Offshore Wind Farm *Gemini*

Ecological monitoring of underwater noise during piling at Offshore Wind Farm *Gemini*

Version 4

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Abstract

Buitengaats C.V. (Gemini) conducted pile driving works for the Offshore Wind Farm (OWF) *Gemini* in the Northern Sea (Dutch area). According to the permit, one of the requirements for the construction and operation of the wind farm *Gemini* is the conduction of a monitoring and evaluation program (MEP). One part of this MEP is the measurement of underwater noise during piling and of ambient noise before or after piling.

In accordance with the requirements, underwater noise during pile driving was measured at two different Monopiles (foundation structure of the wind turbines) and one Pin-pile (jacket foundation of the Offshore High Voltage Station), at four distances (MP1 to MP4 at 750 m to approx. 60 km) to the source. The technical differences between the piles are listed in Table 1. The aim of the measurements during pile driving was to evaluate the influence of distance to the piling source on the underwater noise. Furthermore, a comparison between the underwater noises of the different pile designs was conducted. 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. Scope of this report are the detailed documentation of the conducted underwater noise measurements and the presentations of the results.

Table 1: *Pile and foundation conditions for the Monopiles U8 and Z2 and the pin pile of OHVS1.*

Foundation	U8	Z2	OHVS1 (B3)
Pile	Monopile	Monopile	Pin pile
Diameter [m]	7.00	6.60	2.44
Pile length [m]	66.5	63.4	58.4
Penetration depth [m]	27.41	28.40	44.00
Water depth [m]	34.09	30.00	34.99
Total blows	3,361	3,560	4,421
Total blow energy [kJ]	3,258,197	2,285,504	2,718,286
Max. blow energy [kJ]	1,486	894	1,044

The measured Sound Exposure Levels (SEL) including standard deviations (SD) during pile driving activities are listed in the following tables:

Table 2: *Overview of pile driving noise at foundation U8.*

U8 (Monopile, Water depth: 34.09 m)							
Measurement-height above seabed	Position	Distance [m]	Distribution level of SEL [dB re 1 µPa²s]				
			minimum	mean	median	max	SD
2 m	$MP1_{U8}$	732	177	180	180	183	1
	MP2	7,017	159	163	163	164	1
	MP3	31,816	140	144	144	148	1
	MP4	65,764	119	129	129	133	3
10 m	$MP1_{U8}$	732	176	180	180	182	1
	MP2	7,017	159	162	163	165	1
	MP3	31,816	141	145	145	149	1
	MP4	65,764	122	130	130	133	2

Table 3: *Overview of pile driving noise at foundation Z2.*

Z2 (Monopile, Water depth: 30.00 m)							
Measurement-height above seabed	Position	Distance [m]	Distribution level of SEL [dB re 1 µPa²s]				
			minimum	mean	median	max	SD
2 m	$MP1_{Z2}$	677	170	180	180	181	1
	MP2	3,933	151	167	167	169	1
	MP3	28,059	140	144	144	146	1
	MP4	61,891	126	129	129	132	1
10 m	$MP1_{Z2}$	677	170	180	180	181	1
	MP2	3,933	150	166	166	168	1
	MP3	28,059	141	146	146	148	1
	MP4	61,891	126	130	130	134	1

Table 4: *Overview of pile driving noise at foundation OHVS1.*

OHVS1 (Pin pile B3, Water depth: 34.99 m)							
Measurement-height above seabed	Position	Distance [m]	Distribution level of SEL [dB re 1 µPa²s]				
			minimum	mean	median	max	SD
2 m	$MP1_{OHVS1}$	921	165	170	170	173	1
	MP2	5,100	147	157	157	160	1
	MP3	20,136	131	141	142	144	2
	MP4	54,069	118*	126*	127*	129*	2
10 m	$MP1_{EL42}$	921	166	171	171	173	1
	MP2	5,100	134	156	157	158	1
	MP3	20,136	133	144	145	147	2
	MP4	54,069	119*	128*	129*	133*	3

*The Ratio between piling noise and ambient noise was below 6 dB, so the determination of the SEL was also influenced by the background noise. Not all blows could be detected.

Impact of different pile designs

Caused by the smaller size of the sound radiating surface in the water column, the Sound Exposure Level (SEL) was lower for the smaller Pin-pile B3 of the jacket-structure OHVS1 than for the lager Monopiles, as expected. For the Monopiles, no significant differences were measured.

Attenuation over large distances

By using common propagation models like the geometrical absorption - *15* log_{10}*(d – distance ratio)* or the common attenuation approach for good weather conditions of Thiele & Schellstede (1980), the measured attenuation of the pile driving noise at large distances was higher than expected. Only by using the model for rough sea (wave height above 2 m) by Thiele & Schellstede (1980), the predicted values were close to the measured values at large distances.

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 111 dB and 155 dB re 1 µPa^2, in periods without underwater noise generated by pile driving. The mean values for the ambient noise were between 115 dB and 138 dB re 1 µPa^2. Values above 140 dB can be explained by vessel traffic. At the measuring positions MP1 to MP3 and at MP4, the noise level during pile driving at the Monopile foundations was at least 6 dB higher than the ambient noise level measured between the single blows and thus clearly determined.

Oldenburg, the 21st June 2016

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

List of changes

Version	Date	Changes
Version 1	22.10.2015	Draft
Version 2	18.11.2015	Integrated change requests by the client
Version 3	14.01.2016	Integrated change requests by the client
Version 4	21.06.2016	Integrated change requests by RWS

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1. Assignment of Tasks and Local Conditions

The company *Buitengaats C.V. (Gemini)* is building the OWF *Gemini* in the Northern Sea (Dutch area). This OWF consists of two wind farms, *Buitengaats* and *ZeeEnergie,* each including 75 offshore wind turbines (OWT) and an Offshore High Voltage Station (OHVS), see Figure 1 and Figure 2. The offshore wind turbines are fixed in the seabed (sediment) by Monopiles and the Offshore High Voltage Stations by Jacket-constructions with Pin-piles. All foundation pile structures are founded in the sediment by using impulse pile driving.

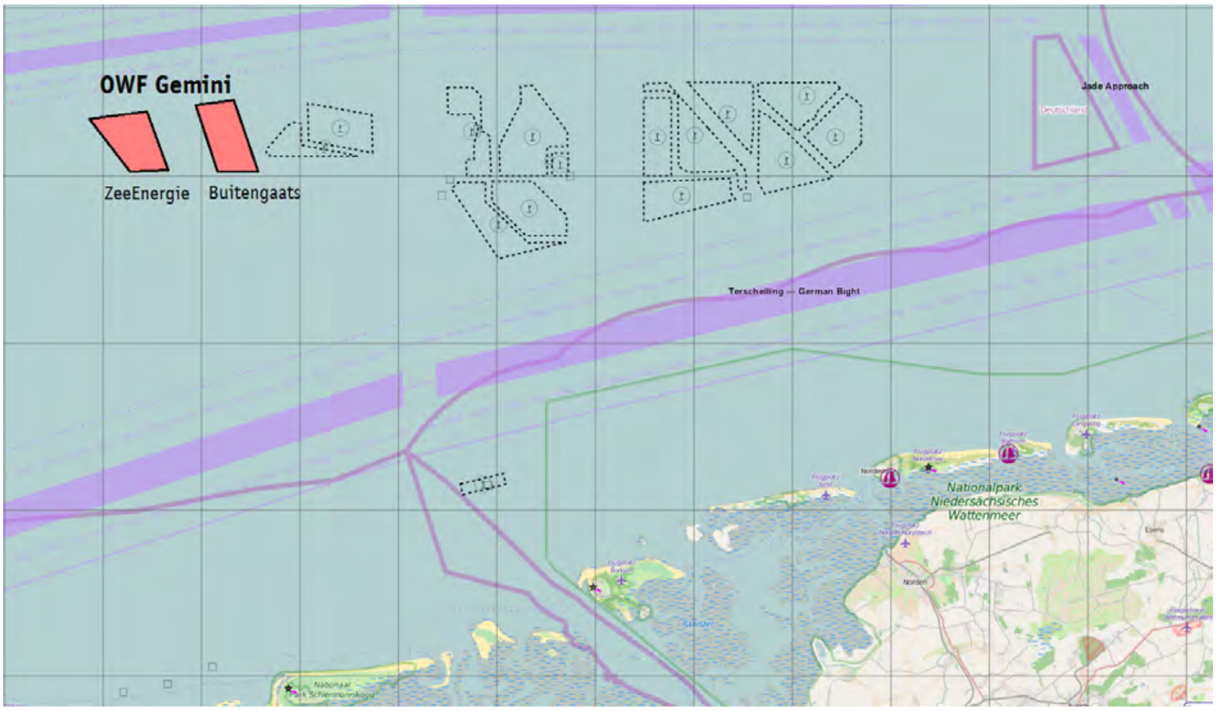


Figure 1: *Overview map from the area around Offshore Wind Farm "Gemini". The main traffic routes are marked by violet arrows (source: www.openseamap.org).*

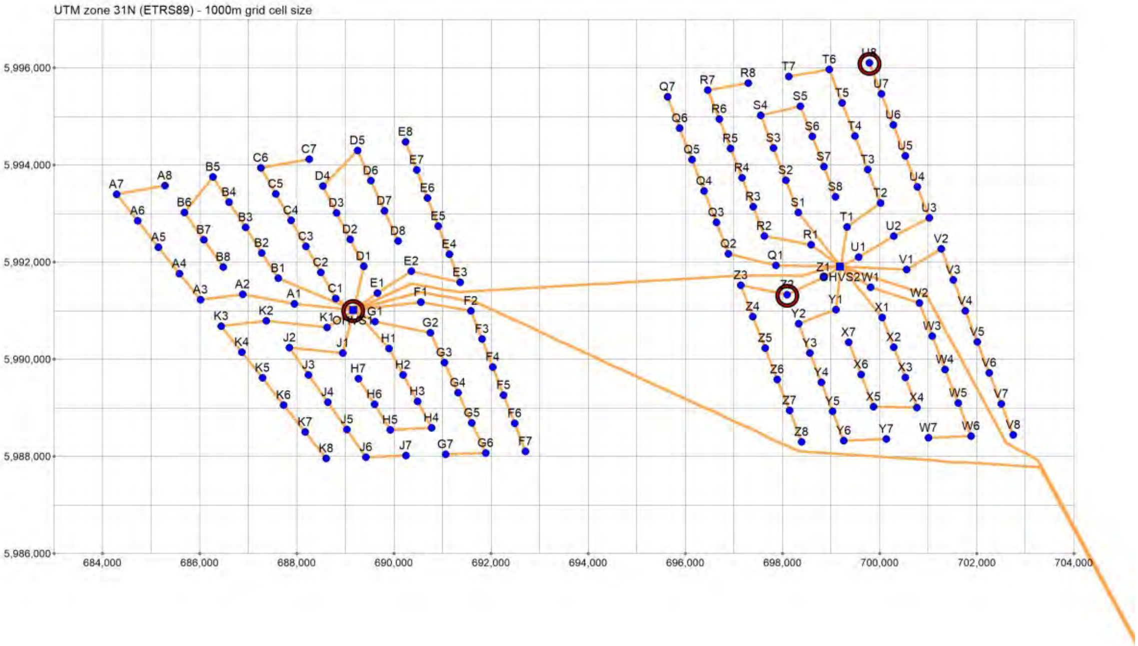


Figure 2: *Overview map of the Offshore Wind Farm "Gemini". The locations for the underwater noise measurements U8, Z2 and OHVS1 are marked by red circles.*

The permit (Dutch approval authority: Rijkswaterstaat Zee & Delta) imposed general requirements regarding underwater noise measurements during the installations:

- The underwater noise of hammering two Monopiles (pile driving activity) – in different water depths – and a pin pile from a jacket leg must be measured at various distances from the source. These data will be used by TNO for the validation of their 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 pile installations has to be measured.

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

2. Hydro Sound Measurements

2.1 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 that will be used by TNO to validate their underwater sound propagation models. Two questions need to be answered by this monitoring program at OWF *Gemini*:

1) What are the differences in underwater noise between the piles?
2) What are the underwater noise levels caused by piling at larger distances (> 20 km range)?

For this reason, the underwater noise was measured during pile driving at four positions of two different Monopiles (U8 at 34.09 m water depth and Z2 at 30.00 m water depth) and one Pin-pile of the jacket foundation (pile B3 of the OHVS1 at 33.6 m water depth). The measurement positions MP2 to MP4 were fixed outside the OWF area; measurement position MP1 was inside the OWF area and individually adjusted to each piling activity for having a fixed distance of 750 m to the sound source. At each measurement position, four hydrophones in two different heights were applied, at 2 m and 10 m above the seabed. Furthermore, two hydrophones were applied for ambient noise and two for pilling noise. Table 5 gives an overview of the relevant pile parameter. The measurement positions are listed in Table 6 and Figure 3. All measurement positions inside and outside the OWF construction area were selected in cooperation with *Buitengaats C.V. (Gemini)*, the construction company (*Van Oord*) and the competent authority.

Table 5: *Pile parameter of the locations U8, Z2 and B3 (OHVS1).*

Parameter	Foundation		
	U8	Z2	B3 (OHVS1)
Position [WGS 84]	54° 04.460′ N 006° 3.233′ E	54° 01.929′ N 006° 1.494′ E	54° 01.957′ N 005° 53.316′ E
Foundation Type	Monopile	Monopile	Pin pile
Diameter [m]	7.00	6.60	2.44
Pile length [m]	66.5	63.4	58.4
Penetration depth [m]	27.41	28.40	44.00
Start piling*	21-7-2015 13:10	22-7-2015 06:04	4-8-2015 07:07
Stop piling*	21-7-2015 16:04	22-7-2015 08:25	4-8-2015 08:55
Total time [h:m]	02:54	02:21	01:48
Net time [h:m]	01:13	01:22	01:36
Water depth [m]	34.09	30.00	34.99

*Local time = UTC +2 hours.

Table 6*: Measurement positions and distances.*

Position	Location [WGS84]		Distance [m]		
	Lat	Lon	to U8	to Z2	to OHVS1
$MP1_{U8}$	54° 04,835′ N	006° 03,446′ E	732	5,796	12,277
$MP1_{Z2}$	54° 01,880′ N	006° 00,879′ E	5,433	677	8,260
$MP1_{OHVS1}$	54° 01,624′ N	005° 52,692′ E	12,653	9,629	921
MP2	54° 02,306′ N	005° 57,949′ E	7,017	3,933	5,100
MP3	53° 56,096′ N	005° 37,816′ E	31,816	28,059	20,136
MP4	53° 46,922′ N	005° 11,029′ E	65,764	61,891	54,069

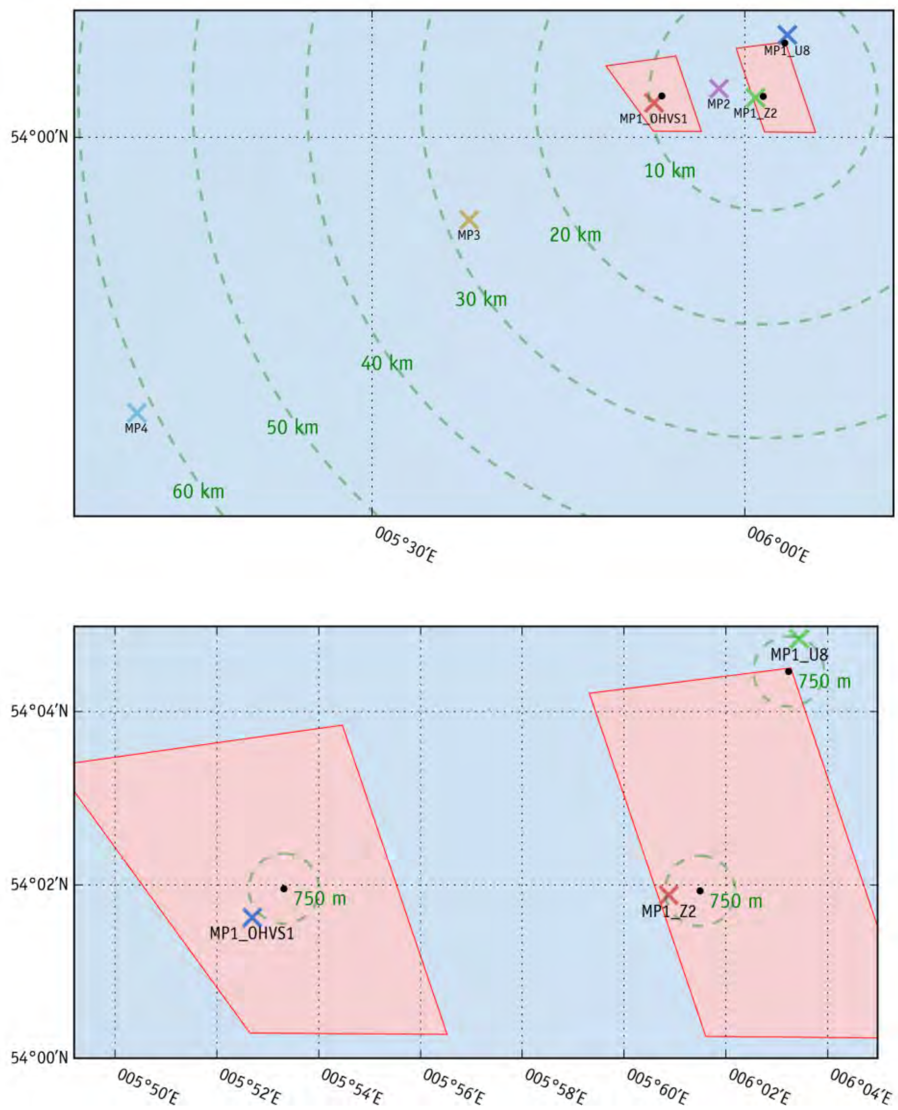


Figure 3: *Measurement positions inside and outside the OWF construction area.*

2.2 Underwater noise Measurement Device

2.2.1 General

For all measurement locations, the same type of measuring device was 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 underwater noise sound are stand-alone (deployed) measuring systems that were developed and built by *itap GmbH*. Figure 4 shows a photographical picture of an underwater noise measuring system incl. small anchorage (mooring system, see details in chapter 3.2.2).

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

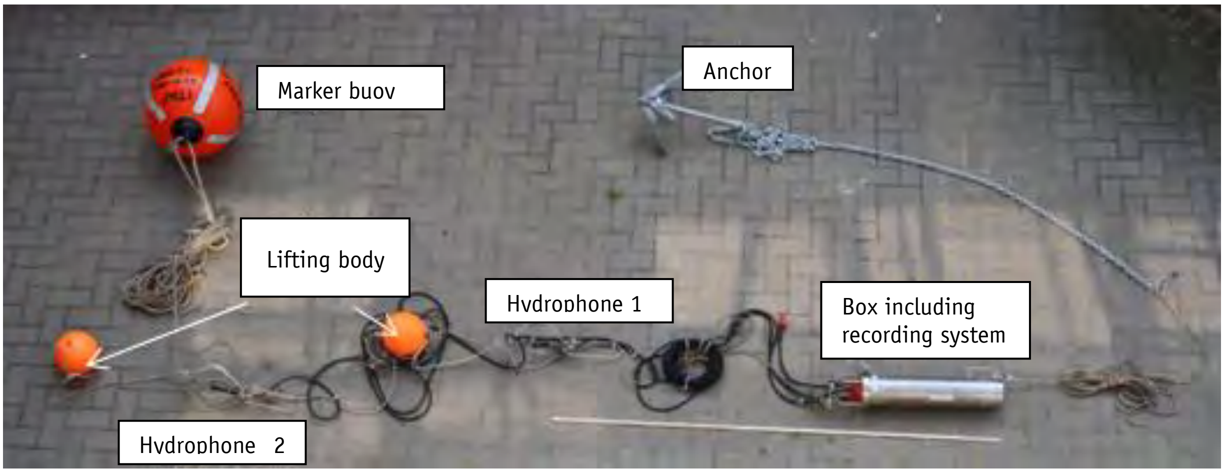


Figure 4: *Stand-alone deployed underwater noise measurement device with small anchorage and marking in a two-channel hydrophone design by itap GmbH. For the measurements, two of these systems were used for one measurement position, one device for ambient noise and one device for pilling noise.*

2.2.2 Mooring system

The underwater noise measurement devices at the locations outside the OWF area (MP2, MP3 and MP4) were attached to a big mooring system (Figure 5). On every location, two underwater noise measurement devices were attached to the sediment rope from the big 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 big anchor (anchor #1 in Figure 5) of the 100 m long “sediment rope”. To avoid disturbing noise from movements of the measurement setup, only ropes with steel cores and textile jackets were used.

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

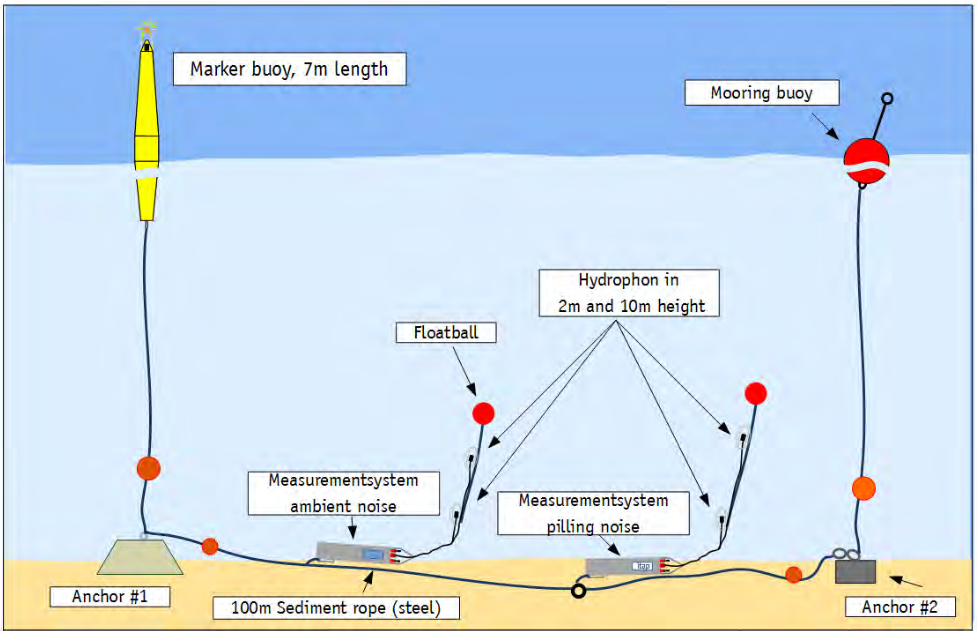


Figure 5: *Schematic depiction of a long-term underwater noise recording for measurement locations outside the OWF area (MP2 to MP4) with two devices (not to scale). The two devices were fixed to the sediment rope and each system had two hydrophones at two different heights: 2 m and 10 m above seabed.*

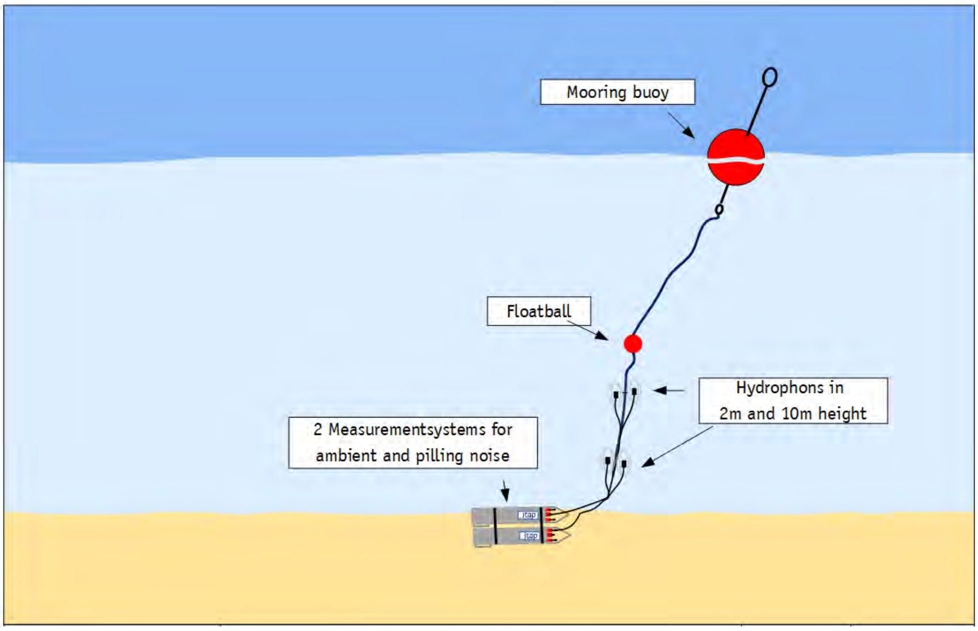


Figure 6: *Schematic diagram of an underwater noise measuring system incl. small anchorage (for the measurement location inside the OWF area – MP1). (not to scale)*

2.2.3 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 applied (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 applied depending on the distance to the source of sound. Table 7 and Table 8 provide an overview of all applied devices and hydrophones. A detailed overview is listed in the Annex A2.

2.2.4 File formats (signal specifications)

The underwater noise measurement devices are able to record the time signal of the measured underwater noise 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 underwater noise 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 are 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 at 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): The measuring systems recorded the underwater noise signals lossless (uncompressed) and in compliance with the actually 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 underwater noise max. 36 h (storage / operational time is limited).

Compressed file format (MP2 to MP4): The measuring systems recorded the underwater noise signals in a compressed file format (MPEG1[1], 48 kHz sampling-rate). In this recording mode, the underwater noise could be stored (operational time) for a period of four weeks. The difference between a signal recorded in a lossless format or in MPEG1 is much smaller than the Measuring Uncertainty (see Chapter 3.4.2).

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

2.2.5 Overview of used devices

The main components used for the underwater noise measurements are listed in Table 7. Table 8 gives an overview of the different set-ups used at every position. All measuring devices applied are in accordance with the measuring instruction for underwater sound

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

measurements from the German approval authority (Müller & Zerbst, 2011) and also fulfill the requirements of the WD ISO 18406 (2014) + TNO report (2011).

Table 7: *Devices applied for underwater noise 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: about 0.5 pC/Pa number: 12 pieces
Hydrophone B&K 8106	Bruel & Kjær	sensitivity: ca. 2 mV/Pa number: 4 pieces
Charge amplifier	Itap GmbH	0.1 mV/pC (only for TC4033)

Table 8: *Hydrophones and file formats applied at every measurement 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	compressed (on OHVS1 lossless and compressed)	compressed (on OHVS1 lossless and compressed)	big
	10	TC4033	TC4033	compressed (on OHVS1 lossless and compressed)	compressed (on OHVS1 lossless and compressed)	
MP3	2	TC4033	B&K 8106	compressed	compressed	big
	10	TC4033	B&K 8106	compressed	compressed	
MP4	2	TC4033	B&K 8106	compressed	compressed	big
	10	TC4033	B&K 8106	compressed	compressed	

2.3 Practical implementation

All underwater noise measuring systems inside and outside the construction site were deployed a few hours prior to commencement of pile driving works according to a coordinated procedure. At MP1, the devices were retrieved immediately upon the end of pile driving. The measurement devices at MP2 to MP4 were deployed and retrieved twice, once before and after both Monopile driving activities and once before and after the Pin-pile installation. The measurement times and the quality status of these measurements are listed in Table 9 for each position.

All deployment and recovery works were done from the vessel *Reykjanes* by an employee of *itap GmbH* and instructed personnel 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 in 750 m distance leads to an inaccuracy of 1.3 % and to 0.7 % in 1,500 m distance.

Table 9: *Recording times of each measurement position and quality status for each used device.*

Position	Measurement time [utc]		Raw data status
	start	end	
$MP1_{U8}$	20.07.15 19:28	21.07.15 17:17	Data of all 4 hydrophones are valid.
$MP1_{Z2}$	21.07.15 20:35	22.07.15 08:36	Data of all 4 hydrophones are valid.
$MP1_{OHVS1}$	03.08.15 17:01	05.08.15 05:21	Data of all 4 hydrophones are valid.
MP2	18.07.15 13:05	23.07.15 13:31	Data of all 4 hydrophones are valid.
	03.08.15 09:39	05.08.15 06:41	Data of all 8 hydrophones are valid.
MP3	18.07.15 11:18	23.07.15 15:52	Data of all 4 hydrophones are valid.
	03.08.15 07:34	05.08.15 09:16	Data of all 4 hydrophones are valid.
MP4	18.07.15 08:09	23.07.15 18:31	Data of all 4 hydrophones are valid.
	03.08.15 04:42	05.08.15 12:38	Data of all 4 hydrophones are valid.

3. Evaluation of Underwater noise Measurements

3.1 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 and the Pin-pile were evaluated and the results were summarized, which includes all measuring positions in- and outside the construction site. For this purpose, *Buitengaats C.V. (Gemini)* provided the respective pile driving protocol.

3.2 Definitions

For the following evaluation, the 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 *(τ_x)* for transient sounds

The time during which a specified percentage x of unweighted sound exposure occurs (e. g. τ_{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*.

3.3 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 6th order).

Determination of 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 filter bank according to IEC 1260:1995 standard. Third octave spectra are limited to the frequency range >12.5 Hz ≤ 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.

3.4 Measuring Uncertainty and Measuring Variance

3.4.1 Measuring Uncertainty

According to the measuring concept for underwater sound measurements of the German approval authority BSH (BSH, 2011), only measuring systems, whose entire measurement chain has a deviation with sensitivity of < 2 dB and ± 1 dB, may be applied. This is in accordance with the newly upcoming ISO standard (ISO/DIS 18406, 2015). 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 applied hydrophones are regularly calibrated by the manufacturer (full spectrum calibration every 2 years) and by *itap GmbH* (point source calibration). Additionally, each measurement device (recorder) has been calibrated by a defined electrical point source before and after each offshore application.

However, an unsystematic measurement uncertainty in repeated measurements in the range of ≥ 2 dB is generally to be expected during field measurements under offshore conditions, even with calm sea. A systematic study on this issue is currently not available.

3.4.2 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 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 a higher noise level than a small surface). The main difference is found between the large monopiles and the much smaller pin pile used for the OHVS foundation.

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 underwater noise (ground coupling effects). Whether and to what extent further parameters have an impact is currently studied in other research projects, for instance within the German research project BORA (project ID 0325421A/B/C funded by BMU, BMWi and PTJ), publication is expected within 2016.

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).

4. Measurement Results

The measured underwater noise pollutions (immissions) during the installation phase of the two selected Monopiles U8 and Z2 as well as the Pin-pile B3 (OHVS1) 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 (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 anthropometric noise like vessel noise.

4.1 Pile-Driving Noise

4.1.1 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 bending 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 7). The complete acoustical energy transmitted into 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 (τ_{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. This means that the energy of one impulse, normally a few milliseconds in duration (see Figure **7**), will be distributed to an interval of one second.

(ii) The maximum zero-to-peak Level (L_{Peak}) expresses the value of the maximal sound pressure during one blow as a level (red arrow in Figure 7).

(iii) The signal duration (τ_{90}) describes the time window, during which 90% of the energy arrives (grey shaded area in Figure 7). 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 to more than 10%. In this case, the signal duration (τ_{90}) is increasing rapidly. Smaller variances (< 100 ms for distances < 10 km) can be caused depending on the distance due to dispersion (see Chapter 5.2.2).

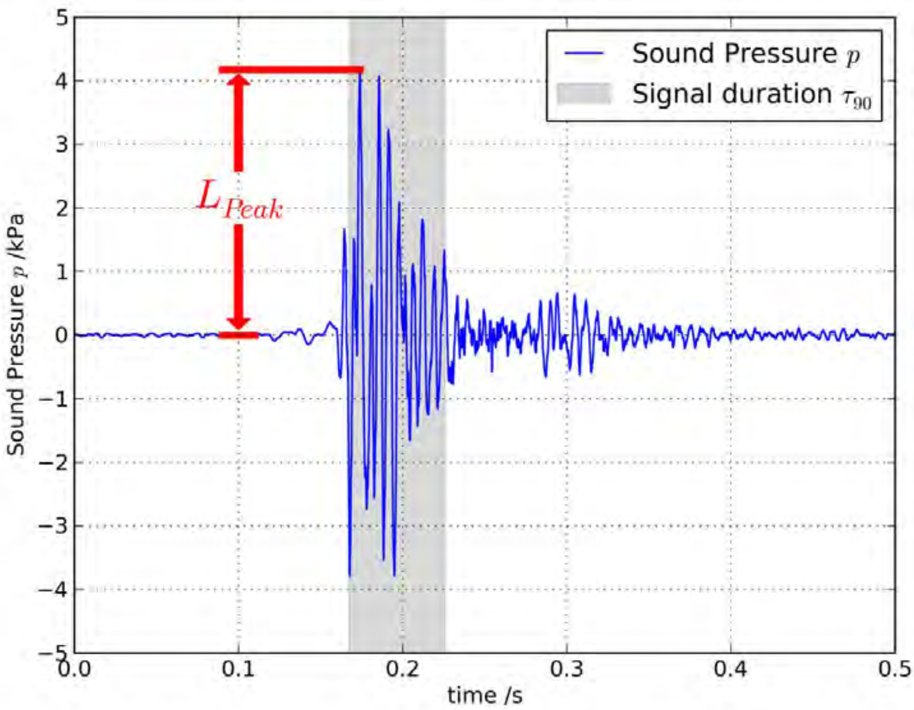


Figure 7: *Sample of pile-driving noise (transient noise) measured in 750 m distance. Blue: time signal of 0.5 seconds (1 blow) during pile driving. Grey: Signal duration* τ_{90}.

4.1.2 Underwater noise during pile driving

The distribution of the Sound Exposure Levels (SEL), separated for each measurement position during the pile driving activities, are summarized in Table 10 (Monopile U8), Table 11 (Monopile Z2) and Table 12 (Pin-pile).

Table 10: *Overview of pile driving noise at foundation U8.*

U8 (Monopile, Water depth: 34.09 m)							
Measurement-height above seabed	Position	Distance [m]	Distribution level of SEL [dB re 1 µPa²s]				
			minimum	mean	median	max	SD
2 m	$MP1_{U8}$	732	177	180	180	183	1
	MP2	7,017	159	163	163	164	1
	MP3	31,816	140	144	144	148	1
	MP4	65,764	119	129	129	133	3
10 m	$MP1_{U8}$	732	176	180	180	182	1
	MP2	7,017	159	162	163	165	1
	MP3	31,816	141	145	145	149	1
	MP4	65,764	122	130	130	133	2

Table 11: *Overview of pile driving noise at foundation Z2.*

Z2 (Monopile, Water depth: 30.00 m)							
Measurement-height above seabed	Position	Distance [m]	Distribution level of SEL [dB re 1 µPa²s]				
			minimum	mean	median	max	SD
2 m	$MP1_{Z2}$	677	170	180	180	181	1
	MP2	3,933	151	167	167	169	1
	MP3	28,059	140	144	144	146	1
	MP4	61,891	126	129	129	132	1
10 m	$MP1_{Z2}$	677	170	180	180	181	1
	MP2	3,933	150	166	166	168	1
	MP3	28,059	141	146	146	148	1
	MP4	61,891	126	130	130	134	1

Table 12: *Overview of pile driving noise at foundation OHVS1.*

OHVS1 (Pin pile B3, Water depth: 34.99 m)							
Measurement-height above seabed	Position	Distance [m]	Distribution level of SEL [dB re 1 µPa²s]				
			minimum	mean	median	max	SD
2 m	$MP1_{OHVS1}$	921	165	170	170	173	1
	MP2	5,100	147	157	157	160	1
	MP3	20,136	131	141	142	144	2
	MP4	54,069	118*	126*	127*	129*	2
10 m	$MP1_{EL42}$	921	166	171	171	173	1
	MP2	5,100	134	156	157	158	1
	MP3	20,136	133	144	145	147	2
	MP4	54,069	119*	128*	129*	133*	3

*The Ratio between piling noise and ambient noise was below 6 dB. Not all blows could be detected.

A detailed overview of all results at all measurement positions and all foundations is summarized in Appendix A1. As an example, Figure 8 to Figure 10 show the measurement results for $MP1_{U8}$ in 750 m distance for the hydrophone at the 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 8 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 Figure 10. 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 applied blow energy on the radiated pile driving noise (third plot of Figure 8). The last plot in Figure 8 shows the time dependent signal duration τ_{90} for each single blow.

Figure 9 shows the Sound Exposure Level (SEL) distribution as 1/3-octave spectra for the pile installation U8 at the measurement position $MP1_{U8}$ in 750 m distance as an example of the results of Table 10. In the histogram in Figure 10, the distribution of the Sound Exposure Level (SEL) at this measurement position is depicted. On this position, all measured Sound Exposure Levels (SEL) were within a range between 177 dB and 183 dB. During this measurement, more than 1,000 blows had a Sound Exposure Level (SEL) of 182 dB.

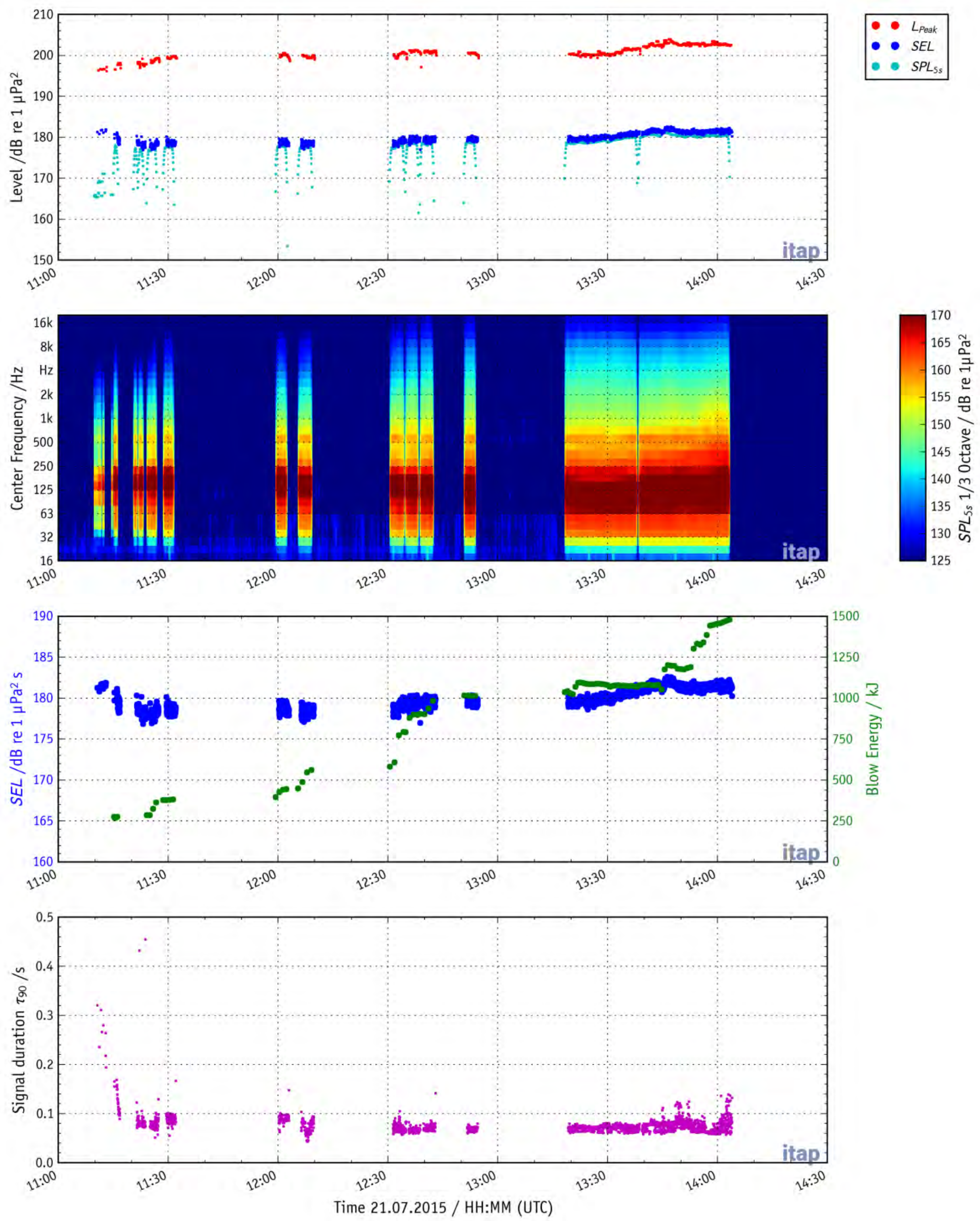


Figure 8: *Results of the pile driving noise at foundation U8 (Monopile) in 750 m distance ($MP1_{U8}$; hydrophone height: 2 m above seabed). Plot on top: Time depending Sound Exposure Level (SEL), Sound Pressure Level (SPL_{5s}) and Peak Level (L_{Peak}). 2^{nd} plot: 1/3-octave spectrogram of the SEL (depending on time and frequency). The Y-axis is conforming to DIN 461. Hz between 8k and 2k should be read as 4k. This is the case in all figures in the report. 3^{rd} plot: SEL as well as applied blow energy as function of time (presented times of SEL and blow energy are not synchronized, time differences of a few minutes are possible), bottom: measured signal duration (τ_{90}).*

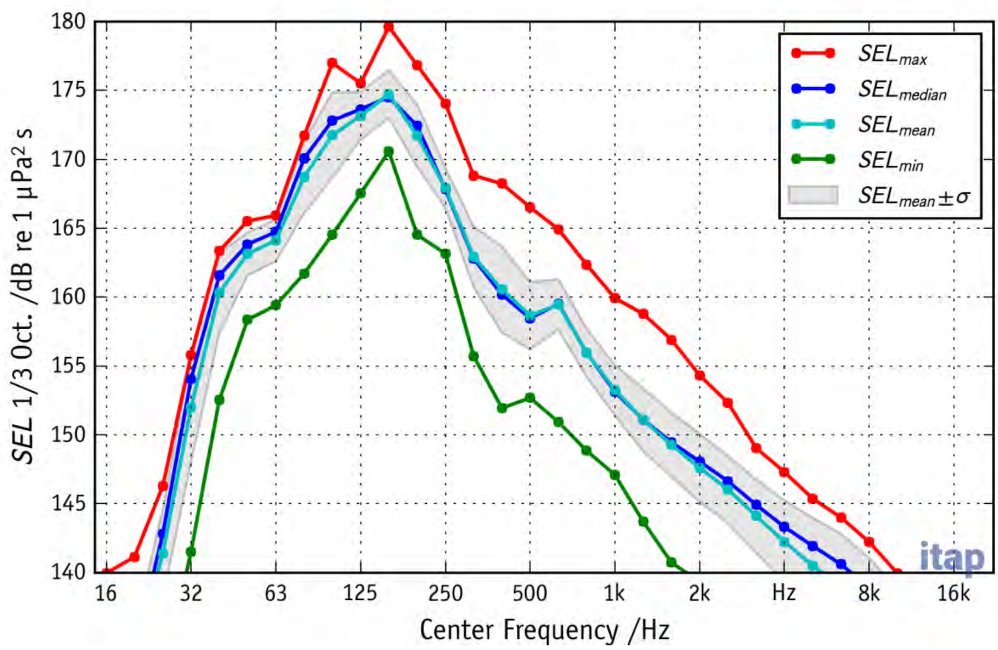


Figure 9: *1/3-Octave spectra of the Sound Exposure Level (SEL) measured at $MP1_{U8}$ (hydrophone height: 2 m above seabed).*

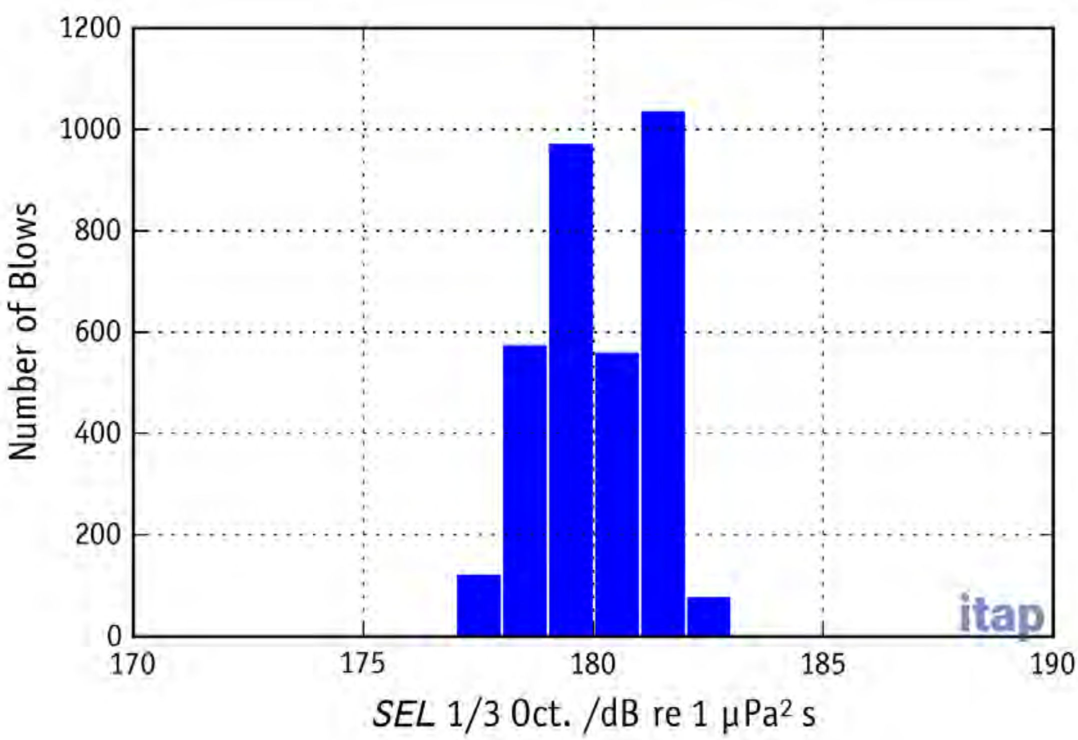


Figure 10: *Histogram of the Sound Exposure Level (SEL) measured in 750 m distance ($MP1_{U8}$) during the installation of the Monopile at U8 (hydrophone height: 2 m above seabed).*

4.2 Ambient Noise

The continuous ambient noise is analyzed in averaged unweighted Sound Pressure Levels (SPL) for a period of five seconds (SPL_{5s}). The ambient noise includes all natural and anthropogenic sound events at the measurement positions except the pile driving. The biggest impact has the vessel traffic. For the evaluation of the ambient noise, two time windows per pile foundation were chosen, before and directly after the respective pile driving activity at that location took place. The chosen time windows are listed in Table 13 for each foundation. The piling activities took place during the period between the first and the second time window. According to the attached weather data, the wave heights during the whole measurements were between 0.5 m and 2 m.

Table 13: *Evaluation periods for each foundation for ambient noise.*

Foundation	Time window [utc]		
	Date	Start-time	End-time
U8	2015-07-20/21	20:00	11:00
	2015-07-21	14:15	17:00
Z2	2015-07-21/22	21:00	04:00
	2015-07-22	06:30	08:00
OHVS1	2015-08-03/04	17:00	05:00
	2015-08-04	07:00	10:30

The distribution of the measured Sound Pressure Level (SPL_{5s}) at all measurement positions before and after each pile driving activity is expressed in different percentiles and summarized in Table 14 and Table 15. The percent values of the percentiles refer to the time during the evaluation periods given in Table 13. The differences between the measurement positions are mainly caused by the vessel traffic and their distances to the measurement positions. A presentation of the above mentioned distribution levels as a function of frequency and the distribution are shown in Appendix A.1. Similar to the figures of the piling noise, the time dependent SPL_{5s} behavior is shown as broadband value and in a frequency dependent analysis (spectrogram). Figure 11 to Figure 13 give an example for the measurement position MP1 at a hydrophone height of 2 m, in 750 m distance to the Monopile U8.

Table 14: *Evaluation of the measured ambient noise by using the Sound Pressure Level (SPL_{5s}) distribution before (15 hours) and after (2.75 hours) the installation of the Monopile U8.*

U8 (Monopile, Water depth: 34.09 m)									
Hydrophone-height	Position	Distance [m]	Sound Pressure Level SPL_{5s} [dB re 1 μPa²]						
			min	95 % exceedance	mean	median	5 % exceedance	max	SD
2 m	$MP1_{U8}$	732	120	121	128	127	138	146	5
	MP2	7,017	129	131	133	133	137	142	2
	MP3	31,816	111	112	115	115	120	128	3
	MP4	65,764	112	114	120	120	126	129	4
10 m	$MP1_{U8}$	732	120	121	128	127	139	146	5
	MP2	7,017	129	131	133	133	137	142	2
	MP3	31,816	111	112	115	115	120	128	3
	MP4	65,764	110	112	117	117	124	126	4

Table 15: *Evaluation of the measured ambient noise by using the Sound Pressure Level (SPL_{5s}) distribution before (7 hours) and after (1.5 hours) the installation of the Monopile Z2.*

Z2 (Monopile, Pile length: 30.00 m)									
Hydrophone-height	Position	Distance [m]	Sound Pressure Level SPL_{5s} [dB re 1 μPa²]						
			min	95 % exceedance	mean	median	5 % exceedance	max	SD
2 m	$MP1_{Z2}$	677	120	120	129	130	133	136	3
	MP2	3,933	129	132	138	138	144	152	4
	MP3	20,123	113	114	116	116	119	122	2
	MP4	61,891	116	118	122	122	128	130	3
10 m	$MP1_{Z2}$	677	120	120	129	130	133	136	3
	MP2	3,933	129	132	138	138	144	152	4
	MP3	20,123	113	114	116	115	118	122	1
	MP4	61,891	114	115	120	120	125	128	3

Table 16: *Evaluation of the measured ambient noise by using the Sound Pressure Level (SPL_{5s}) distribution before (12 hours) and after (3.5 hours) the installation of the Pin pile B3 (OHVS1).*

OHVS1 (Pin pile B3, Water depth: 34.99 m)									
Measure-ment-height above seabed	Position	Distance [m]	Sound Pressure Level SPL_{5s} [dB re 1 µPa^2]						
			mini-mum	95 % exceedance	mean	median	5 % exceedance	max	SD
2 m	$MP1_{OHVS1}$	921	114	115	127	128	134	155	6
	MP2	5,100	109	112	125	124	136	141	7
	MP3	20,136	108	110	119	118	129	140	6
	MP4	54,069	112	115	120	120	125	145	4
10 m	$MP1_{OHVS1}$	921	114	115	127	128	134	155	6
	MP2	5,100	109	113	125	125	137	142	7
	MP3	20,136	105	107	116	116	126	137	6
	MP4	54,069	110	113	118	118	123	143	4

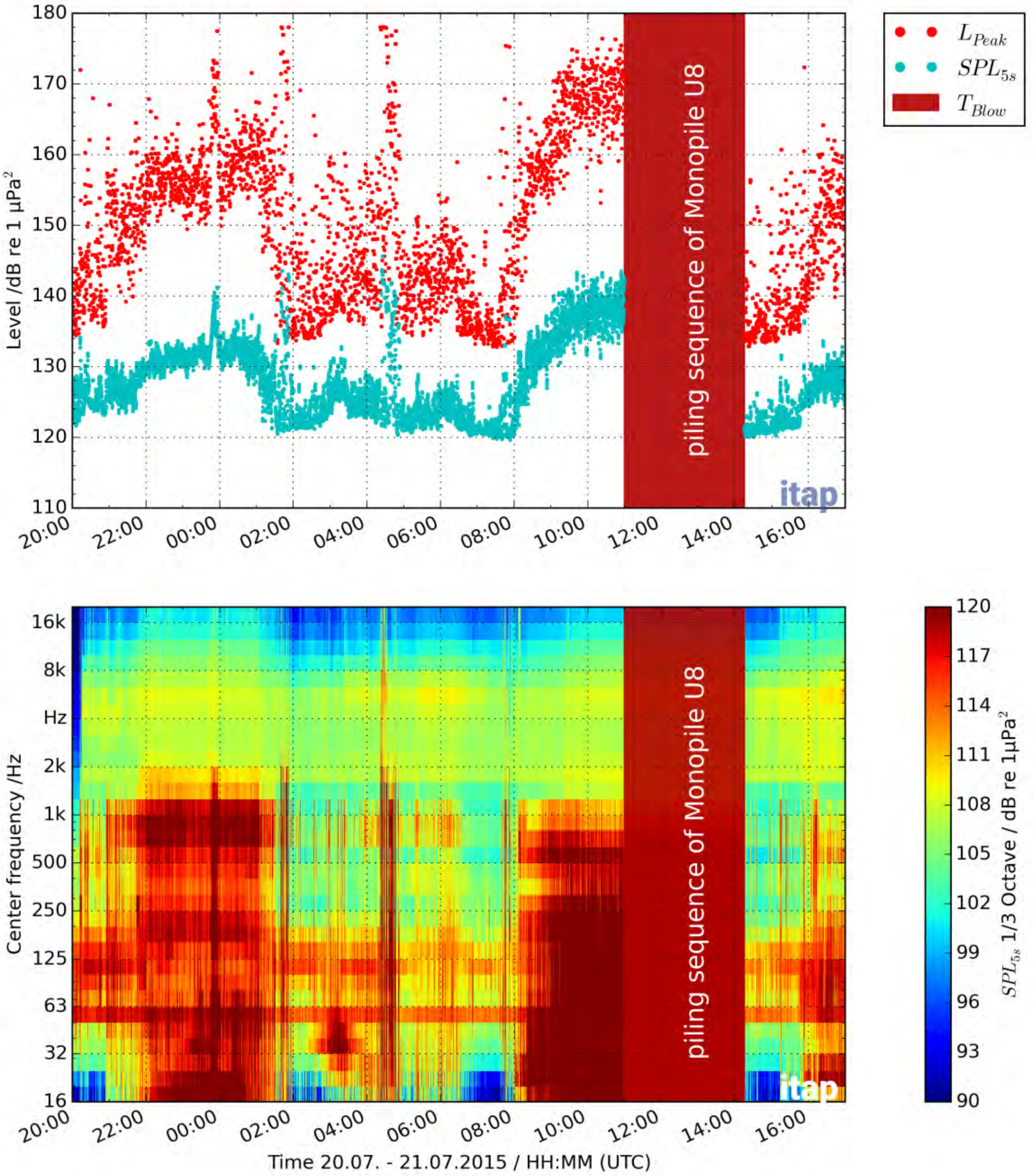


Figure 11: *Time dependent zero-to-peak (L_{Peak}) and Sound Pressure Level (SPL_{5s}) distribution of the ambient noise measurements at the measurement position $MP1_{U8}$ before and after the installation of the Monopile U8 (hydrophone height: 2 m above seabed). Top: SPL_{5s} and L_{Peak} values versus time. Bottom: Spectrogram of SPL_{5s} (frequency resolution in 1/3 Octaves). Between 21:00 and 01:00 and between 08:00 and 12:00 two noticeable events occurred. These events sound like friction noise close to the hydrophone. The reason cannot be clarified.*

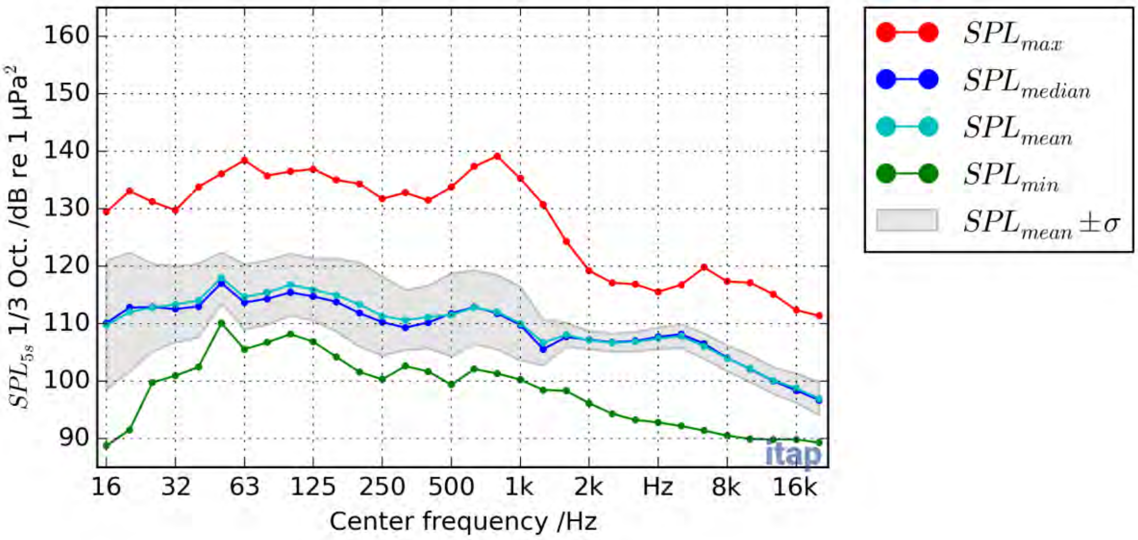


Figure 12: *Measured Sound Pressure Level (SPL_{5s}) in 1/3 Octave bands at $MP1_{U8}$ before and after the installation of the Monopile U8 (hydrophone height: 2 m above seabed).*

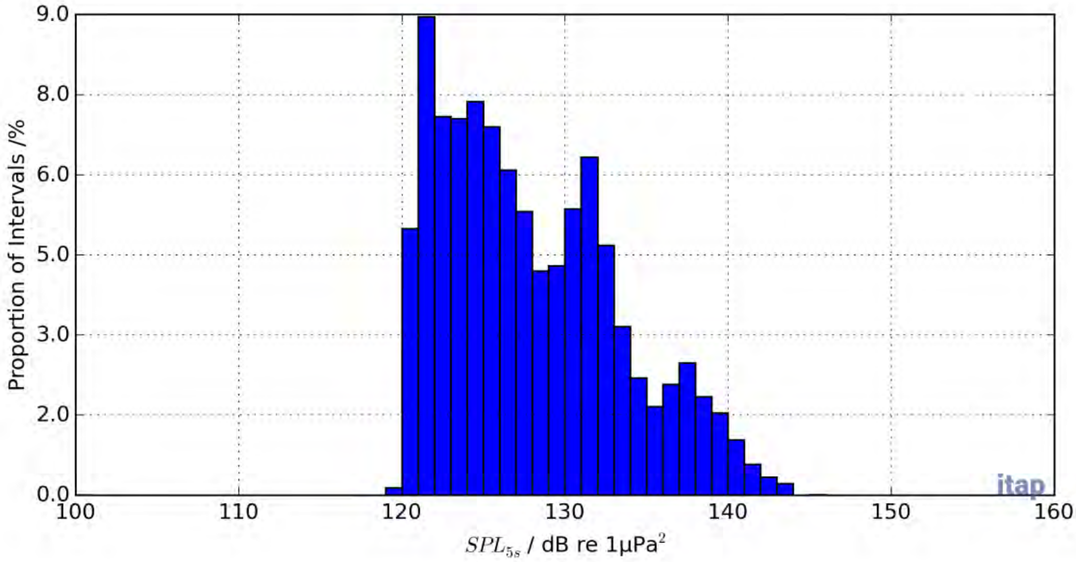


Figure 13: *Histogram of the Sound Pressure Level (SPL_{5s}) measured at $MP1_{U8}$ before and after the installation of the Monopile U8 (hydrophone height: 2 m above seabed).*

5. Discussion

Besides the validation of the TNO underwater sound propagation models (which will be done by TNO and is 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 piles?
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 parameters. 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 have to be determined and compared with common propagation models.

5.1 Variances of the source level caused by different pile designs

Generally, the source level symbolizes 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 at a single point (moving point source see chapter 4.1). 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.

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 pile vibrations are depending inter alia on the energy transmitted by the hammer into the pile and the soil conditions. The sound radiating surface is determined primarily by the pile diameter and length as well as by the water depth.

The Pin-pile has a smaller diameter than the Monopiles and therefore a smaller sound radiating surface in the water column. This leads to an approx. 7 dB lower Sound Exposure

Level (SEL) compared with the Monopile. As it is shown in Figure 14 and Figure 15, the Sound Exposure Level is decreasing at the end of the piling sequence, although the blow energy is increasing. This decrease is typically for Pin-piles, because the top of the Pin-pile went below the water surface and the sound radiating surface got smaller. At approx. 05:45 UTC time, the top of the pin-pile went below the water surface. The half of the water depth was attained at approx. 06:40, see last axis on Figure 14. Caused by missing time stamps in the pile driving protocol and missing synchronization between measurement devices and pile hammer, it was only possible to determine time windows for an occurring event.

The two Monopiles differ in diameter, water depth and the applied maximum blow energy, see Table 17. Because the sound radiating surface and the applied maximum blow energy were higher at Monopile U8, higher sound pressure levels between 2 dB and 3 dB were expected. However in Figure 14 can be seen that this is only the case during the last stage of the piling sequence of Monopile U8: from approx. 13:20, when the blow energy is increased above 1,000 kJ the Sound Exposure Level (SEL) increases above 180 dB. The mean and median distribution level of the Sound Exposure Level (SEL_{50}) is however the same for both Monopiles.

Usually, the Sound Exposure Level (SEL) is increasing with increasing blow energy. With an increase of the blow energy to double, an increase of approx. 2.5 dB is expected (Gündert, 2014). In the present case, the Sound Exposure Level during the soft start at Monopile Z2 and at the Pin-pile is already as high as if the maximum blow energy would have been applied. The reason for this is unclear. Occasionally, this effect was measured during Pile driving works in Germany. Possible influences could be the contact between the pile hammer and the pile or coupling effects with the pile guiding frame.

Table 17: *Pile and foundation conditions for the Piles U8, Z2 and B3 (OHVS1).*

Foundation	U8	Z2	OHVS1 (B3)
Pile	Monopile	Monopile	Pin-pile
Diameter [m]	7.00	6.60	2.44
Pile length [m]	66.5	63.4	58.4
Penetration depth [m]	27.41	28.40	44.00
Water depth [m]	34.09	30.00	34.99
Total blows	3,361	3,560	4,421
Total blow energy [kJ]	3,258,197	2,285,504	2,718,286

Max. blow energy [kJ]	1,486	894	1,044

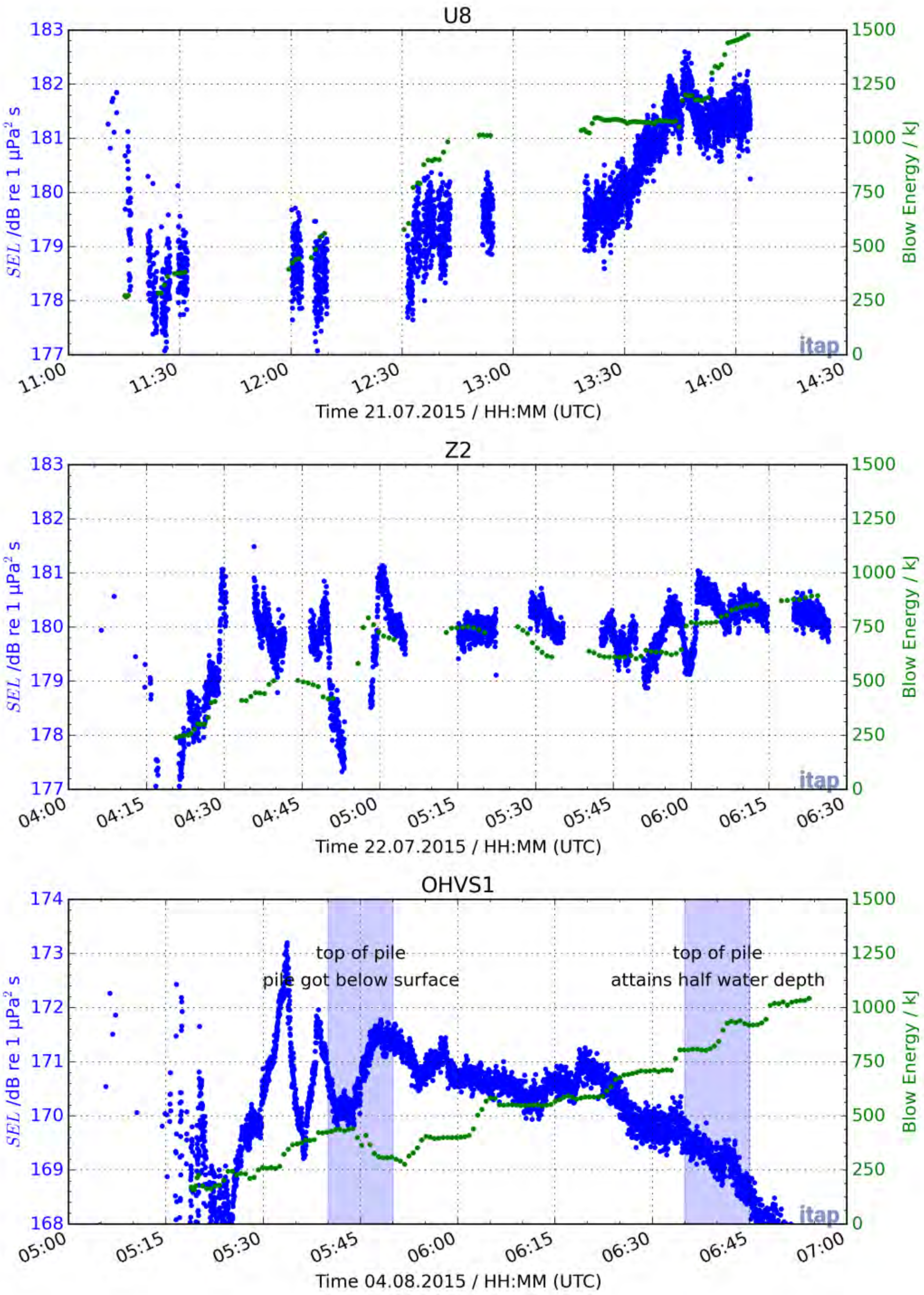


Figure 14: *SEL as well as applied blow energy as function of time for all three measured piles on MP1 in 750 m distance. Presented times of SEL and blow energy are not synchronized, time differences of a few minutes are possible.*

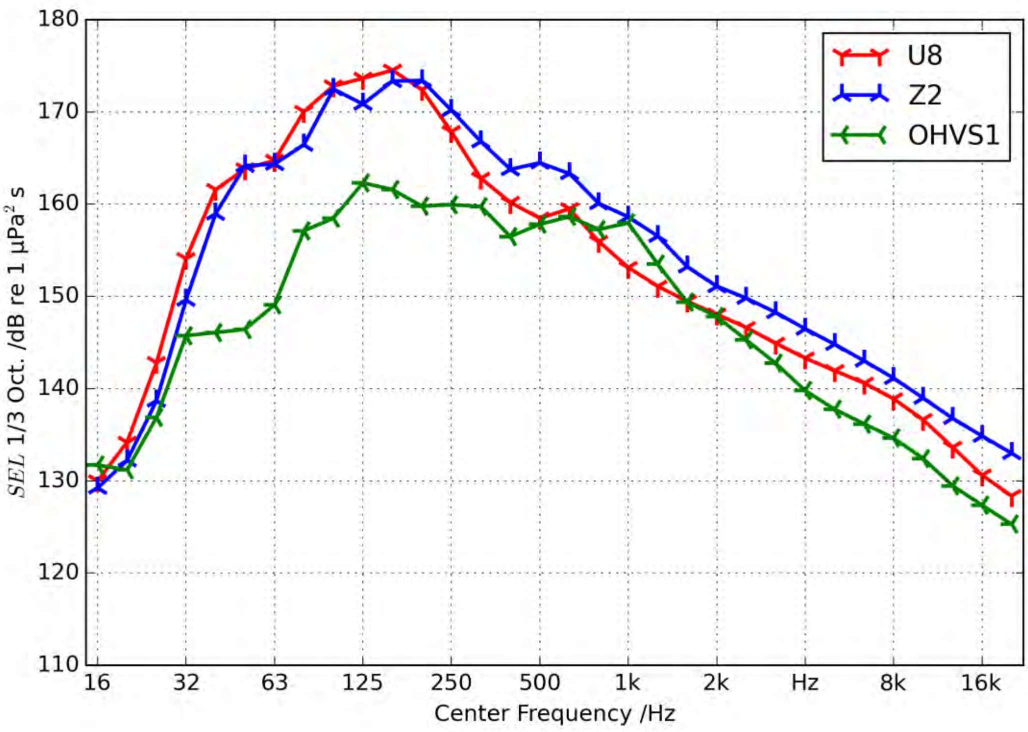


Figure 15: *1/3-Octave spectra of the median Sound Exposure Level (SEL_{50}) measured at MP1 in 750 m distance for all piles (hydrophone height: 2 m above seabed).*

5.2 Sound propagation

5.2.1 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 validating 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*[4] project or Thiele & Schellstede, 1980). Figure 16 displays the predicted sound propagation 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 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 underwater noise 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 calm seas during wintertime, when the lowest transmission loss is expected. The cyan colored line represents a rough sea with wave heights above 2 m.

