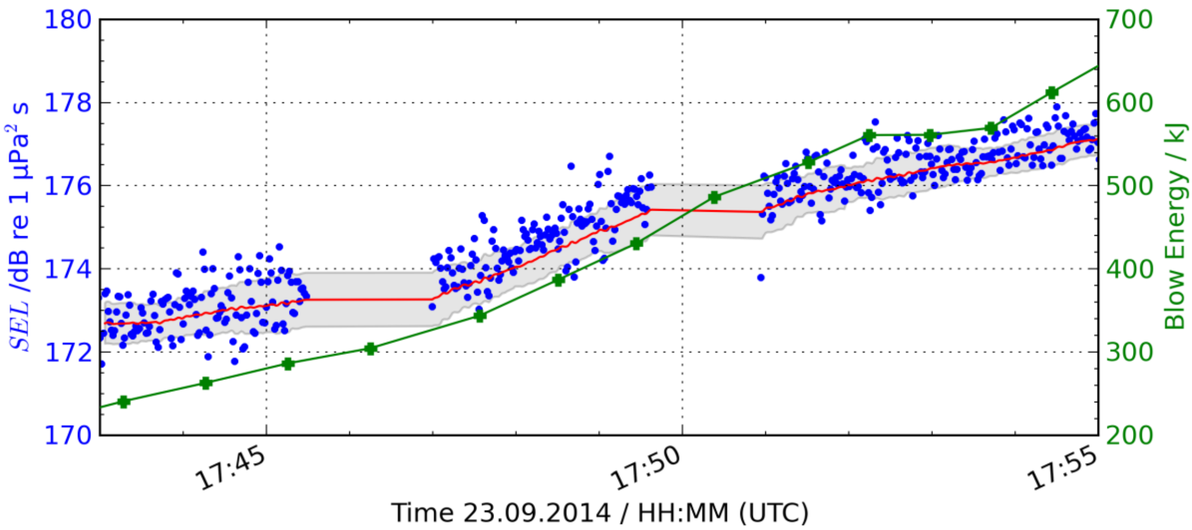



***Figure 18:*** *Sound Exposure Level (SEL, blue) and blow energy (green) on MP1$_{EL39}$ at 2 m hydrophone height during a chosen time window. Red: median of the SEL over 50 blows. Grey: median ± SD.*

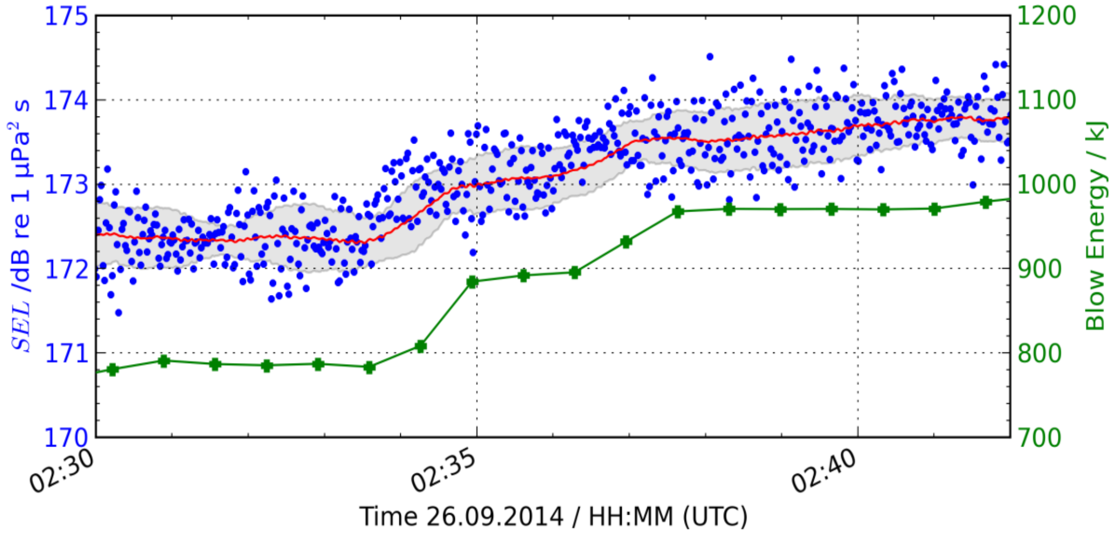



***Figure 19:*** *Sound Exposure Level (SEL, blue) and blow energy (green) on MP1$_{EL42}$ at 2 m hydrophone height during a chosen time window. Red: median of the SEL over 50 blows. Grey: median ± SD.*

### 6.1.2 Impact of differences in pile geometry and location

The broadband Sound Exposure Level (SEL) for the monopile EL39 were between 2 dB to 3 dB louder than for the monopile EL42 (see Table 10, Table 12 and Figure 16). The fact that the Sound Exposure Level (SEL) on EL39 is higher over the whole installation leads to the assumption that the reason must be a difference which is continuing over the whole installation.

As listed in Table 14 the piles have the same diameter but are different in the length. It is expected that the spectra for Sound Exposure Level (SEL) on the longer pile is shifted to deeper frequencies due to deeper natural resonance frequency (eigen frequency). But a higher radiation of sound energy is theoretically not expected because the longer pile will not lead to a higher radiating surface in water in this case (monopile installation). In Figure 20 the 1/3-octave spectra of the median Sound Exposure Level (SEL$_{50}$) measured in a distance of 750 m and the results measured in a distance of 5 km are plotted for EL 42 and EL39. There are only slightly changes of attenuation over the distance between the different monopiles for each 1/3 Octave Band (see 1/3-octave spectra in the Appendix A1.1 and A1.2). The frequency bandwidth is nearly similar for both piles, but the spectrum of EL42 is shifted slightly to deeper frequencies as expected.

At the location EL39 the water depth is nearly 1.3 m higher than at EL42. The water depth can have a significant influence on pile driving noise since the water depth can limit the radiated frequency range. For instance in water depth of 10 m the limiting frequency of radiated pile driving sound can be around 100 Hz depending on the sediment resistance. But usually all relevant frequencies for pile driving noise will be radiated in water depth from 20 m onwards. It is rather unlikely that the slightly higher radiating surface of monopile El39 will caused an increase of 2 dB for the SEL because in relation to the whole water depth of around 20 m this is only a small difference of around 6%. Furthermore such an influence was not observed during other pile driving measurements by *itap GmbH* before or reported in the literature. The water depth consequently may not be the main reason for the higher levels.

It is possible that variances in the soil formation affected the sound radiated behavior of the pile. According to information from the client, significantly variances in the soil formation can be excluded. The distance between these piles is approximately 700 m. Slightly variances in the soil formation are only possible for short sections but the Sound Exposure Level (SEL) was higher during the whole pile driving at EL39 (see Figure 16).

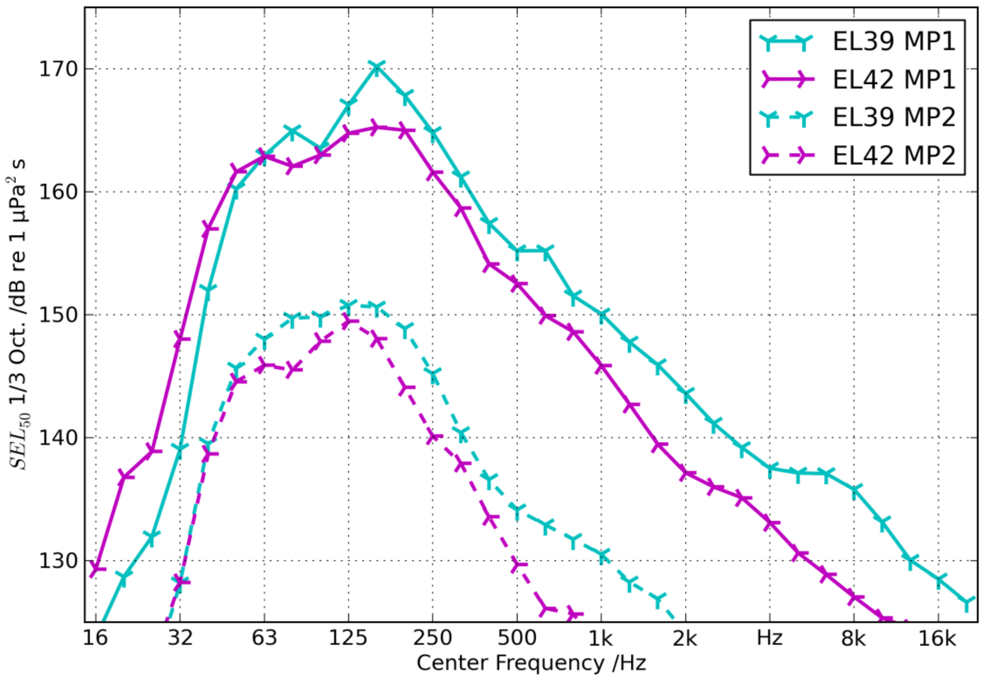



***Figure 20:*** *1/3-Octave spectra of the SEL for EL39 (cyan) and EL42 (magenta) at 750 m and approx. 5 km distance.*

The higher penetration depth of EL42 could lead to slightly lower Sound Exposure Levels but only at the end of the piling activity. Therefore an obvious reason for the higher Sound Exposure Level (SEL) on foundation EL39 could not be identified. The 1/3-octave spectra in Figure 20 shows over all frequencies greater than 63 Hz the median Sound Exposure Level ($SEL_{50}$) frequency band levels are higher for EL39 than for EL42. Another significant difference is the “peak” in the 160 Hz 1/3-octave band for EL39 in 750 m distance. If this peak is the impact of a natural resonance from the pile, a similar peak is expected in the spectra for EL42, only in a deeper 1/3-octave band. However, the reason for this peak is not determinable with these measurements. Beside the measurement results at 750 m distance, the results in approximately 5 km distance are also plotted in Figure 20. The peak in the 160 Hz 1/3-octave band for EL39 has vanished over the distance. Instead of a characteristic radiating behavior, it seems to be a modal wave in the water column.

Based on our measurements it was not possible to verify the reason for the higher measured sound pressure levels at $MP1_{EL39}$ than at $MP1_{EL42}$. It must be comment that the measurement uncertainty of underwater noise measurements is around 2 dB and only one sample of each monopile design was measured. For this reasons it cannot be excluded that the measured differences between the two monopiles are mainly caused by measurement uncertainties.

### 6.1.3 Comparison with underwater noise in other Offshore Wind Farms

Figure 21 shows the median Sound Exposure Level (SEL) measured at different windfarms in the North Sea and the Baltic Sea at a distance of 750 m as a function of diameter. The blue line is the average Sound Exposure Level (SEL) in dependence of the diameter. The gray shaded area shows that most of the median Sound Exposure Levels (SEL) are within a range of ± 5 dB. The red crosses are the median Sound Exposure Level (SEL) at the locations EL39 and EL42. This figure shows that the measured values for both piles are within the expected range.

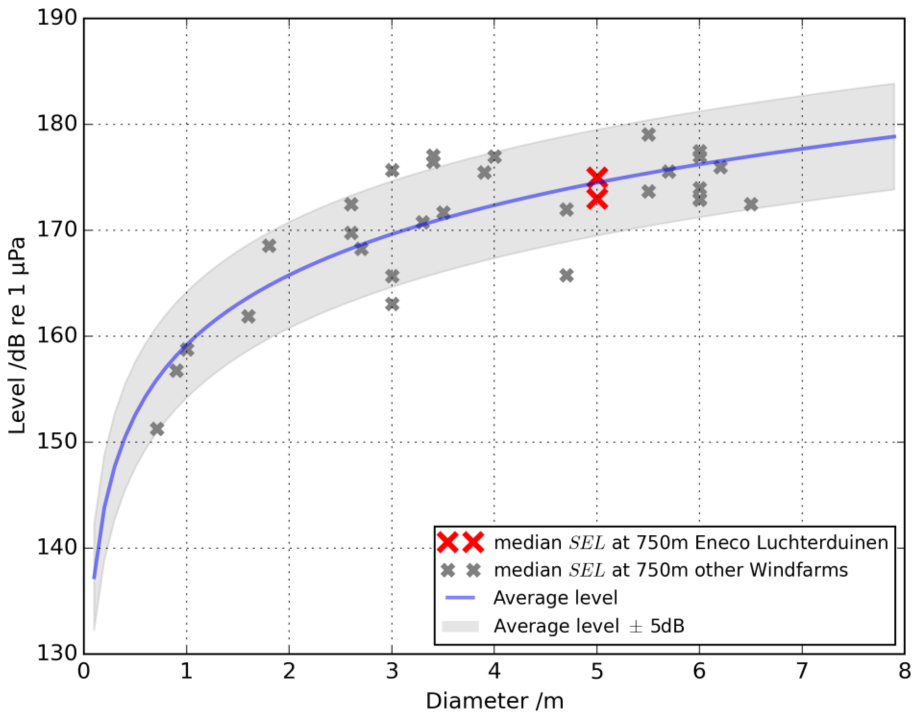



***Figure 21:*** *Measured Sound Exposure Level (SEL) in different windfarms over the diameter. The red crosses marked the median Sound Exposure Level measured at EL39 and EL42 and gray crosses the median Sound Exposure Level measured in other wind farms.*

## 6.2 Sound propagation

### 6.2.1 Comparison of the attenuation with calculation models

The purpose of measuring underwater noise during piling was to gather information about the (propagation of) underwater noise generated by pile driving and more specific to gather data for validation of the TNO underwater sound propagation model. The validation of the TNO underwater sound propagation model is not scope of this report. But to predict the sound propagation in water a lot of arbitrarily complex models are available (for example: the *BORA*[6] project or Thiele & Schellstede, 1980). Figure 22 displays the predicted sound propagations after some common model approaches as a function of distance. The red line shows a sound propagation *TL = Source Level - 15* $\log_{10}(d)$ *(geometric propagation loss; d – distance ratio)*. This is a good approximation for transmission losses over short distances in

[6] BORA: Entwicklung eines Berechnungsmodells zur Vorhersage des Unterwasserschalls bei Rammarbeiten zur Gründung von OWEA, founded by PTJ and BMU, project ID 0325421A/B/C.

the North Sea. The green and cyan lines show a frequency dependent sound propagation according to Thiele & Schellstede (1980). This model is a semi-empirical model based on hydro sound measurements during detonations in the North Sea for different areas and weather conditions. The green line shows the common form often used for sound propagation calculations in the German Bight. This model considers a sound propagation at flat sea during wintertime, when the lowest transmission loss is expected. The cyan colored line represents weather conditions in autumn.

For comparison the measured median Sound Exposure Level ($SEL_{50}$) is also plotted in this figure (blue marks). On position MP4 the pile driving noise was partially audible but it was not possible to determine the Sound Exposure Level (SEL) accurate due to less than 6 dB signal-to-noise ratio, therefore the blue errorbar marks a range for the expected Sound Exposure Level (SEL). The grey shaded area presents the measured ambient noise. The upper border marks the highest measured 5 % exceedance Sound Pressure Level ($SPL_{05}$) and the lower border presents the lowest measured 95 % exceedance Sound Pressure Level ($SPL_{95}$). The grey crosses present the median Sound Pressure Level ($SPL_{50}$) on each measurement position.

If the measurements of pile driving noise are compared with the presented sound propagation models, the levels seem to be overestimated at distances over approximately 5 km. The results suggest that until a distance of at least 30 km the pile driving noise (the median Sound Exposure Level $SEL_{50}$) was significant higher than the ambient noise (Sound Pressure Level SPL). The ambient noise is at MP1 and MP4 higher than at MP2 and MP3 (around 10 dB). Probably it was due to the vessel noise of the construction process at MP1 and the close public vessel traffic lane in approx. 2 km distance at MP4. It is expected that due to the pile driving noise and the ambient noise in the measurement campagne the Sound Exposure Level (SEL) can be calculated for each blow up to a distance of 30 km to 35 km accurate. For higher distances the Sound Exposure Level (SEL) for pile driving activity is not calculable due to poor signal-to-noise ratio (SNR > 6 dB after WD ISO 18406).

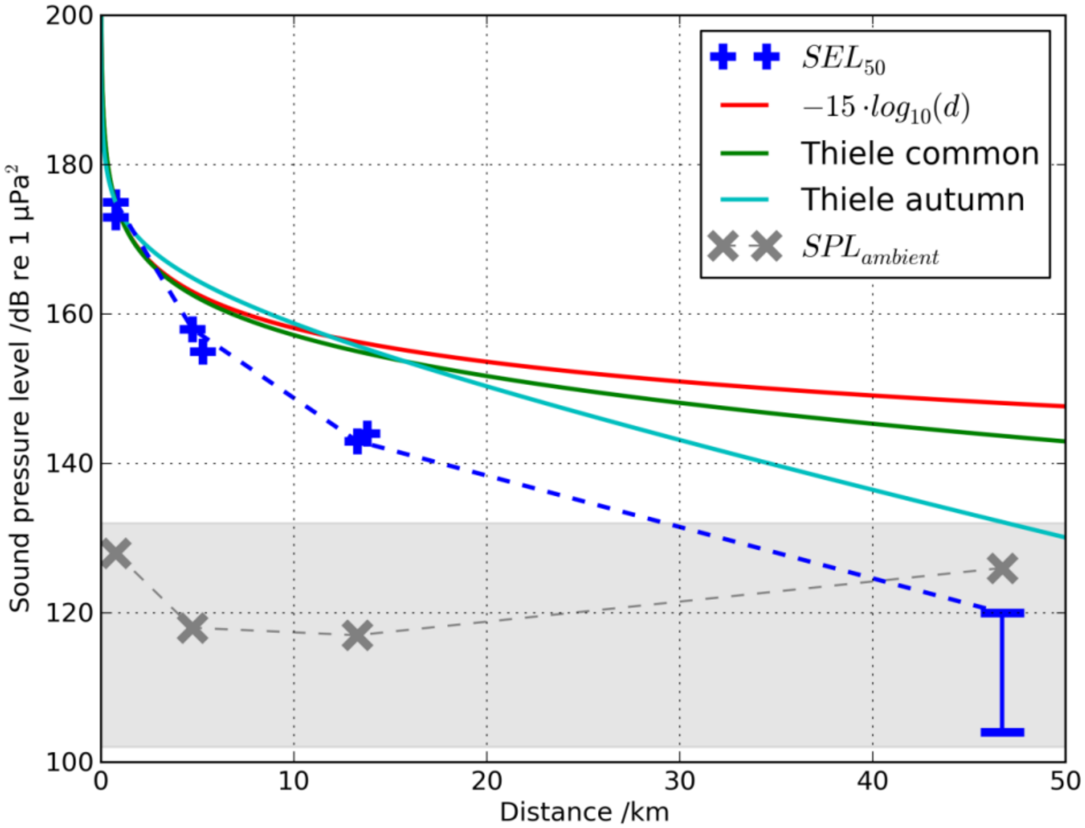



***Figure 22:*** *Measured Sound Exposure Level (SEL, blue) as a function of distance. In comparison the predicted propagation for the sound attenuation of three different common approaches are plotted. On position MP4 it was not possible to determine the Sound Exposure Level (SEL) due to a poor signal-to-noise ratio therefore the blue errorbar marks a range for the expected Sound Exposure Level (SEL). The grey shaded area presents the measured ambient noise. The upper border is highest measured 5 % exceedance Sound Pressure Level ($SPL_{05}$) and the lower border presents the lowest measured 95 % exceedance Sound Pressure Level ($SPL_{95}$). The grey crosses present the median Sound Pressure Level (SPL) on each measurement position.*

### 6.2.2 Sound propagation in time domain

Beside the attenuation there are more effects in sound propagation. The sound interacts with the boundary layers surface and the seabed several times during the propagation in water (multi reflections). Parts of the sound are reflected and other parts are transmitted, this leads to refraction (Jensen et al., 2000). The refraction is varying with the frequency. Similar to white light in a prism, the frequency dependent refraction is making a lot of colors visible (the colors are analog to the frequency). Besides the frequency dependent attenuation this leads to different run times for different frequencies between the source and the observing point (e. g. measurement position). Consequently each frequency arrived at a different time to a specified point. This effect is called dispersion. The duration in which all frequencies arrived the specified point is increasing with the distance.

To make this effect visible in Figure 23 the sound pressure (p) as a function of time for one single blow (blow number 1.523 of foundation EL39) is plotted for all measurement positions at 2 m height. The signal duration ($\tau_{90}$) is displayed by the grey shaded area. Beside the decreasing amplitudes of the sound pressure (attenuation) this figure shows the increase of the signal duration ($\tau_{90}$) for growing distances. On the measurement position MP4 in 46,711 km distance the pile driving noise was audible but the signal to noise ratio was to poor, so no Sound Exposure Level (SEL) and with them no signal duration ($\tau_{90}$) could be detected. In Table 15 the signal durations $\tau_{90}$ are listed for the measuring positions MP1, MP2 and MP3. As expected, the signal duration is increasing with the distance and shows slightly difference regarding the hydrophone heights.

***Table 15:*** *Median of the signal duration $\tau_{90}$ for different measuring positions.*

| Position | Distance | Measuring height [m] | Median of $\tau_{90}$ [s] | |
|---|---|---|---|---|
| | | | EL39 | EL42 |
| MP1 | 750 | 2 | 0.060 | 0.082 |
| | | 10 | 0.059 | 0.075 |
| MP2 | approx. 5 km | 2 | 0.131 | 0.107 |
| | | 10 | 0.070 | n.v.[7] |
| MP3 | approx. 13.5 km | 2 | 0.168 | 0.166 |
| | | 10 | 0.178 | 0.176 |

[7] The hydrophone cable for the pile driving noise measurement was damaged during the 2nd deployment mechanically (technical defect of the used hydrophone).

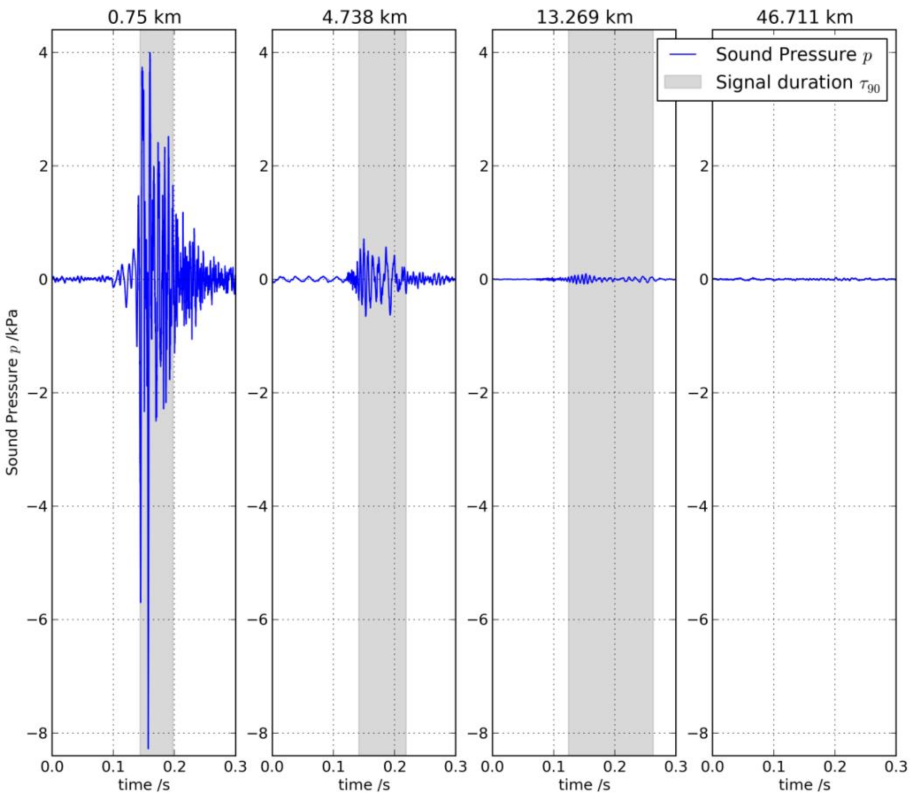



***Figure 23:*** *Sound pressure (p) as a function of time for one single blow.(blow number 1.523 of foundation EL39) for all measurement positions in 2 m height. The signal duration ($\tau_{90}$) is displayed by the grey shaded area.*

## 6.2.3 Sound propagation in frequency domain

The attenuation of sound in water is affected by changes in the geometry (surface and soil conditions) as well as the composition and properties of the medium (e. g. caused by wind and waves). This leads to different propagation speeds and transmission losses for different frequencies. Usually the transmission loss is increasing with frequency (Thiele & Schellstede, 1980). Figure 24 shows the 1/3-octave spectra of the $SEL_{50}$ measured at the positions MP1, MP2 and MP3 during pile driving of foundation EL39 for both measuring heights. As expected the transmission loss over the distance is higher for high frequencies than for low frequencies. For example is the difference between MP1 and MP2 approx. 10 dB at 32 Hz and > 15 dB for frequencies > 500 Hz. This effect is stronger 2 m above seabed than 10 m above seabed. This may be caused by changes in the topography and interactions of the sound with the seabed.

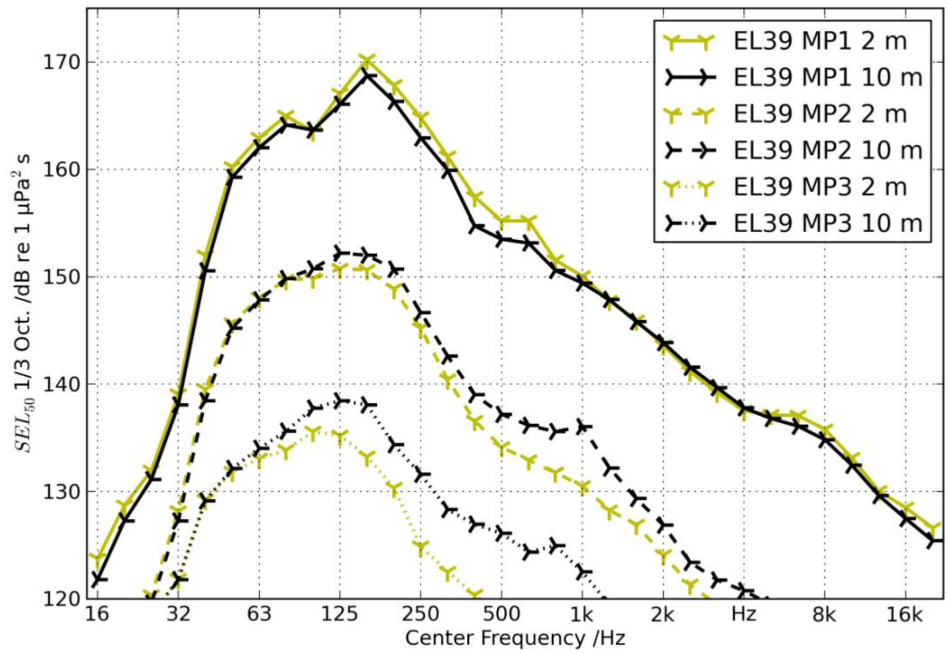



***Figure 24:*** *$SEL_{50}$ 1/3-octave for the pile EL39 on the measuring positions MP1, MP2 and MP3 for 2 m and 10 m hydrophone height.*

## 6.3 Conclusions

### Impact of different pile designs

The results show as expected a spectra shifted to deeper frequencies for the Sound Exposure Level (SEL) on the longer pile due to deeper natural resonance frequency (eigen frequency).

The Sound Exposure Level (SEL) for the shorter monopile with scour protection was between 2 dB to 3 dB louder than for the longer monopile. It was not possible to verify a reason for this difference. Most likely the higher levels were due to the measurement uncertainties.

### Attenuation over large distances

When using common propagation models like the geometrical absorption - *15* $log_{10}$*(d – distance ratio)* or the semi-empirical attenuation approach of Thiele & Schellstede (1980), the calculated attenuation of the pile driving noise at large distances was much lower than the observed attenuation. The observed attenuation in 2 m above the seabed was slightly higher than in 10 m above the seabed.

Up to a distance of 30 km the median Sound Pressure Level (SPL) was higher than the Sound Pressure Level (SPL) of the ambient noise. Due to a variance in ambient noise this distance in some cases increased to more than 40 km.

### Comparison with other windfarms

By comparison the underwater noise of both piles with pilling noise from other Offshore Wind Farms the measured Sound Exposure Levels were within the expected range (measured data from *itap GmbH*). The measured impact of blow energy to the Sound Exposure Level (SEL) was also within the expected range of 2.5 dB to 4 dB by doubling blow energy.

# 7. Literature

[1] **TNO report (2011)** Standard for measurement and monitoring of underwater noise, Part II: procedures for measuring underwater noise in connection with offshore wind farm licensing, TNO, Den Haag

[2] **BSH (2011)** Messvorschrift für Unterwasserschallmessungen – Aktuelle Vorgehensweise mit Anmerkungen. Bericht im Rahmen des Forschungsvorhabens „Ökologische Begleitforschung am Offshore-Testfeldvorhaben alpha ventus zur Evaluierung des Standarduntersuchungskonzeptes des BSH (StUKplus)“, Förderkennzeichen 0327689A

[3] **Thiele R, Schellstede G (1980)** Standardwerte zur Ausbreitungsdämpfung in der Nordsee. FWG-Bericht 1980-7, Forschungsanstalt der Bundeswehr für Wasserschall und Geophysik.

[4] **Gündert S (2014)** Empirische Prognosemodelle für Hydroschallimmissionen zum Schutz des Gehörs und der Gesundheit von Meeressäugern. Masterarbeit an der Universität Oldenburg, Institut für Physik, AG Akustik

[5] **Bellmann MA, Gündert S & Remmers P (2013)** Offshore Messkampagne 1 (OMK 1) für das Projekt BORA im Windpark BARD Offshore 1 - Hydroakustische Messungen zur Evaluierung der Wirksamkeit des Schallminderungssystems „Small Bubble Curtain (SBC)“ und zur Untersuchung der Schallabstrahlung eines zu rammenden Pfahles - Projektbericht der itap GmbH, Projekt Nr. 1924-12-mb, Förderkennzeichen 0325421A/B/C

[6] **Jensen et al. (2000),** Jensen FB, Kupermann WA, Porter MB, Schnmidt H: Computational Ocean Acoustics, Springer-Verlag New York, Inc.

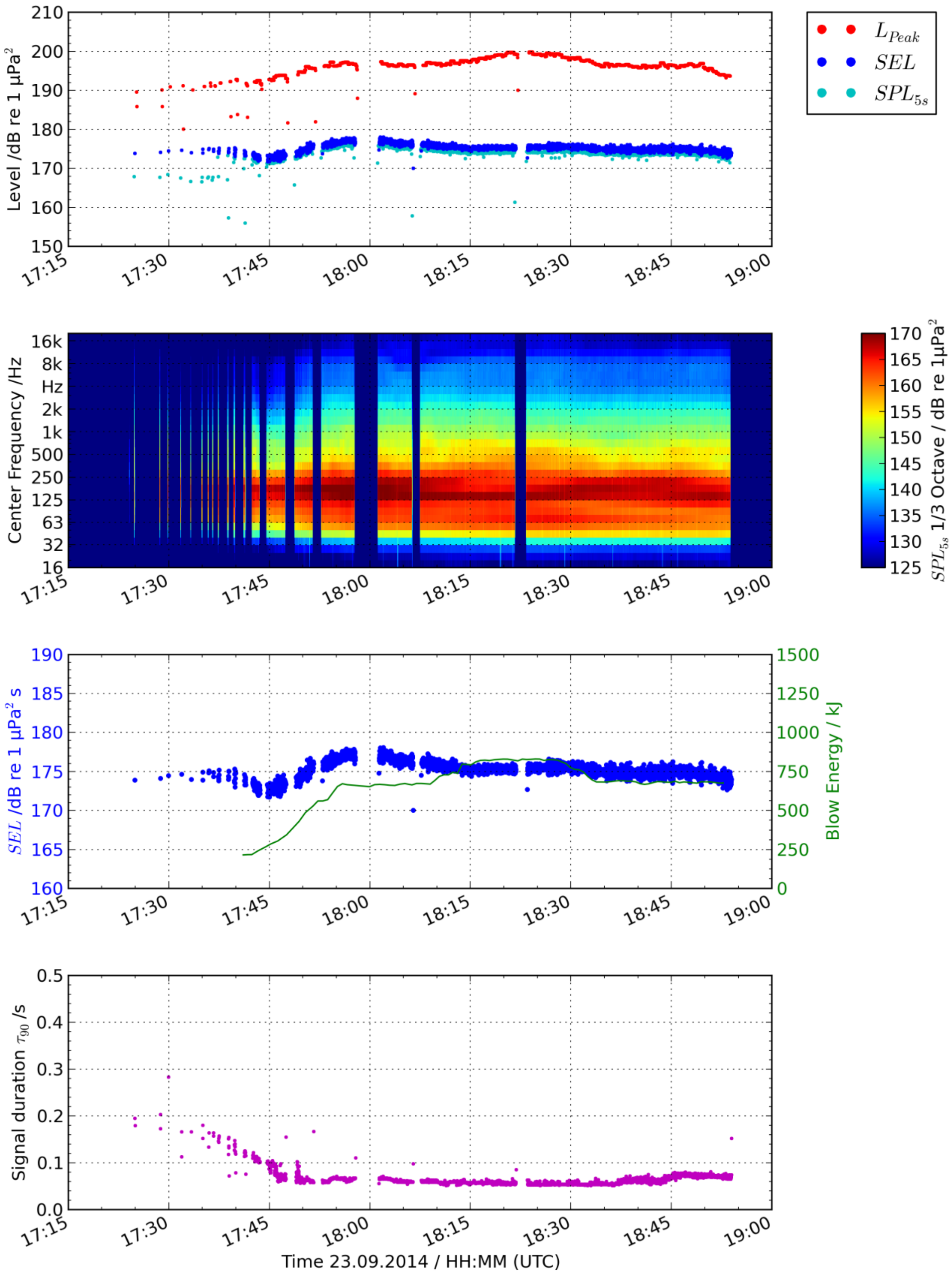
[7] **Medwin H (1975),** Speed of Sound in Water for Realistic Paramters, J. Acoust. Soc. Am.

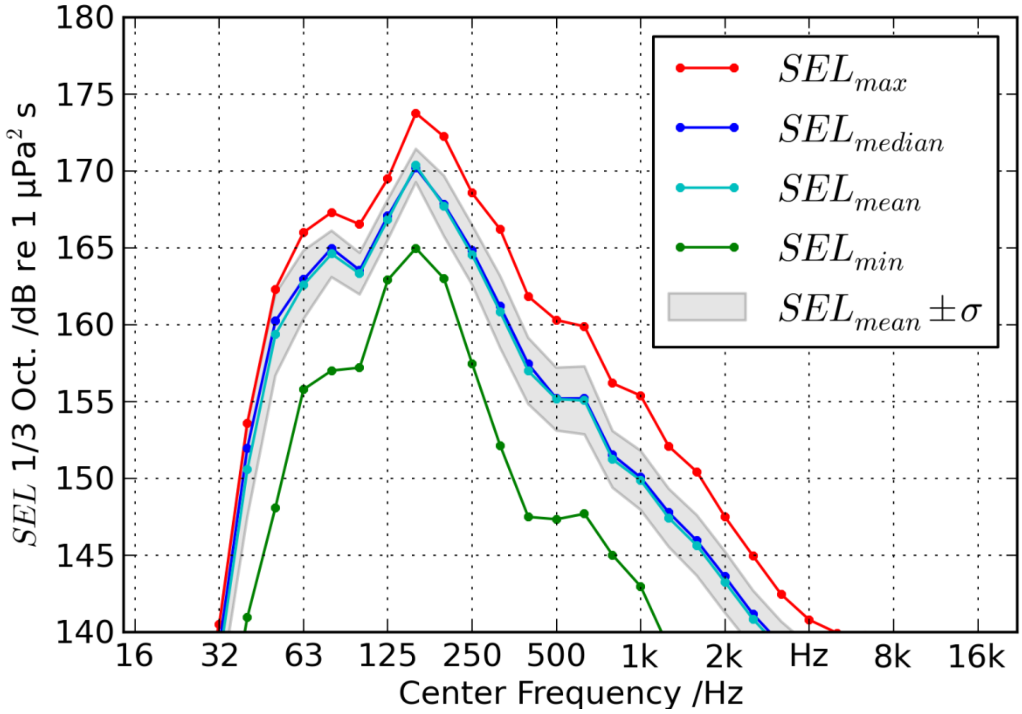
[8] **MacKenzie KV (1981),** Nine-term Equation for Sound Speed in the Oceans. J. Acoust. Soc. Am.

