Report on results of uncertainty assessment

Final Version of 10/03/2021

Deliverable Number D.3.6.3.

Project Acronym	SOUNDSCAPE
Project ID Number	10043643
Project Title	Soundscapes in the north Adriatic Sea and their impact on marine biological resources
Priority Axis	3
Specific Objective	3.2
Work Package Number	3
Work Package Title	Soundscape assessment
Activity Number	3.6
Activity Title	Processing of data input for modelling and uncertainty analysis
Partner in Charge	IOF
Partners Involved	CNR, BWI, ARPA FVG
Authors	Predrag Vukadin (IOF)
Status	Final
Distribution	Public
Citation	Vukadin P., Report on results of uncertainty assessment. SOUNDSCAPE project, WP3, 17 pp, 2021.

Summary

1 Abstract

The gained knowledge and knowledge gaps on the uncertainty of continuous underwater sound levels measurement and processing are critically assessed and documented. The uncertainty budget is set and estimated overall uncertainty assessed.

2 Methodology of the continuous underwater sound monitoring used in soundscape project

For Soundscape project the continuous underwater sound produced by anthropogenic activities such are marine traffic (both commercial and recreational) and hydrocarbon exploitation is monitored by its measurement using single channel continuous underwater sound measuring system, shown in Figure 1) The measuring system consists of a hydrophone, signal conditioning electronics, A/D convertor and data storage.

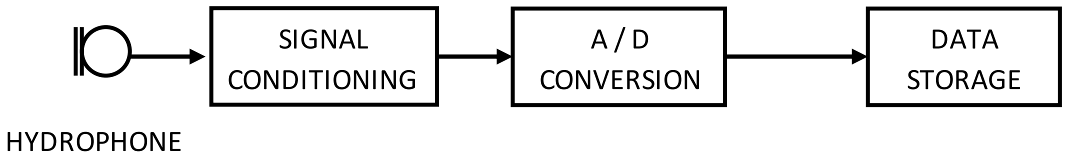


Figure 1 A single channel continuous underwater sound measuring system

Hydrophone is an electro acoustic transducer which, in case of passive (listening) systems, converts variations in the underwater pressure caused by underwater sound sources to variations in electrical voltage on its output. The output of the hydrophone is impedance matched, amplified and frequency shaped (filtered) by the signal conditioning electronics. At the high end of the spectrum the filtering is needed to avoid aliasing (low pass filtering). At the low end of the spectrum filtering is needed to avoid low frequency pressure variations not related to underwater sound but mainly to deployment related issues (high pass filtering). A/D converter converts analogue conditioned signal from hydrophone to digital form of data. Data in the digital form are then stored in the memory from which it can be downloaded to external computer for final storage and processing. Recordings are continuous e.g. system records the underwater sound throughout the entire deployment period.

The continuous underwater sound measuring system is deployed on the sea bottom (bottom mounted). All system parts except the hydrophone are placed into the waterproof pressure resistant housing (container) to ensure their functionality under the water. The hydrophone is packed separately but close to the container to which it is elastically connected with a short cable, as can be seen from the Figures 2 and 8. The sound coming to the hydrophone from the water column is subjected to all physical phenomena of the sound propagation in the sea environment. Its spatial position (especially to the reflecting surfaces such are sea surface, bottom, system container and other parts of the deployment rig) can affect the received sound level.