For comparison, the measured median Sound Exposure Level (SEL_{50}) is also plotted in this figure (blue marks). For distances above 5 km, the model of Thiele & Schellstede for rough seas predicts the pile-driving noise most accurately.

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

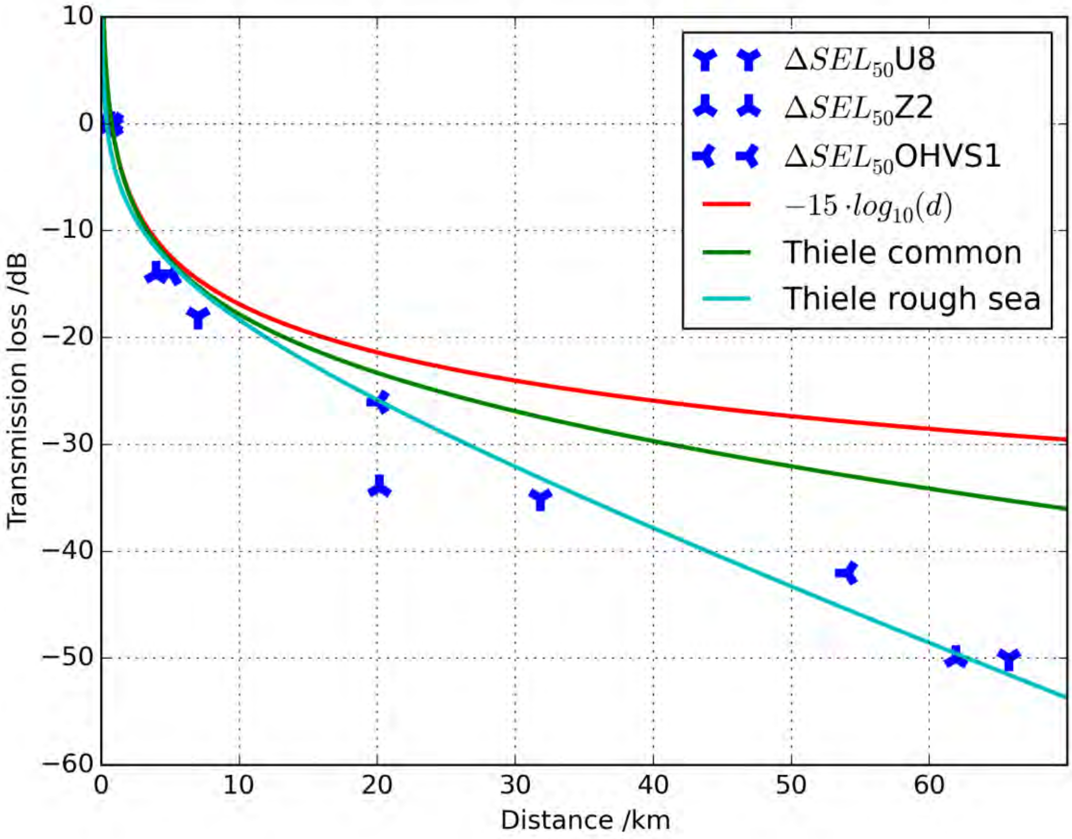


Figure 16: *Measured Sound Exposure Level (SEL, blue) as a function of distance. In comparison, the predicted propagation for the sound attenuation of three different common approaches are plotted.*

5.2.2 Sound propagation in time domain

Besides the attenuation there are more effects on 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 arrives at a different time at a specified point. This effect is called dispersion. The duration in which all frequencies arrive at the specified point is increasing with the distance.

To make this effect visible, the sound pressure (p) as a function of time for one single blow (blow number 1.271 of foundation U8) is plotted for all measurement positions at 2 m height in Figure 17. The signal duration (τ_{90}) is displayed by the grey shaded area. Besides the decreasing amplitudes of the sound pressure (attenuation), this figure shows the increase of the signal duration (τ_{90}) for growing distances. In Table 18, the signal durations τ_{90} are listed for the Monopile U8 at all measuring positions MP1 to MP4. For the positions MP1 to MP3, the signal duration is increasing with the distance, as expected. Between MP3 and MP4, no further increase could be detected.

Table 18: *Median of the signal duration τ_{90} for different measuring positions during the piling activities at Monopile U8.*

Position	Distance	Measuring height [m]	Median of τ_{90} U8 [s]
MP1	750	2	0.075
		10	0.075
MP2	approx. 7 km	2	0.294
		10	0.226
MP3	approx. 32 km	2	0.581
		10	0.571
MP4	approx. 65 km	2	0.518
		10	0.513

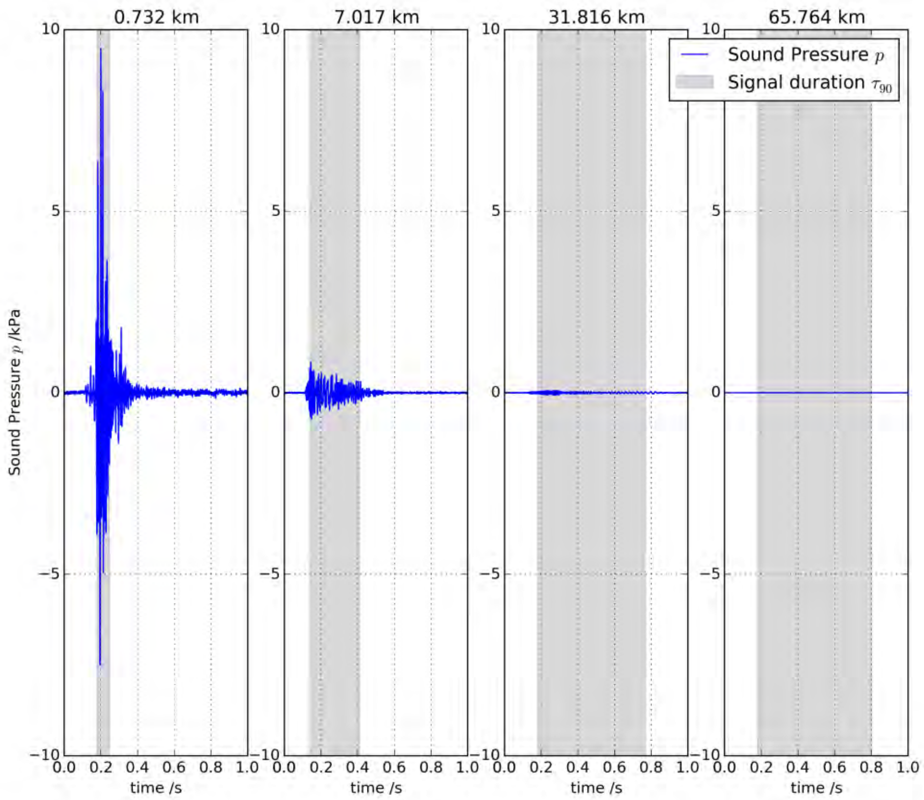


Figure 17: *Sound pressure (p) as a function of time for one single blow (blow number 1,271 of foundation U8) for all measurement positions in 2 m height. The signal duration (τ_{90}) is displayed by the grey shaded area.*

5.2.3 Sound propagation in frequency domain

The Transmission Loss 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 18 shows the 1/3-octave spectra of the SEL_{50} measured at the positions MP1, MP2, MP3 and MP4 during pile driving of foundation U8. As expected, the transmission loss over distance is higher for high frequencies than for low frequencies. For example, the difference between MP1 and MP2 is approx. 12 dB at 32 Hz and > 15 dB for frequencies > 500 Hz.

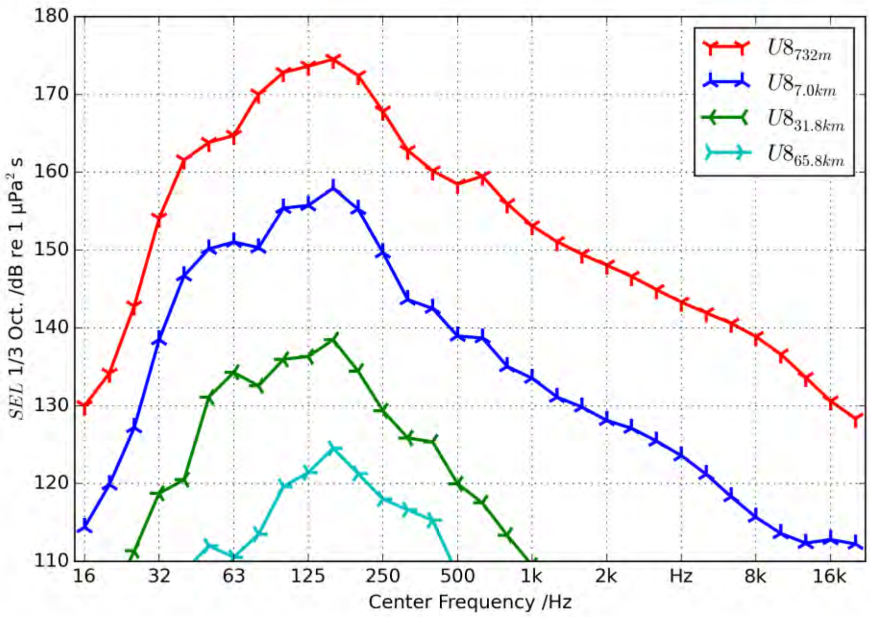


Figure 18: *SEL_{50} 1/3-octave for the pile U8 at the measuring positions MP1, MP2, MP3 and MP4 at a hydrophone height of 2 m.*

5.3 Conclusions

Impact of different pile designs

Caused by the smaller size of the sound radiating surface in the water column, the Sound Exposure Level (SEL) was lower for the smaller Pin-pile B3 at OHVS1 than for the larger Monopiles, as expected. Despite differences in blow energy and pile diameter, no significant differences were measured for the Monopiles.

Attenuation over large distances

By using common propagation models like the geometrical absorption - *15 log_{10}(d – distance ratio)* or the common attenuation approach for good weather conditions of Thiele & Schellstede (1980), the measured attenuation of the pile driving noise at large distances was higher than expected. Only by using the model for rough seas (wave height above 2 m) by Thiele & Schellstede (1980), the predicted values were close to the measured values at large distances. Although, the significant wave height was below 2 m during pile driving works, see Annex 4.

6. 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.

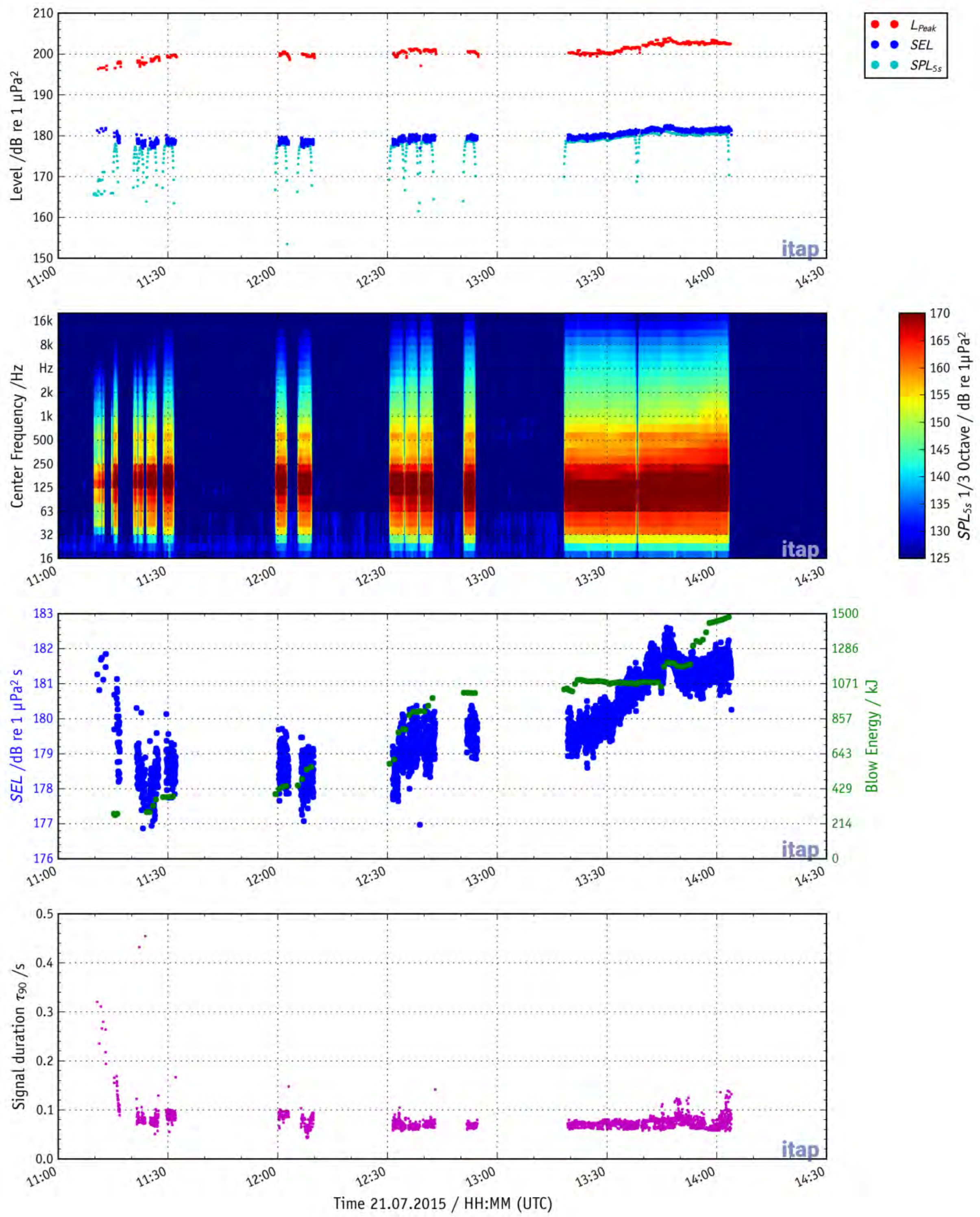
[8] **MacKenzie KV (1981),** Nine-term Equation for Sound Speed in the Oceans. J. Acoust. Soc. Am.

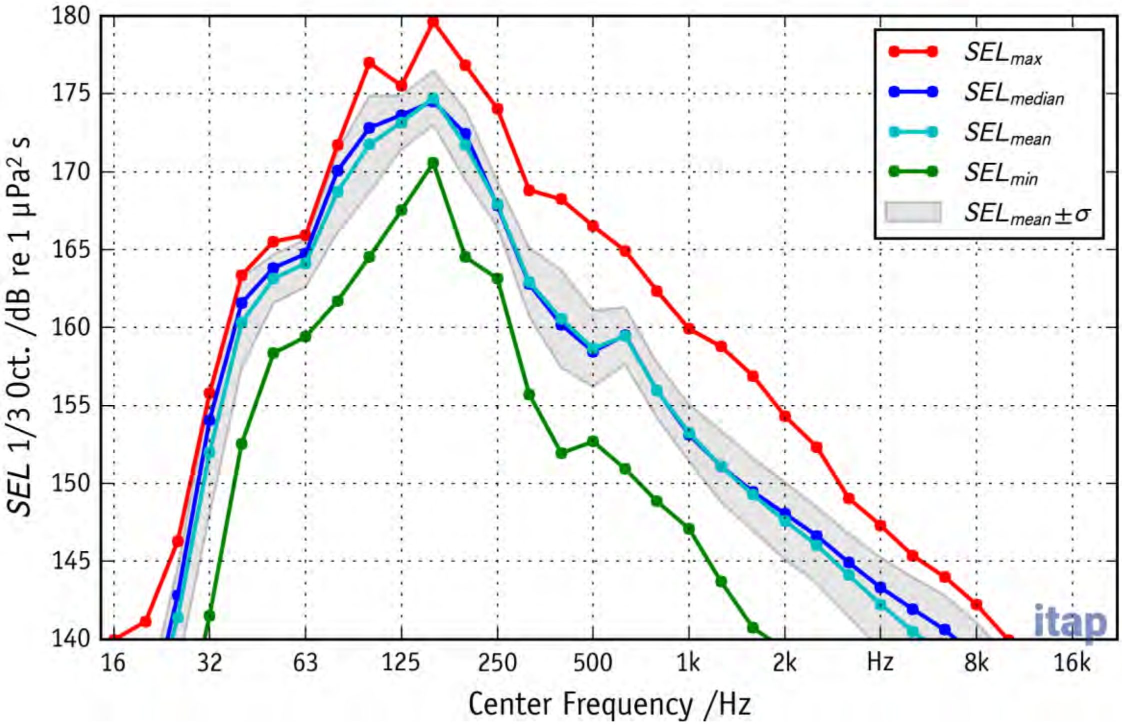
[9] **ISO/DIS 18406 (2015),** Underwater acoustics – Measurement of underwater radiated sound percussive pile driving, Draft International Standard

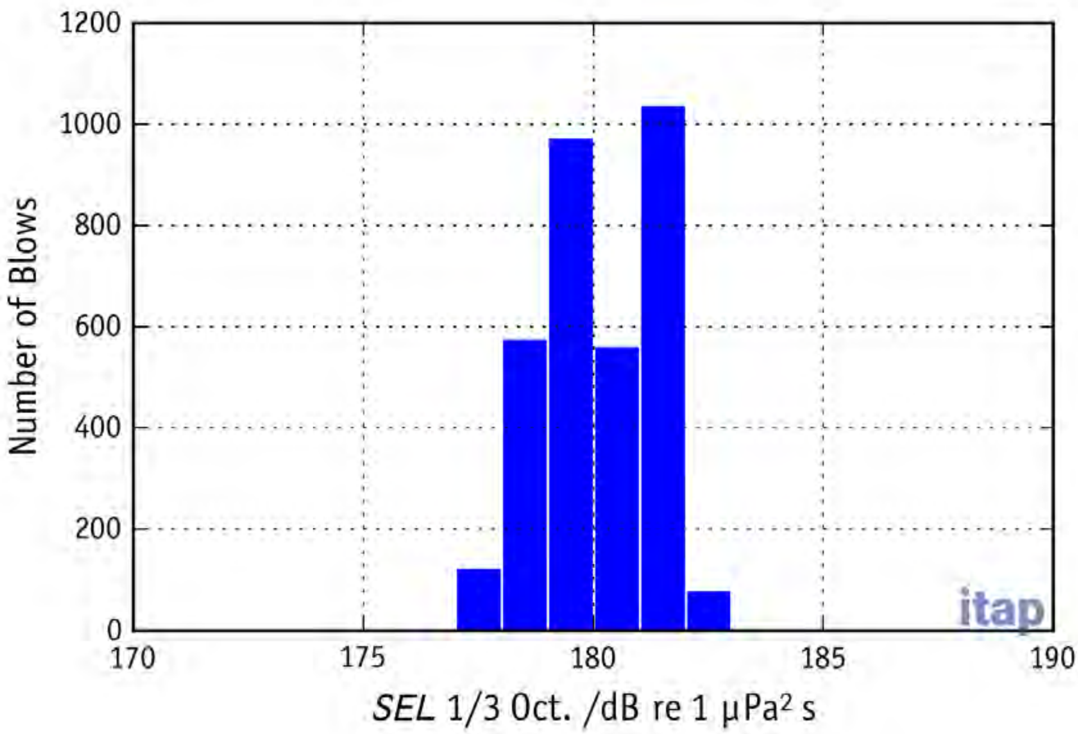
Annex 1: Plots of measurement results at each measuring position and for each pile

A1.1 Pile Driving Noise at Monopile U8

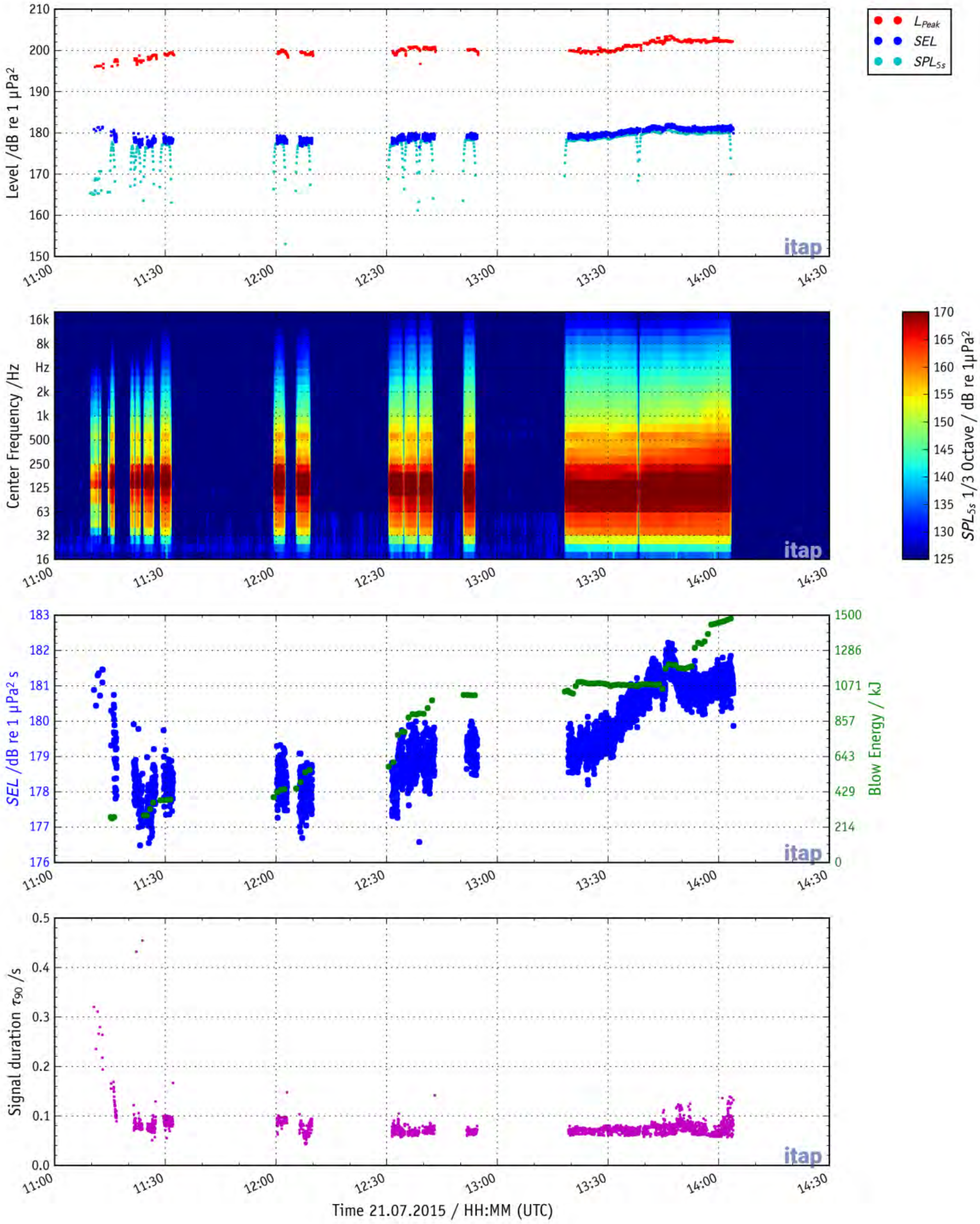
U8 MP1, 2 m pile driving noise

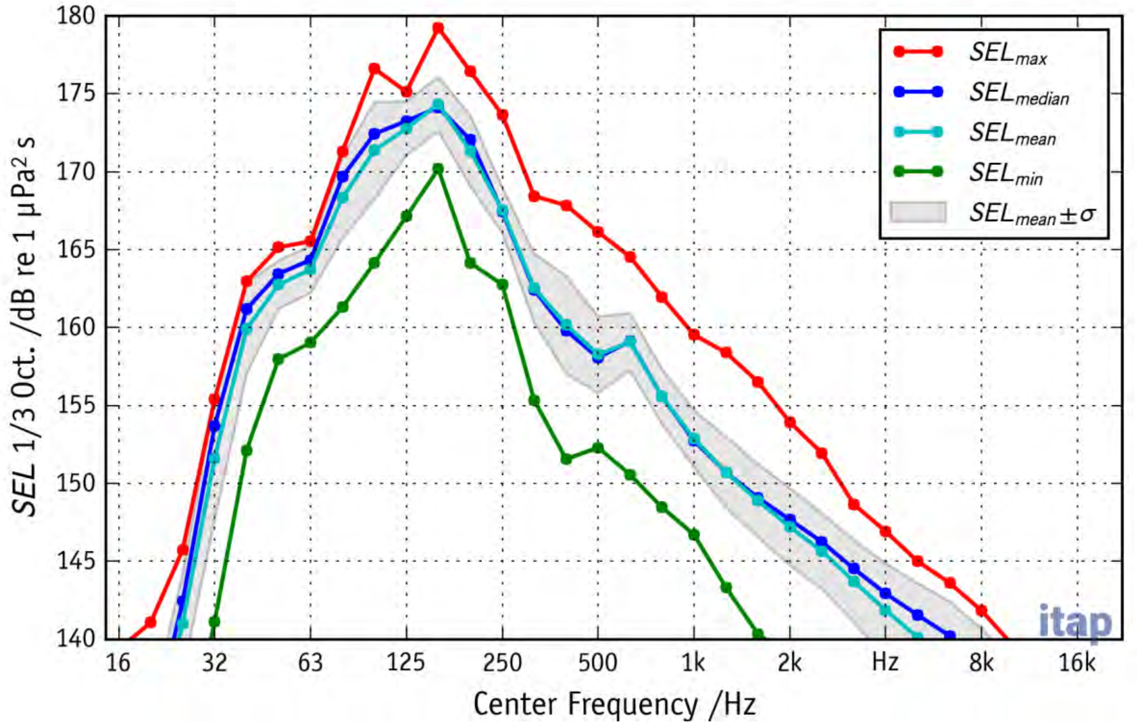



SEL 1/3 Oct. /dB re 1 µPa² s
Center Frequency /Hz
16
32
63
125
250
500
1k
2k
Hz
8k
16k
140
145
150
155
160
165
170
175
180
SELmax
SELmedian
SELmean
SELmin
SELmean ± σ
itap

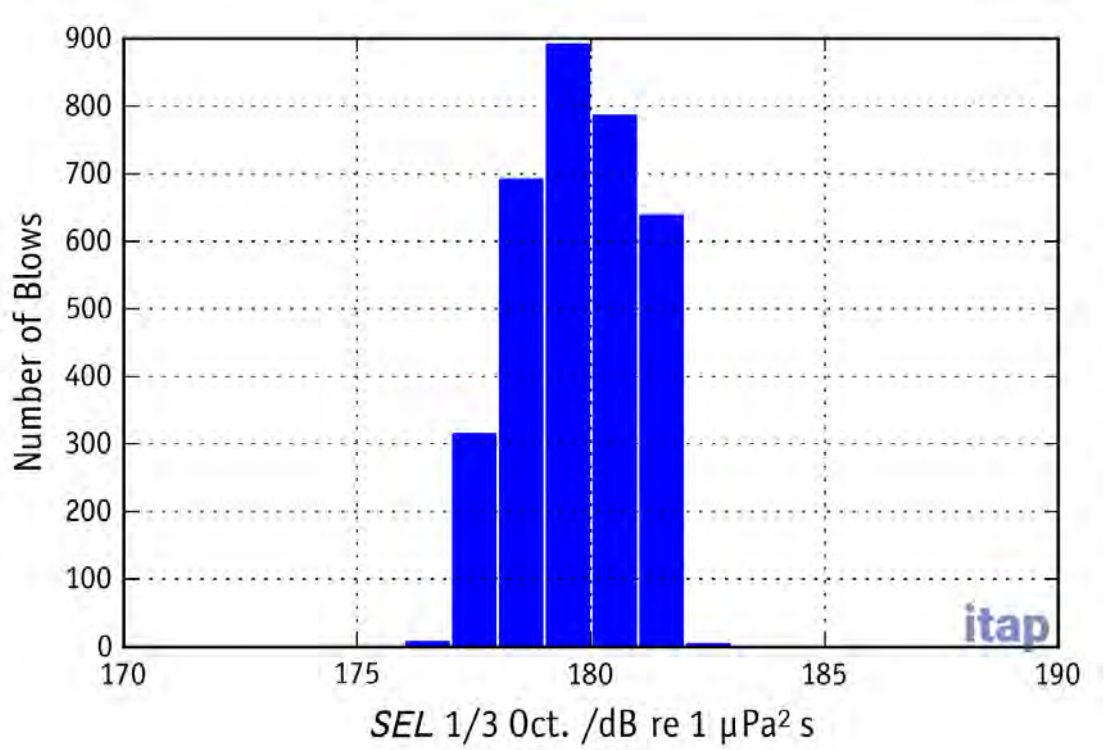

Number of Blows
SEL 1/3 Oct. /dB re 1 µPa² s
0
200
400
600
800
1000
1200
170
175
180
185
190
itap

U8 MP1, 10 m pile driving noise



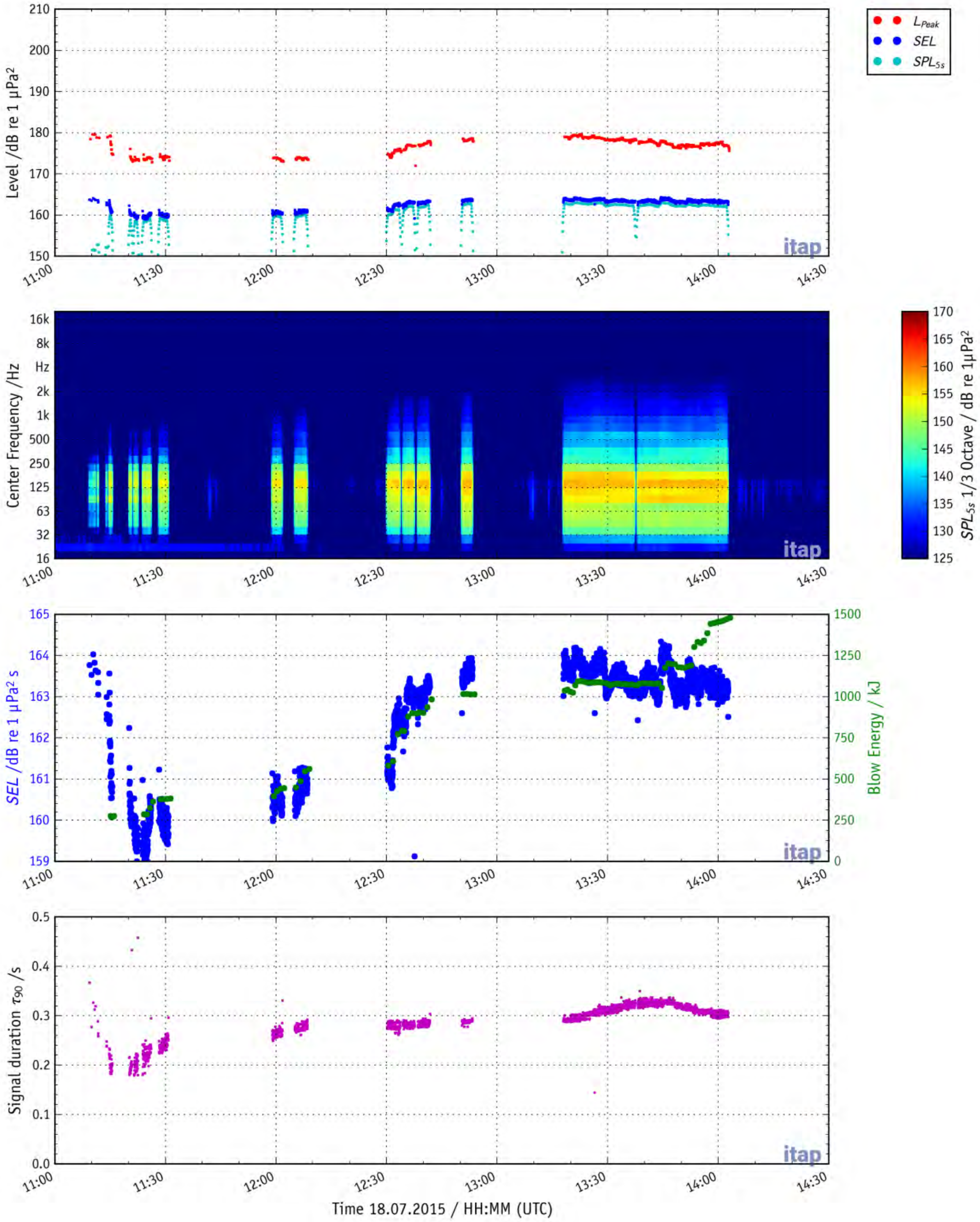


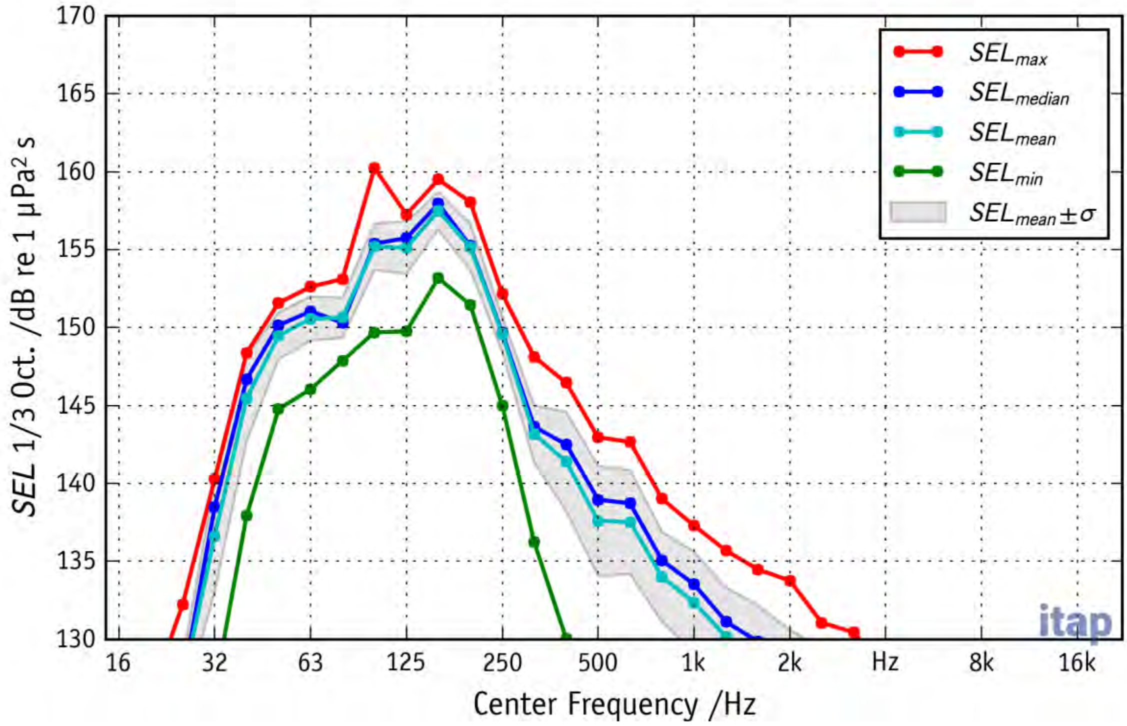
SEL_max
SEL_median
SEL_mean
SEL_min
SEL_mean ± σ
SEL 1/3 Oct. /dB re 1 µPa² s
180
175
170
165
160
155
150
145
140
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center Frequency /Hz
itap

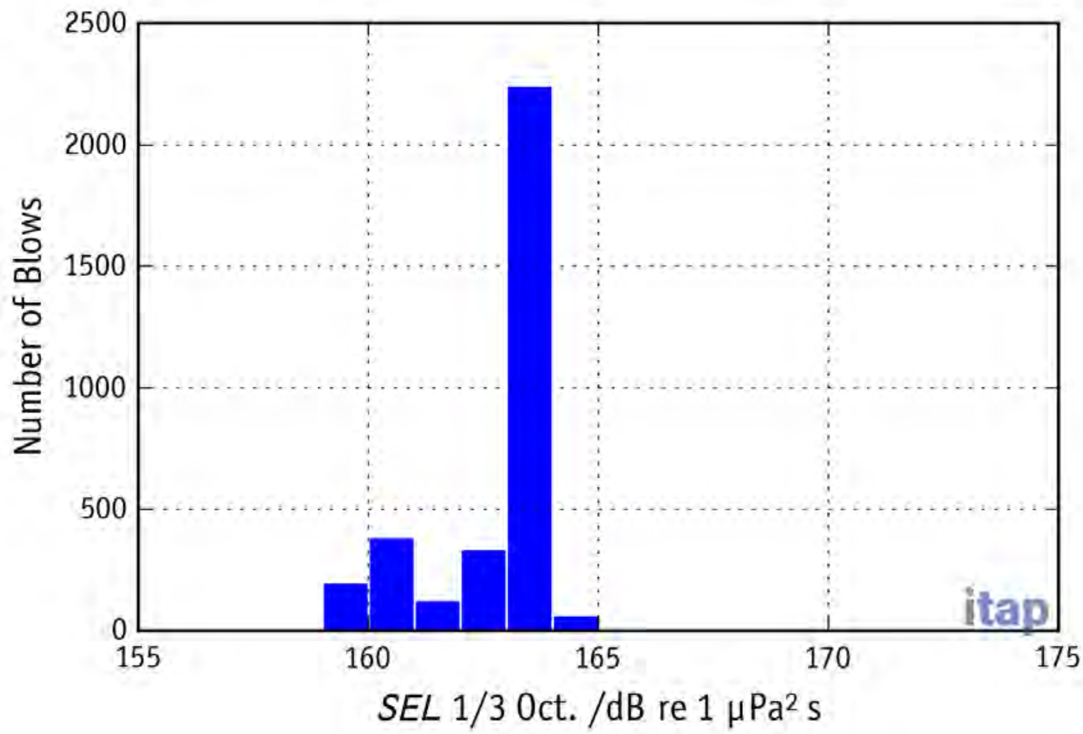


Number of Blows
900
800
700
600
500
400
300
200
100
0
170
175
180
185
190
SEL 1/3 Oct. /dB re 1 µPa² s
itap

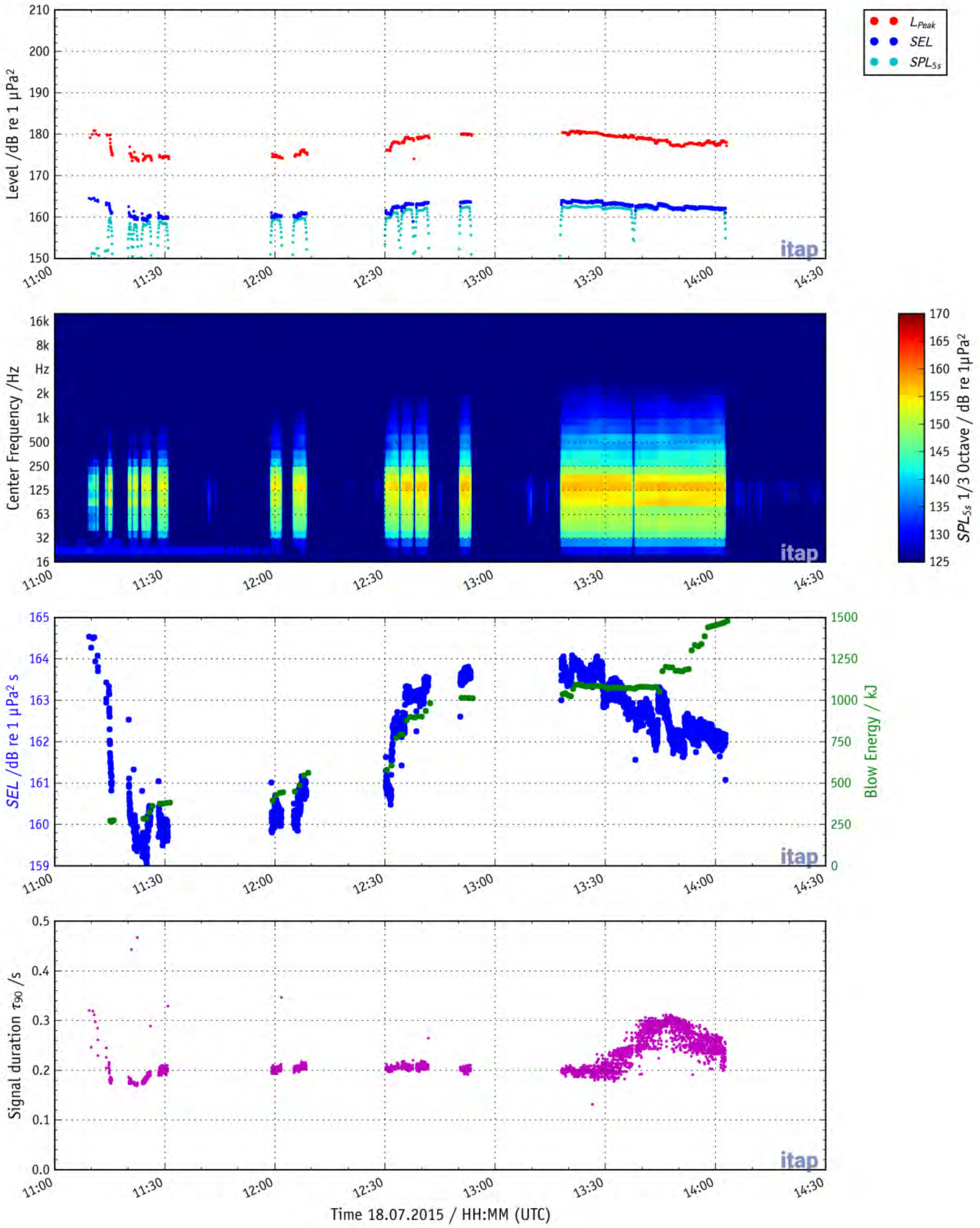
U8 MP2, 2 m pile driving noise

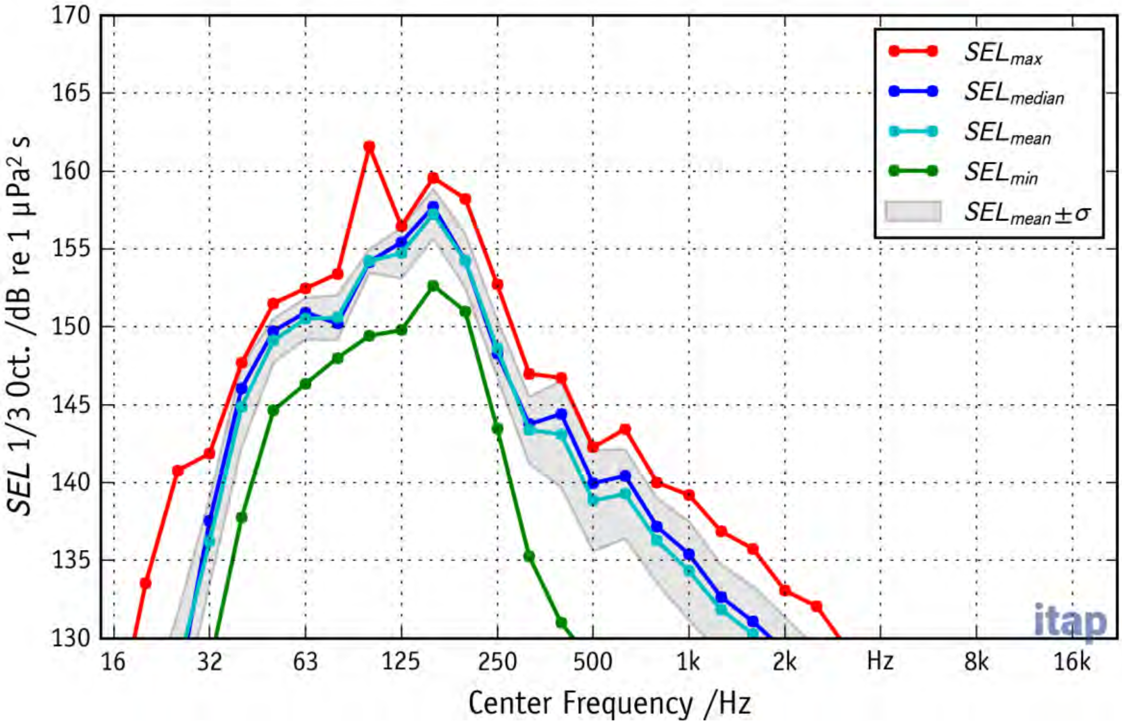


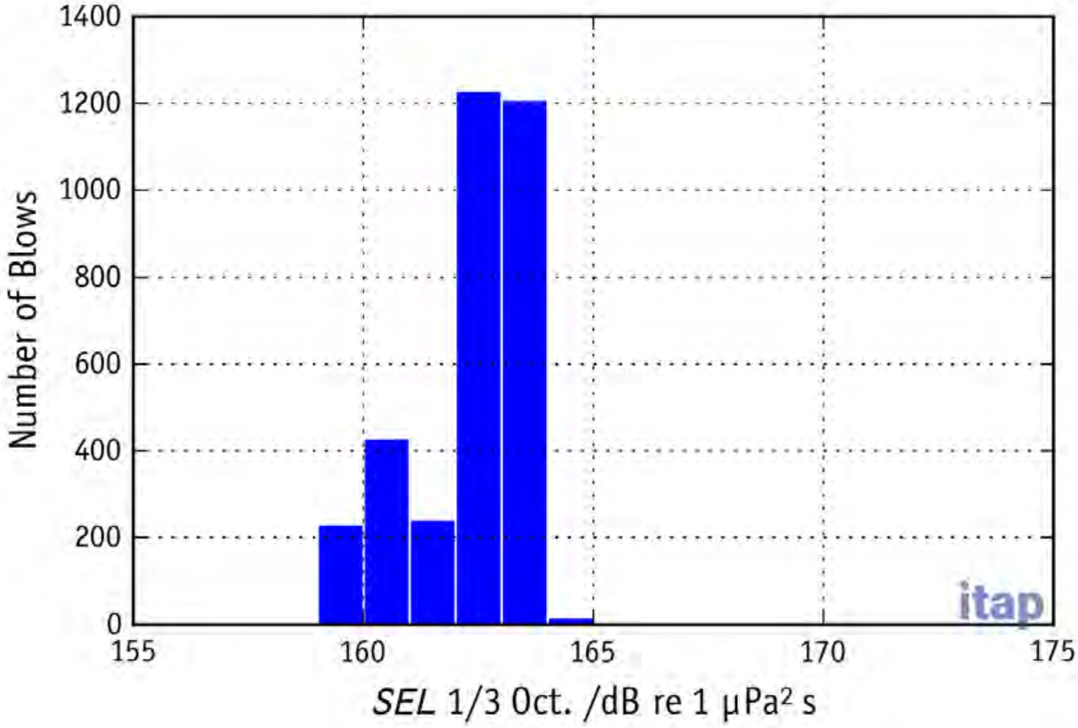

SEL 1/3 Oct. /dB re 1 µPa² s
Center Frequency /Hz
170
165
160
155
150
145
140
135
130
16
32
63
125
250
500
1k
2k
Hz
8k
16k
SELmax
SELmedian
SELmean
SELmin
SELmean±σ
itap


Number of Blows
SEL 1/3 Oct. /dB re 1 µPa² s
2500
2000
1500
1000
500
0
155
160
165
170
175
itap

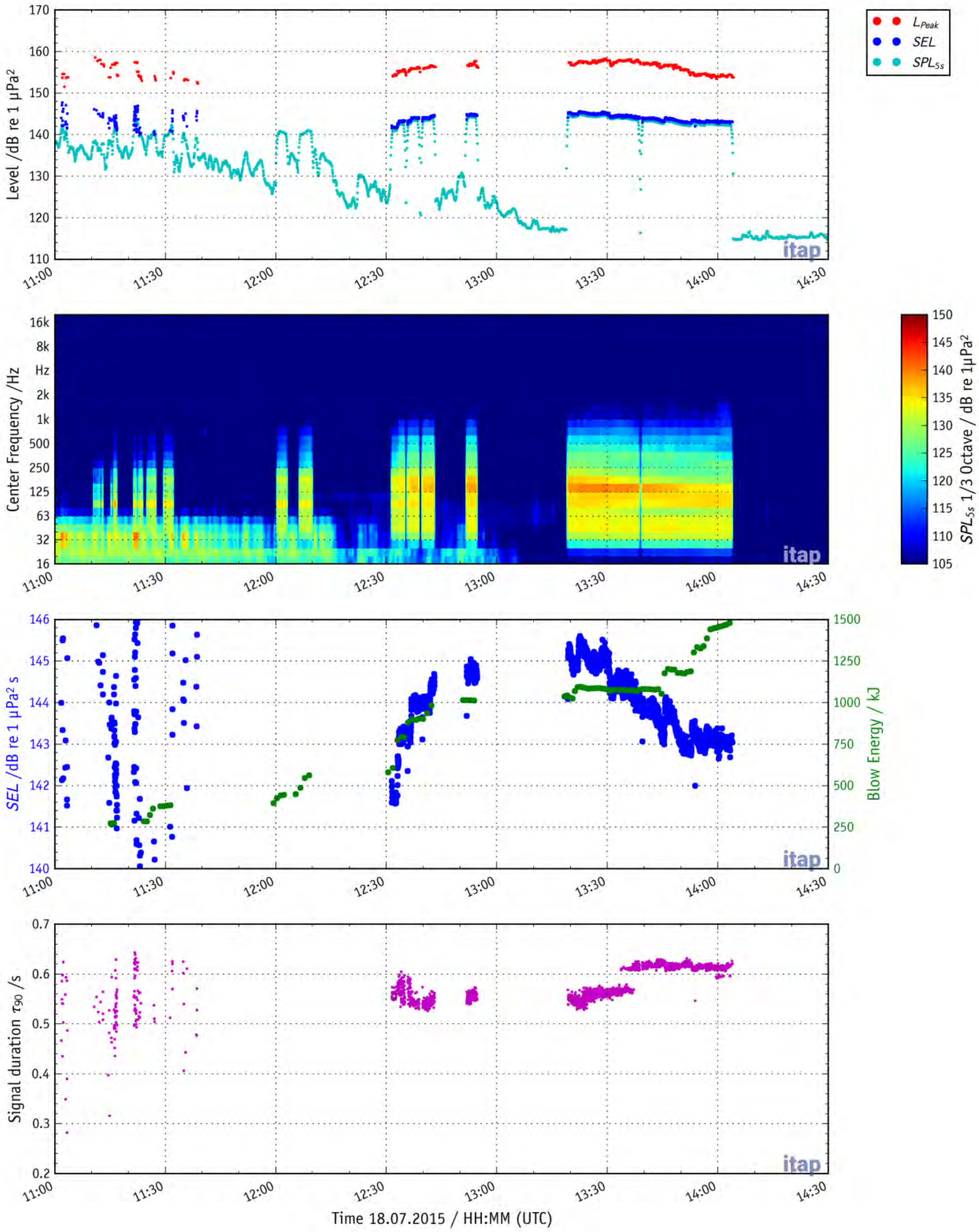
U8 MP2, 10 m pile driving noise

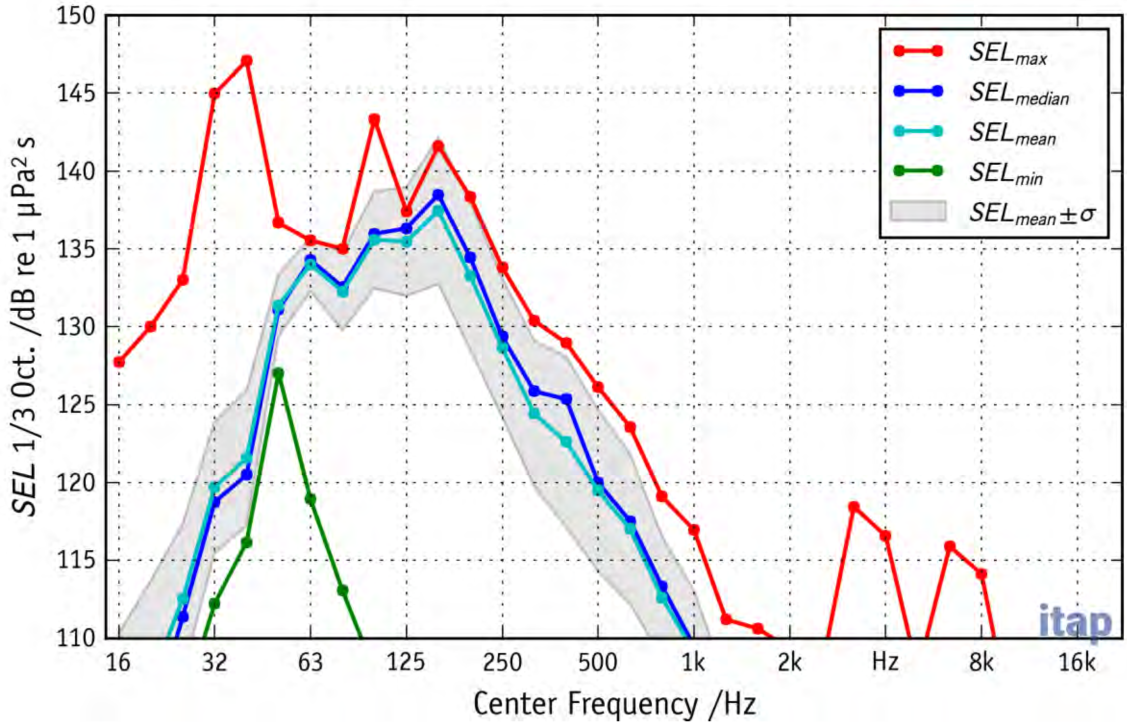



SEL_max
SEL_median
SEL_mean
SEL_min
SEL_mean ± σ
SEL 1/3 Oct. /dB re 1 µPa² s
Center Frequency /Hz
170
165
160
155
150
145
140
135
130
16
32
63
125
250
500
1k
2k
Hz
8k
16k
itap

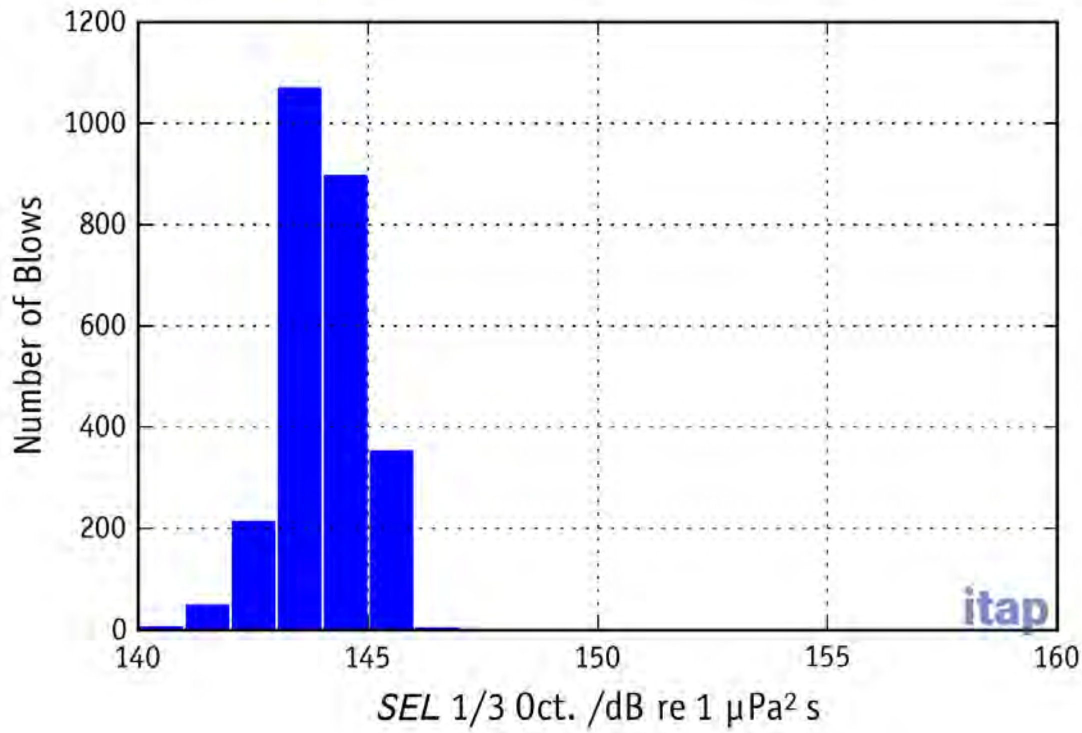

Number of Blows
SEL 1/3 Oct. /dB re 1 µPa² s
1400
1200
1000
800
600
400
200
0
155
160
165
170
175
itap

U8 MP3, 2 m pile driving noise



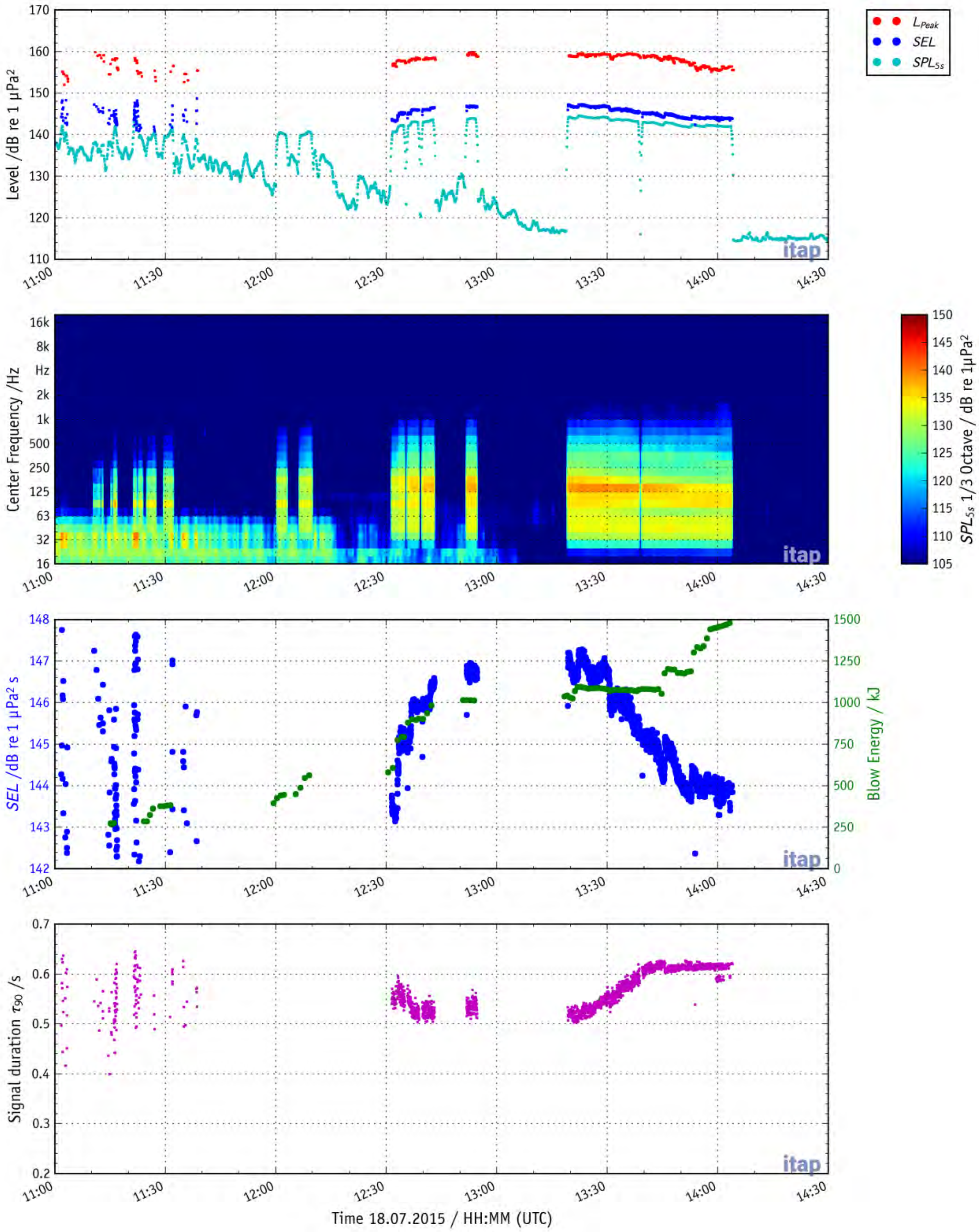


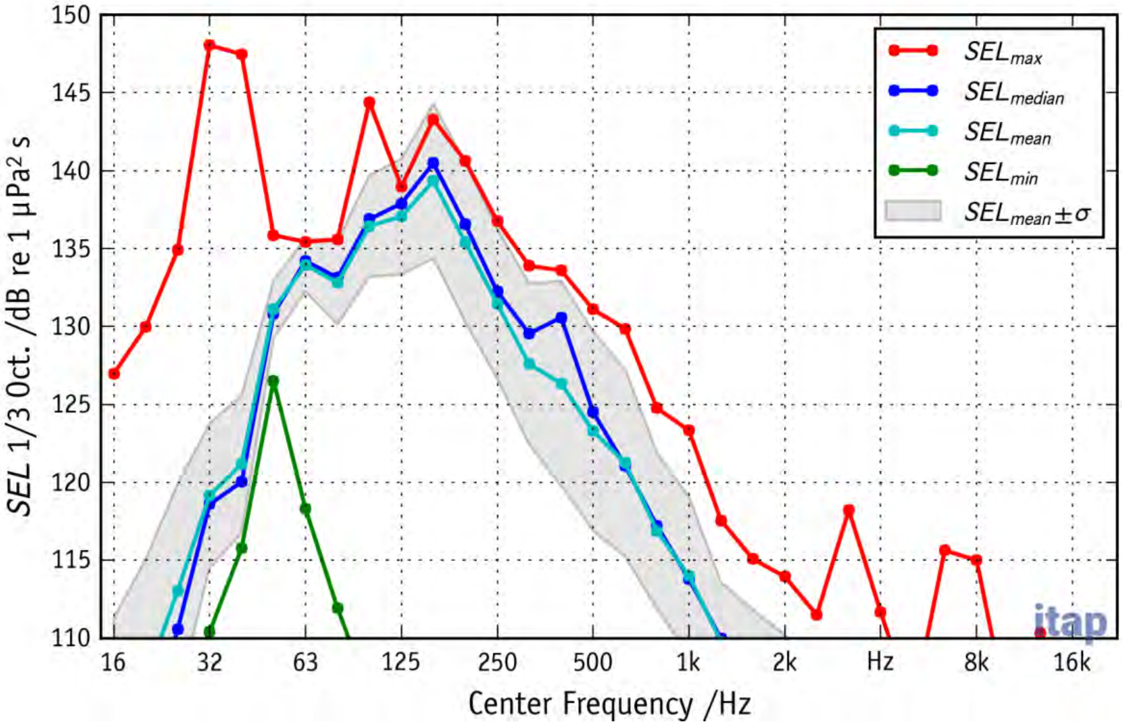
SEL 1/3 Oct. /dB re 1 µPa² s
150
145
140
135
130
125
120
115
110
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center Frequency /Hz
SEL max
SEL median
SEL mean
SEL min
SEL mean ±σ
itap