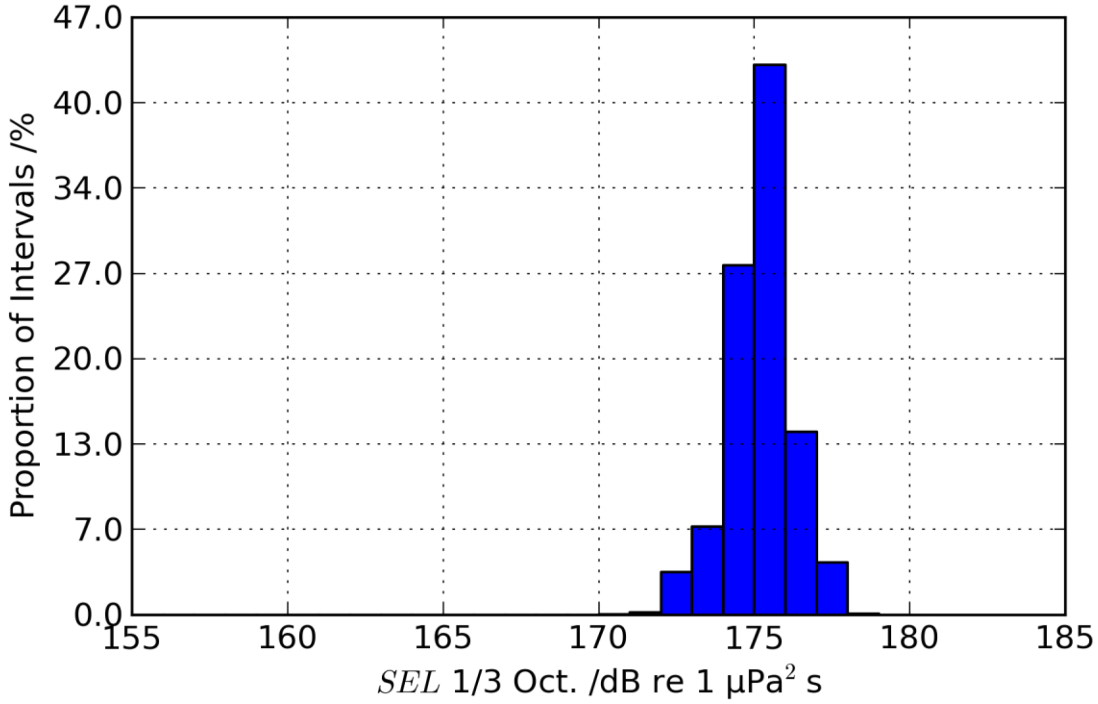
# Annex 1: Plots of measurement results for each measuring position and each pile

## A1.1 Pile Driving Noise for monopile EL39

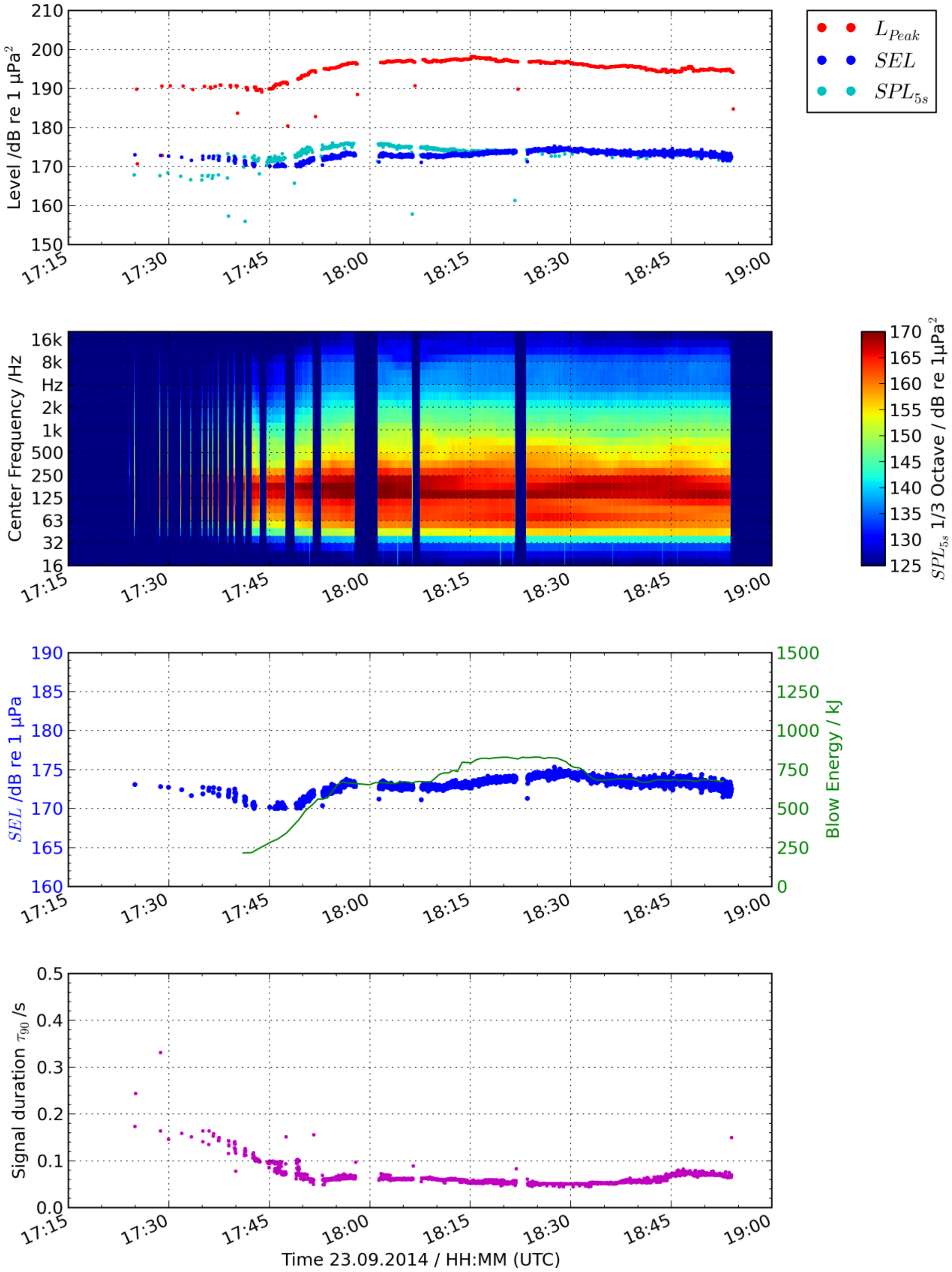
## EL39 MP1 2 m pile driving noise

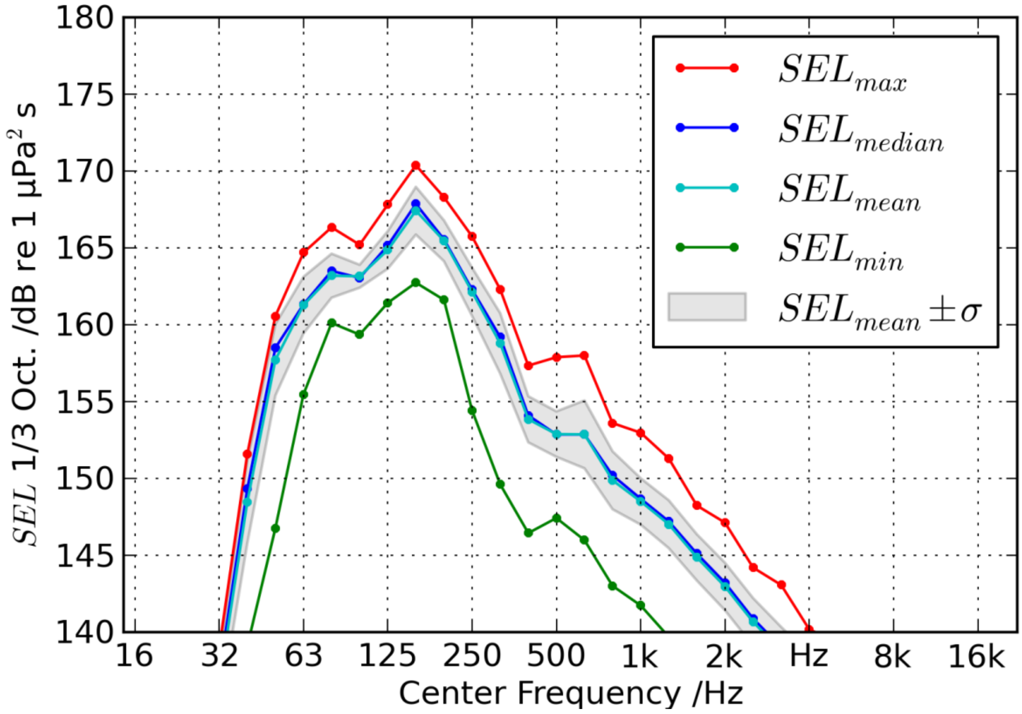



$SEL_{max}$
$SEL_{median}$
$SEL_{mean}$
$SEL_{min}$
$SEL_{mean} \pm \sigma$
$SEL$ 1/3 Oct. /dB re 1 µPa$^2$ s
Center Frequency /Hz
180
175
170
165
160
155
150
145
140
16
32
63
125
250
500
1k
2k
Hz
8k
16k

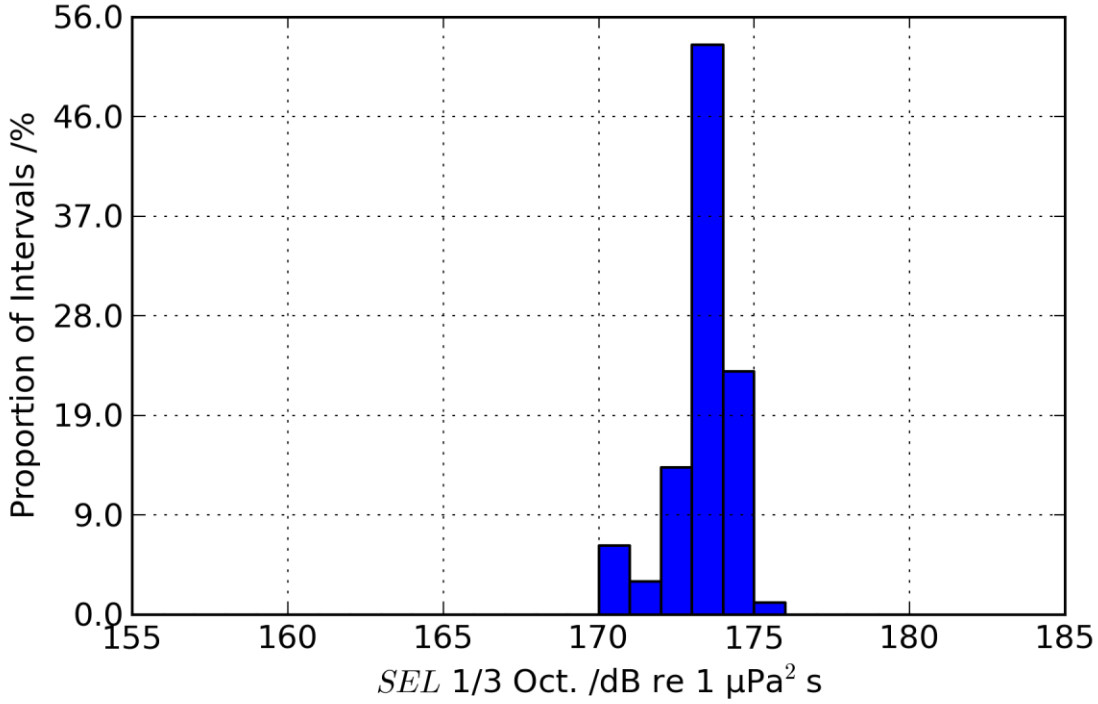

Proportion of Intervals /%
$SEL$ 1/3 Oct. /dB re 1 µPa$^2$ s
47.0
40.0
34.0
27.0
20.0
13.0
7.0
0.0
155
160
165
170
175
180
185

# EL39 MP1 10 m pile driving noise



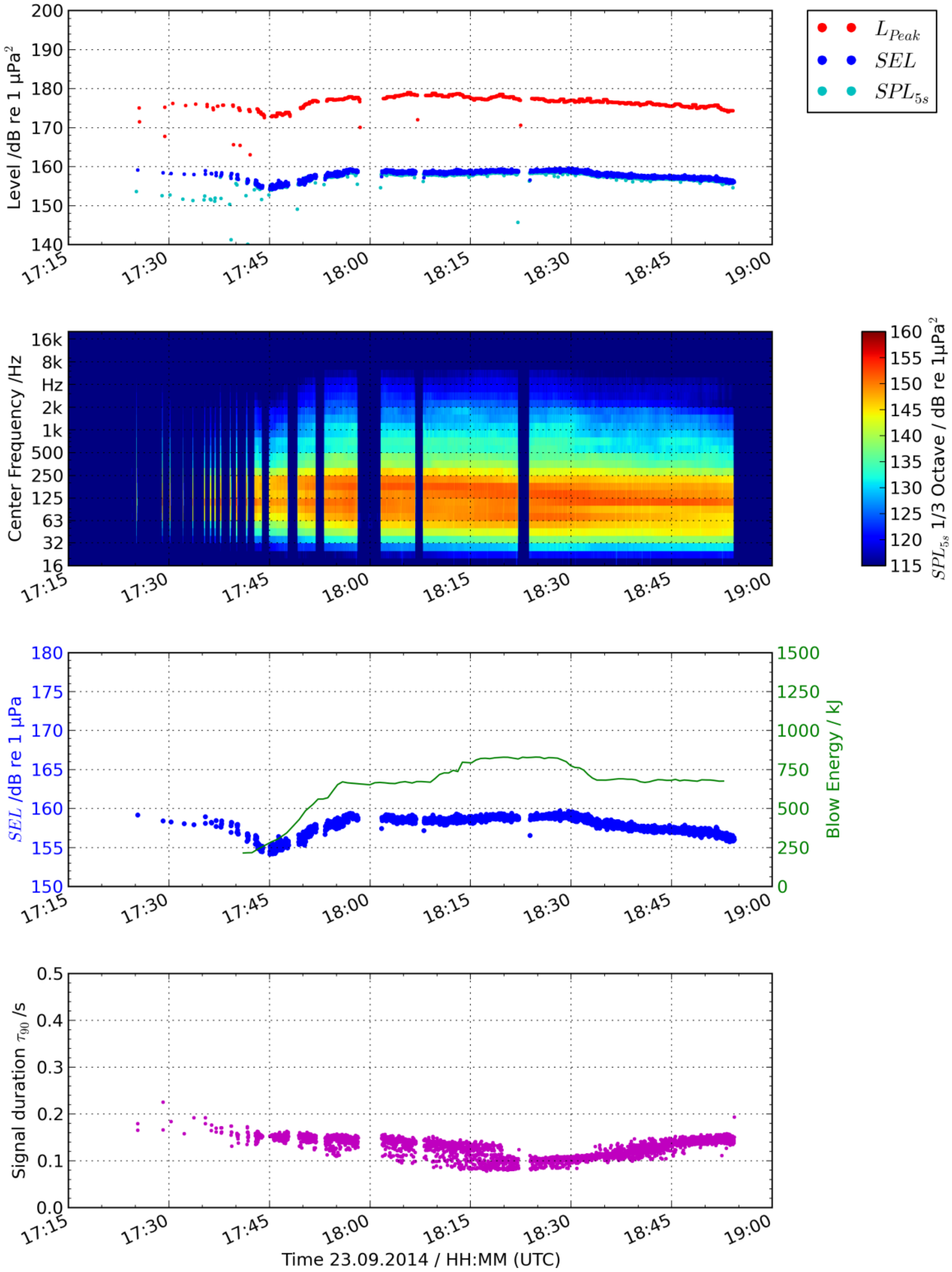


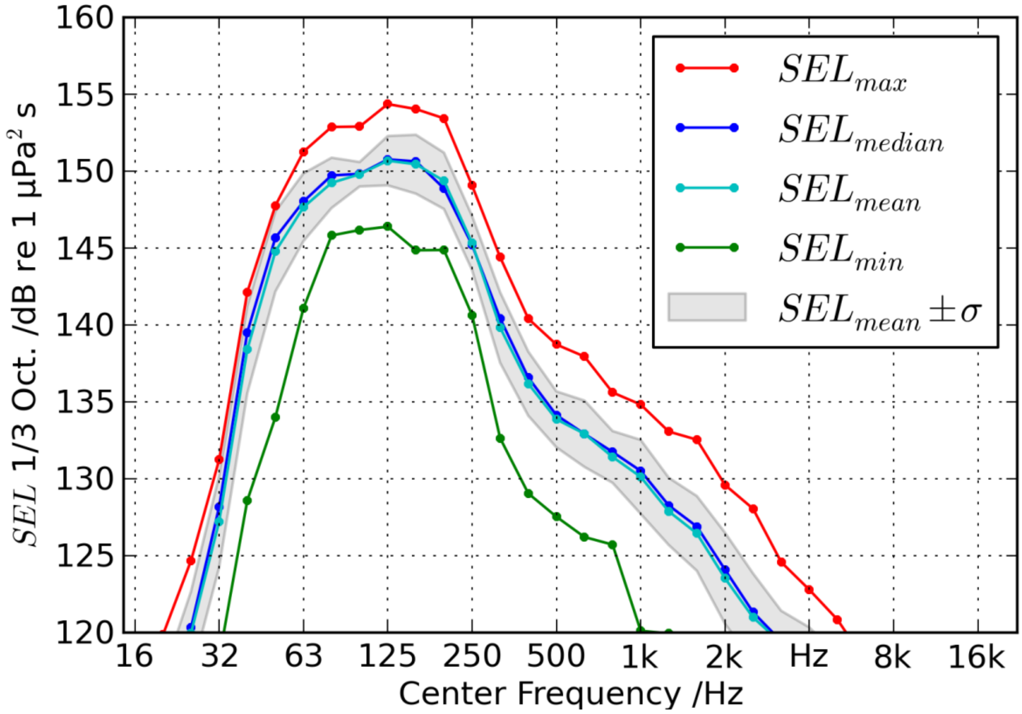
180
175
170
165
160
155
150
145
140
$SEL$ 1/3 Oct. /dB re 1 µPa$^2$ s
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center Frequency /Hz
$SEL_{max}$
$SEL_{median}$
$SEL_{mean}$
$SEL_{min}$
$SEL_{mean} \pm \sigma$

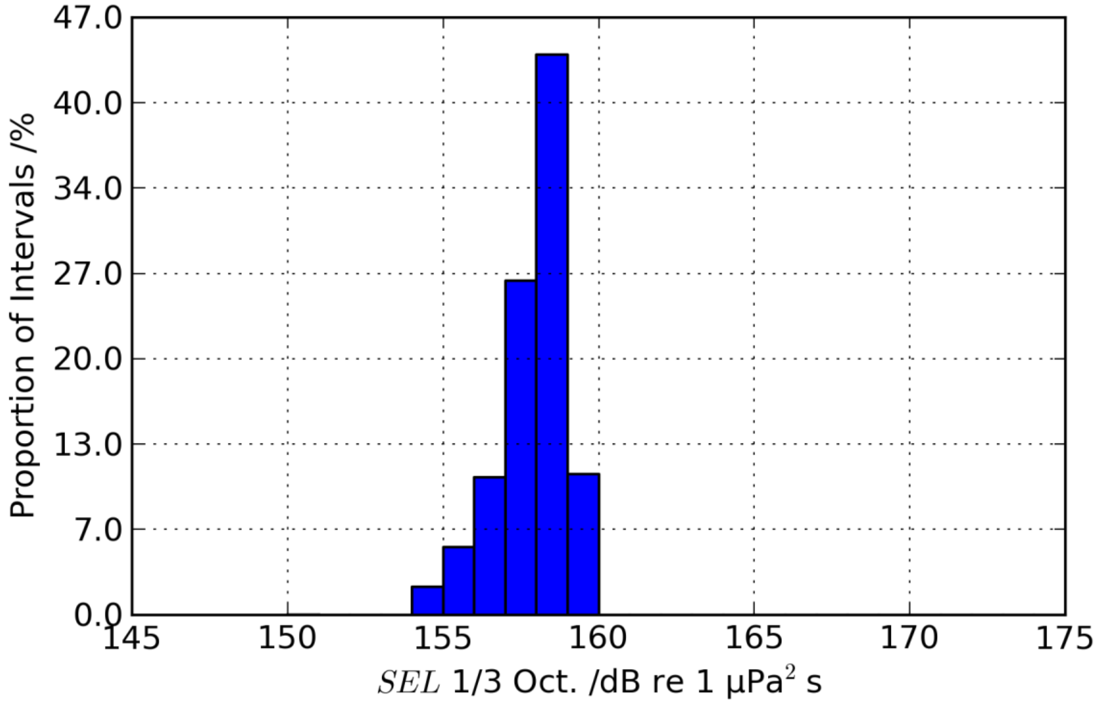



56.0
46.0
37.0
28.0
19.0
9.0
0.0
Proportion of Intervals /%
155
160
165
170
175
180
185
$SEL$ 1/3 Oct. /dB re 1 µPa$^2$ s

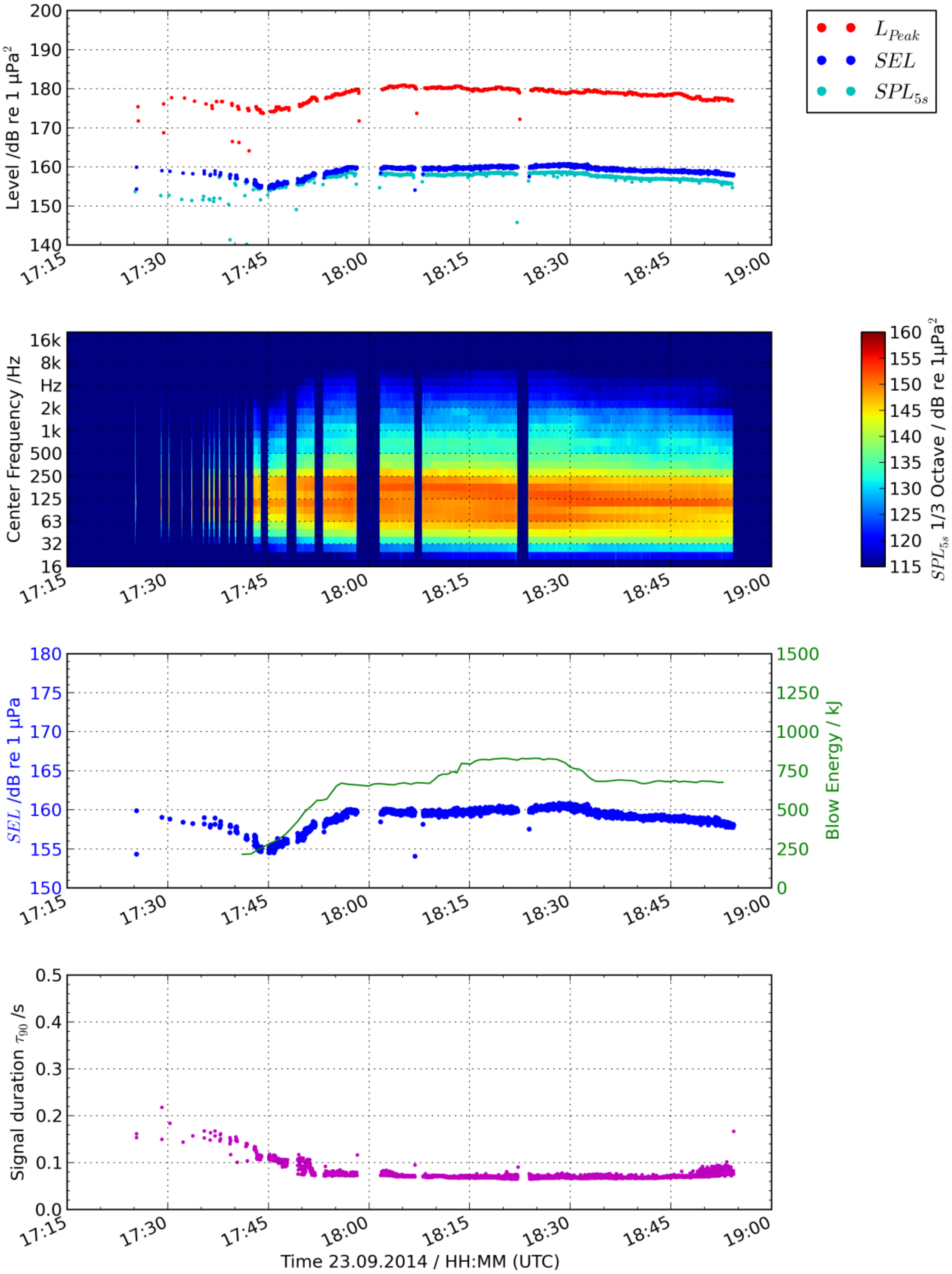
# EL39 MP2 2 m pile driving noise

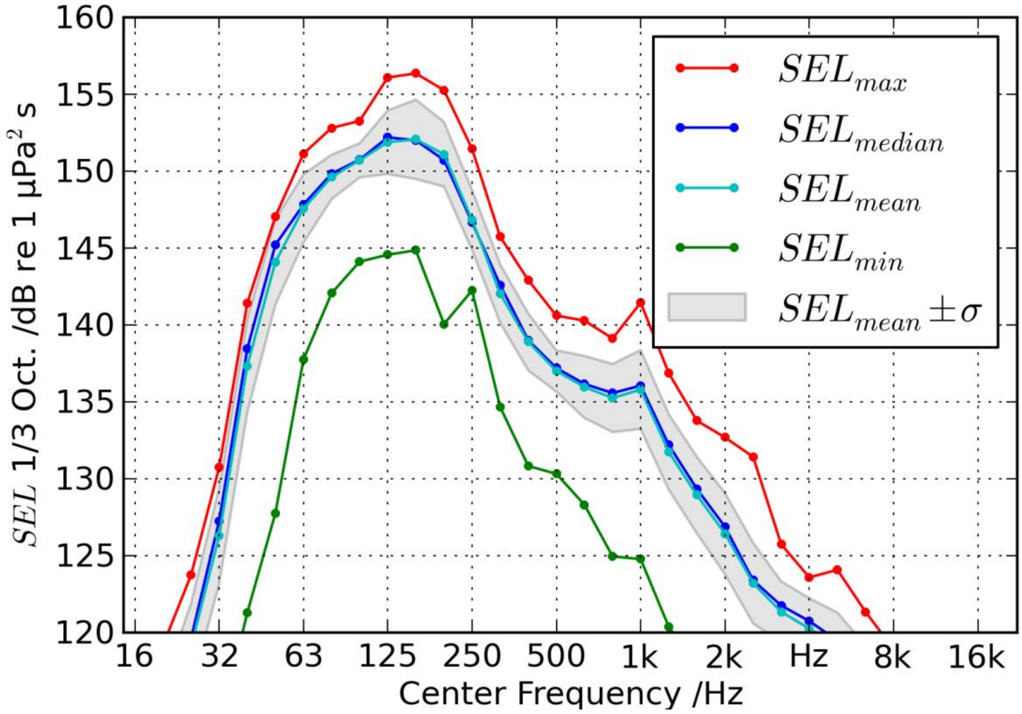


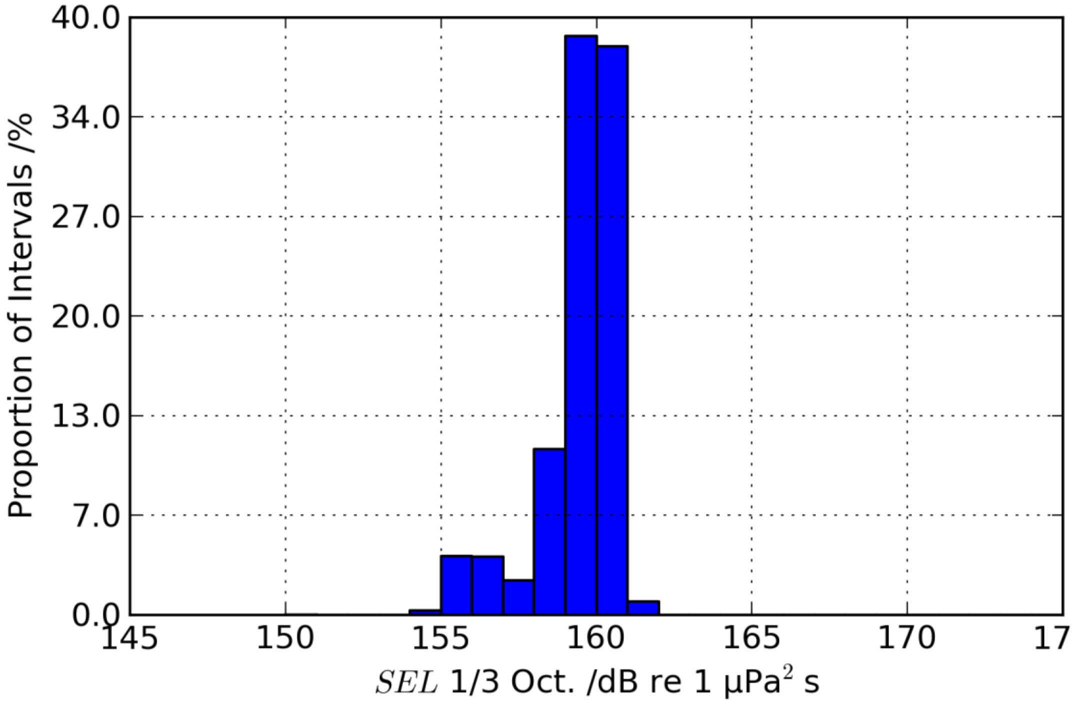

$SEL_{max}$
$SEL_{median}$
$SEL_{mean}$
$SEL_{min}$
$SEL_{mean} \pm \sigma$
$SEL$ 1/3 Oct. /dB re 1 µPa$^2$ s
Center Frequency /Hz
16
32
63
125
250
500
1k
2k
Hz
8k
16k
160
155
150
145
140
135
130
125
120


Proportion of Intervals /%
$SEL$ 1/3 Oct. /dB re 1 µPa$^2$ s
47.0
40.0
34.0
27.0
20.0
13.0
7.0
0.0
145
150
155
160
165
170
175

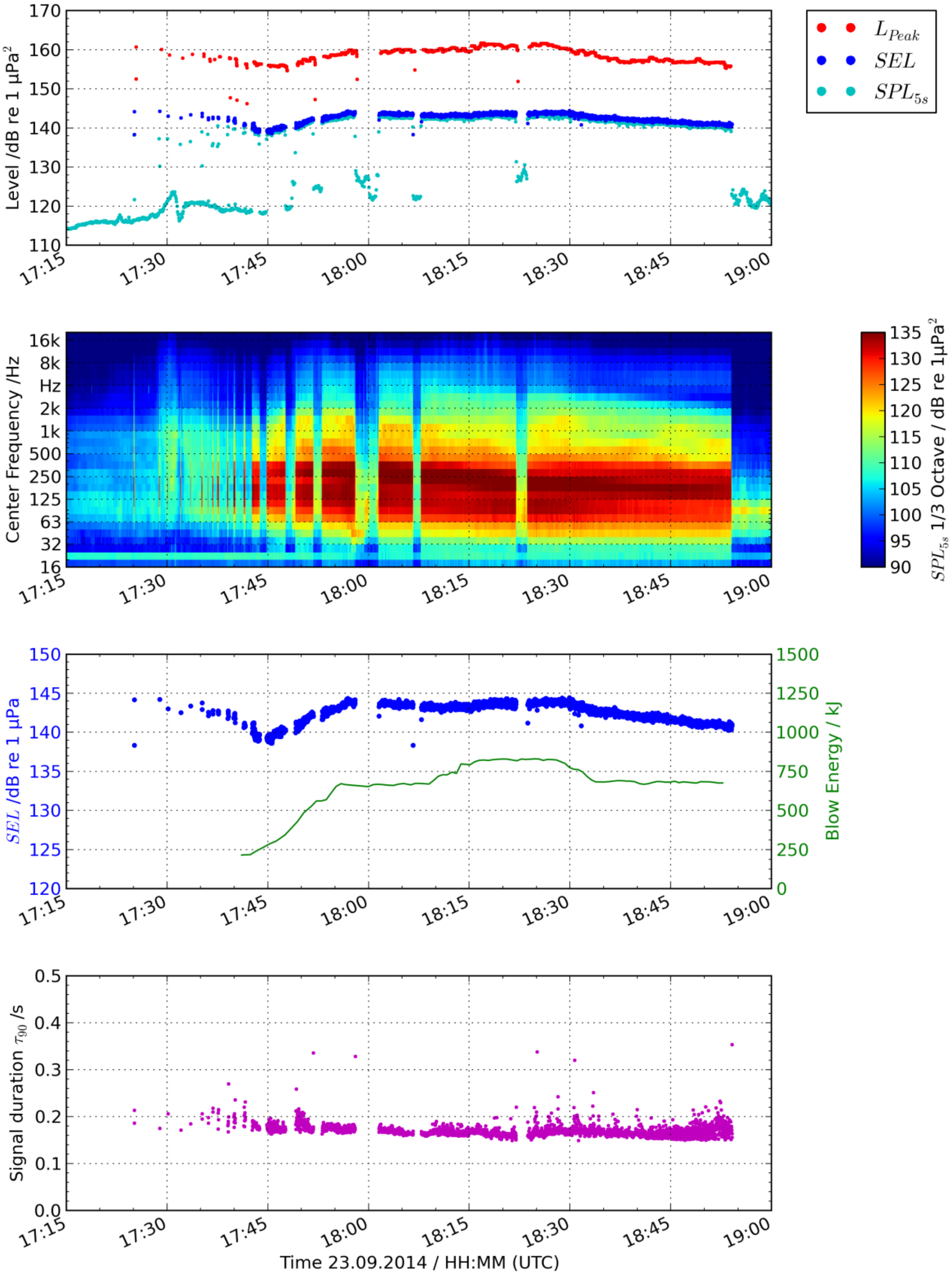
# EL39 MP2 10 m pile driving noise

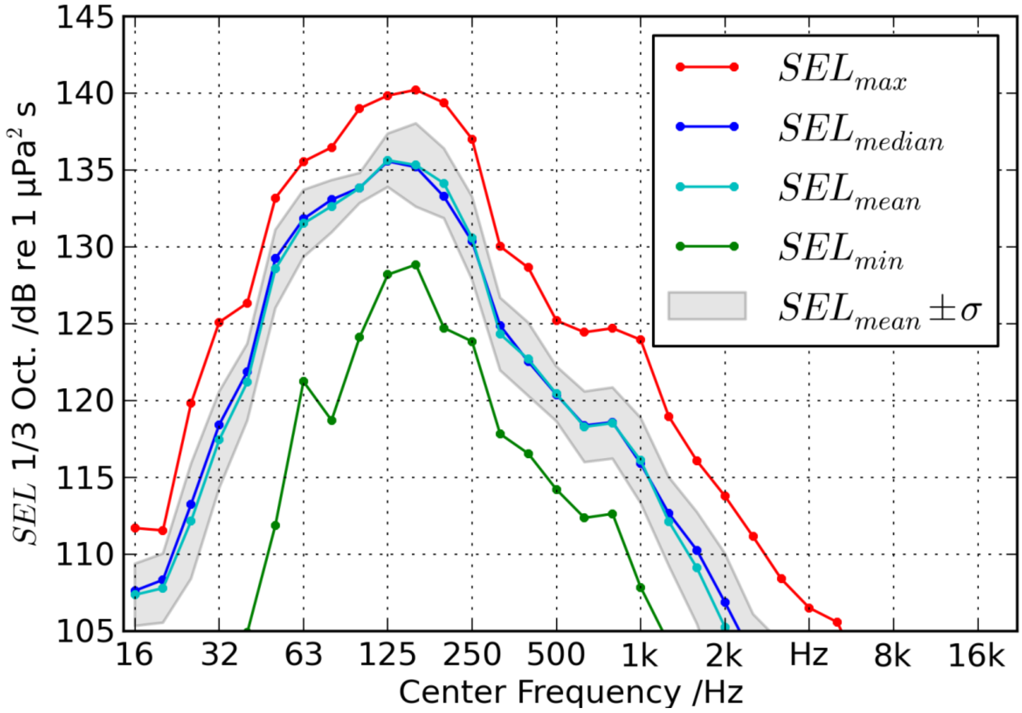



160
155
150
145
140
135
130
125
120
$SEL$ 1/3 Oct. /dB re 1 µPa$^2$ s
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center Frequency /Hz
$SEL_{max}$
$SEL_{median}$
$SEL_{mean}$
$SEL_{min}$
$SEL_{mean} \pm \sigma$

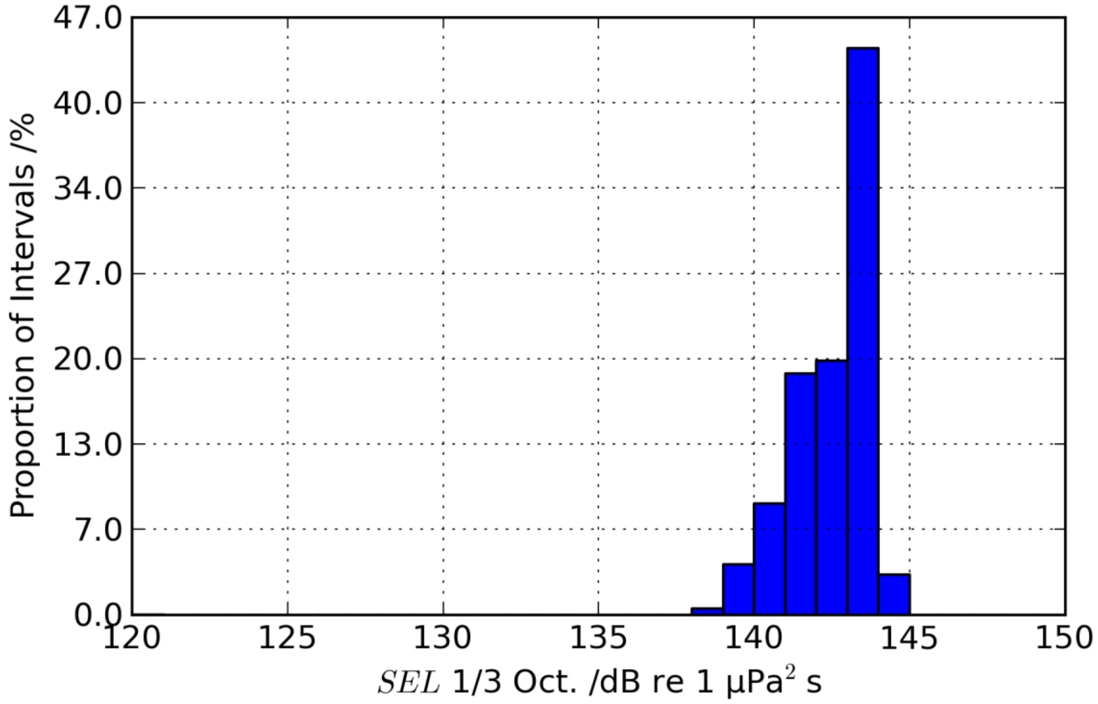

40.0
34.0
27.0
20.0
13.0
7.0
0.0
Proportion of Intervals /%
145
150
155
160
165
170
175
$SEL$ 1/3 Oct. /dB re 1 µPa$^2$ s

## EL39 MP3 2 m pile driving noise



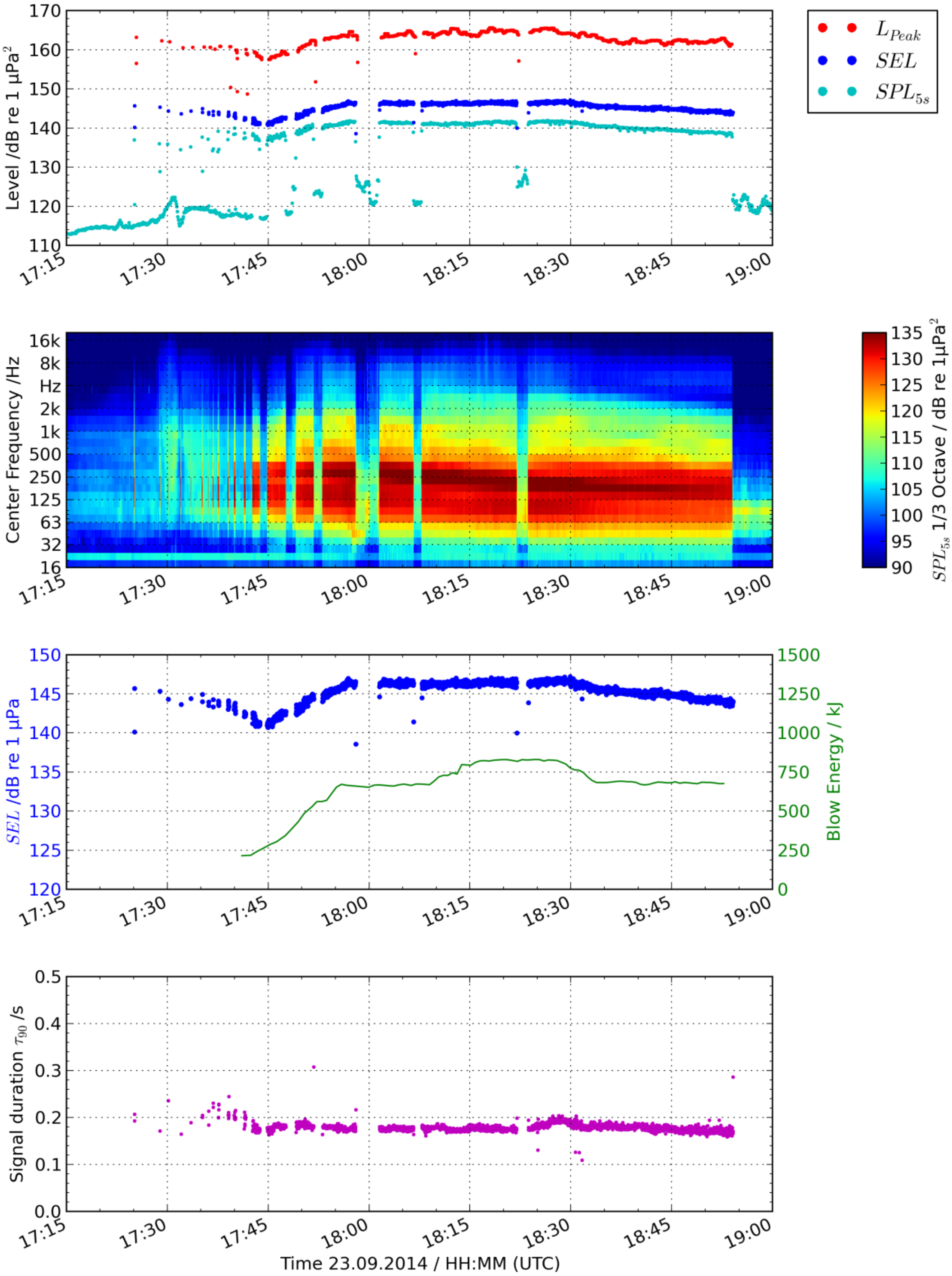


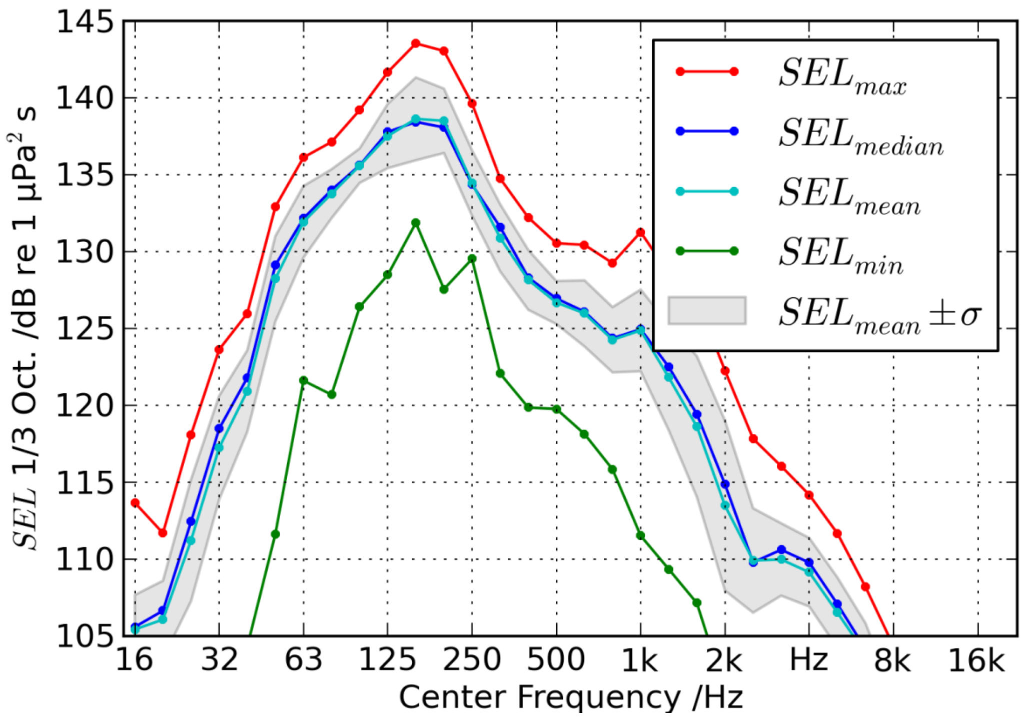
145
140
135
130
125
120
115
110
105
SEL 1/3 Oct. /dB re 1 µPa² s
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center Frequency /Hz
$SEL_{max}$
$SEL_{median}$
$SEL_{mean}$
$SEL_{min}$
$SEL_{mean} \pm \sigma$

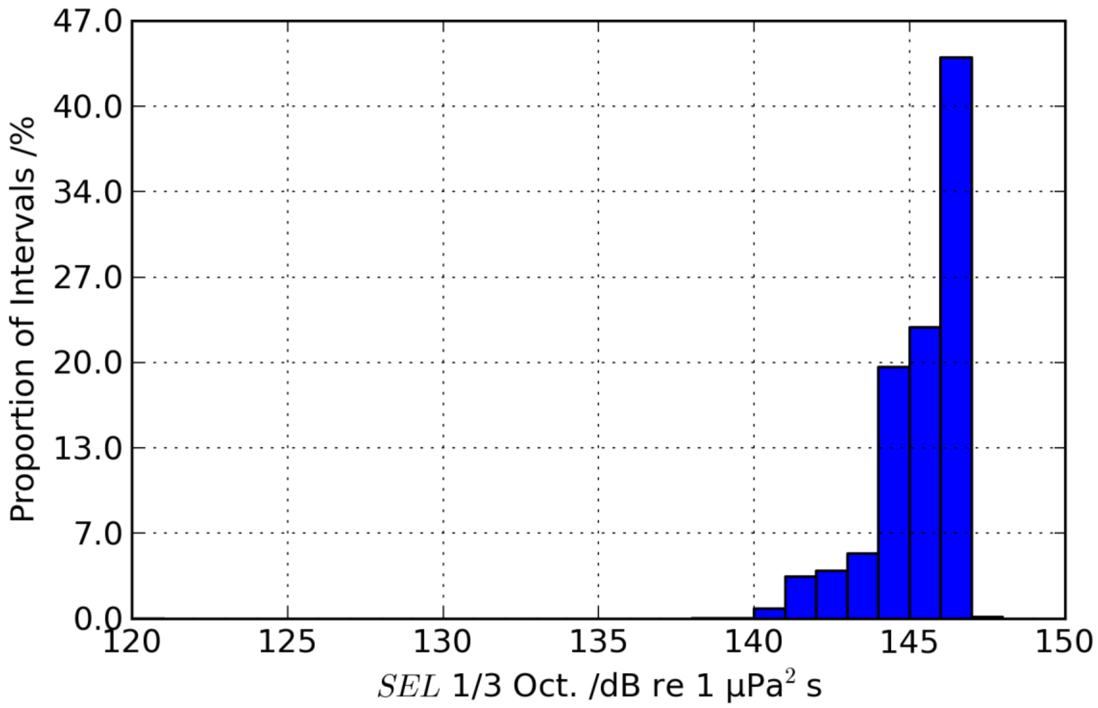



47.0
40.0
34.0
27.0
20.0
13.0
7.0
0.0
Proportion of Intervals /%
120
125
130
135
140
145
150
SEL 1/3 Oct. /dB re 1 µPa² s

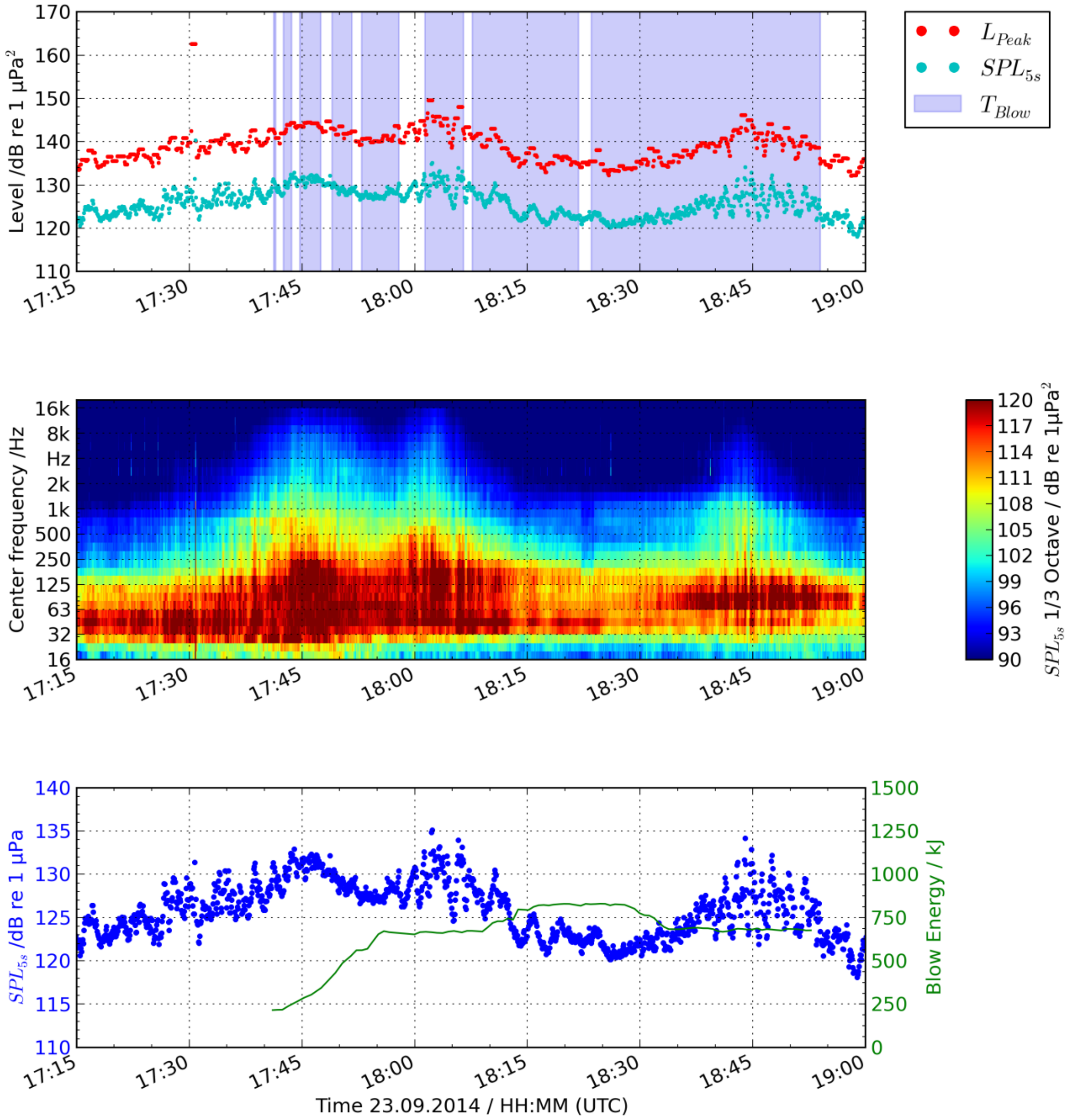
# EL39 MP3 10 m pile driving noise

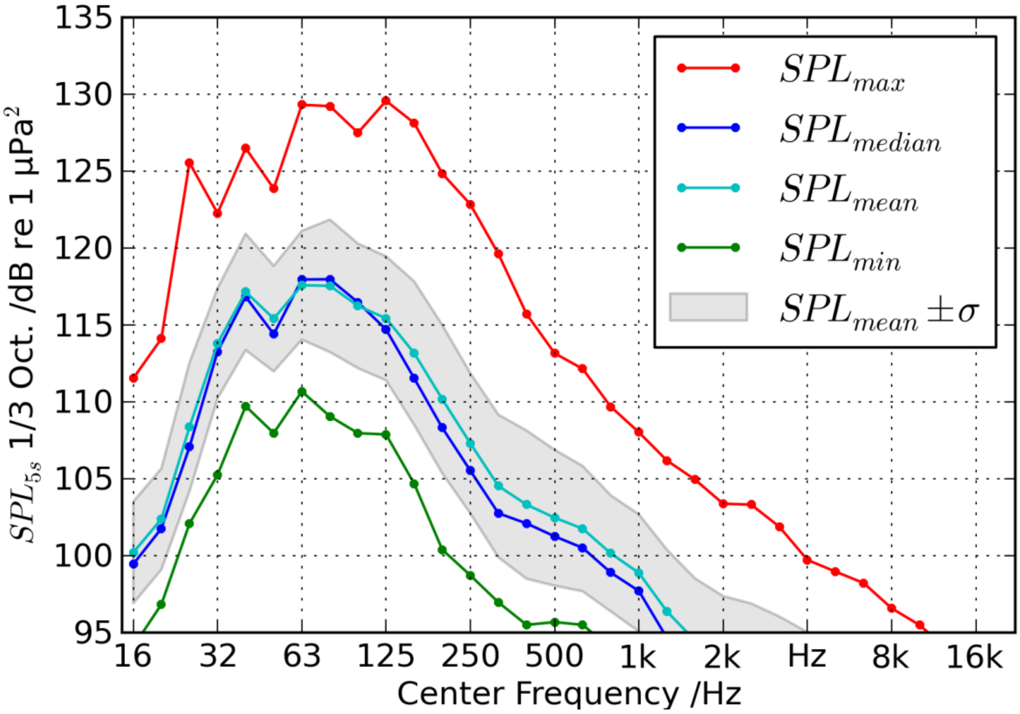


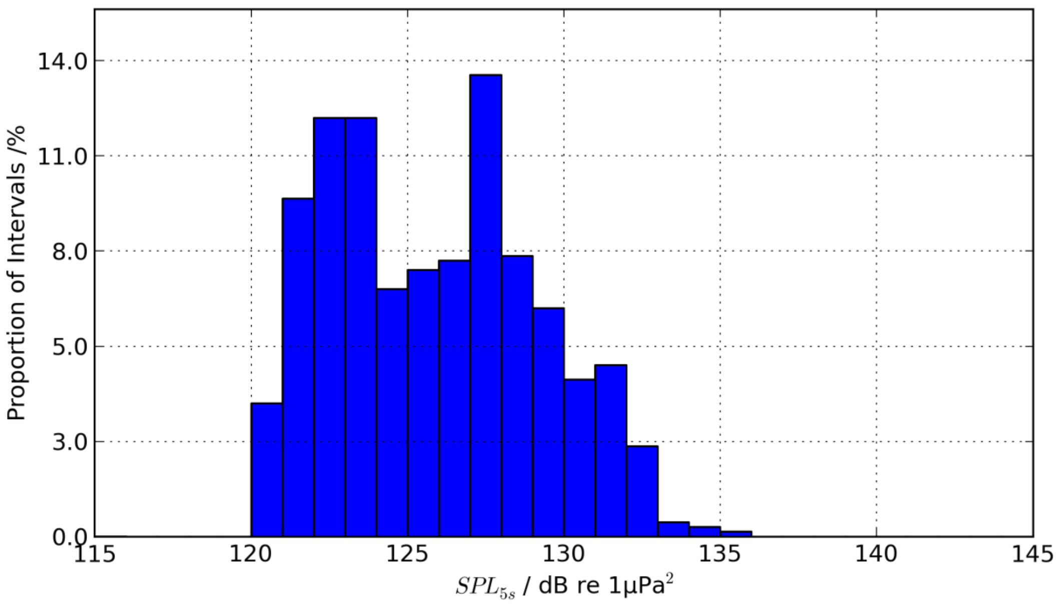

145
140
135
130
125
120
115
110
105
SEL 1/3 Oct. /dB re 1 µPa² s
16 32 63 125 250 500 1k 2k Hz 8k 16k
Center Frequency /Hz
$SEL_{max}$
$SEL_{median}$
$SEL_{mean}$
$SEL_{min}$
$SEL_{mean} \pm \sigma$


47.0
40.0
34.0
27.0
20.0
13.0
7.0
0.0
Proportion of Intervals /%
120 125 130 135 140 145 150
SEL 1/3 Oct. /dB re 1 µPa² s

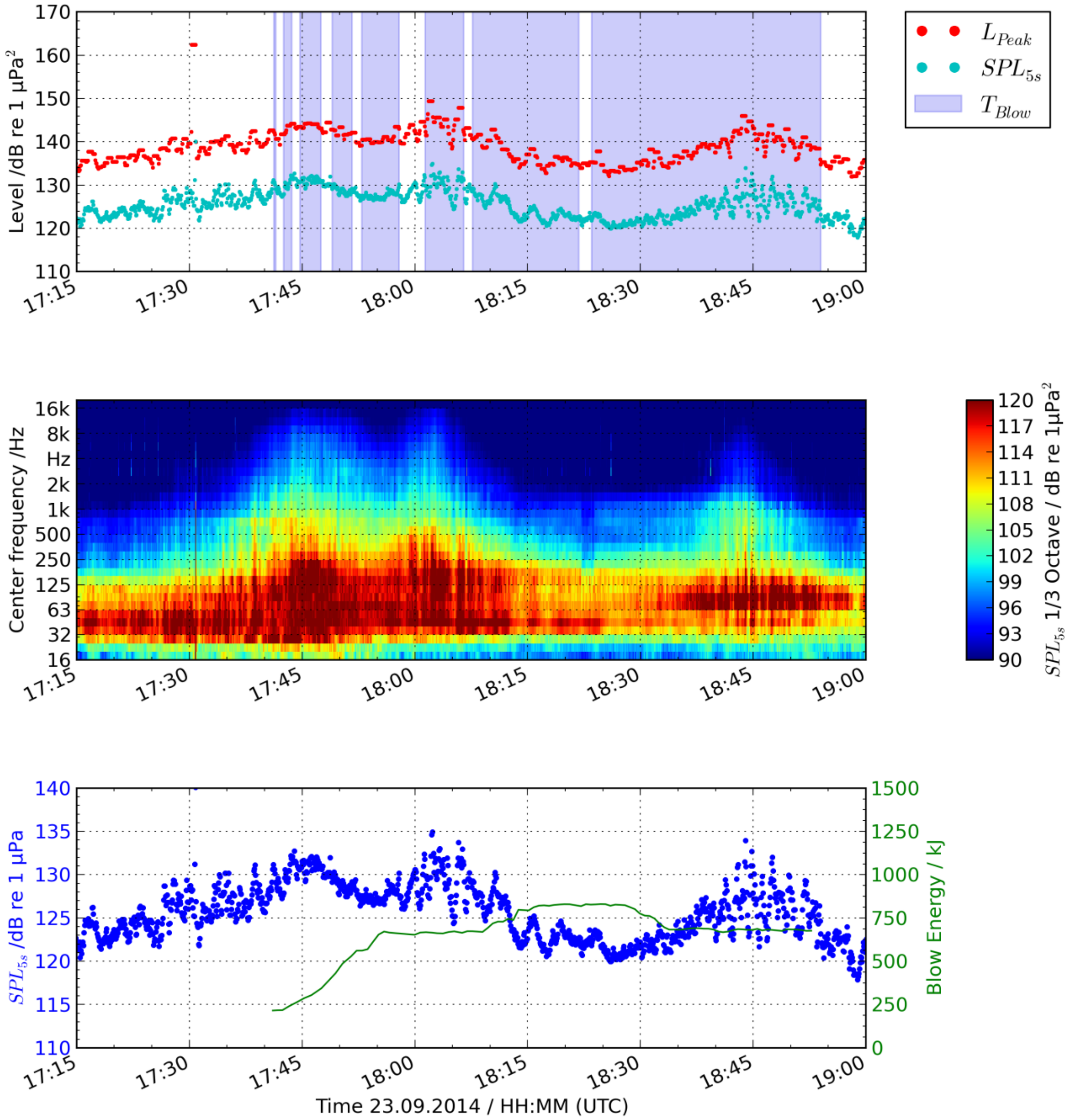
# EL39 MP4 2 m pile driving noise

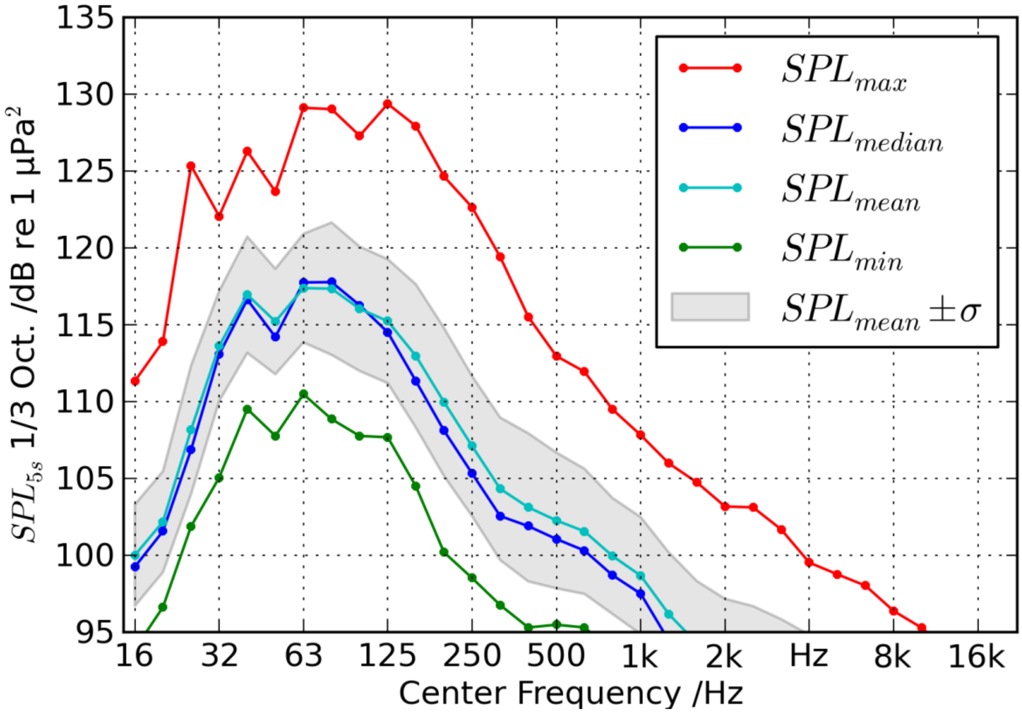


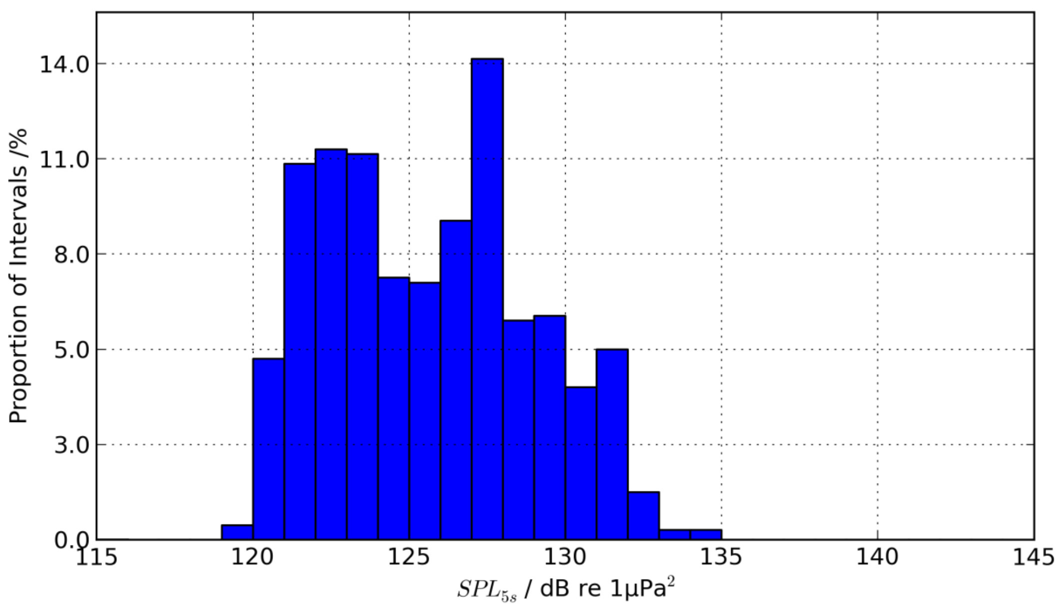

135
130
125
120
115
110
105
100
95
$SPL_{5s}$ 1/3 Oct. /dB re 1 µPa²
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center Frequency /Hz
$SPL_{max}$
$SPL_{median}$
$SPL_{mean}$
$SPL_{min}$
$SPL_{mean} \pm \sigma$


14.0
11.0
8.0
5.0
3.0
0.0
Proportion of Intervals /%
115
120
125
130
135
140
145
$SPL_{5s}$ / dB re 1µPa²

# EL39 MP4 10 m pile driving noise

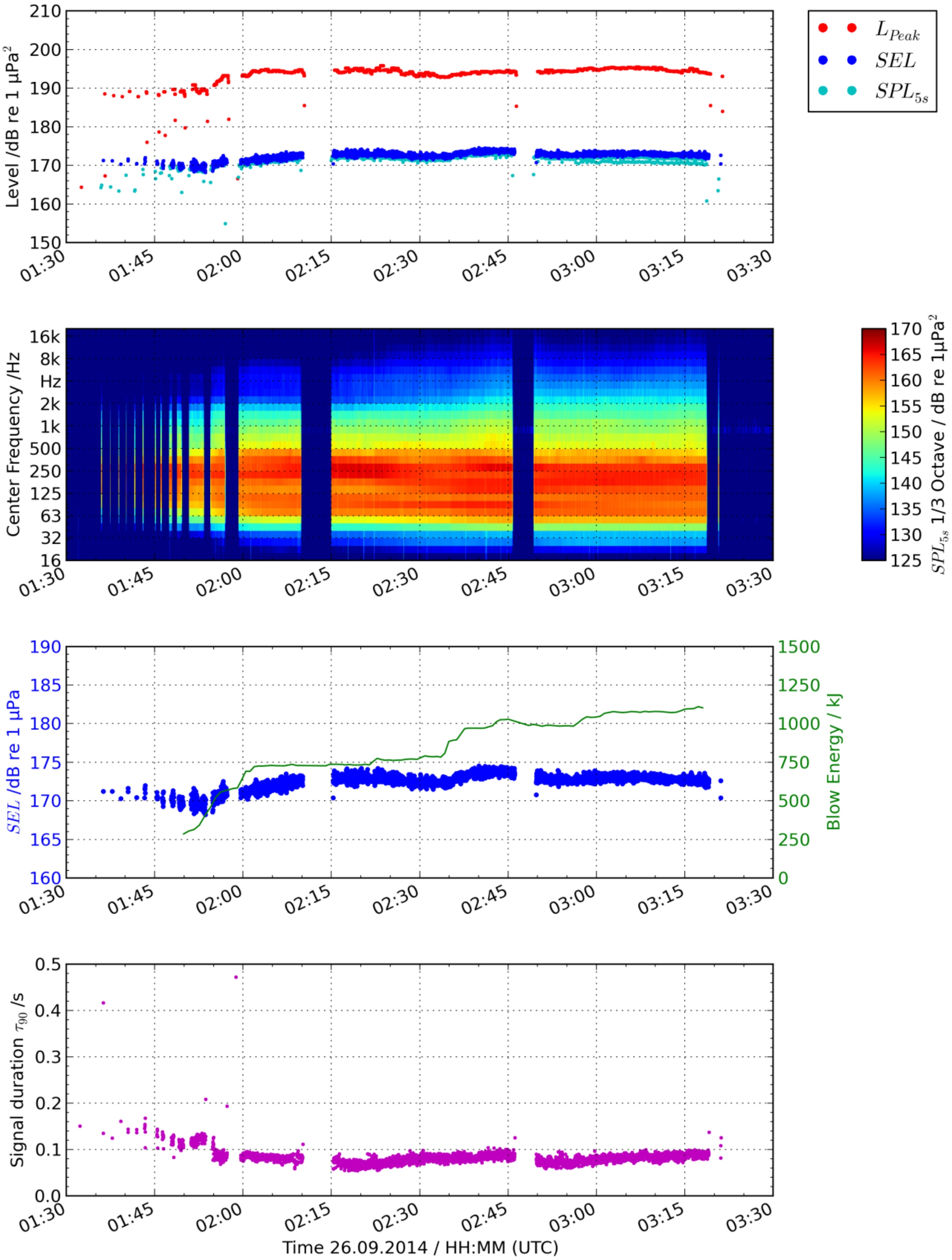


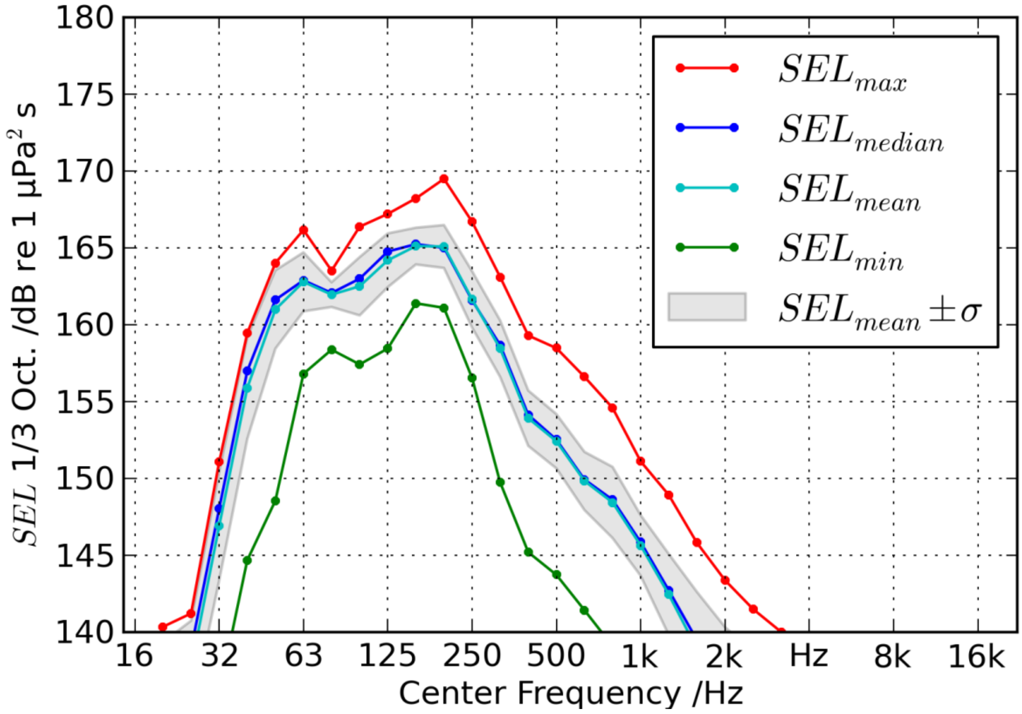

$SPL_{max}$
$SPL_{median}$
$SPL_{mean}$
$SPL_{min}$
$SPL_{mean} \pm \sigma$
$SPL_{5s}$ 1/3 Oct. /dB re 1 µPa$^2$
Center Frequency /Hz
135
130
125
120
115
110
105
100
95
16
32
63
125
250
500
1k
2k
Hz
8k
16k


Proportion of Intervals /%
$SPL_{5s}$ / dB re 1µPa$^2$
14.0
11.0
8.0
5.0
3.0
0.0
115
120
125
130
135
140
145

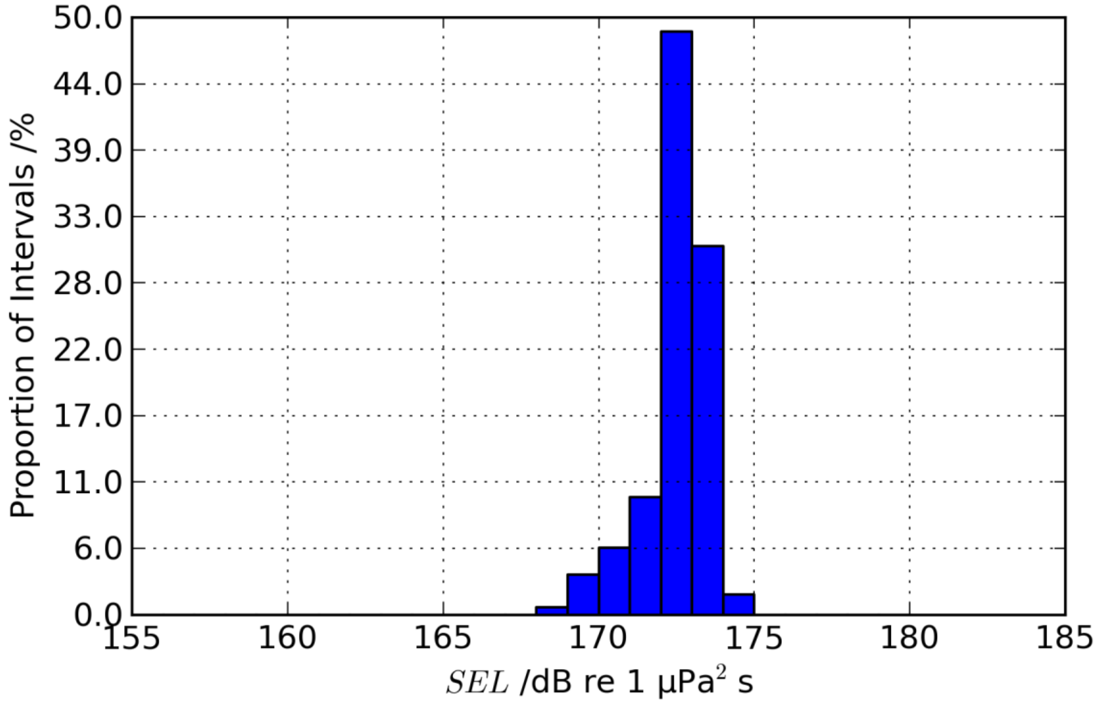
## A1.2 Pile Driving Noise for monopile EL42

## EL42 MP1 2 m pile driving noise



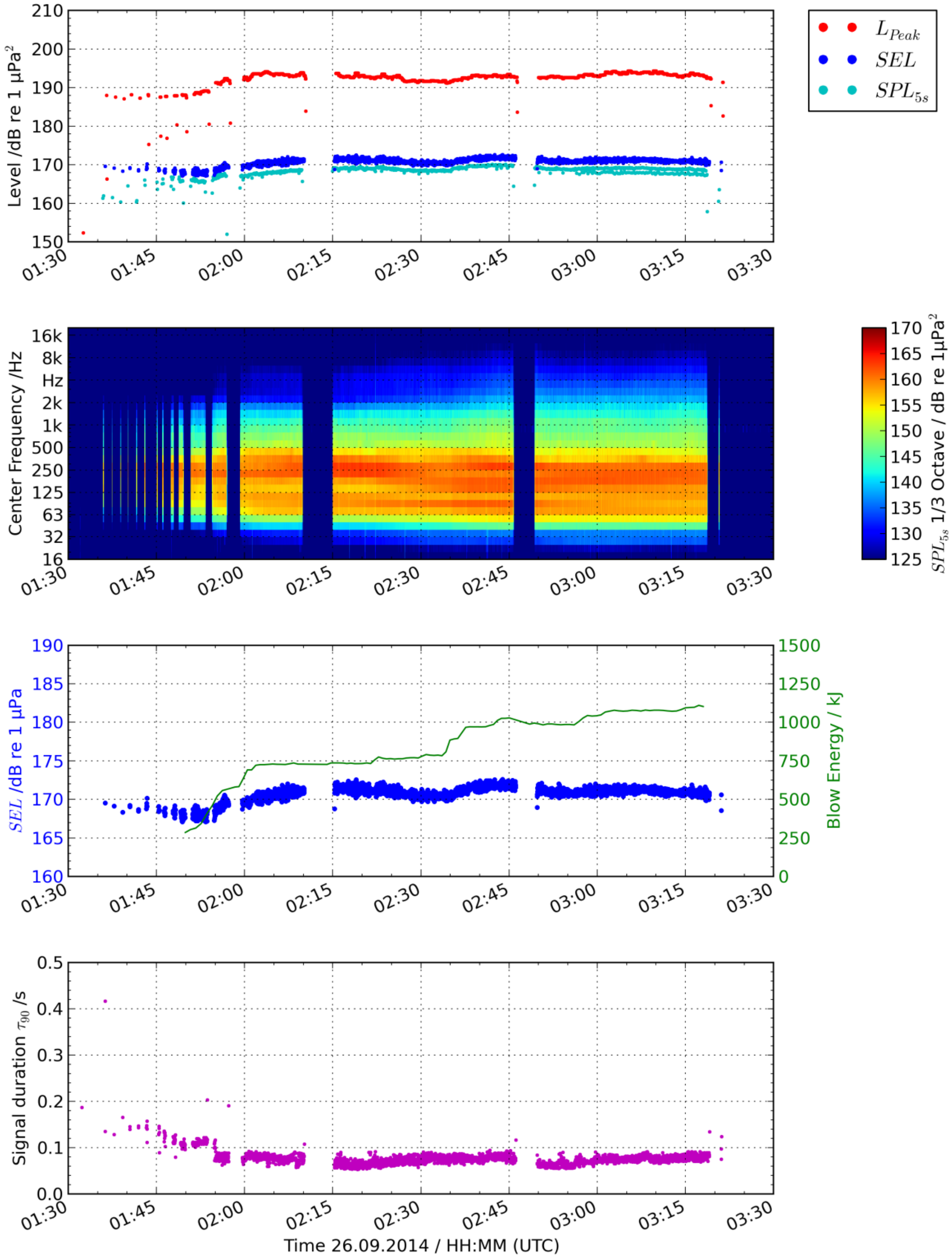


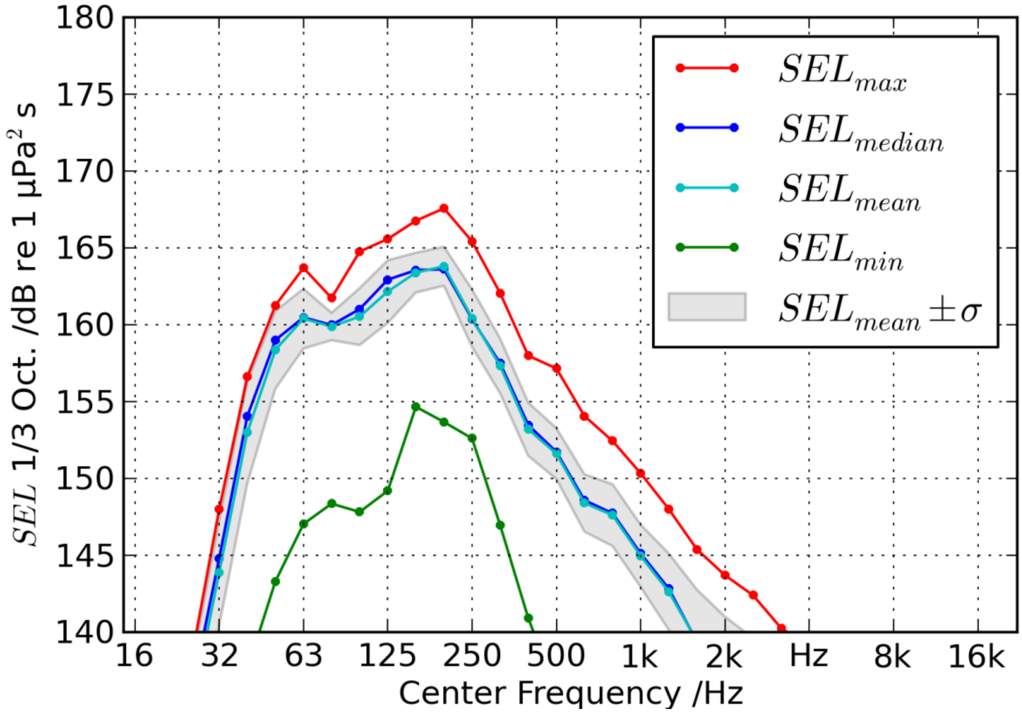
180
175
170
165
160
155
150
145
140
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center Frequency /Hz
SEL 1/3 Oct. /dB re 1 µPa² s
SEL_max
SEL_median
SEL_mean
SEL_min
SEL_mean ±σ

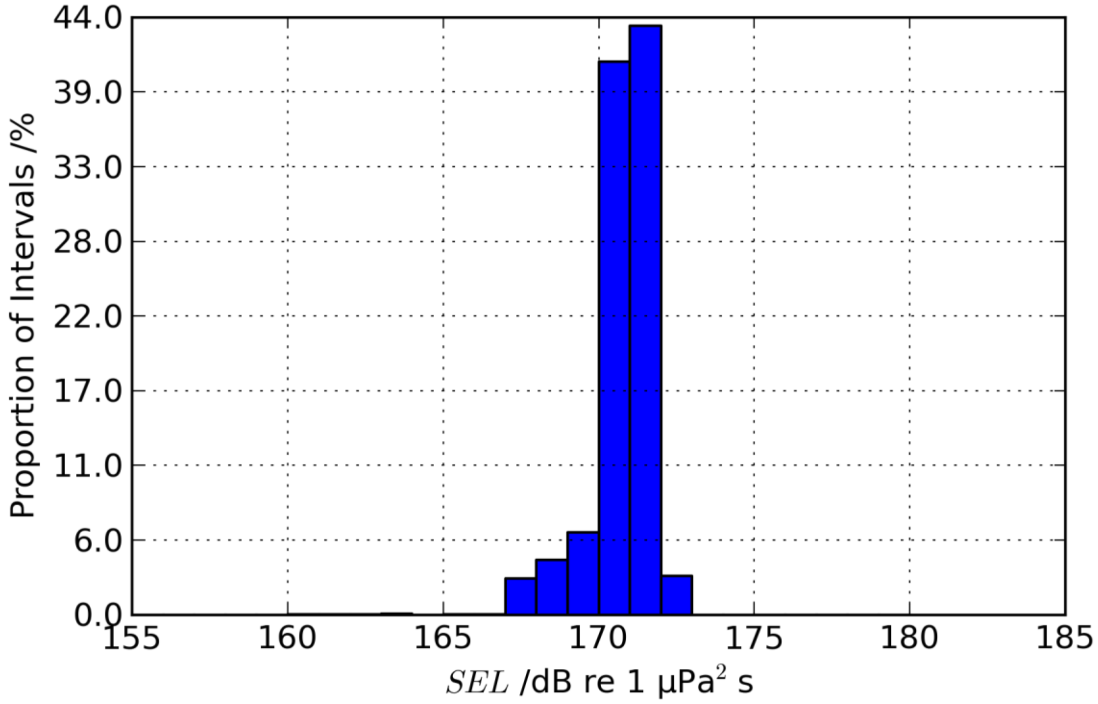
50.0
44.0
39.0
33.0
28.0
22.0
17.0
11.0
6.0
0.0
155
160
165
170
175
180
185
Proportion of Intervals /%
SEL /dB re 1 µPa² s