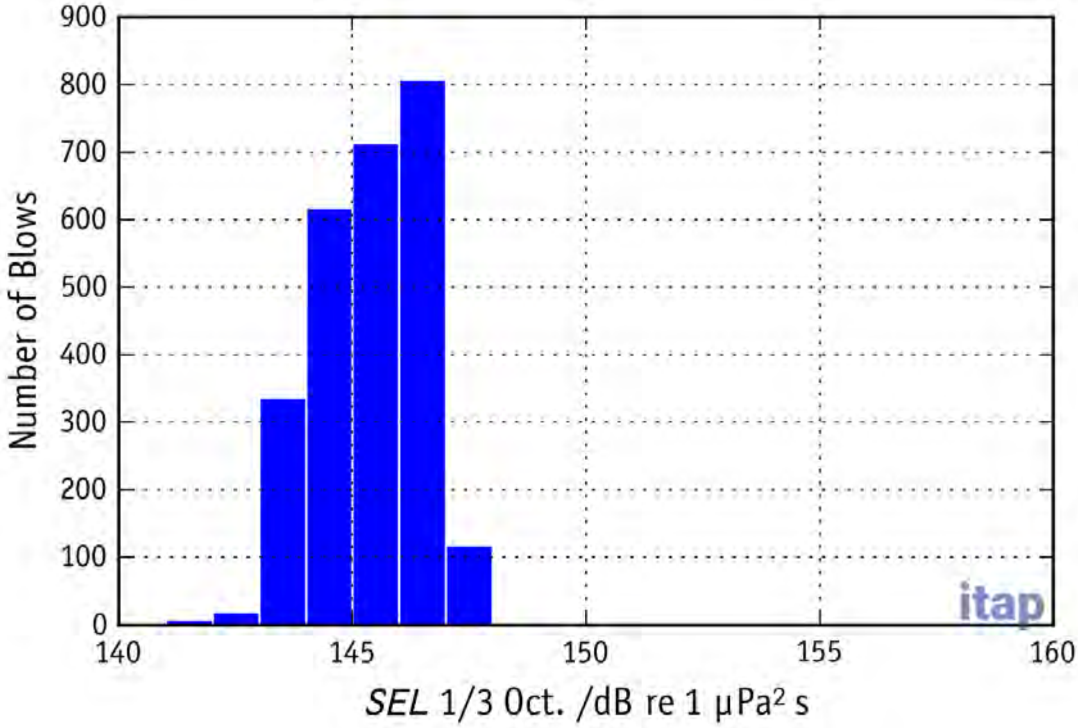


Number of Blows
1200
1000
800
600
400
200
0
140
145
150
155
160
SEL 1/3 Oct. /dB re 1 µPa² s
itap

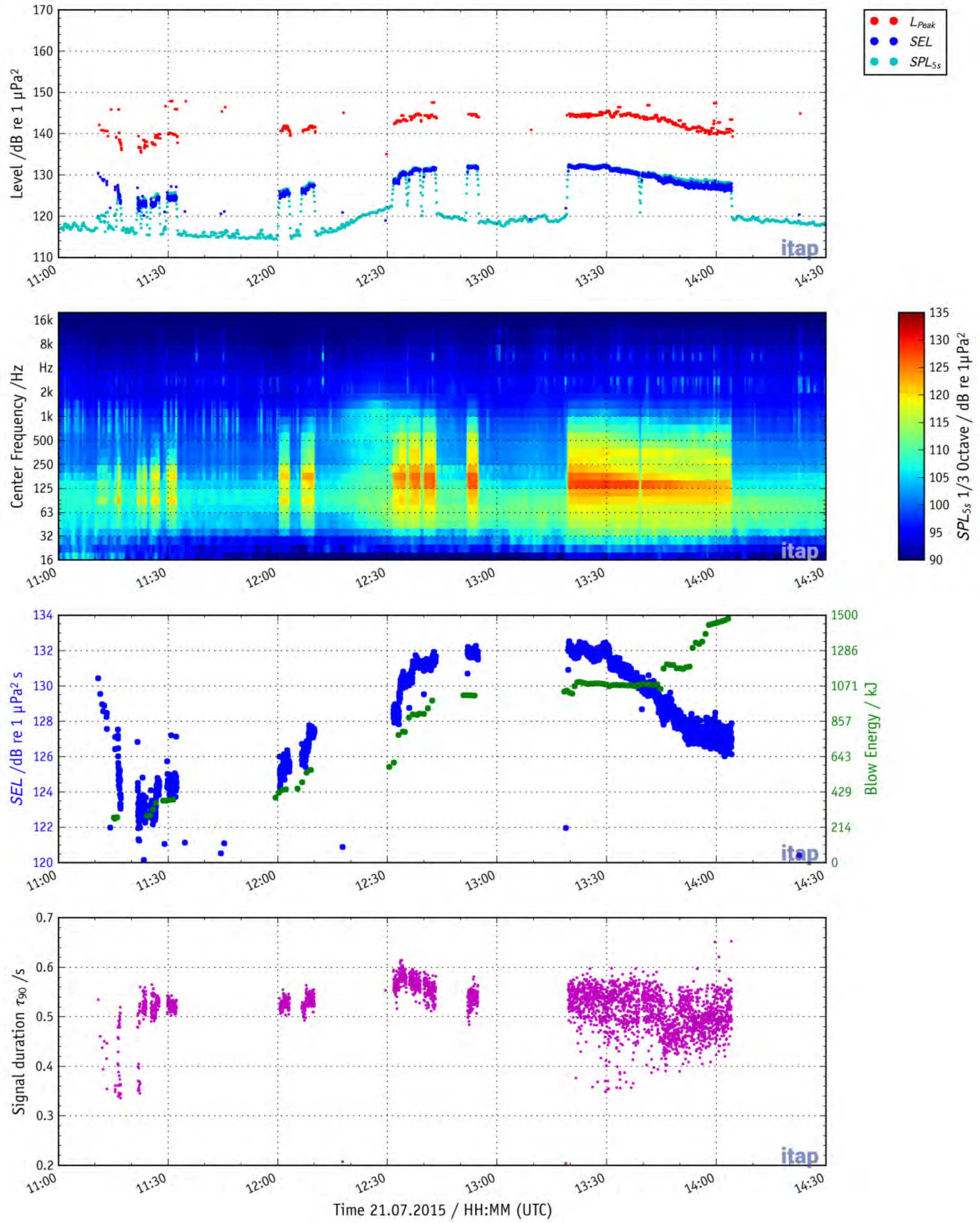
U8 MP3, 10 m pile driving noise

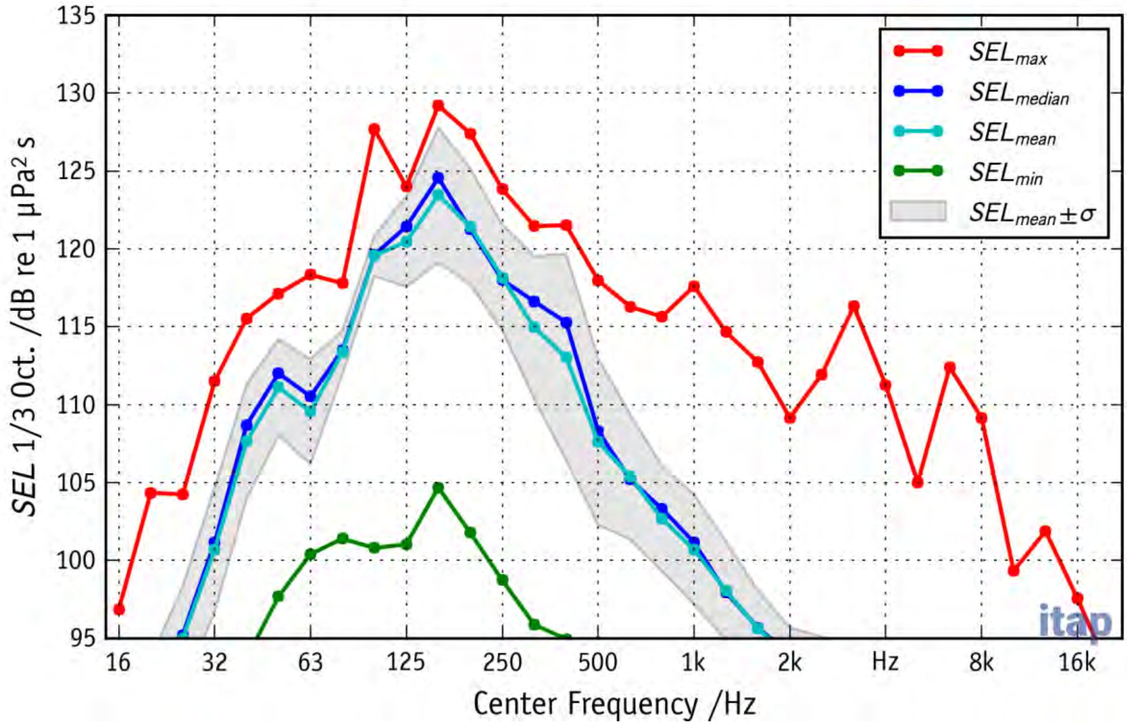


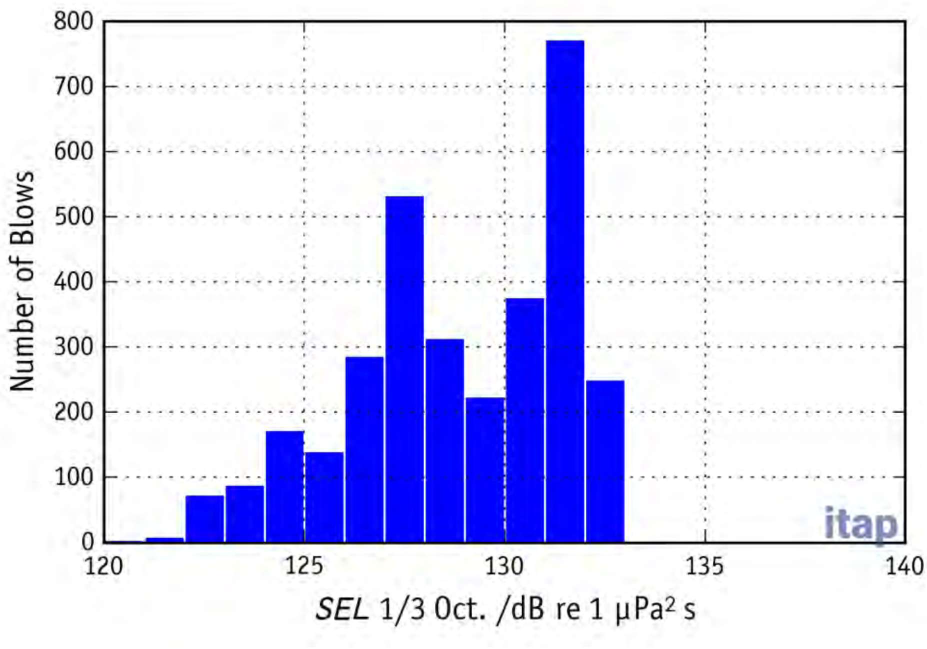

SELmax
SELmedian
SELmean
SELmin
SELmean±σ
SEL 1/3 Oct. /dB re 1 µPa² s
150
145
140
135
130
125
120
115
110
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center Frequency /Hz
itap


Number of Blows
900
800
700
600
500
400
300
200
100
0
140
145
150
155
160
SEL 1/3 Oct. /dB re 1 µPa² s
itap

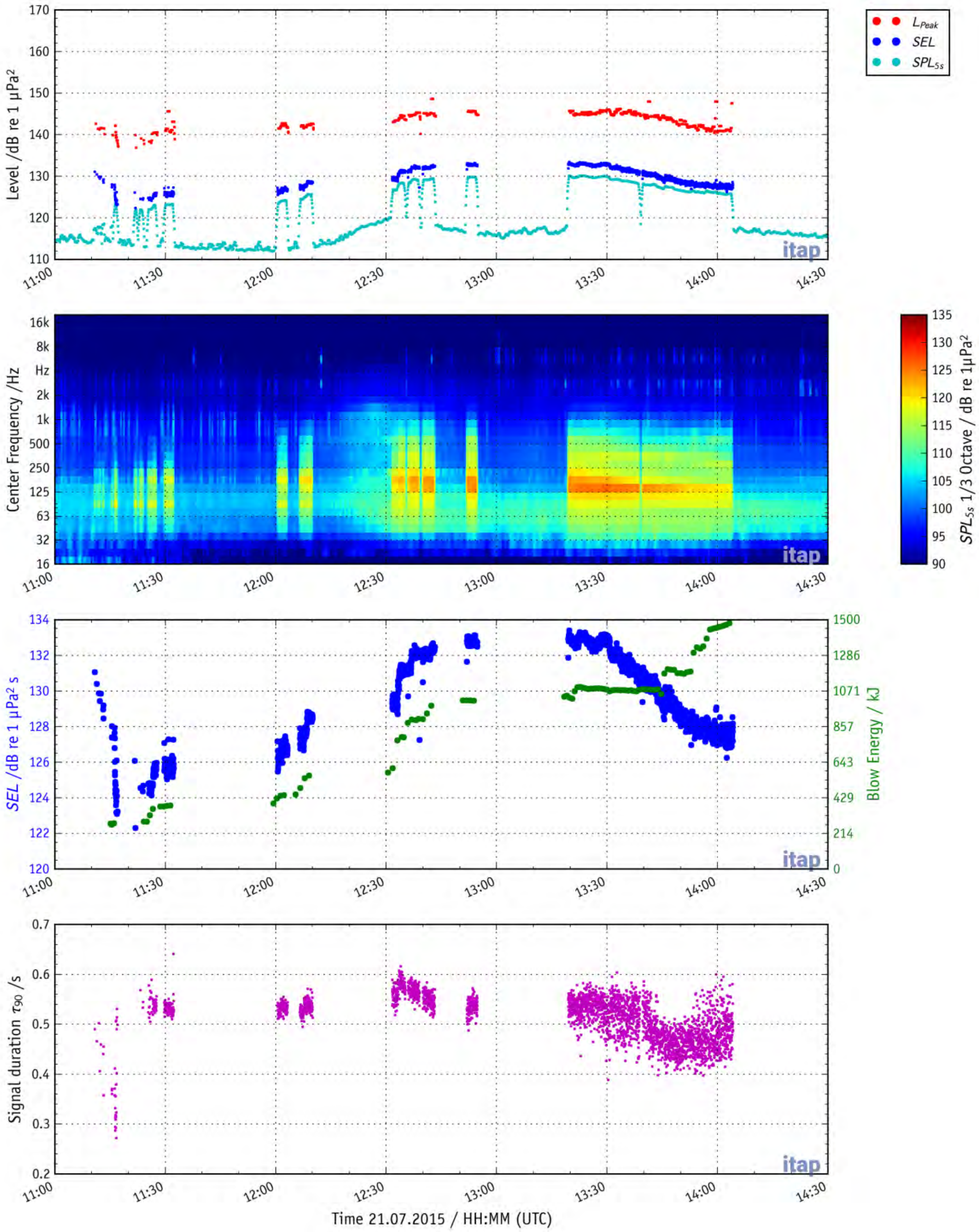
U8 MP4, 2 m pile driving noise

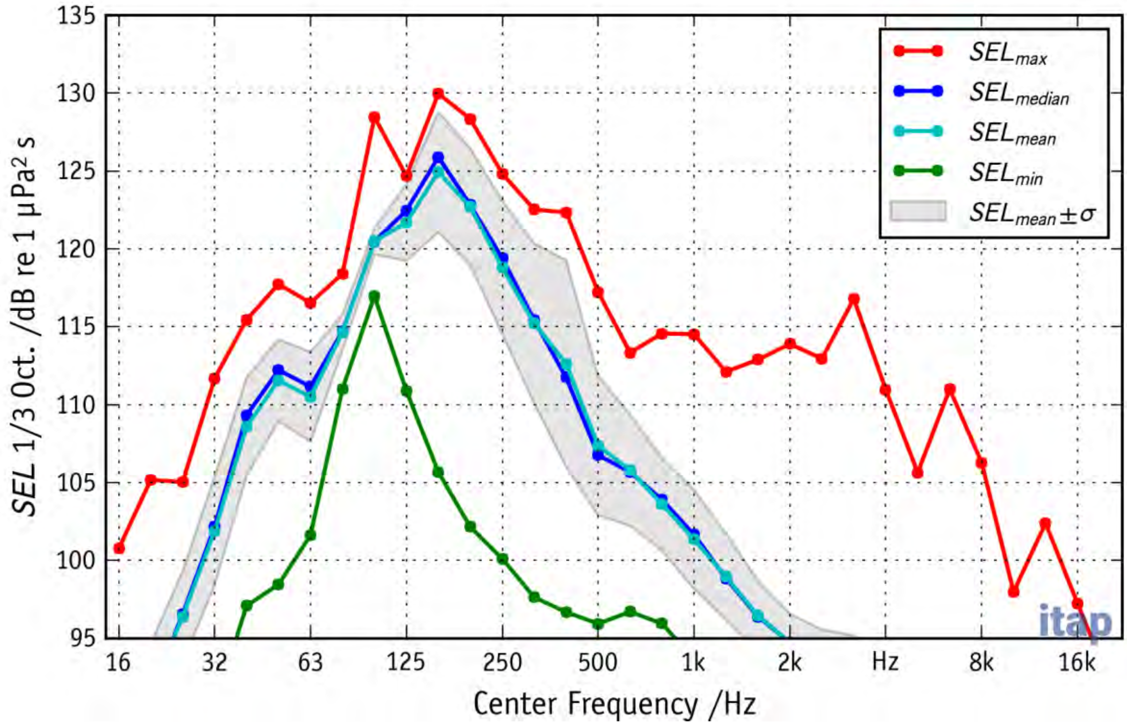



SEL 1/3 Oct. /dB re 1 µPa² s
Center Frequency /Hz
SELmax
SELmedian
SELmean
SELmin
SELmean ± σ
135
130
125
120
115
110
105
100
95
16
32
63
125
250
500
1k
2k
Hz
8k
16k
itap

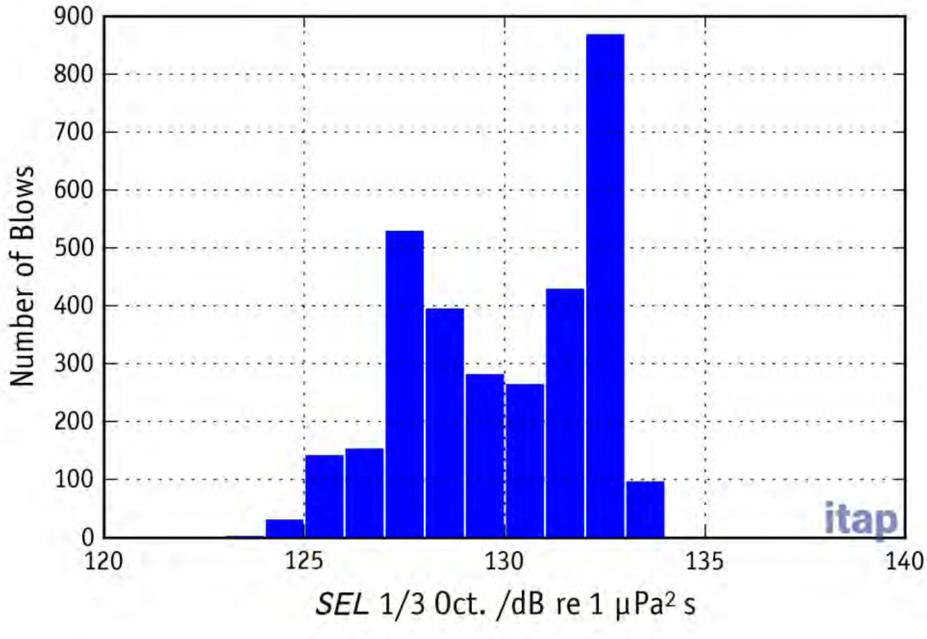

Number of Blows
SEL 1/3 Oct. /dB re 1 µPa² s
800
700
600
500
400
300
200
100
0
120
125
130
135
140
itap

U8 MP4, 10 m pile driving noise





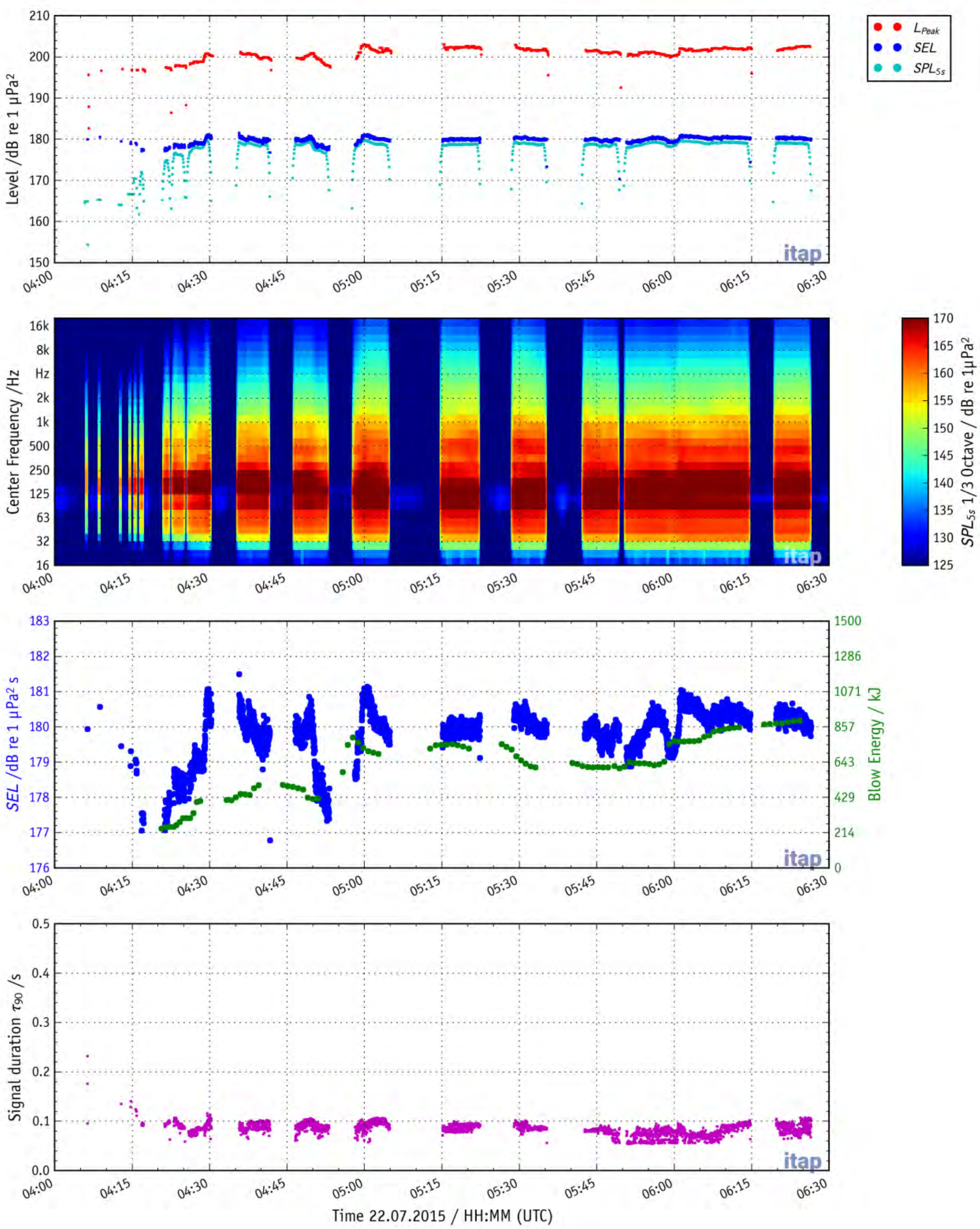
SEL_max
SEL_median
SEL_mean
SEL_min
SEL_mean ± σ
SEL 1/3 Oct. /dB re 1 µPa² s
Center Frequency /Hz
16
32
63
125
250
500
1k
2k
Hz
8k
16k
95
100
105
110
115
120
125
130
135
itap

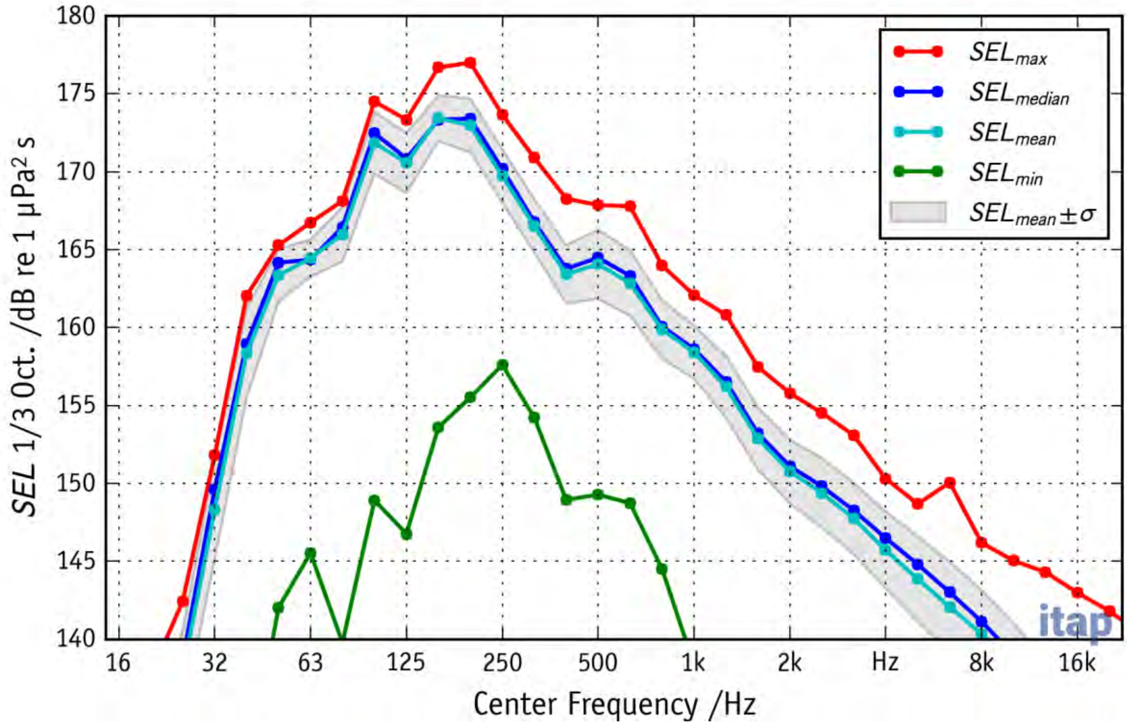


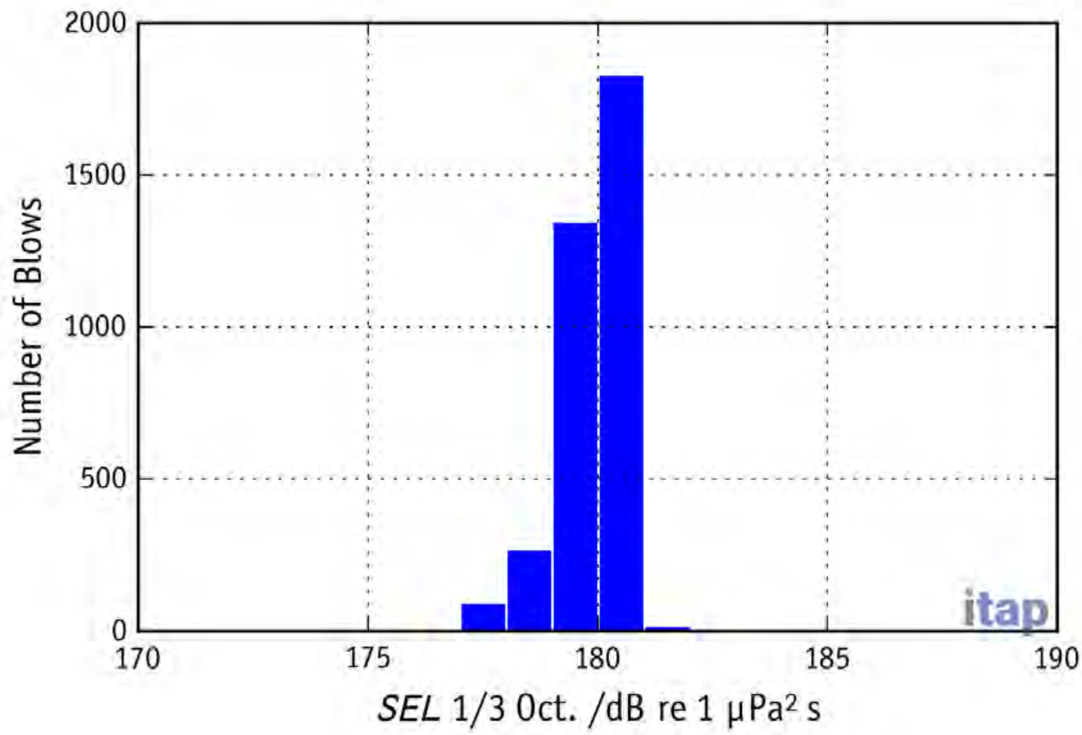
Number of Blows
SEL 1/3 Oct. /dB re 1 µPa² s
0
100
200
300
400
500
600
700
800
900
120
125
130
135
140
itap

A1.2 Pile Driving Noise at Monopile Z2

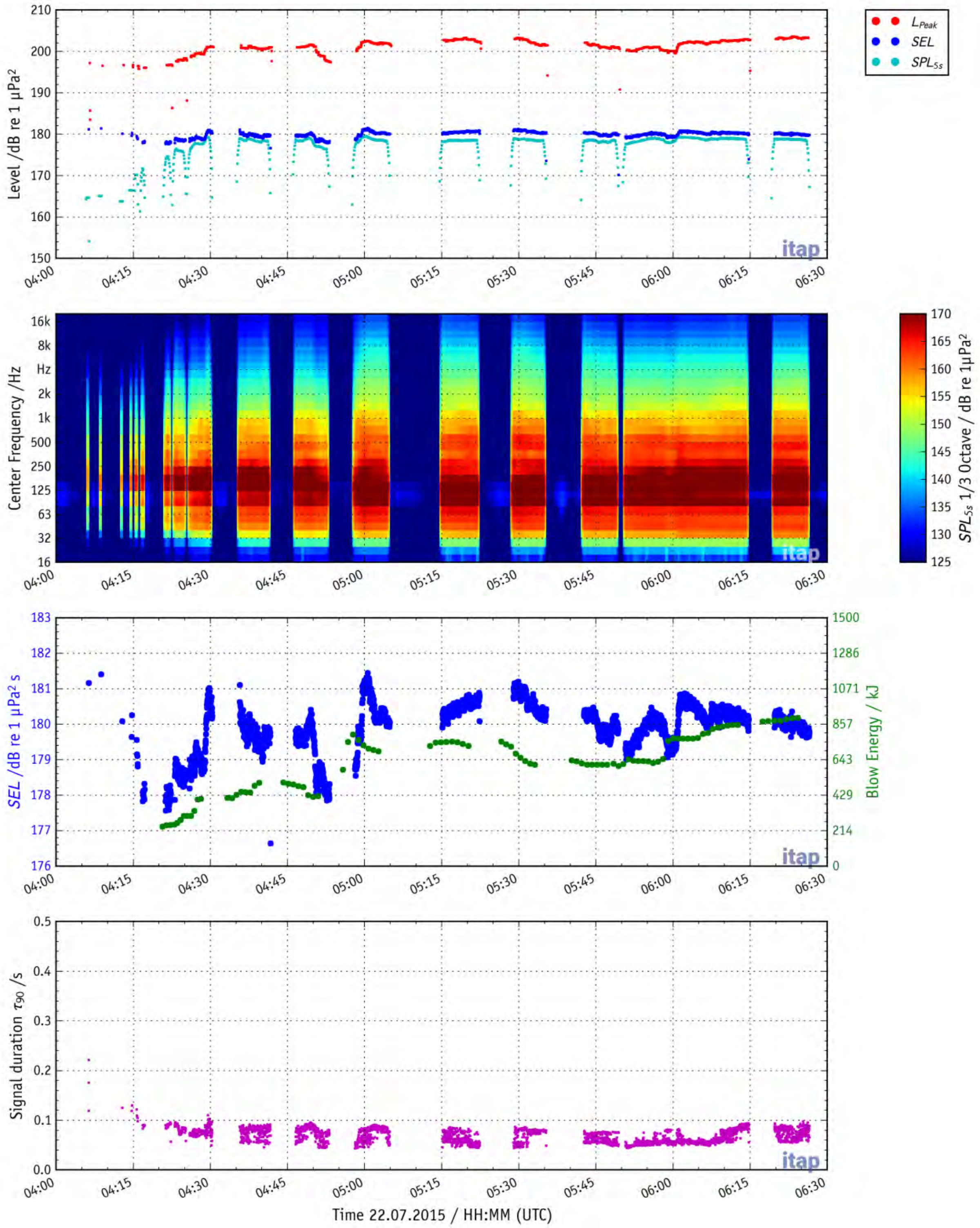
Z2 MP1, 2 m pile driving noise

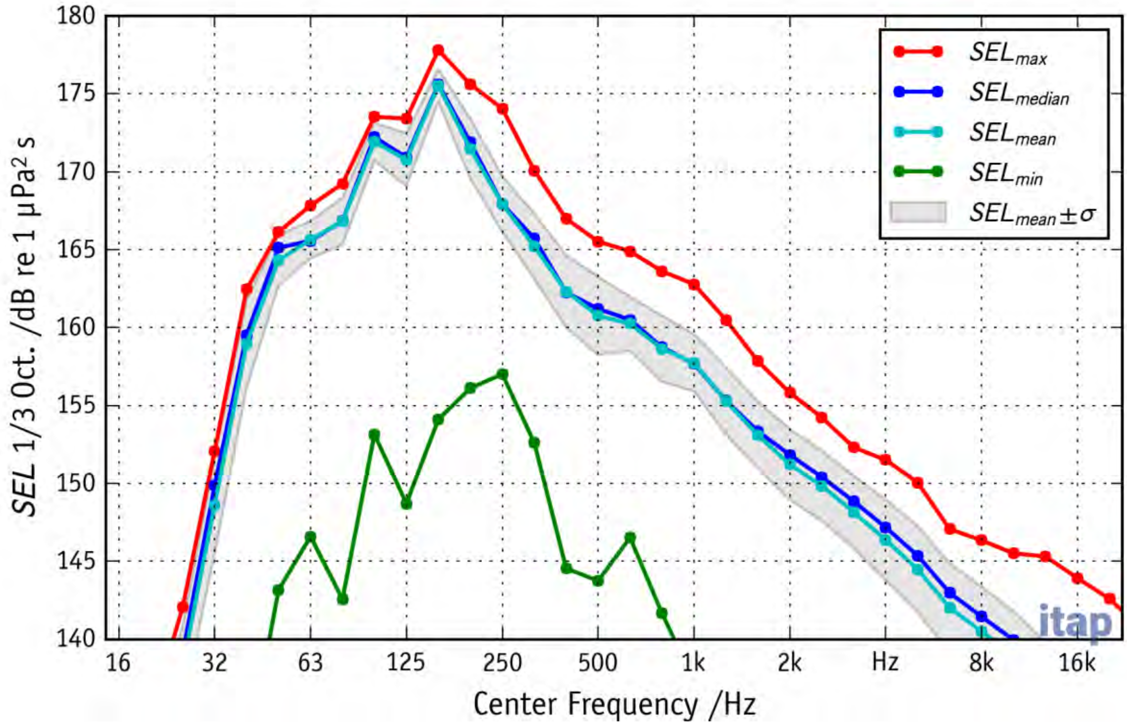



180
175
170
165
160
155
150
145
140
SEL 1/3 Oct. /dB re 1 µPa² s
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center Frequency /Hz
SEL_{max}
SEL_{median}
SEL_{mean}
SEL_{min}
$SEL_{mean} \pm \sigma$
itap

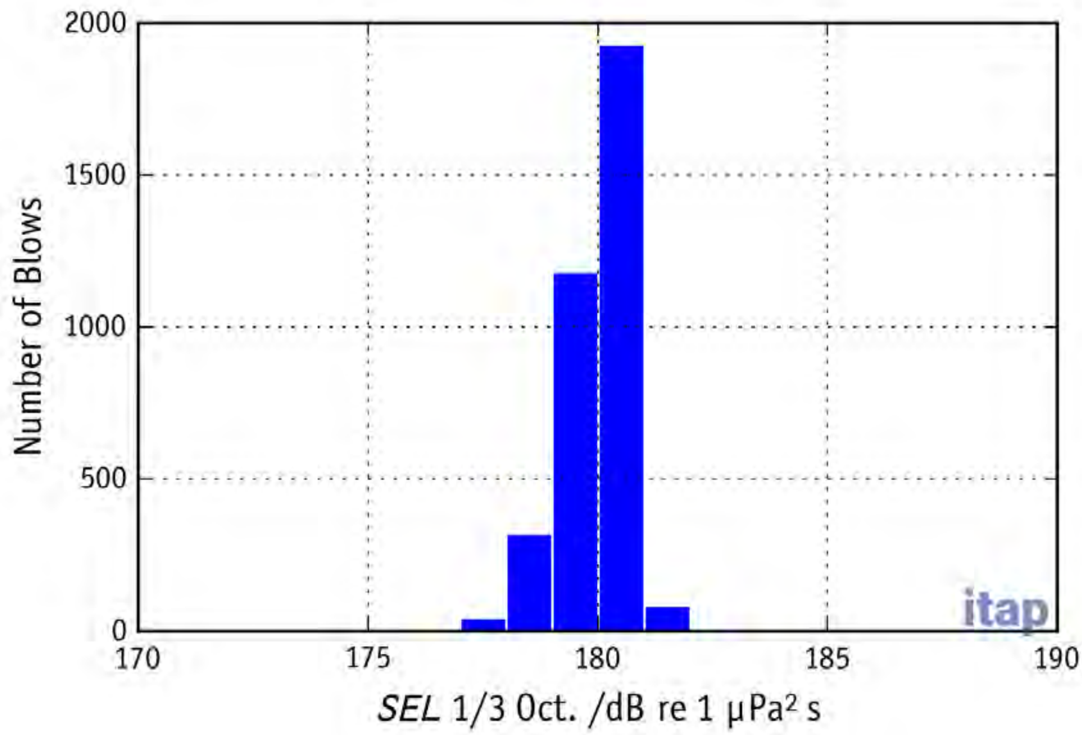

2000
1500
1000
500
0
Number of Blows
170
175
180
185
190
SEL 1/3 Oct. /dB re 1 µPa² s
itap

Z2 MP1, 10 m pile driving noise



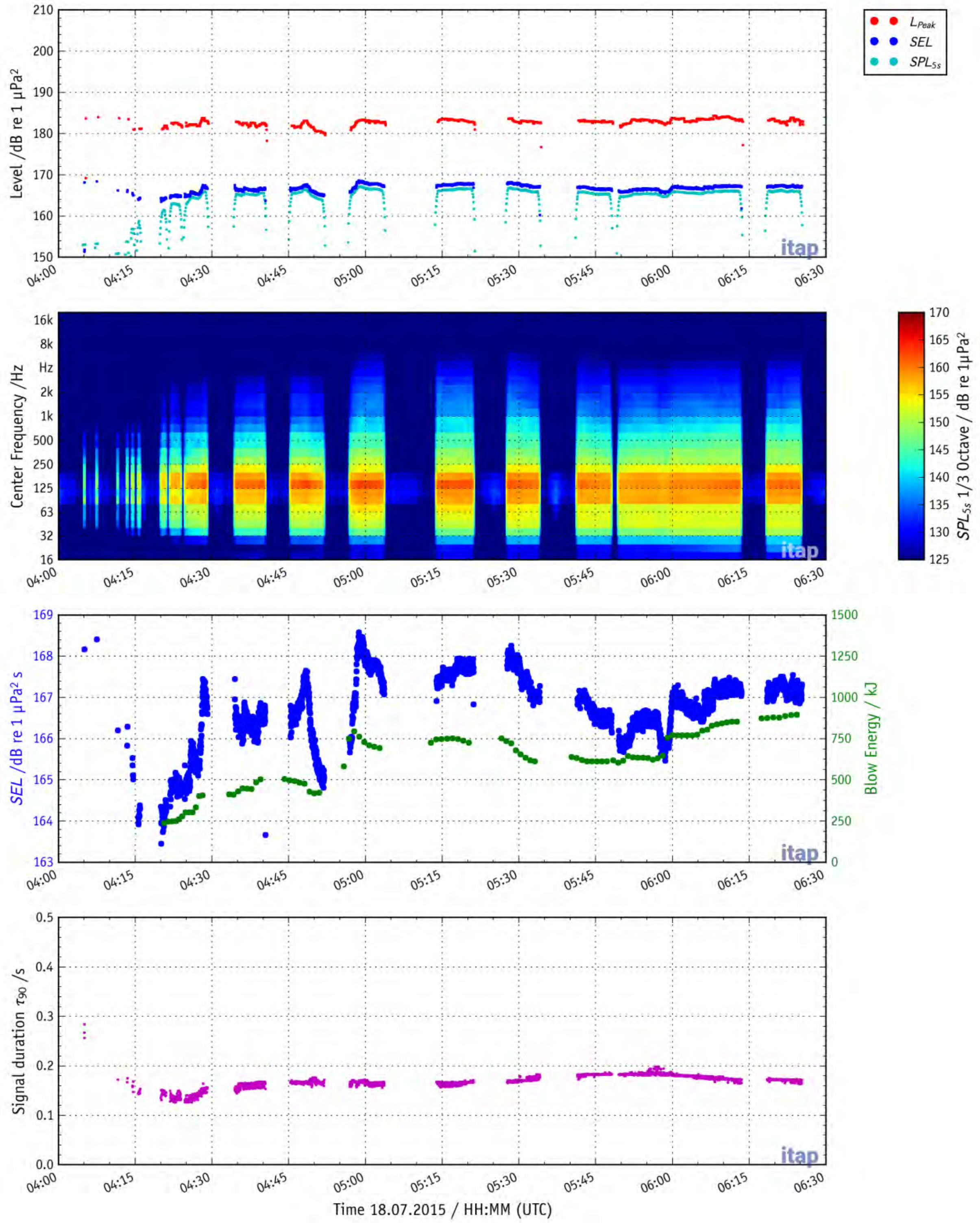


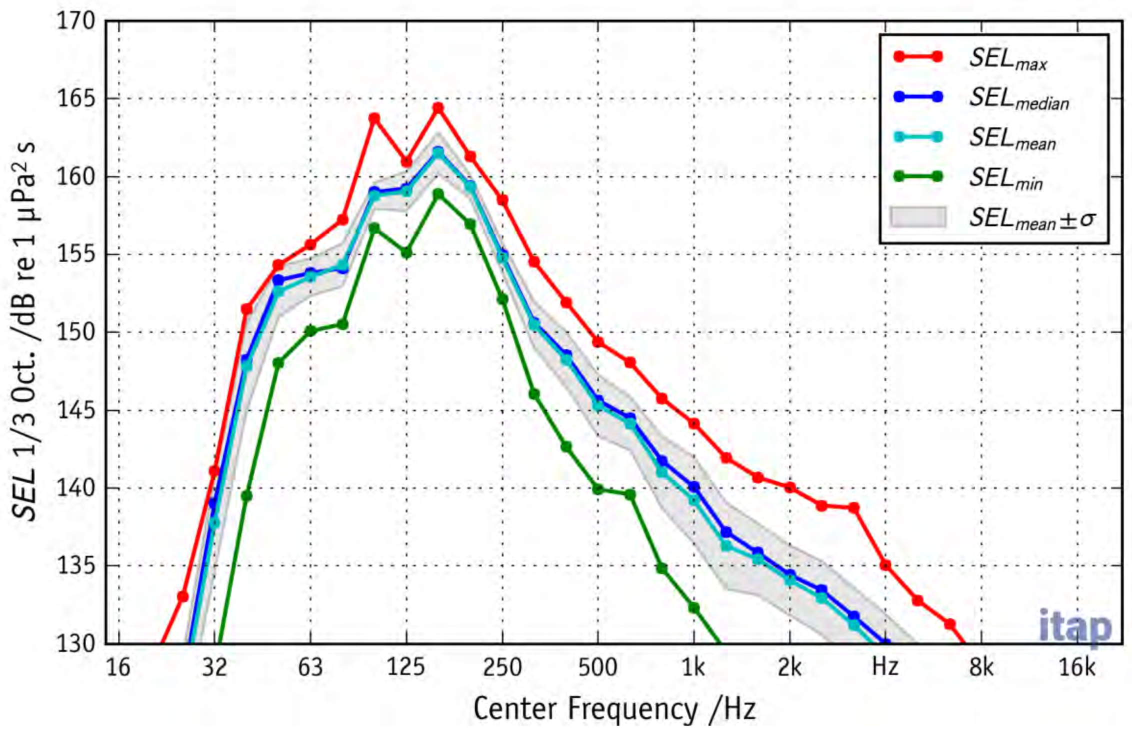
180
175
170
165
160
155
150
145
140
SEL 1/3 Oct. /dB re 1 µPa² s
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center Frequency /Hz
SELmax
SELmedian
SELmean
SELmin
SELmean±σ
itap

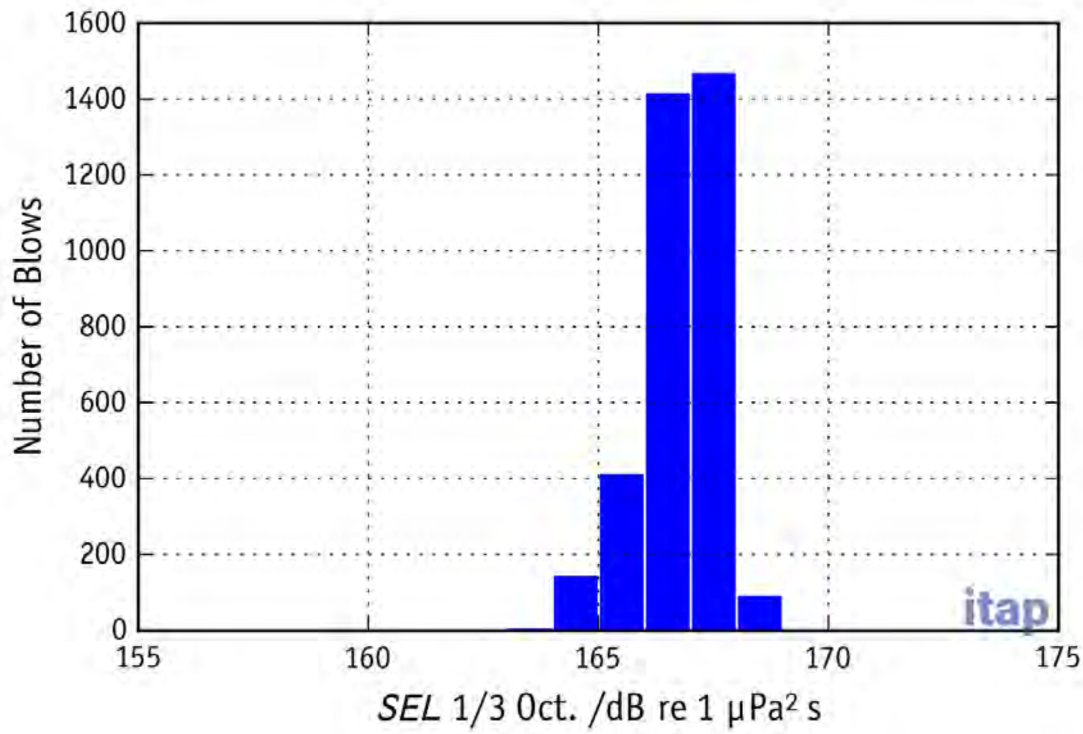


2000
1500
1000
500
0
Number of Blows
170
175
180
185
190
SEL 1/3 Oct. /dB re 1 µPa² s
itap

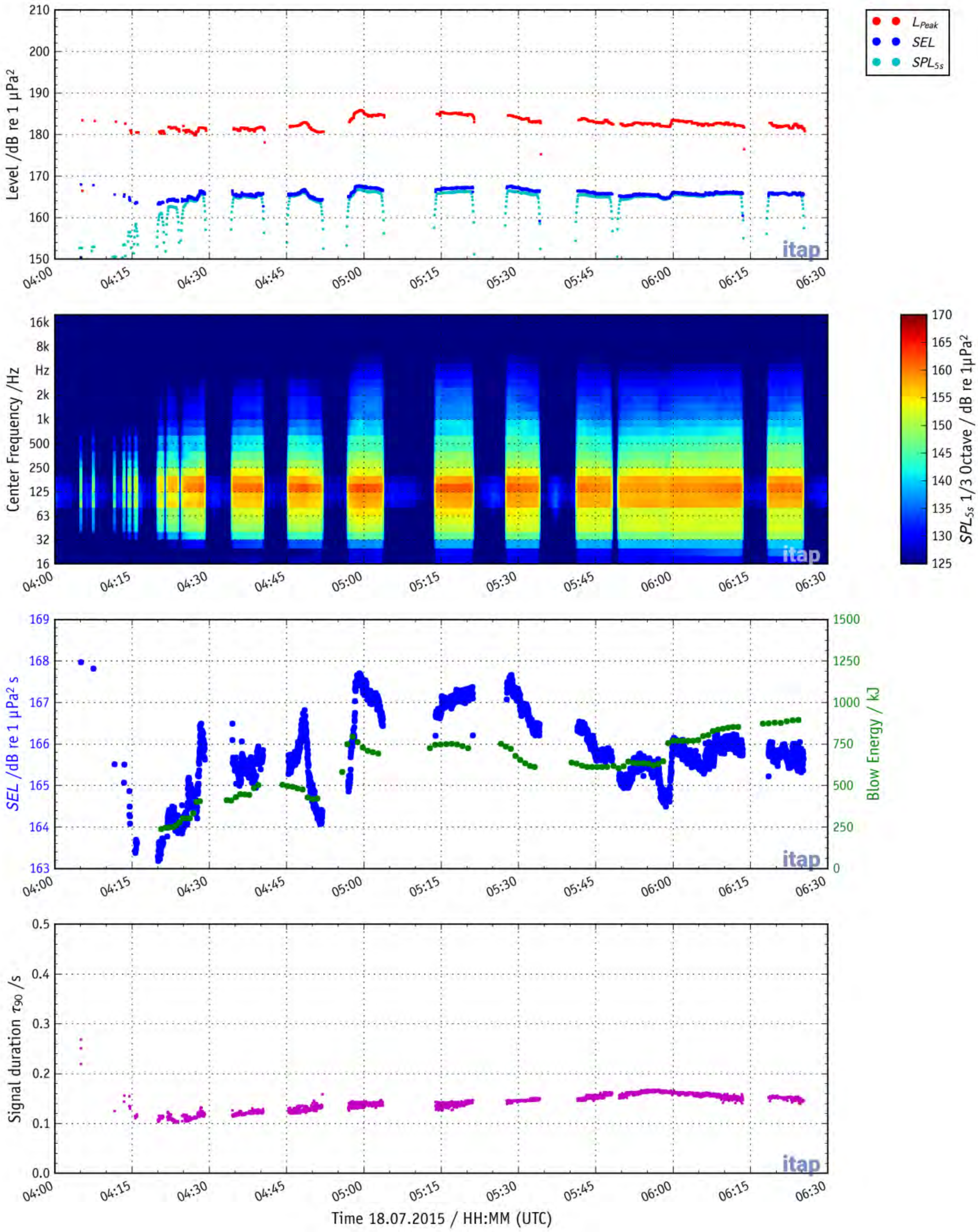
Z2 MP2, 2 m pile driving noise

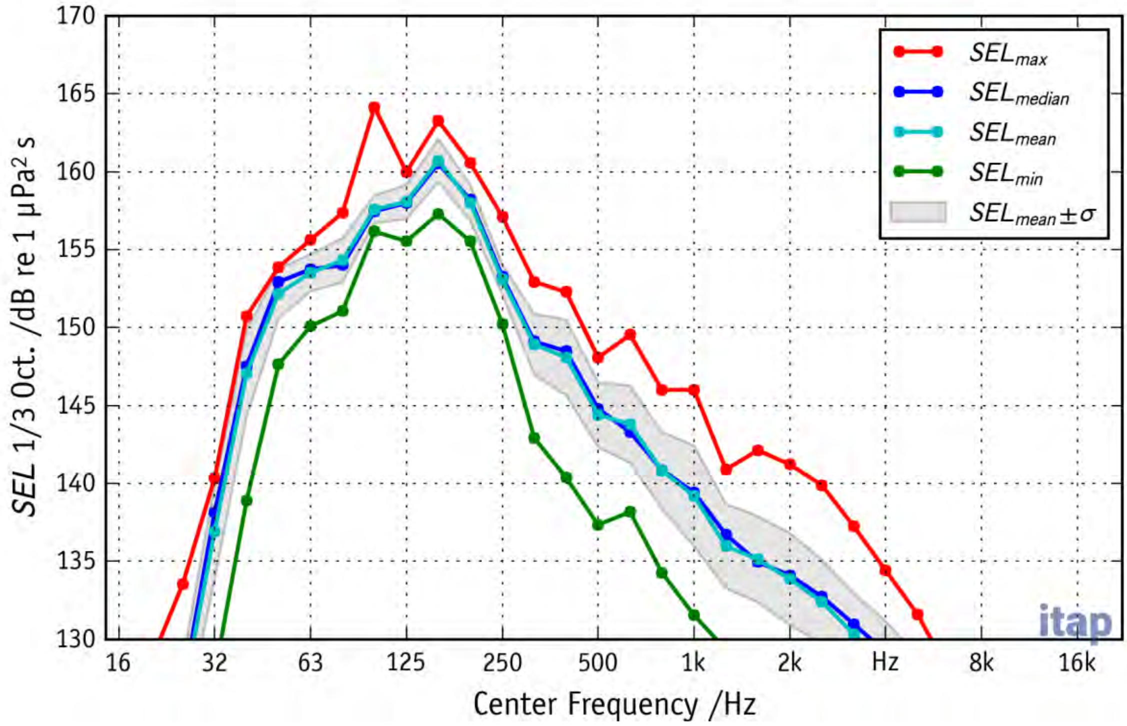



170
165
160
155
150
145
140
135
130
SEL 1/3 Oct. /dB re 1 µPa² s
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center Frequency /Hz
SELmax
SELmedian
SELmean
SELmin
SELmean±σ
itap

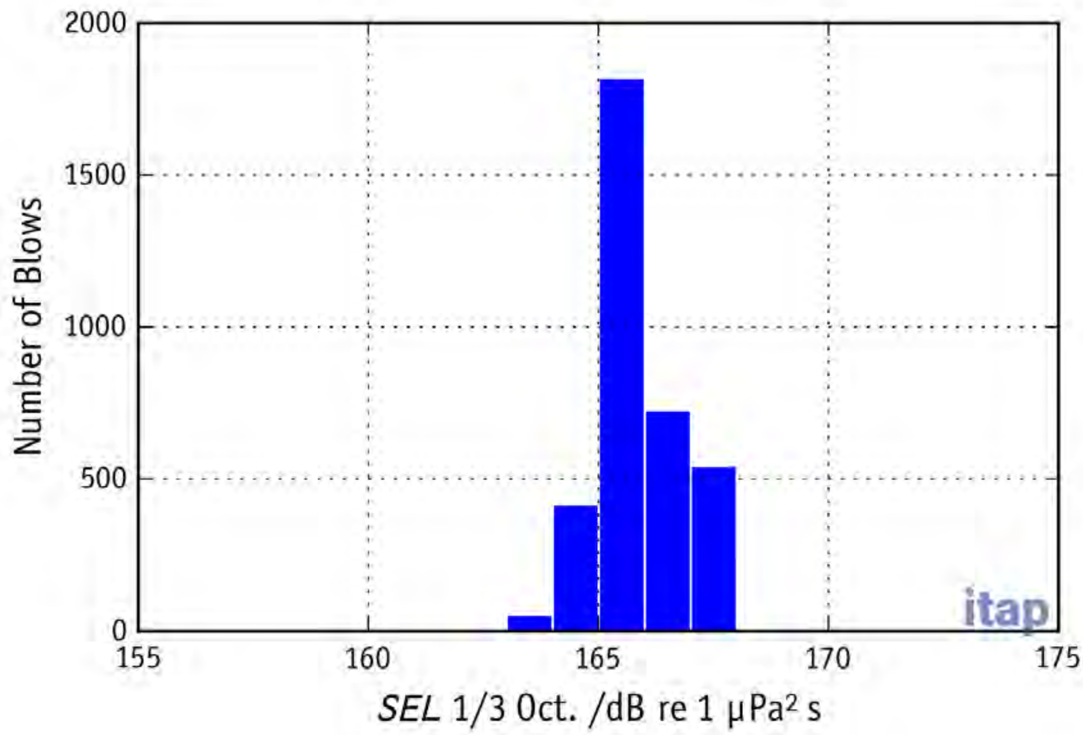

1600
1400
1200
1000
800
600
400
200
0
Number of Blows
155
160
165
170
175
SEL 1/3 Oct. /dB re 1 µPa² s
itap

Z2 MP2, 10 m pile driving noise



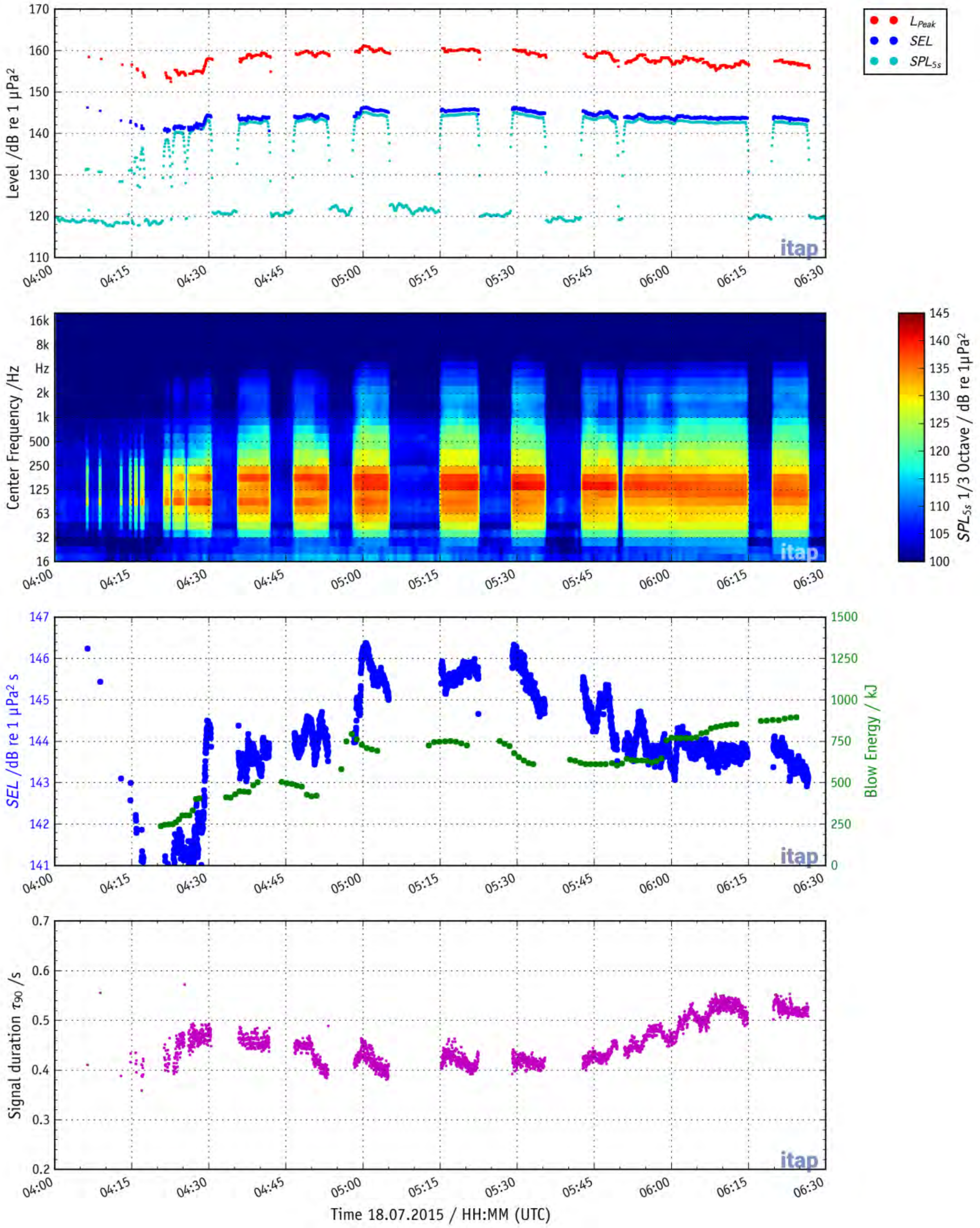


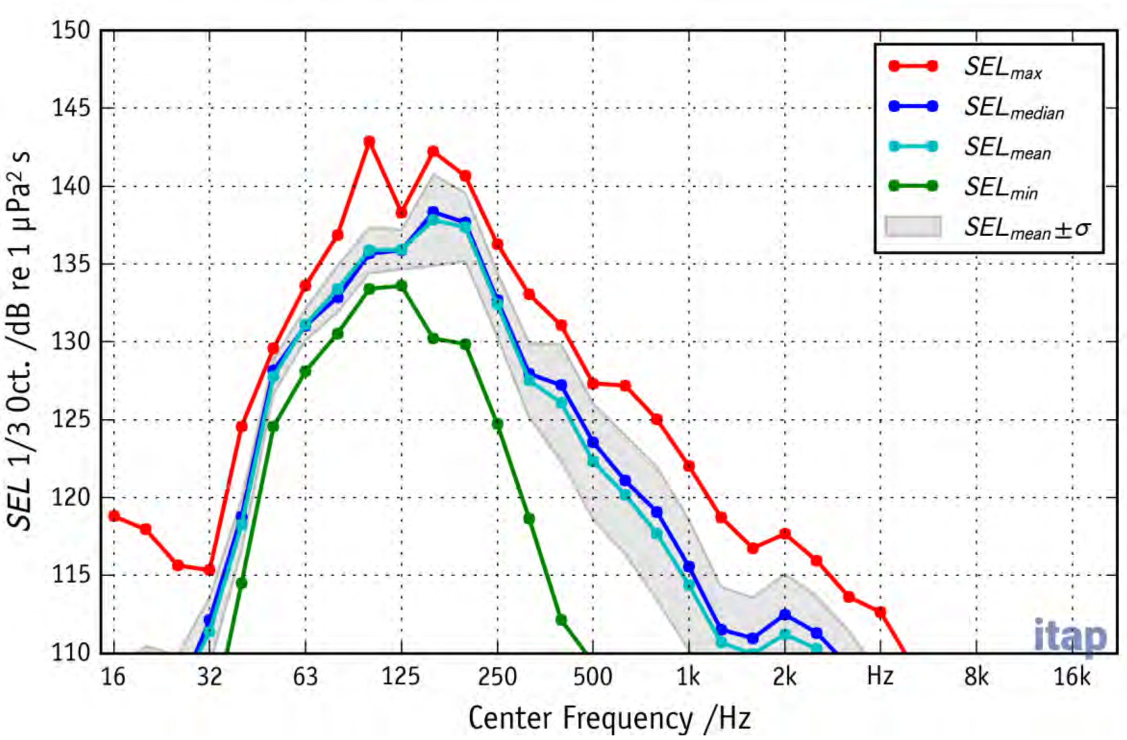
170
165
160
155
150
145
140
135
130
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center Frequency /Hz
SEL 1/3 Oct. /dB re 1 µPa² s
SELmax
SELmedian
SELmean
SELmin
SELmean ± σ
itap

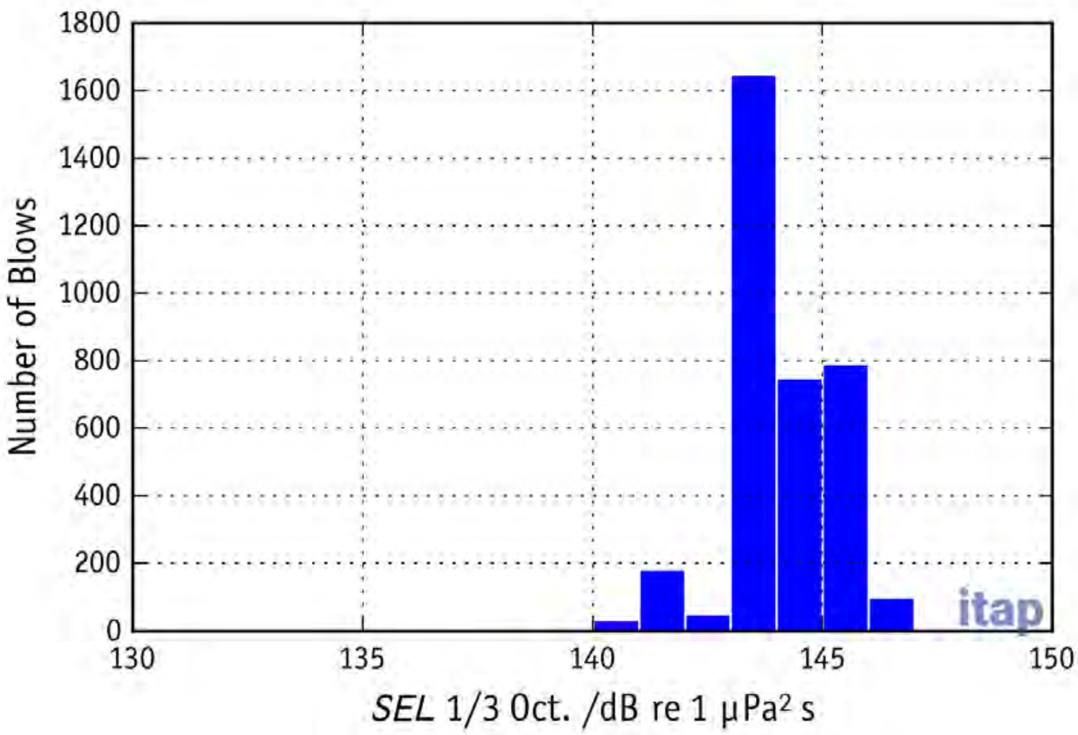


2000
1500
1000
500
0
155
160
165
170
175
Number of Blows
SEL 1/3 Oct. /dB re 1 µPa² s
itap

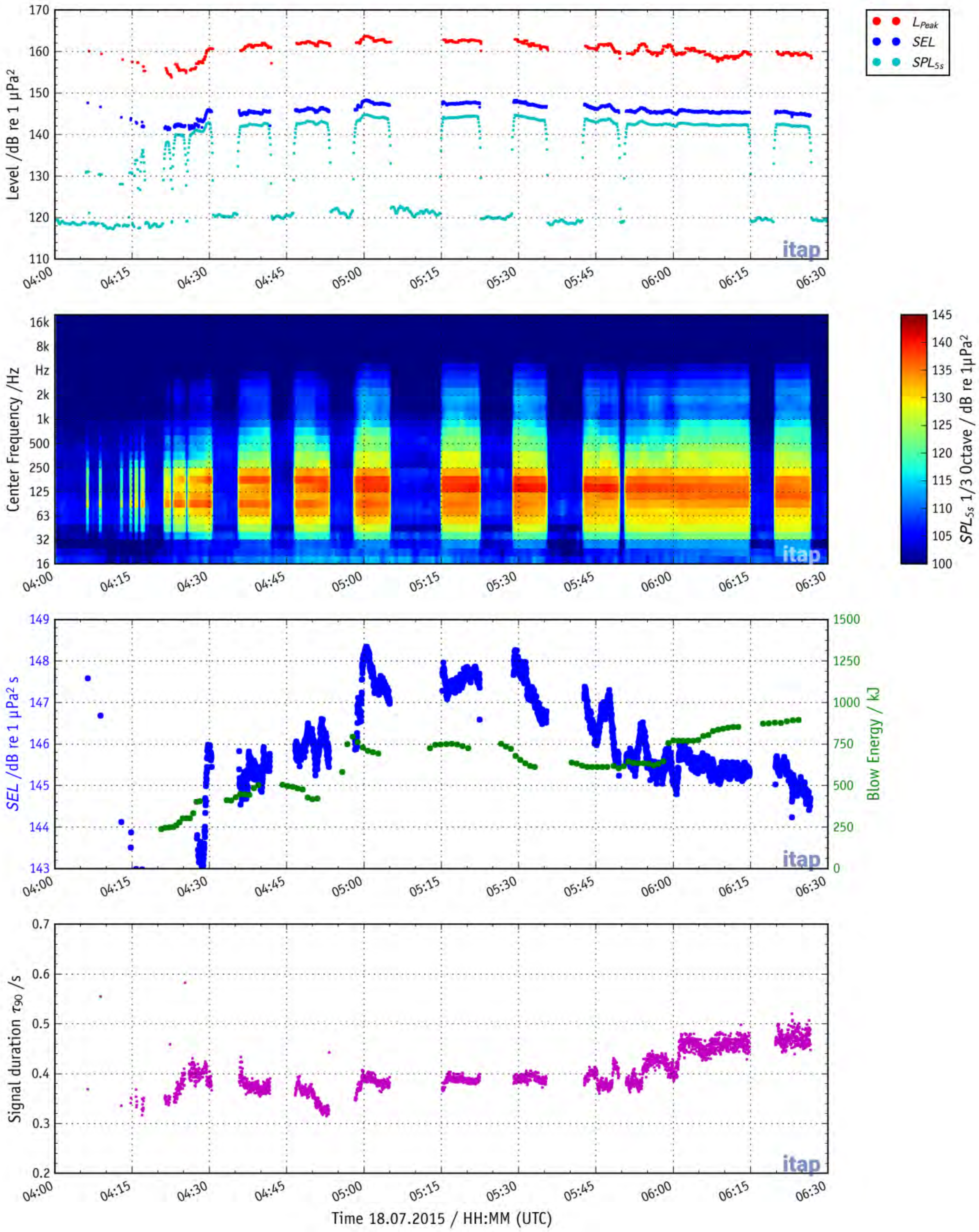
Z2 MP3, 2 m pile driving noise

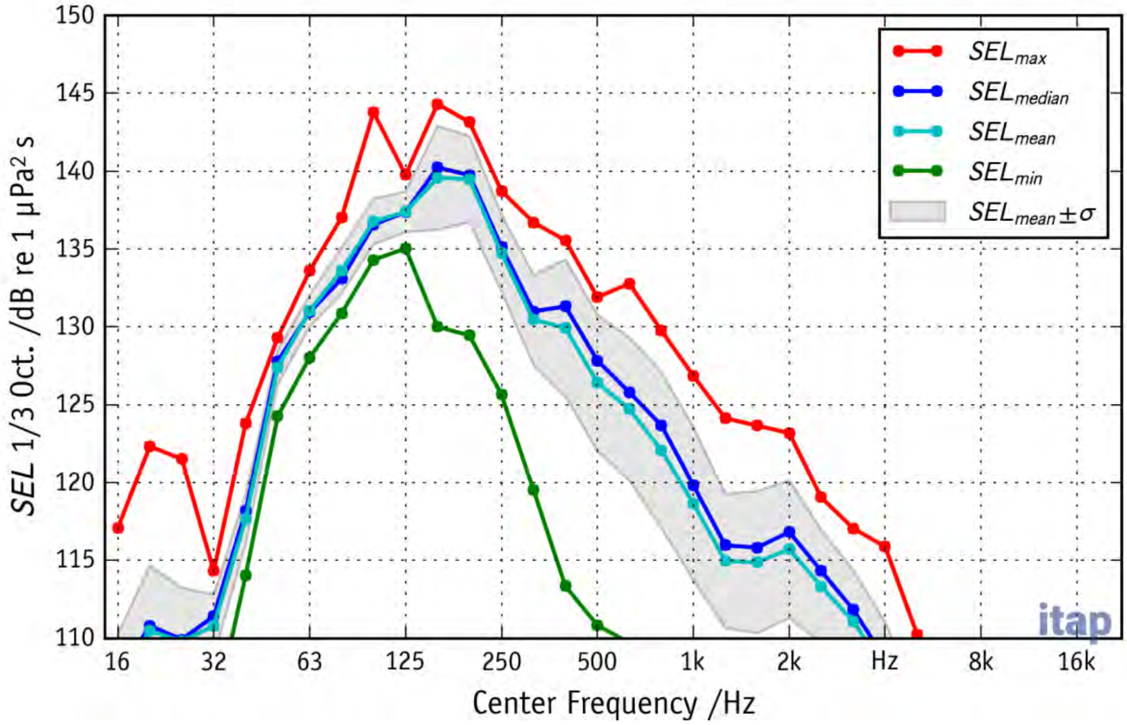


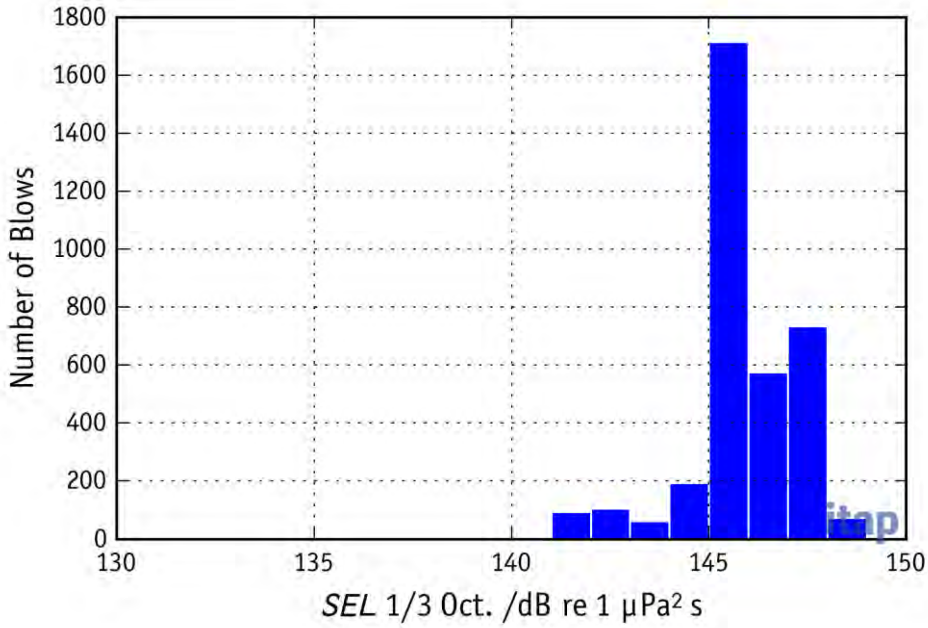

150
145
140
135
130
125
120
115
110
SEL 1/3 Oct. /dB re 1 µPa² s
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center Frequency /Hz
SELmax
SELmedian
SELmean
SELmin
SELmean ± σ
itap


1800
1600
1400
1200
1000
800
600
400
200
0
Number of Blows
130
135
140
145
150
SEL 1/3 Oct. /dB re 1 µPa² s
itap

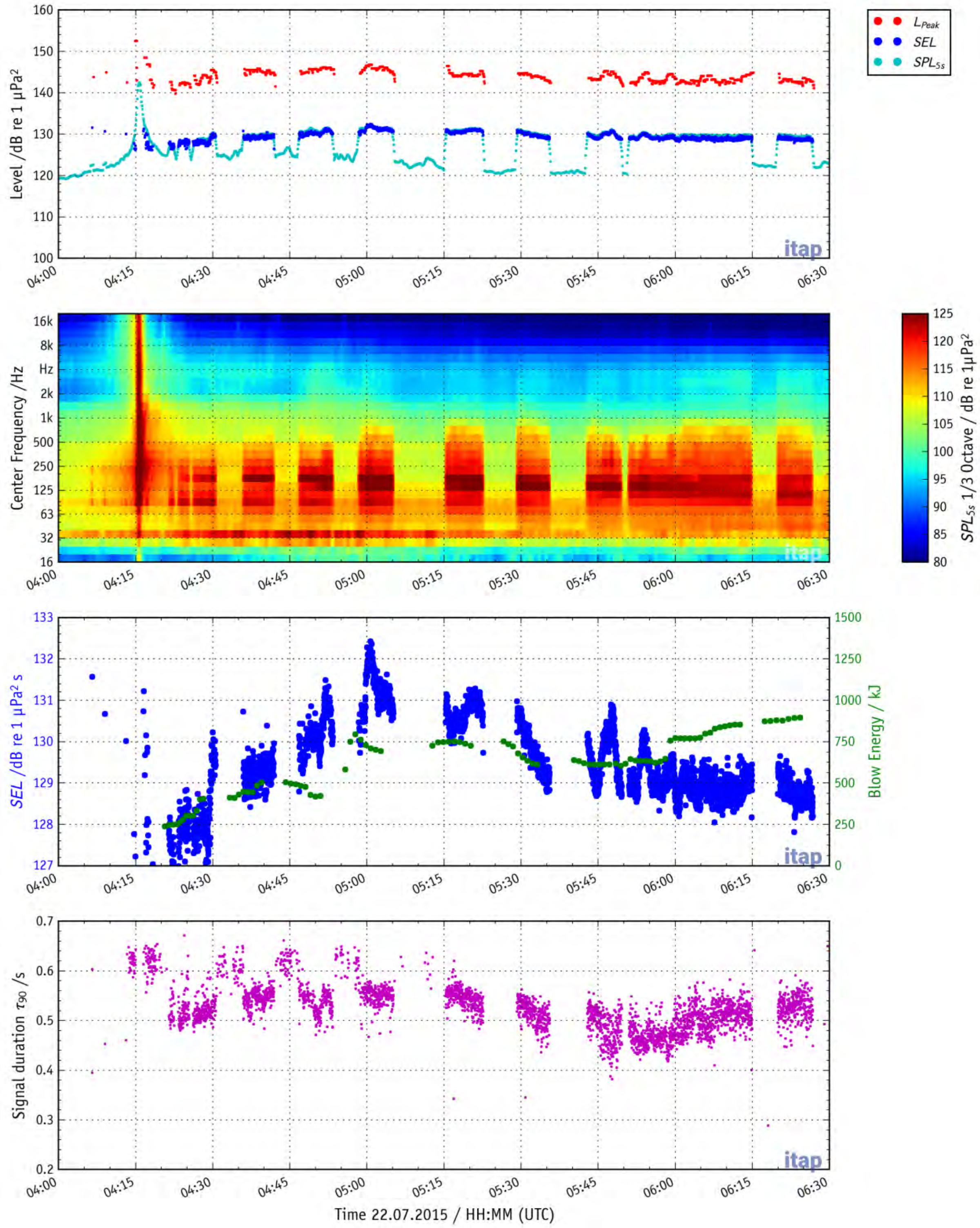
Z2 MP3, 10 m pile driving noise

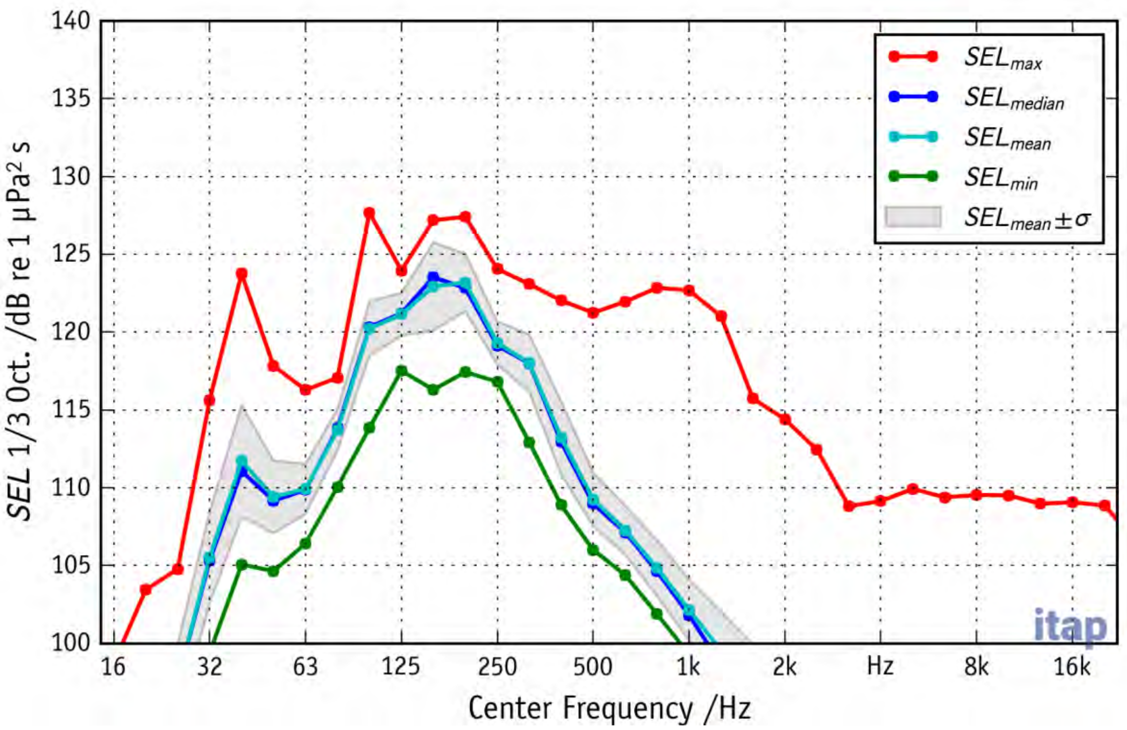


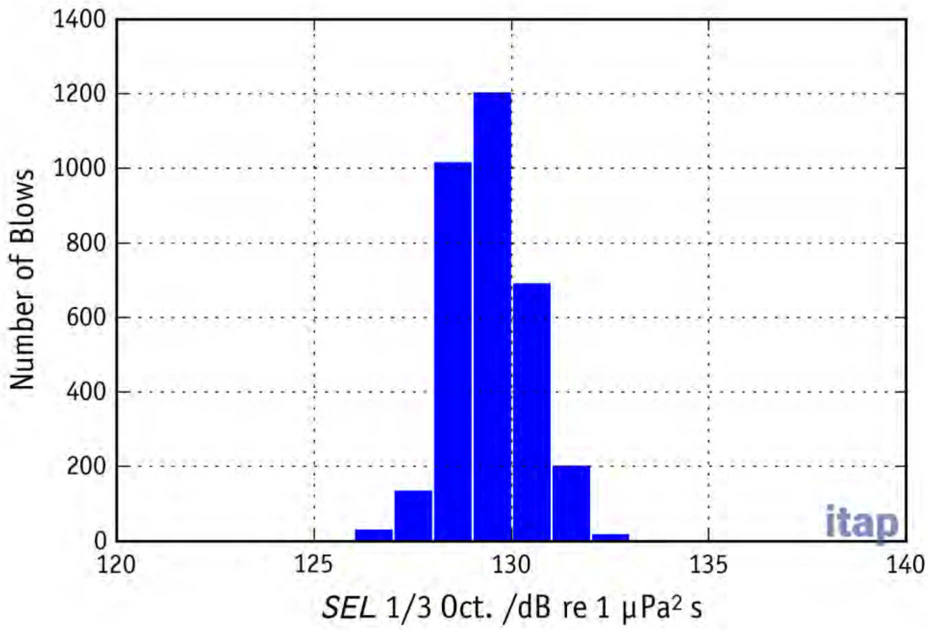

SEL 1/3 Oct. /dB re 1 μPa² s
Center Frequency /Hz
SEL_{max}
SEL_{median}
SEL_{mean}
SEL_{min}
$SEL_{mean} \pm \sigma$
150
145
140
135
130
125
120
115
110
16
32
63
125
250
500
1k
2k
Hz
8k
16k
itap


Number of Blows
SEL 1/3 Oct. /dB re 1 μPa² s
1800
1600
1400
1200
1000
800
600
400
200
0
130
135
140
145
150
itap

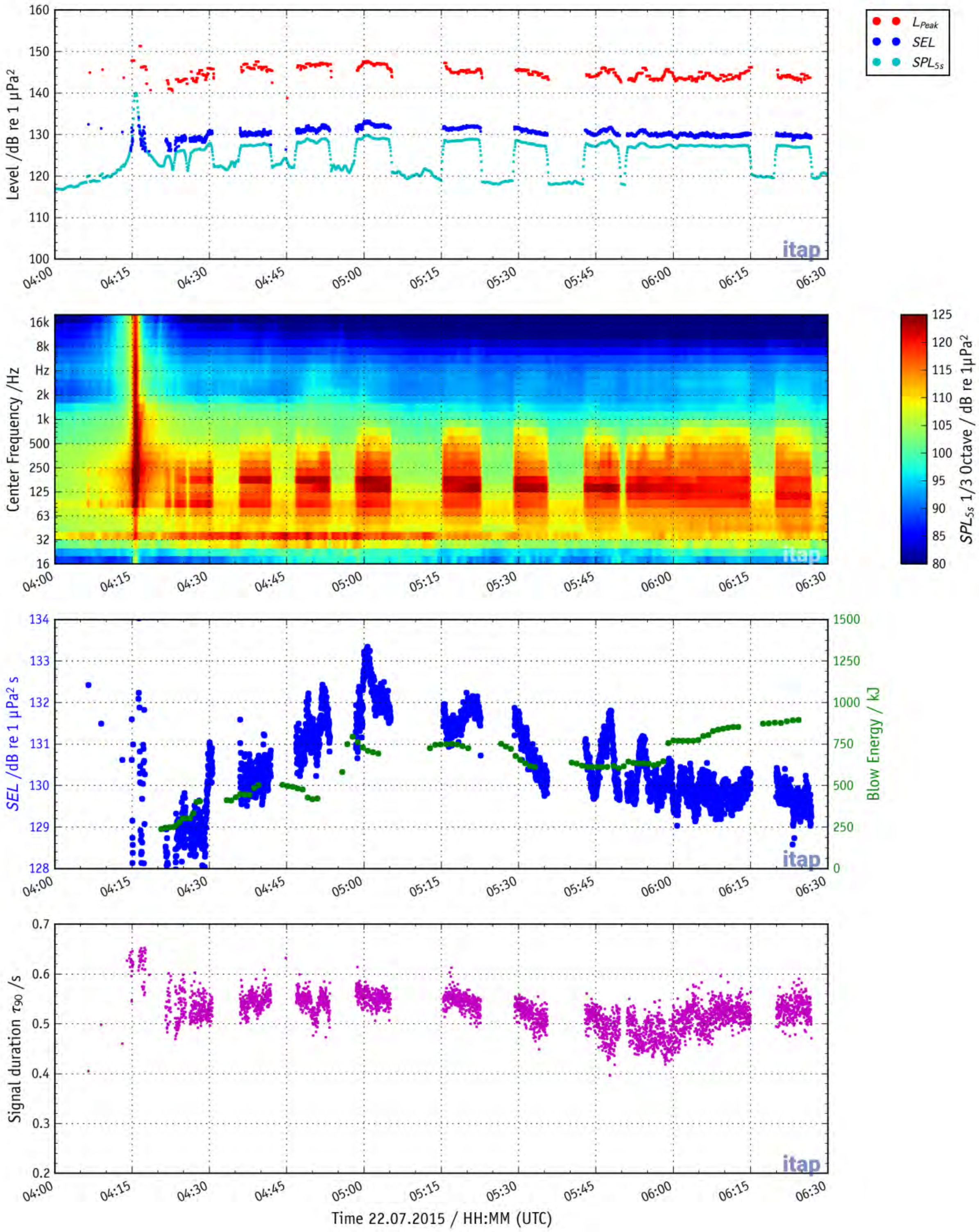
Z2 MP4, 2 m pile driving noise

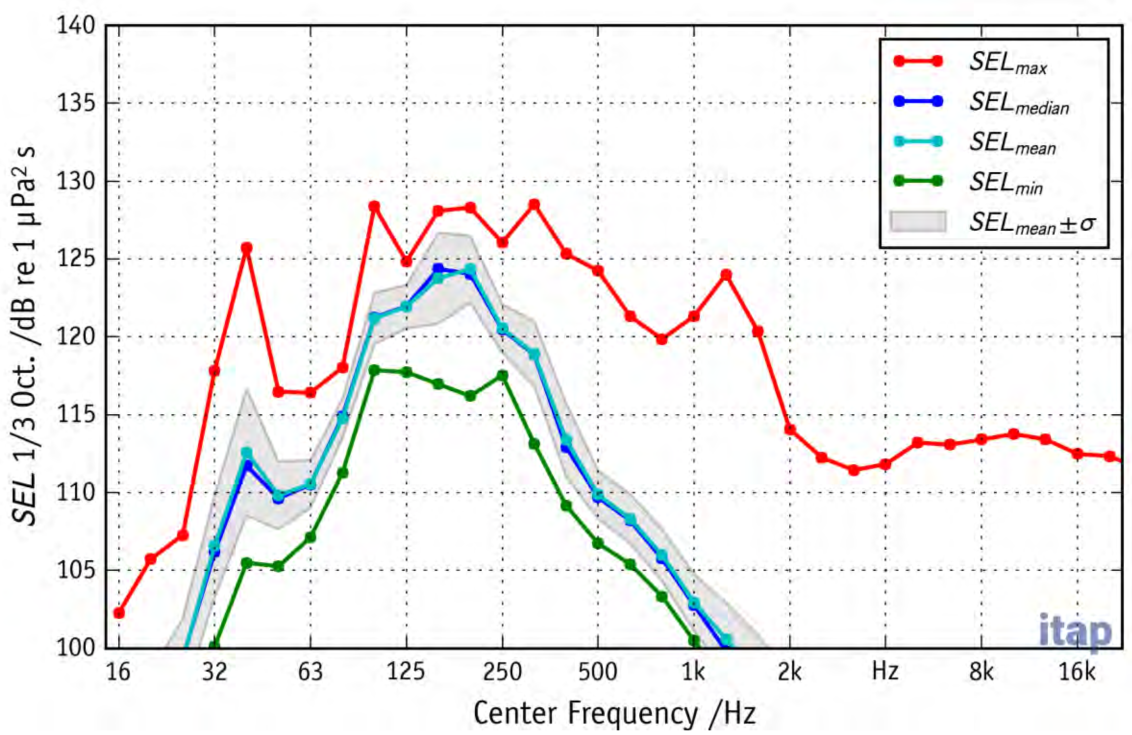


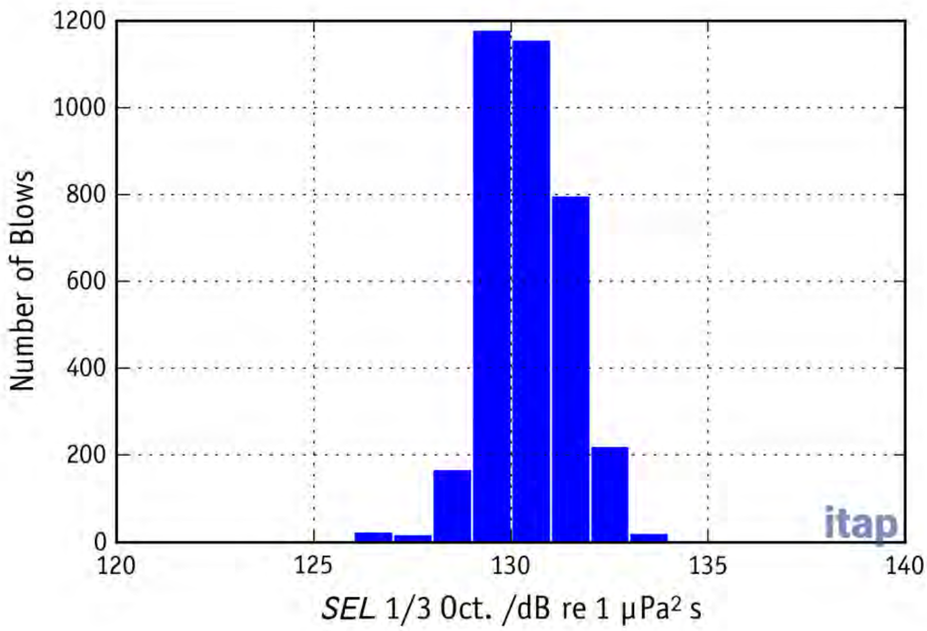

SEL 1/3 Oct. /dB re 1 µPa² s
Center Frequency /Hz
SELmax
SELmedian
SELmean
SELmin
SELmean ± σ
itap


Number of Blows
SEL 1/3 Oct. /dB re 1 µPa² s
itap

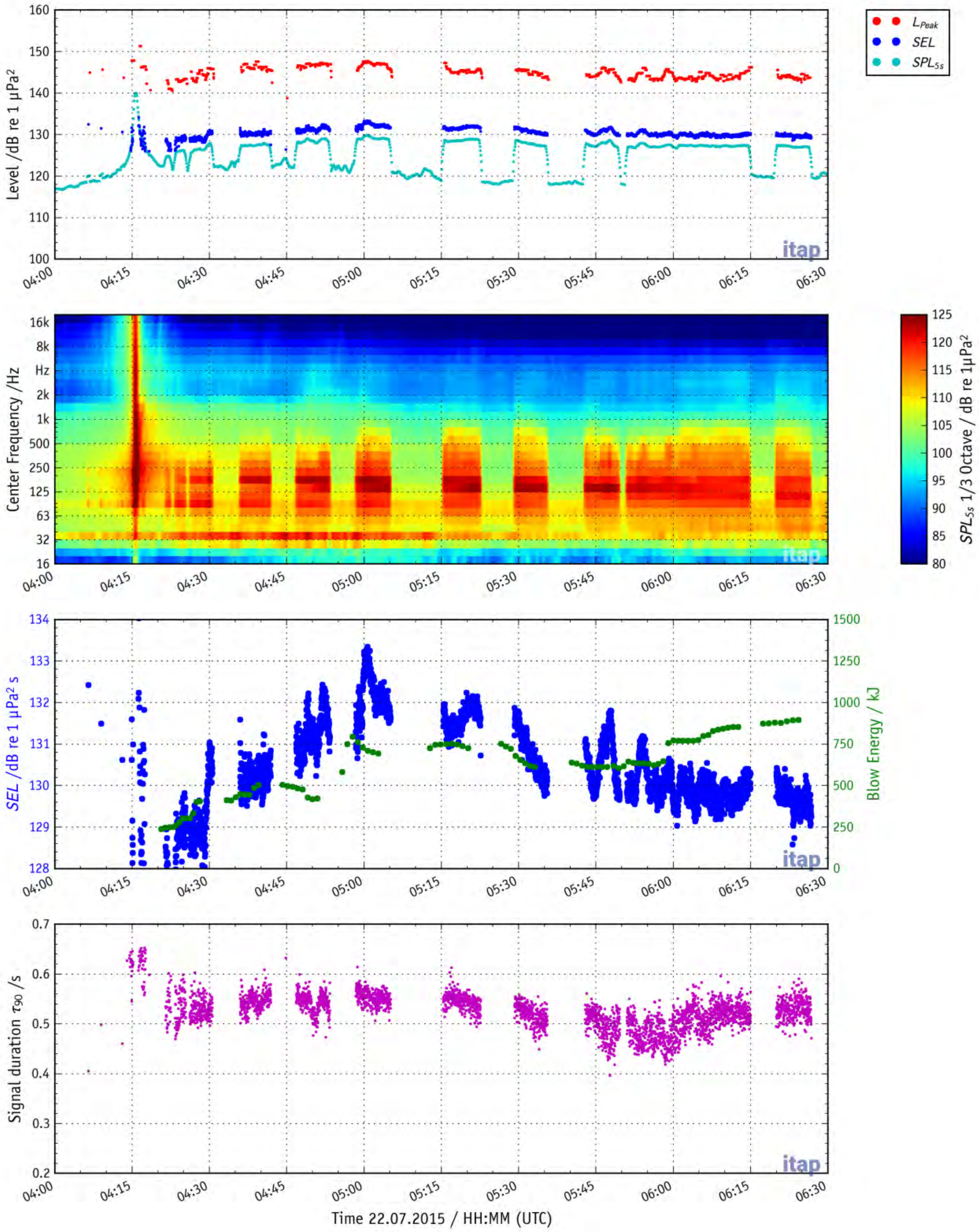
Z2 MP4, 10 m pile driving noise

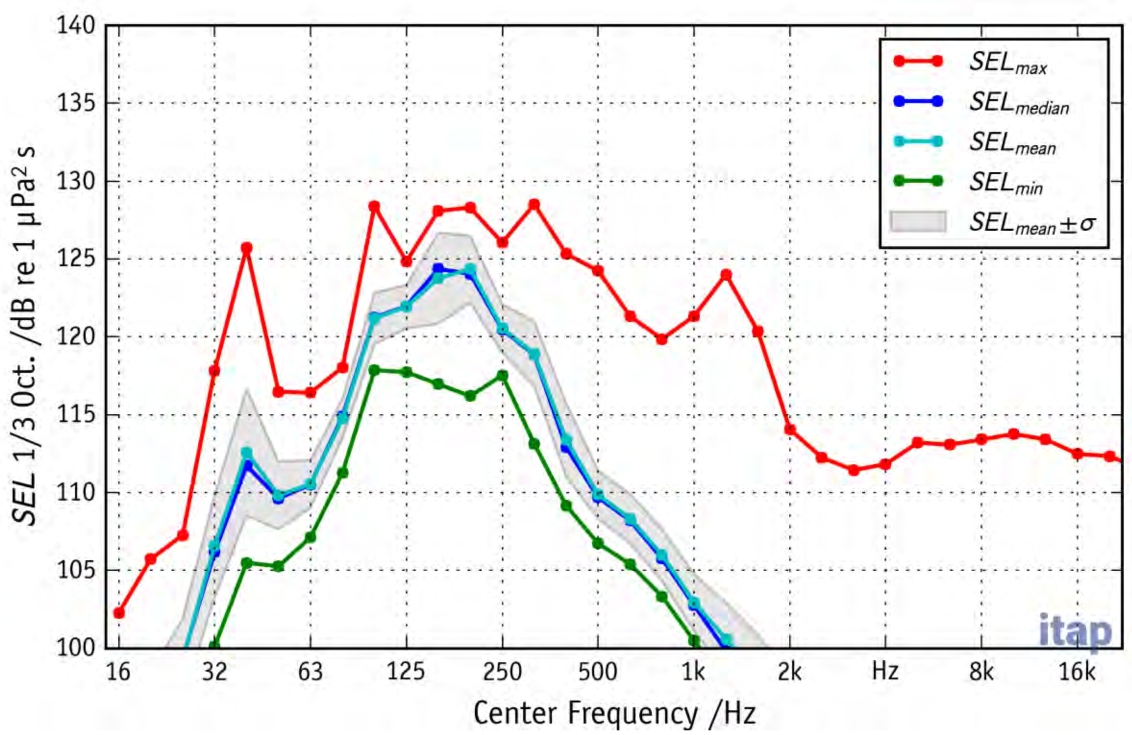



140
135
130
125
120
115
110
105
100
SEL 1/3 Oct. /dB re 1 µPa² s
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center Frequency /Hz
SEL_{max}
SEL_{median}
SEL_{mean}
SEL_{min}
$SEL_{mean} \pm \sigma$
itap

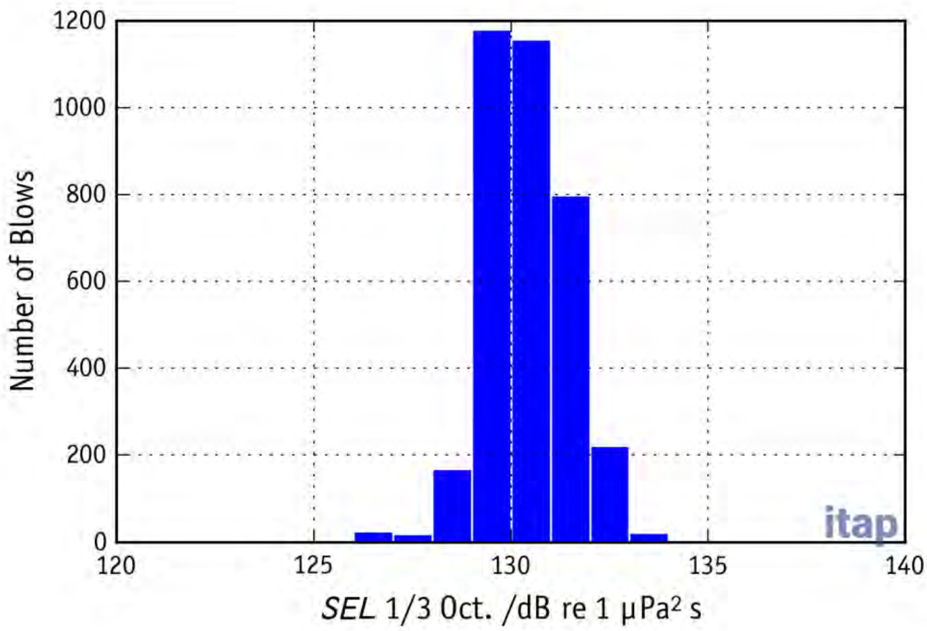

1200
1000
800
600
400
200
0
Number of Blows
120
125
130
135
140
SEL 1/3 Oct. /dB re 1 µPa² s
itap

Z2 MP4, 10 m pile driving noise





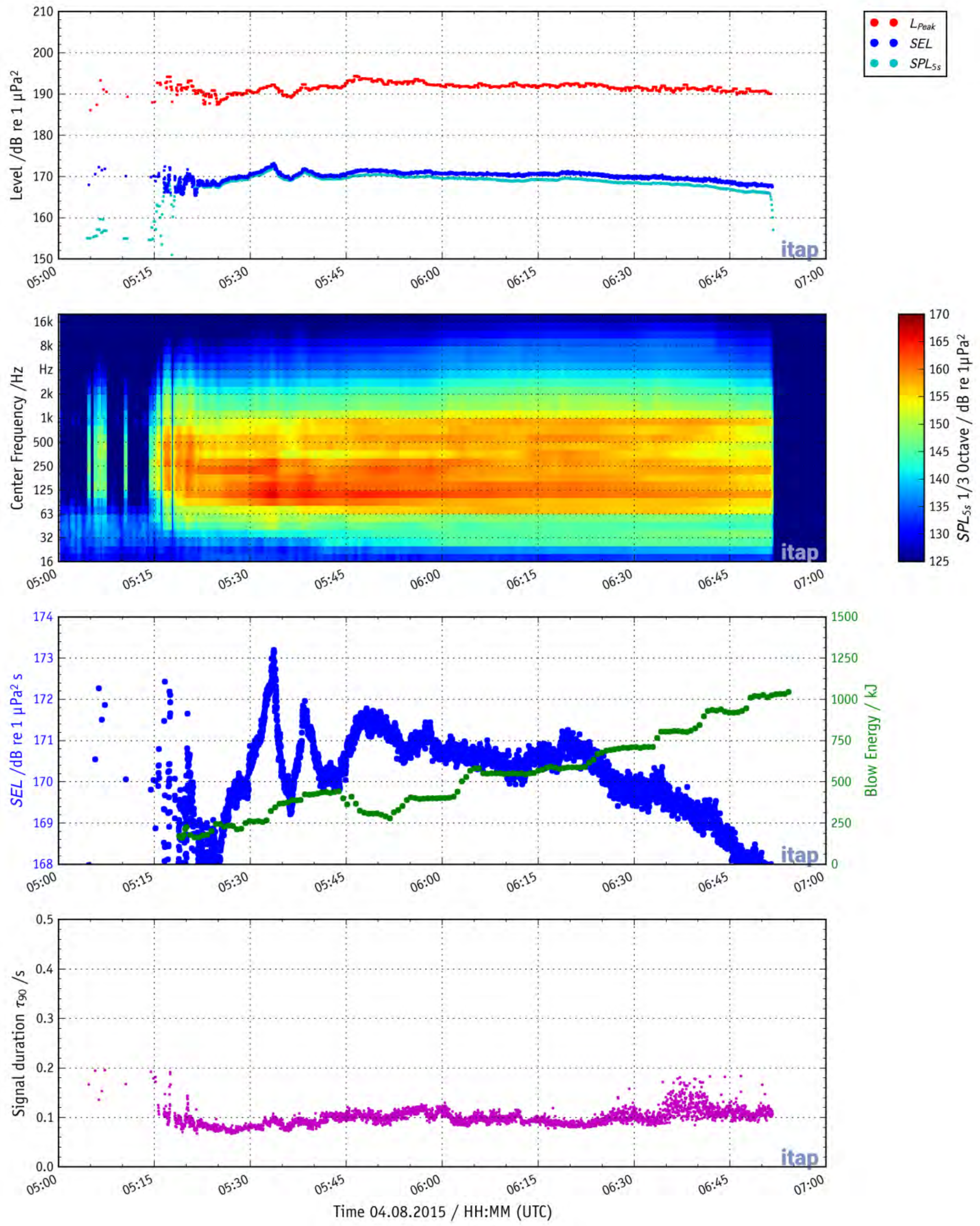
SEL 1/3 Oct. /dB re 1 µPa² s
Center Frequency /Hz
SELmax
SELmedian
SELmean
SELmin
SELmean ± σ
itap

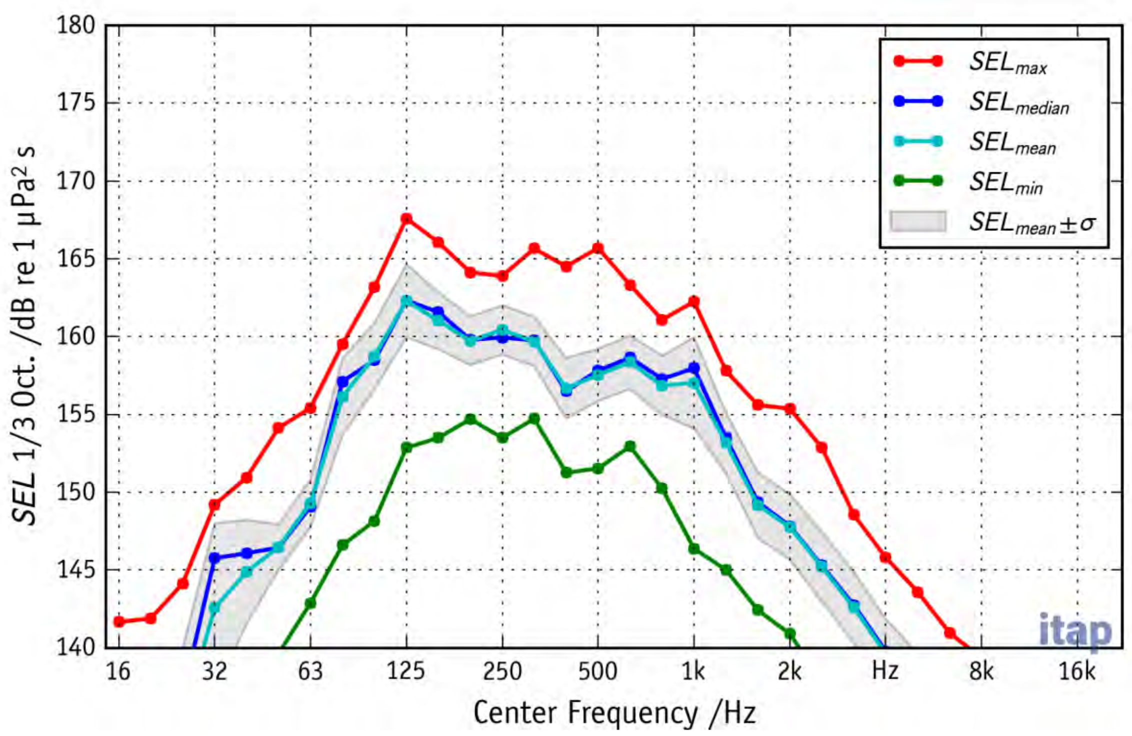


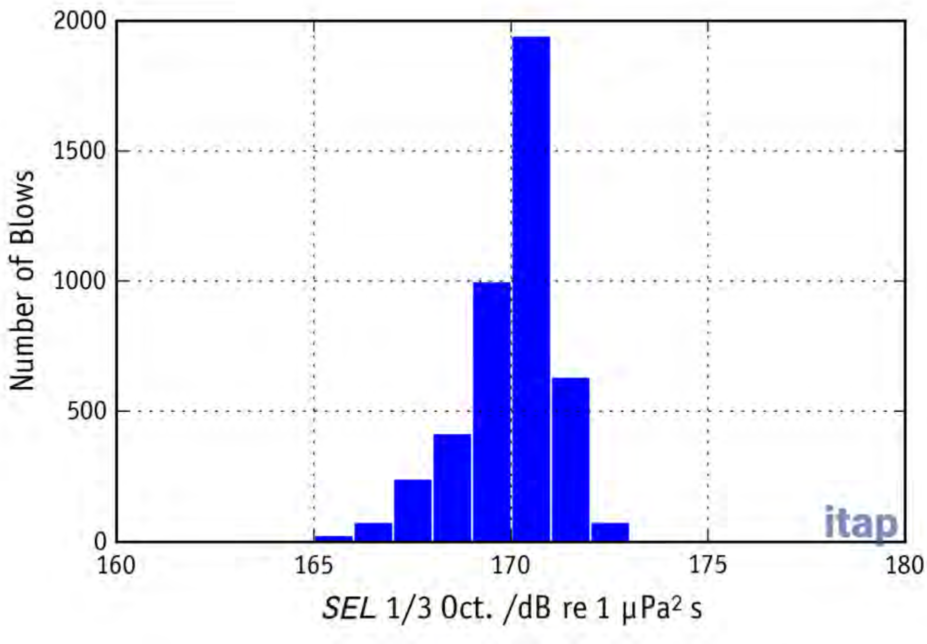
Number of Blows
SEL 1/3 Oct. /dB re 1 µPa² s
itap

A1.2 Pile Driving Noise at pin pile B3 (OHVS1)

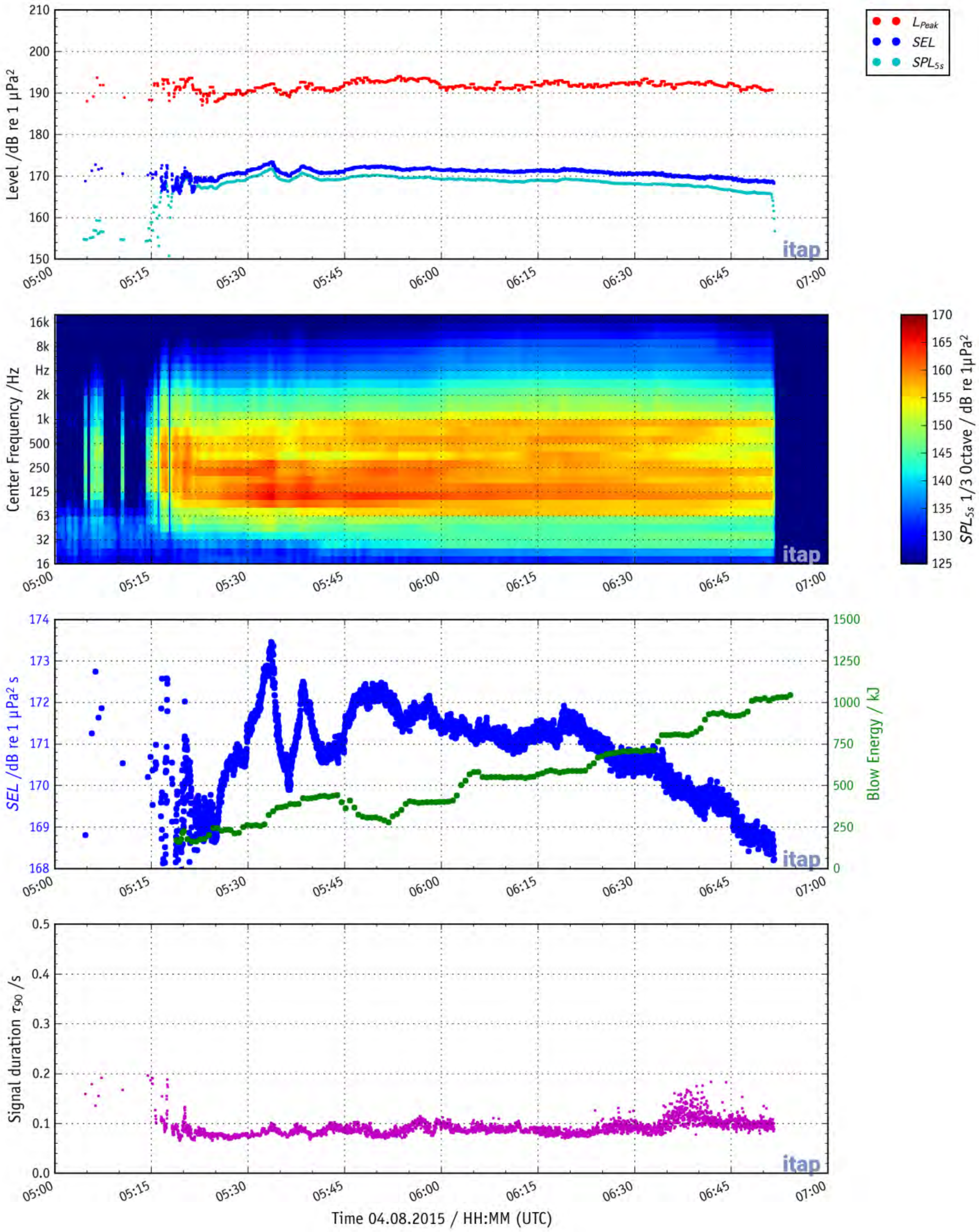
OHVS1 MP1, 2 m pile driving noise

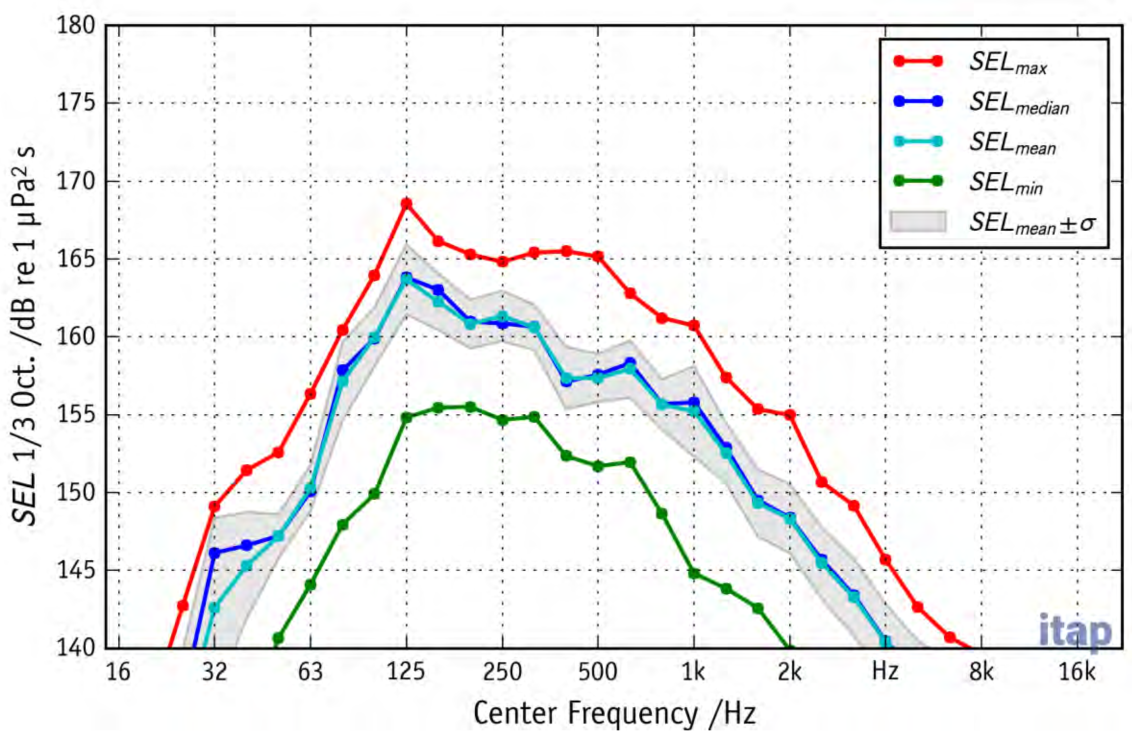



180
175
170
165
160
155
150
145
140
SEL 1/3 Oct. /dB re 1 µPa² s
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center Frequency /Hz
SEL_{max}
SEL_{median}
SEL_{mean}
SEL_{min}
$SEL_{mean} \pm \sigma$
itap

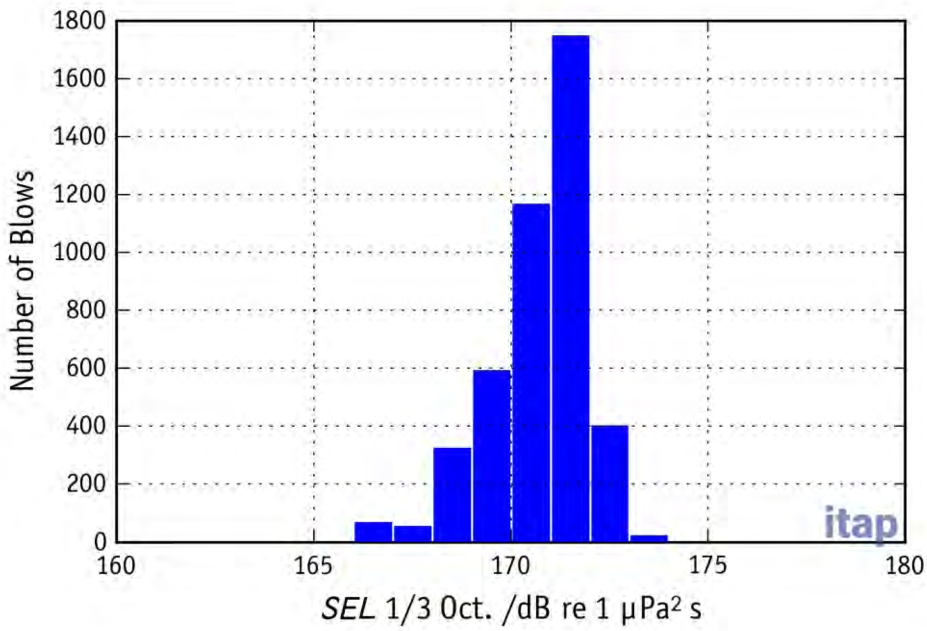

2000
1500
1000
500
0
Number of Blows
160
165
170
175
180
SEL 1/3 Oct. /dB re 1 µPa² s
itap

OHVS1 MP1, 10 m pile driving noise



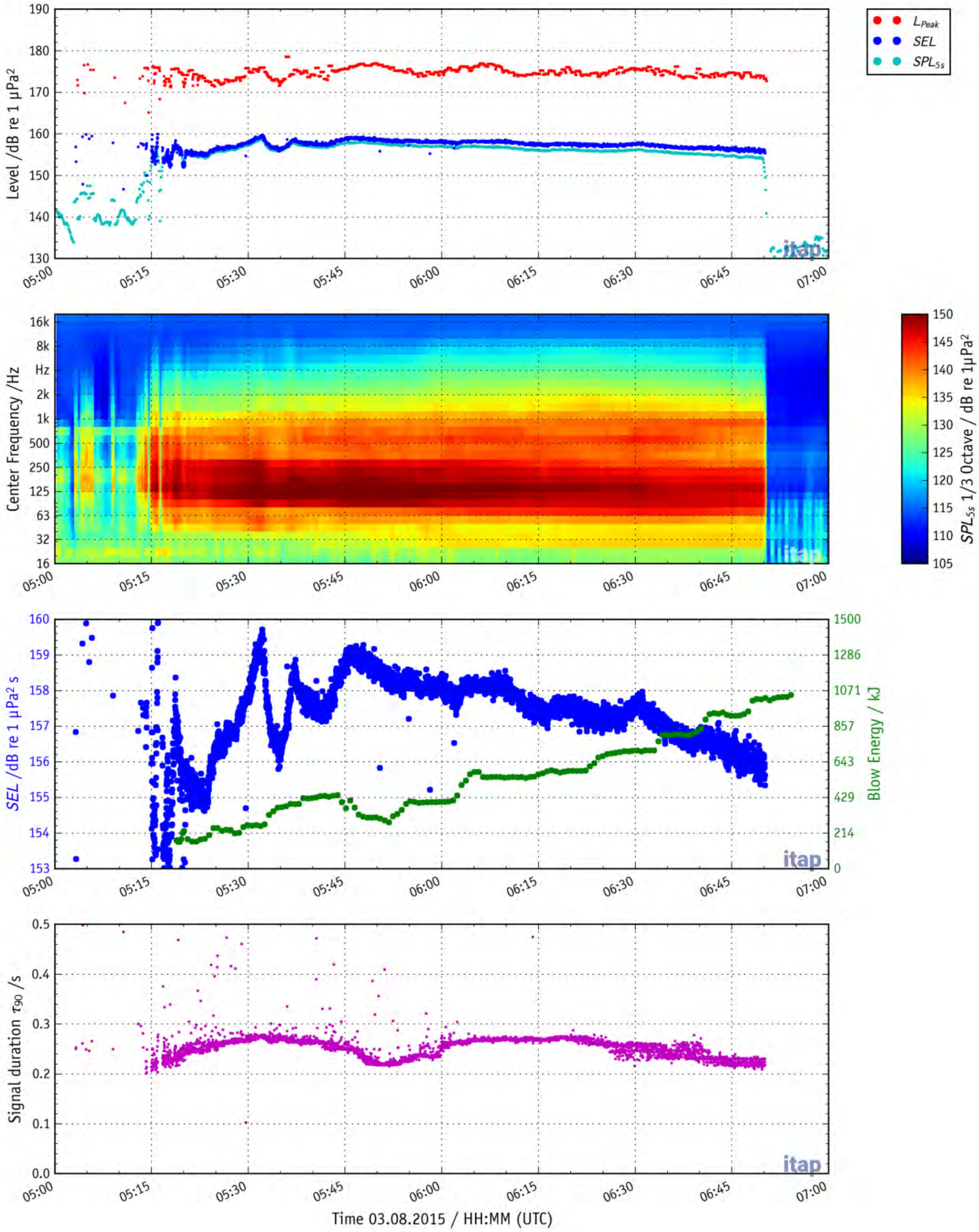


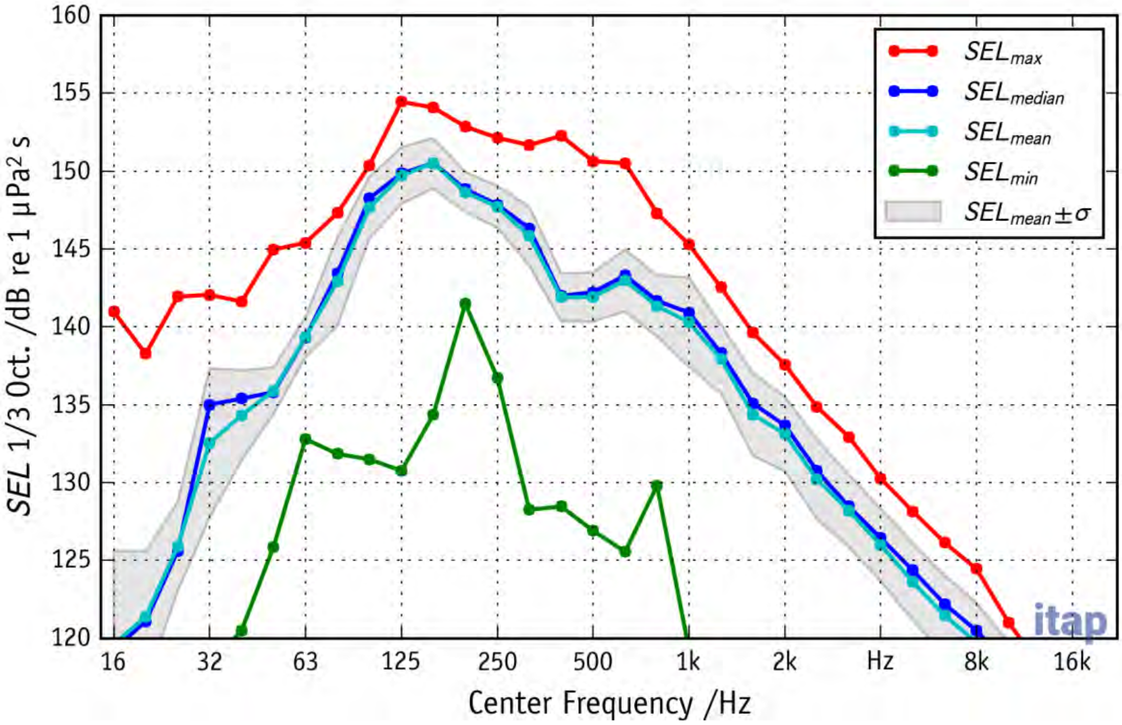
SEL_{max}
SEL_{median}
SEL_{mean}
SEL_{min}
$SEL_{mean} \pm \sigma$
SEL 1/3 Oct. /dB re 1 µPa² s
Center Frequency /Hz
16
32
63
125
250
500
1k
2k
Hz
8k
16k
140
145
150
155
160
165
170
175
180
itap



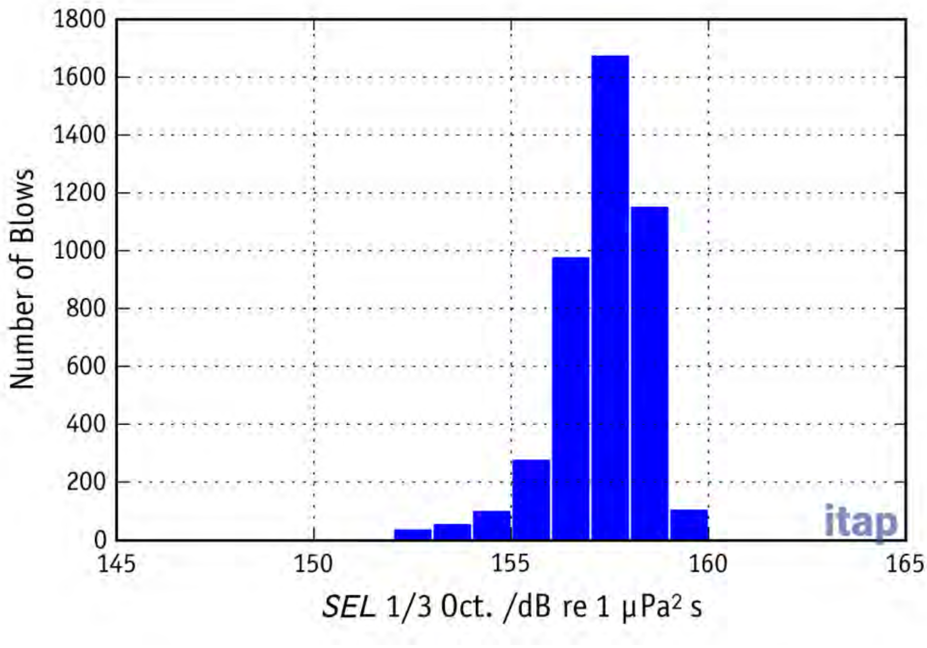
Number of Blows
SEL 1/3 Oct. /dB re 1 µPa² s
0
200
400
600
800
1000
1200
1400
1600
1800
160
165
170
175
180
itap