# EL42 MP1 10 m pile driving noise



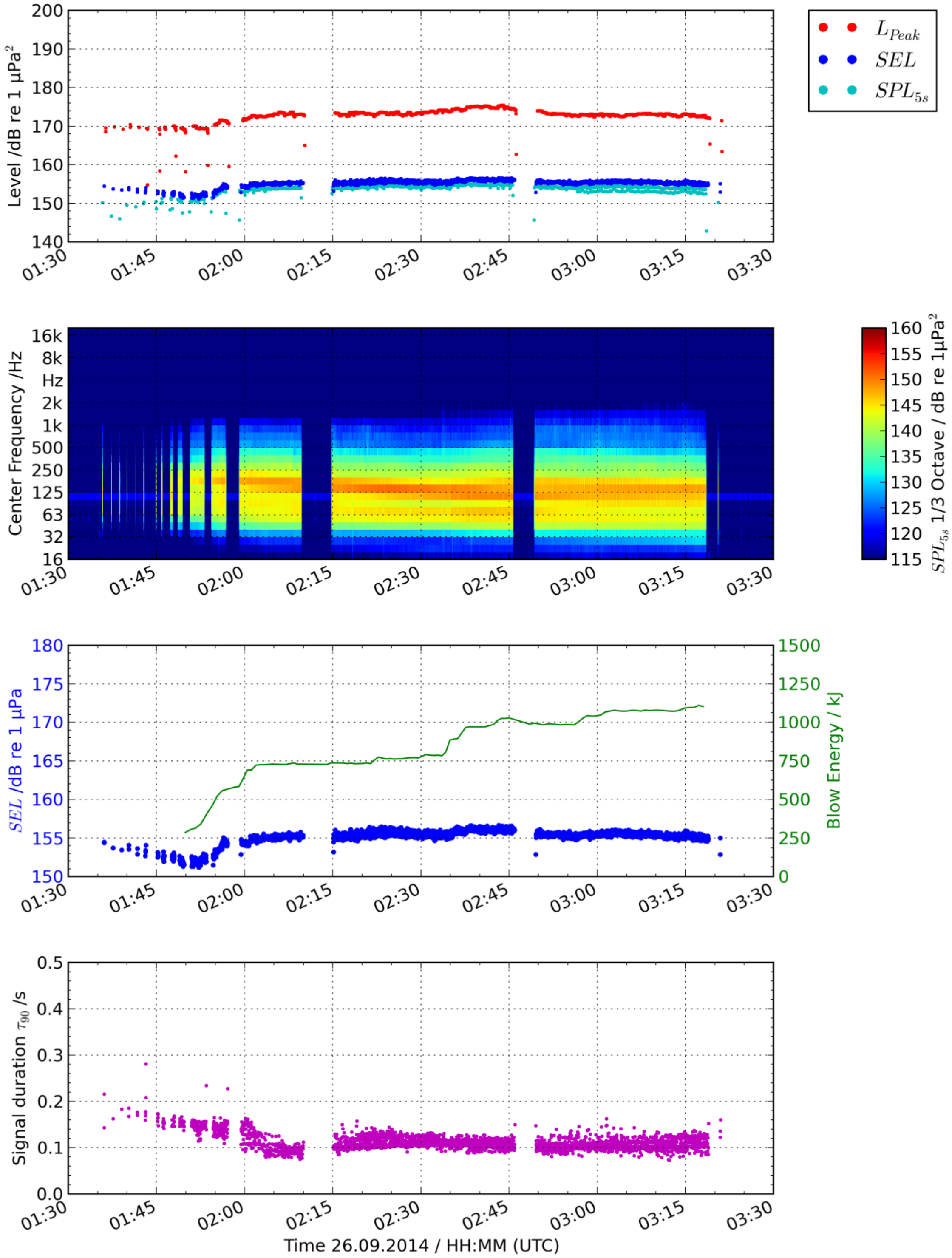


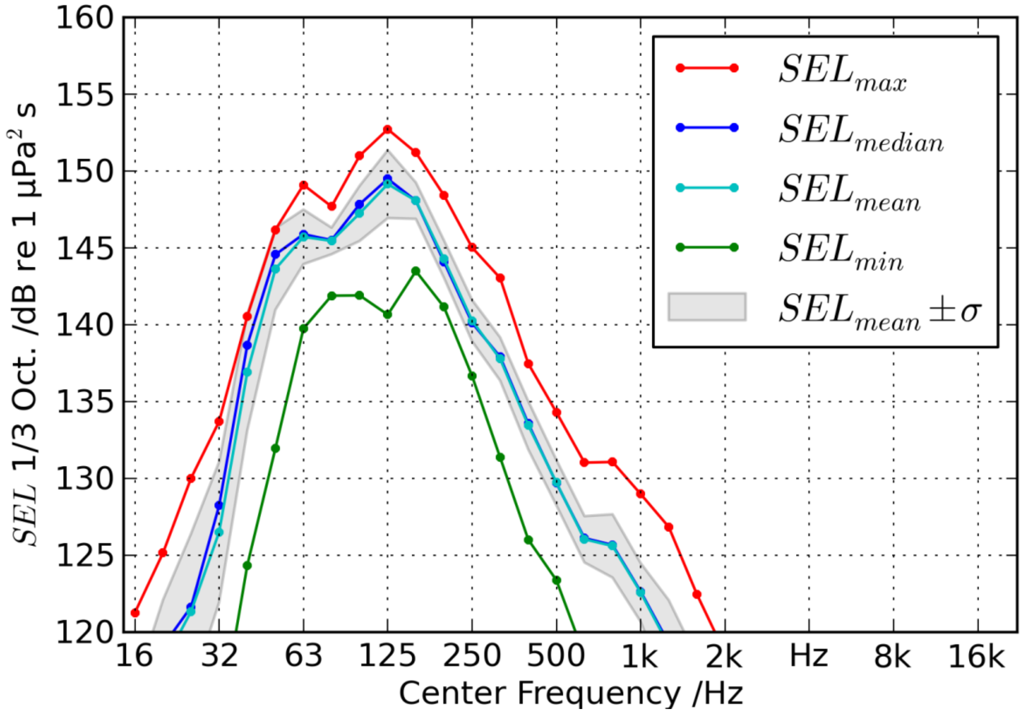
180
175
170
165
160
155
150
145
140
$SEL$ 1/3 Oct. /dB re 1 µPa² s
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center Frequency /Hz
$SEL_{max}$
$SEL_{median}$
$SEL_{mean}$
$SEL_{min}$
$SEL_{mean} \pm \sigma$

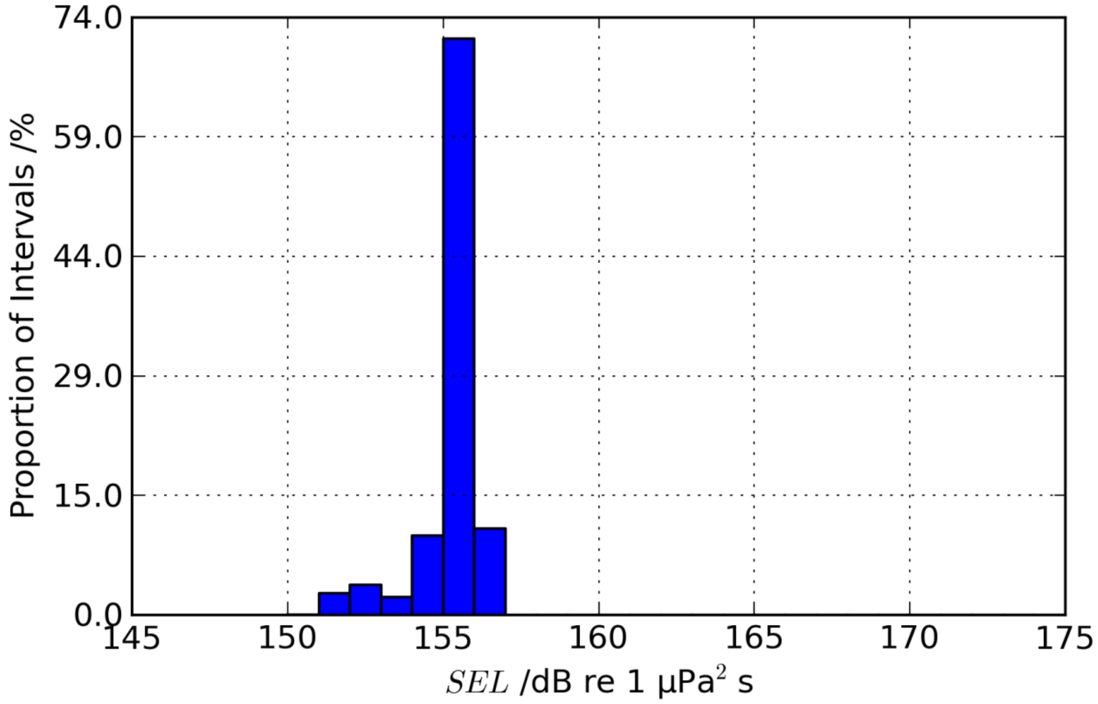



44.0
39.0
33.0
28.0
22.0
17.0
11.0
6.0
0.0
Proportion of Intervals /%
155
160
165
170
175
180
185
$SEL$ /dB re 1 µPa² s

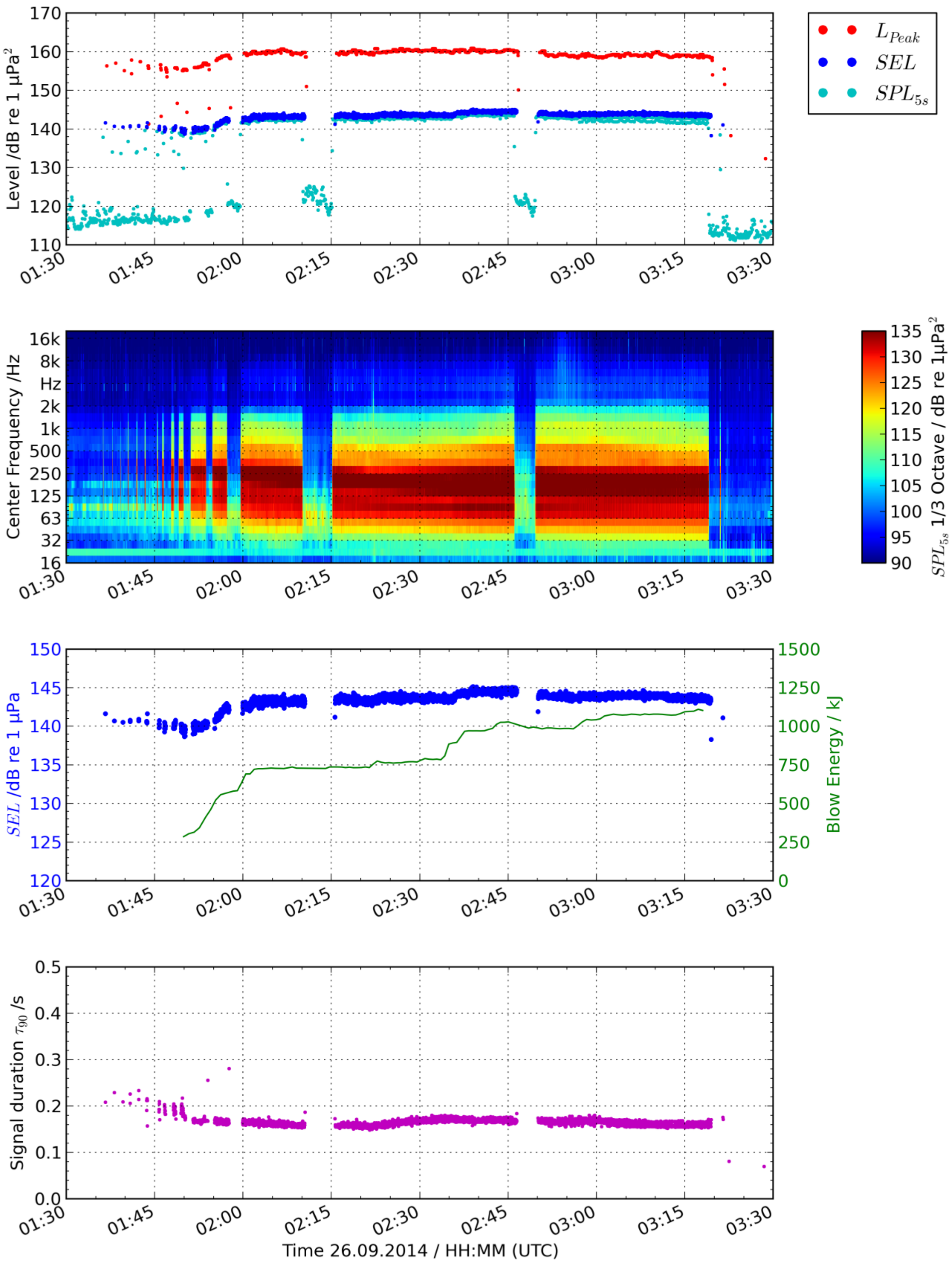
## EL42 MP2 2 m pile driving noise

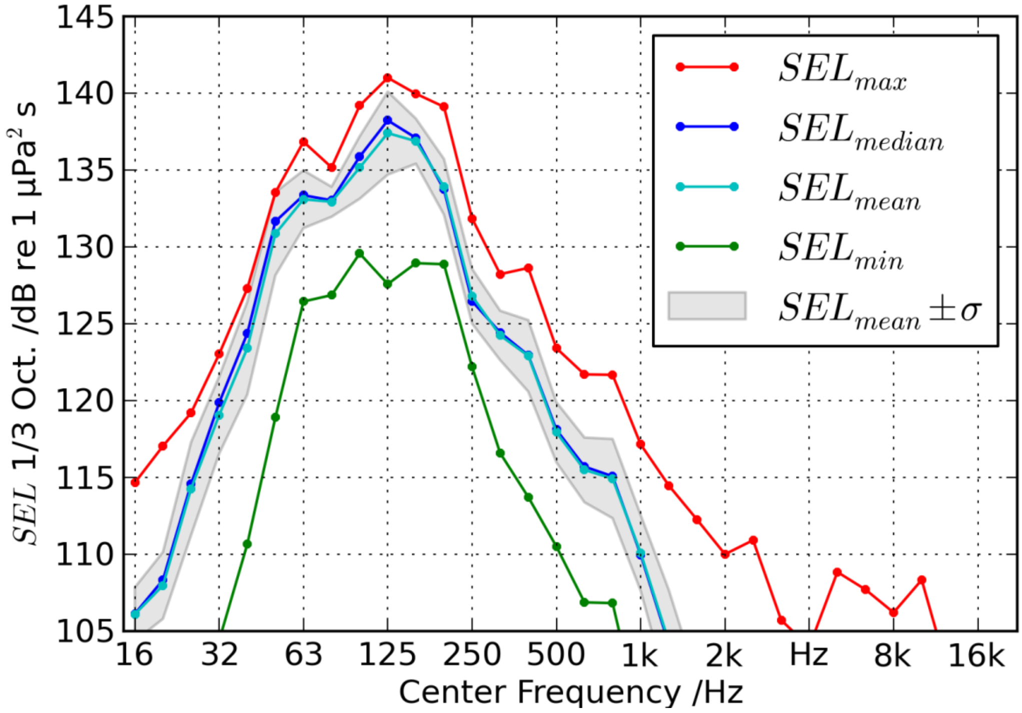


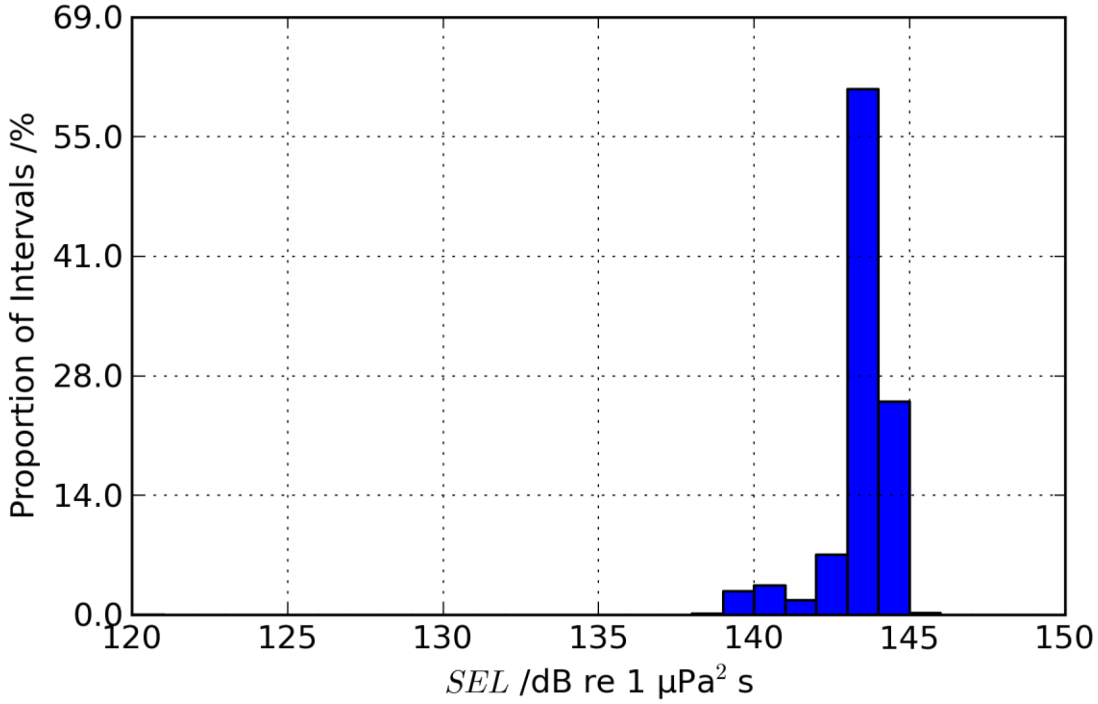

160
155
150
145
140
135
130
125
120
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center Frequency /Hz
$SEL$ 1/3 Oct. /dB re 1 µPa$^2$ s
$SEL_{max}$
$SEL_{median}$
$SEL_{mean}$
$SEL_{min}$
$SEL_{mean} \pm \sigma$


74.0
59.0
44.0
29.0
15.0
0.0
145
150
155
160
165
170
175
Proportion of Intervals /%
$SEL$ /dB re 1 µPa$^2$ s

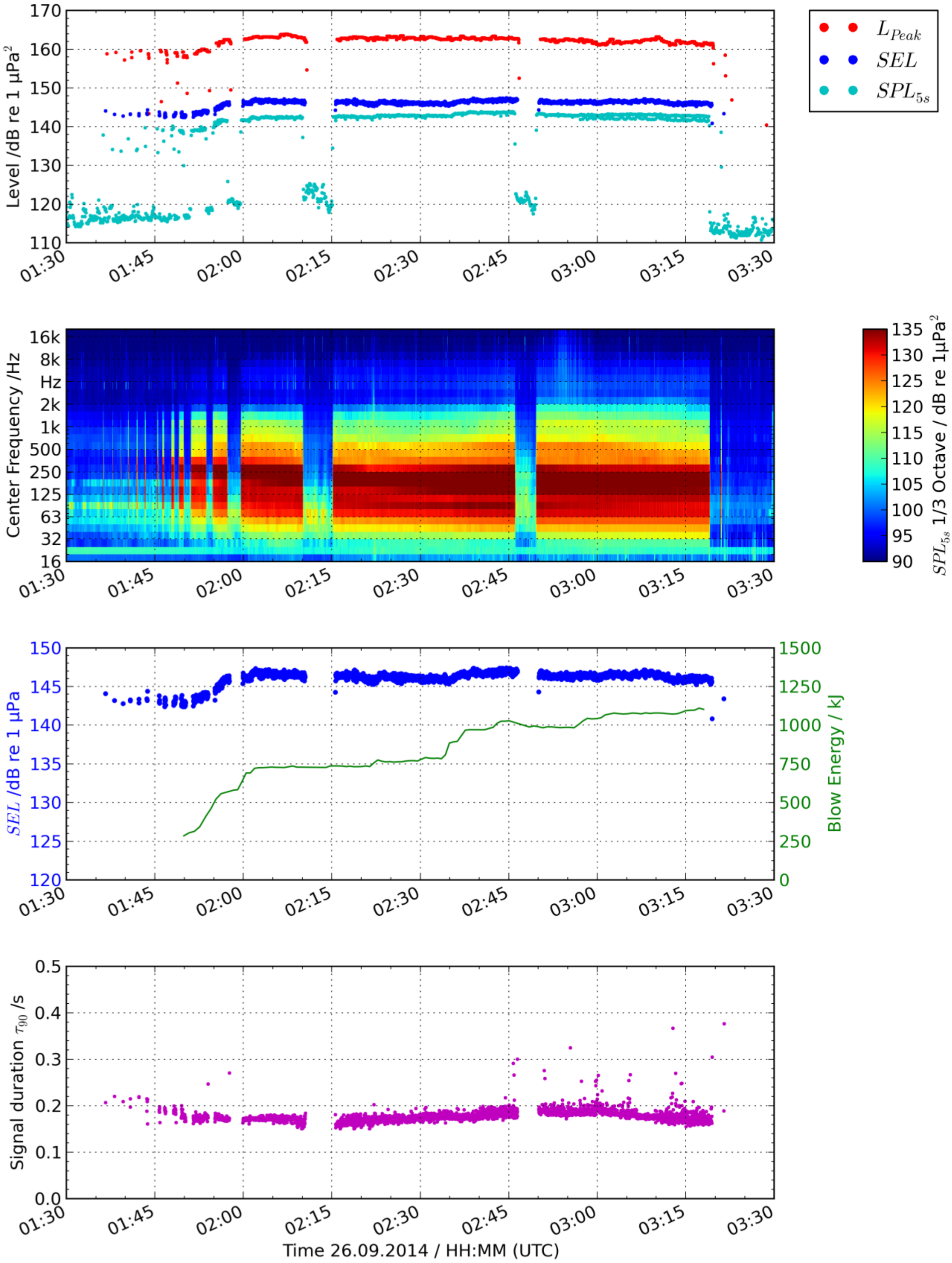
# EL42 MP3 2 m pile driving noise

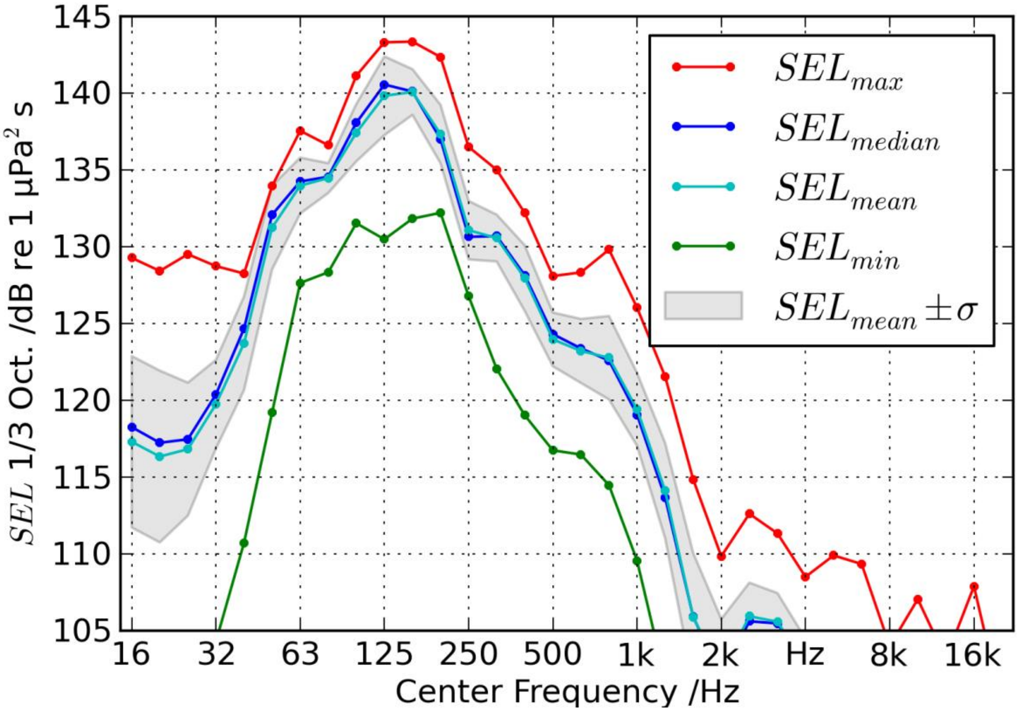



145
140
135
130
125
120
115
110
105
$SEL$ 1/3 Oct. /dB re 1 µPa² s
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center Frequency /Hz
$SEL_{max}$
$SEL_{median}$
$SEL_{mean}$
$SEL_{min}$
$SEL_{mean} \pm \sigma$

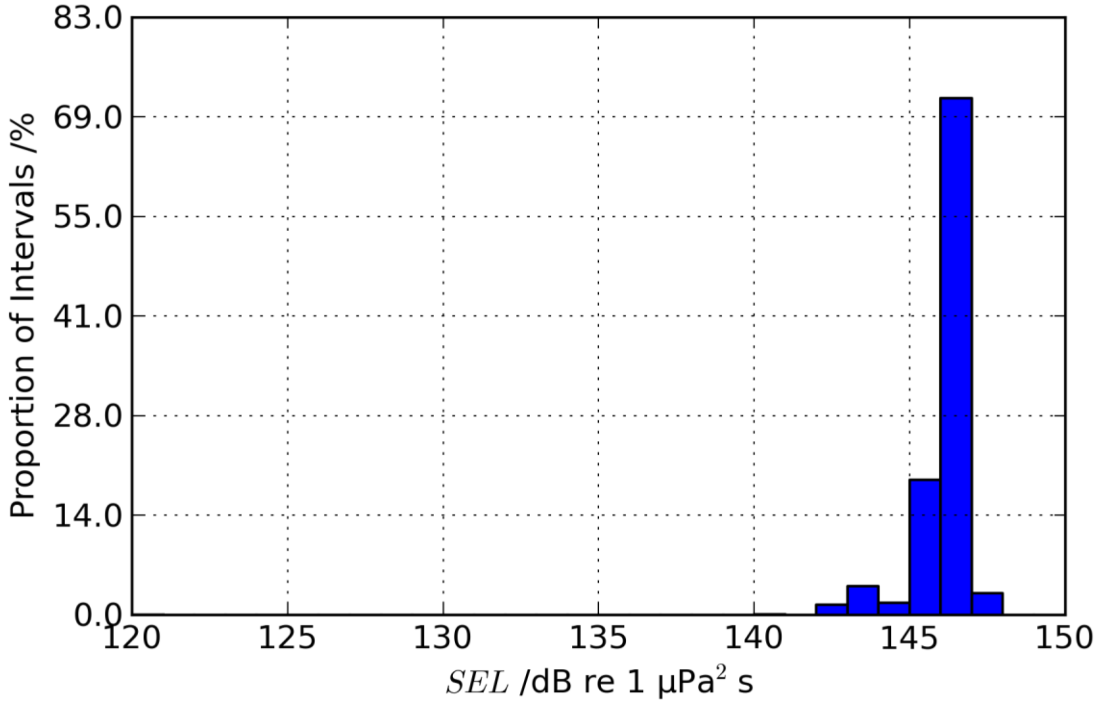

69.0
55.0
41.0
28.0
14.0
0.0
Proportion of Intervals /%
120
125
130
135
140
145
150
$SEL$ /dB re 1 µPa² s

# EL42 MP3 10 m pile driving noise



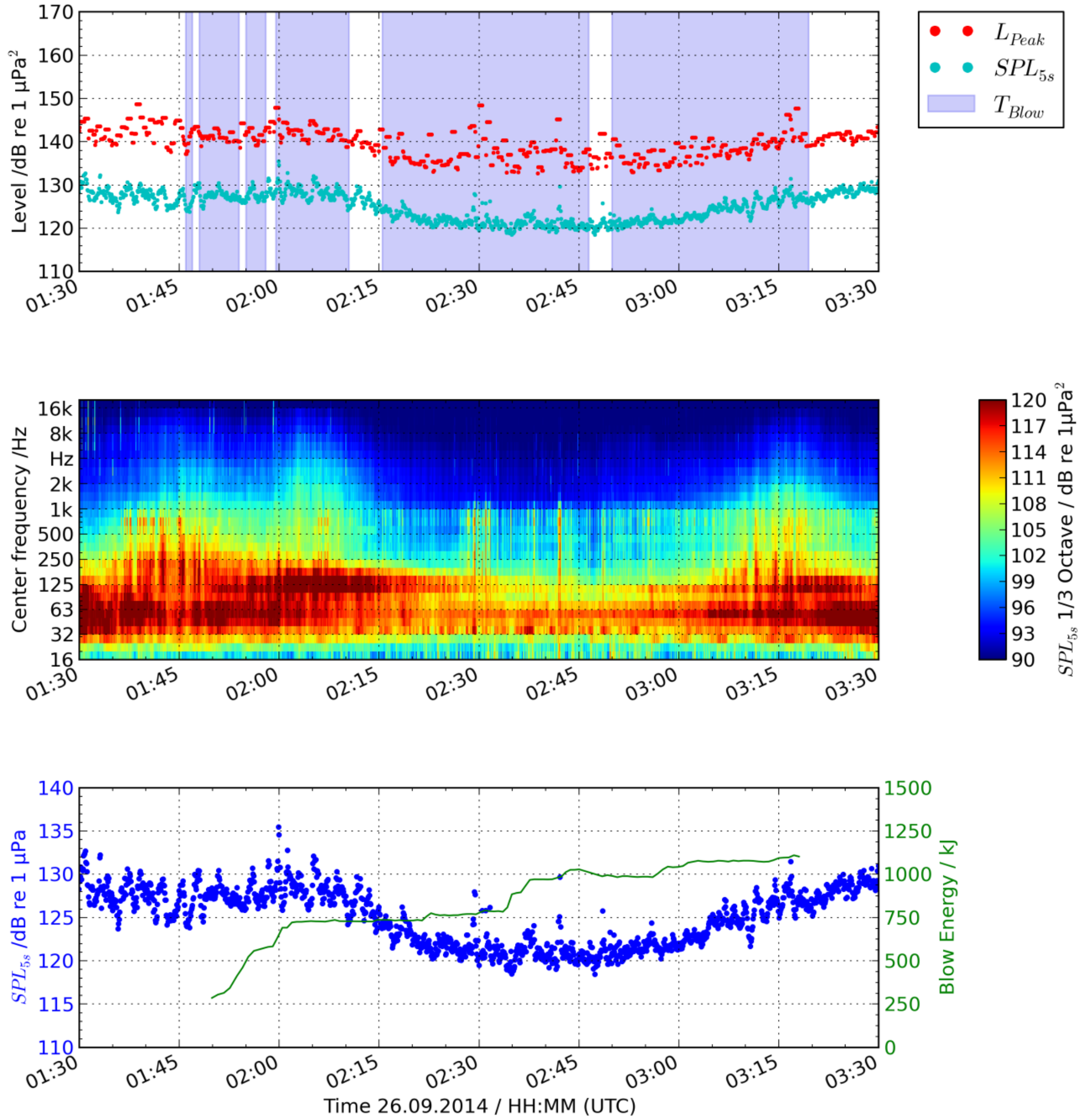


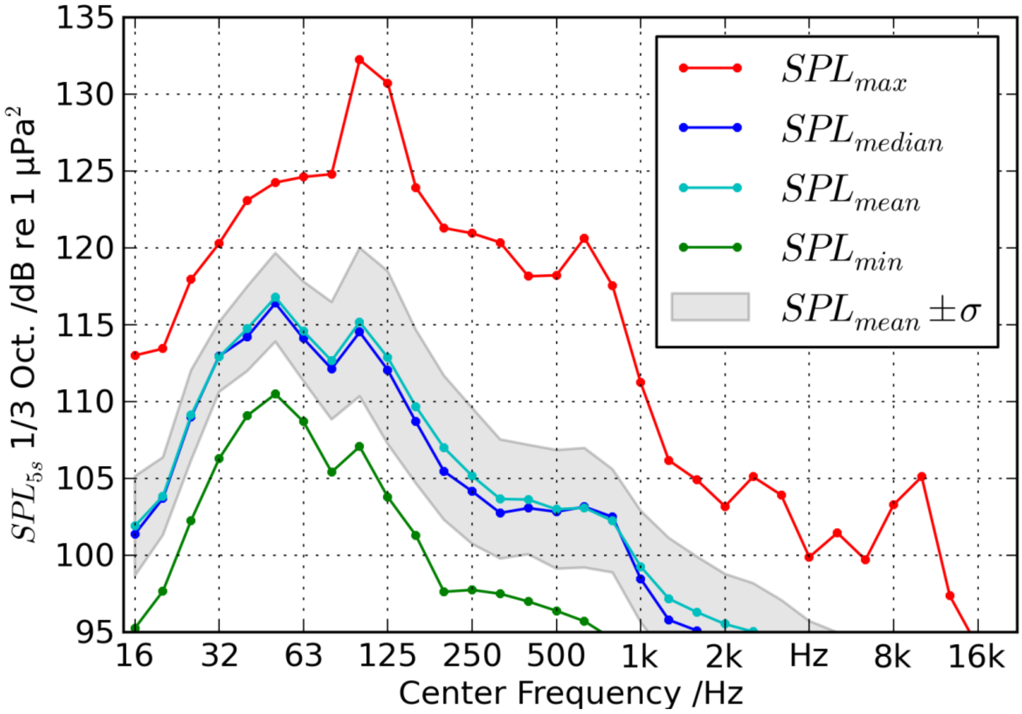
145
140
135
130
125
120
115
110
105
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center Frequency /Hz
$SEL$ 1/3 Oct. /dB re 1 µPa$^2$ s
$SEL_{max}$
$SEL_{median}$
$SEL_{mean}$
$SEL_{min}$
$SEL_{mean} \pm \sigma$

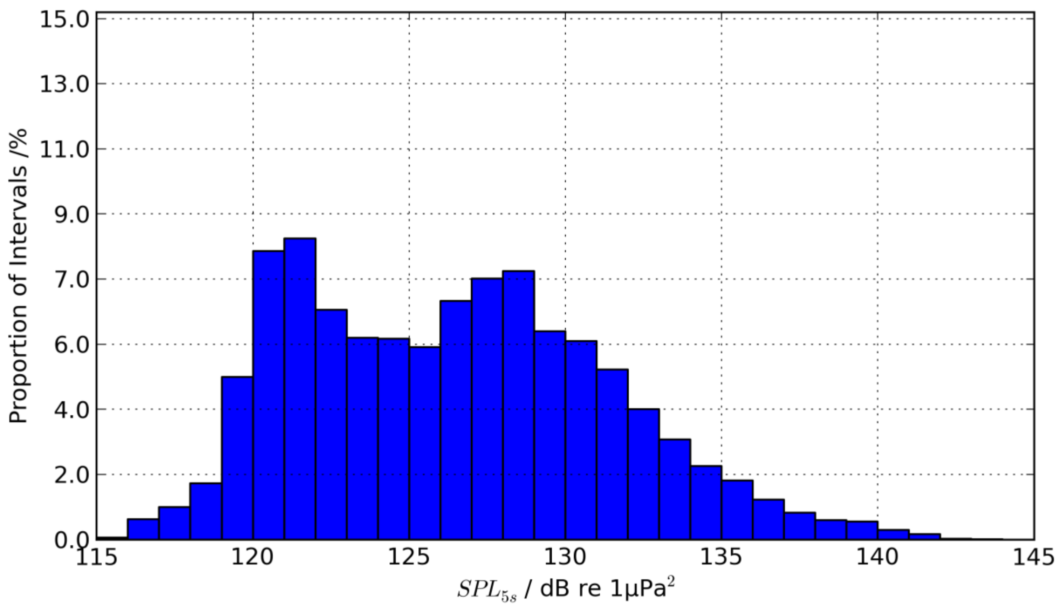



83.0
69.0
55.0
41.0
28.0
14.0
0.0
120
125
130
135
140
145
150
Proportion of Intervals /%
$SEL$ /dB re 1 µPa$^2$ s