OHVS1 MP2, 2 m pile driving noise



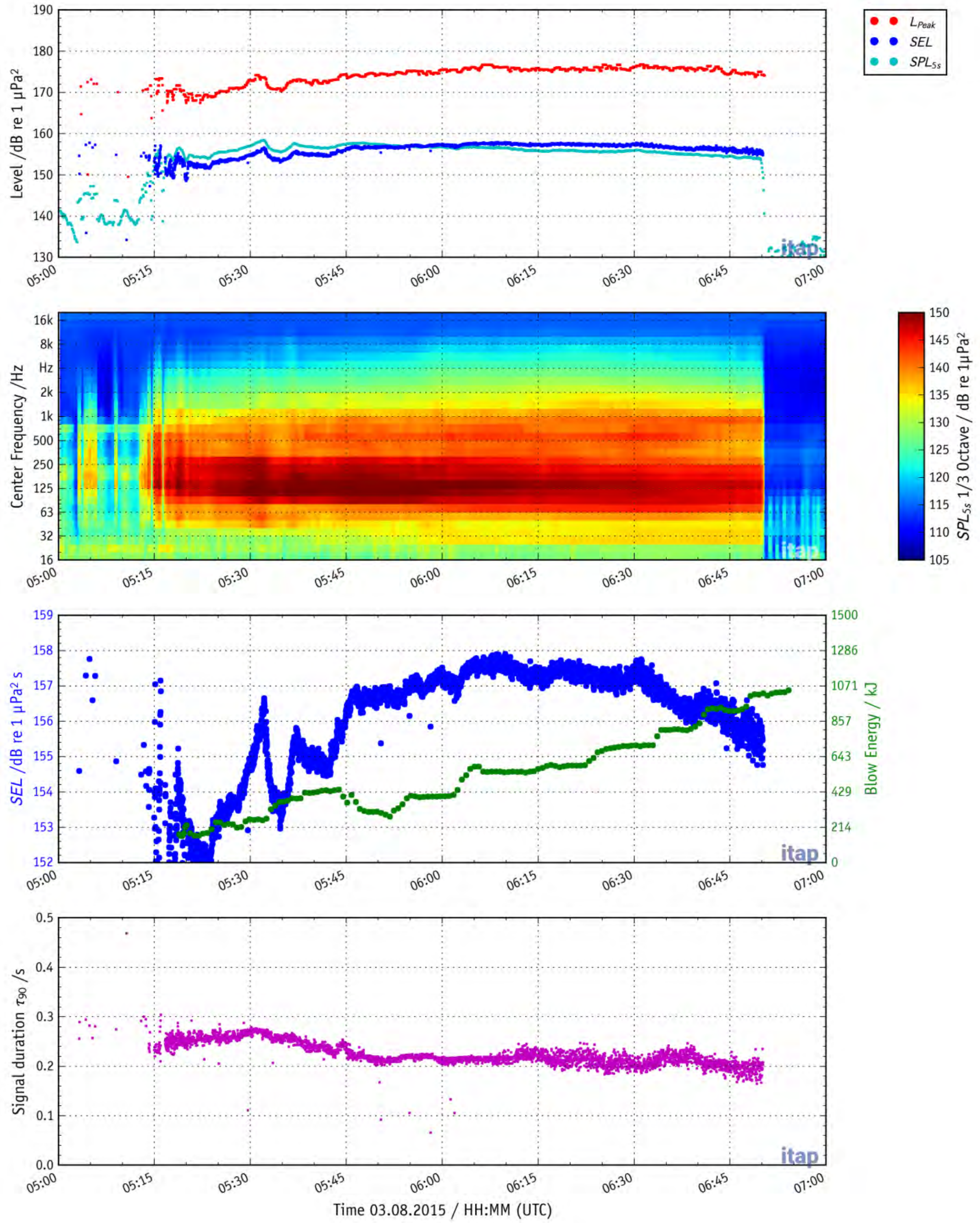


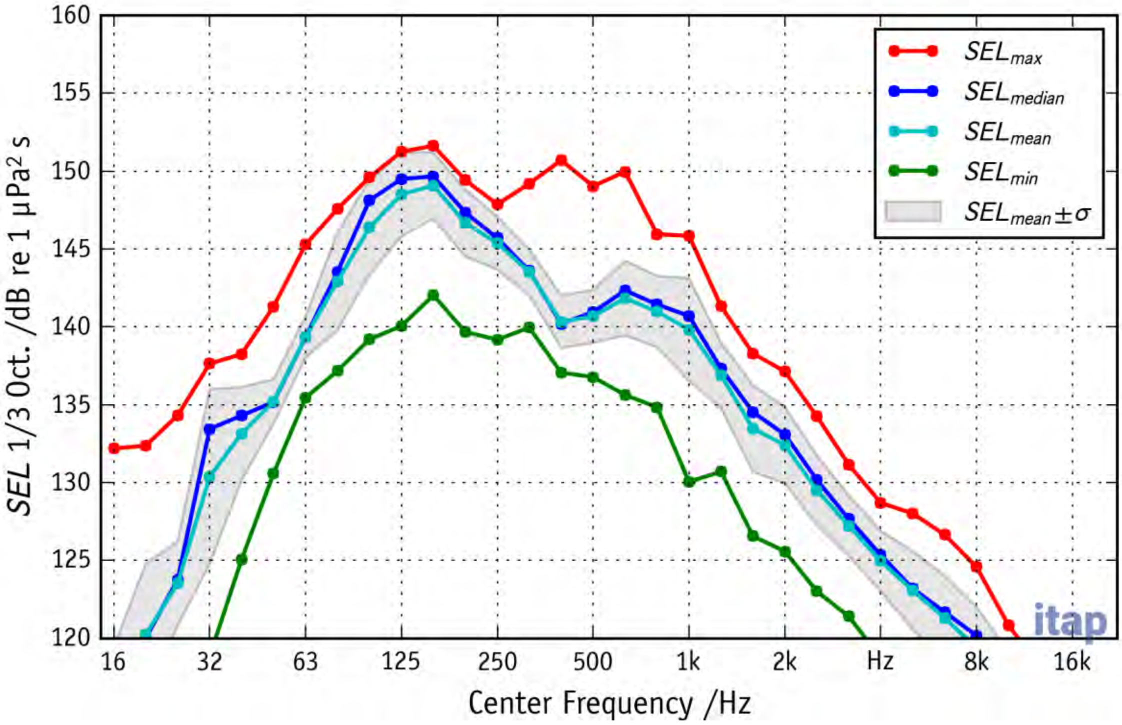
160
155
150
145
140
135
130
125
120
SEL 1/3 Oct. /dB re 1 μPa² s
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center Frequency /Hz
SEL max
SEL median
SEL mean
SEL min
SEL mean ± σ
itap

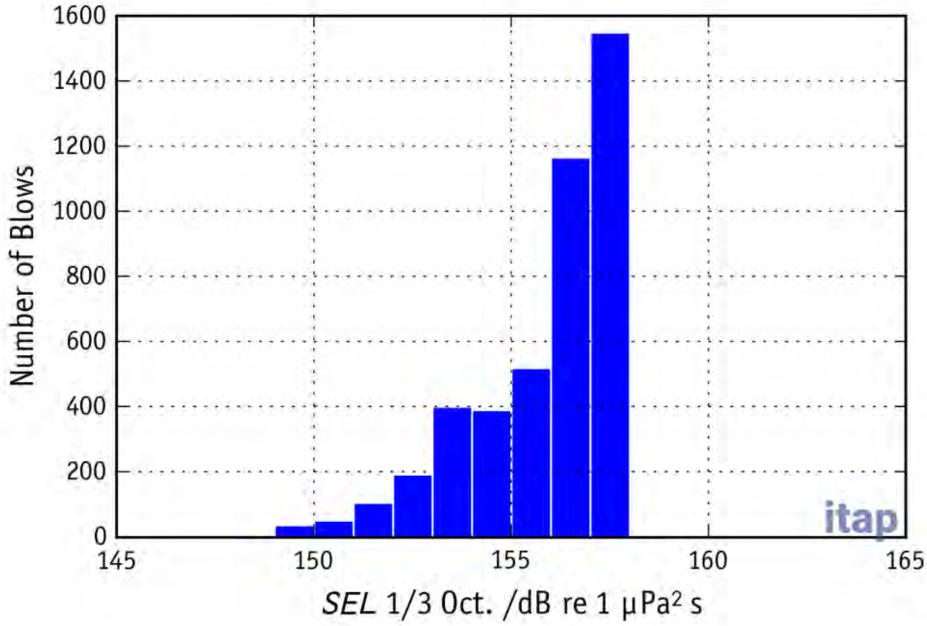


1800
1600
1400
1200
1000
800
600
400
200
0
Number of Blows
145
150
155
160
165
SEL 1/3 Oct. /dB re 1 μPa² s
itap

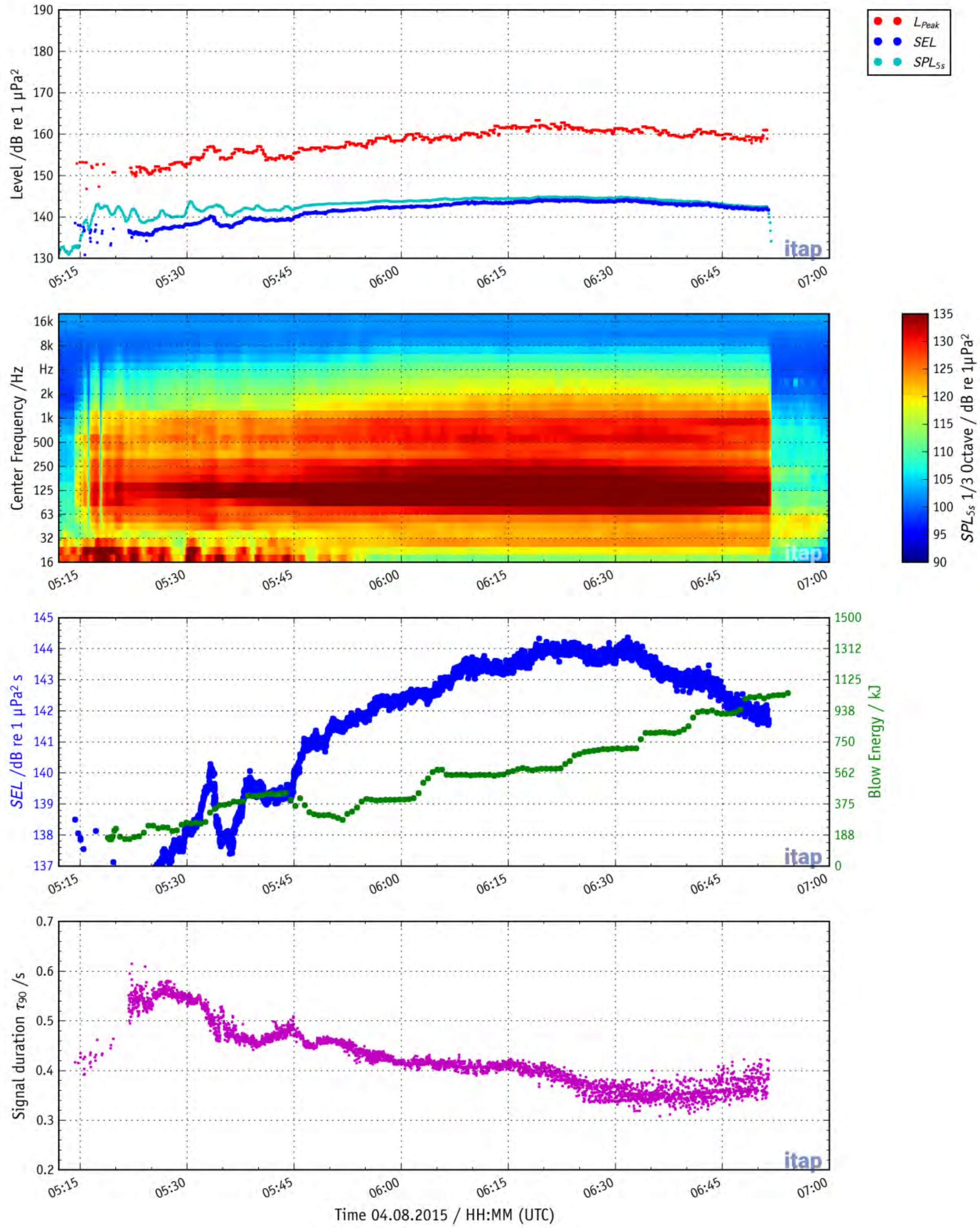
OHVS1 MP2, 10 m pile driving noise

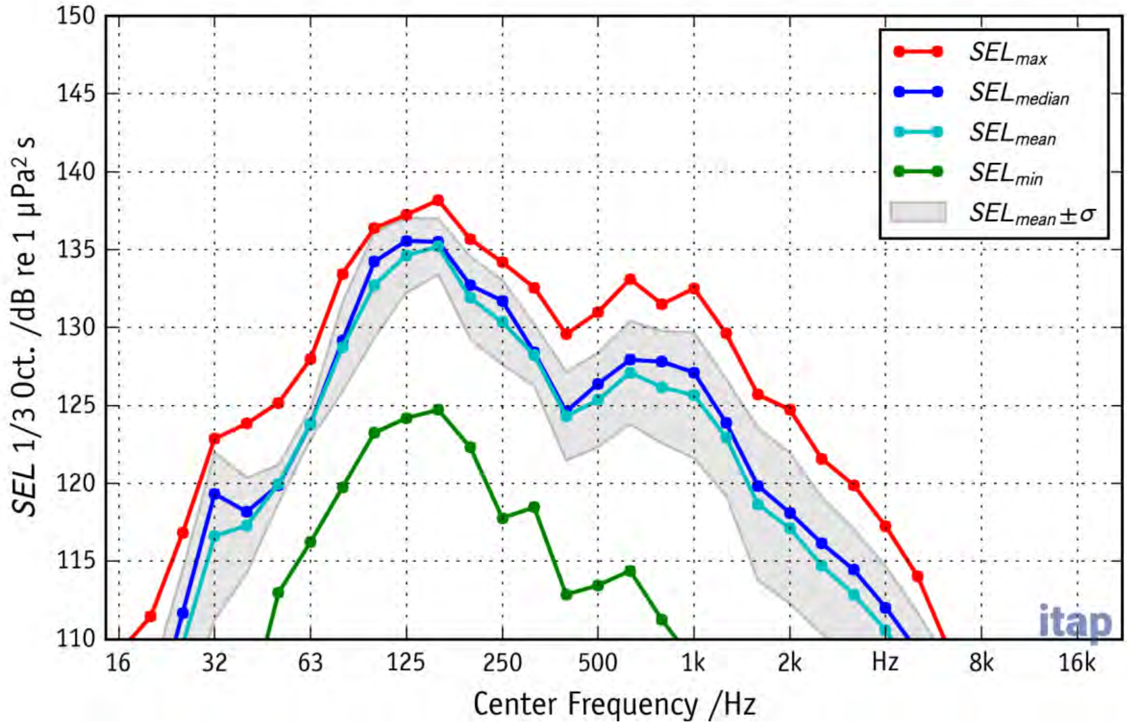


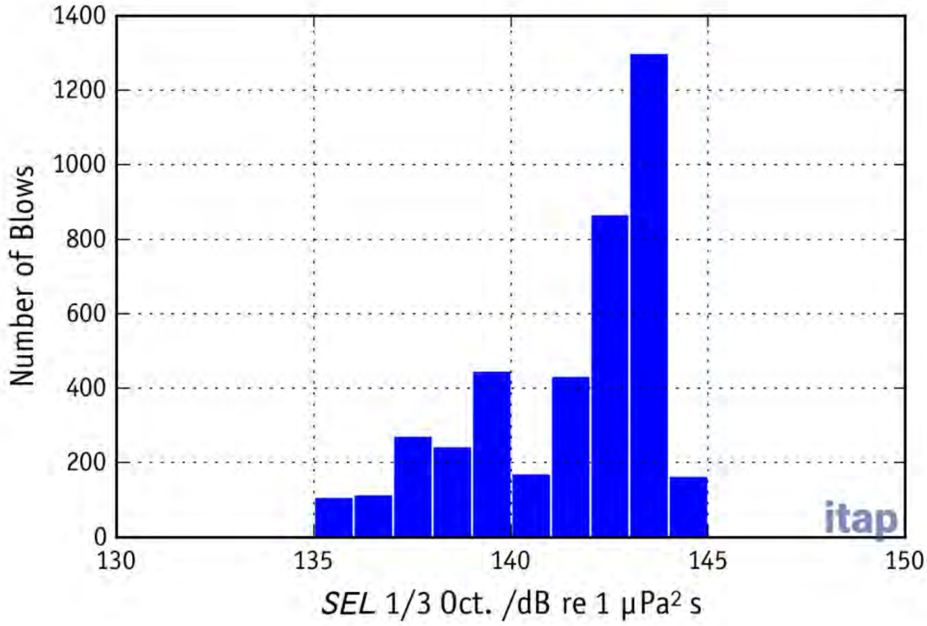

160
155
150
145
140
135
130
125
120
SEL 1/3 Oct. /dB re 1 µPa² s
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center Frequency /Hz
SEL_max
SEL_median
SEL_mean
SEL_min
SEL_mean ± σ
itap


1600
1400
1200
1000
800
600
400
200
0
Number of Blows
145
150
155
160
165
SEL 1/3 Oct. /dB re 1 µPa² s
itap

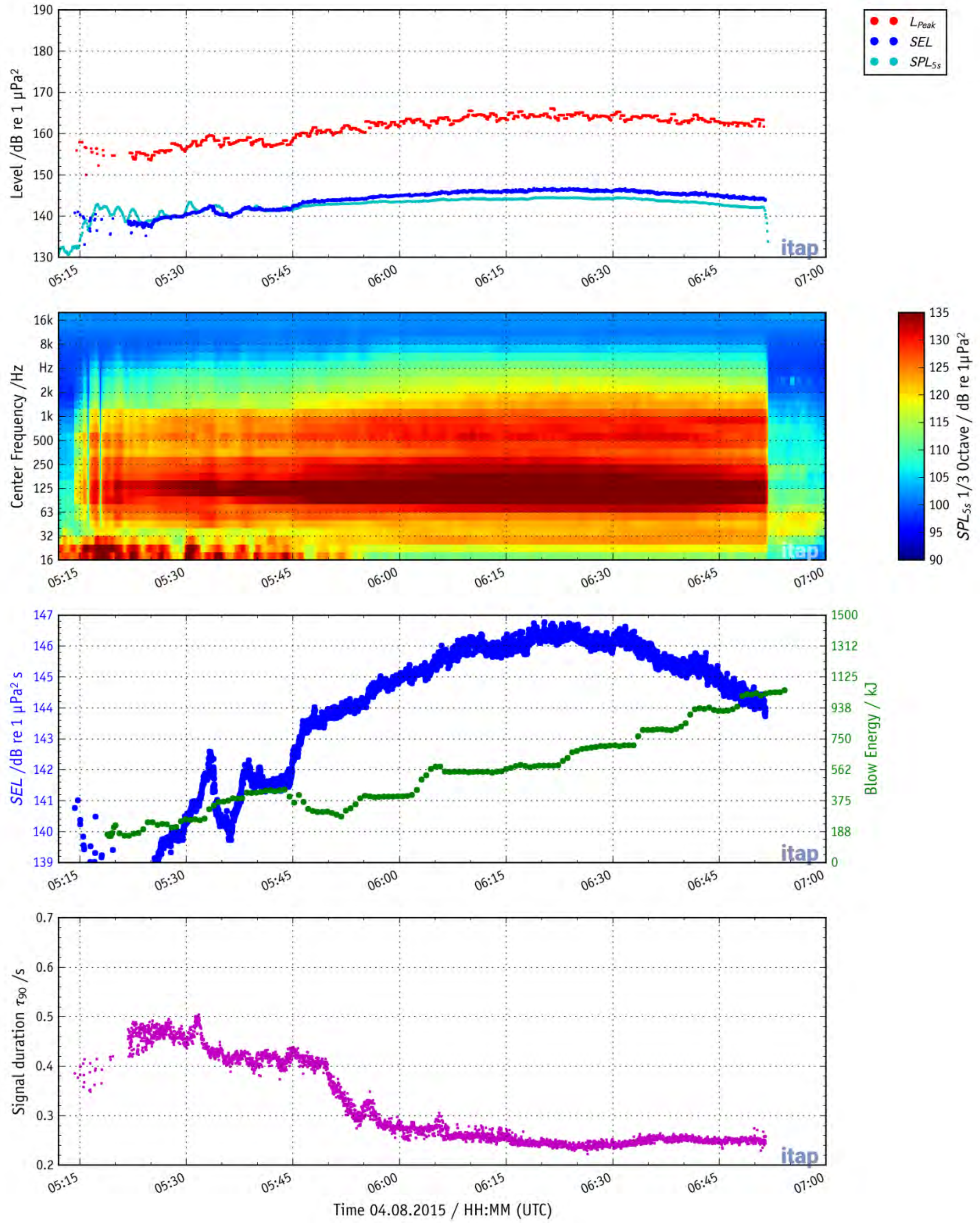
OHVS1 MP3, 2 m pile driving noise

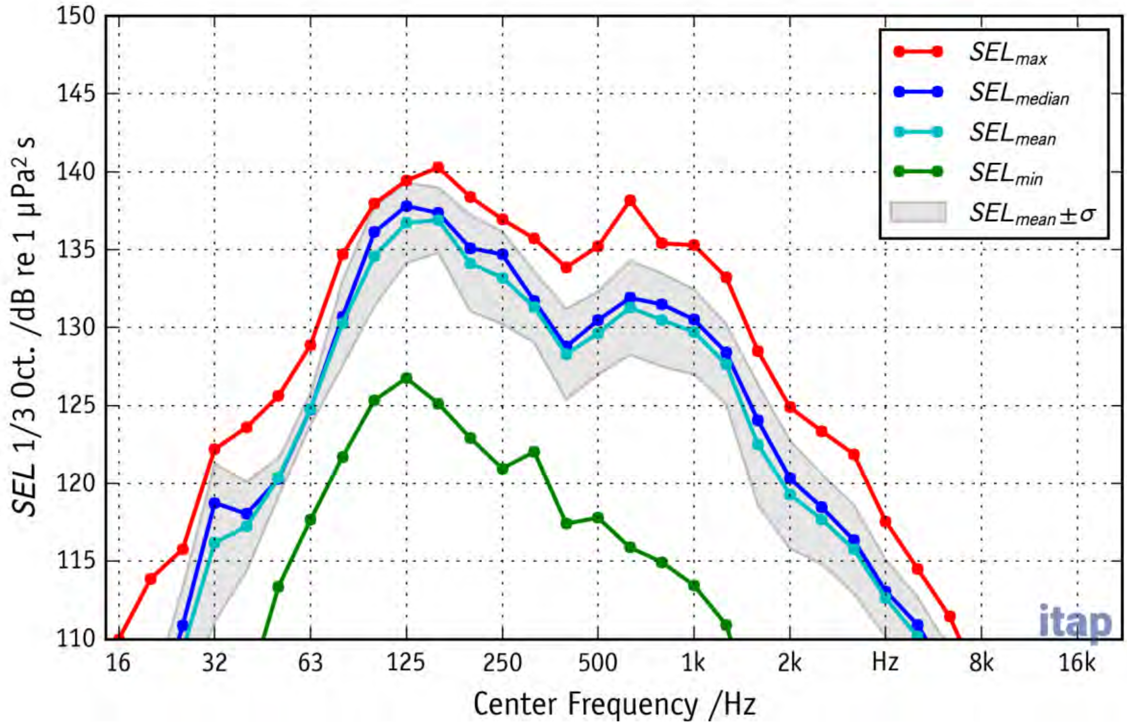


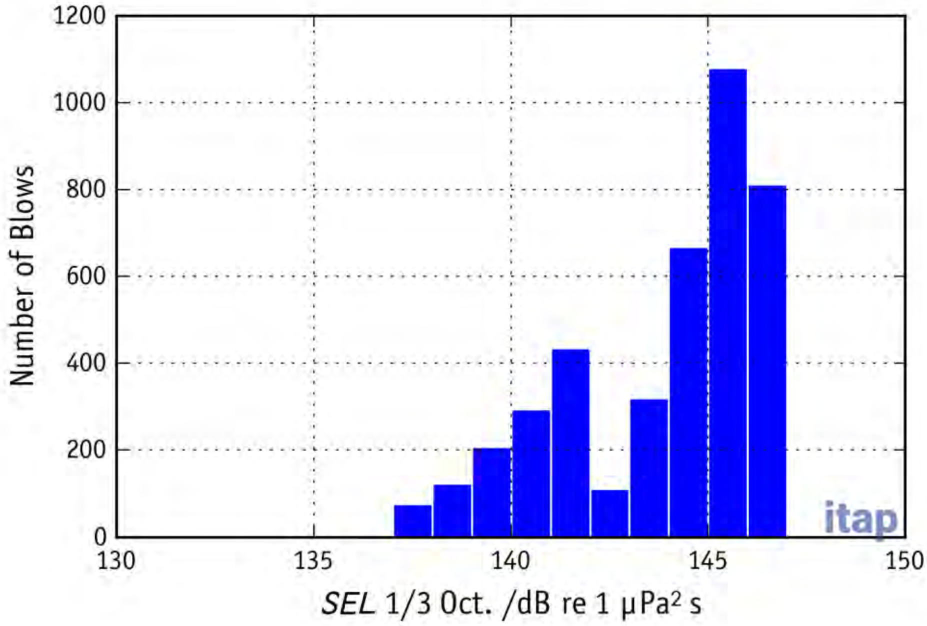

150
145
140
135
130
125
120
115
110
SEL 1/3 Oct. /dB re 1 µPa² s
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center Frequency /Hz
SEL_max
SEL_median
SEL_mean
SEL_min
SEL_mean ± σ
itap


1400
1200
1000
800
600
400
200
0
Number of Blows
130
135
140
145
150
SEL 1/3 Oct. /dB re 1 µPa² s
itap

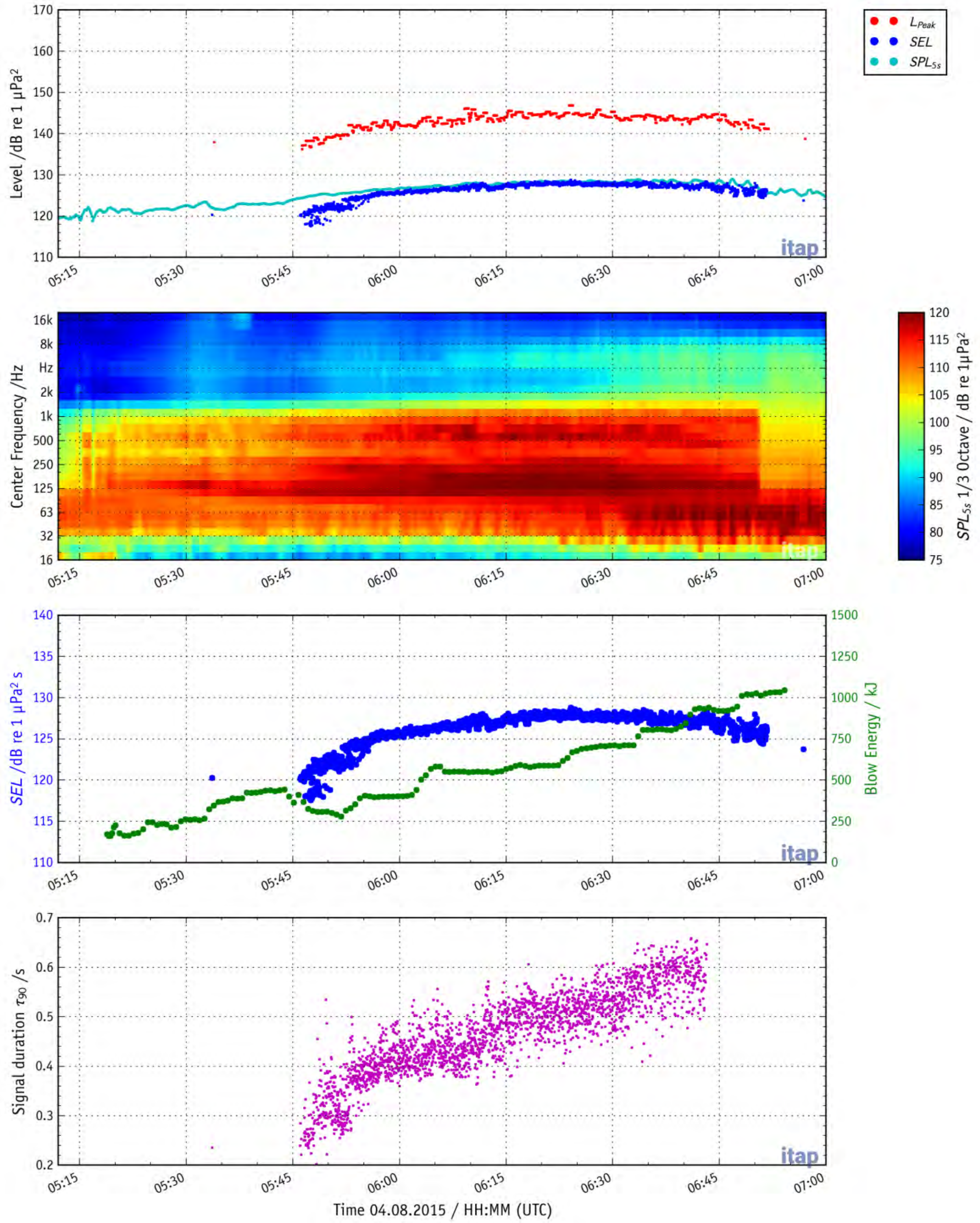
OHVS1 MP3, 10 m pile driving noise

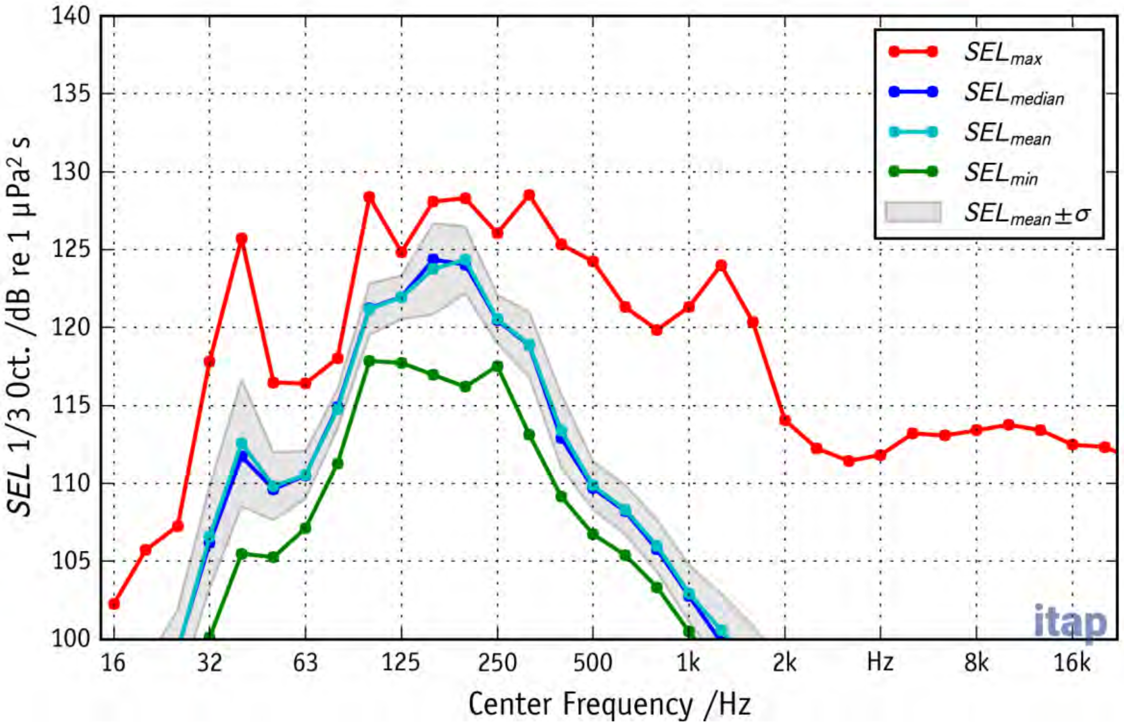



150
145
140
135
130
125
120
115
110
SEL 1/3 Oct. /dB re 1 µPa² s
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center Frequency /Hz
SEL max
SEL median
SEL mean
SEL min
SEL mean ± σ
itap

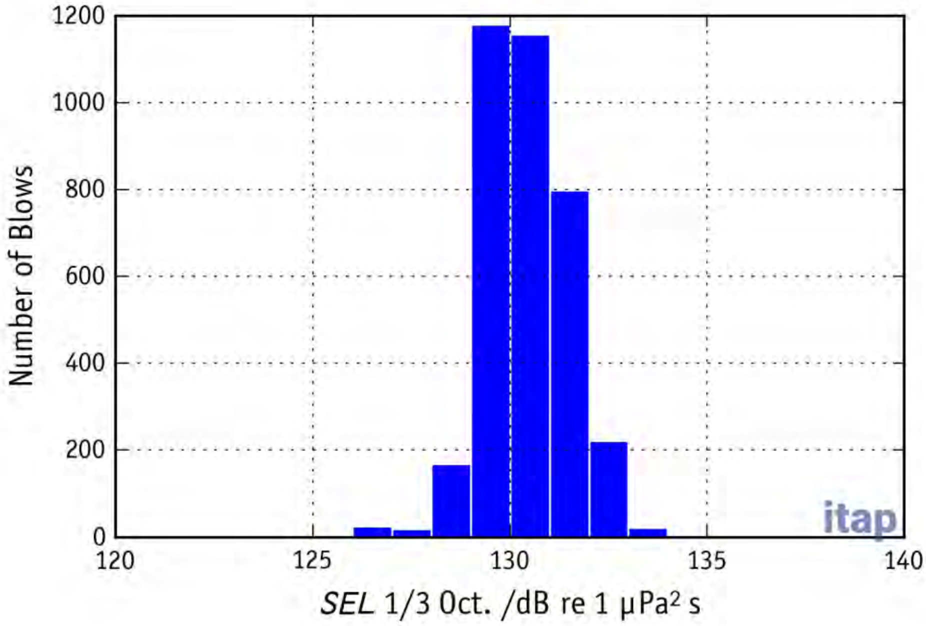

1200
1000
800
600
400
200
0
Number of Blows
130
135
140
145
150
SEL 1/3 Oct. /dB re 1 µPa² s
itap

OHVS1 MP4, 10 m pile driving noise





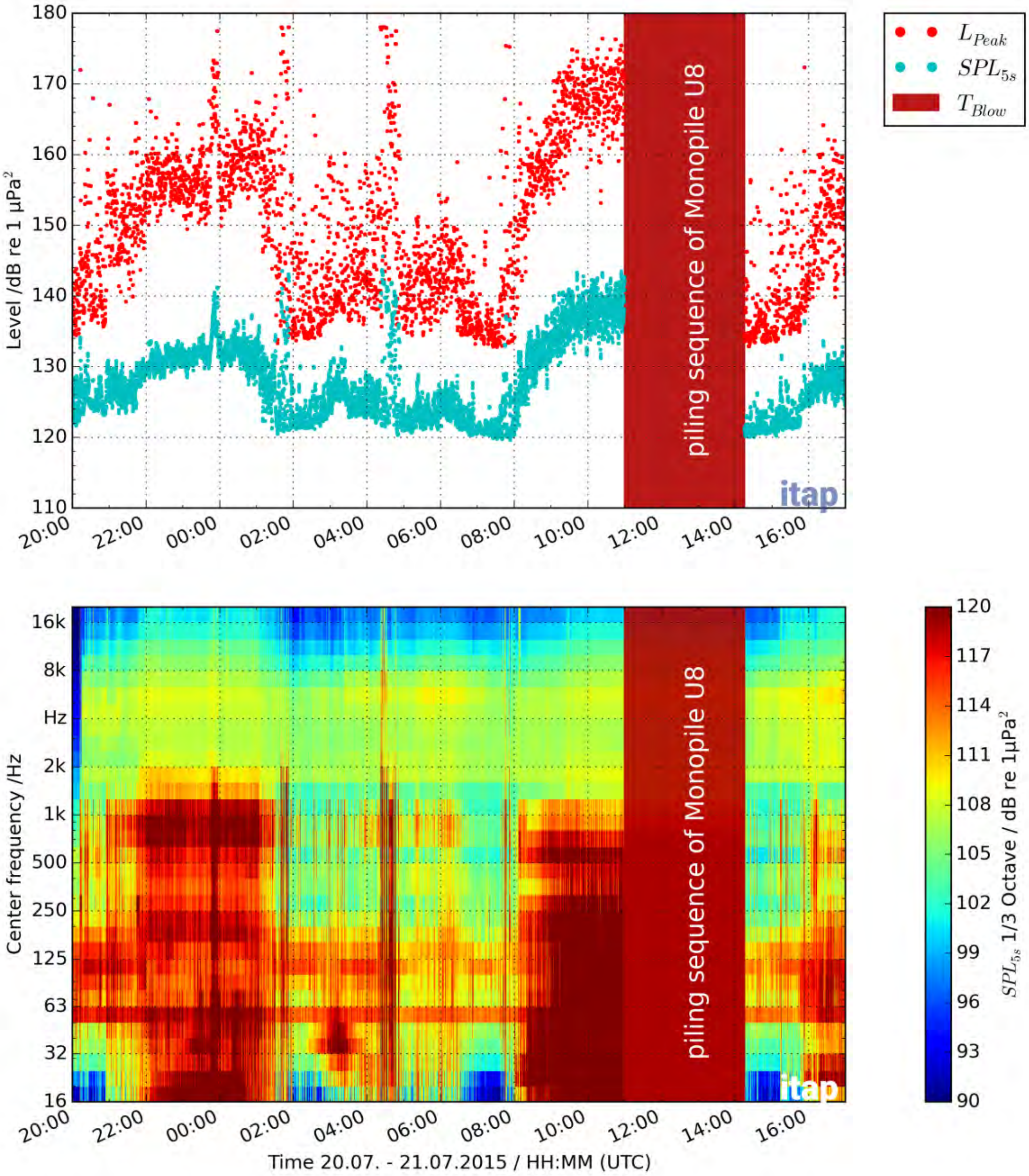
140
135
130
125
120
115
110
105
100
SEL 1/3 Oct. /dB re 1 µPa² s
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center Frequency /Hz
SEL_{max}
SEL_{median}
SEL_{mean}
SEL_{min}
$SEL_{mean} \pm \sigma$
itap

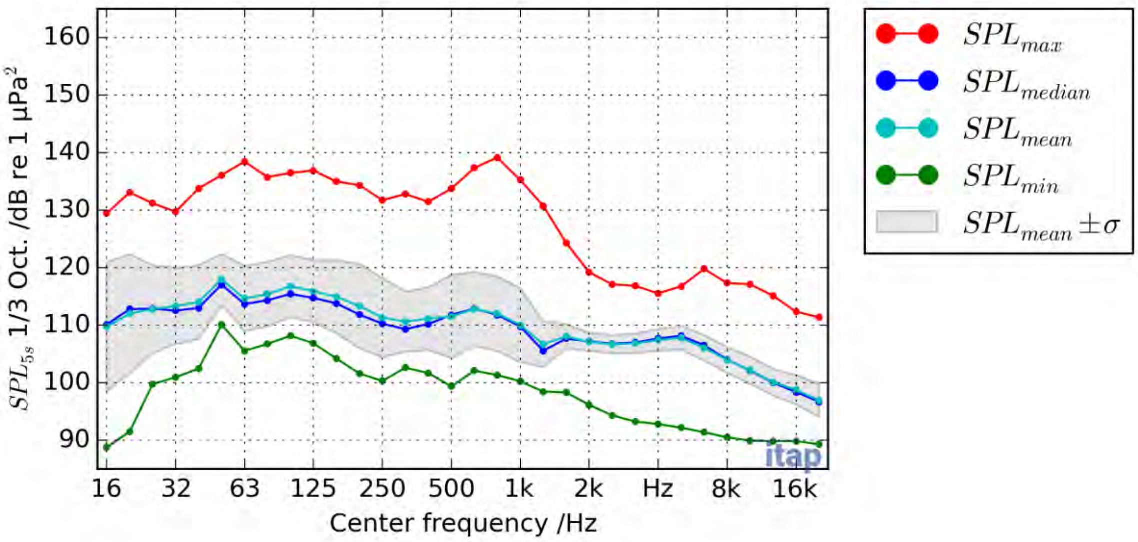


1200
1000
800
600
400
200
0
Number of Blows
120
125
130
135
140
SEL 1/3 Oct. /dB re 1 µPa² s
itap

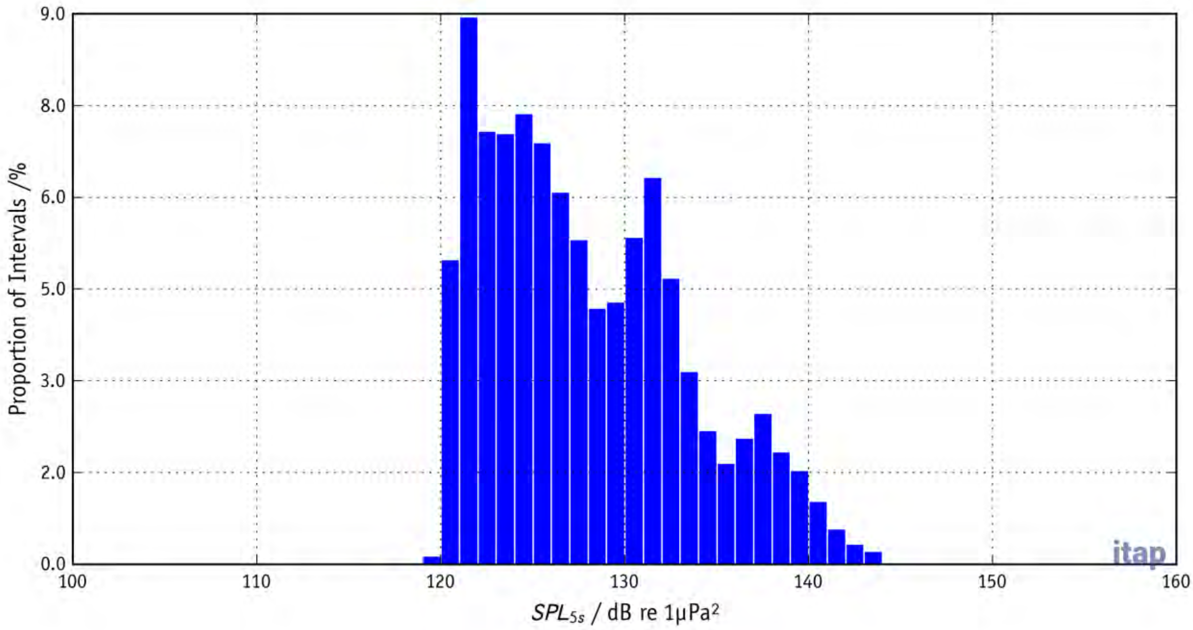
A1.3 Ambient Noise at U8

U8 MP1, 2m ambient noise



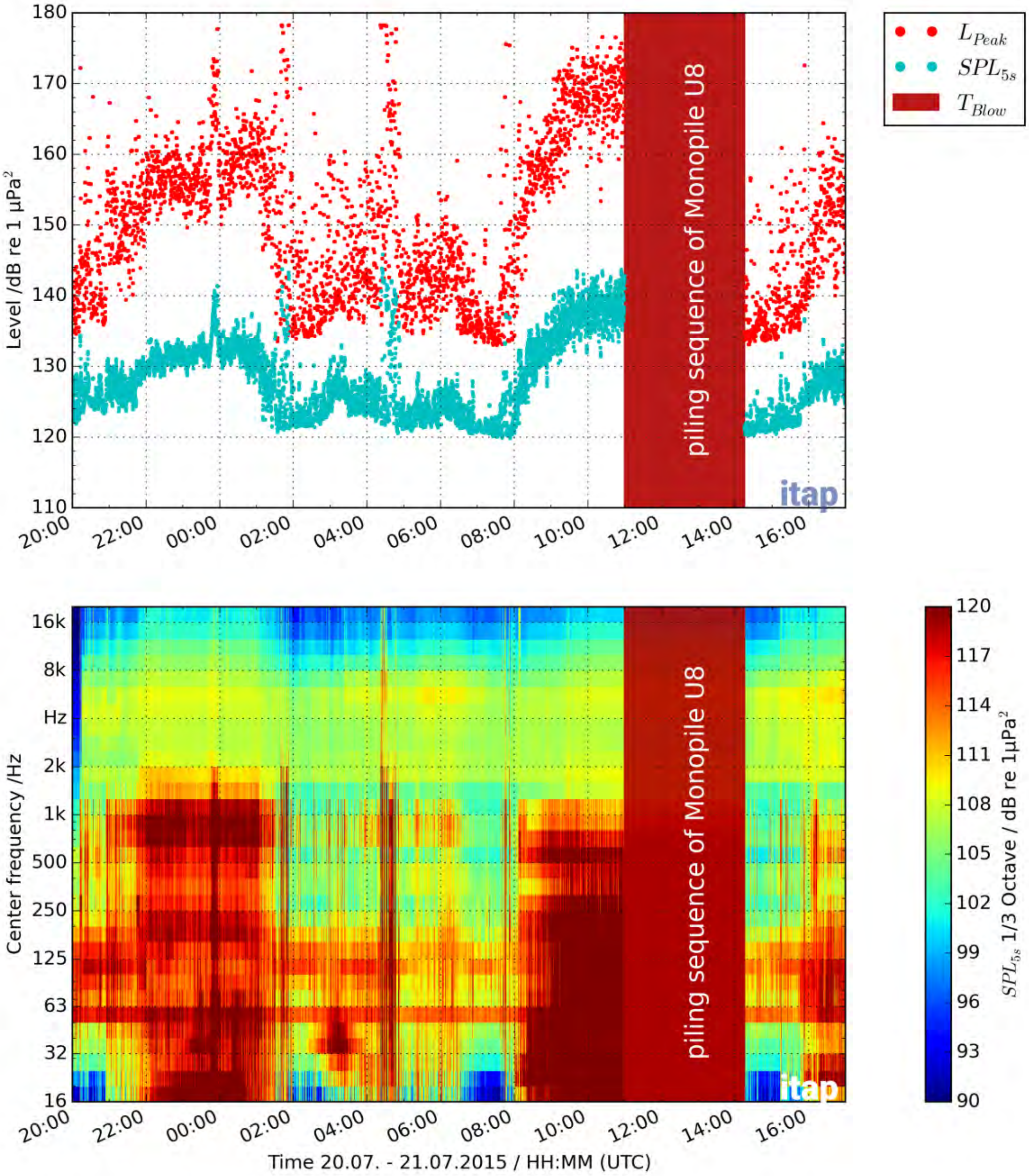


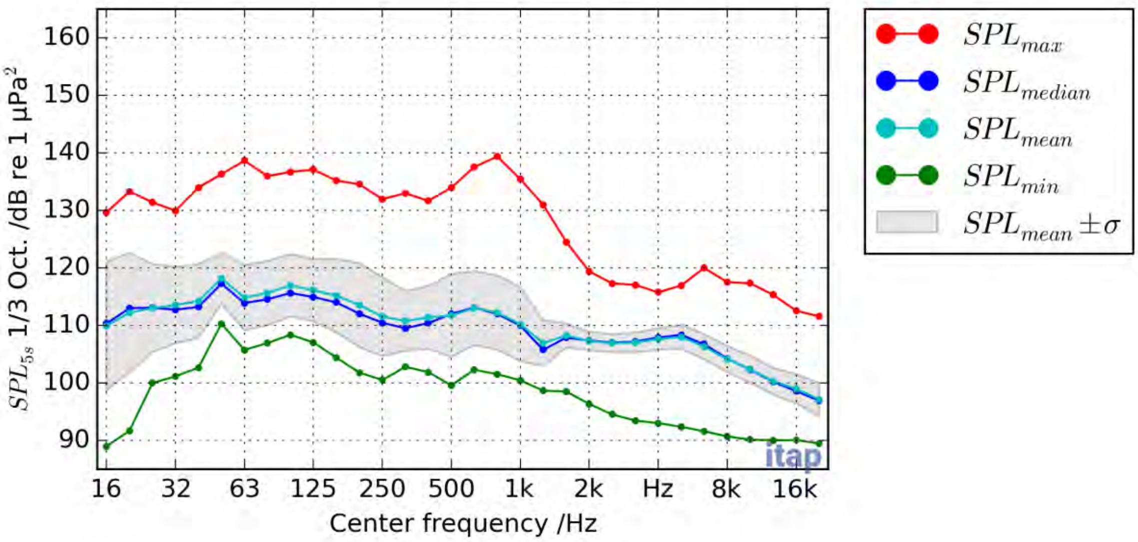
160
150
140
130
120
110
100
90
SPL_{5s} 1/3 Oct. /dB re 1 µPa²
16 32 63 125 250 500 1k 2k Hz 8k 16k
Center frequency /Hz
SPL_{max}
SPL_{median}
SPL_{mean}
SPL_{min}
$SPL_{mean} \pm \sigma$
itap

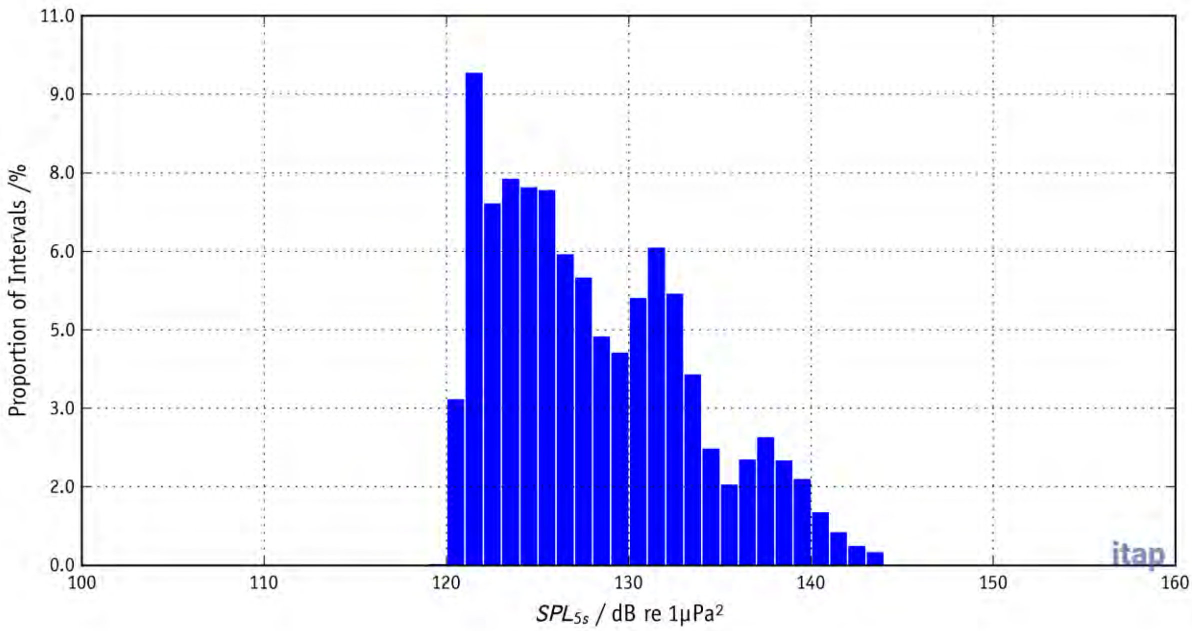


9.0
8.0
6.0
5.0
3.0
2.0
0.0
Proportion of Intervals /%
100 110 120 130 140 150 160
SPL_{5s} / dB re 1µPa²
itap

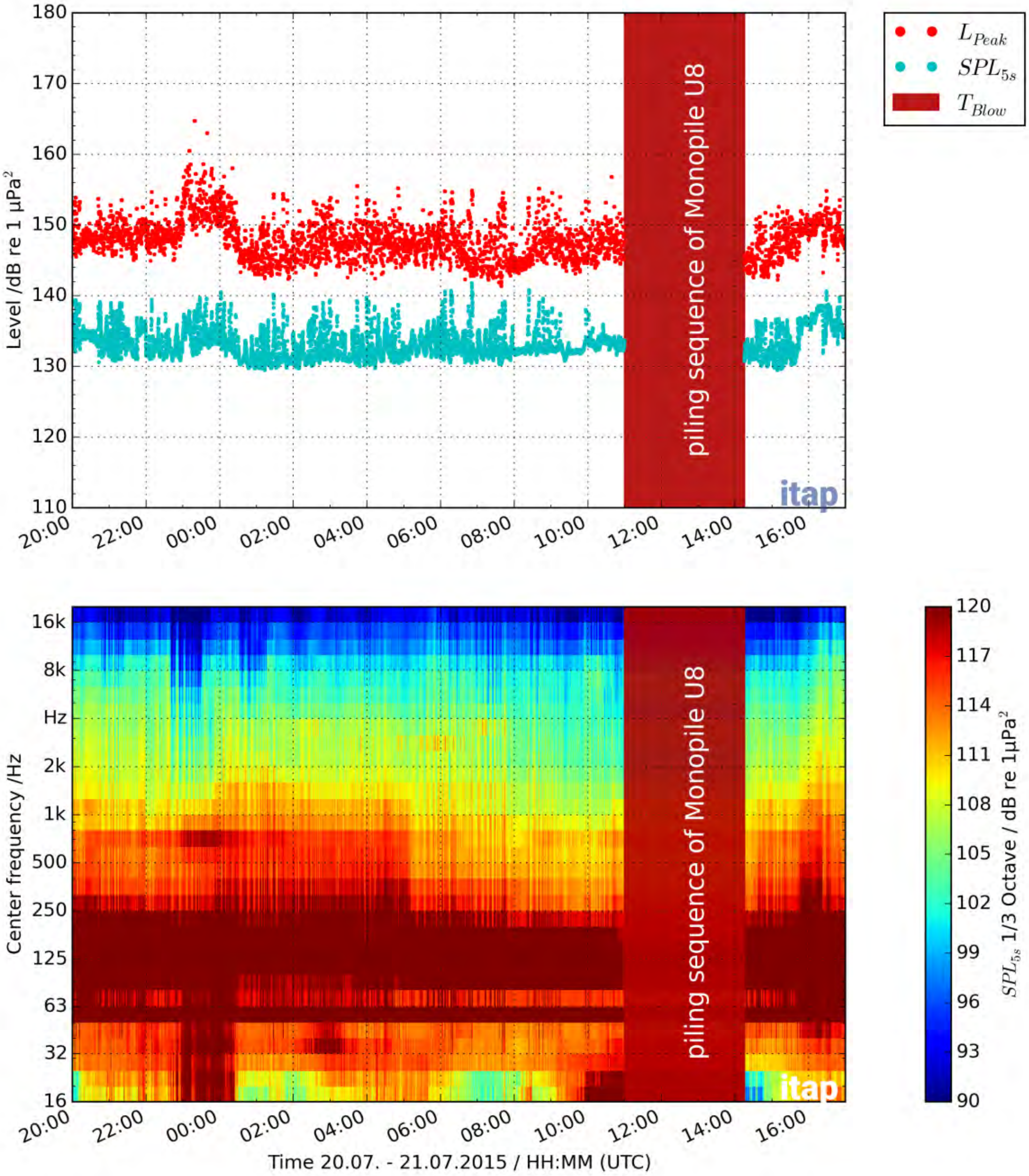
U8 MP1, 10 m ambient noise

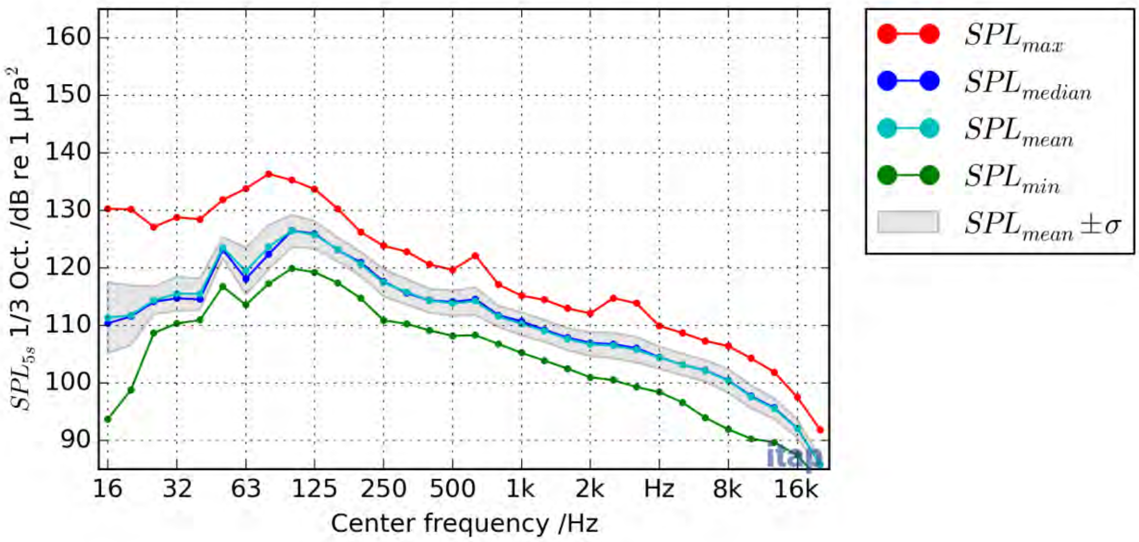


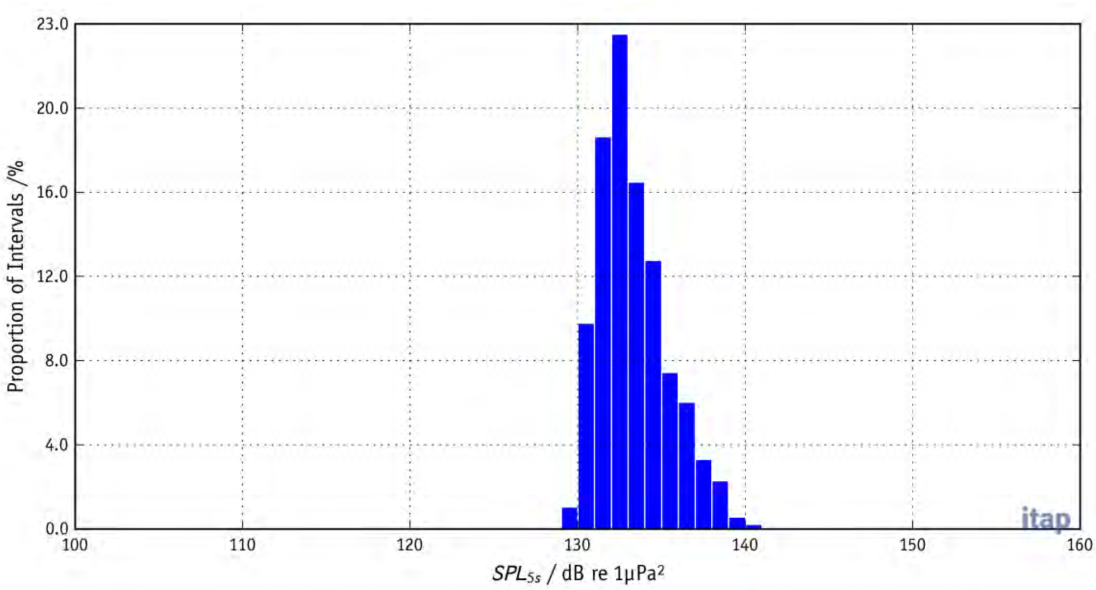

160
150
140
130
120
110
100
90
SPL_{5s} 1/3 Oct. /dB re 1 µPa²
16 32 63 125 250 500 1k 2k Hz 8k 16k
Center frequency /Hz
SPL_{max}
SPL_{median}
SPL_{mean}
SPL_{min}
$SPL_{mean} \pm \sigma$
itap


11.0
9.0
8.0
6.0
5.0
3.0
2.0
0.0
Proportion of Intervals /%
100 110 120 130 140 150 160
SPL_{5s} / dB re 1µPa²
itap

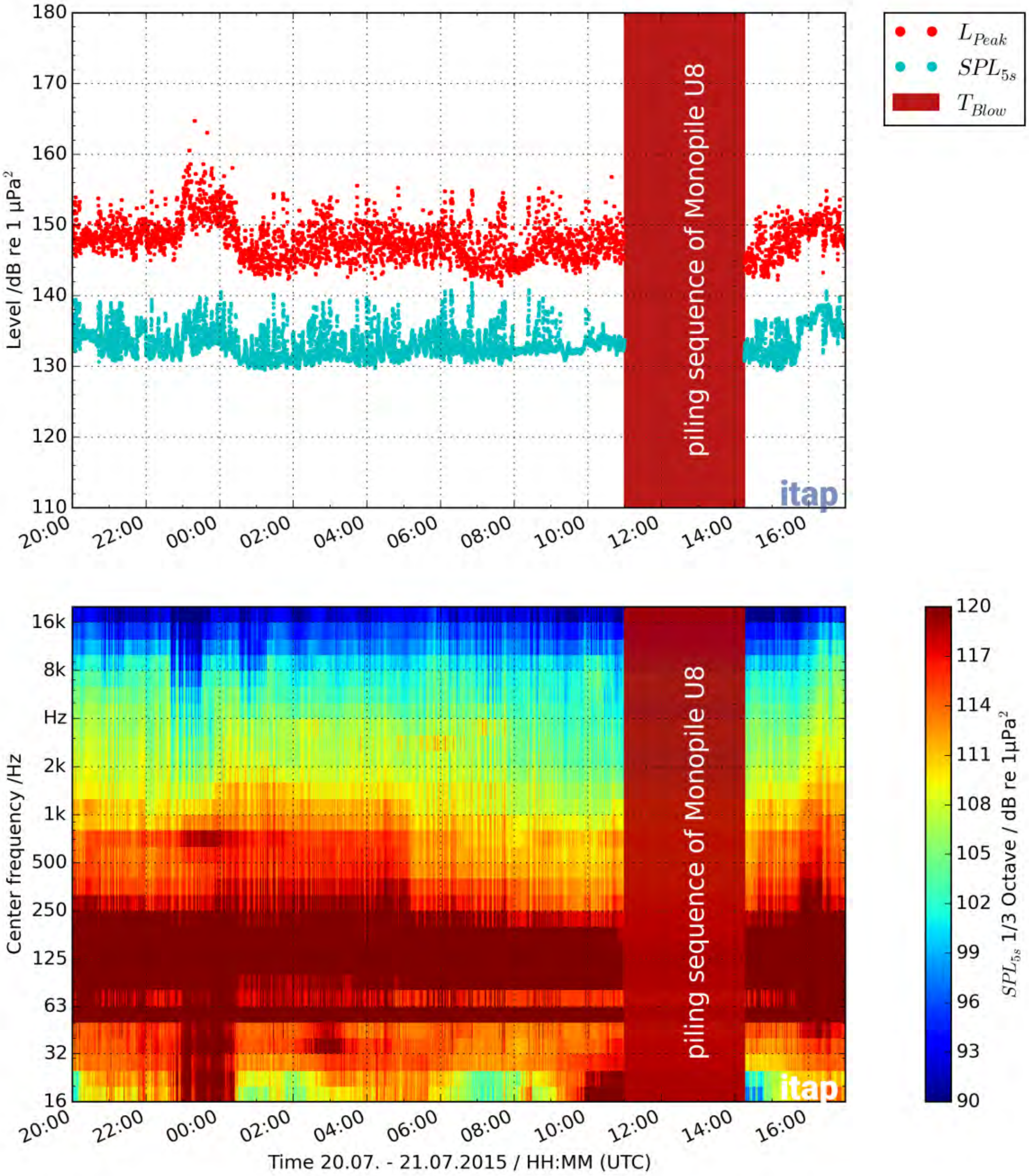
U8 MP2, 2 m ambient noise

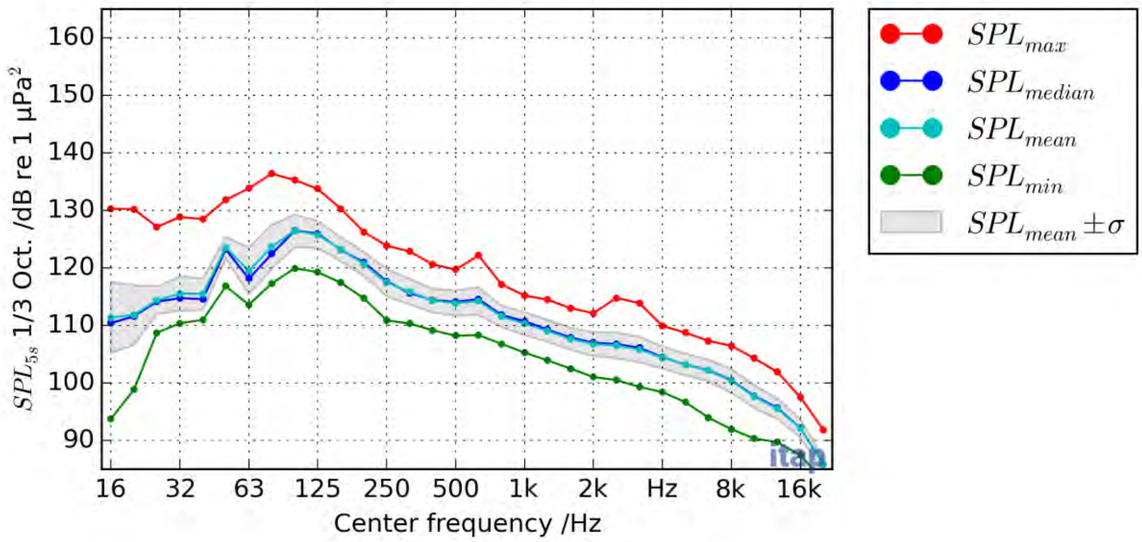



160
150
140
130
120
110
100
90
SPL_{5s} 1/3 Oct. /dB re 1 µPa²
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center frequency /Hz
SPL_{max}
SPL_{median}
SPL_{mean}
SPL_{min}
$SPL_{mean} \pm \sigma$
itap

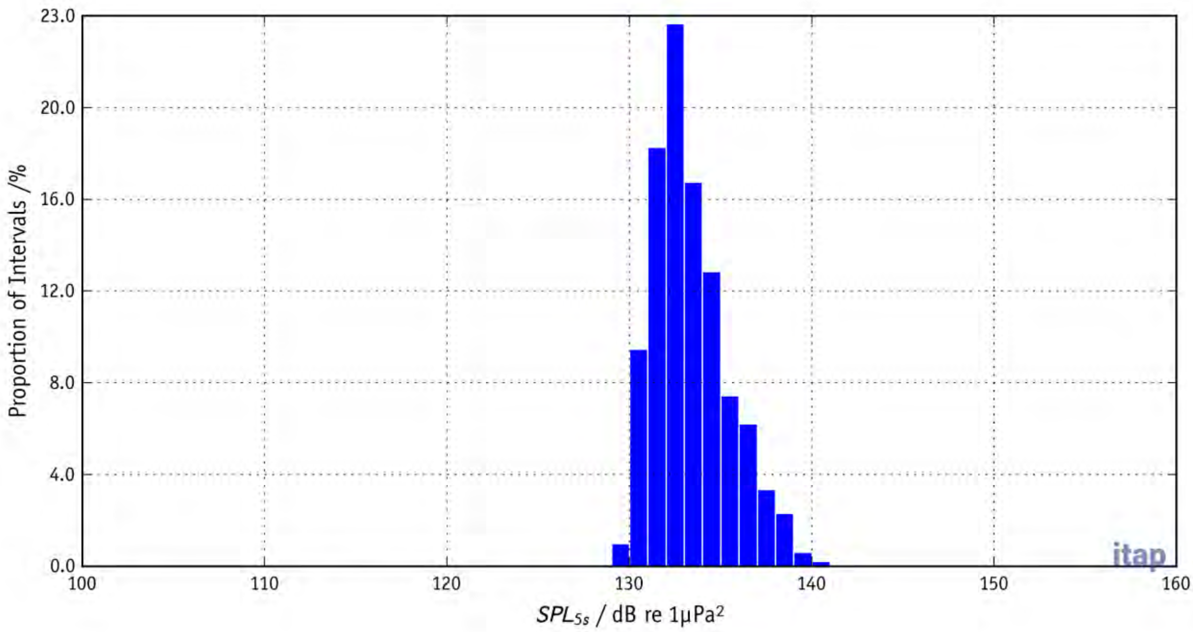

23.0
20.0
16.0
12.0
8.0
4.0
0.0
Proportion of Intervals /%
100
110
120
130
140
150
160
SPL_{5s} / dB re 1µPa²
itap