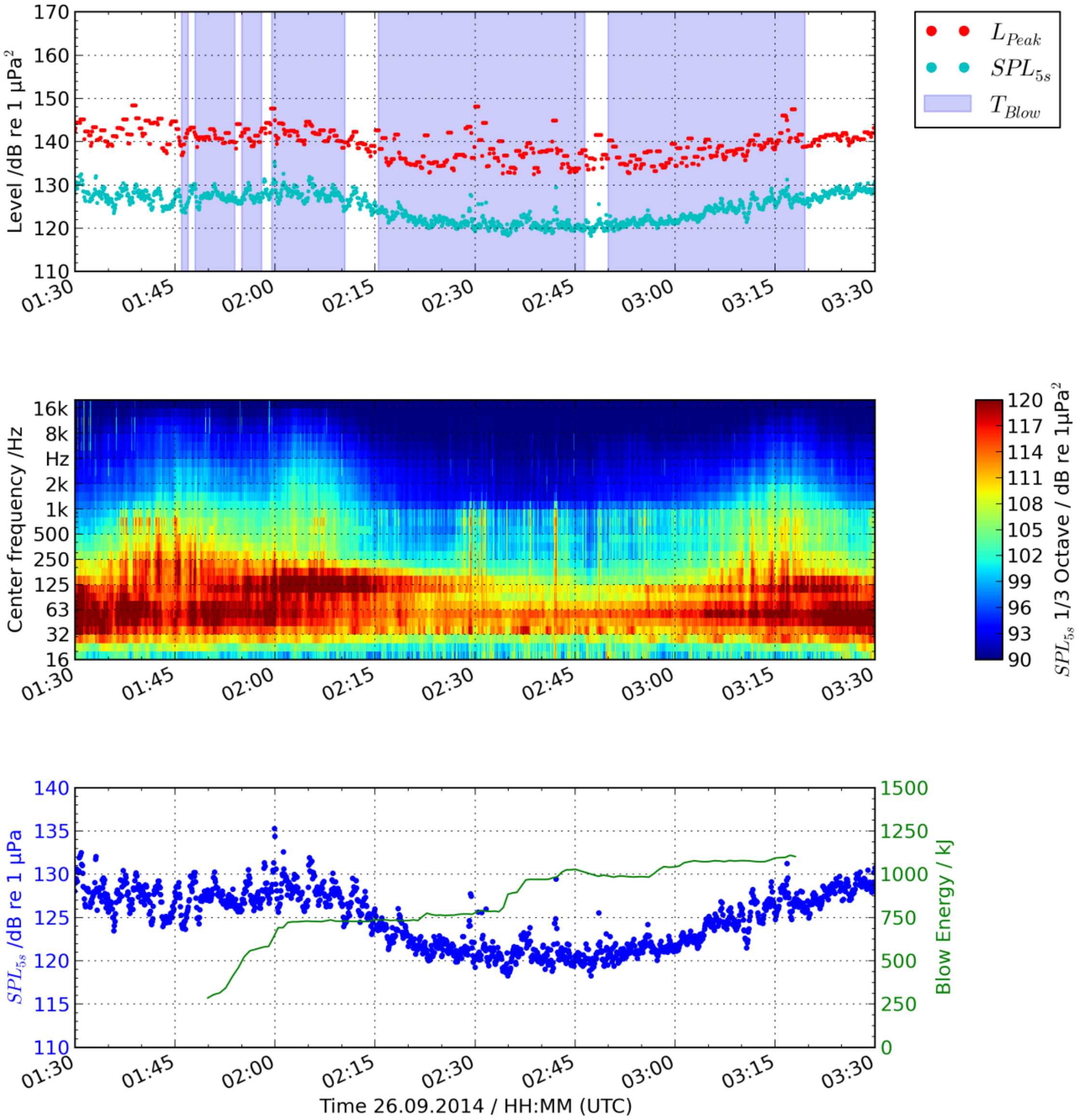
# EL42 MP4 2 m pile driving noise

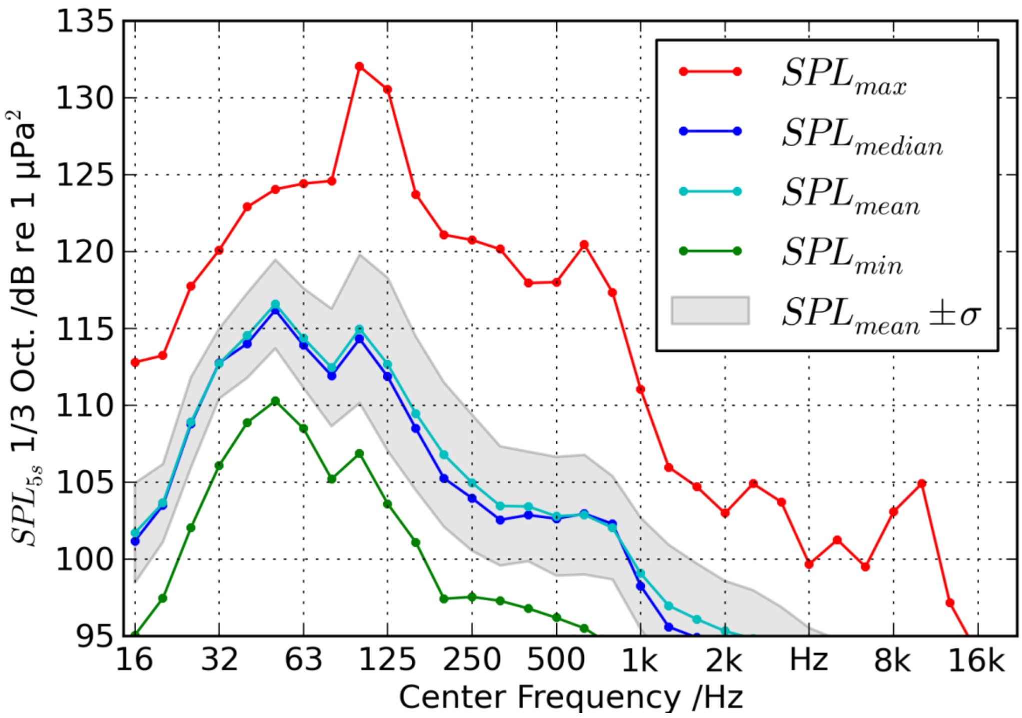



$SPL_{max}$
$SPL_{median}$
$SPL_{mean}$
$SPL_{min}$
$SPL_{mean} \pm \sigma$
$SPL_{5s}$ 1/3 Oct. /dB re 1 µPa$^2$
135
130
125
120
115
110
105
100
95
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center Frequency /Hz

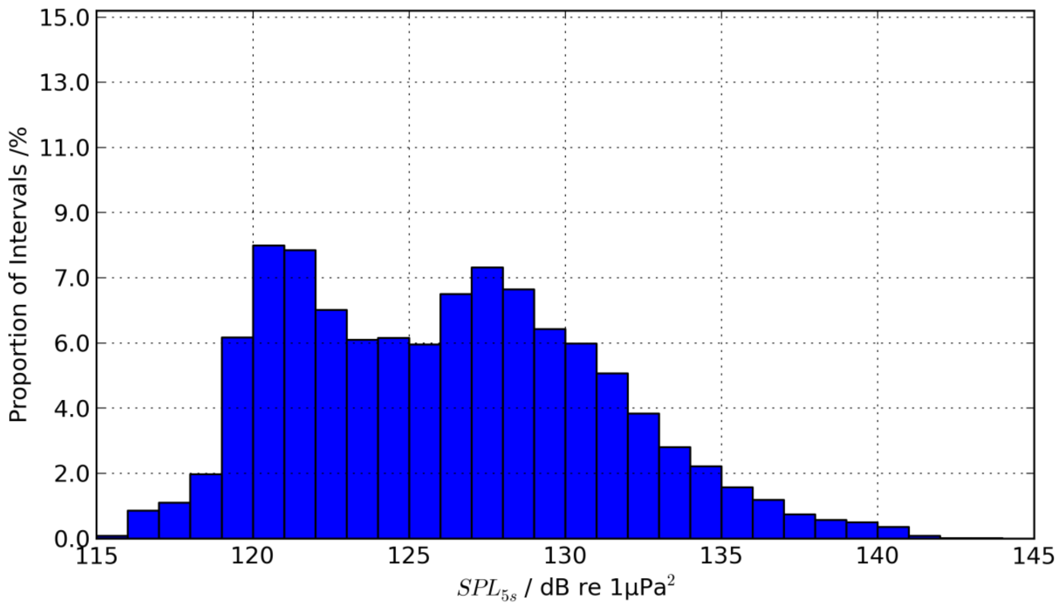

Proportion of Intervals /%
15.0
13.0
11.0
9.0
7.0
6.0
4.0
2.0
0.0
115
120
125
130
135
140
145
$SPL_{5s}$ / dB re 1µPa$^2$

# EL42 MP4 10 m pile driving noise





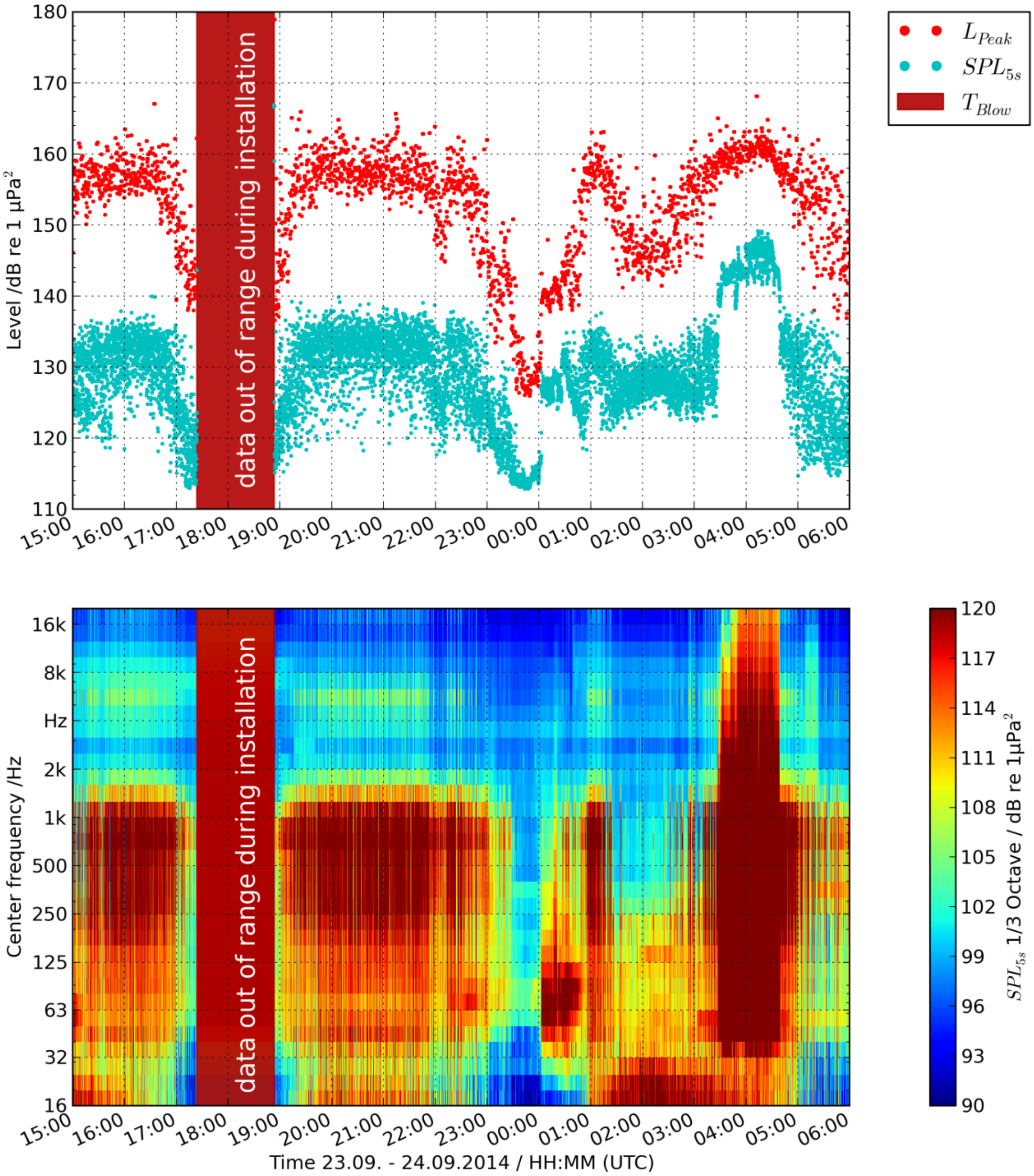
$SPL_{max}$
$SPL_{median}$
$SPL_{mean}$
$SPL_{min}$
$SPL_{mean} \pm \sigma$
$SPL_{5s}$ 1/3 Oct. /dB re 1 µPa²
Center Frequency /Hz
16
32
63
125
250
500
1k
2k
Hz
8k
16k
95
100
105
110
115
120
125
130
135

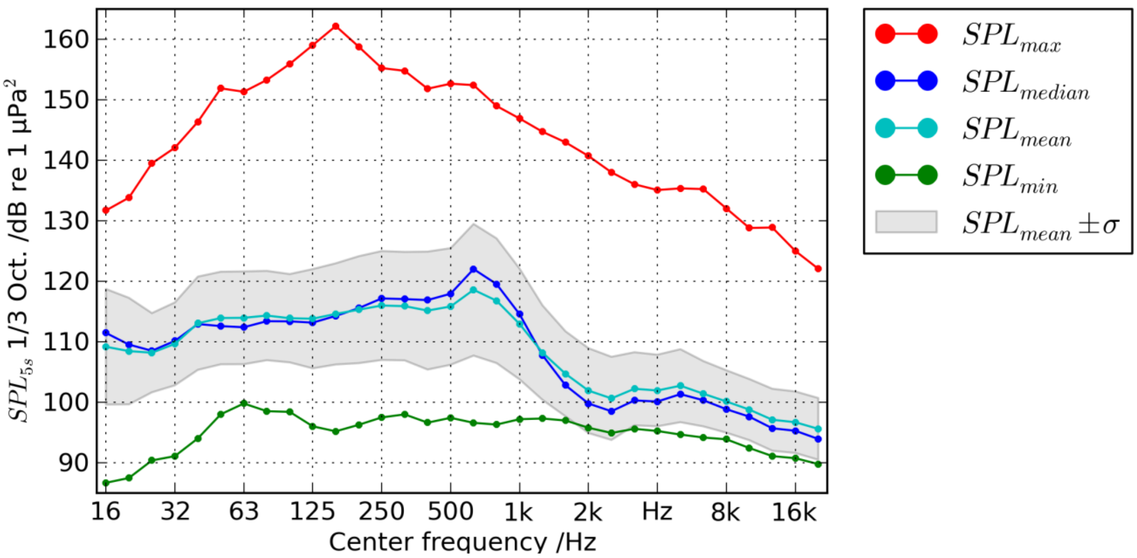



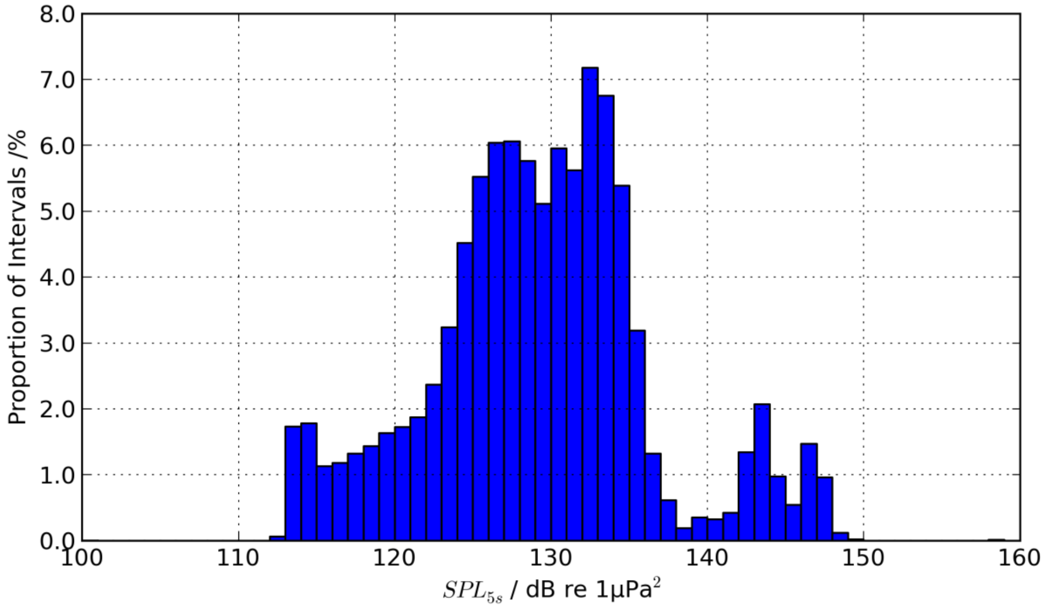
Proportion of Intervals /%
$SPL_{5s}$ / dB re 1µPa²
0.0
2.0
4.0
6.0
7.0
9.0
11.0
13.0
15.0
115
120
125
130
135
140
145

## A1.3 Ambient Noise for EL39

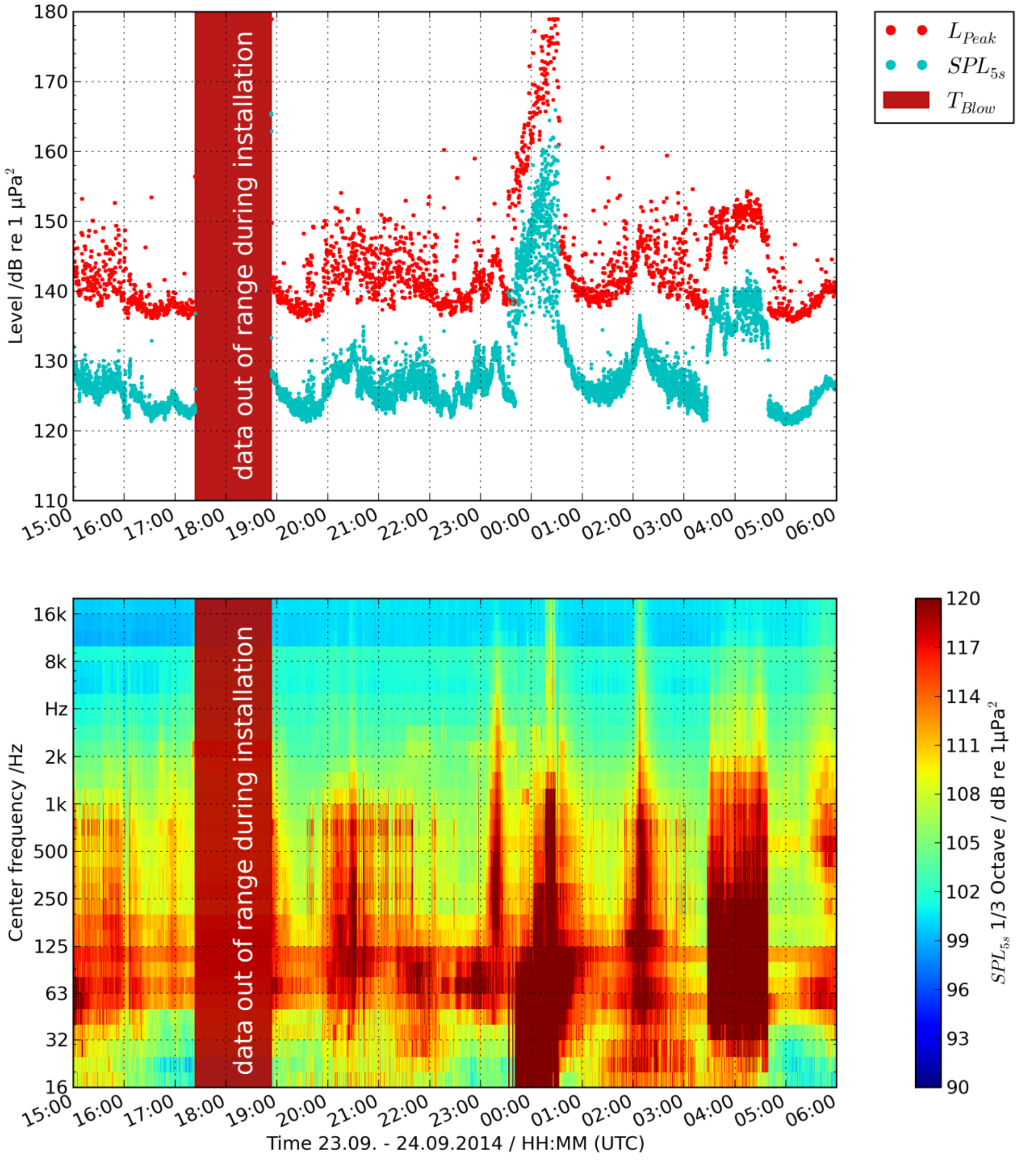
### EL39 MP1 2m ambient noise

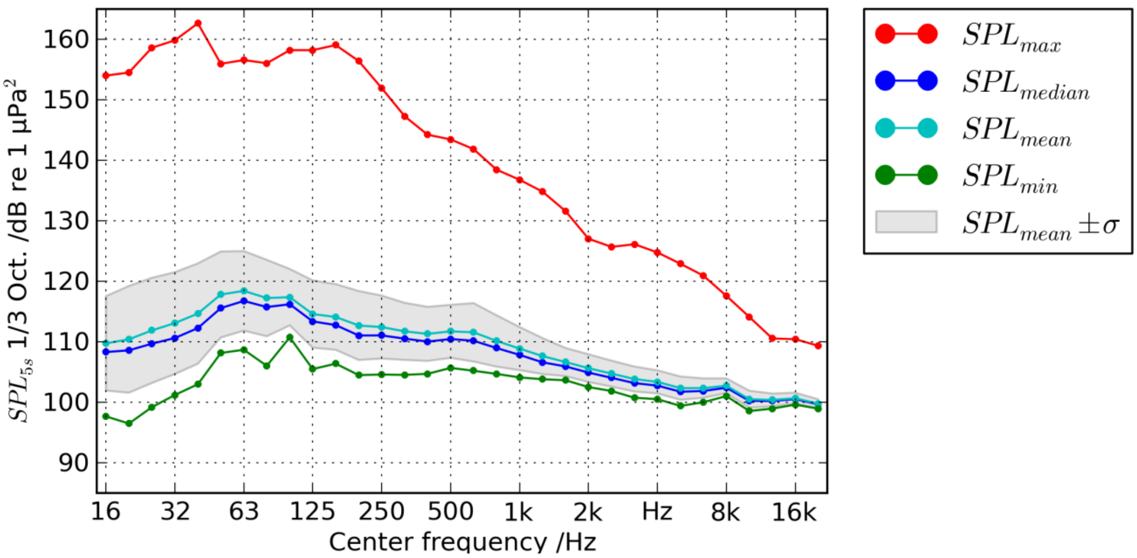



$SPL_{5s}$ 1/3 Oct. /dB re 1 µPa$^2$
Center frequency /Hz
16
32
63
125
250
500
1k
2k
Hz
8k
16k
$SPL_{max}$
$SPL_{median}$
$SPL_{mean}$
$SPL_{min}$
$SPL_{mean} \pm \sigma$

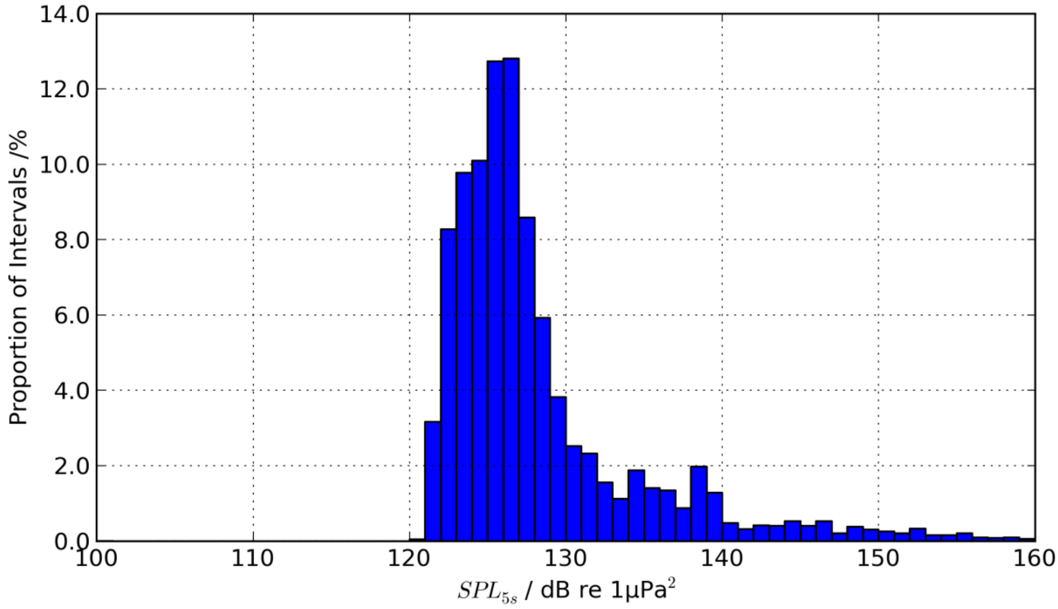

Proportion of Intervals /%
$SPL_{5s}$ / dB re 1µPa$^2$

# EL 39 MP1 10 m ambient noise



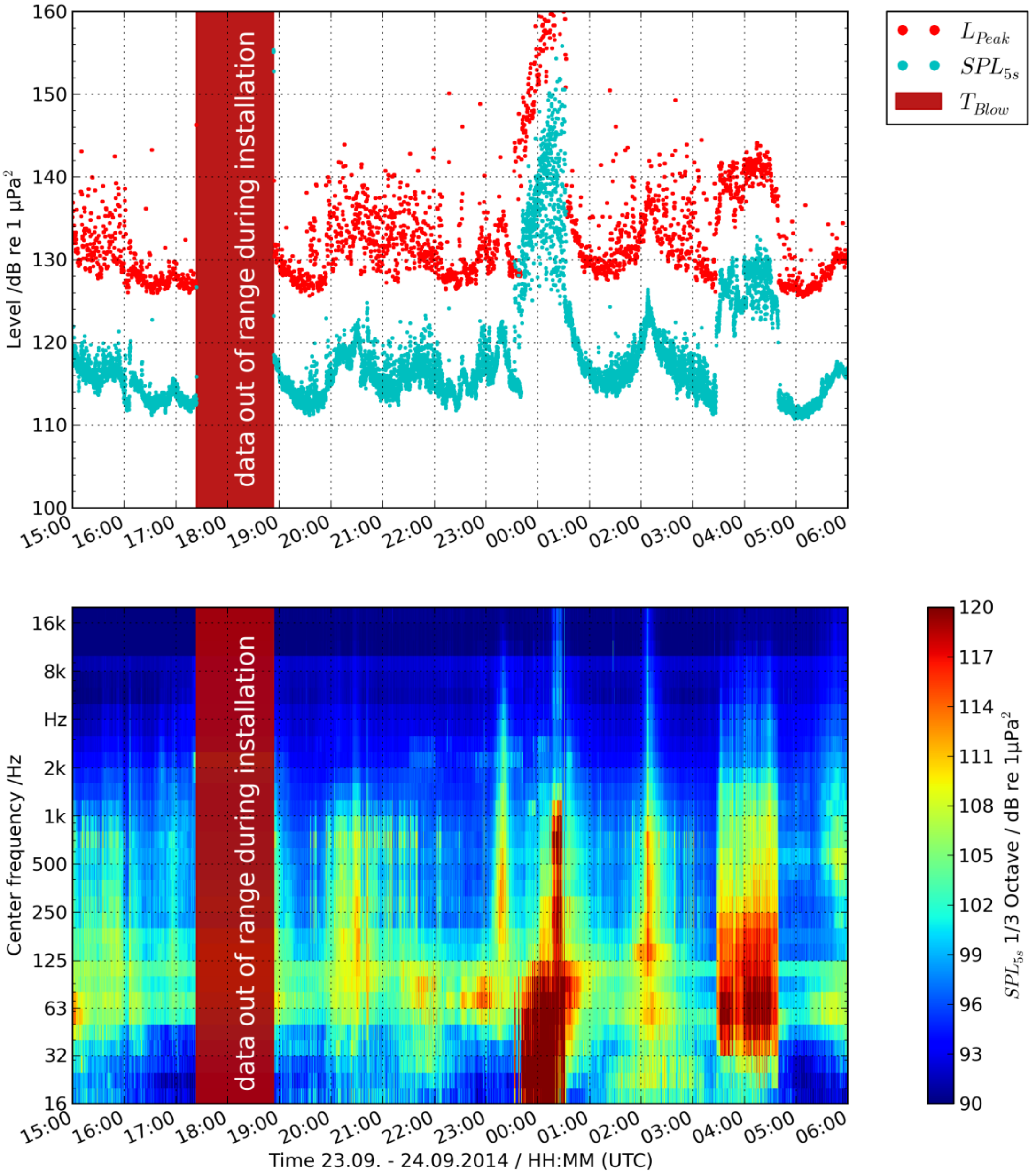


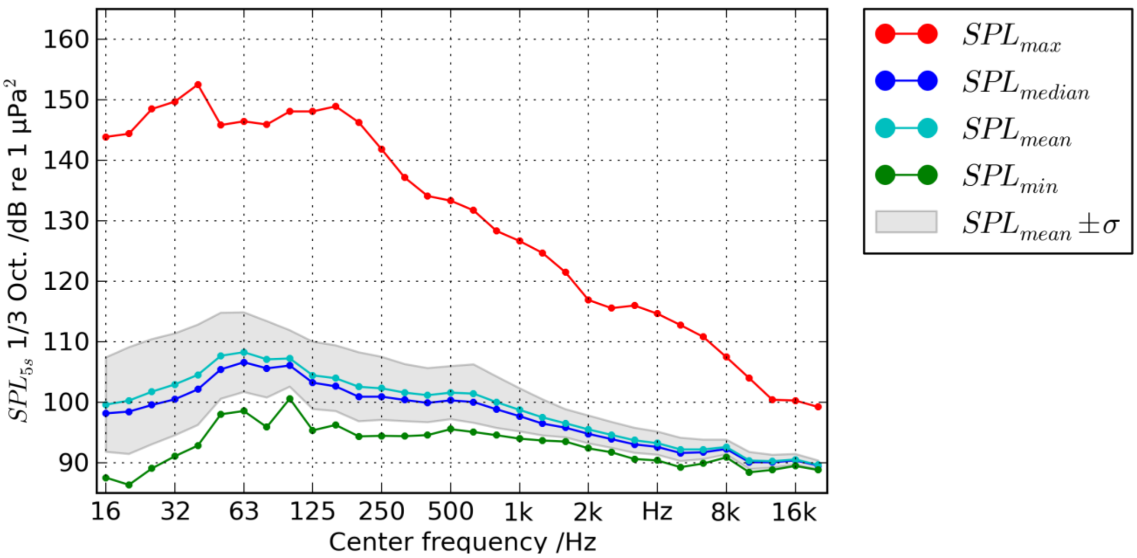
$SPL_{5s}$ 1/3 Oct. /dB re 1 µPa²
Center frequency /Hz
16
32
63
125
250
500
1k
2k
Hz
8k
16k
90
100
110
120
130
140
150
160
$SPL_{max}$
$SPL_{median}$
$SPL_{mean}$
$SPL_{min}$
$SPL_{mean} \pm \sigma$

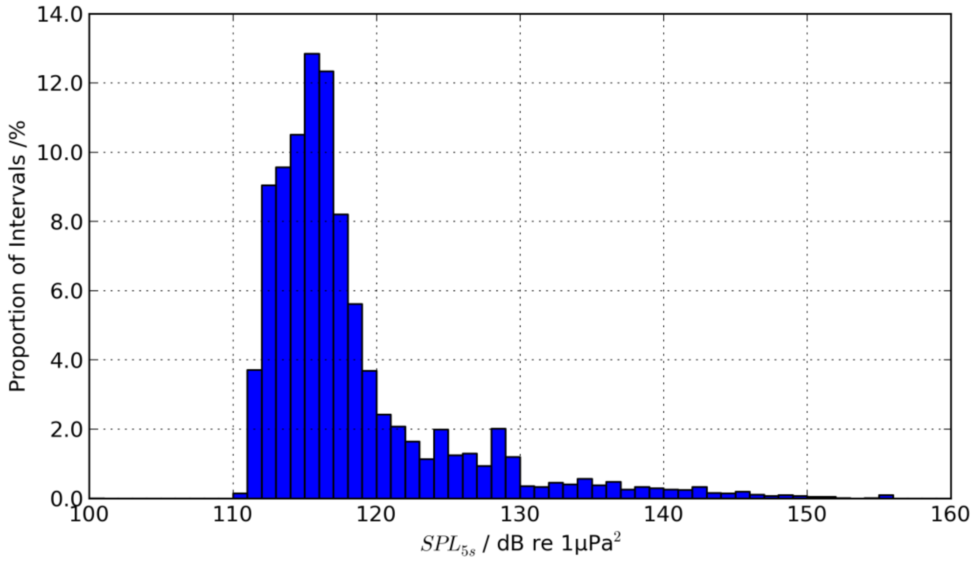



Proportion of Intervals /%
$SPL_{5s}$ / dB re 1µPa²
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
100
110
120
130
140
150
160

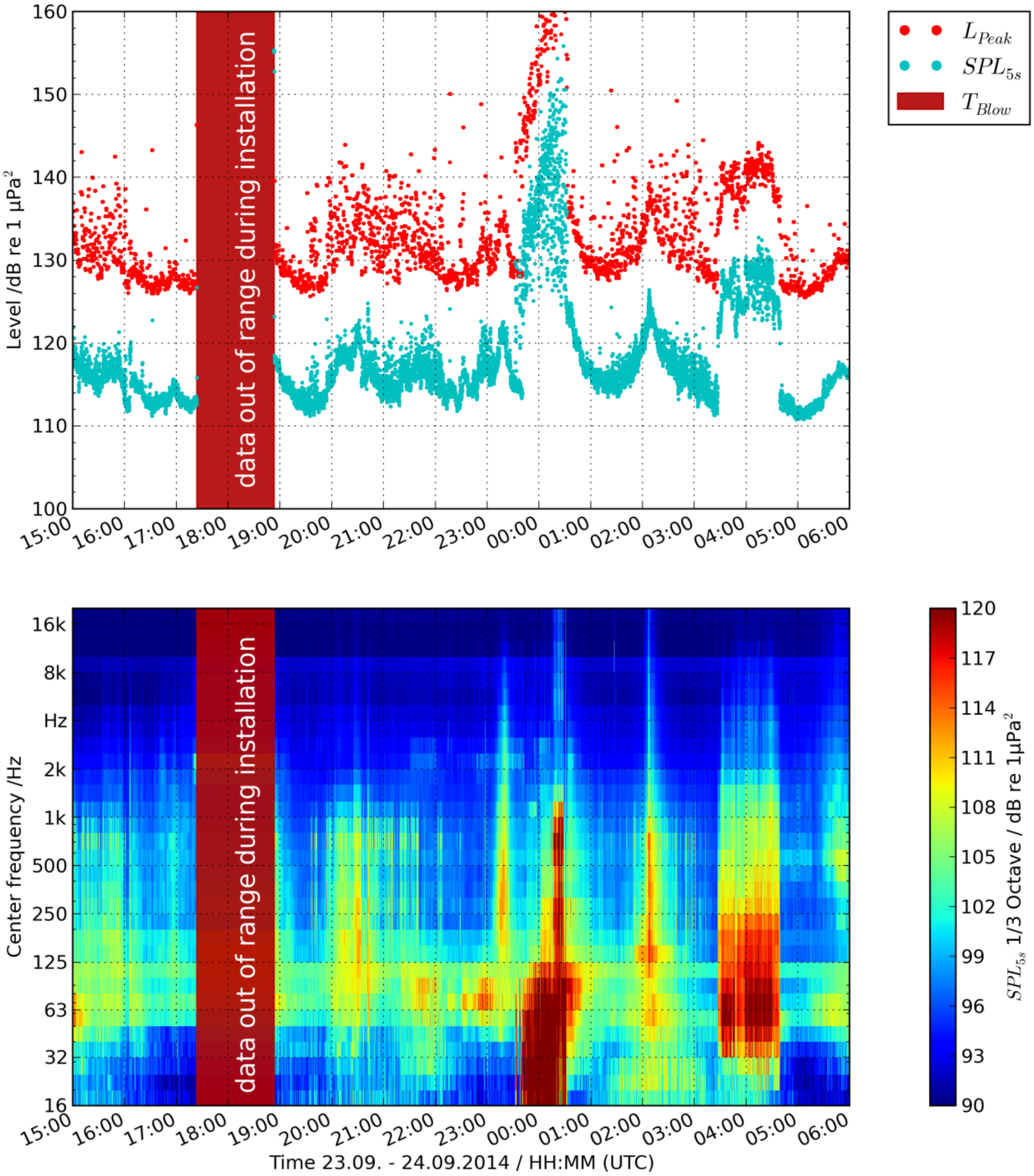
## EL 39 MP2 2 m ambient noise

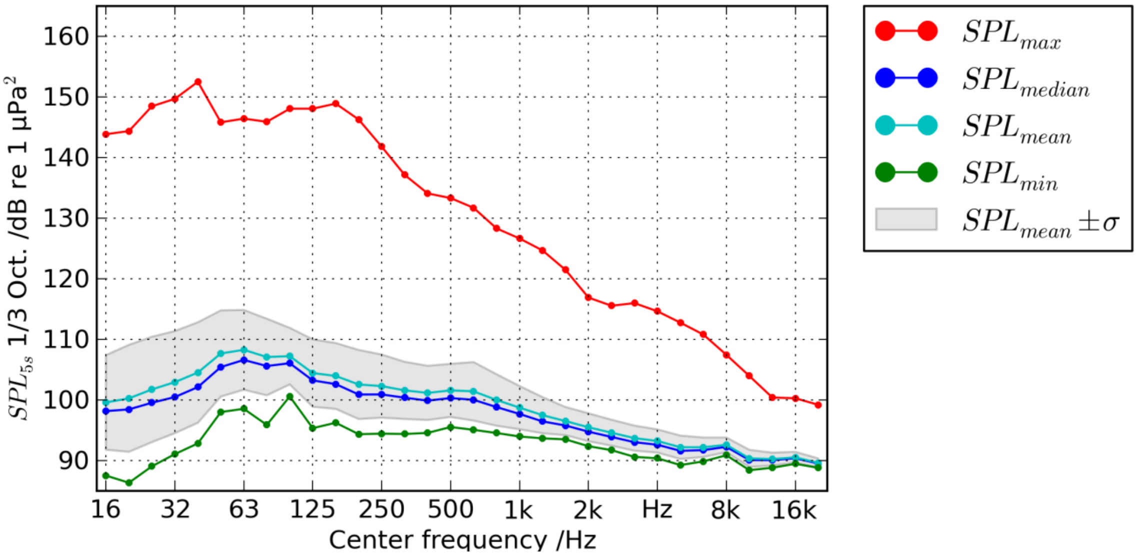



160
150
140
130
120
110
100
90
$SPL_{5s}$ 1/3 Oct. /dB re 1 µPa$^2$
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center frequency /Hz
$SPL_{max}$
$SPL_{median}$
$SPL_{mean}$
$SPL_{min}$
$SPL_{mean} \pm \sigma$

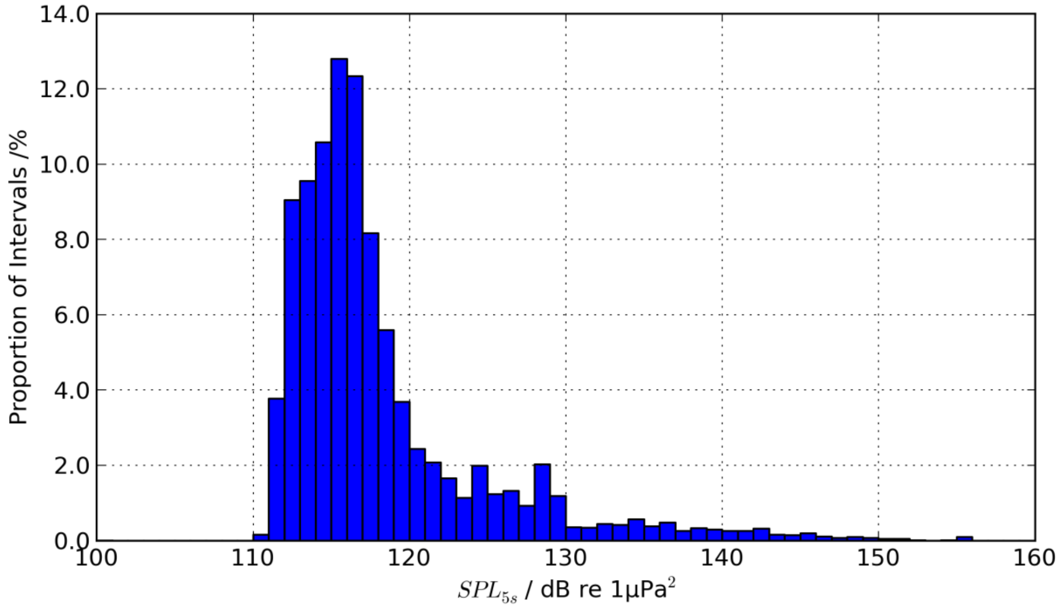

14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Proportion of Intervals /%
100
110
120
130
140
150
160
$SPL_{5s}$ / dB re 1µPa$^2$

## EL 39 MP2 10 m ambient noise



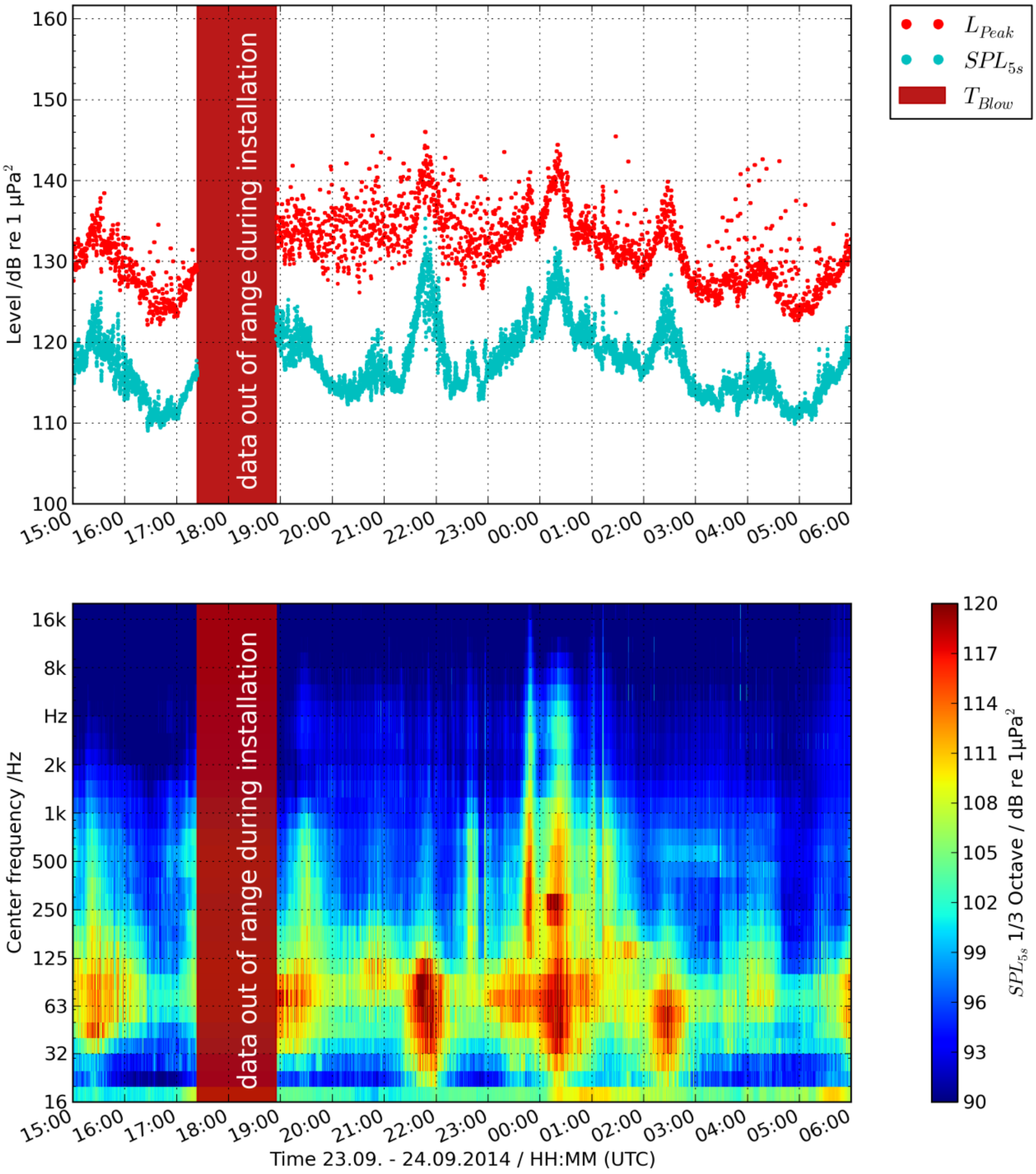


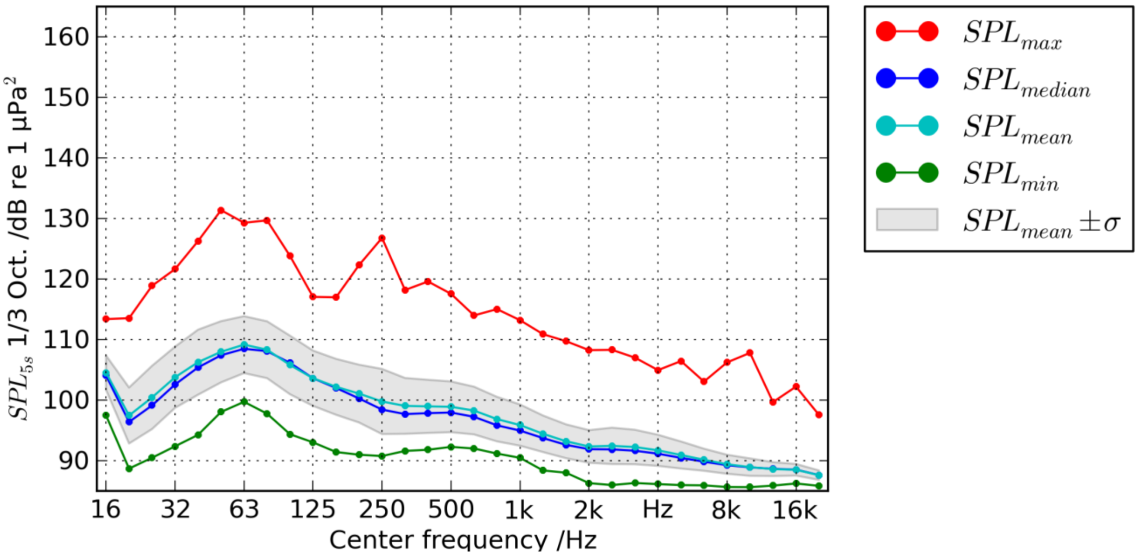
160
150
140
130
120
110
100
90
$SPL_{5s}$ 1/3 Oct. /dB re 1 µPa$^2$
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center frequency /Hz
$SPL_{max}$
$SPL_{median}$
$SPL_{mean}$
$SPL_{min}$
$SPL_{mean} \pm \sigma$

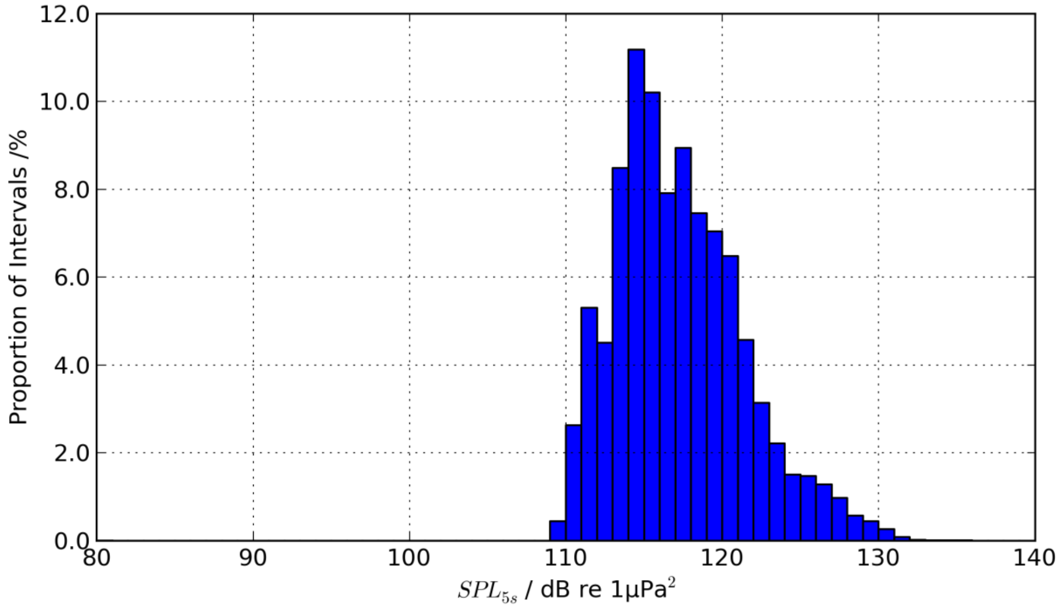
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Proportion of Intervals /%
100
110
120
130
140
150
160
$SPL_{5s}$ / dB re 1µPa$^2$

## EL 39 MP3 2 m ambient noise



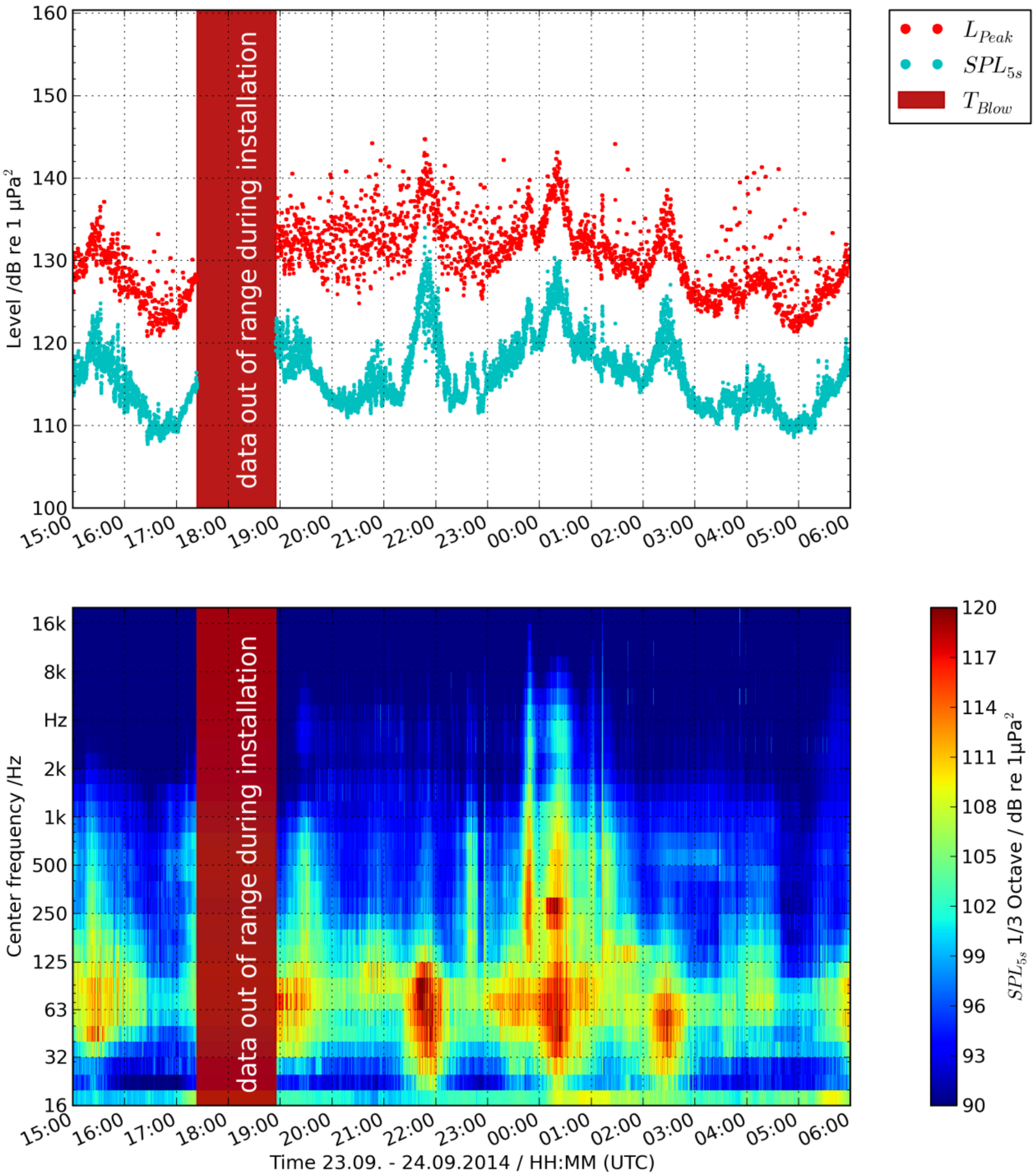


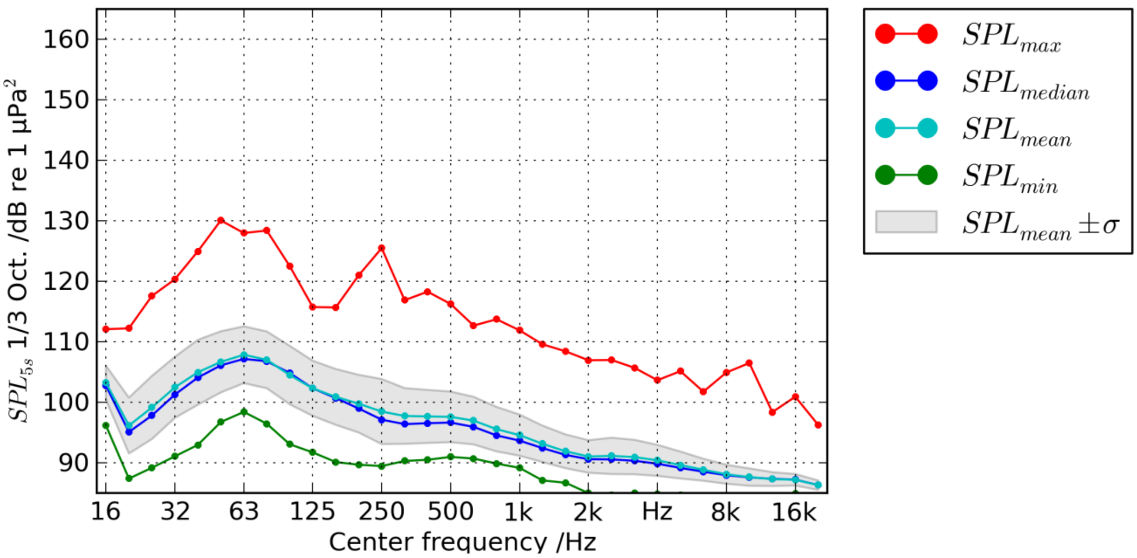
160
150
140
130
120
110
100
90
$SPL_{5s}$ 1/3 Oct. /dB re 1 µPa$^2$
16 32 63 125 250 500 1k 2k Hz 8k 16k
Center frequency /Hz
$SPL_{max}$
$SPL_{median}$
$SPL_{mean}$
$SPL_{min}$
$SPL_{mean} \pm \sigma$

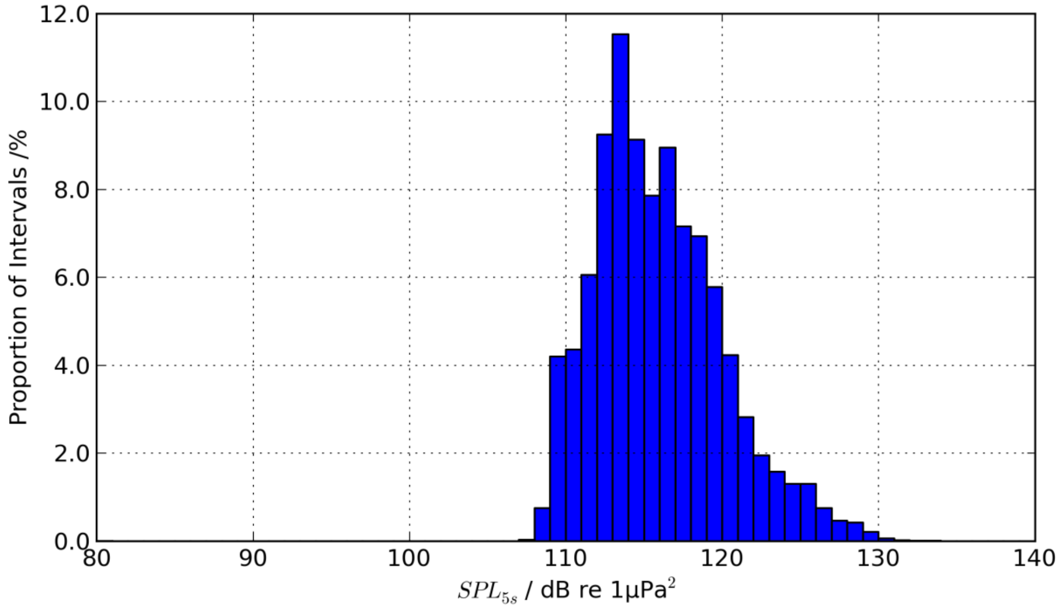
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Proportion of Intervals /%
80 90 100 110 120 130 140
$SPL_{5s}$ / dB re 1µPa$^2$

# EL 39 MP3 10 m ambient noise



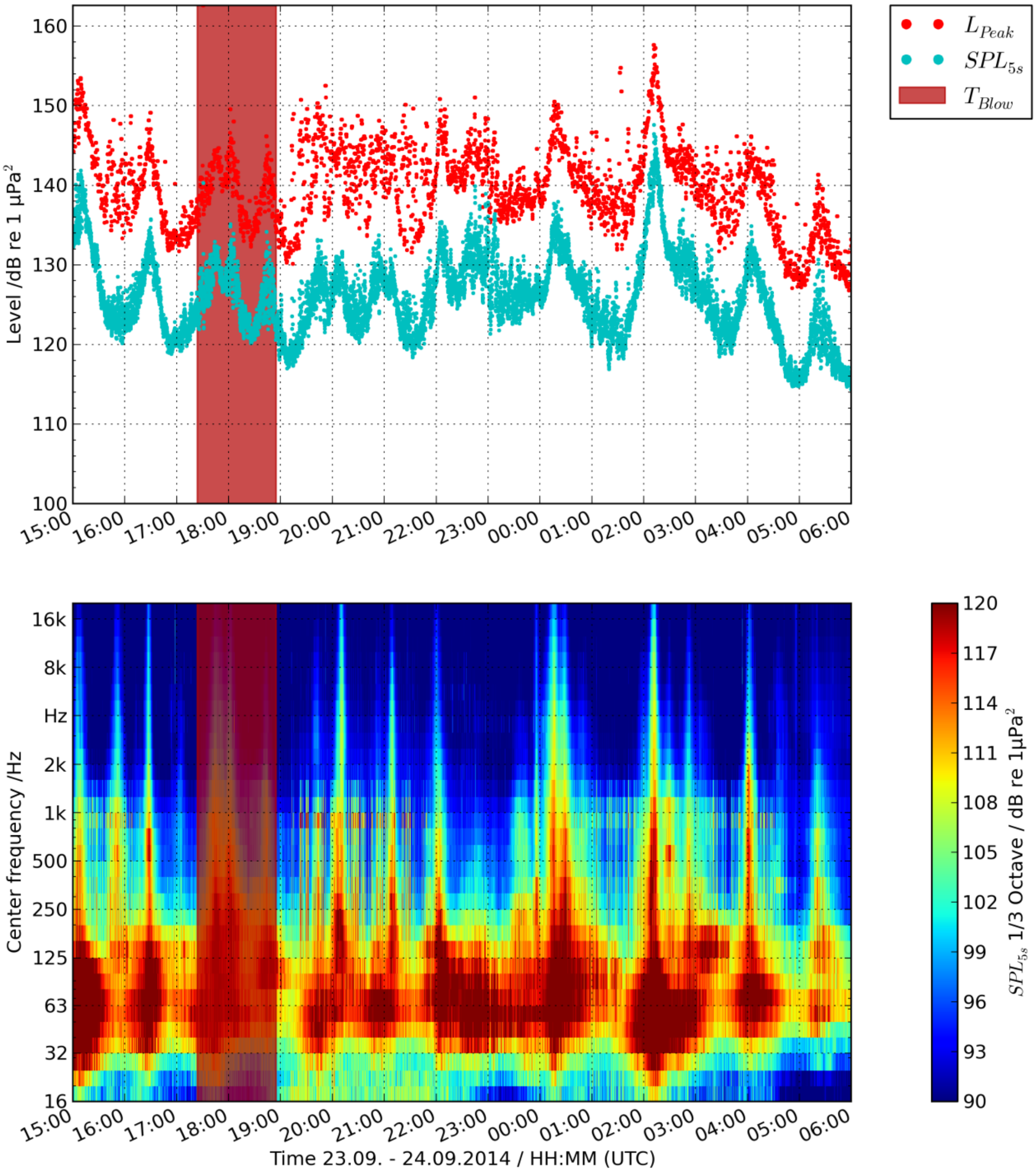


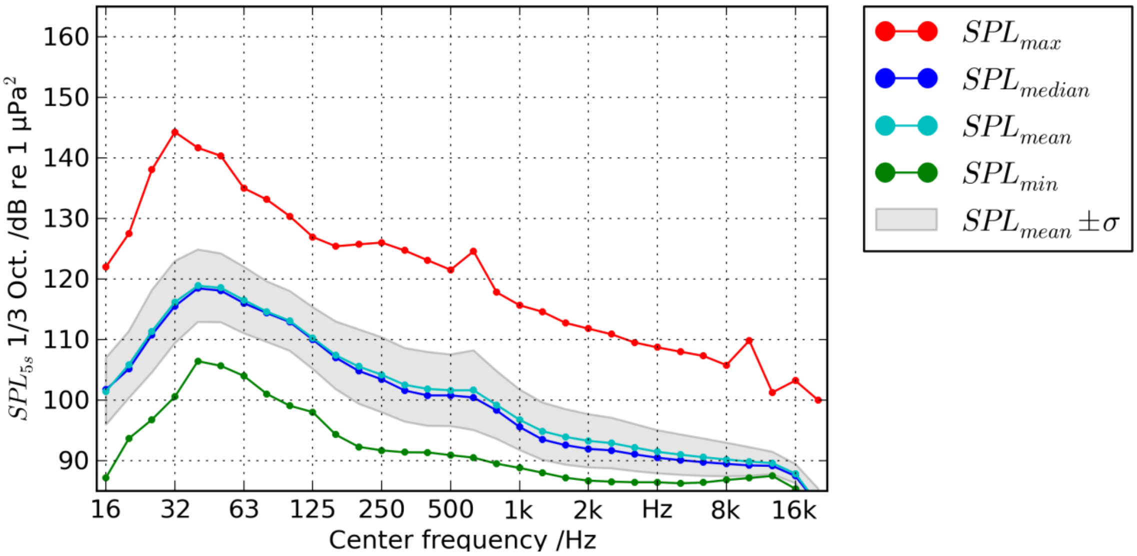
$SPL_{max}$
$SPL_{median}$
$SPL_{mean}$
$SPL_{min}$
$SPL_{mean} \pm \sigma$
$SPL_{5s}$ 1/3 Oct. /dB re 1 µPa$^2$
Center frequency /Hz

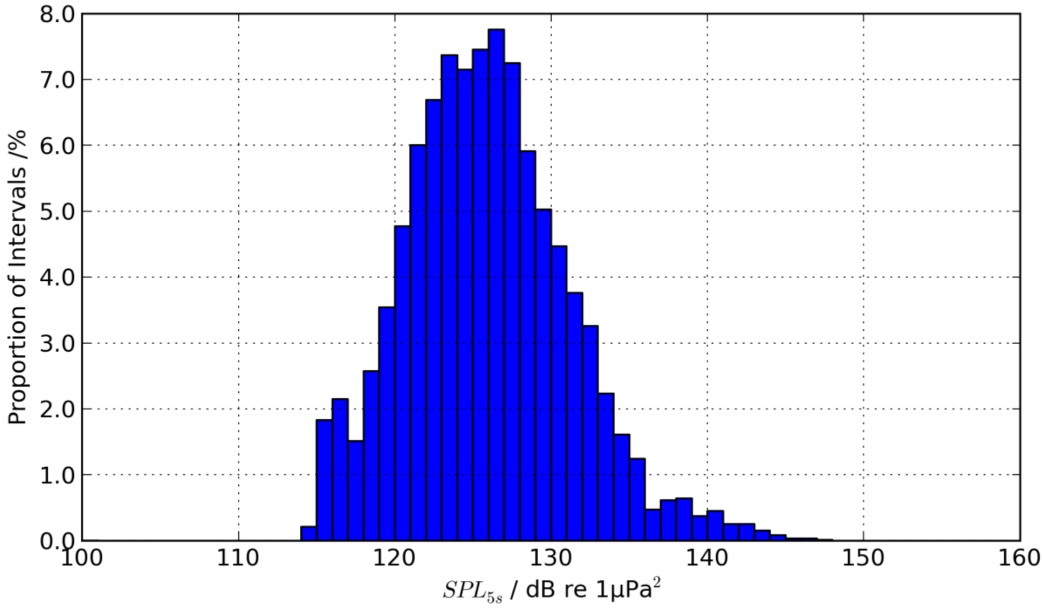



Proportion of Intervals /%
$SPL_{5s}$ / dB re 1µPa$^2$

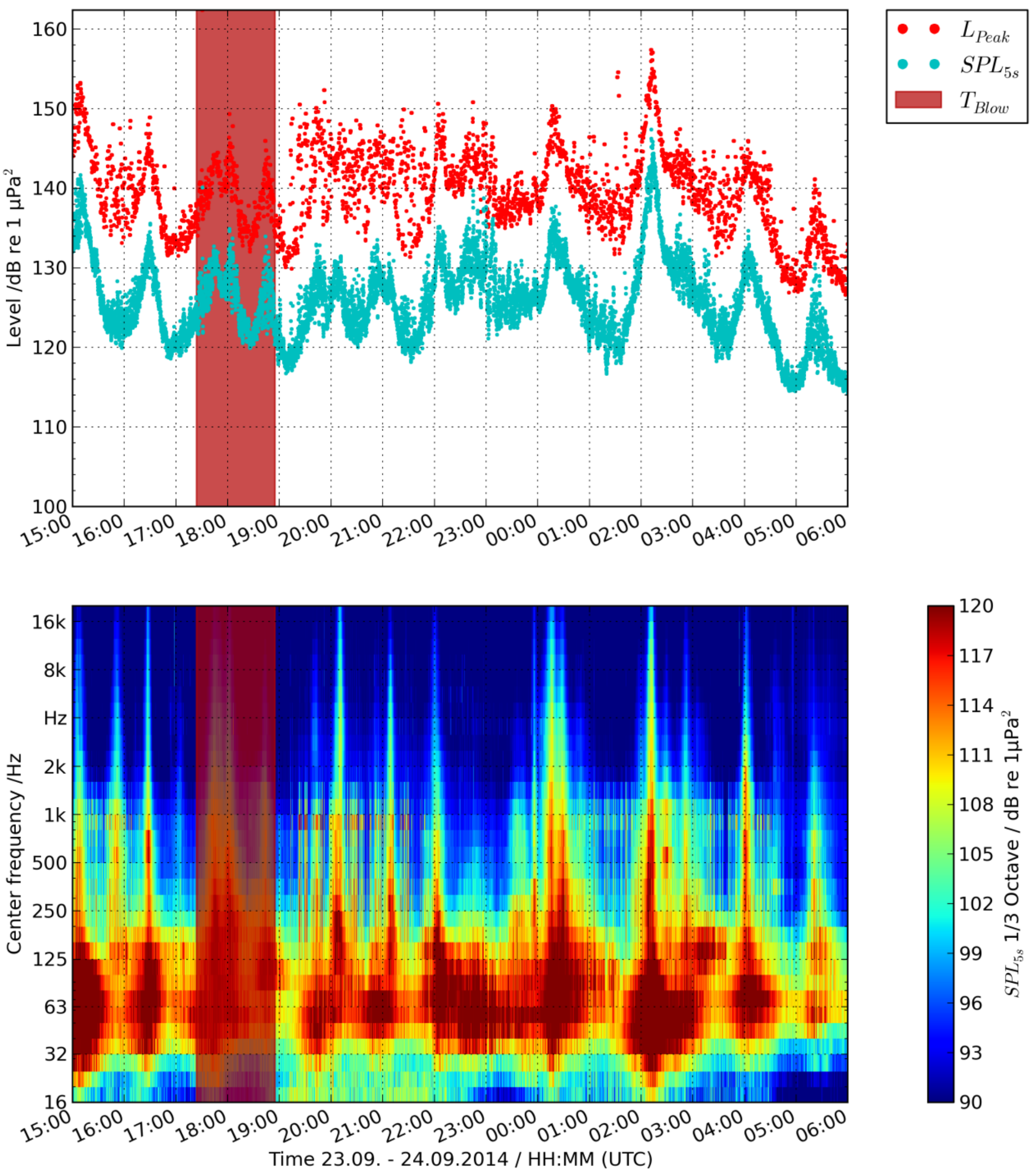
# EL 39 MP4 2 m ambient noise

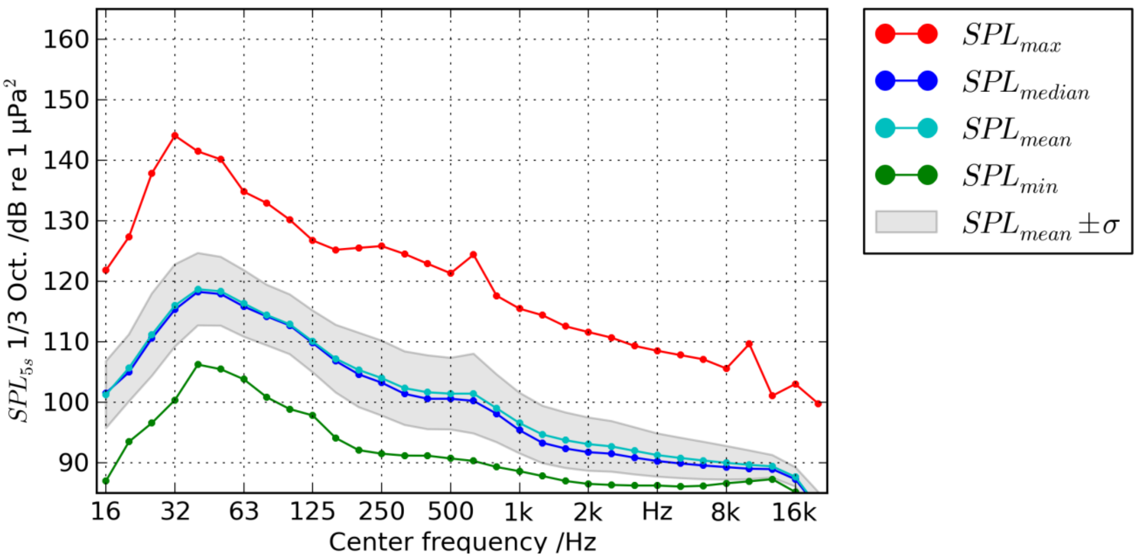


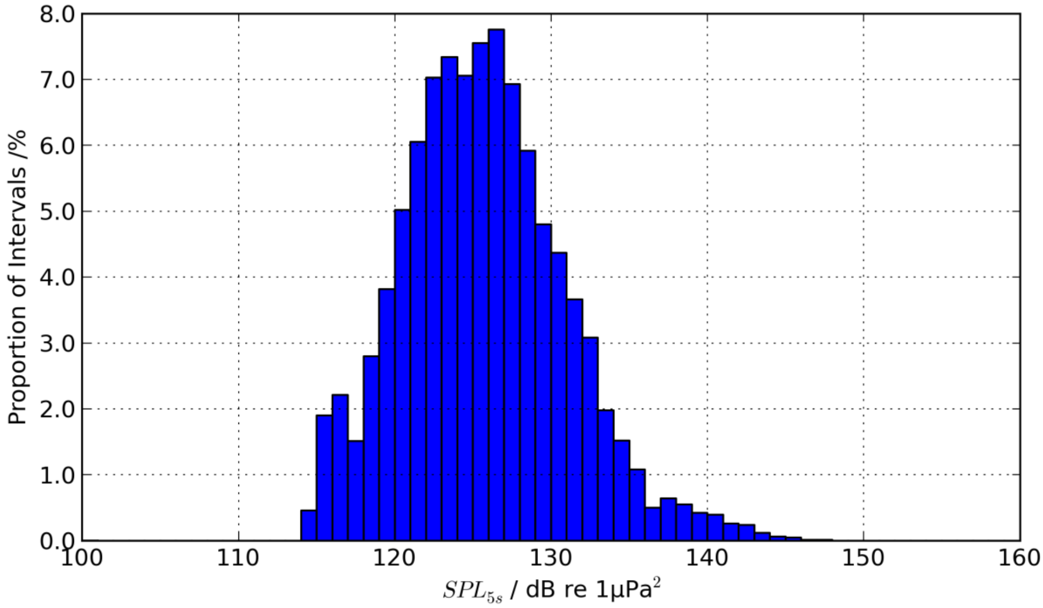

160
150
140
130
120
110
100
90
$SPL_{5s}$ 1/3 Oct. /dB re 1 µPa$^2$
16 32 63 125 250 500 1k 2k Hz 8k 16k
Center frequency /Hz
$SPL_{max}$
$SPL_{median}$
$SPL_{mean}$
$SPL_{min}$
$SPL_{mean} \pm \sigma$


8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Proportion of Intervals /%
100 110 120 130 140 150 160
$SPL_{5s}$ / dB re 1µPa$^2$

# EL 39 MP4 10 m ambient noise

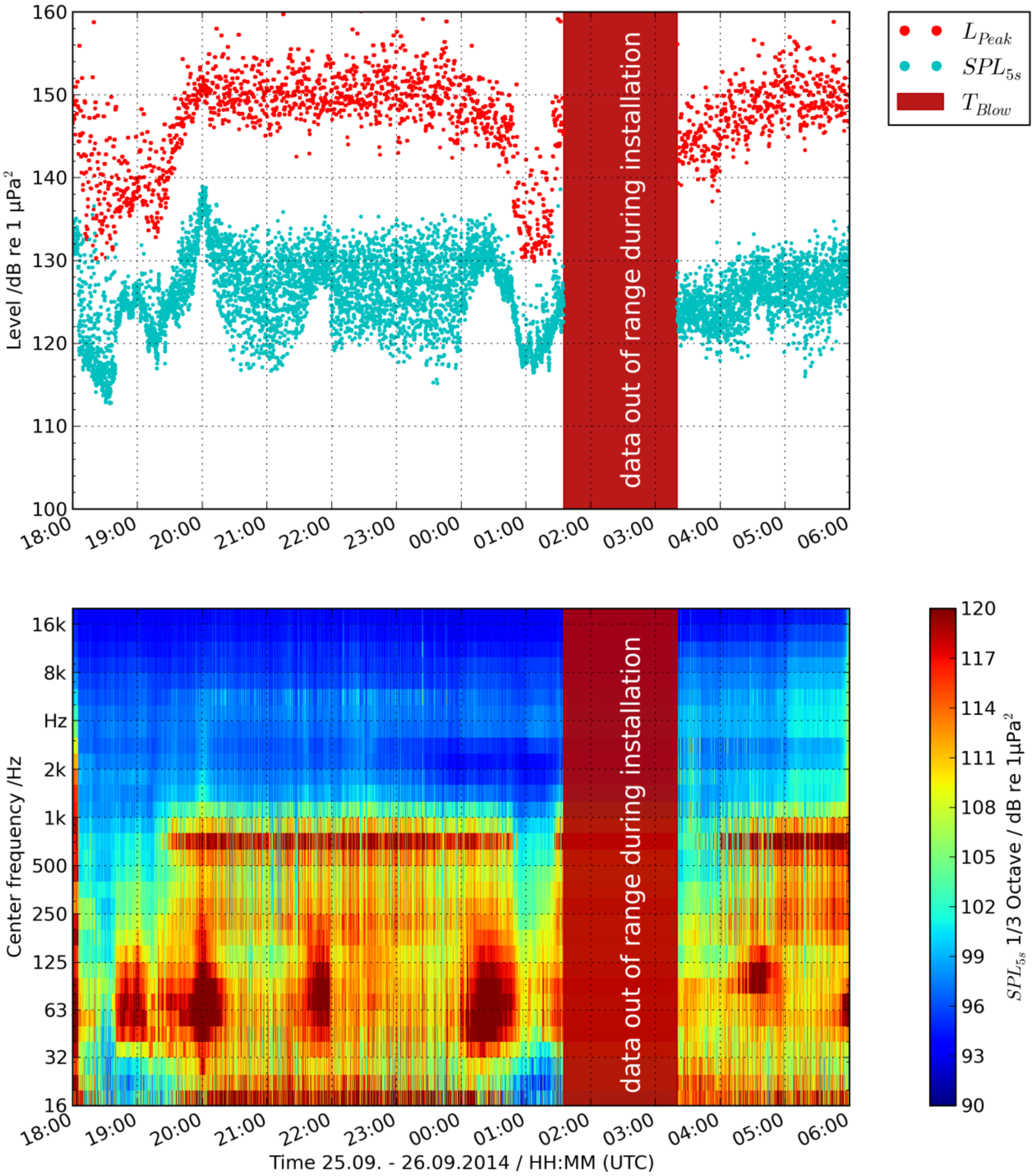


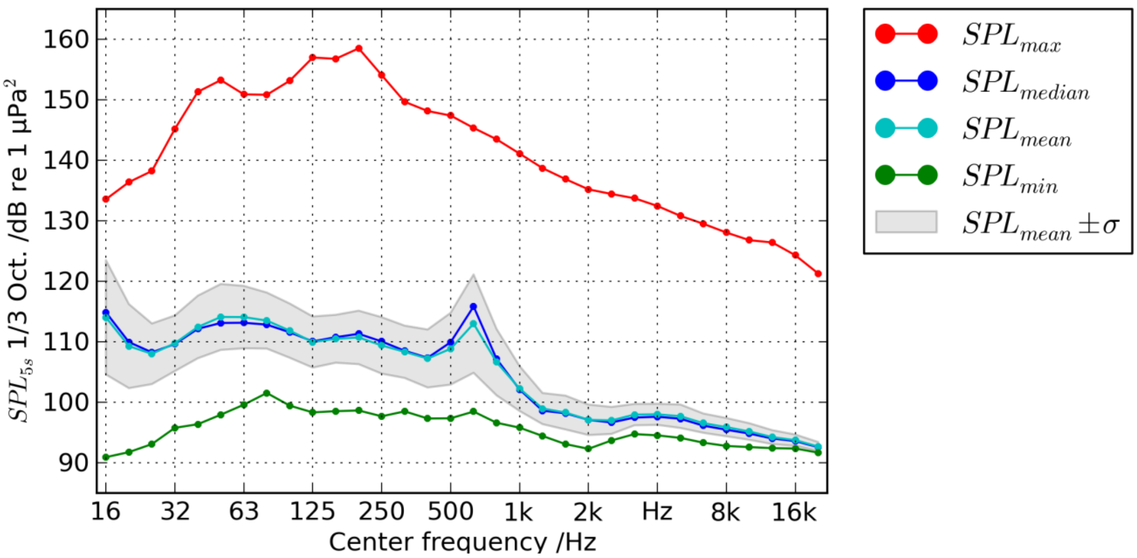

160
150
140
130
120
110
100
90
$SPL_{5s}$ 1/3 Oct. /dB re 1 µPa$^2$
16 32 63 125 250 500 1k 2k Hz 8k 16k
Center frequency /Hz
$SPL_{max}$
$SPL_{median}$
$SPL_{mean}$
$SPL_{min}$
$SPL_{mean} \pm \sigma$


8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Proportion of Intervals /%
100 110 120 130 140 150 160
$SPL_{5s}$ / dB re 1µPa$^2$