U8 MP2, 10 m ambient noise



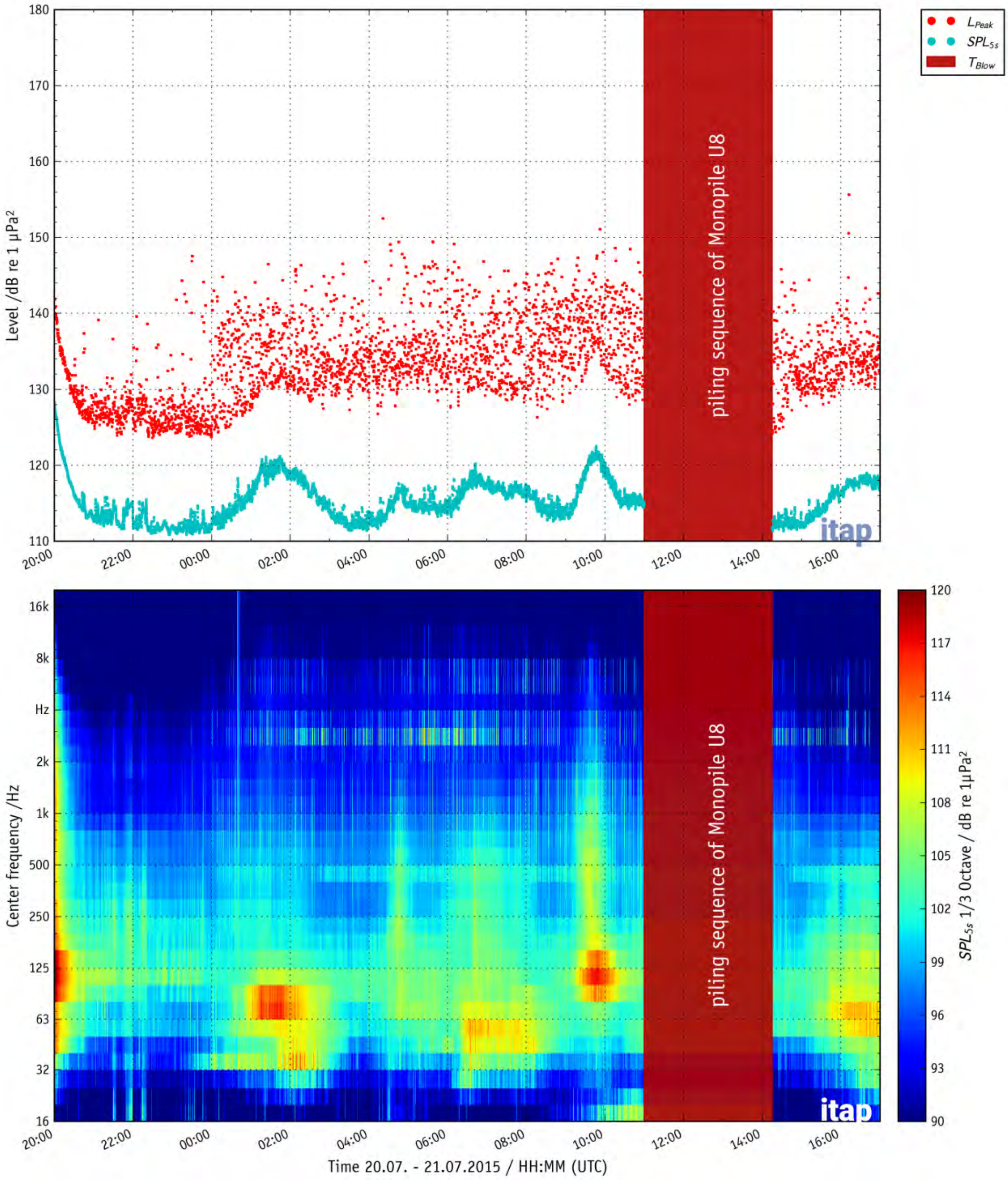


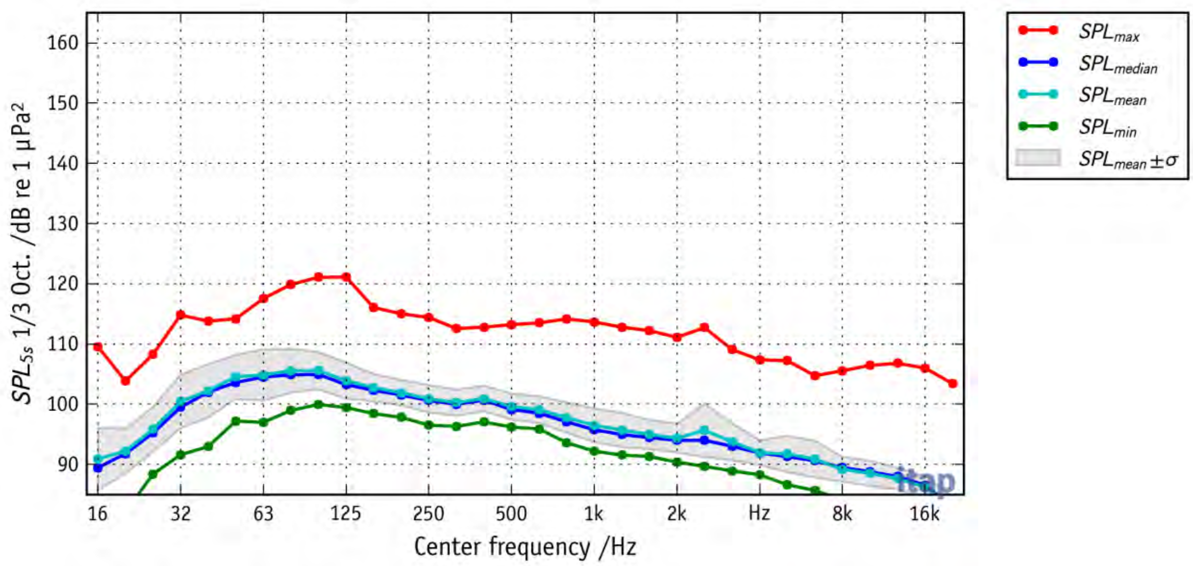
SPL_{max}
SPL_{median}
SPL_{mean}
SPL_{min}
$SPL_{mean} \pm \sigma$
SPL_{5s} 1/3 Oct. /dB re 1 μPa²
Center frequency /Hz
16
32
63
125
250
500
1k
2k
Hz
8k
16k
160
150
140
130
120
110
100
90
itap



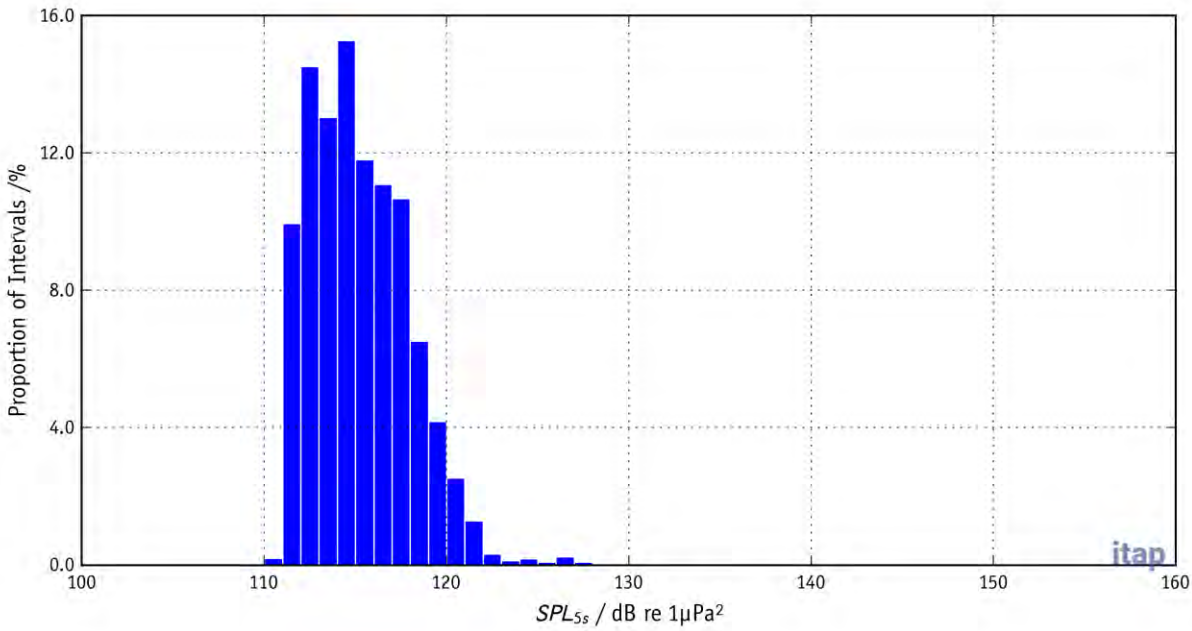
Proportion of Intervals /%
SPL_{5s} / dB re 1μPa²
23.0
20.0
16.0
12.0
8.0
4.0
0.0
100
110
120
130
140
150
160
itap

U8 MP3, 2 m ambient noise



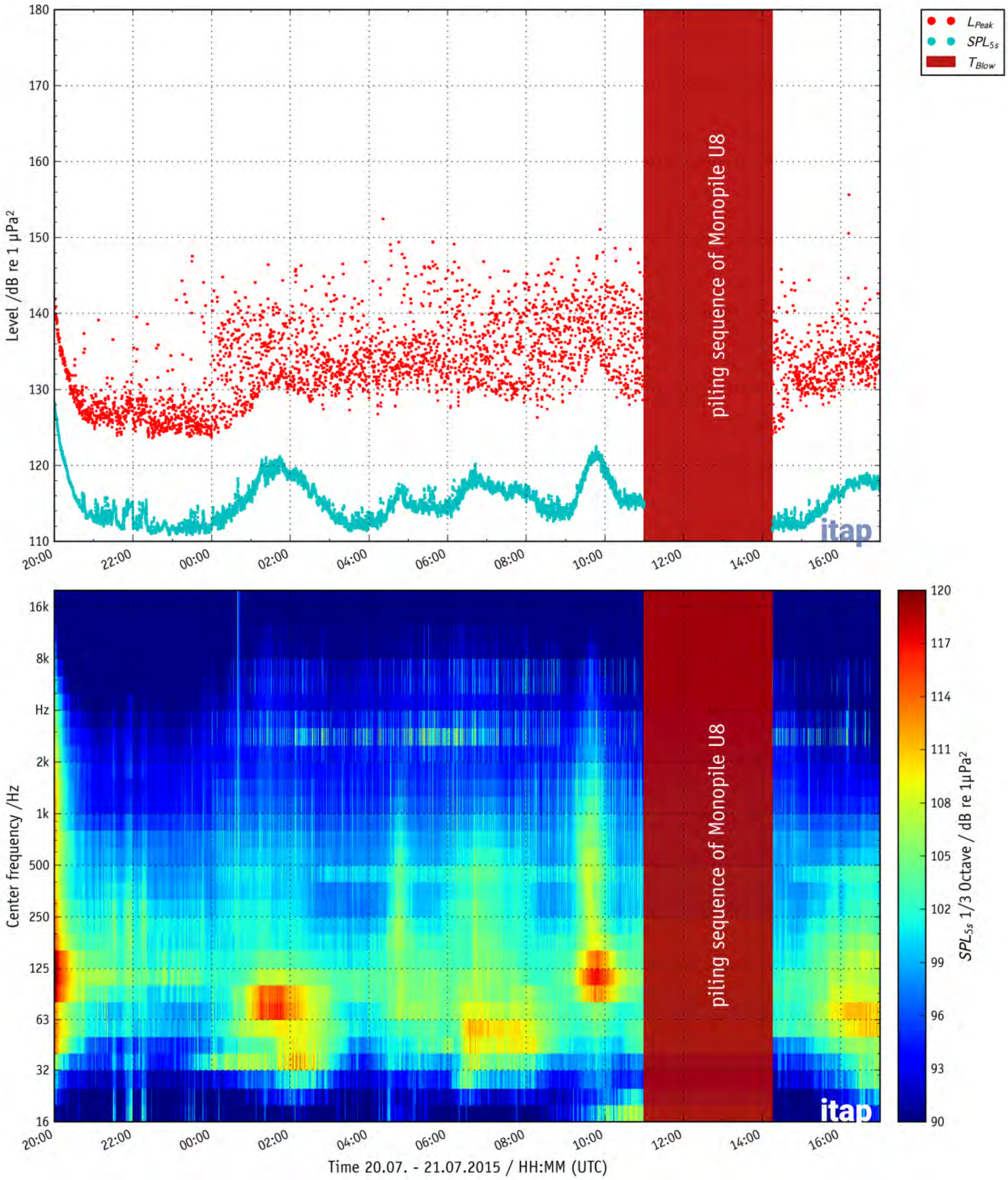


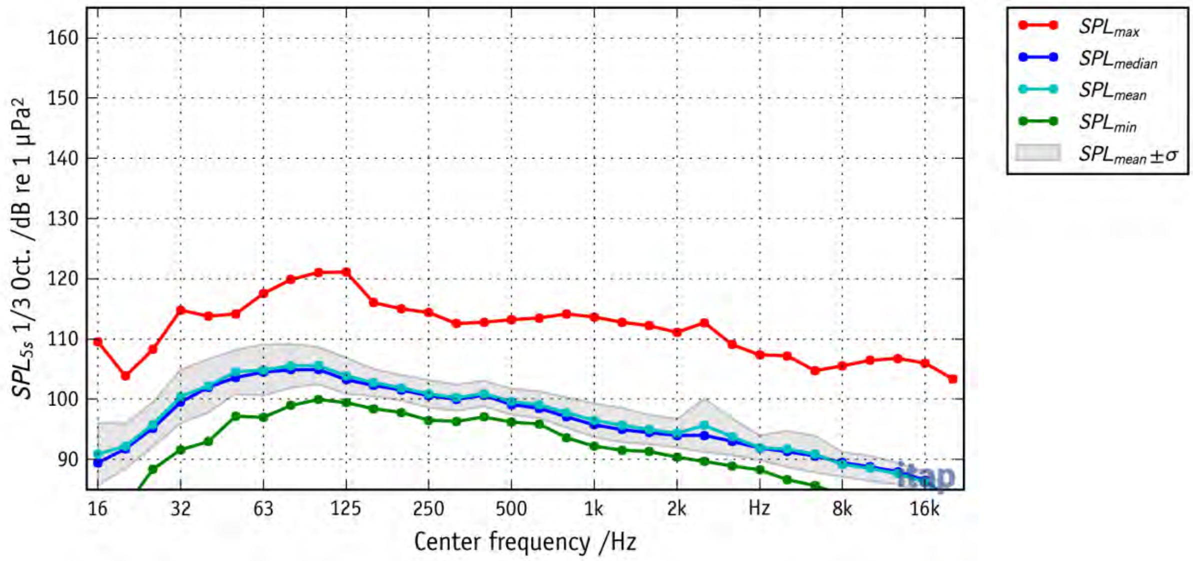
160
150
140
130
120
110
100
90
SPL5s 1/3 Oct. /dB re 1 µPa²
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center frequency /Hz
SPLmax
SPLmedian
SPLmean
SPLmin
SPLmean ±σ
itap

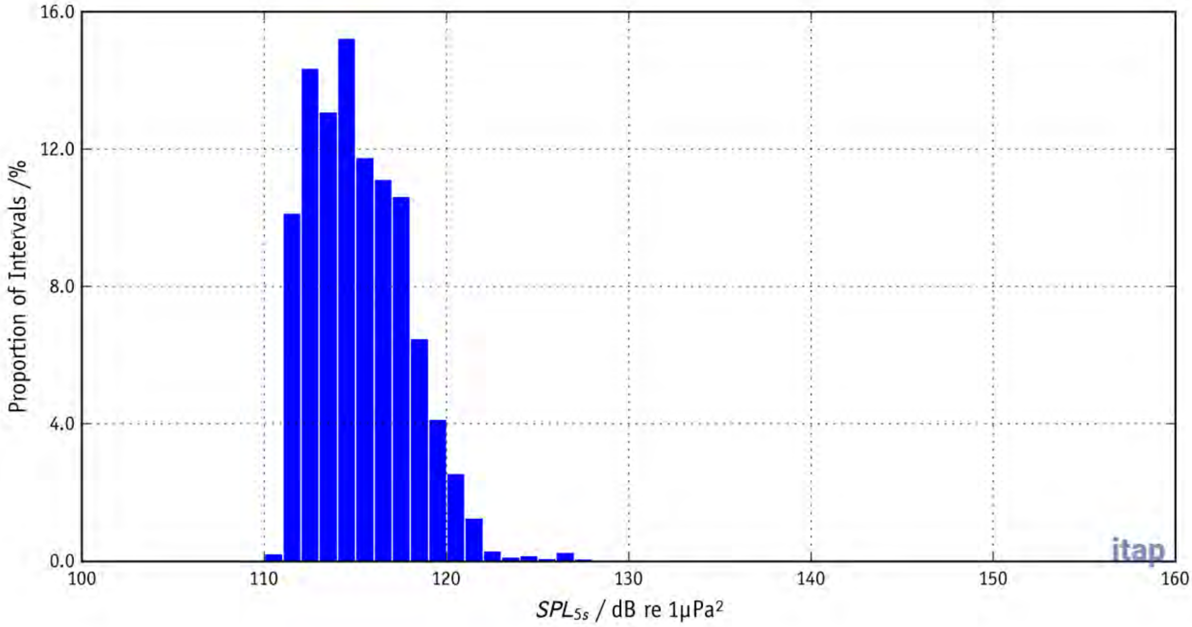


16.0
12.0
8.0
4.0
0.0
Proportion of Intervals /%
100
110
120
130
140
150
160
SPL5s / dB re 1µPa²
itap

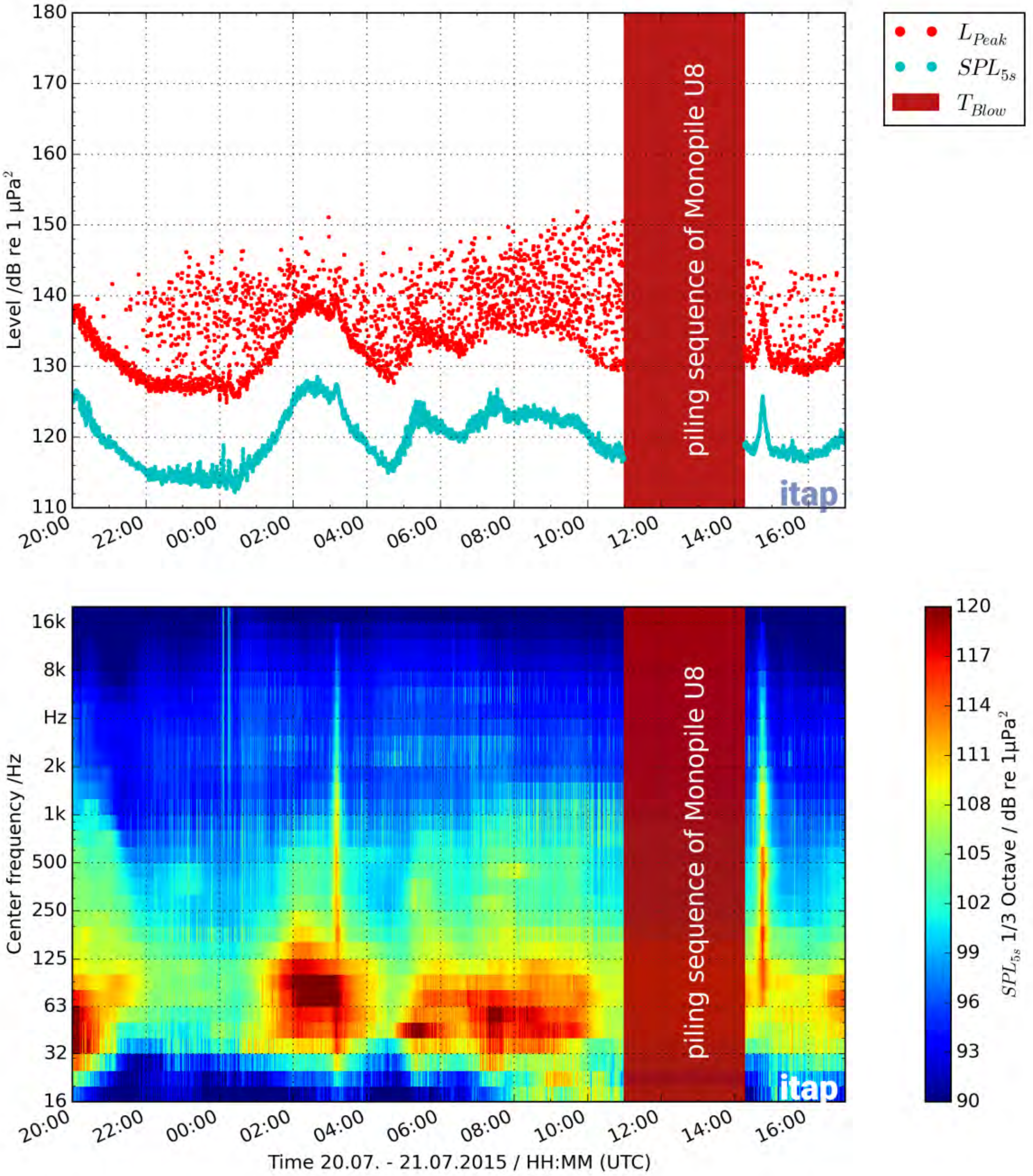
U8 MP3, 10 m ambient noise

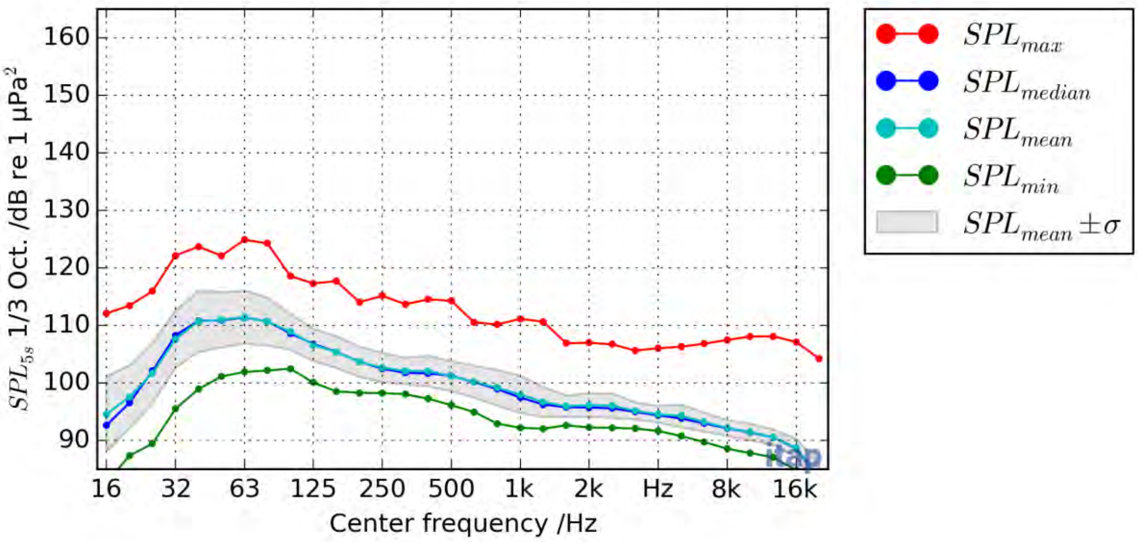


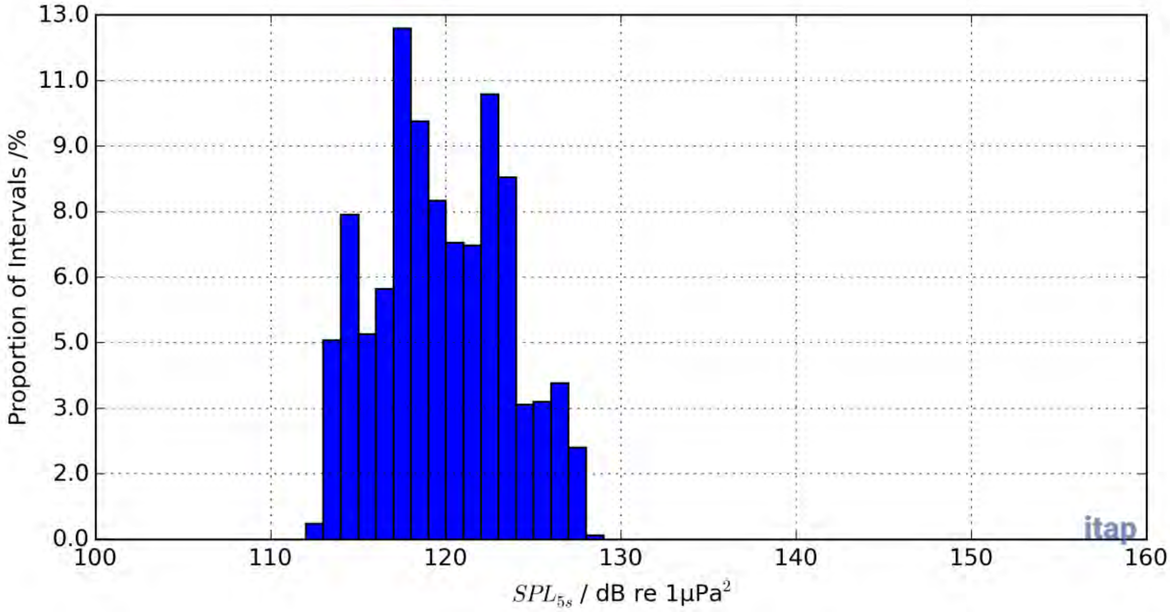

160
150
140
130
120
110
100
90
SPL5s 1/3 Oct. /dB re 1 µPa²
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center frequency /Hz
SPLmax
SPLmedian
SPLmean
SPLmin
SPLmean ±σ
itap


16.0
12.0
8.0
4.0
0.0
Proportion of Intervals /%
100
110
120
130
140
150
160
SPL5s / dB re 1µPa²
itap

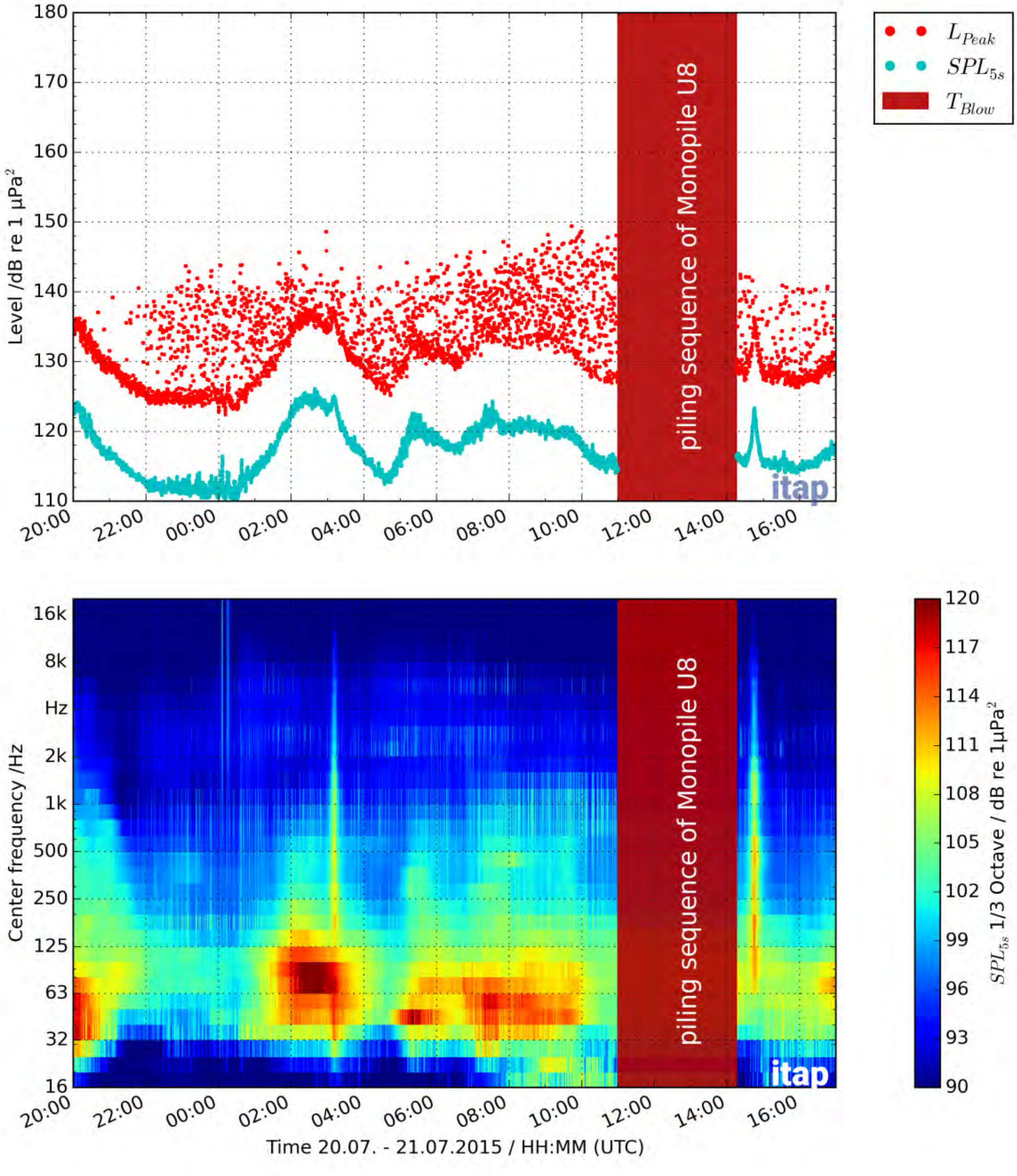
U8 MP4, 2 m ambient noise

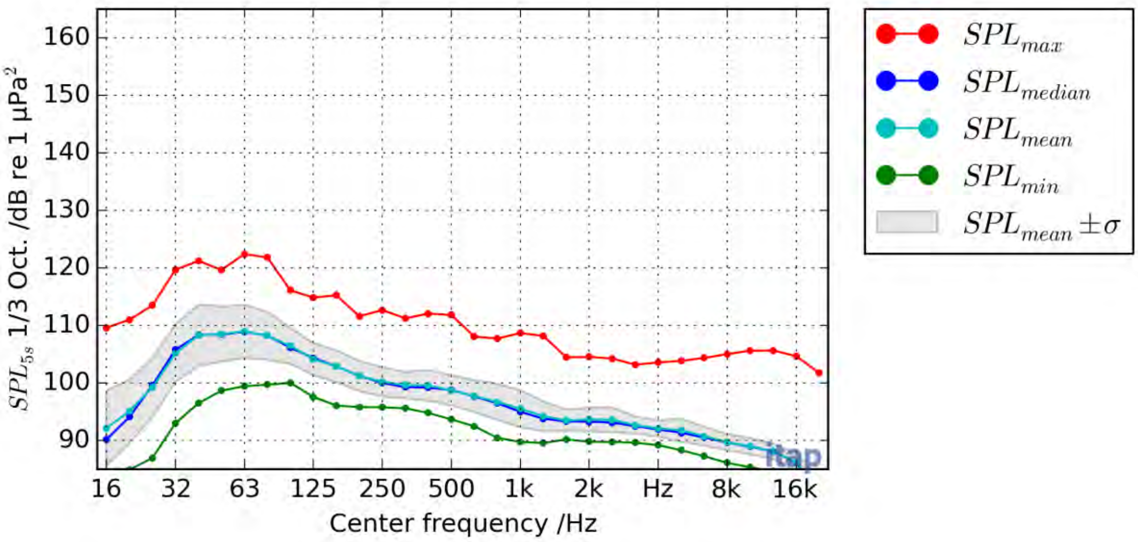


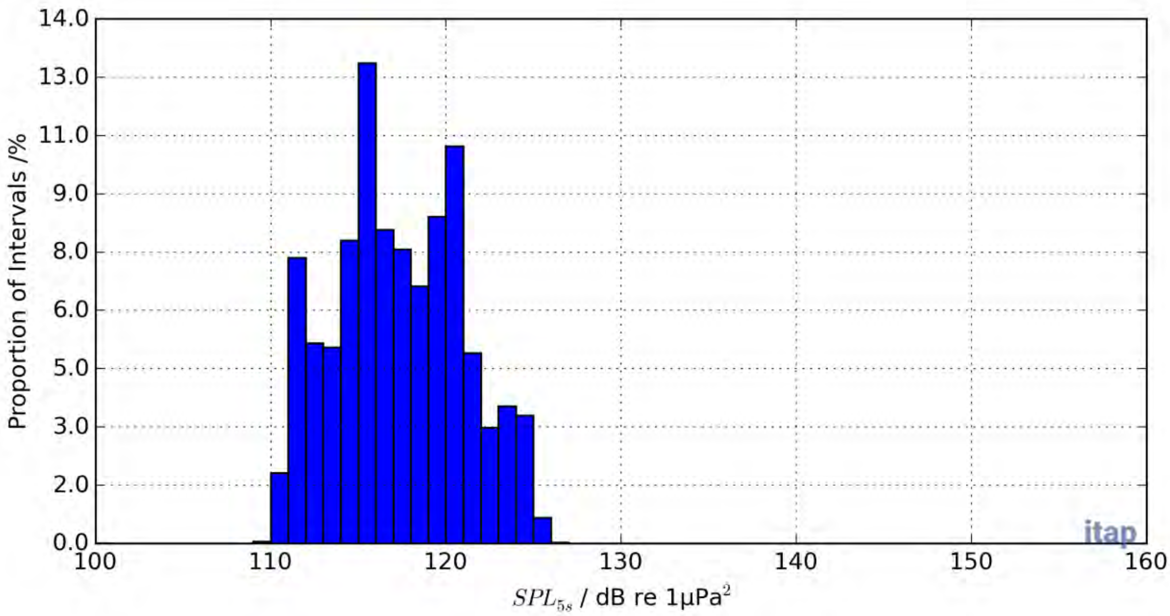

160
150
140
130
120
110
100
90
SPL_{5s} 1/3 Oct. /dB re 1 µPa^2
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center frequency /Hz
SPL_{max}
SPL_{median}
SPL_{mean}
SPL_{min}
$SPL_{mean} \pm \sigma$
itap


13.0
11.0
9.0
8.0
6.0
5.0
3.0
2.0
0.0
Proportion of Intervals /%
100
110
120
130
140
150
160
SPL_{5s} / dB re 1µPa^2
itap

U8 MP4, 10 m ambient noise

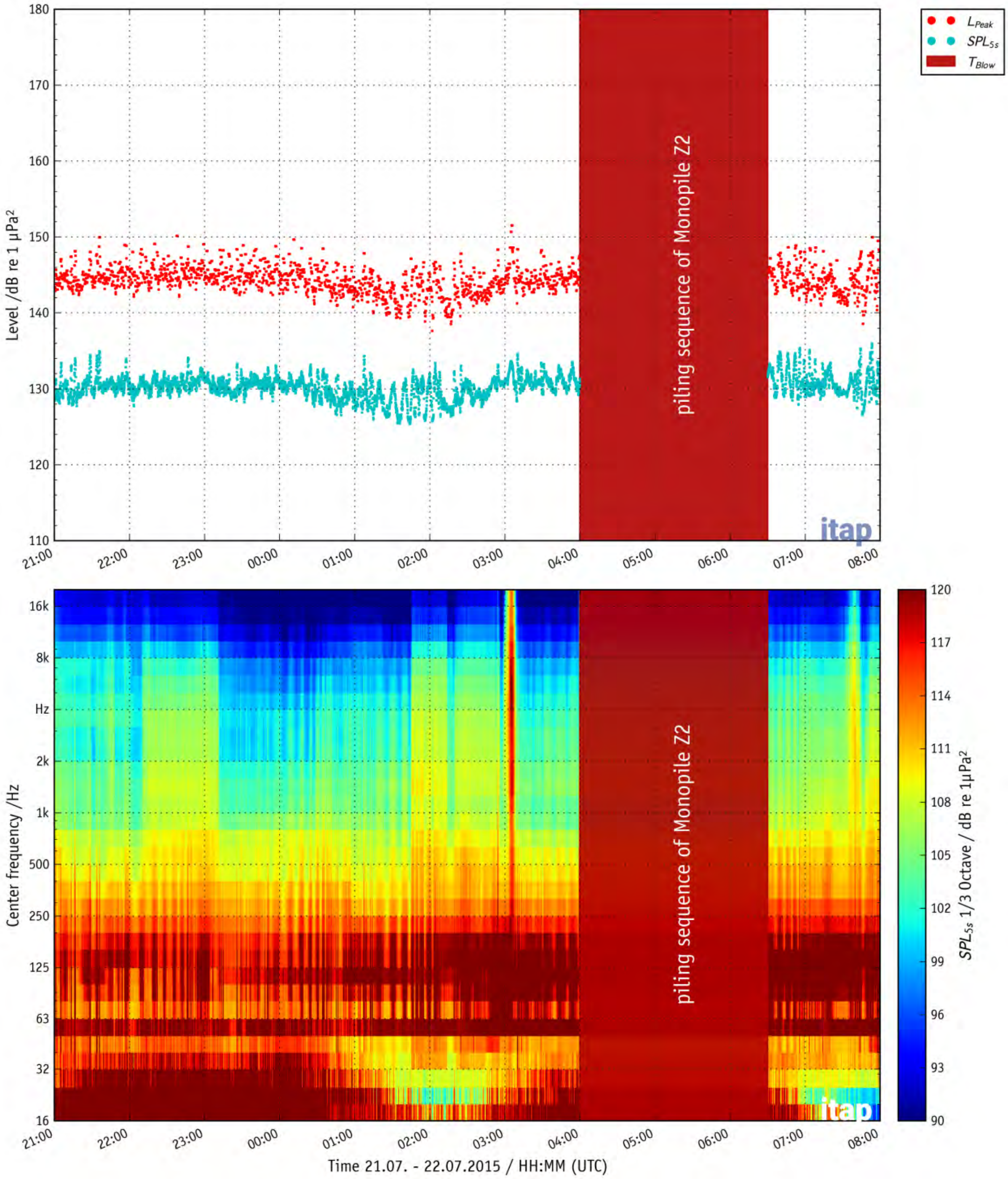


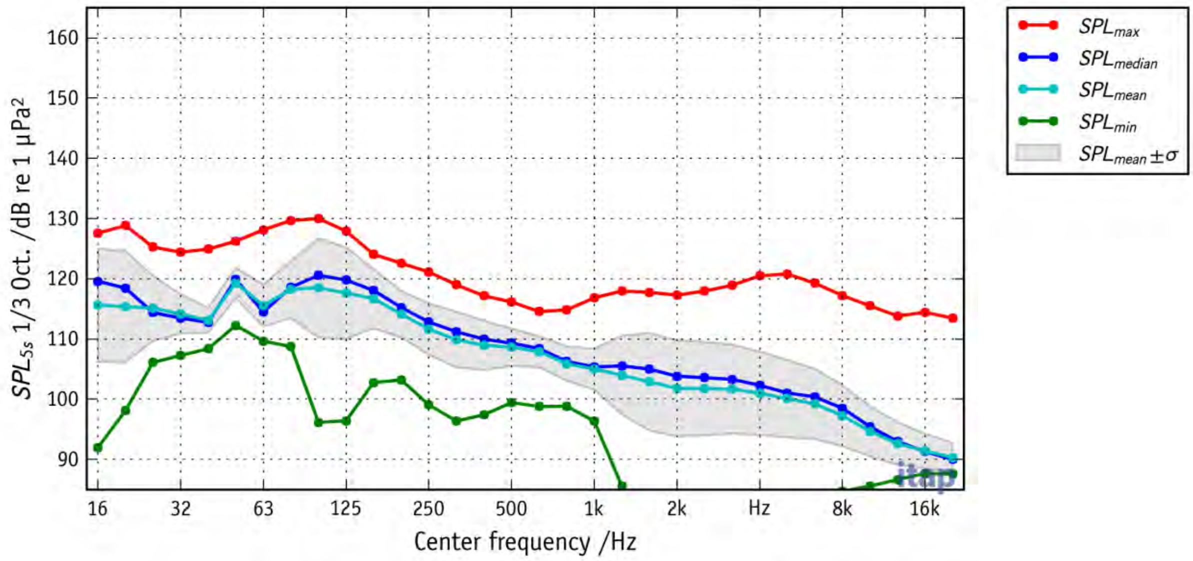

SPL_max
SPL_median
SPL_mean
SPL_min
SPL_mean ±σ
SPL_5s 1/3 Oct. /dB re 1 µPa²
160
150
140
130
120
110
100
90
16 32 63 125 250 500 1k 2k Hz 8k 16k
Center frequency /Hz
itap


Proportion of Intervals /%
14.0
13.0
11.0
9.0
8.0
6.0
5.0
3.0
2.0
0.0
100 110 120 130 140 150 160
SPL_5s / dB re 1µPa²
itap

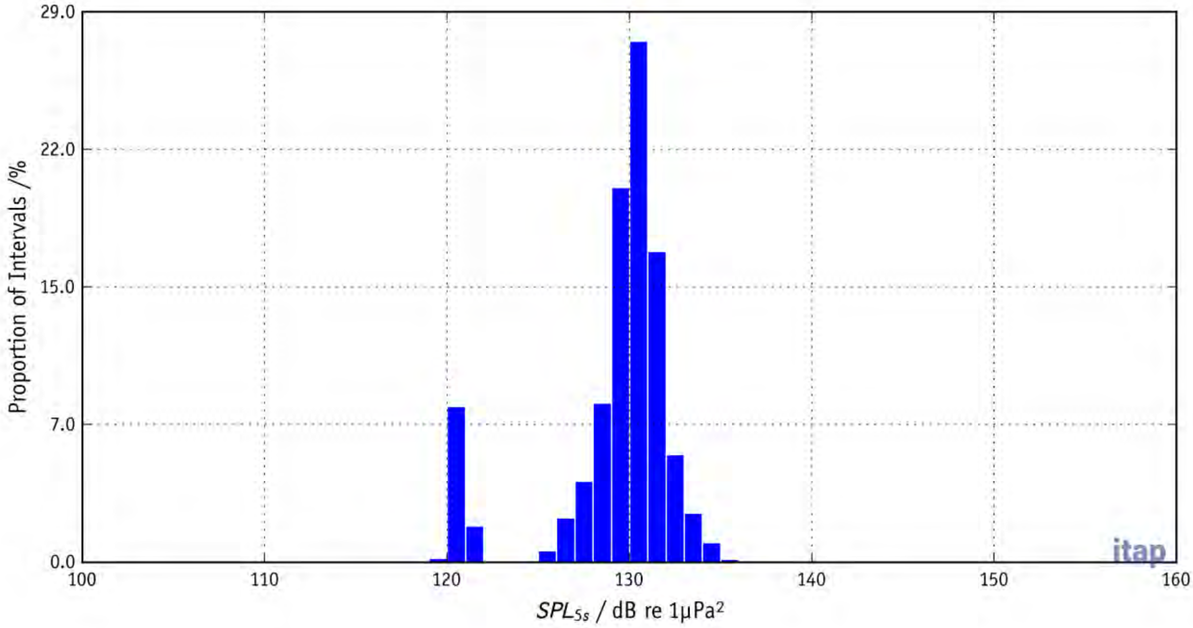
A1.4 Ambient Noise at Monopile Z2

Z2 MP1, 2 m ambient noise



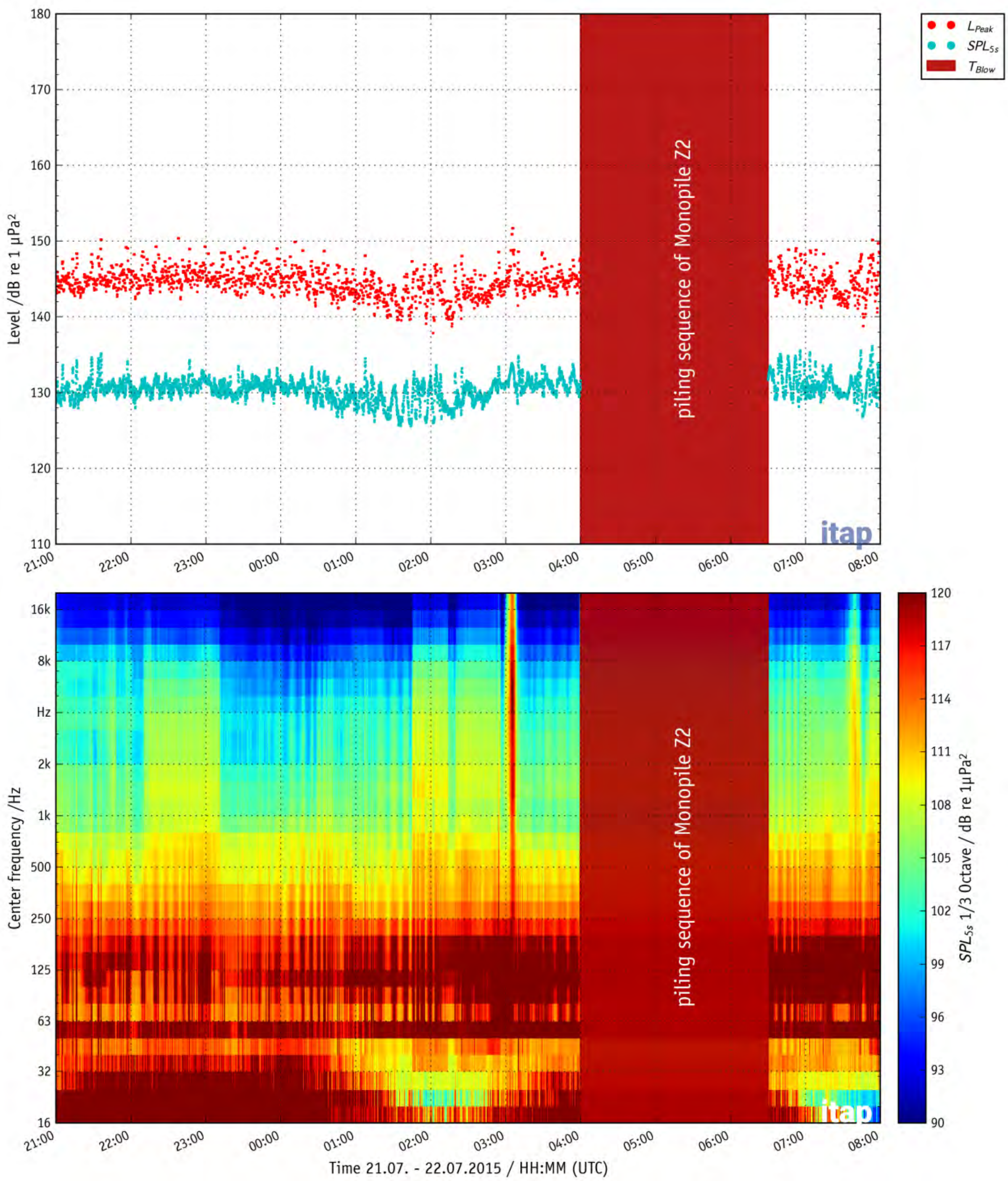


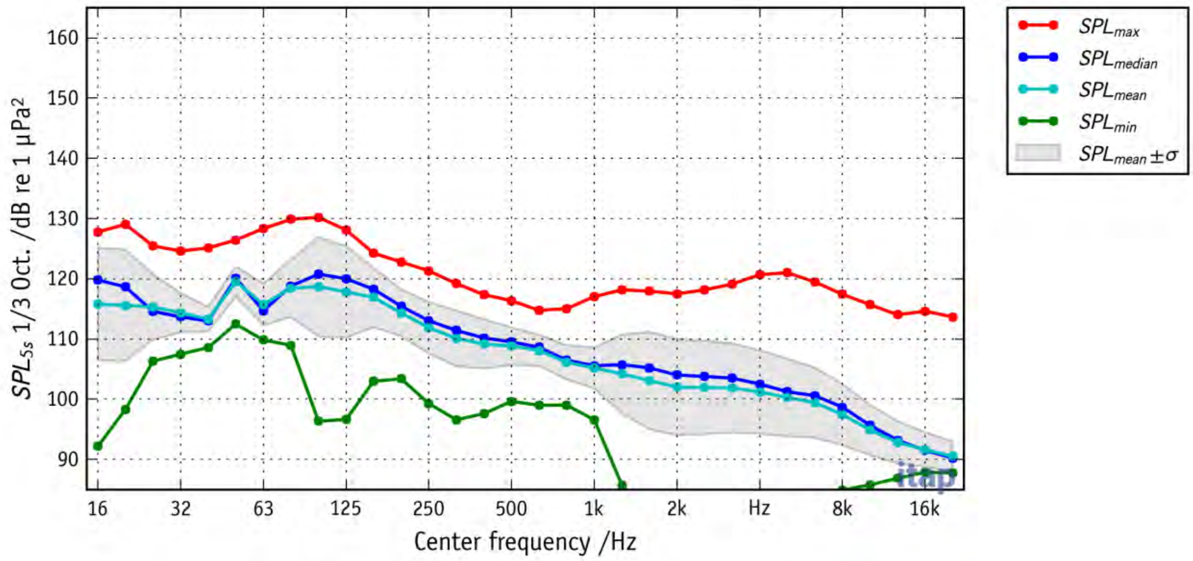
160
150
140
130
120
110
100
90
SPL_{5s} 1/3 Oct. /dB re 1 µPa²
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center frequency /Hz
SPL_{max}
SPL_{median}
SPL_{mean}
SPL_{min}
$SPL_{mean} \pm \sigma$
itap

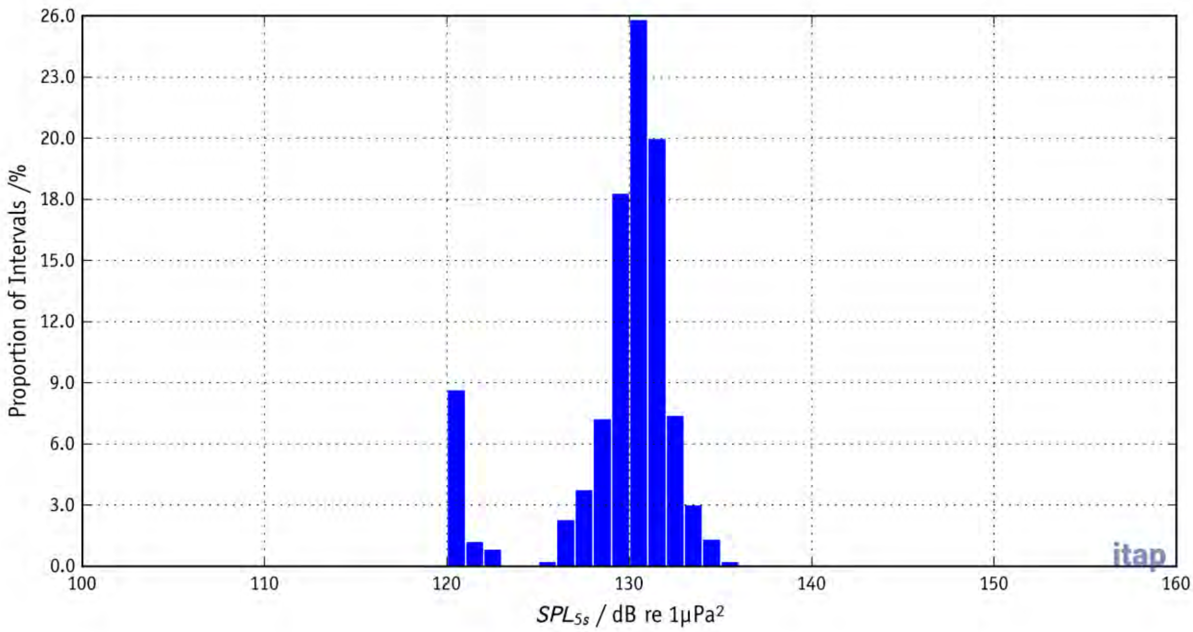


29.0
22.0
15.0
7.0
0.0
Proportion of Intervals /%
100
110
120
130
140
150
160
SPL_{5s} / dB re 1µPa²
itap

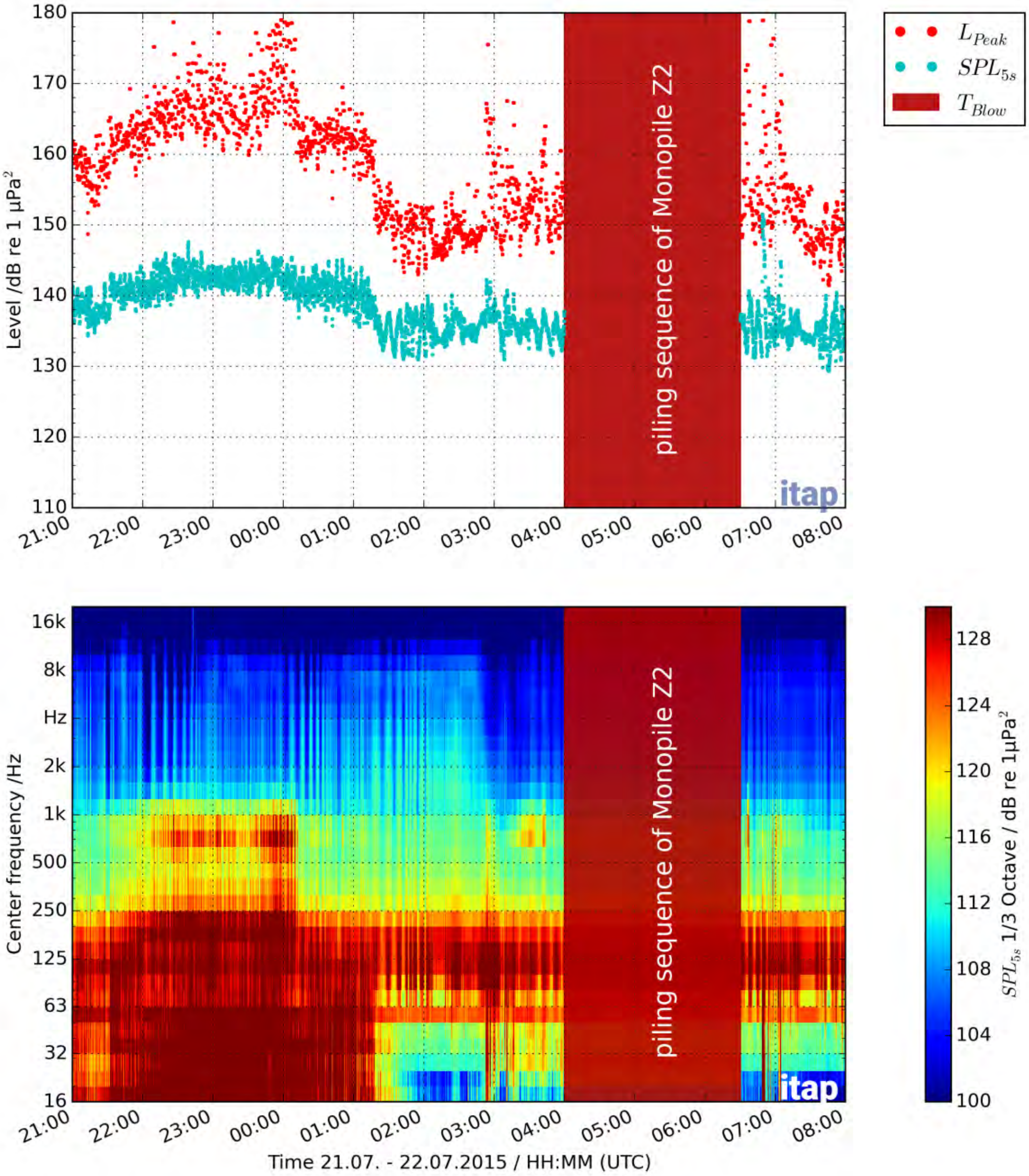
Z2 MP1, 10 m ambient noise

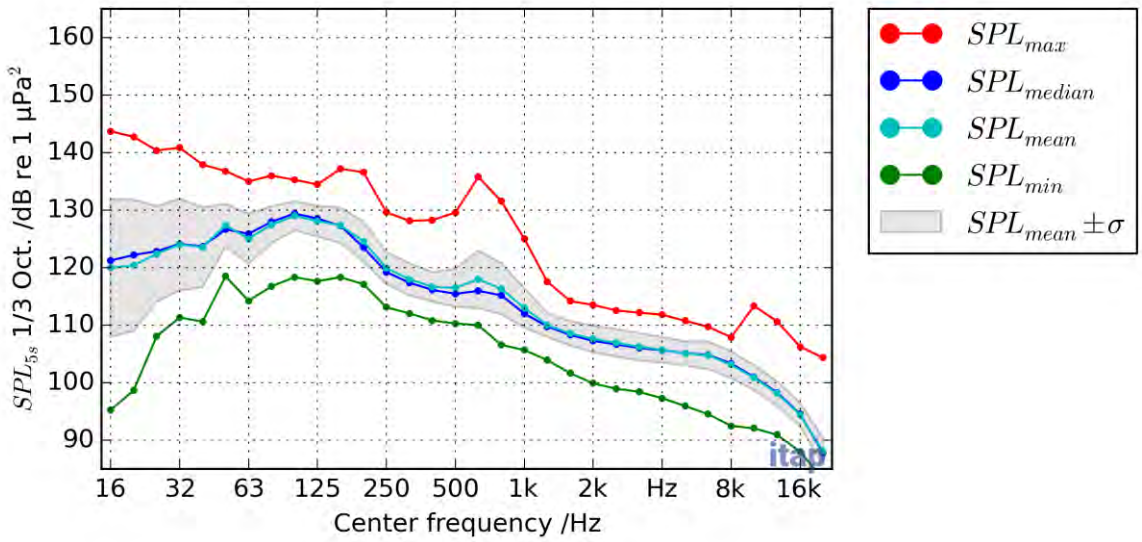



SPL_max
SPL_median
SPL_mean
SPL_min
SPL_mean ± σ
SPL_5s 1/3 Oct. /dB re 1 µPa²
Center frequency /Hz
16
32
63
125
250
500
1k
2k
Hz
8k
16k
160
150
140
130
120
110
100
90
itap

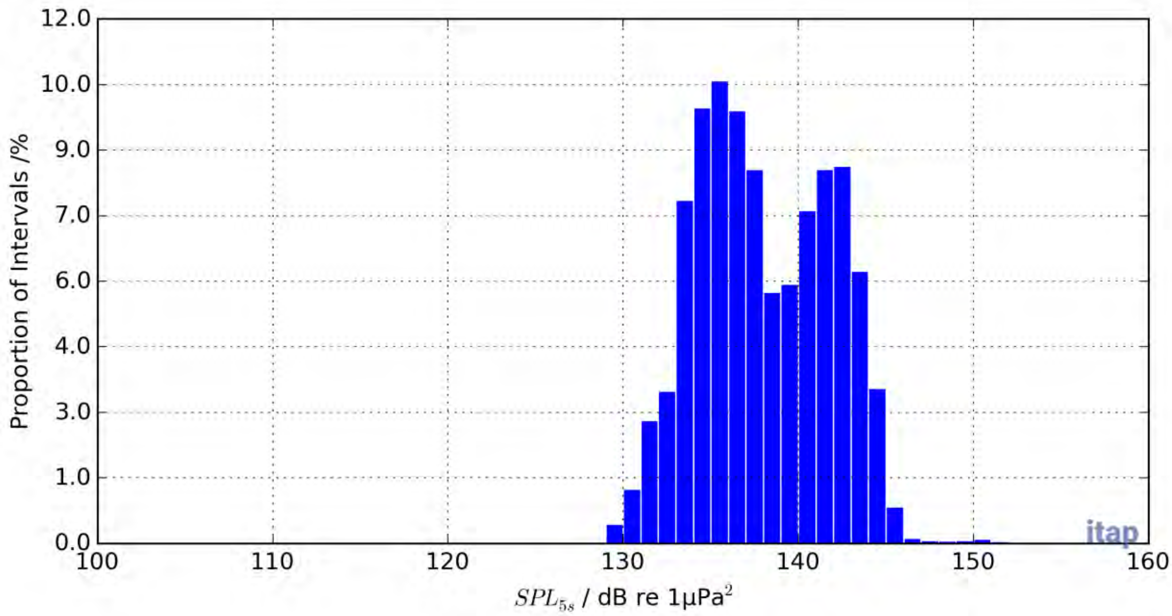

Proportion of Intervals /%
SPL_5s / dB re 1µPa²
26.0
23.0
20.0
18.0
15.0
12.0
9.0
6.0
3.0
0.0
100
110
120
130
140
150
160
itap

Z2 MP2, 2 m ambient noise



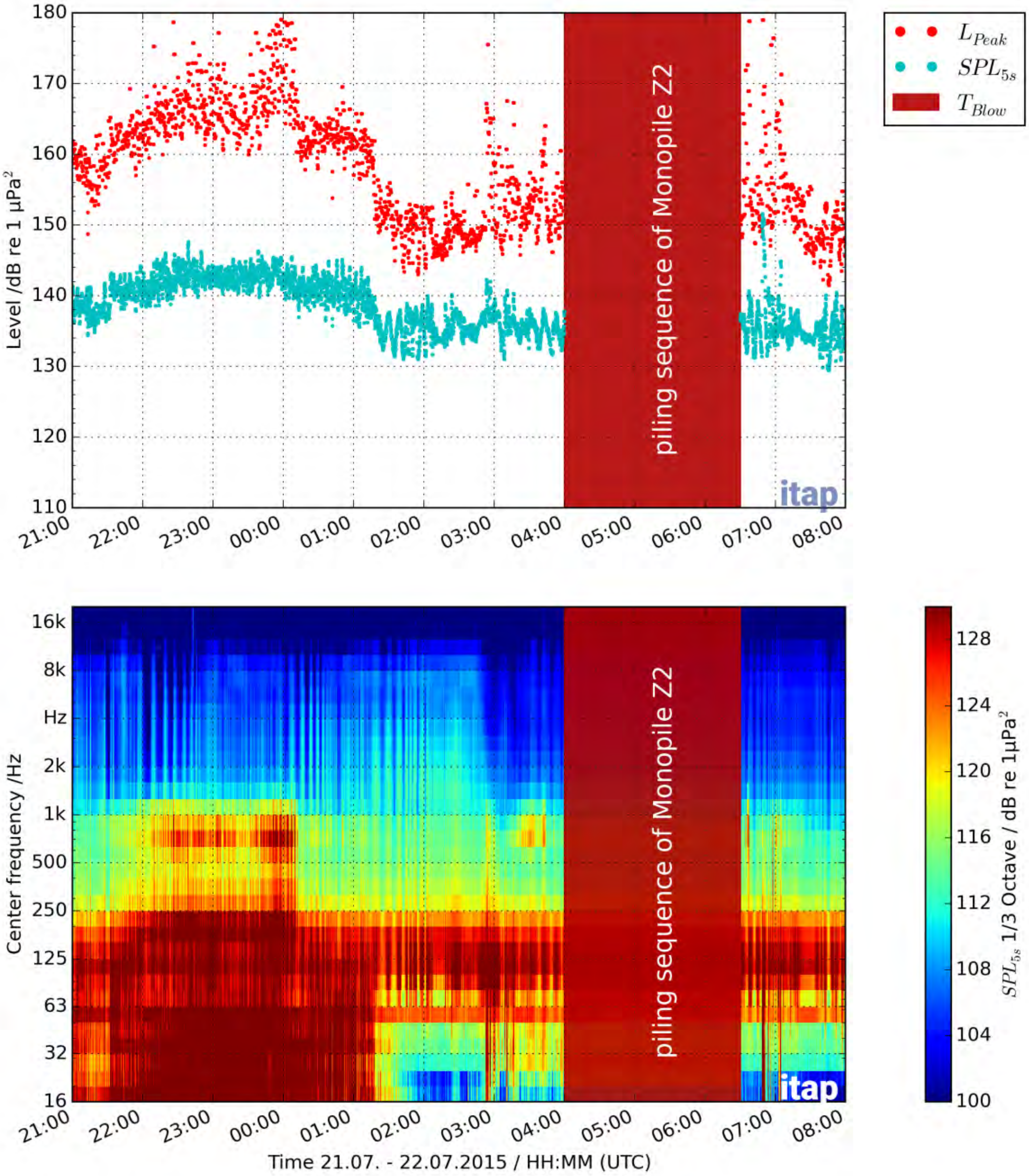


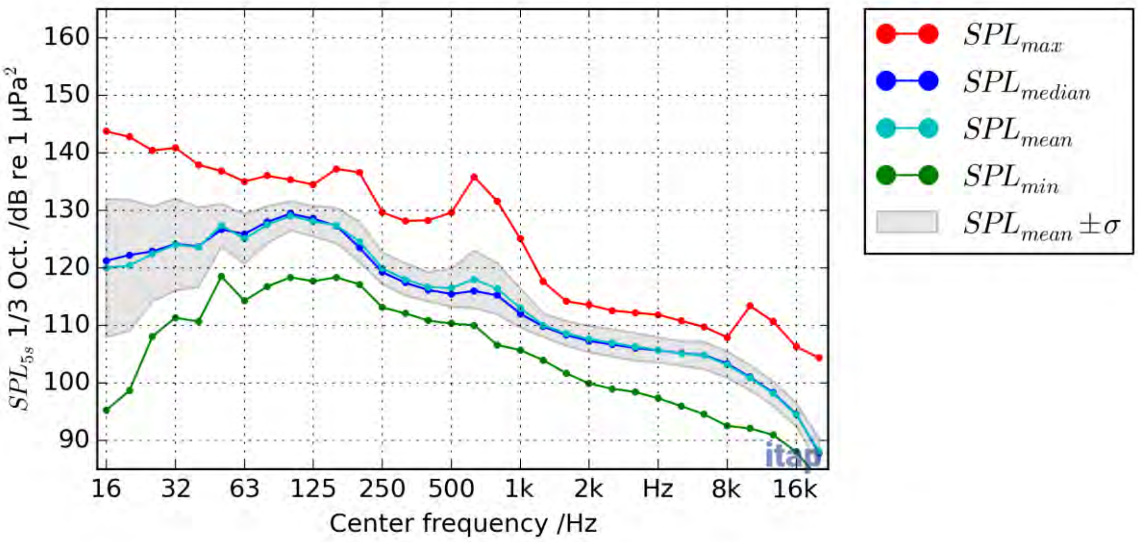
160
150
140
130
120
110
100
90
SPL_{5s} 1/3 Oct. /dB re 1 µPa^2
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center frequency /Hz
SPL_{max}
SPL_{median}
SPL_{mean}
SPL_{min}
$SPL_{mean} \pm \sigma$
itap



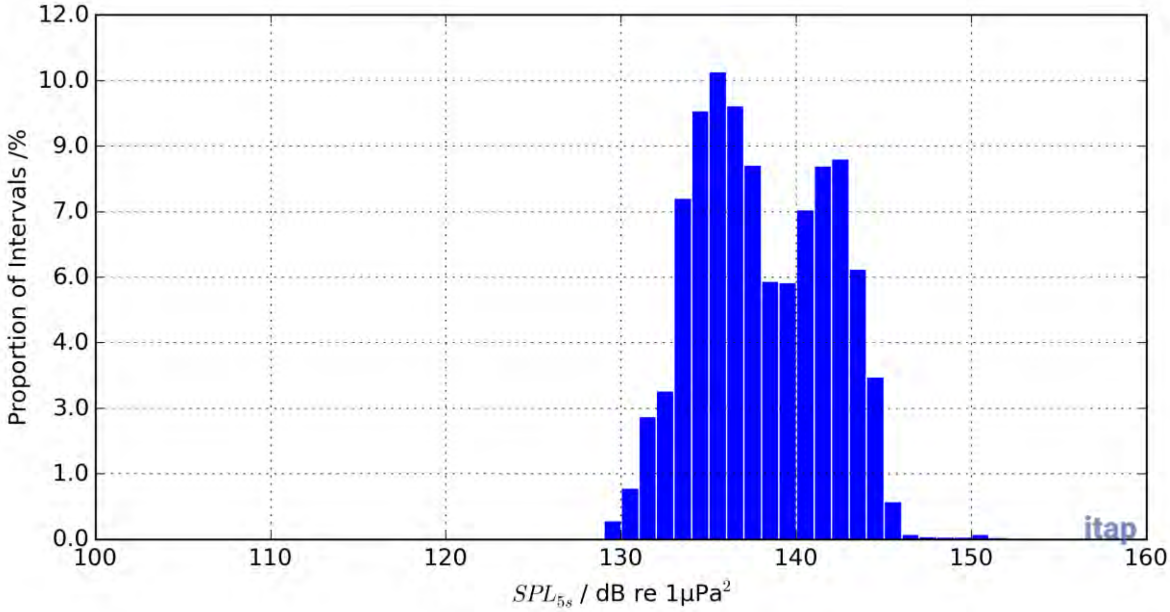
12.0
10.0
9.0
7.0
6.0
4.0
3.0
1.0
0.0
Proportion of Intervals /%
100
110
120
130
140
150
160
SPL_{5s} / dB re 1µPa^2
itap

Z2 MP2, 10 m ambient noise



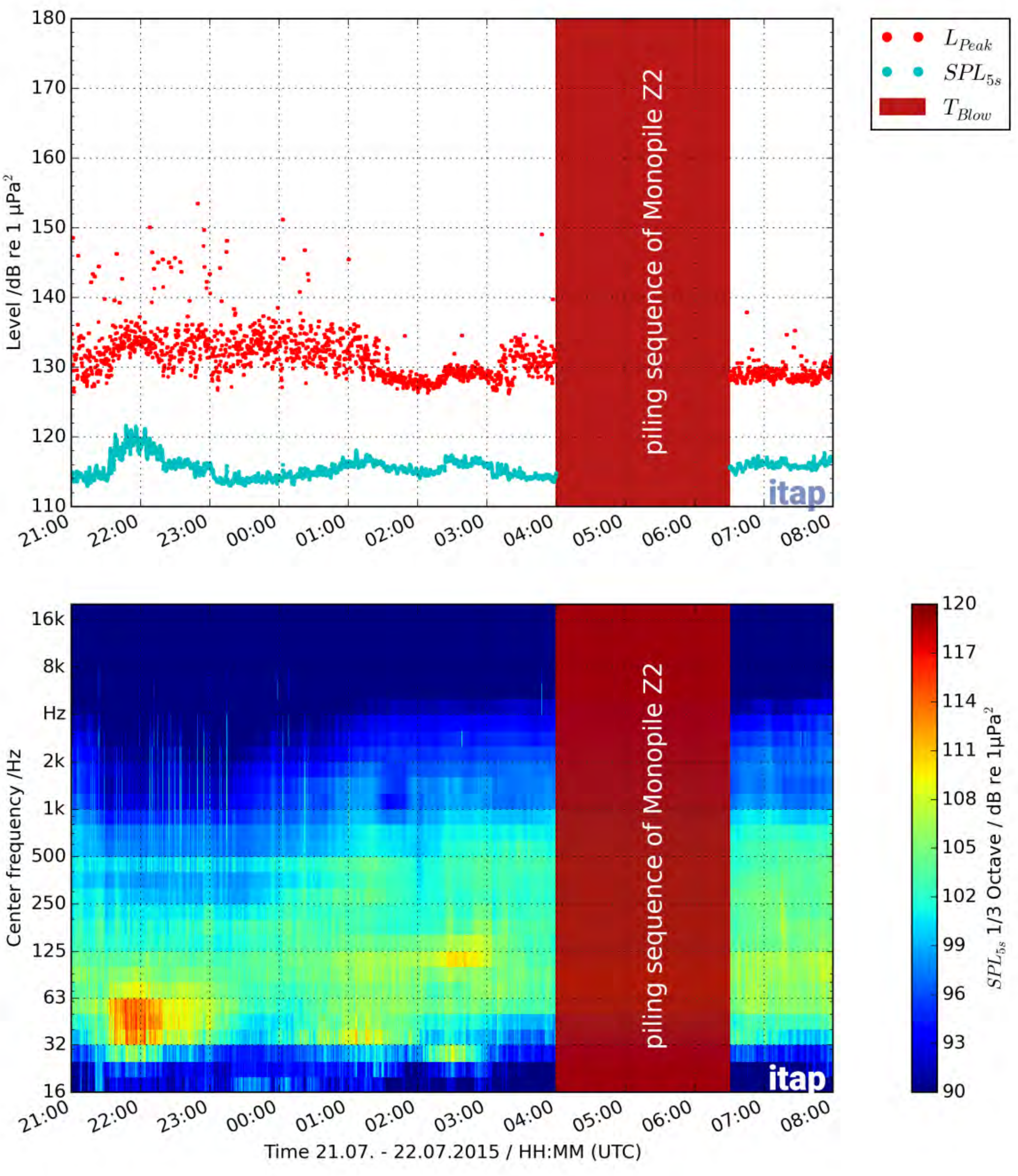


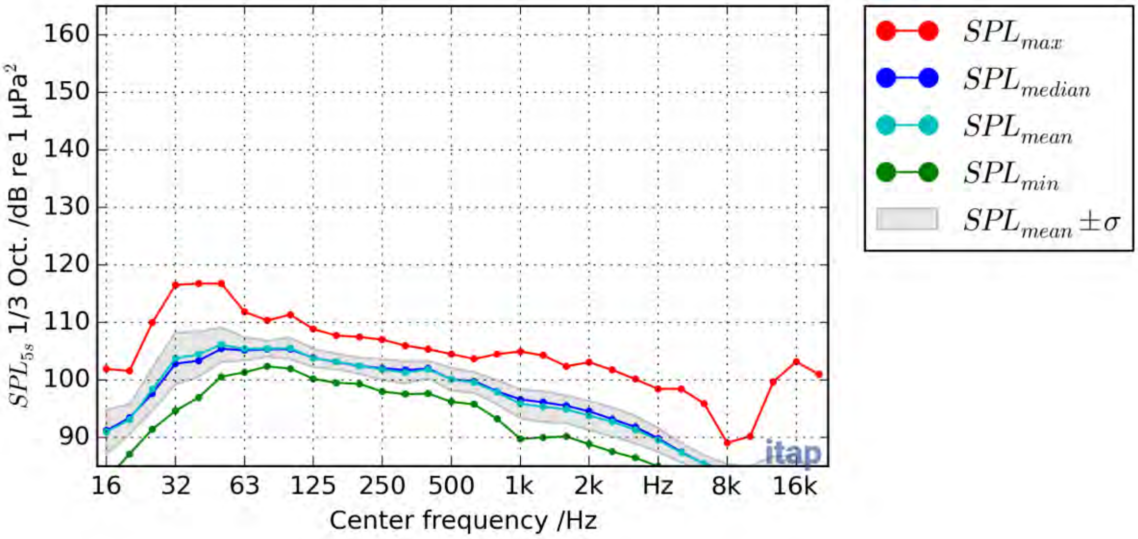
SPL_{5s} 1/3 Oct. /dB re 1 µPa^2
160
150
140
130
120
110
100
90
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center frequency /Hz
SPL_{max}
SPL_{median}
SPL_{mean}
SPL_{min}
$SPL_{mean} \pm \sigma$
itap

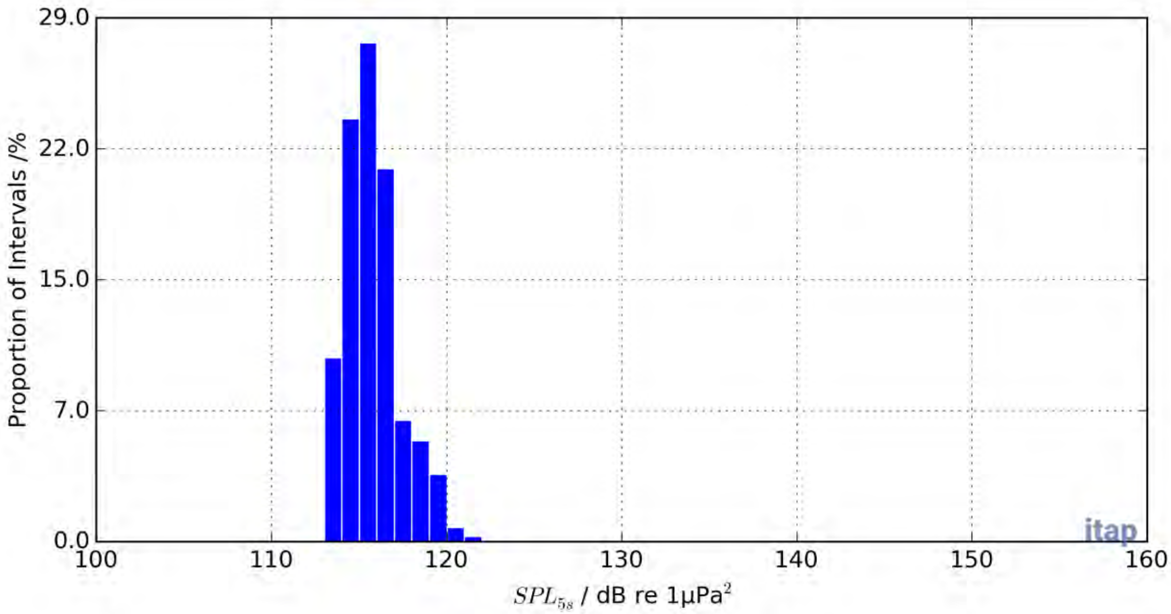


Proportion of Intervals /%
12.0
10.0
9.0
7.0
6.0
4.0
3.0
1.0
0.0
100
110
120
130
140
150
160
SPL_{5s} / dB re 1µPa^2
itap

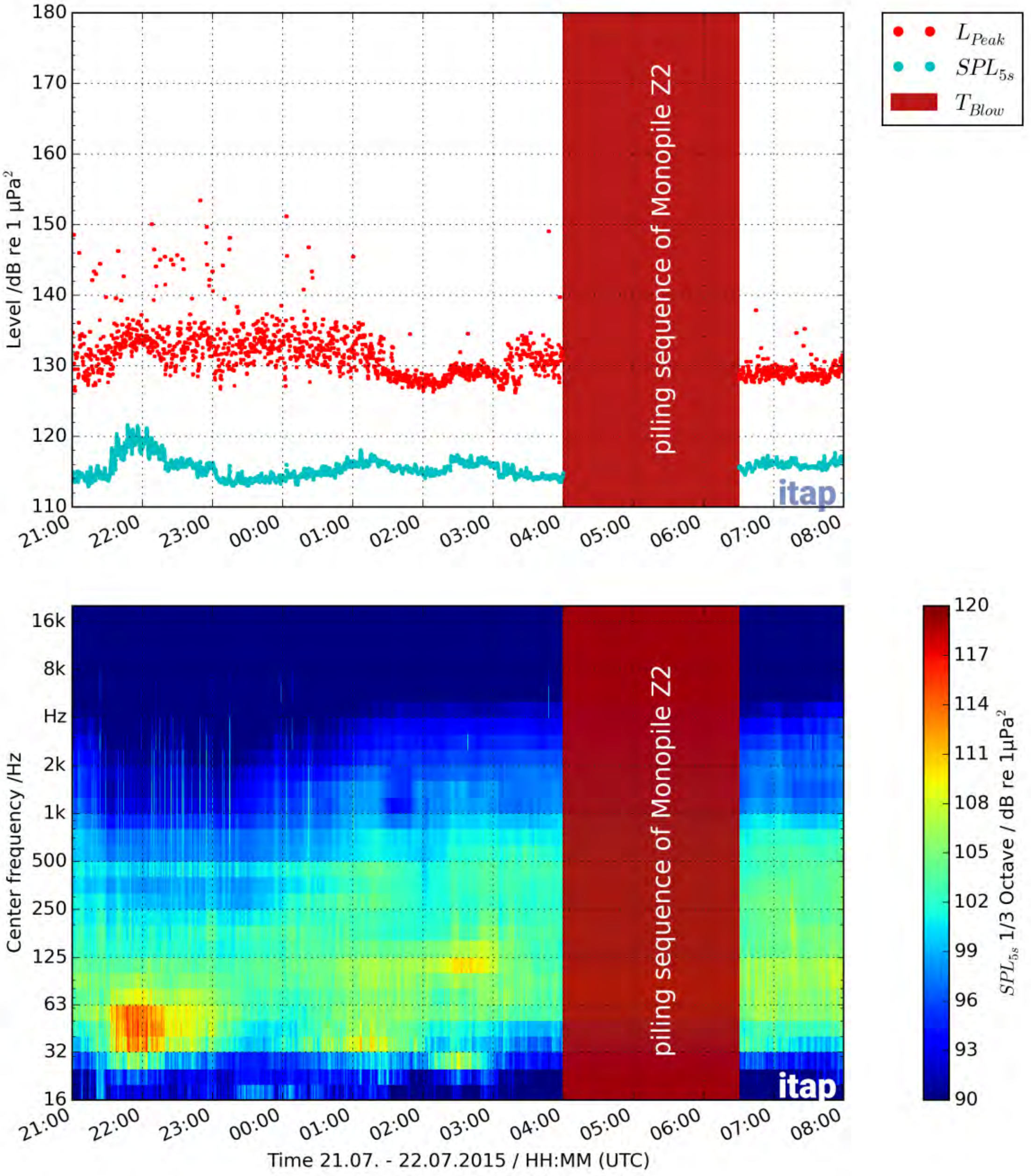
Z2 MP3, 2 m ambient noise

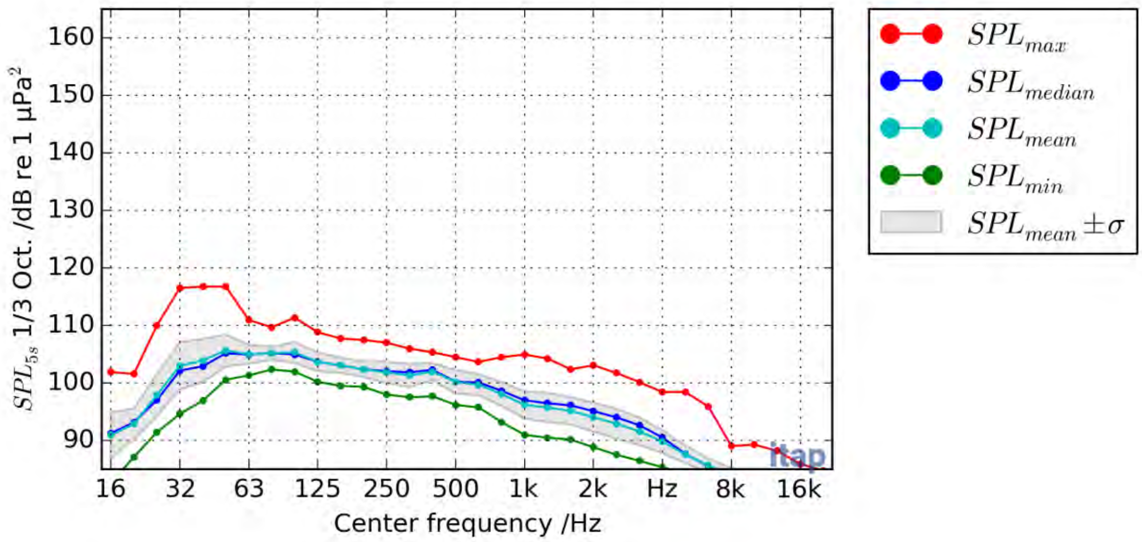


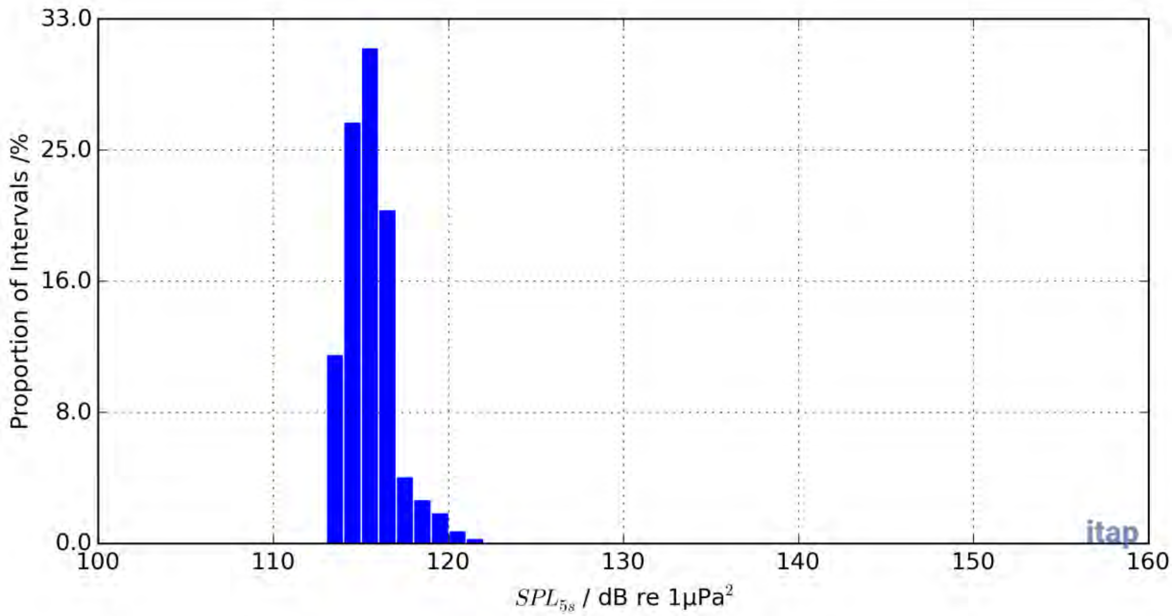

160
150
140
130
120
110
100
90
SPL_{5s} 1/3 Oct. /dB re 1 µPa²
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center frequency /Hz
SPL_{max}
SPL_{median}
SPL_{mean}
SPL_{min}
$SPL_{mean} \pm \sigma$
itap


29.0
22.0
15.0
7.0
0.0
Proportion of Intervals /%
100
110
120
130
140
150
160
SPL_{5s} / dB re 1µPa²
itap

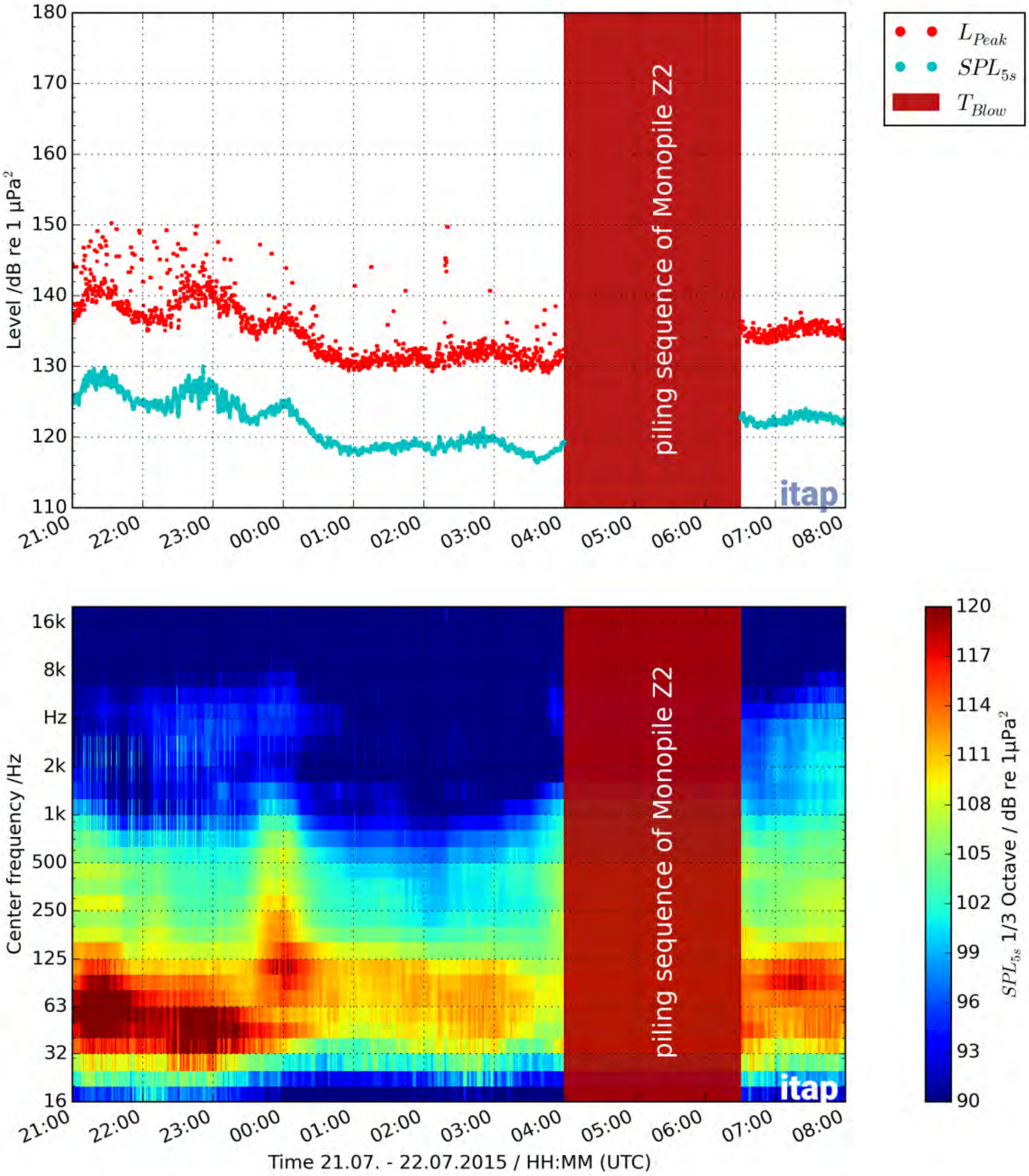
Z2 MP3, 10 m ambient noise

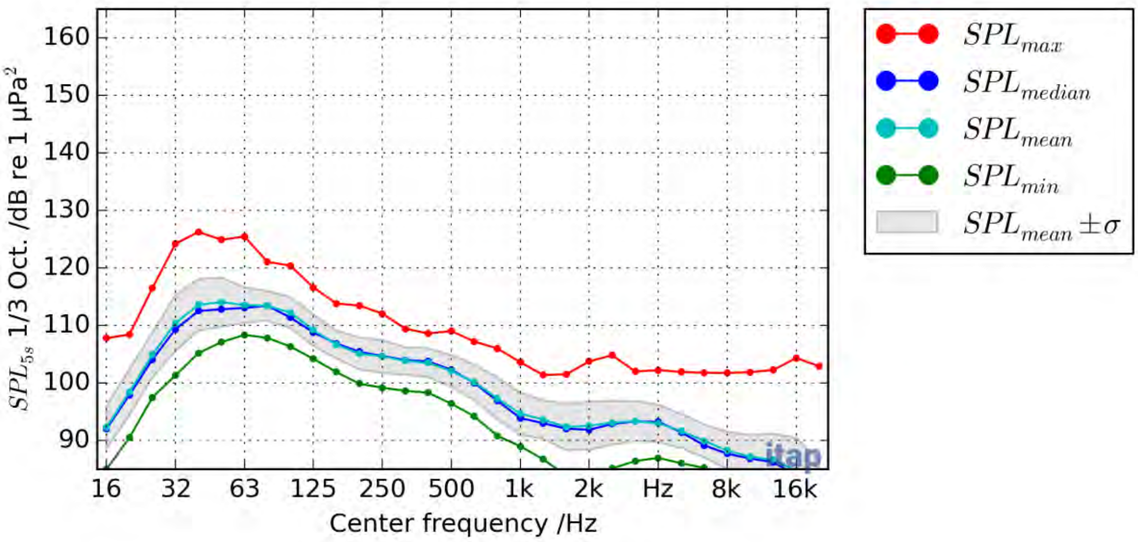



160
150
140
130
120
110
100
90
SPL_{5s} 1/3 Oct. /dB re 1 µPa²
16 32 63 125 250 500 1k 2k Hz 8k 16k
Center frequency /Hz
itap
SPL_{max}
SPL_{median}
SPL_{mean}
SPL_{min}
$SPL_{mean} \pm \sigma$

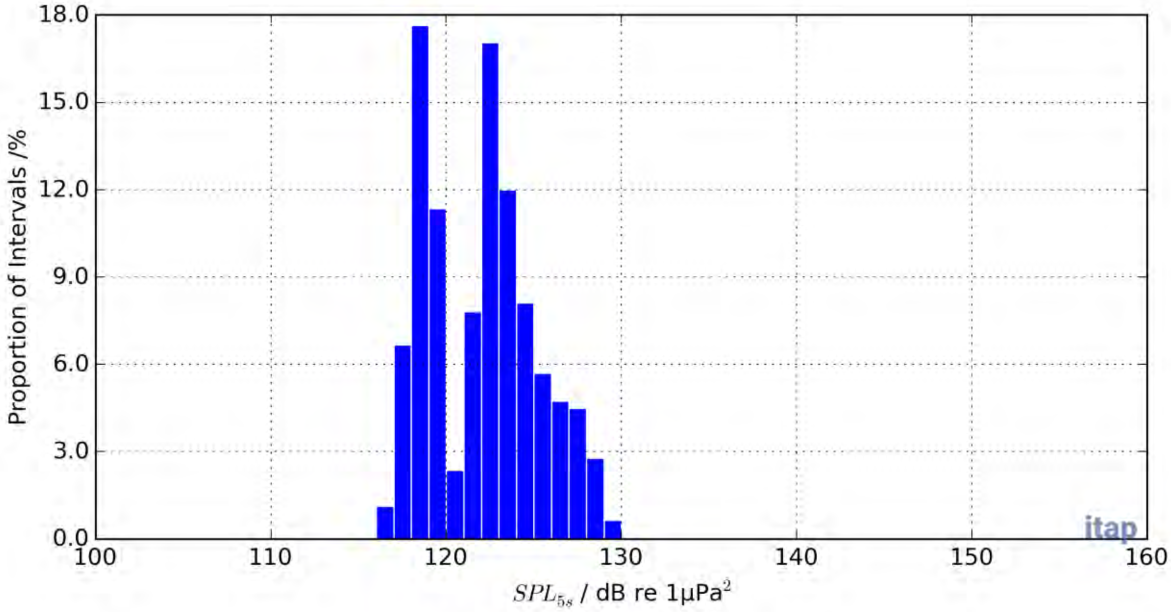

33.0
25.0
16.0
8.0
0.0
Proportion of Intervals /%
100 110 120 130 140 150 160
SPL_{5s} / dB re 1µPa²
itap

Z2 MP4, 2 m ambient noise



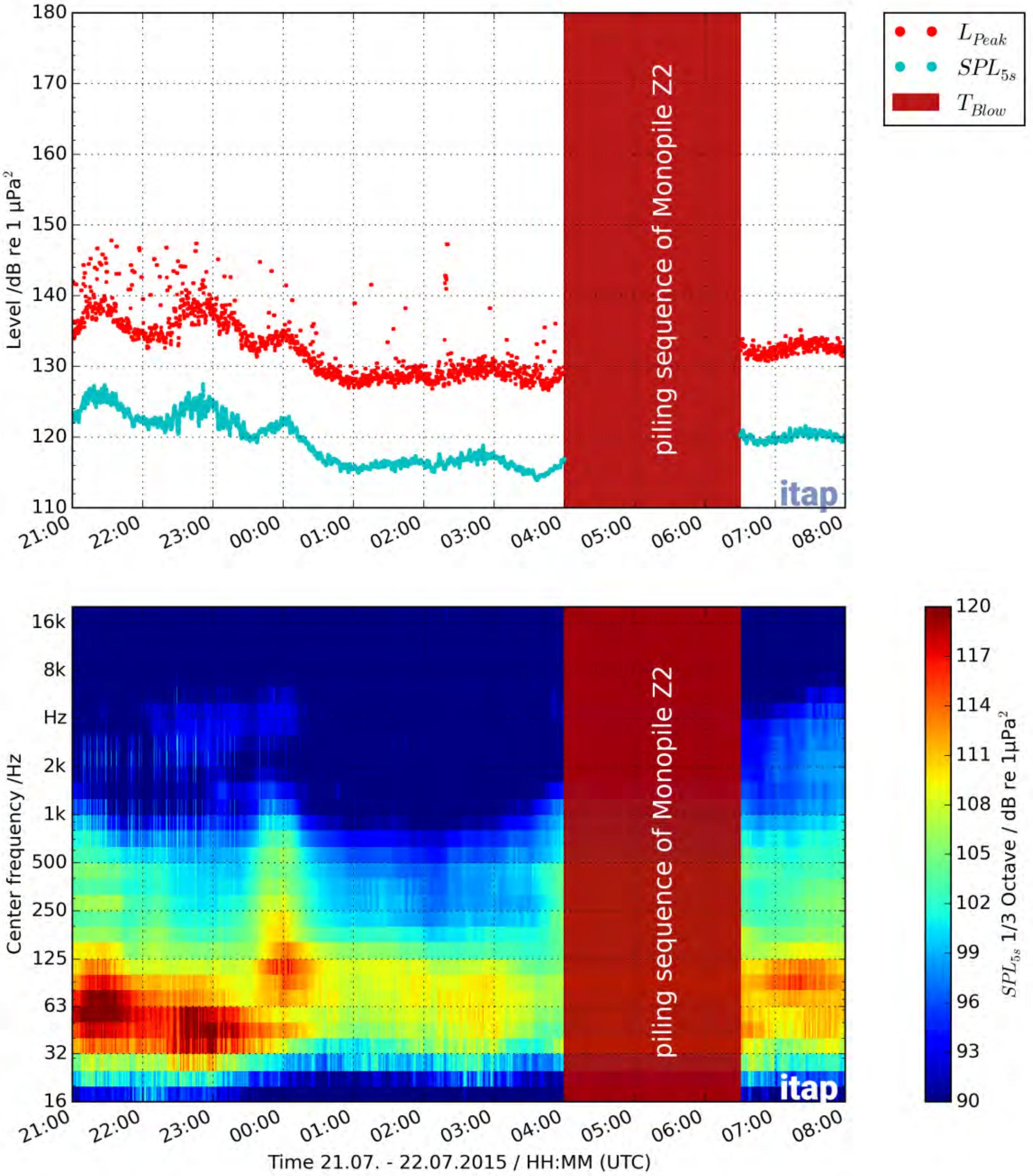


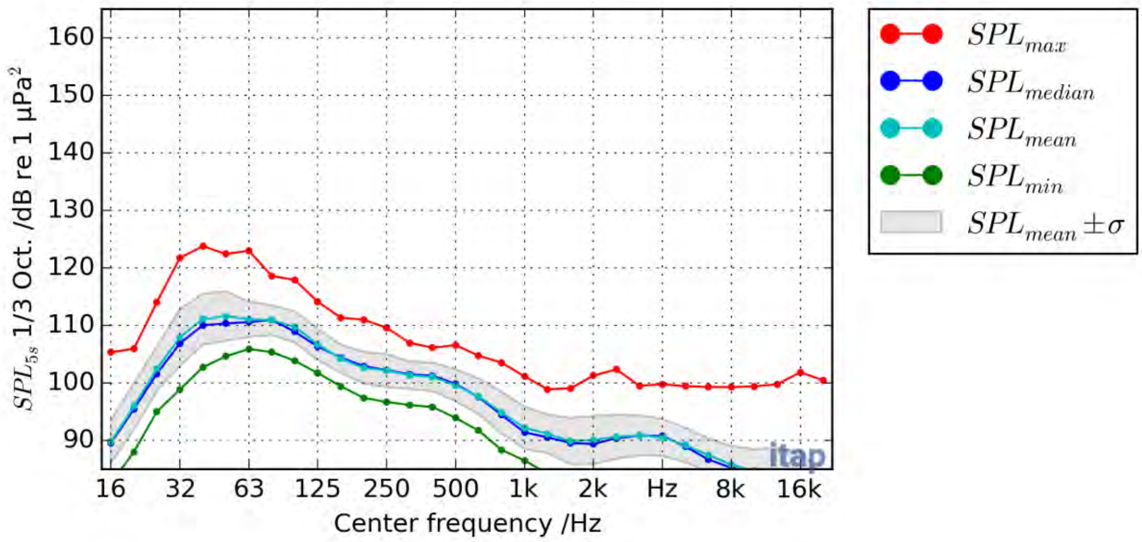
160
150
140
130
120
110
100
90
SPL_{5s} 1/3 Oct. /dB re 1 µPa²
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center frequency /Hz
SPL_{max}
SPL_{median}
SPL_{mean}
SPL_{min}
$SPL_{mean} \pm \sigma$
itap

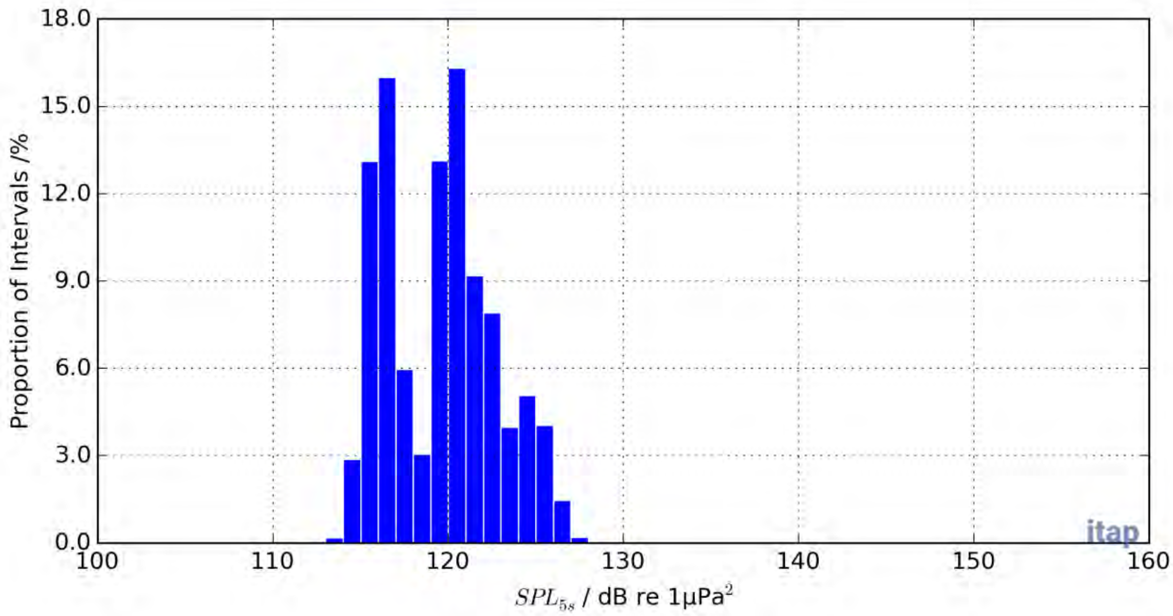


18.0
15.0
12.0
9.0
6.0
3.0
0.0
Proportion of Intervals /%
100
110
120
130
140
150
160
SPL_{5s} / dB re 1µPa²
itap

Z2 MP4, 10 m ambient noise

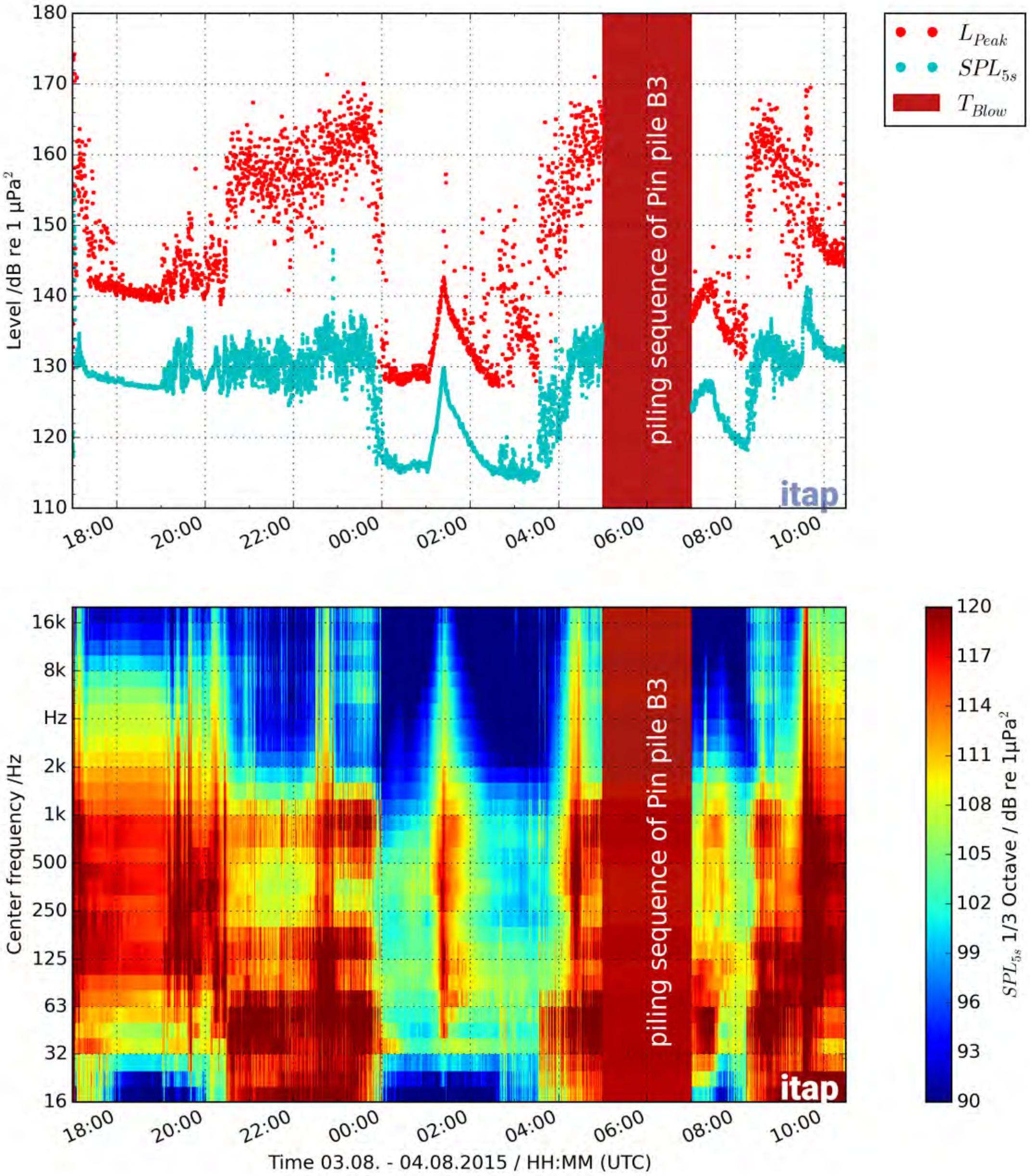


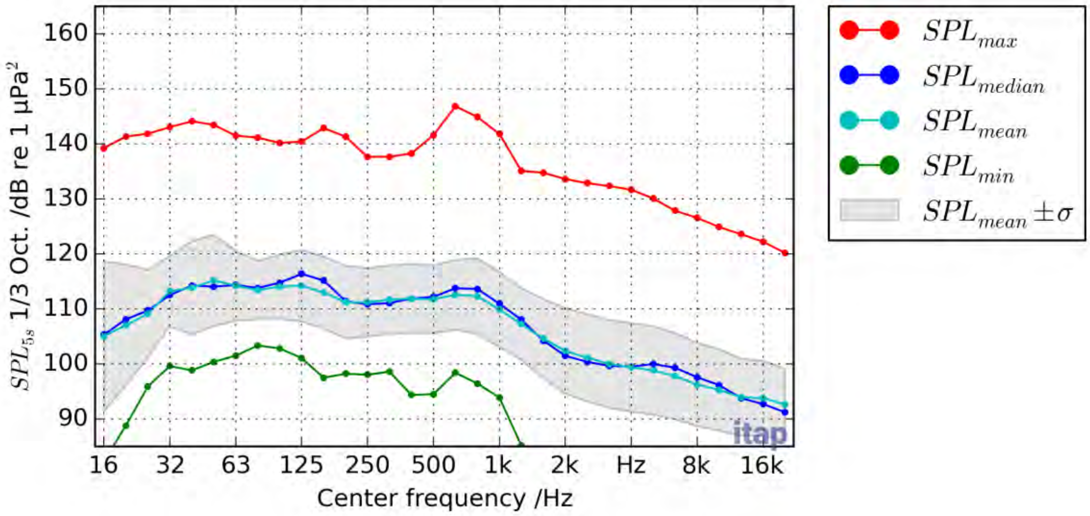

160
150
140
130
120
110
100
90
SPL_{5s} 1/3 Oct. /dB re 1 µPa^2
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center frequency /Hz
itap
SPL_{max}
SPL_{median}
SPL_{mean}
SPL_{min}
$SPL_{mean} \pm \sigma$


18.0
15.0
12.0
9.0
6.0
3.0
0.0
Proportion of Intervals /%
100
110
120
130
140
150
160
SPL_{5s} / dB re 1µPa^2
itap

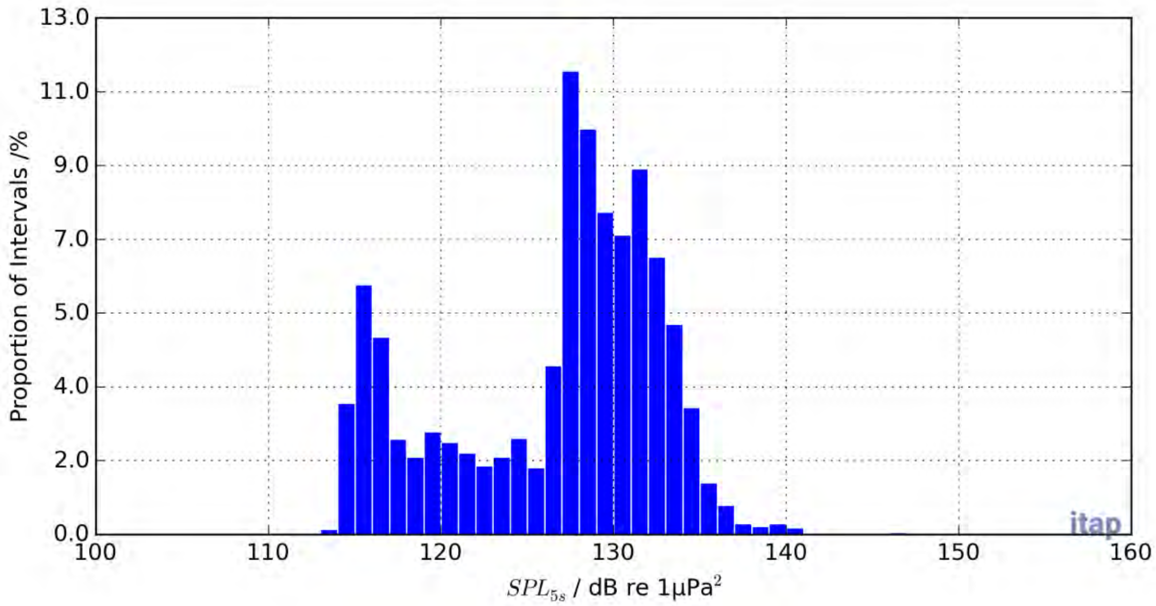
A1.4 Ambient Noise at pin pile B3 (OHVS1)

OHVS1 MP1, 2 m ambient noise



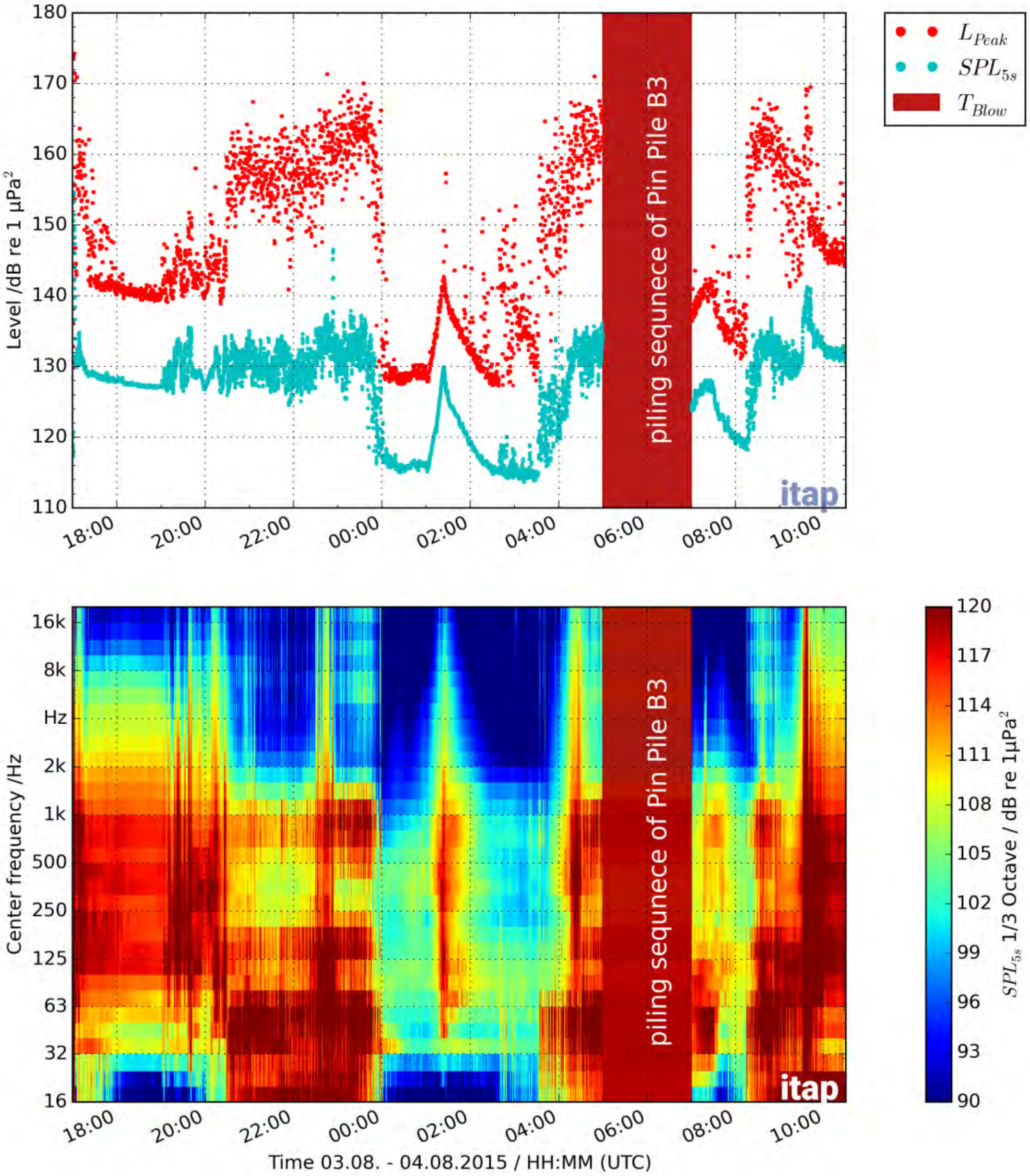


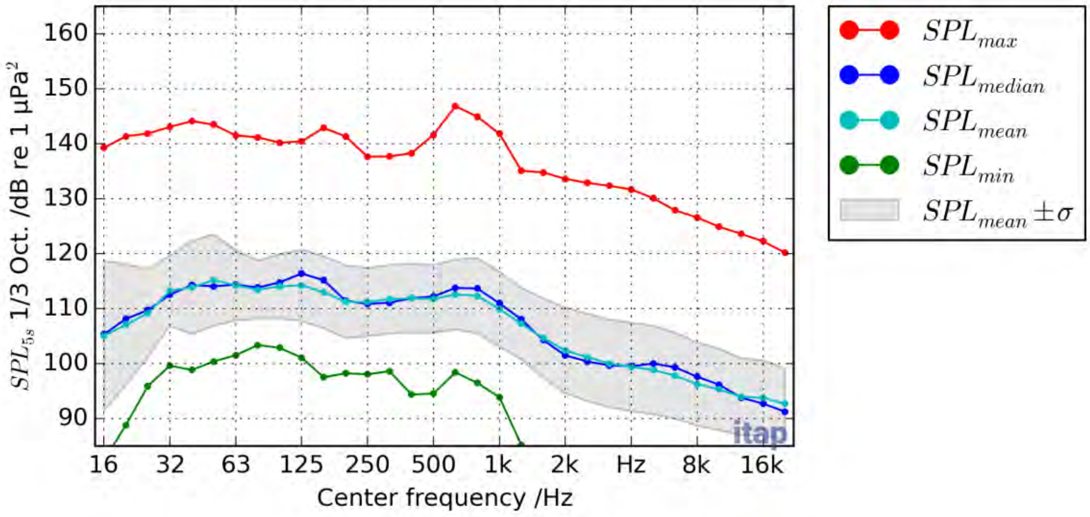
160
150
140
130
120
110
100
90
SPL_{5s} 1/3 Oct. /dB re 1 µPa²
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center frequency /Hz
SPL_{max}
SPL_{median}
SPL_{mean}
SPL_{min}
$SPL_{mean} \pm \sigma$
itap



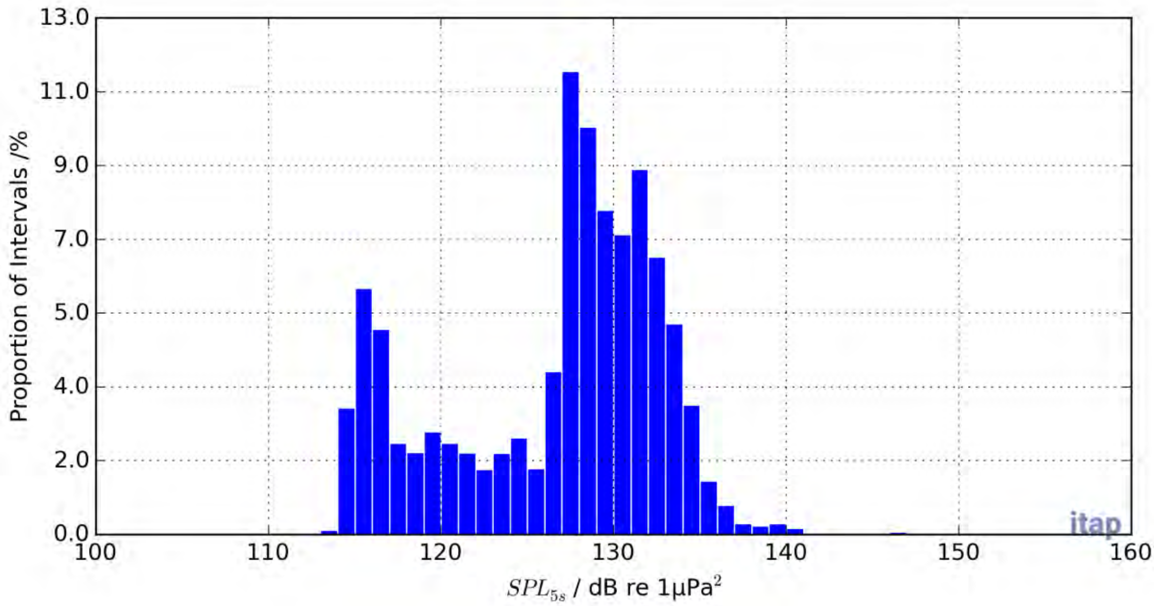
13.0
11.0
9.0
7.0
5.0
4.0
2.0
0.0
Proportion of Intervals /%
100
110
120
130
140
150
160
SPL_{5s} / dB re 1µPa²
itap

OHVS1 MP1, 10 m ambient noise



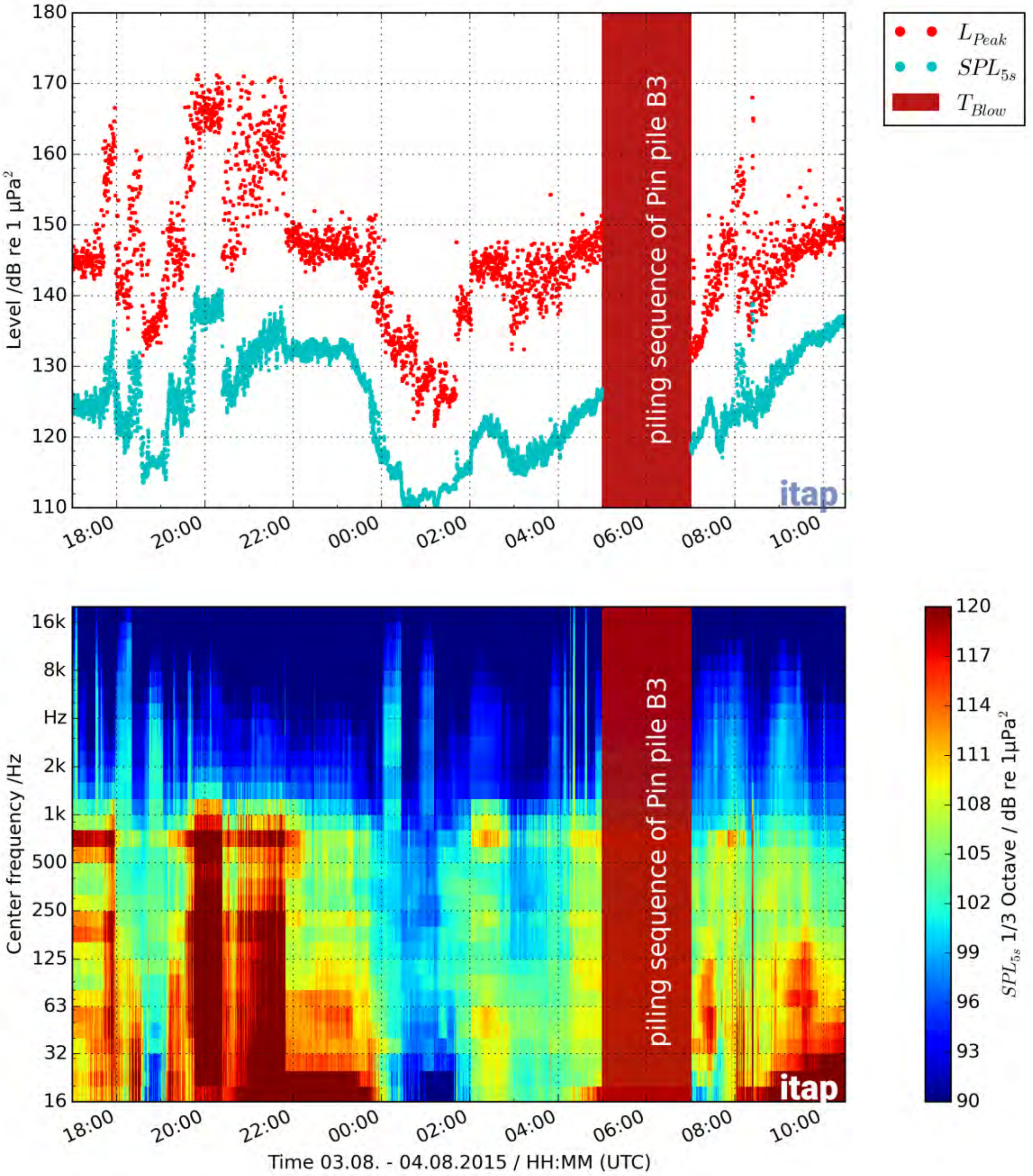


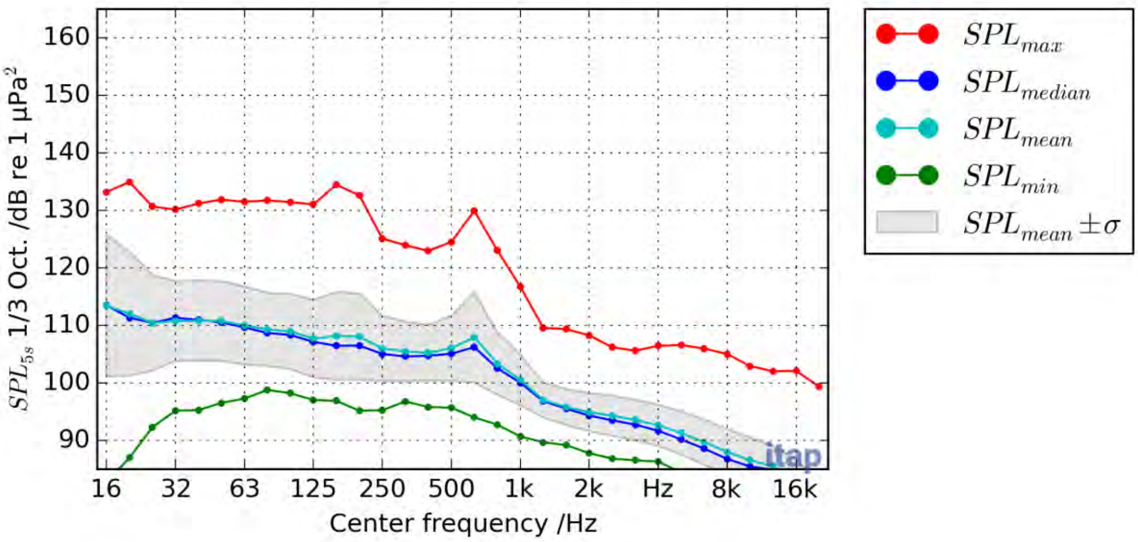
160
150
140
130
120
110
100
90
SPL_{5s} 1/3 Oct. /dB re 1 µPa²
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center frequency /Hz
SPL_{max}
SPL_{median}
SPL_{mean}
SPL_{min}
$SPL_{mean} \pm \sigma$
itap

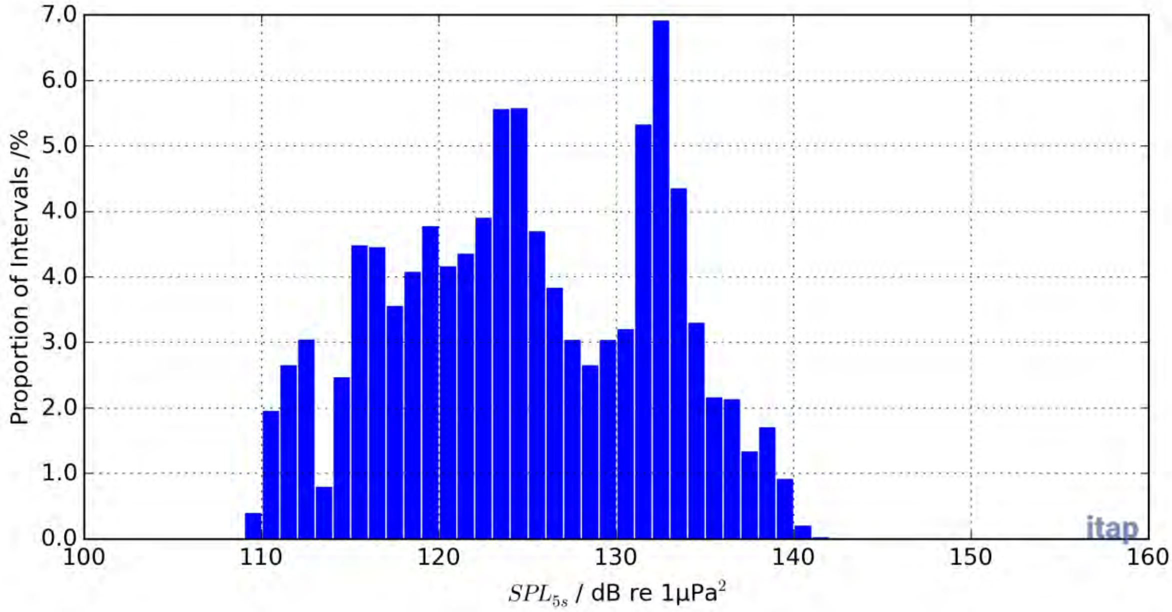


13.0
11.0
9.0
7.0
5.0
4.0
2.0
0.0
Proportion of Intervals /%
100
110
120
130
140
150
160
SPL_{5s} / dB re 1µPa²
itap