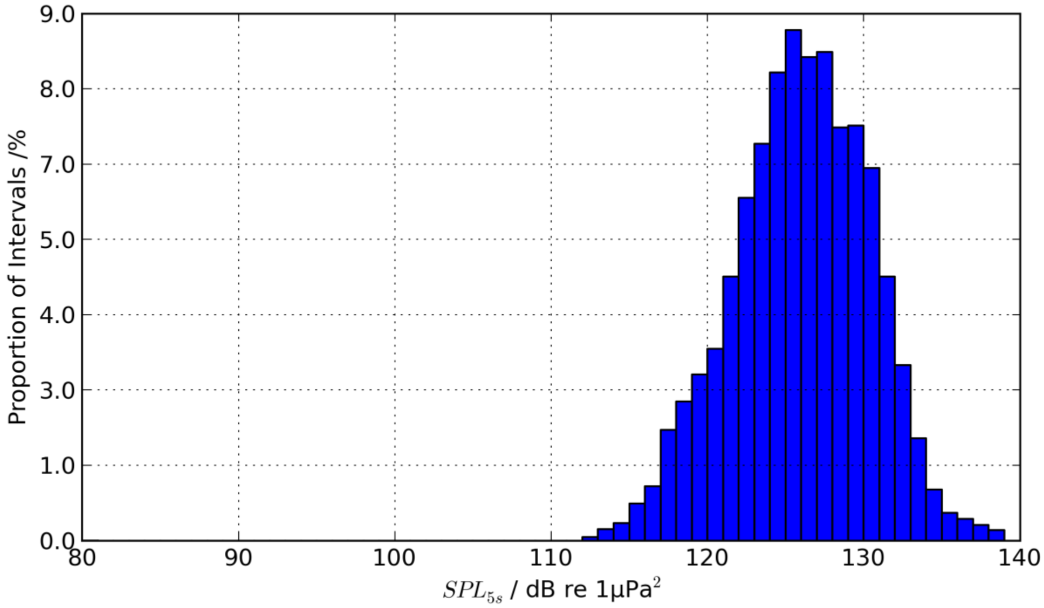
# A1.4 Ambient Noise for monopile EL42

## EL 42 MP1 2 m ambient noise



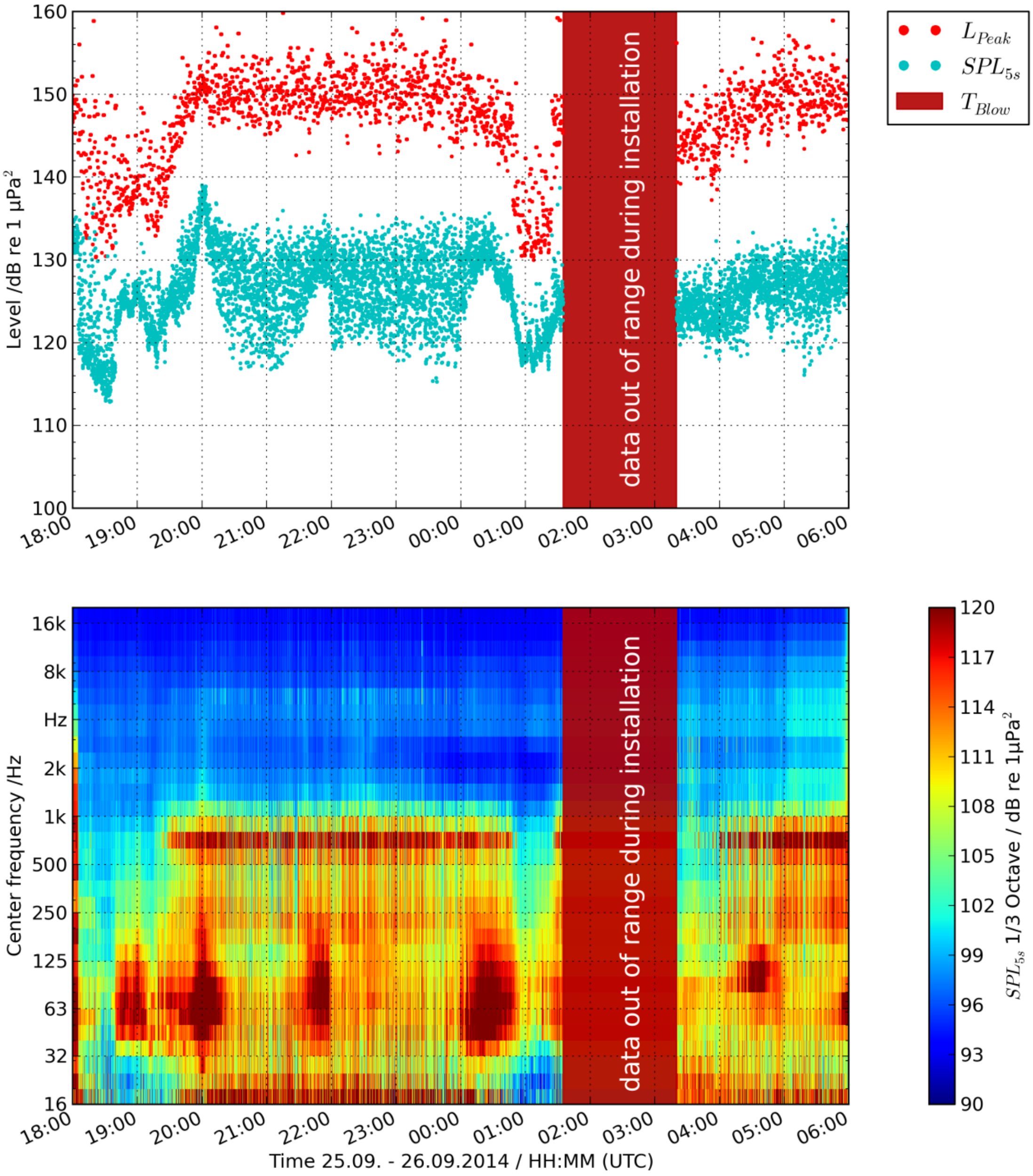


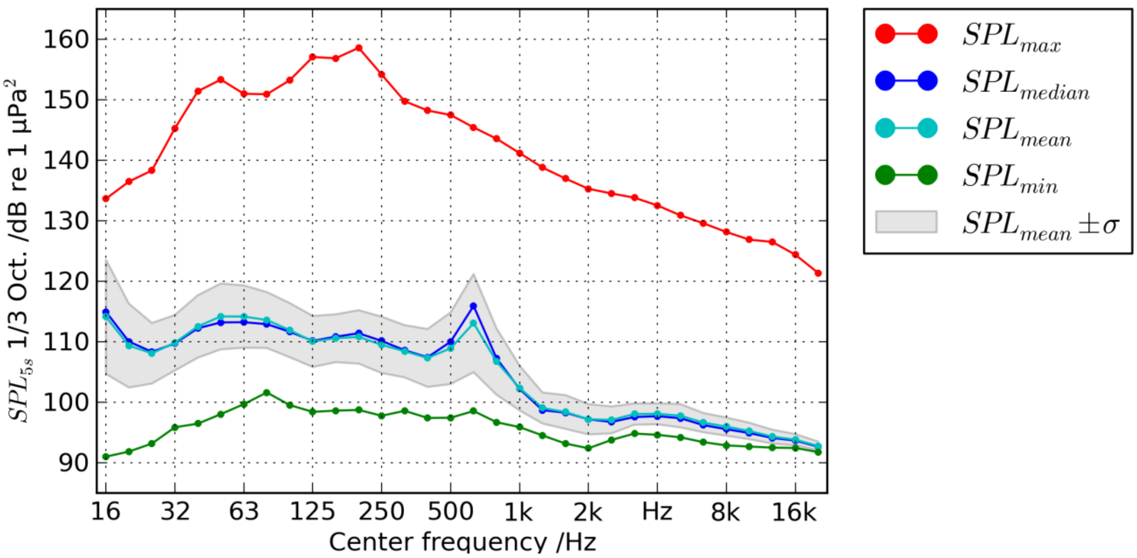
$SPL_{5s}$ 1/3 Oct. /dB re 1 µPa$^2$
160
150
140
130
120
110
100
90
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center frequency /Hz
$SPL_{max}$
$SPL_{median}$
$SPL_{mean}$
$SPL_{min}$
$SPL_{mean} \pm \sigma$

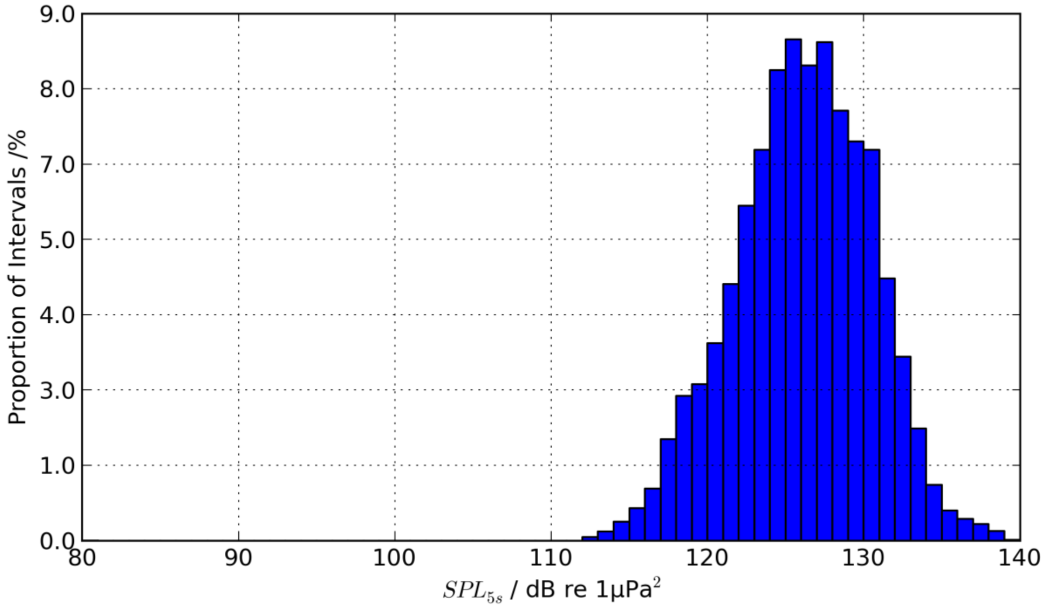



Proportion of Intervals /%
9.0
8.0
7.0
5.0
4.0
3.0
1.0
0.0
80
90
100
110
120
130
140
$SPL_{5s}$ / dB re 1µPa$^2$

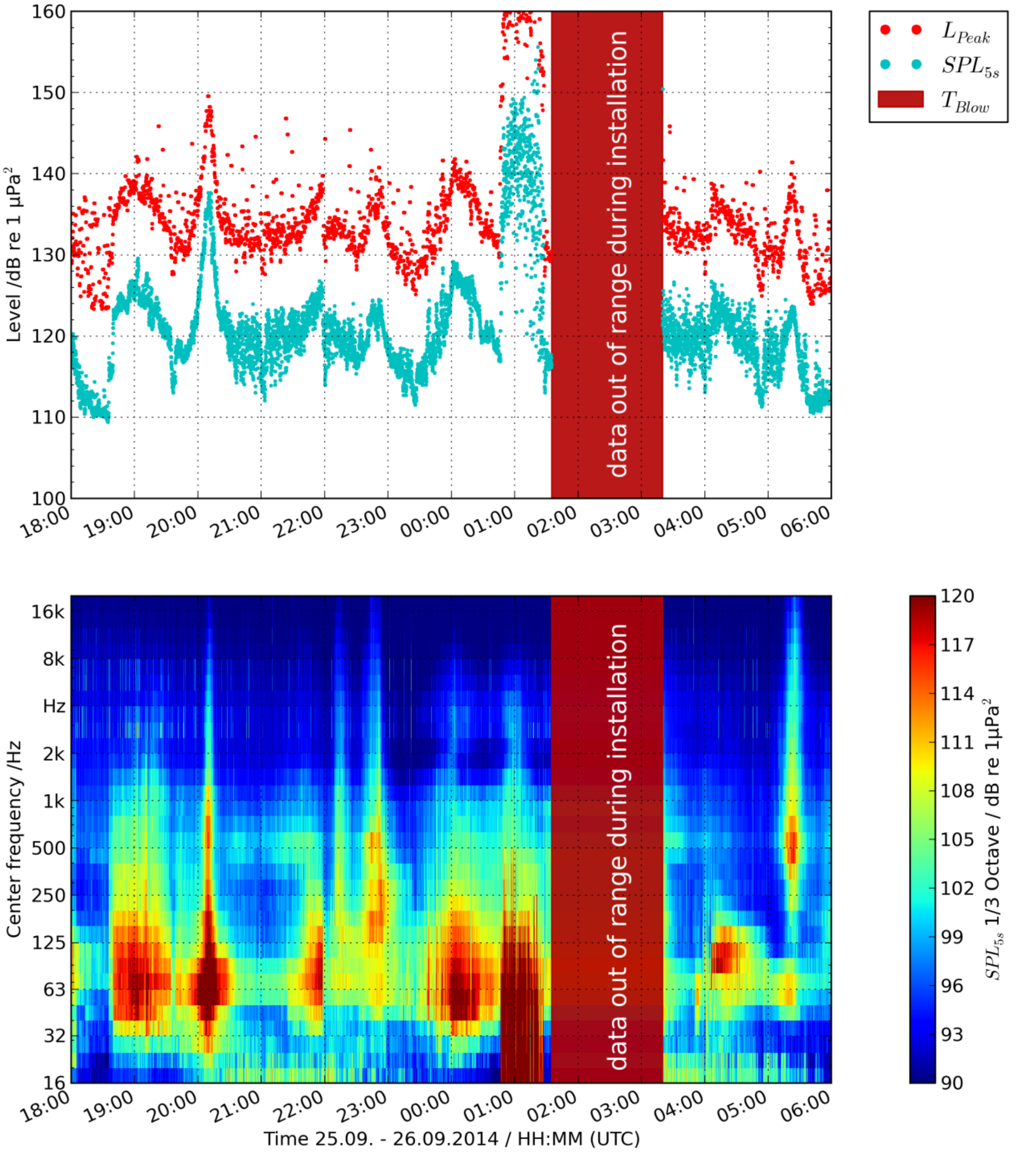
# EL 42 MP1 10 m ambient noise

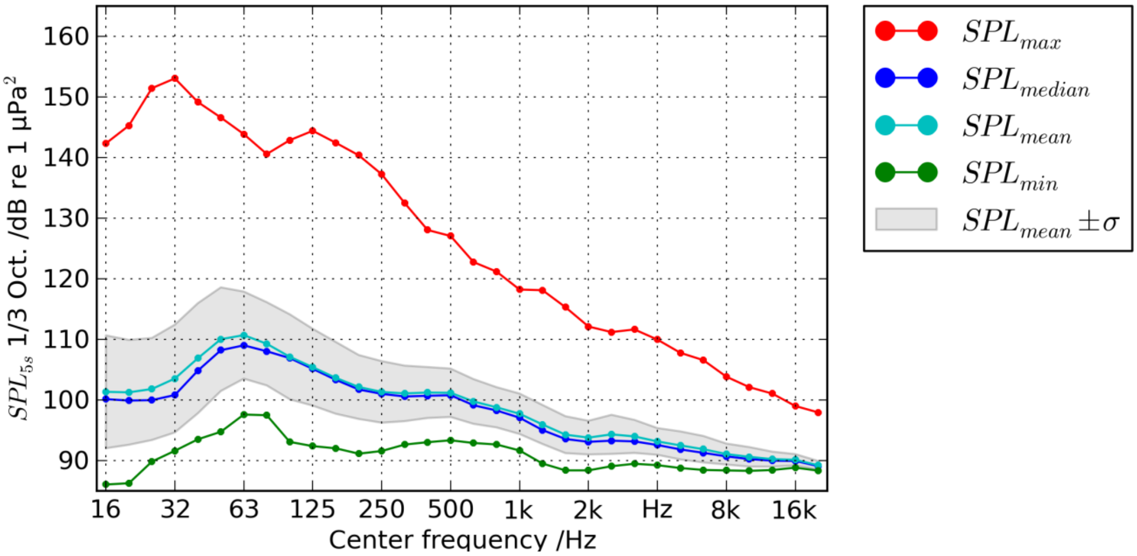



160
150
140
130
120
110
100
90
$SPL_{5s}$ 1/3 Oct. /dB re 1 µPa$^2$
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center frequency /Hz
$SPL_{max}$
$SPL_{median}$
$SPL_{mean}$
$SPL_{min}$
$SPL_{mean} \pm \sigma$

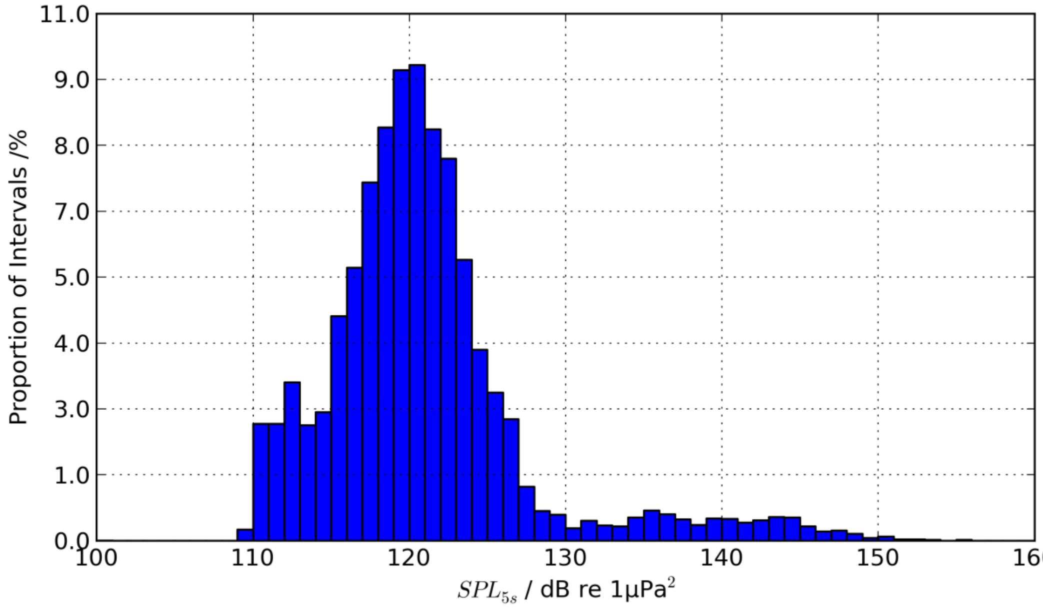

9.0
8.0
7.0
5.0
4.0
3.0
1.0
0.0
Proportion of Intervals /%
80
90
100
110
120
130
140
$SPL_{5s}$ / dB re 1µPa$^2$

# EL 42 MP2 2 m ambient noise



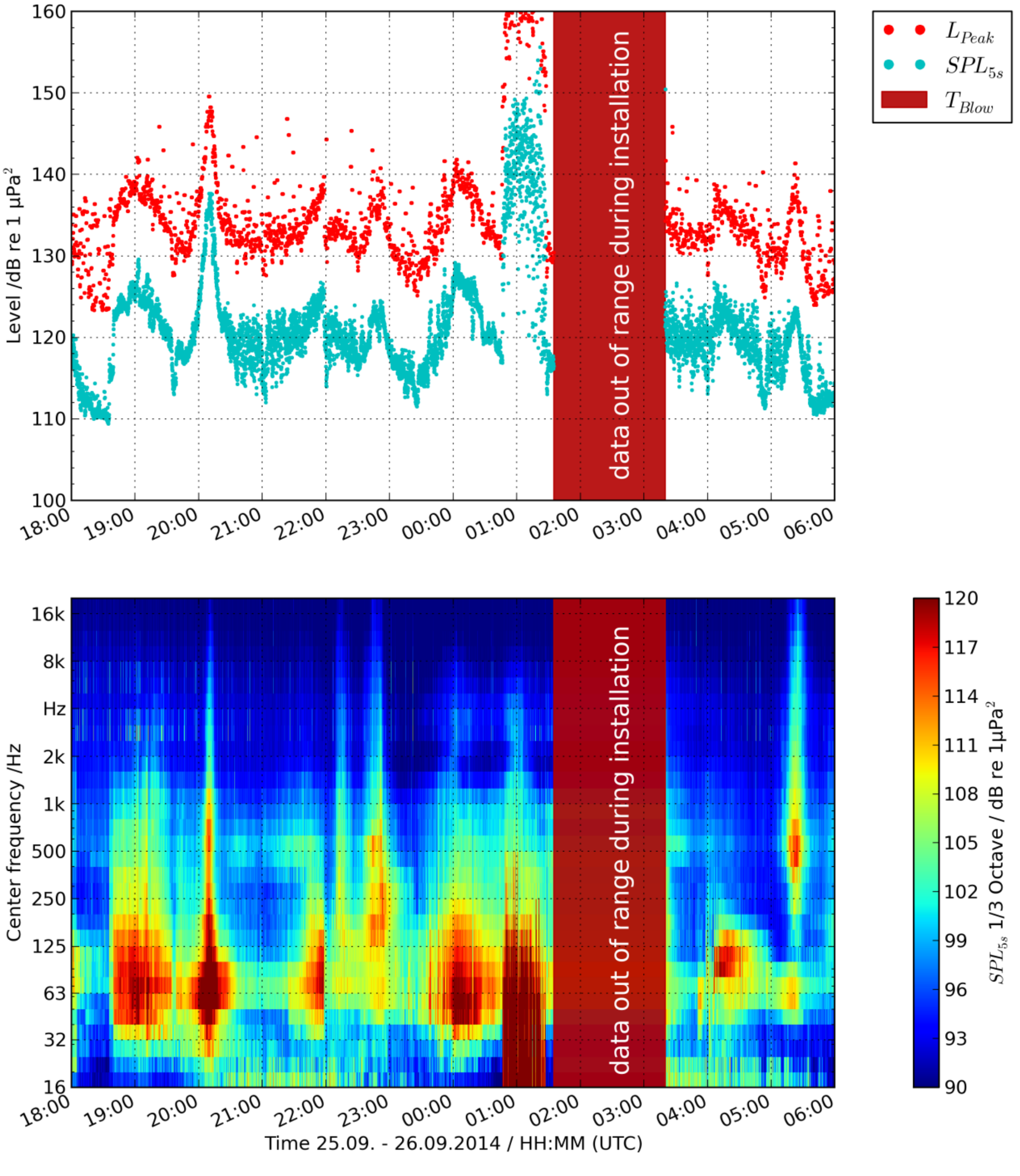


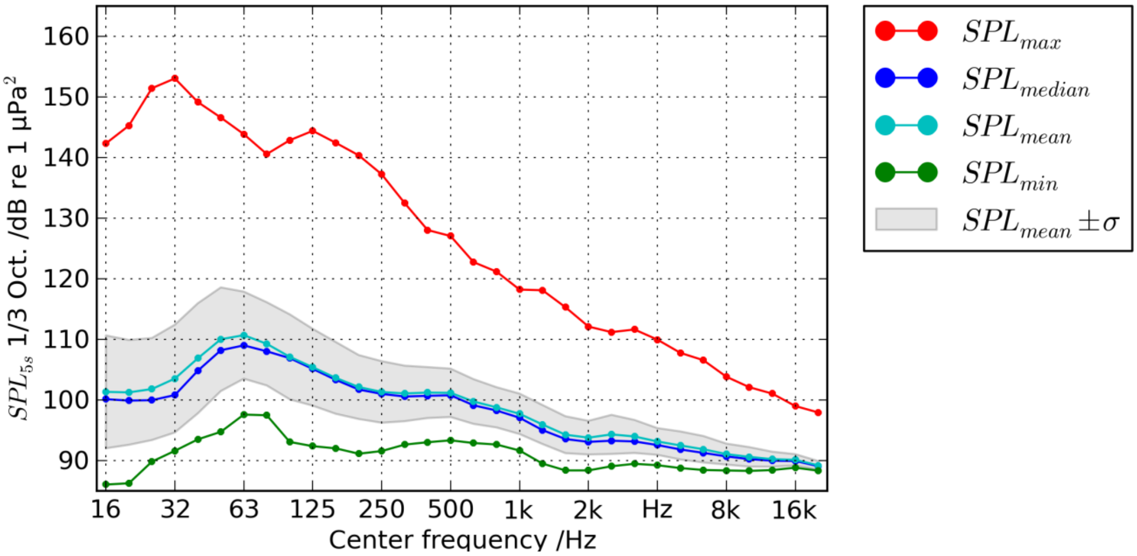
$SPL_{max}$
$SPL_{median}$
$SPL_{mean}$
$SPL_{min}$
$SPL_{mean} \pm \sigma$
$SPL_{5s}$ 1/3 Oct. /dB re 1 µPa$^2$
160
150
140
130
120
110
100
90
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center frequency /Hz

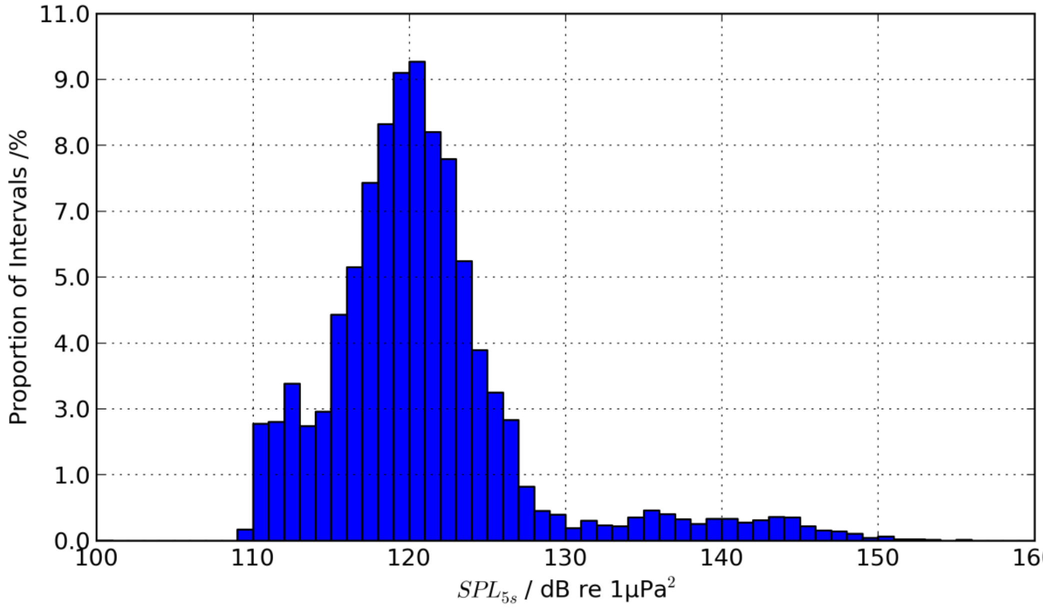



Proportion of Intervals /%
11.0
9.0
8.0
7.0
5.0
4.0
3.0
1.0
0.0
100
110
120
130
140
150
160
$SPL_{5s}$ / dB re 1µPa$^2$

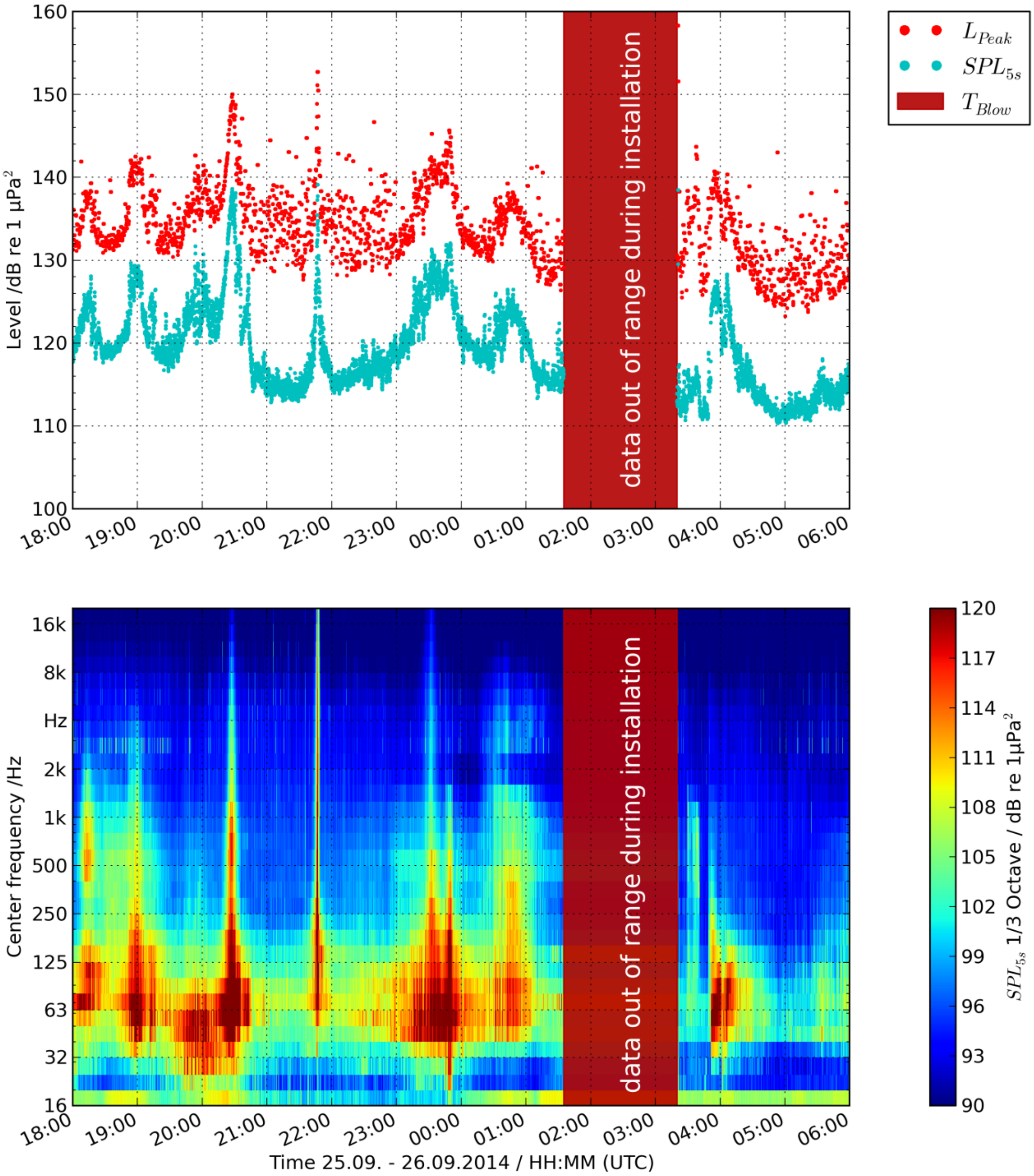
## EL 42 MP2 10 m ambient noise

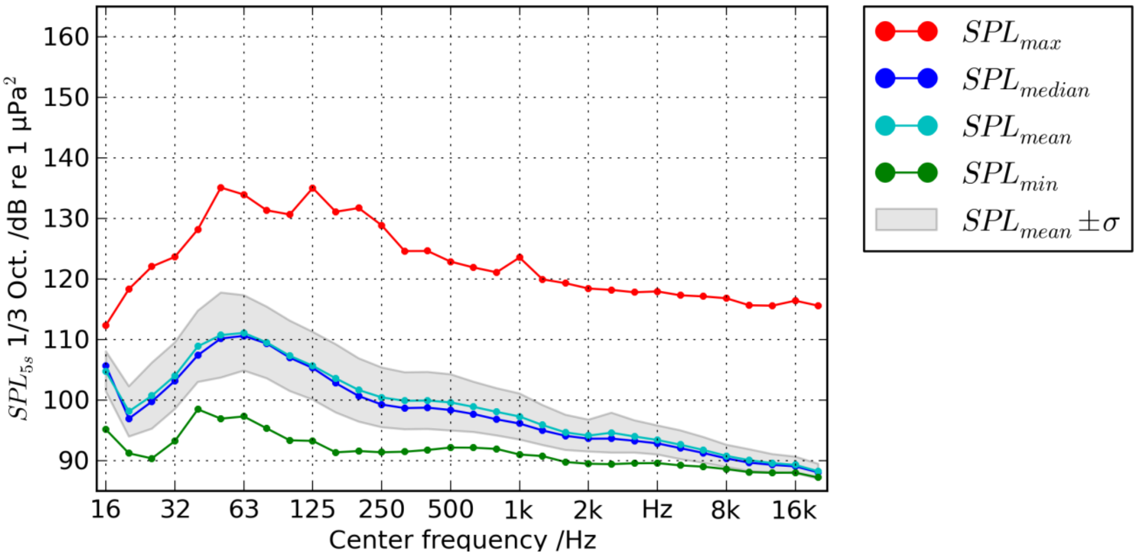



160
150
140
130
120
110
100
90
$SPL_{5s}$ 1/3 Oct. /dB re 1 µPa²
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center frequency /Hz
$SPL_{max}$
$SPL_{median}$
$SPL_{mean}$
$SPL_{min}$
$SPL_{mean} \pm \sigma$

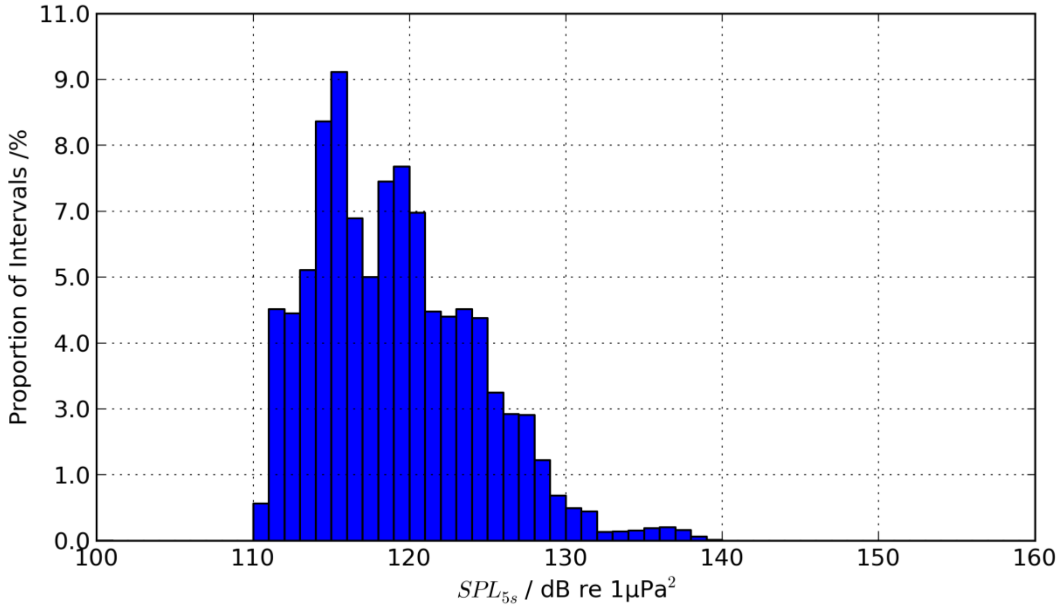

11.0
9.0
8.0
7.0
5.0
4.0
3.0
1.0
0.0
Proportion of Intervals /%
100
110
120
130
140
150
160
$SPL_{5s}$ / dB re 1µPa²

# EL 42 MP3 2 m ambient noise



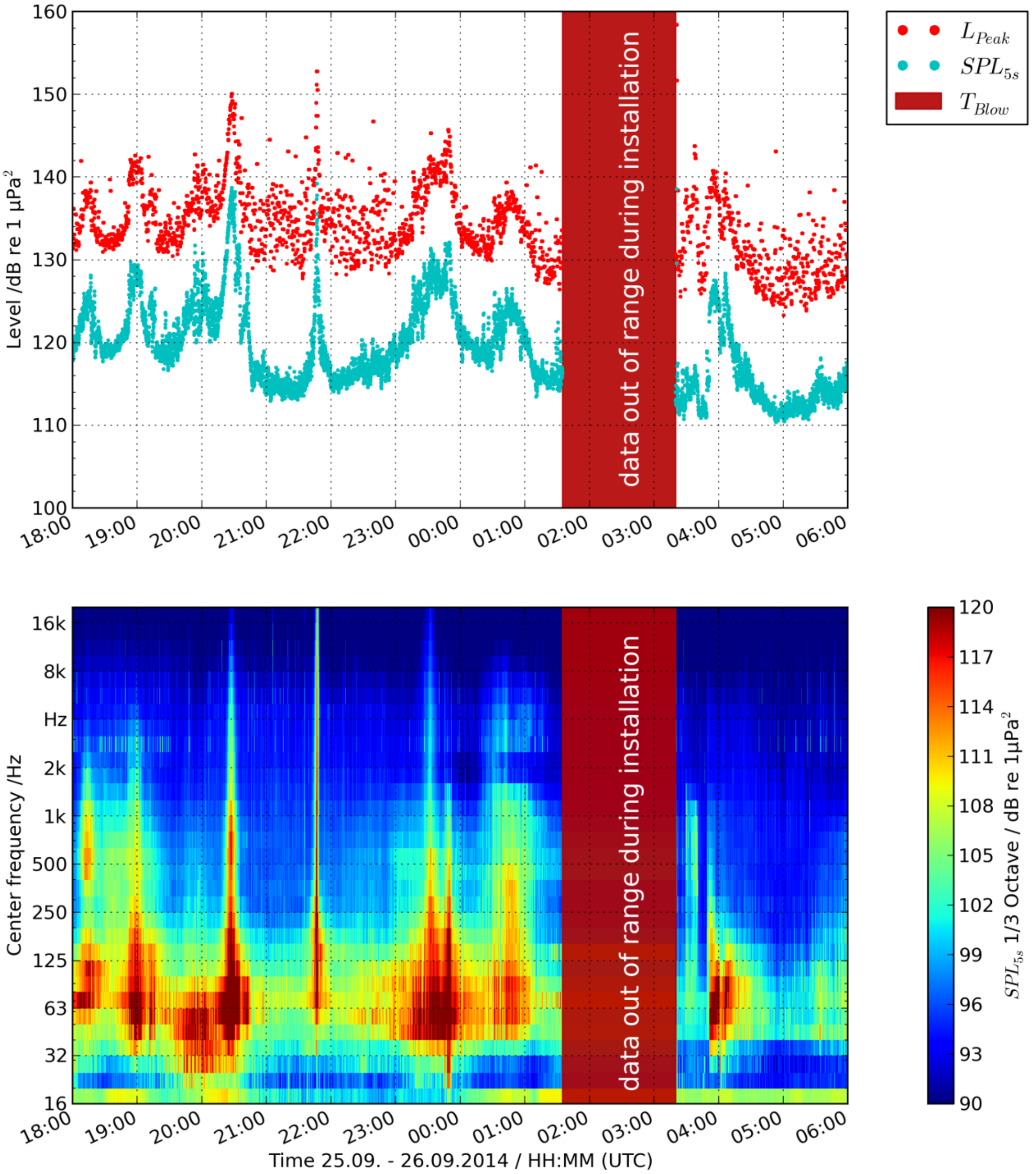


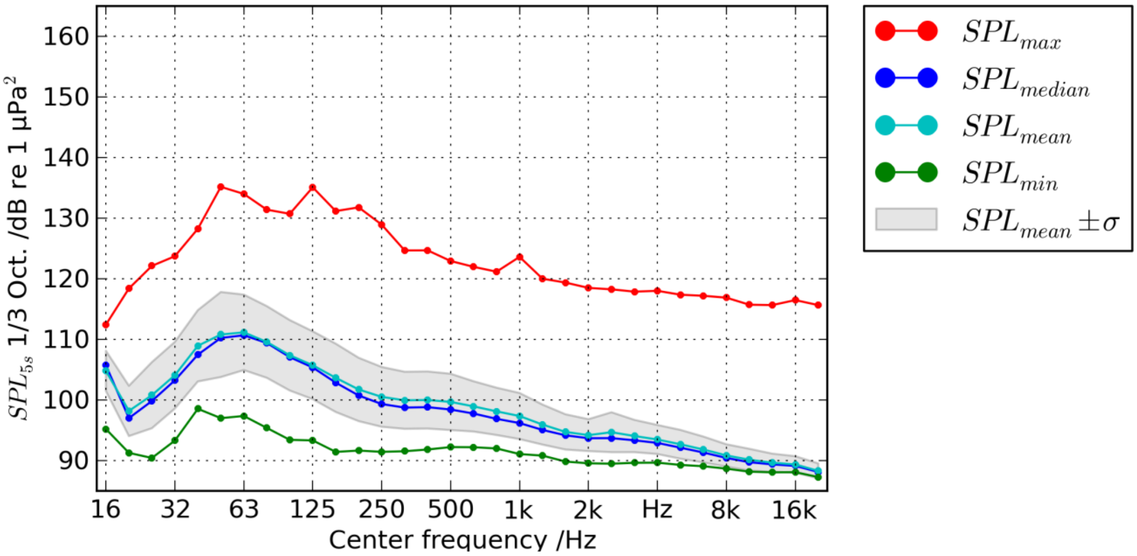
160
150
140
130
120
110
100
90
$SPL_{5s}$ 1/3 Oct. /dB re 1 µPa$^2$
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center frequency /Hz
$SPL_{max}$
$SPL_{median}$
$SPL_{mean}$
$SPL_{min}$
$SPL_{mean} \pm \sigma$