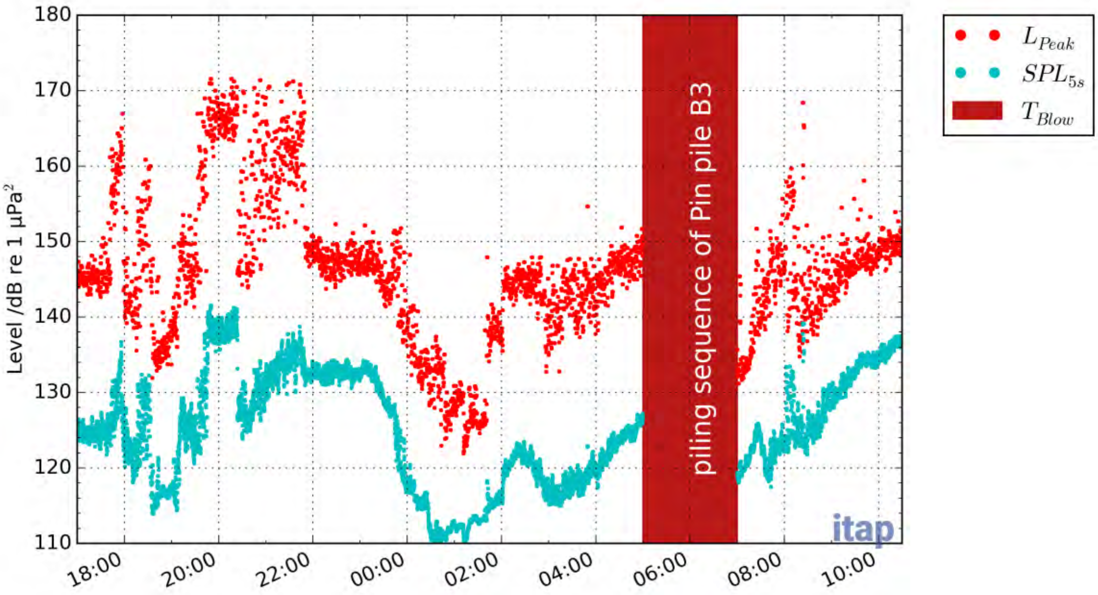
OHVS1 MP2, 2 m ambient noise

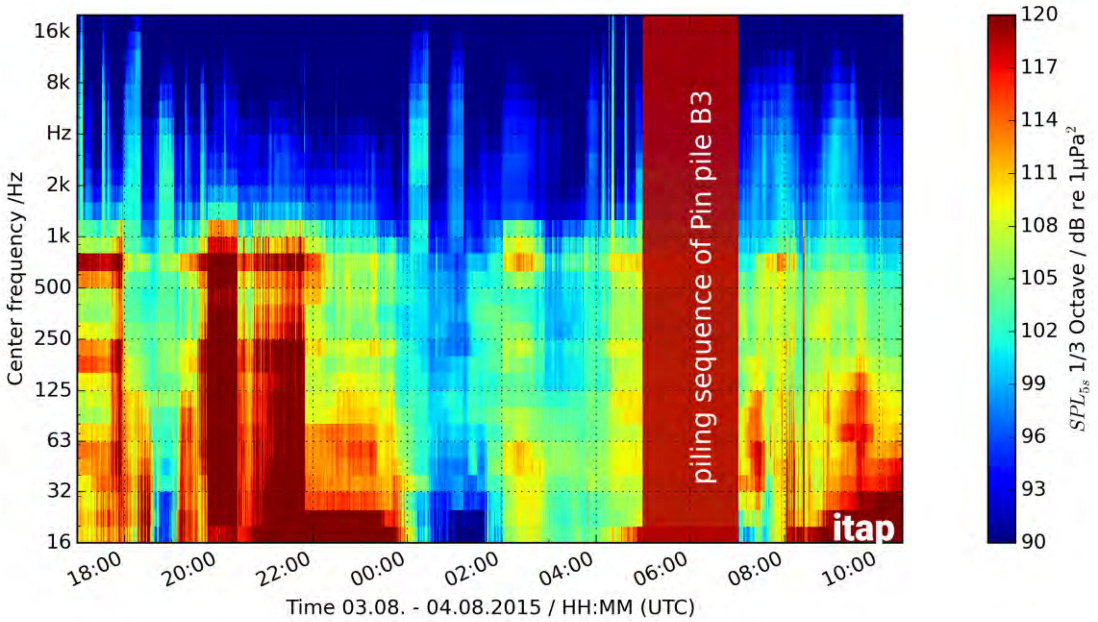


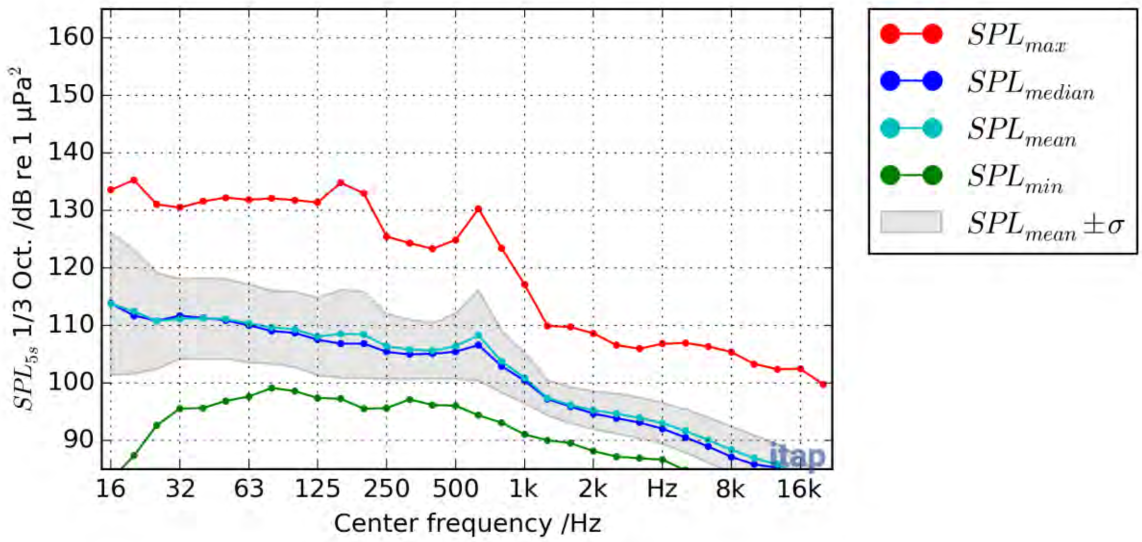

160
150
140
130
120
110
100
90
SPL_{5s} 1/3 Oct. /dB re 1 µPa²
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center frequency /Hz
SPL_{max}
SPL_{median}
SPL_{mean}
SPL_{min}
$SPL_{mean} \pm \sigma$
itap

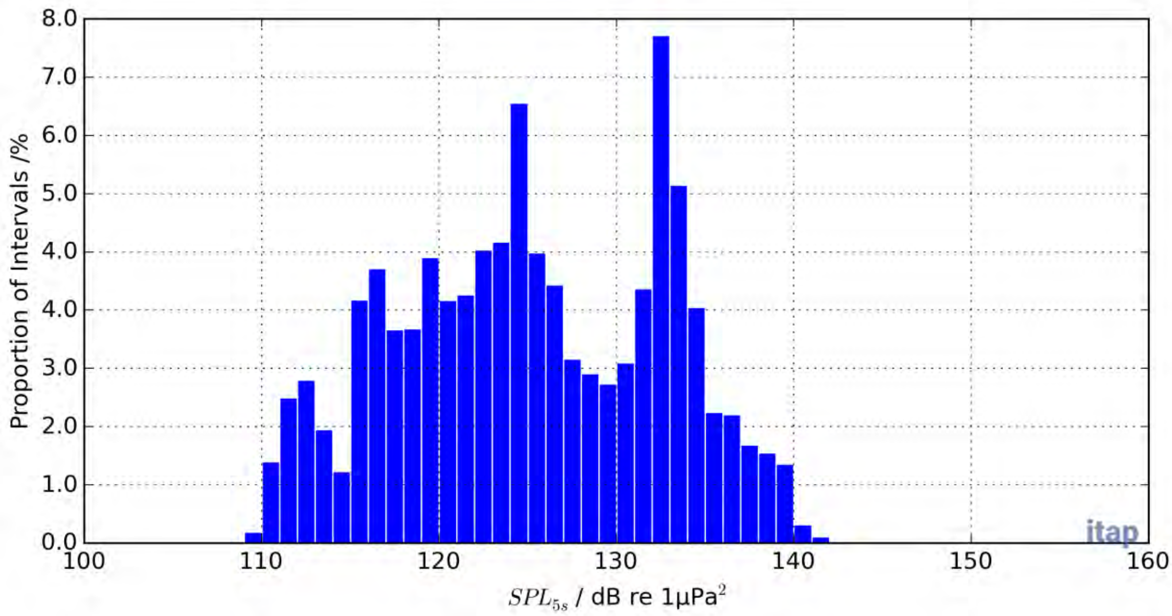

7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Proportion of Intervals /%
100
110
120
130
140
150
160
SPL_{5s} / dB re 1µPa²
itap

OHVS1 MP2, 10 m ambient noise

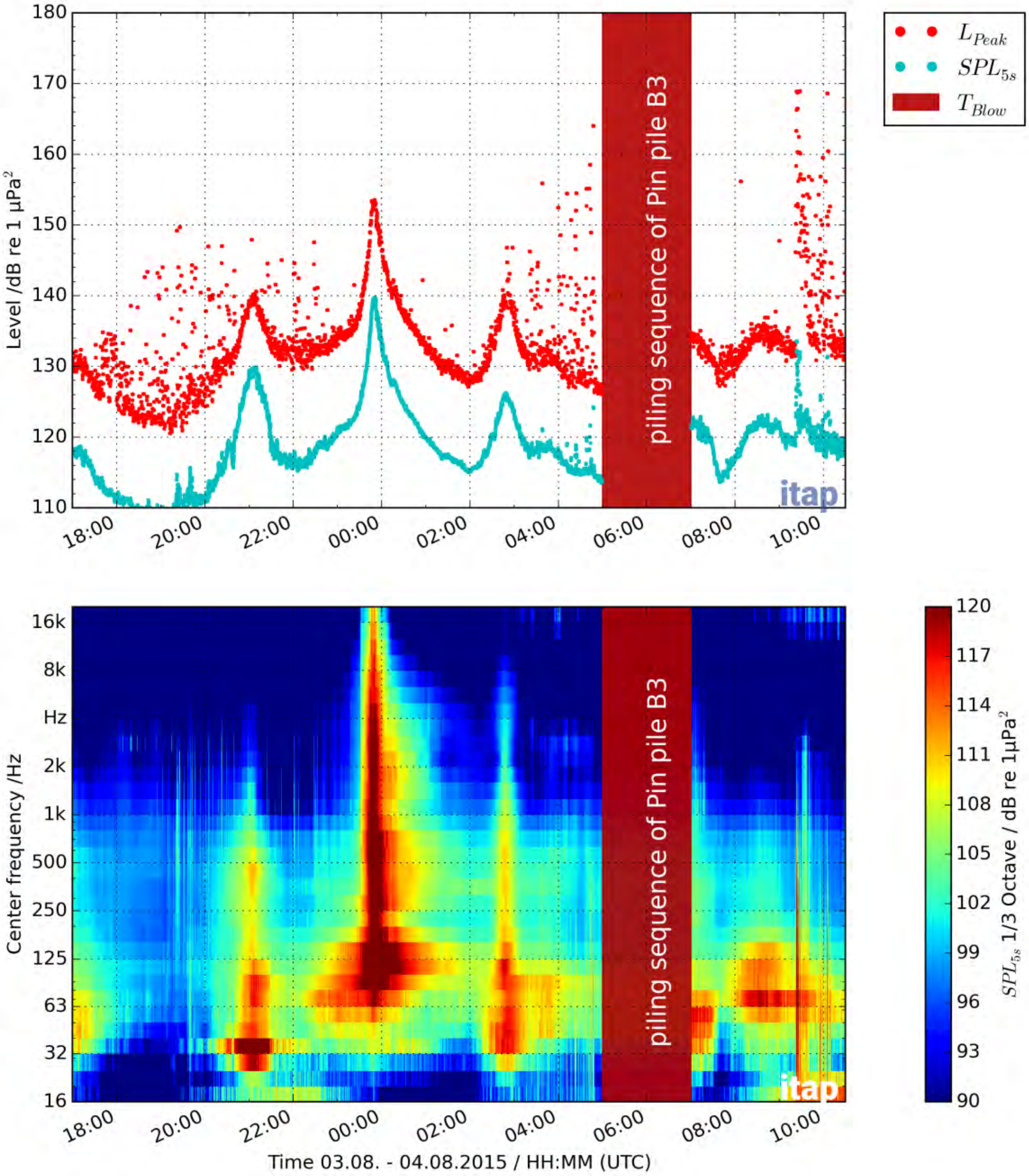


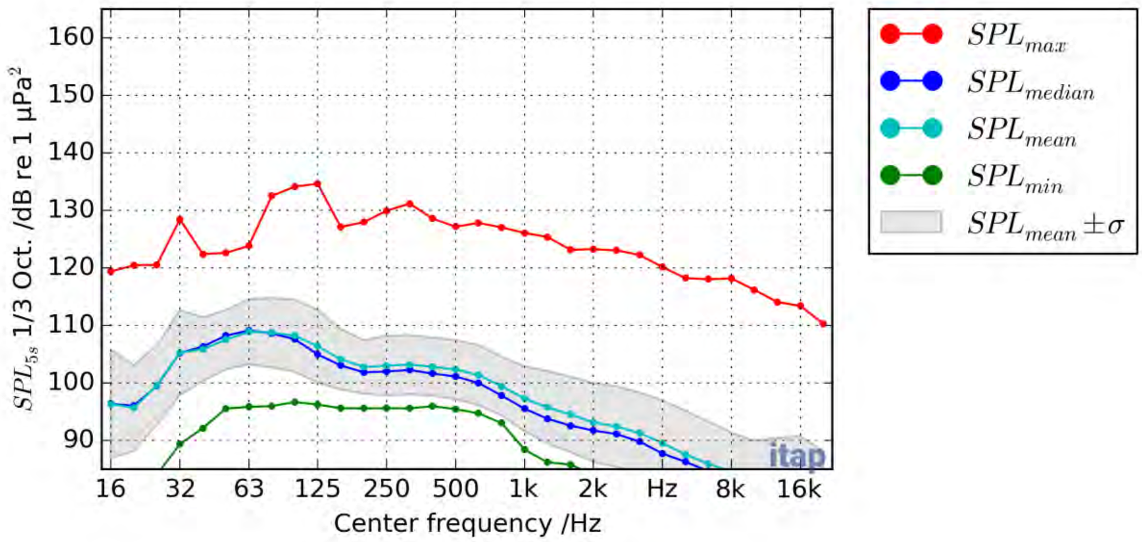



160
150
140
130
120
110
100
90
SPL_{5s} 1/3 Oct. /dB re 1 µPa²
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center frequency /Hz
SPL_{max}
SPL_{median}
SPL_{mean}
SPL_{min}
$SPL_{mean} \pm \sigma$
itap

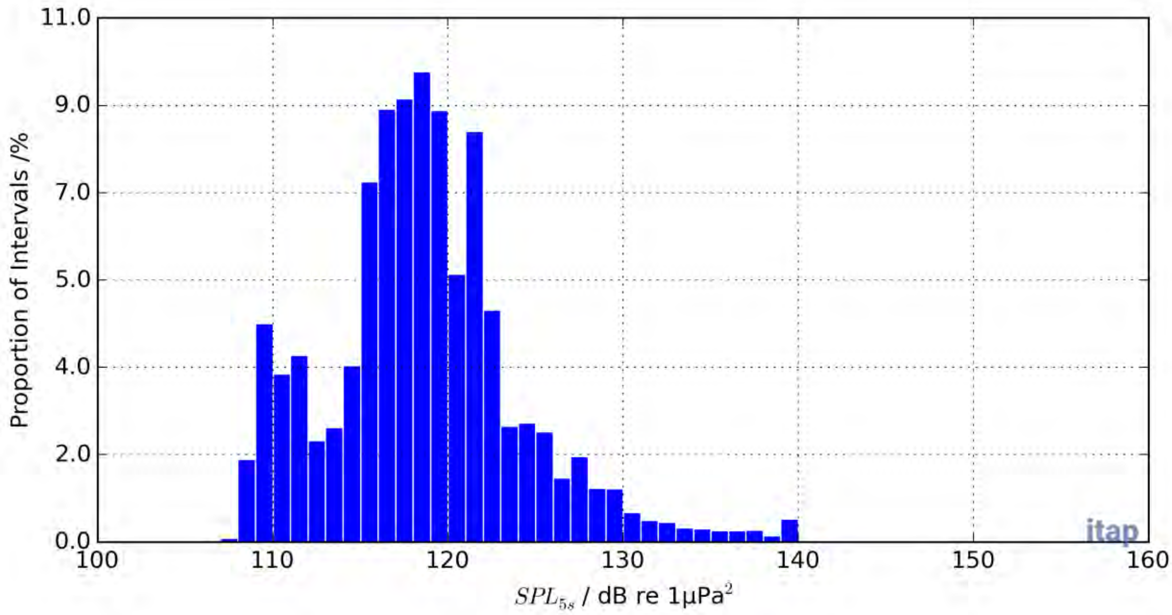

8.0
7.0
6.0
5.0
4.0
4.0
3.0
2.0
1.0
0.0
Proportion of Intervals /%
100
110
120
130
140
150
160
SPL_{5s} / dB re 1µPa²
itap

OHVS1 MP3, 2 m ambient noise



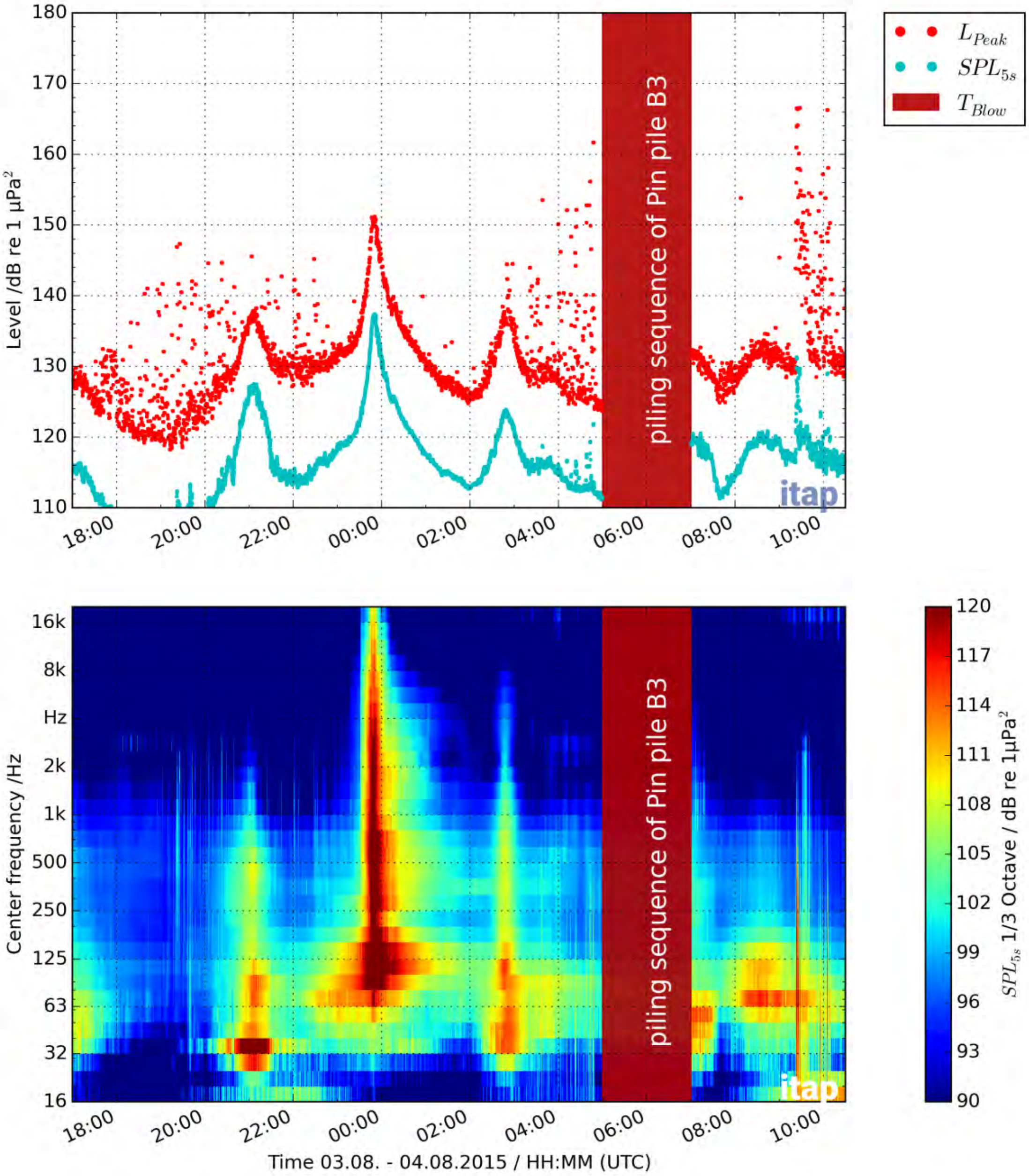


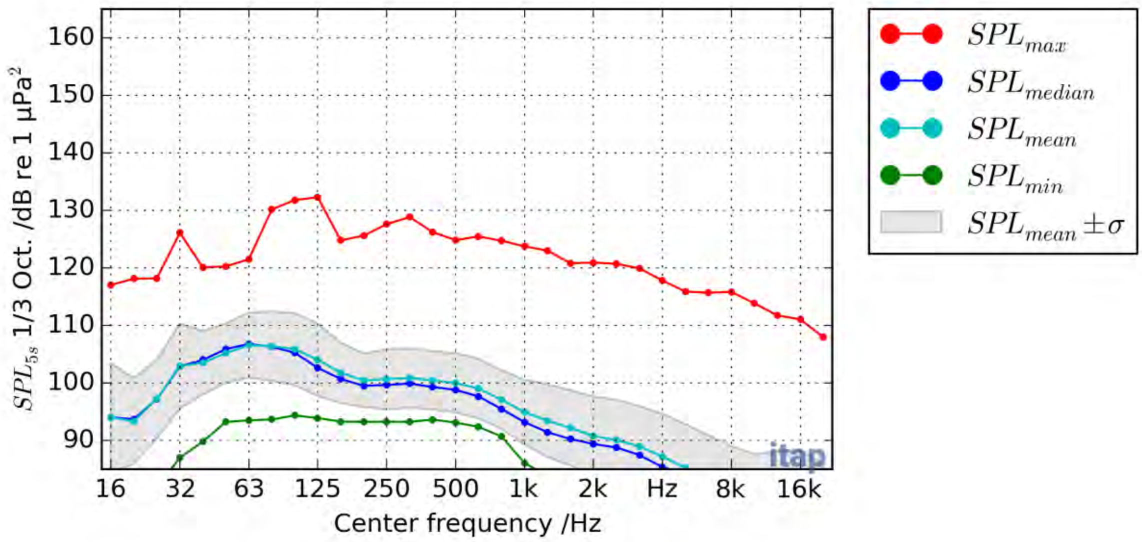
160
150
140
130
120
110
100
90
SPL_{5s} 1/3 Oct. /dB re 1 µPa²
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center frequency /Hz
itap
SPL_{max}
SPL_{median}
SPL_{mean}
SPL_{min}
$SPL_{mean} \pm \sigma$

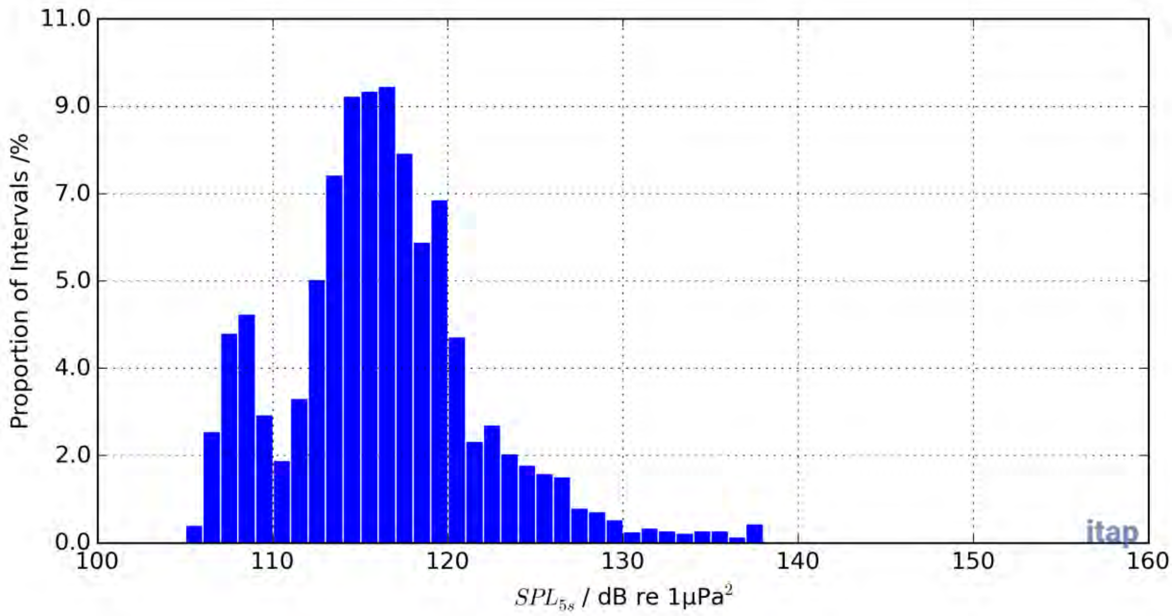


11.0
9.0
7.0
5.0
4.0
2.0
0.0
Proportion of Intervals /%
100
110
120
130
140
150
160
SPL_{5s} / dB re 1µPa²
itap

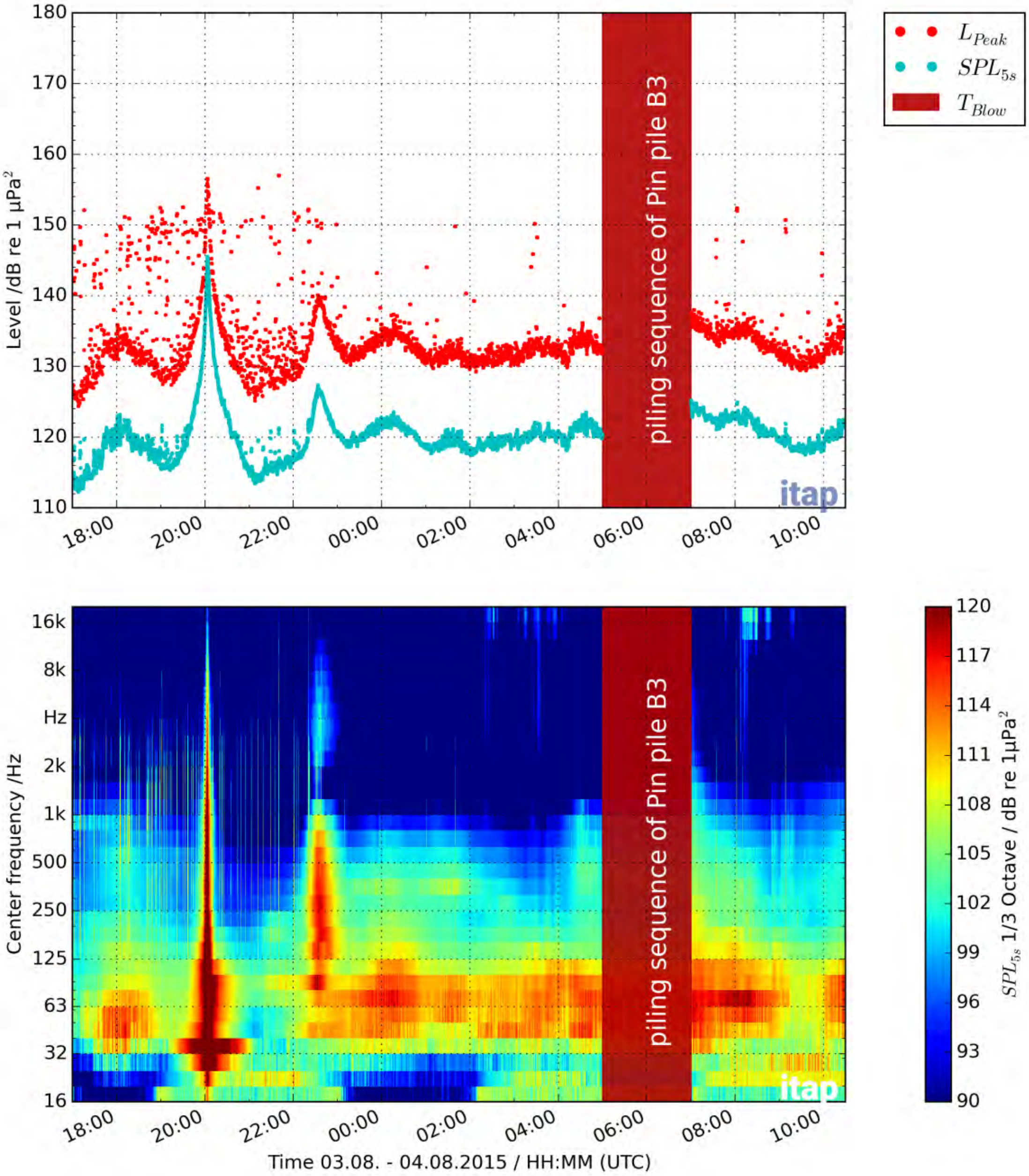
OHVS1 MP3, 10 m ambient noise

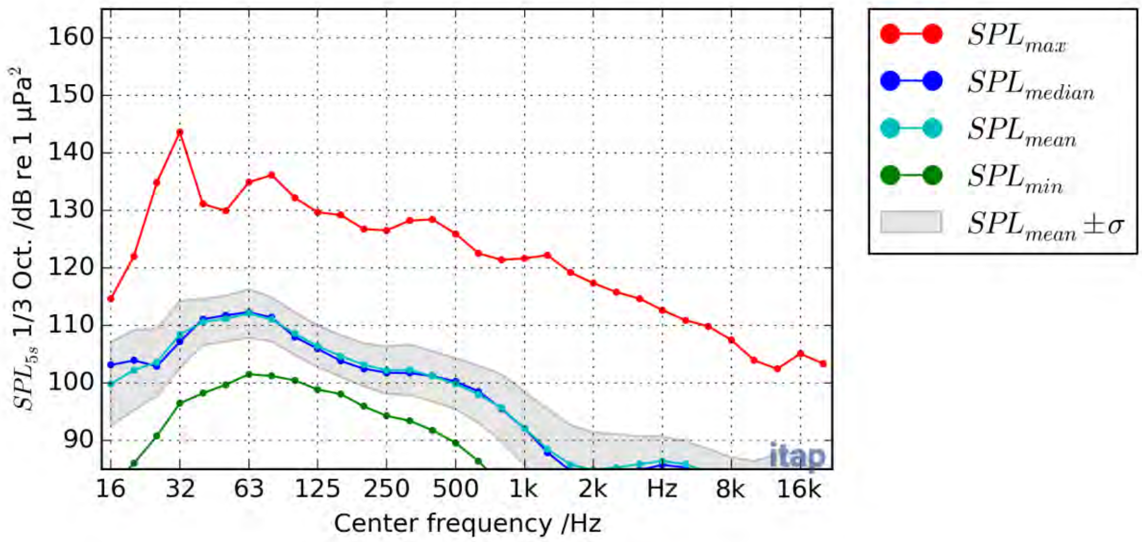


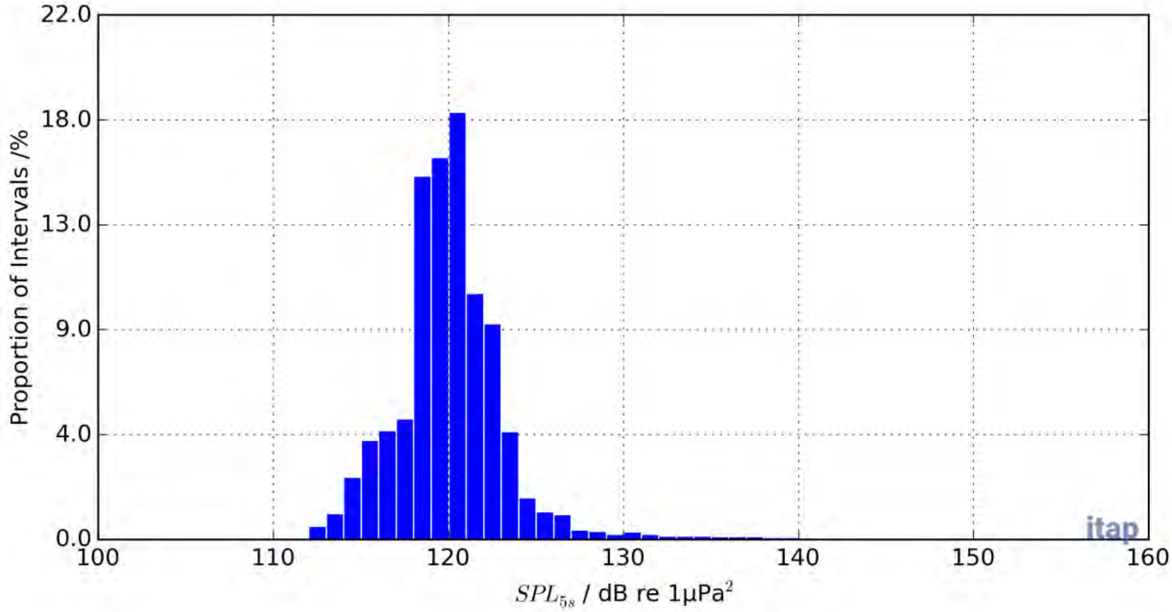

160
150
140
130
120
110
100
90
SPL_{5s} 1/3 Oct. /dB re 1 µPa^2
16
32
63
125
250
500
1k
2k
Hz
8k
16k
Center frequency /Hz
itap
SPL_{max}
SPL_{median}
SPL_{mean}
SPL_{min}
$SPL_{mean} \pm \sigma$


11.0
9.0
7.0
5.0
4.0
2.0
0.0
Proportion of Intervals /%
100
110
120
130
140
150
160
SPL_{5s} / dB re 1µPa^2
itap

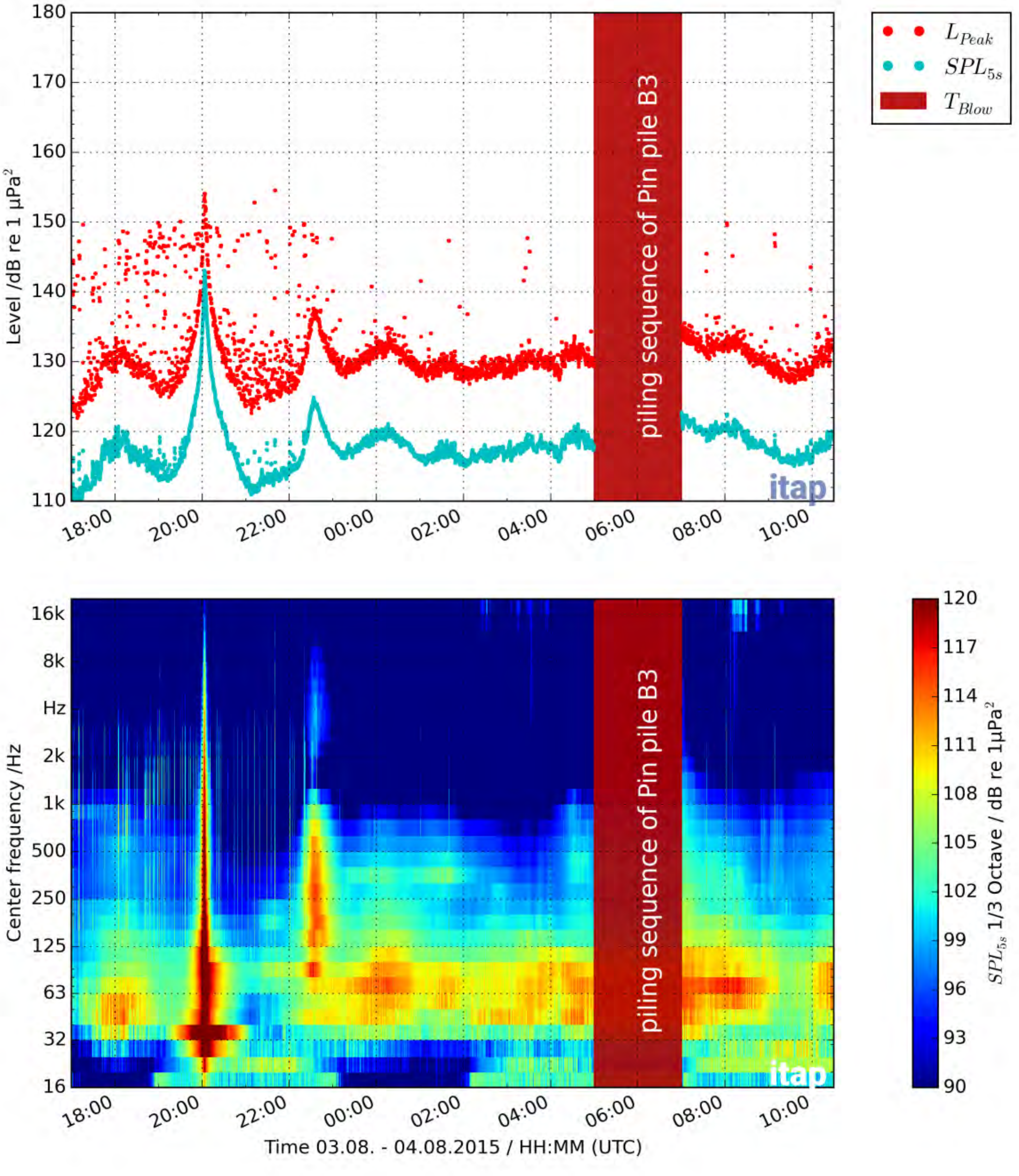
OHVS1 MP4, 2 m ambient noise

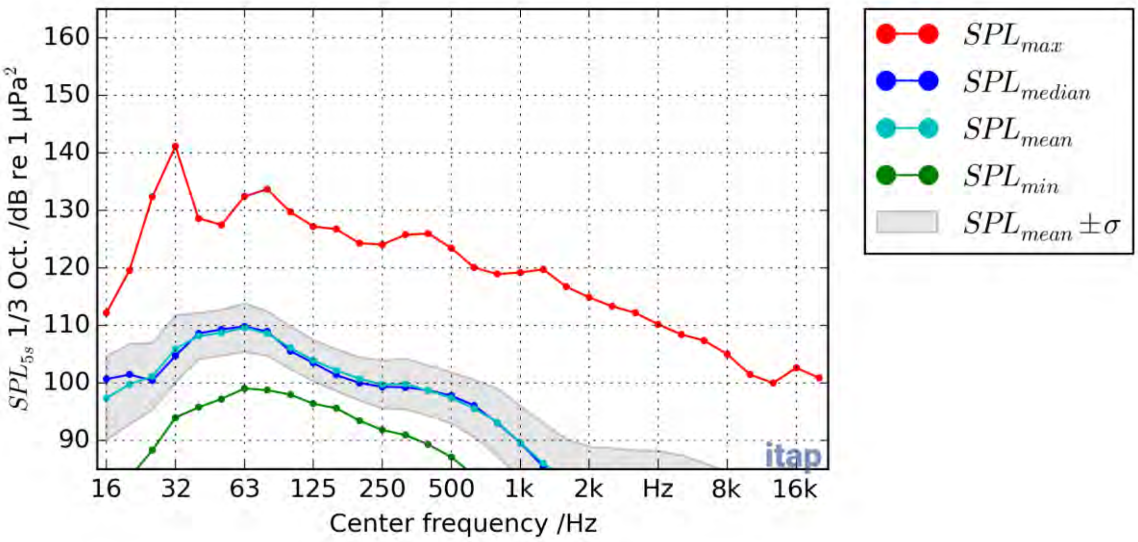



160
150
140
130
120
110
100
90
SPL_{5s} 1/3 Oct. /dB re 1 µPa²
16 32 63 125 250 500 1k 2k Hz 8k 16k
Center frequency /Hz
SPL_{max}
SPL_{median}
SPL_{mean}
SPL_{min}
$SPL_{mean} \pm \sigma$
itap

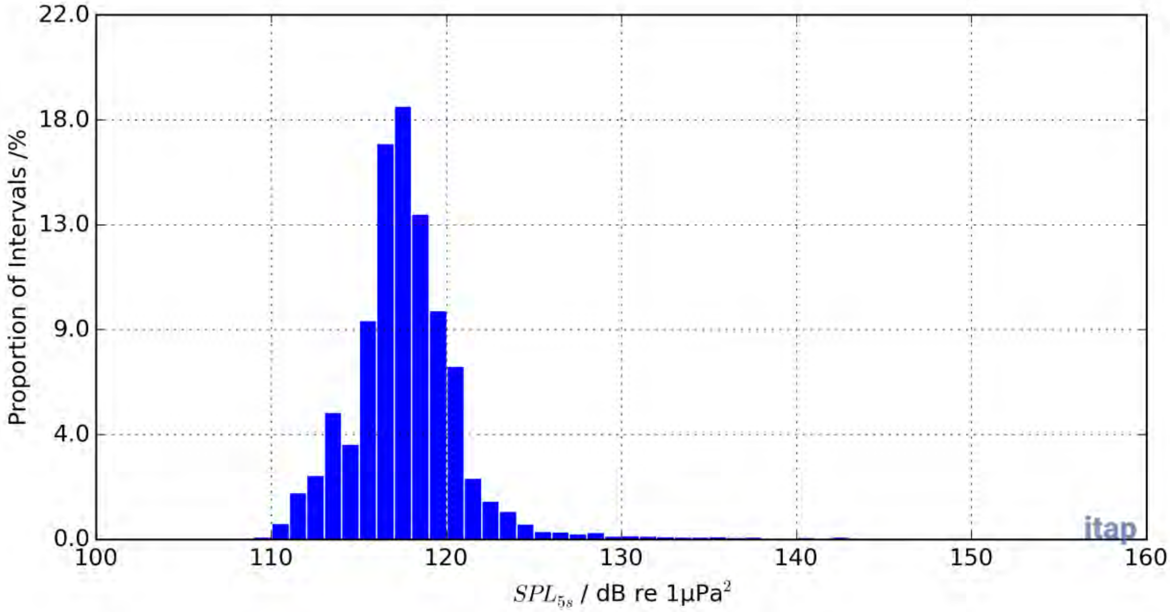

22.0
18.0
13.0
9.0
4.0
0.0
Proportion of Intervals /%
100 110 120 130 140 150 160
SPL_{5s} / dB re 1µPa²
itap

OHVS1 MP4, 10 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
itap
SPL_{max}
SPL_{median}
SPL_{mean}
SPL_{min}
$SPL_{mean} \pm \sigma$



Proportion of Intervals /%
22.0
18.0
13.0
9.0
4.0
0.0
100
110
120
130
140
150
160
SPL_{5s} / dB re 1µPa^2
itap

Annex 2: Measurement Devices

Pile	Task	Pos.	Device	Hydrophone			Calibration	
				Height	Type	Serial no.	File	Amplitude
U8	Ambient	MP1	1558	2	TC4033	4711065	CalSig1	100 pC
				10	TC4033	0415020	CalSig2	100 pC
		MP2	1537	2	TC4033	2513008	CalSig1	100 pC
				10	TC4033	0415023	CalSig2	100 pC
		MP3	1539	2	B&K 8106	2799792	CalSig1	100 mV
				10	B&K 8106	2799806	CalSig2	100 mV
		MP4	1541	2	B&K 8106	2799805	CalSig1	100 mV
				10	B&K 8106	2931741	CalSig2	100 mV
	Pile driving	MP1	1557	2	TC4033	1912036	CalSig1	100 pC
				10	TC4033	3912005	CalSig2	100 pC
		MP2	1536	2	TC4033	3105092	CalSig1	100 pC
				10	TC4033	1912062	CalSig2	100 pC
		MP3	1538	2	TC4033	2213060	CalSig1	100 pC
				10	TC4033	2513016	CalSig2	100 pC
		MP4	1540	2	TC4033	1611310	CalSig1	100 pC
				10	TC4033	0415024	CalSig2	100 pC
Z2	Ambient	MP1	1548	2	TC4033	4711065	CalSig1	100 pC
				10	TC4033	0415020	CalSig2	100 pC
		MP2	1537	2	TC4033	2513008	CalSig1	100 pC
				10	TC4033	0415023	CalSig2	100 pC
		MP3	1539	2	B&K 8106	2799792	CalSig1	100 mV
				10	B&K 8106	2799806	CalSig2	100 mV
		MP4	1541	2	B&K 8106	2799805	CalSig1	100 mV
				10	B&K 8106	2931741	CalSig2	100 mV
	Pile driving	MP1	1547	2	TC4033	1912063	CalSig1	100 pC
				10	TC4033	3912005	CalSig2	100 pC
		MP2	1536	2	TC4033	3105092	CalSig1	100 pC
				10	TC4033	1912062	CalSig2	100 pC
		MP3	1538	2	TC4033	2213060	CalSig1	100 pC
				10	TC4033	2513016	CalSig2	100 pC
		MP4	1540	2	TC4033	1611310	CalSig1	100 pC
				10	TC4033	0415024	CalSig2	100 pC
OHVS1	Ambient	MP1	1550	2	TC4033	4711065	CalSig1	100 pC
				10	TC4033	0415020	CalSig2	100 pC
		MP2	1551	2	TC4033	2513008	CalSig1	100 pC
				10	TC4033	0415023	CalSig2	100 pC
		MP3	1554	2	B&K 8106	2799792	CalSig1	100 mV
				10	B&K 8106	2799806	CalSig2	100 mV
		MP4	1556	2	B&K 8106	2799805	CalSig1	100 mV
				10	B&K 8106	2931741	CalSig2	100 mV
	Pile driving	MP1	1549	2	TC4033	1912036	CalSig1	100 pC
				10	TC4033	3912005	CalSig2	100 pC
		MP2	1552	2	TC4033	3105092	CalSig1	100 pC
				10	TC4033	1912062	CalSig2	100 pC
		MP3	1553	2	TC4033	2213060	CalSig1	100 pC
				10	TC4033	2513016	CalSig2	100 pC
		MP4	1555	2	TC4033	1611310	CalSig1	100 pC
				10	TC4033	0415024	CalSig2	100 pC

Additional Measurements

Pile	Pos.	Task	Device	Hydrophone			Calibration	
				Height	Type	Serial no.	File	Amplitude
Z7	MP1 54° 00.785′ N 006° 00.766′ E	Ambient	1529	2	TC4033	4711065	AR001	100 pC
				10	TC4033	0415020	AR003	100 pC
		Pile driving	1528	2	TC4033	1912063	AL001	100 pC
				10	TC4033	3912005	AL003	100 pC
Z8	MP1 54° 00.089′ N 006° 01.043′ E	Ambient	1531	2	TC4033	4711044	AE001	100 pC
				10	TC4033	4711052	AE002	100 pC
		Pile driving	1530	2	TC4033	2513028	AN001	100 pC
				10	TC4033	3912012	AN002	100 pC
OHVS1 Back up	MP2	Ambient	1535	2	TC4033	2513009	CC001	100 pC
				10	TC4033	4711050	CC003	100 pC
		Pile driving	1534	2	TC4033	2513024	BW001	100 pC
				10	TC4033	3814024	BW004	100 pC

Annex 3: Calibration and certifications

I. All used hydrophones have a full calibration certificate from the manufacturer.

II. Before the offshore operation commences, 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 on each device for the upcoming calibration task of 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: Wind and waves

The figures in this appendix present the wind and sea conditions during the period from 18-7-2015 to 5-8-2015. The timing of the piling of the three piles U8, Z2 and OHVS-B3 is indicated in each figure.

All data, except the wind speed, are measured by a wave buoy, equipped with an ADCP (Acoustic Doppler current profiler). The position of the wave buoy was 54° 02.42′ N and 06° 53.14′ E (WGS84).

The wind speed at the site was not continuously measured. The presented data of the wind speed at 10 m height is the (running) predicted 3 hours-ahead location forecast for the wind farm site, as produced by MeteoGroup.

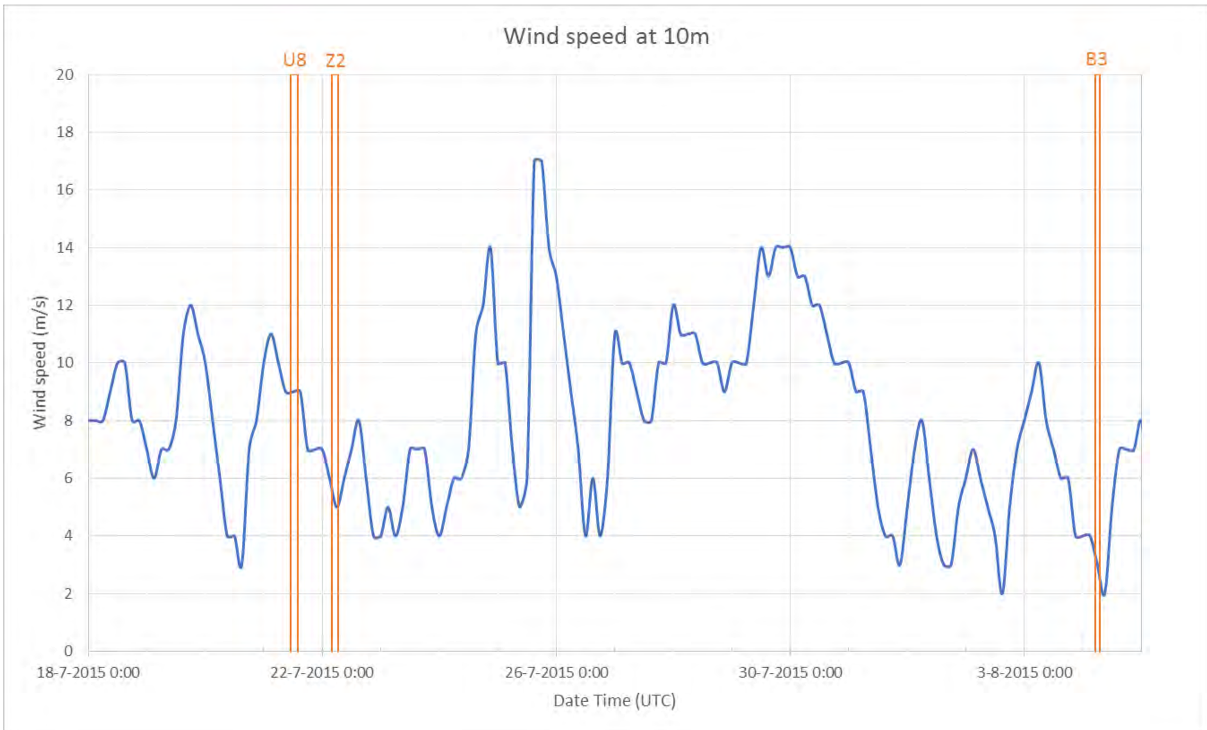


Figure 19: The approximate wind speed at 10 m above sea level (meteo model prediction).

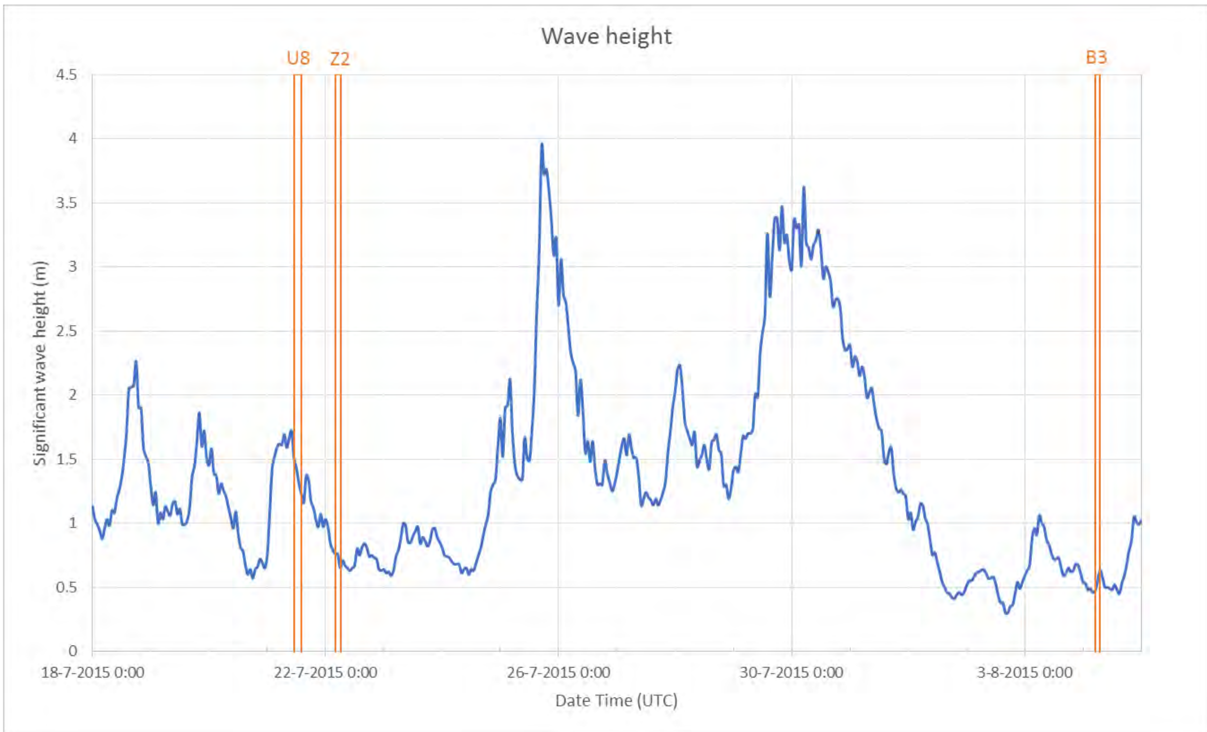


Figure 20: Significant wave height (measured).

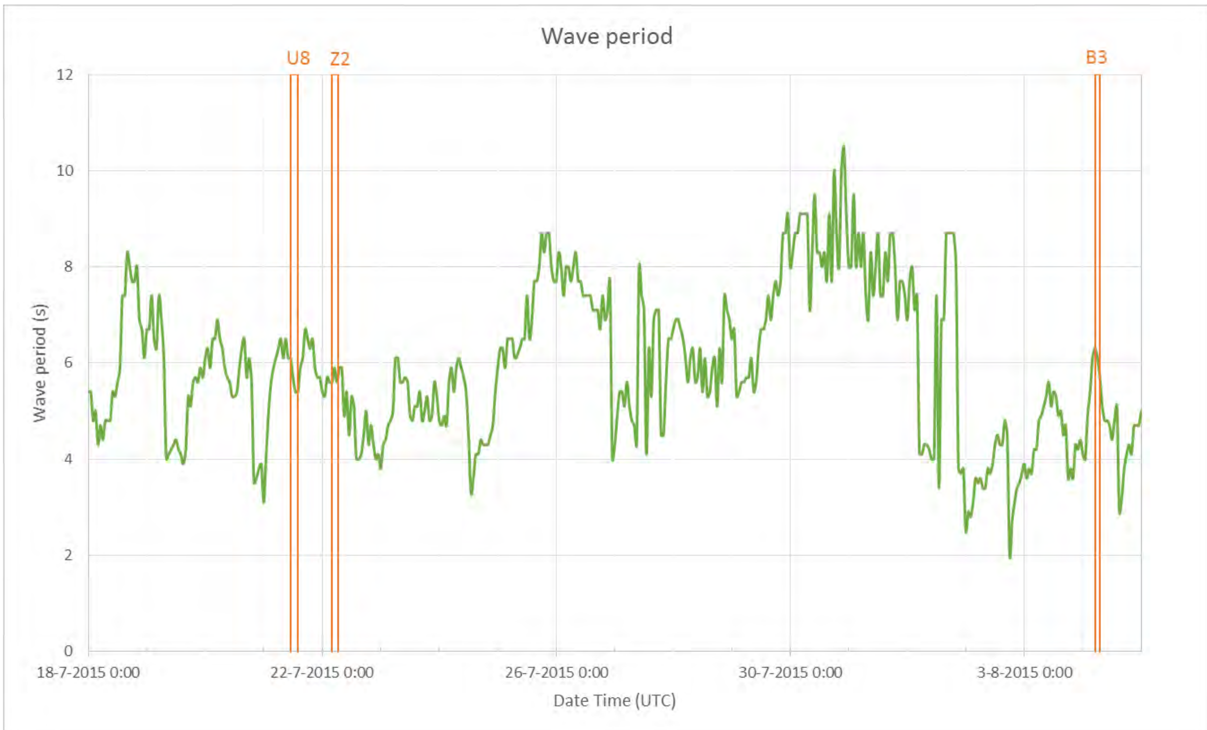


Figure 21: Wave period (measured)

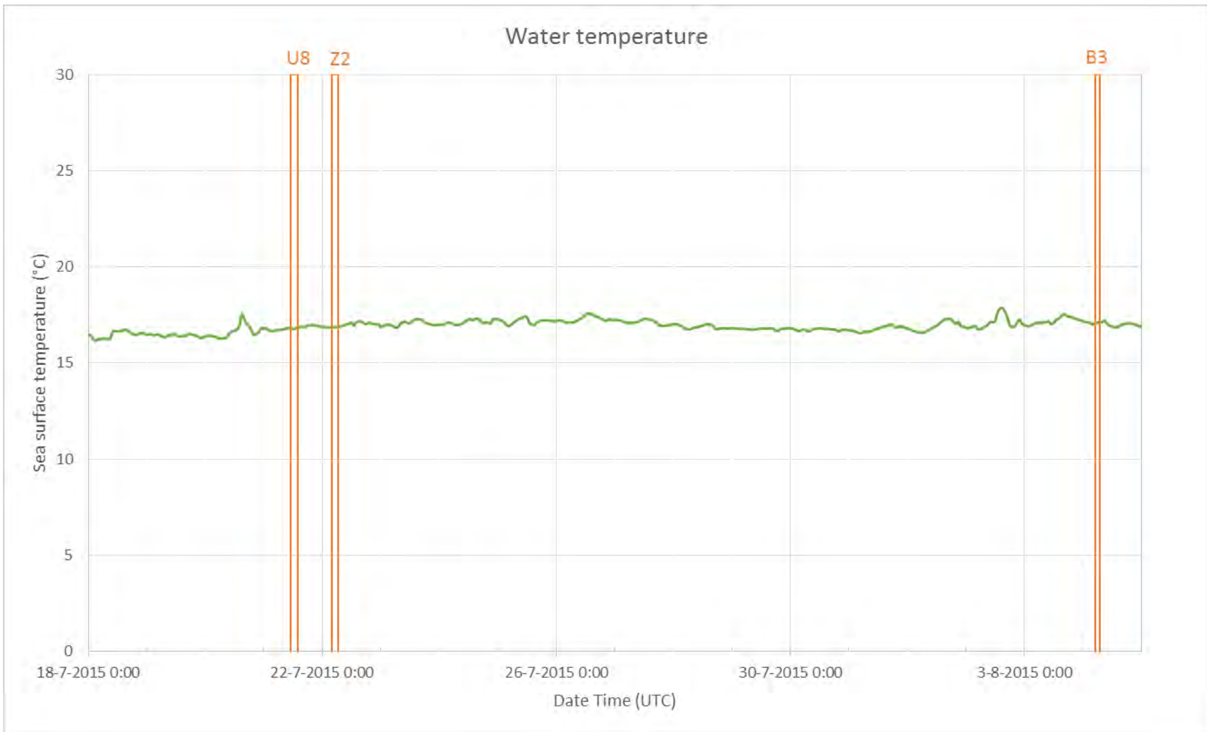


Figure 22: Sea surface water temperature (measured).

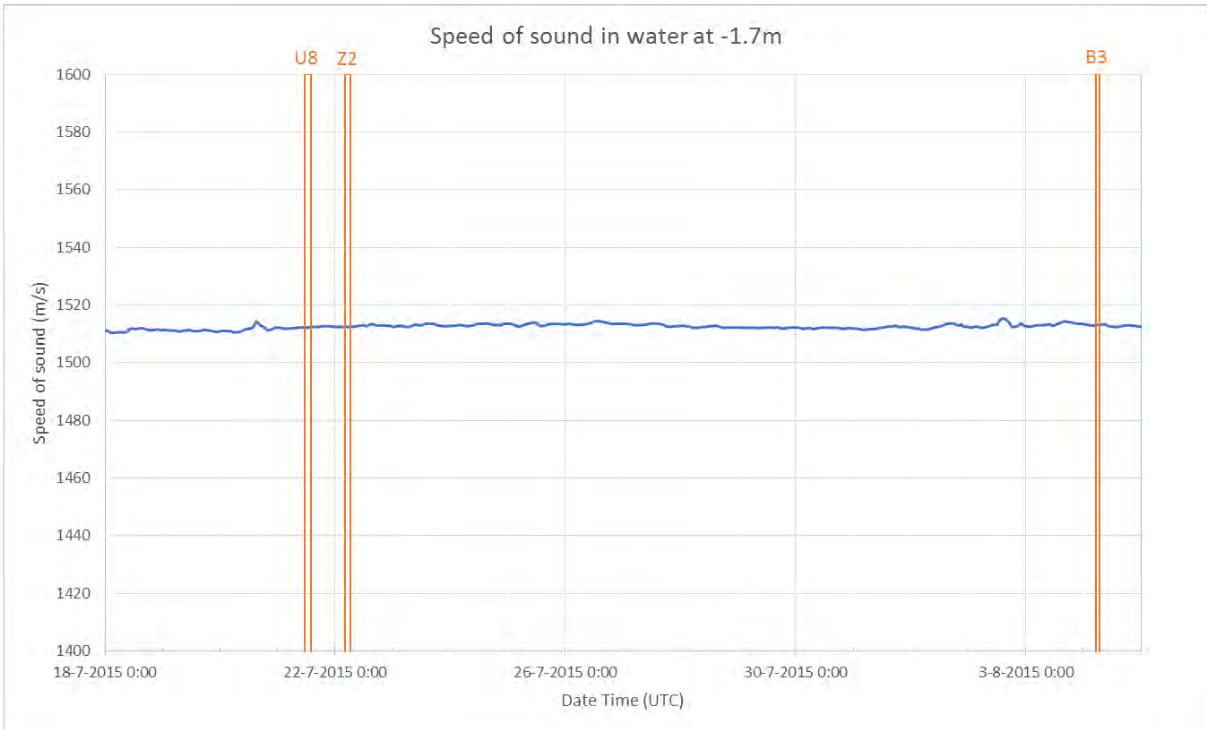


Figure 23: Speed of sound in water at a depth of 1.7 m (measured).

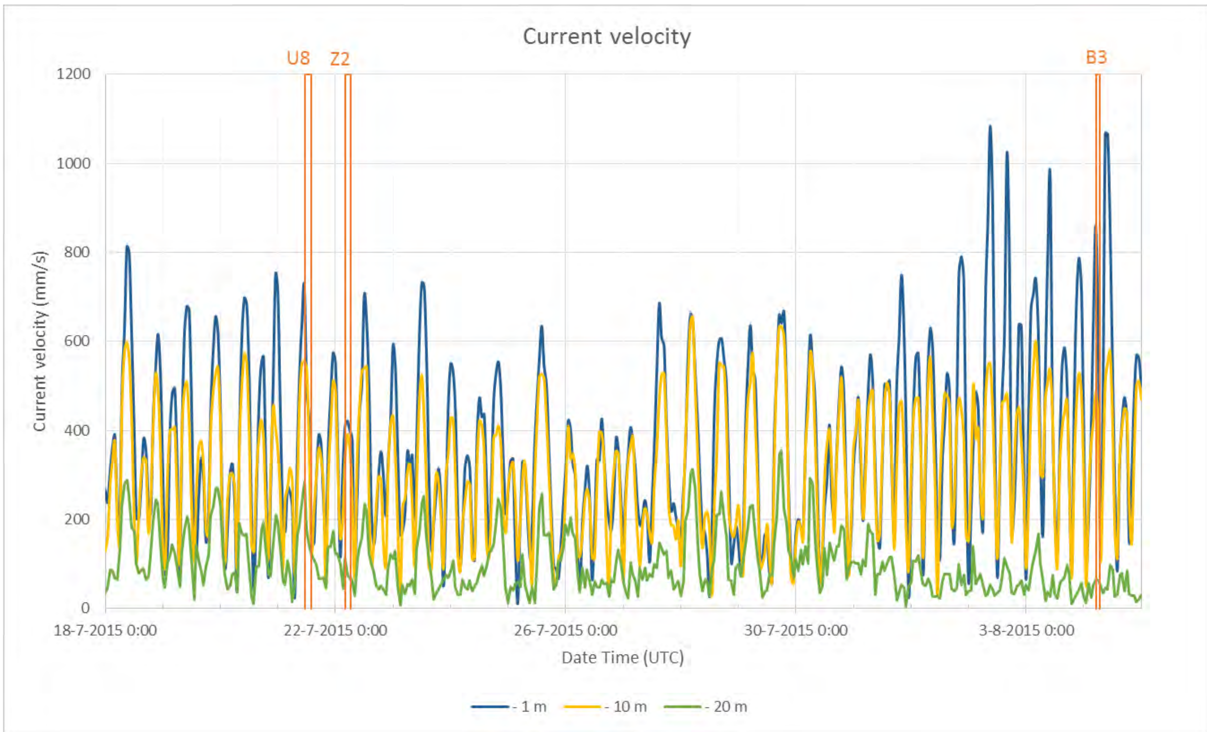


Figure 24: The current velocity at three different depths (measured).

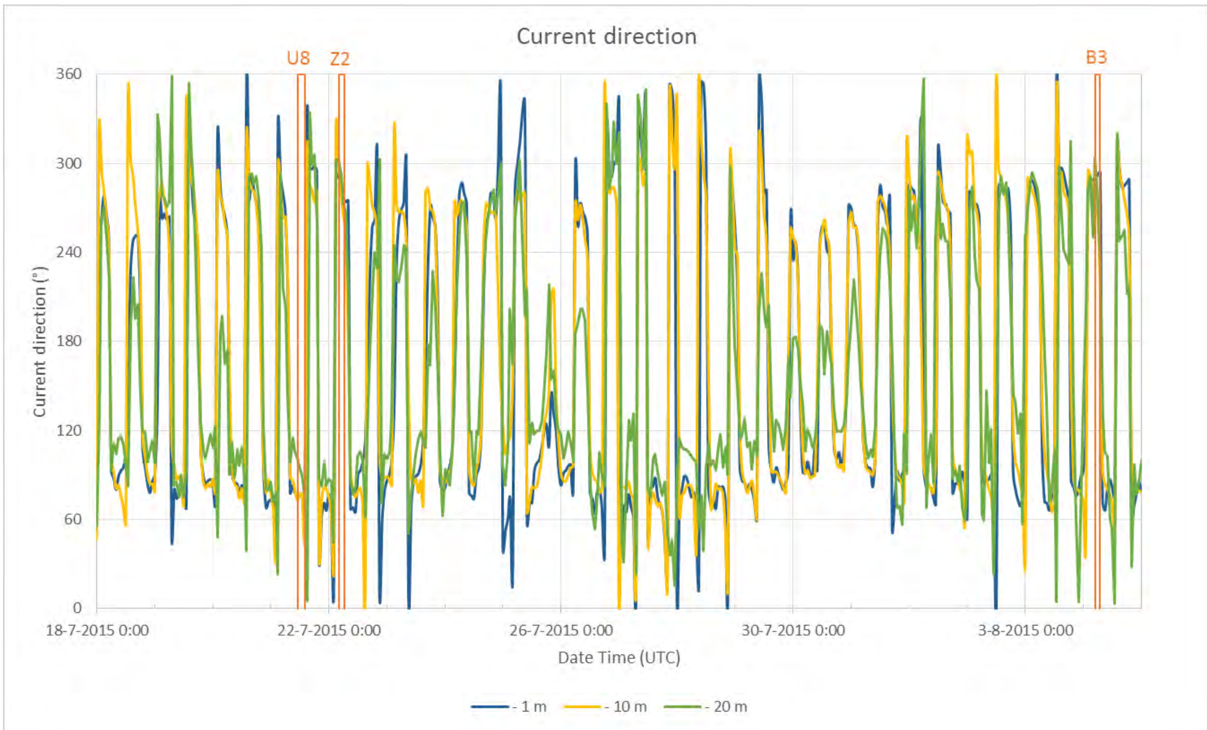


Figure 25: The current direction at three different depths (measured).