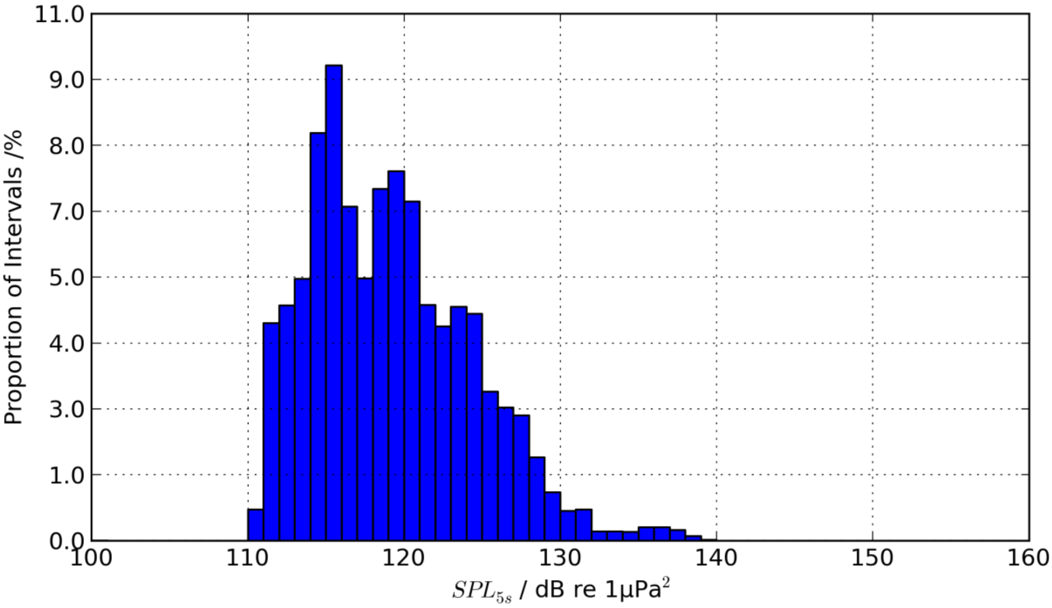



11.0
9.0
8.0
7.0
5.0
4.0
3.0
1.0
0.0
Proportion of Intervals /%
100
110
120
130
140
150
160
$SPL_{5s}$ / dB re 1µPa$^2$

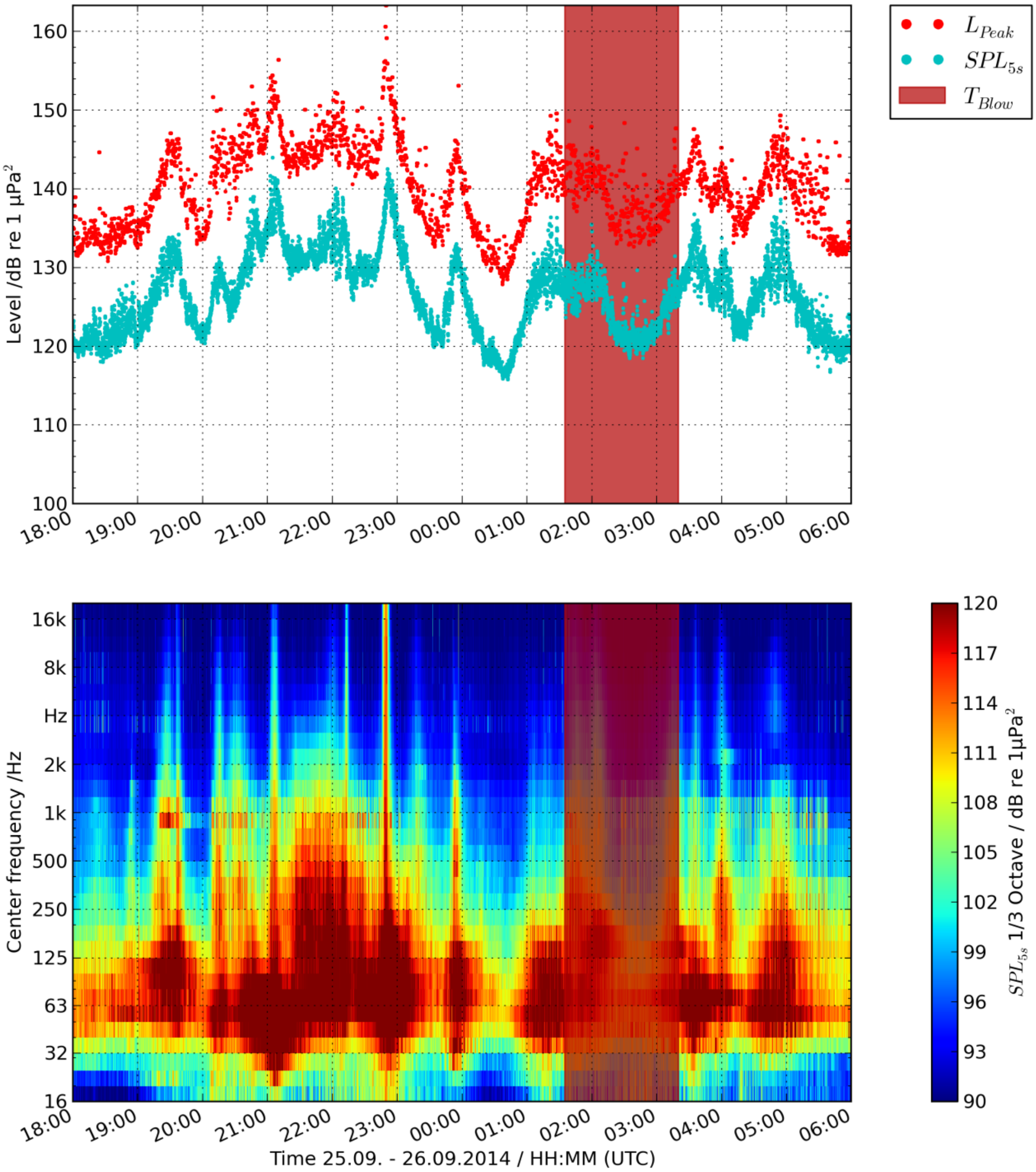
# EL 42 MP3 10 m ambient noise

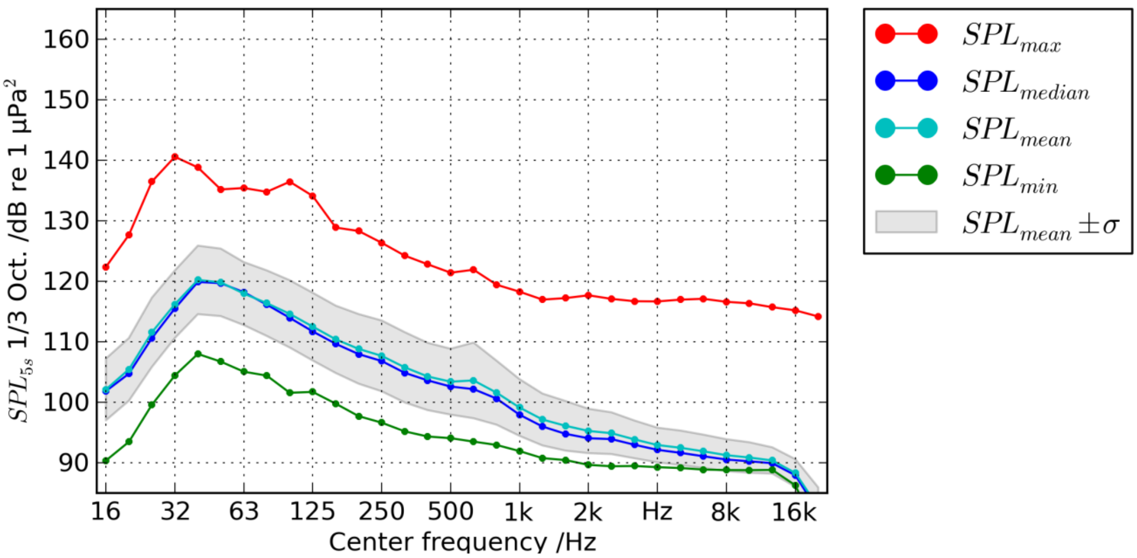


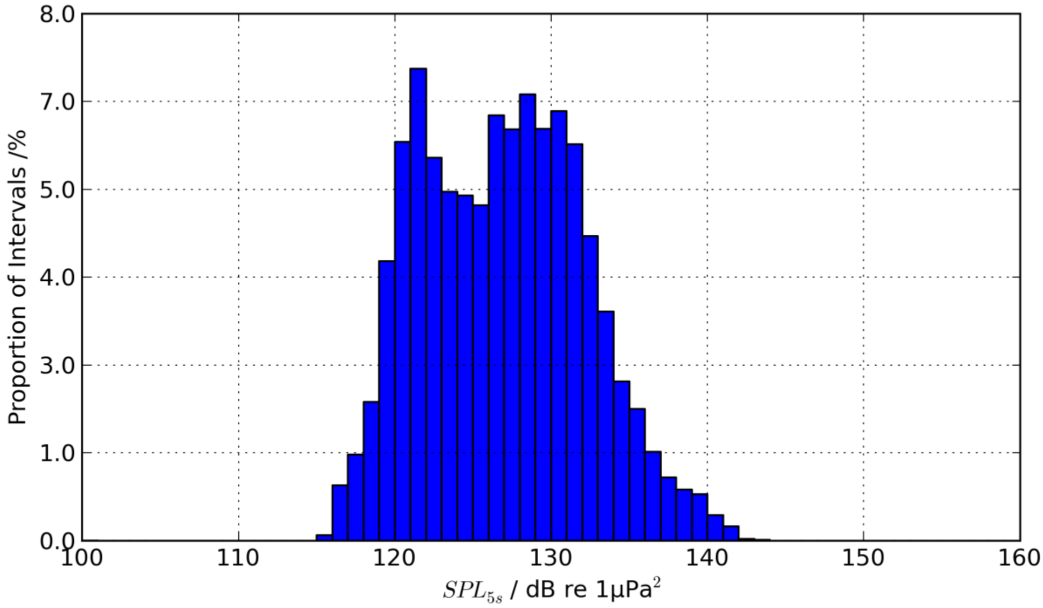

160
150
140
130
120
110
100
90
$SPL_{5s}$ 1/3 Oct. /dB re 1 µPa$^2$
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center frequency /Hz
$SPL_{max}$
$SPL_{median}$
$SPL_{mean}$
$SPL_{min}$
$SPL_{mean} \pm \sigma$


11.0
9.0
8.0
7.0
5.0
4.0
3.0
1.0
0.0
Proportion of Intervals /%
100
110
120
130
140
150
160
$SPL_{5s}$ / dB re 1µPa$^2$

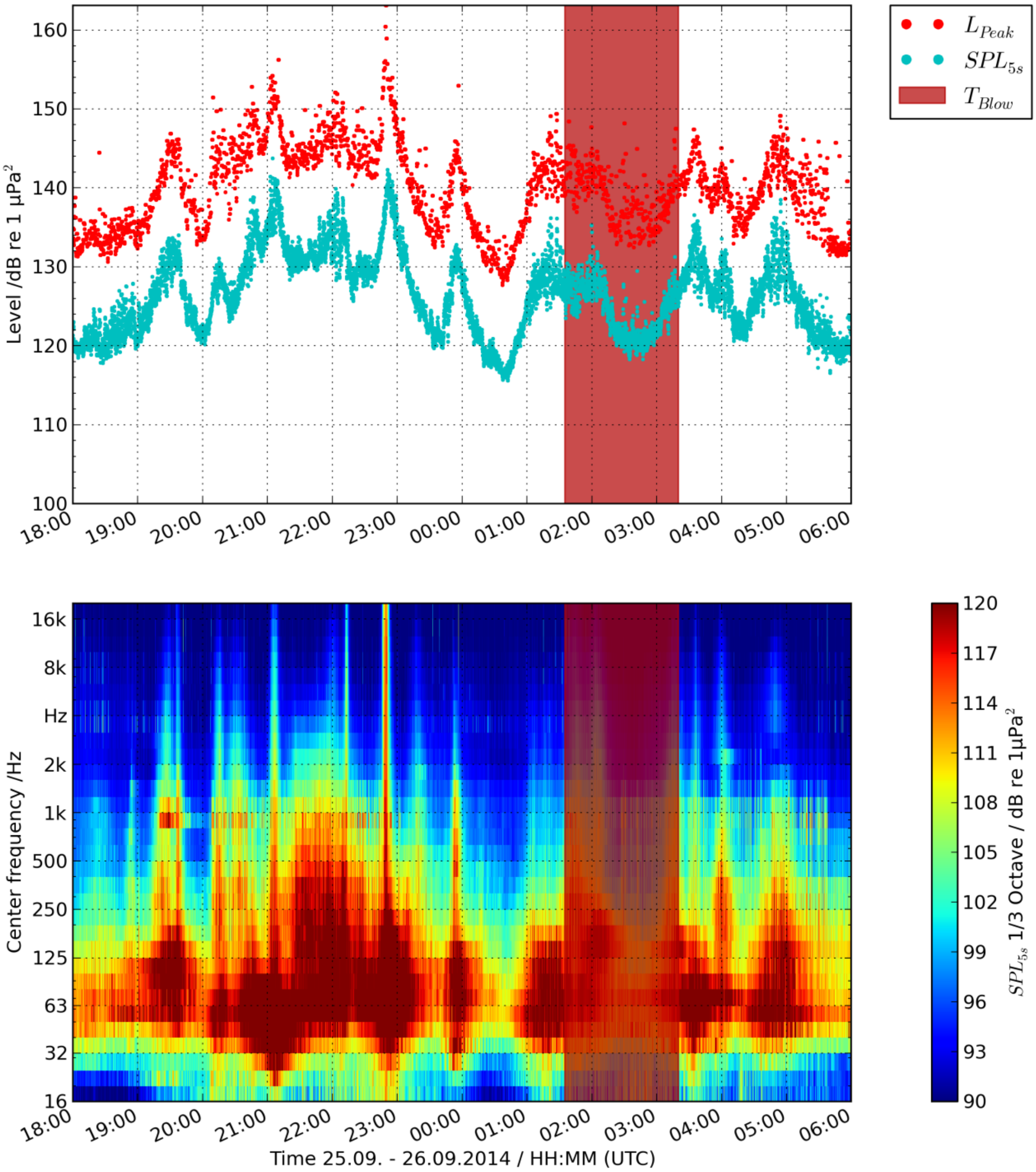
# MP 42 MP4 2 m ambient noise

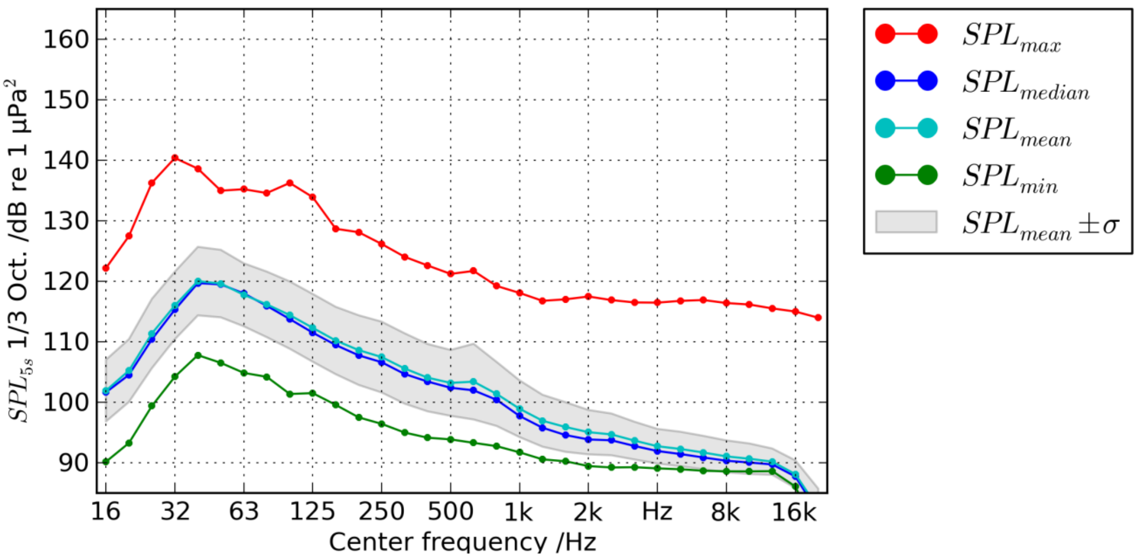



160
150
140
130
120
110
100
90
$SPL_{5s}$ 1/3 Oct. /dB re 1 µPa$^2$
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center frequency /Hz
$SPL_{max}$
$SPL_{median}$
$SPL_{mean}$
$SPL_{min}$
$SPL_{mean} \pm\sigma$

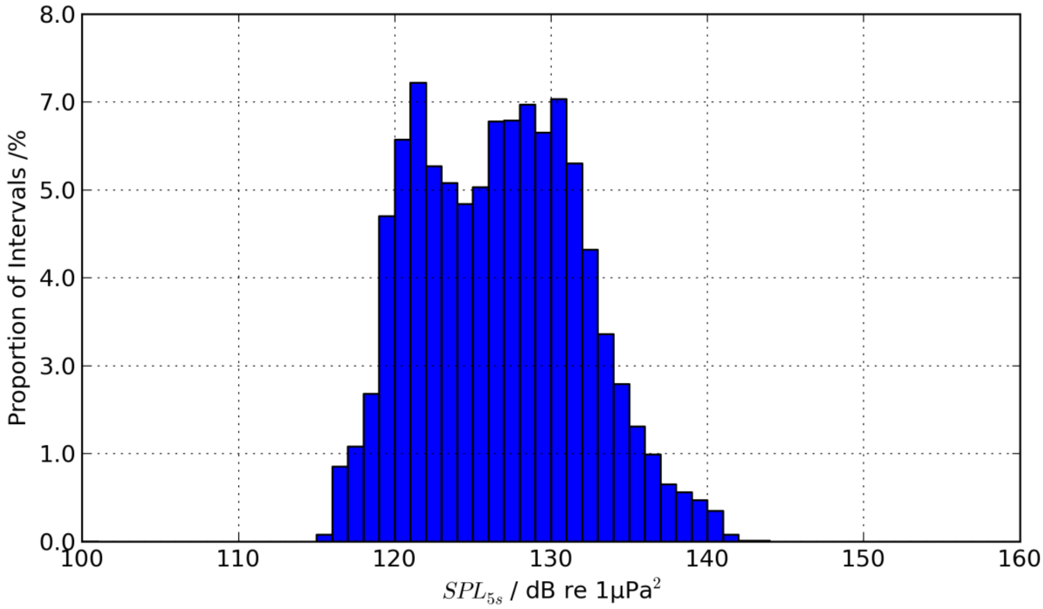

8.0
7.0
5.0
4.0
3.0
1.0
0.0
Proportion of Intervals /%
100
110
120
130
140
150
160
$SPL_{5s}$ / dB re 1µPa$^2$

# MP 42 MP4 10 m ambient noise





160
150
140
130
120
110
100
90
$SPL_{5s}$ 1/3 Oct. /dB re 1 µPa$^2$
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center frequency /Hz
$SPL_{max}$
$SPL_{median}$
$SPL_{mean}$
$SPL_{min}$
$SPL_{mean} \pm \sigma$

8.0
7.0
5.0
4.0
3.0
1.0
0.0
Proportion of Intervals /%
100
110
120
130
140
150
160
$SPL_{5s}$ / dB re 1µPa$^2$

# Annex 2: Measurement Devices

| Pile | Task | Pos. | Device | Hydrophone | | | Calibration | |
|---|---|---|---|---|---|---|---|---|
| | | | | Height | Type | Serial no. | File | Amplitude |
| EL39 | Ambient | MP1 | 953 | 2 | TC4033 | 4512022 | B0001 | 100 pC |
| | | | | 10 | TC4033 | 4711046 | B0002 | 100 pC |
| | | MP2 | 951 | 2 | TC4033 | 2213055 | AT001 | 10 pC |
| | | | | 10 | TC4033 | 4711050 | AT002 | 10 pC |
| | | MP3 | 949 | 2 | B&K 8106 | 2799818 | BM001 | 10 mV |
| | | | | 10 | B&K 8106 | 2931741 | BM002 | 10 mV |
| | | MP4 | 947 | 2 | B&K 8106 | 2720288 | BE002 | 10 mV |
| | | | | 10 | B&K 8106 | 2931739 | BE001 | 10 mV |
| | Pile driving | MP1 | 954 | 2 | TC4033 | 4512032 | BF001 | 100 pC |
| | | | | 10 | TC4033 | 3912008 | BF002 | 100 pC |
| | | MP2 | 952 | 2 | TC4033 | 3912010 | BW001 | 100 pC |
| | | | | 10 | TC4033 | 4711065 | BW001 | 100 pC |
| | | MP3 | 950 | 2 | TC4033 | 2213066 | A0001 | 100 pC |
| | | | | 10 | TC4033 | 1912058 | A0002 | 100 pC |
| | | MP4 | 948 | 2 | TC4033 | 2513015 | AZ001 | 10 pC |
| | | | | 10 | TC4033 | 1912050 | AZ002 | 10 pC |
| EL42 | Ambient | MP1 | 958 | 2 | TC4033 | 2213067 | BL001 | 100 pC |
| | | | | 10 | TC4033 | 3912005 | BL002 | 100 pC |
| | | MP2 | 960 | 2 | TC4033 | 1912068 | BD001 | 10 pC |
| | | | | 10 | TC4033 | 3311026 | BD002 | 10 pC |
| | | MP3 | 957 | 2 | B&K 8106 | 2931737 | AW001 | 10 mV |
| | | | | 10 | B&K 8106 | 2799806 | AW002 | 10 mV |
| | | MP4 | 947 | 2 | B&K 8106 | 2729288 | BE002 | 10 mV |
| | | | | 10 | B&K 8106 | 2931739 | BE001 | 10 mV |
| | Pile driving | MP1 | 955 | 2 | TC4033 | 2513016 | AV001 | 100 pC |
| | | | | 10 | TC4033 | 4711052 | AV002 | 100 pC |
| | | MP2 | 959 | 2 | TC4033 | 2513024 | BC001 | 100 pC |
| | | | | 10 | TC4033 | 3311018 | BC001 | 100 pC |
| | | MP3 | 956 | 2 | TC4033 | 2213069 | AJ002 | 100 pC |
| | | | | 10 | TC4033 | 3912012 | AJ001 | 100 pC |
| | | MP4 | 948 | 2 | TC4033 | 2513015 | AZ001 | 10 pC |
| | | | | 10 | TC4033 | 1912050 | AZ002 | 10 pC |

# Annex 3: Calibration and certifications

I. All used hydrophones have a full calibration certificate from the manufacturer. The calibration certificate will be refreshed latest each 30 month by the manufacturer.

II. Before the offshore operation starts the whole measurement device (including hydrophones, recorders etc.) was checked by an *itap GmbH* employee. Additionally a calibration (pure tone with 160 Hz and fixed amplitude -> "calibration file") was recorded an each device for upcoming calibration task of the measured data.

III. Before the measurement device was deployed in water the correct functioning of the device was checked by an *itap GmbH* employee by using a "custom-made" testing-box.

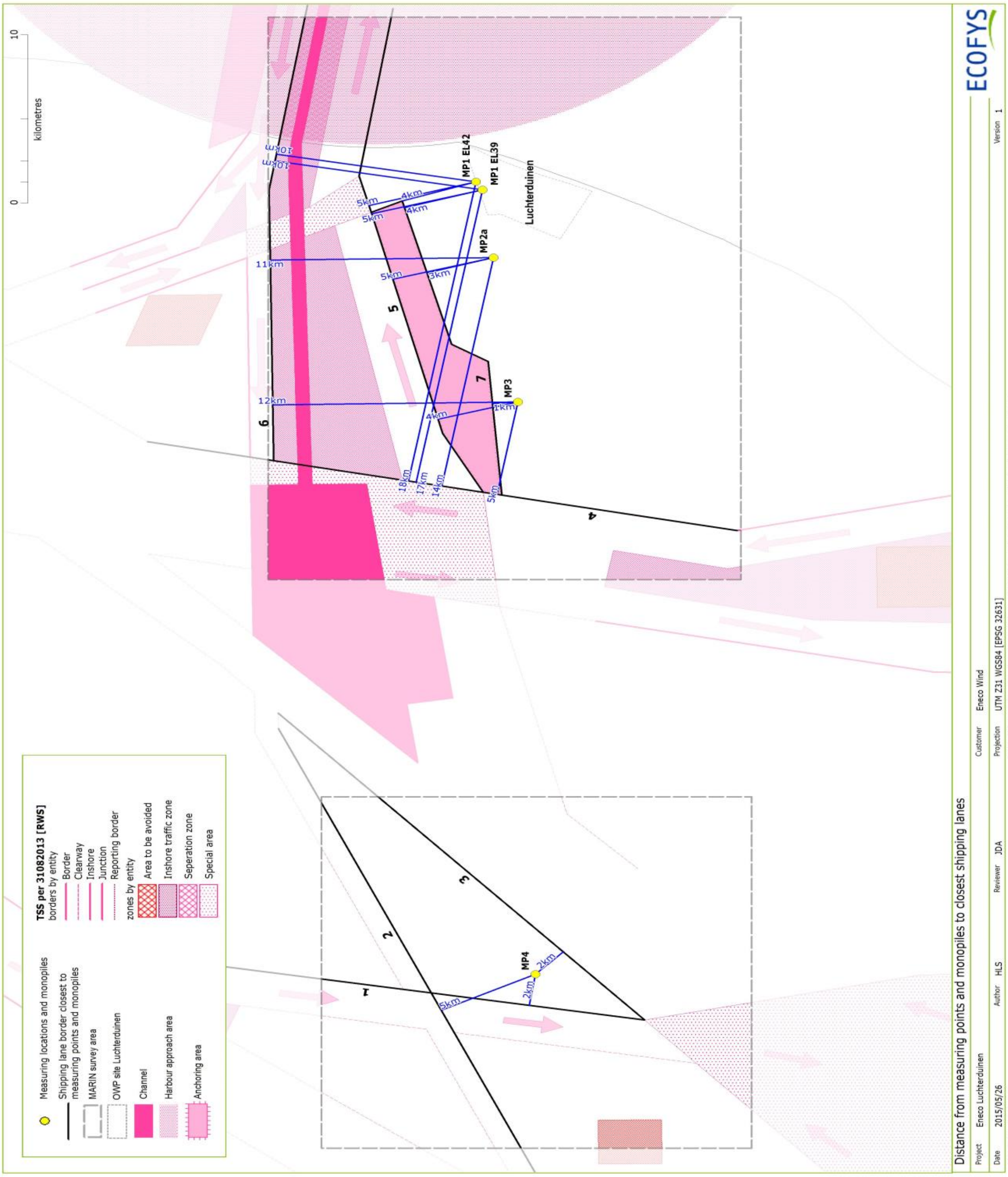
IV. After the recovery of the measurement device the correct functioning was checked again by an itap employee.

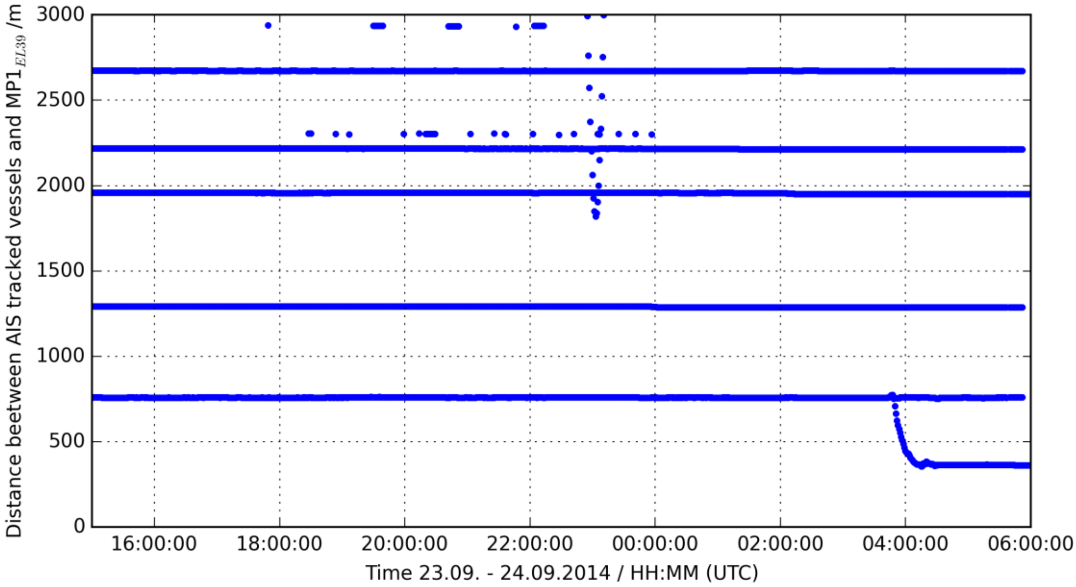
The Equipment used for calibration is listed in the table below.

| **Device** | **Producer** | **Important technical data/number of entities** |
|---|---|---|
| Pressure chamber | Itap GmbH | 80 to 160 Hz, 140 – 155 dB re 1µPa adjustable |
| Microphone-calibrator 4231 | Bruel & Kjær | |
| Microphone 4189 and pre-amplifier 2671 as reference in pressure chamber | Bruel & Kjær | |
| Signal Analyzer 35670a | Hewlett-Packard | |

*Itap GmbH* is a notified measuring agency according to §26 of the BImSchG (Federal Control of Pollution Act) and has an accredited quality management system according to DIN EN ISO 17025 for emission and immission (pollution) measurements of sounds and vibrations since November 28th, 2012 (accreditation in accordance with DAKKs – German accreditation body - for immission (pollution) protection module sounds and vibrations, as well as noise in the workplace and acoustical material testing in the reverberation room).

# Annex 4: Vessel traffic information




Distance beetween AIS tracked vessels and MP1$_{EL39}$ /m
3000
2500
2000
1500
1000
500
0
16:00:00
18:00:00
20:00:00
22:00:00
00:00:00
02:00:00
04:00:00
06:00:00
Time 23.09. - 24.09.2014 / HH:MM (UTC)

# Annex 5: Observed weather conditions

## 23 september 2014 Observed Weather Conditions 00:01 – 24:00

**Weather Today**

| | | 10m | | | | 50m | | Wind Wave | | Swell | | | Wave | | | 10m | Lowest | Air |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| UTC | | Dir | Spd (kts) | Gust (kts) | Risk (kts) | Spd (kts) | Gust (kts) | Hgt (m) | Per (sec) | Dir | Hgt (m) | Per (sec) | Hsig (m) | Max (m) | Risk (m) | | (ft) | (degC) |
| Tuesday, 23 Sep 2014 - Luchterduinen 52º24'N 004º10'E | | | | | | | | | | | | | | | | | | |
| 12 | NSW | SW | 9 | 13 | - | 10 | 14 | 0.6 | 3 | N | 0.7 | 6 | 0.9 | 1.5 | - | good | 2000 | 16 |
| 15 | NSW | WSW | 11 | 15 | - | 12 | 16 | 0.8 | 4 | N | 0.7 | 6 | 1.1 | 1.8 | **1.6** | good | 3500 | 16 |
| 18 | NSW | WSW | 10 | 15 | - | 11 | 15 | 0.7 | 3 | NW | 0.7 | 5 | 1.0 | 1.7 | **1.5** | good | 3500 | 16 |
| 21 | NSW | SW | 13 | 17 | - | 14 | 19 | 0.9 | 4 | NW | 0.6 | 5 | 1.1 | 1.8 | **1.6** | good | 3500 | 17 |
| Wednesday, 24 Sep 2014 - Luchterduinen 52º24'N 004º10'E | | | | | | | | | | | | | | | | | | |
| 00 | NSW | SW | 14 | 19 | - | 16 | 21 | 1.1 | 5 | NW | 0.5 | 5 | 1.2 | 2.0 | **1.7** | good | 3500 | 17 |

## 24 September 2014 Observed Weather Conditions 00:01 – 24:00

**Weather Today**

| Time | WX | Winds | | | | | | Waves | | | | | | | | Vis | Clouds | Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10m | | | | 50m | | Wind Wave | | Swell | | | Wave | | | 10m | Lowest | Air |
| UTC | | Dir | Spd (kts) | Gust (kts) | Risk (kts) | Spd (kts) | Gust (kts) | Hgt (m) | Per (sec) | Dir | Hgt (m) | Per (sec) | Hsig (m) | Max (m) | Risk (m) | | (ft) | (degC) |
| Wednesday, 24 Sep 2014 - Luchterduinen 52º24'N 004º10'E | | | | | | | | | | | | | | | | | | |
| 00 | NSW | SW | 16 | 22 | - | 18 | 24 | 0.9 | 4 | NW | 0.5 | 6 | 1.0 | 1.7 | **1.5** | good | 3500 | 17 |
| 03 | NSW | SW | 17 | 23 | - | 19 | 25 | 1.1 | 5 | NW | 0.5 | 5 | 1.2 | 2.0 | **1.7** | good | 3500 | 16 |
| 06 | SHRA | WSW | 20 | 26 | **23** | 21 | 28 | 1.2 | 5 | W | 0.5 | 5 | 1.3 | 2.2 | **1.8** | md/gd | 3500 | 16 |
| 09 | SHRA | WSW | 20 | 26 | **23** | 22 | 29 | 1.4 | 5 | NW | 0.5 | 6 | 1.5 | 2.5 | **2.0** | md/gd | 1000 | 15 |
| 12 | TS | W | 17 | 23 | **30** | 19 | 25 | 0.8 | 4 | W | 1.0 | 5 | 1.3 | 2.2 | **1.8** | md/gd | 1000 | 15 |
| 15 | TS | WNW | 19 | 25 | **31** | 20 | 26 | 1.0 | 4 | W | 0.8 | 5 | 1.3 | 2.2 | **1.8** | md/gd | 1000 | 15 |
| 18 | SHRA | NW | 19 | 25 | **23** | 21 | 27 | 1.0 | 4 | WSW | 0.6 | 5 | 1.2 | 2.0 | **1.7** | md/gd | 1000 | 15 |
| 21 | SHRA | NW | 21 | 27 | **23** | 23 | 30 | 1.5 | 5 | W | 0.6 | 6 | 1.6 | 2.7 | **2.1** | md/gd | 2000 | 15 |
| Thursday, 25 Sep 2014 - Luchterduinen 52º24'N 004º10'E | | | | | | | | | | | | | | | | | | |
| 00 | NSW | NW | 19 | 25 | - | 21 | 27 | 1.4 | 5 | WNW | 0.7 | 6 | 1.6 | 2.7 | **2.1** | good | 2000 | 16 |

## 25 September 2014 Observed Weather Conditions 00:01 – 24:00

**Weather Today**

| Time | WX | Winds | | | | | | Waves | | | | | | | | Vis | Clouds | Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10m | | | | 50m | | Wind Wave | | Swell | | | Wave | | | 10m | Lowest | Air |
| UTC | | Dir | Spd (kts) | Gust (kts) | Risk (kts) | Spd (kts) | Gust (kts) | Hgt (m) | Per (sec) | Dir | Hgt (m) | Per (sec) | Hsig (m) | Max (m) | Risk (m) | | (ft) | (degC) |
| Thursday, 25 Sep 2014 - Luchterduinen 52º24'N 004º10'E | | | | | | | | | | | | | | | | | | |
| 00 | NSW | NW | 18 | 24 | - | 20 | 26 | 1.5 | 5 | W | 0.8 | 6 | 1.7 | 2.8 | **2.2** | good | 2000 | 15 |
| 03 | NSW | NW | 16 | 22 | - | 18 | 23 | 1.2 | 5 | NW | 1.0 | 6 | 1.6 | 2.7 | **2.1** | good | 2000 | 15 |
| 06 | NSW | WNW | 13 | 18 | - | 14 | 20 | 0.6 | 3 | NW | 1.2 | 6 | 1.3 | 2.2 | **1.8** | good | 3500 | 15 |
| 09 | NSW | WSW | 17 | 23 | - | 19 | 25 | 0.7 | 4 | NW | 0.9 | 6 | 1.1 | 1.8 | **1.6** | good | 2000 | 15 |
| 12 | NSW | WSW | 19 | 25 | - | 20 | 27 | 1.1 | 4 | NW | 0.8 | 6 | 1.4 | 2.3 | **1.9** | good | 2000 | 15 |
| 15 | NSW | WSW | 20 | 26 | **22** | 22 | 28 | 1.1 | 4 | NW | 0.8 | 6 | 1.4 | 2.3 | **1.9** | good | NLC | 16 |
| 18 | NSW | WSW | 19 | 25 | - | 21 | 28 | 1.1 | 4 | NW | 0.7 | 6 | 1.3 | 2.2 | **1.8** | good | 2000 | 17 |
| 21 | NSW | WSW | 18 | 24 | - | 21 | 27 | 1.2 | 4 | NW | 0.6 | 6 | 1.3 | 2.2 | **1.8** | good | 3500 | 18 |
| Friday, 26 Sep 2014 - Luchterduinen 52º24'N 004º10'E | | | | | | | | | | | | | | | | | | |
| 00 | NSW | WSW | 17 | 23 | - | 19 | 25 | 1.0 | 4 | WNW | 0.7 | 6 | 1.2 | 2.0 | **1.7** | good | 1000 | 18 |

## 26 september 2014 Observed Weather Conditions 00:01 – 24:00

**Weather Today**

| Time | WX | Winds | | | | | | Waves | | | | | | | | Vis | Clouds | Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10m | | | | 50m | | Wind Wave | | Swell | | | Wave | | | 10m | Lowest | Air |
| UTC | | Dir | Spd (kts) | Gust (kts) | Risk (kts) | Spd (kts) | Gust (kts) | Hgt (m) | Per (sec) | Dir | Hgt (m) | Per (sec) | Hsig (m) | Max (m) | Risk (m) | | (ft) | (degC) |
| Friday, 26 Sep 2014 - Luchterduinen 52º24'N 004º10'E | | | | | | | | | | | | | | | | | | |
| 00 | DZ | WSW | 18 | 24 | - | 20 | 26 | 0.9 | 4 | W | 0.7 | 5 | 1.1 | 1.8 | **1.6** | md/gd | 1000 | 18 |
| 03 | DZ | WSW | 18 | 24 | - | 20 | 26 | 1.0 | 4 | WNW | 0.5 | 5 | 1.1 | 1.8 | **1.6** | md/gd | 1000 | 17 |
| 06 | DZ | WSW | 19 | 25 | - | 21 | 27 | 1.2 | 5 | WNW | 0.4 | 5 | 1.3 | 2.2 | **1.8** | md/gd | 1000 | 17 |
| 09 | DZ | WSW | 19 | 25 | - | 21 | 27 | 1.4 | 5 | SW | 0.5 | 6 | 1.5 | 2.5 | **2.0** | md/gd | 1000 | 17 |
| 12 | NSW | WSW | 17 | 22 | - | 19 | 25 | 1.2 | 4 | SW | 0.7 | 6 | 1.4 | 2.3 | **1.9** | good | 1000 | 17 |
| 15 | DZ | WNW | 14 | 19 | - | 15 | 21 | 0.8 | 4 | WSW | 0.9 | 5 | 1.2 | 2.0 | **1.7** | md/gd | 1000 | 17 |
| 18 | NSW | WNW | 11 | 15 | - | 12 | 16 | 0.4 | 3 | W | 1.0 | 5 | 1.1 | 1.8 | **1.6** | good | 2000 | 17 |
| 21 | NSW | NW | 9 | 13 | - | 10 | 14 | 0.3 | 2 | WNW | 0.9 | 5 | 0.9 | 1.5 | - | good | 1000 | 17 |