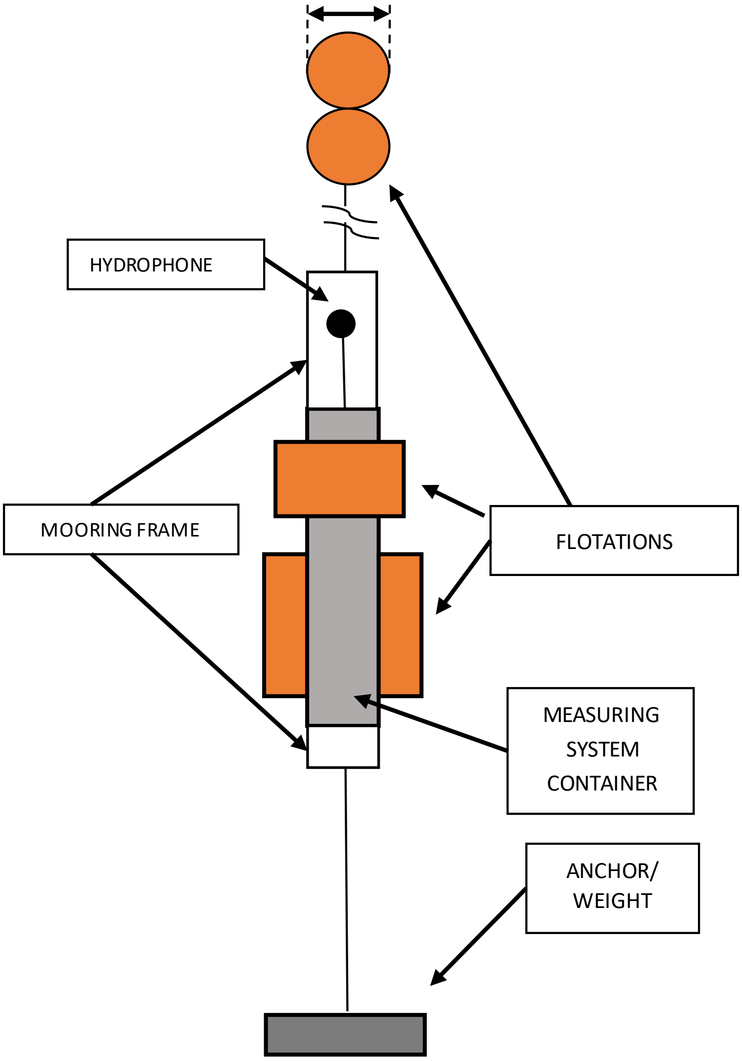


Figure 2 Simplified view of the bottom mounted continuous underwater sound measuring system

3 Introduction on measurement uncertainty in continuous underwater sound measurements

When reporting the result of a measurement of a physical quantity such are sound levels, it is very important that some quantitative indication of the quality of the result be given so that those who use it can assess its reliability. Without such an indication, measurement results are hard to compare. The concept of *uncertainty* as a quantifiable attribute is relatively new in the history of measurement but a worldwide consensus on the evaluation and expression of uncertainty in measurement permits the significance of a vast spectrum of measurement results to be readily understood and properly interpreted.

In general, the concept of *accuracy* is also used to describe how sure we are of the measurement results.

Accuracy of measurement is the older concept, and its internationally agreed definition is "*... the closeness of the agreement between the result of a measurement and a* **true value** of the measurand". The definition adds: "... accuracy is a qualitative concept", so it is often expressed as high or low, but not with numbers.

This concept breaks down in the underwater sound measurements because it inherently assumes that a true value can be defined, known and realised perfectly, which is not the case. As a result, underwater sound levels which are measured are neither known nor defined.

Uncertainty of measurement concept acknowledges that no measurements can be perfect and is defined as a "... ***parameter, associated with the result of a measurement, that characterises the dispersion of values that could reasonably be attributed to the measurand"***. It is typically expressed as a range of values in which the value is estimated to lie within a given statistical confidence. It does not attempt to define or rely on one unique true value.

The "bible" of measurement uncertainty is the document **JCGM 100:2008** – Evaluation of measurement data **– Guide to the expression of uncertainty in measurement** (ISO/IEC Guide 98-3)[1]. Another document Evaluation of the Uncertainty of Measurement in Calibration; Europian Acreditation (EA-4/02 M: 2013)[2] offering numerous usefull uncertainty examples, was extensively used.

The result of any quantitative measurement has two essential components:

- A numerical value that gives the best estimate of the quantity being measured (the measurand). This estimate may well be a single measurement or the mean value of a series of measurements.
- A measure of the uncertainty associated with this estimated value.

An example of the result of underwater sound level measurement is:

SPL = X dB ± Y dB at confidence level Z (%).

The concept of *uncertainty* is an attempt to quantify measurement accuracy without knowledge of the true value. An uncertainty provides bounds around the measured value within which it is believed that the true value lies, with a specified level of confidence. However, it is only possible to state the probability that the value lies within a given interval.

The uncertainty of the result of a measurement generally consists of several components. The components are regarded as random variables and may be grouped into two categories according to the method used to estimate their numerical values:

Type A, which is the method of evaluation of uncertainty by the statistical analysis of series of observations, and

Type B is a method of evaluation of uncertainty by means other than the statistical analysis of a series of observations. These may include:

- Information associated with an authoritative published numerical quantity
- Information associated with the numerical quantity of a certified reference material
- Data obtained from a calibration certificate

- Information obtained from limits deduced through personal experience
- Scientific judgment.

The type A uncertainty (precision) corresponds to the previous classification of *random* uncertainty or *repeatability* and may be assessed by making repeated measurements of a quantity and examining the statistical spread in the results. Thus, type A uncertainty is a measure of the precision in the measurement; high precision is obtained if the measurements are repeatable with little dispersion in the results.

The type B uncertainty (bias) corresponds to the previous classification of *systematic* uncertainty and represents the potential for systematic bias in measurement. This category of uncertainty cannot be assessed using repeated measurements and must be evaluated by consideration of the potential influencing factors on the measurement accuracy.

Any detailed report of the uncertainty should consist of a complete list of the components, specifying each method used to obtain its numerical value.

The combined uncertainty should be characterized by the numerical value obtained by applying the usual method for combining variances. The combined uncertainty and its components should be expressed in the form of “standard deviations”.

In practice, there are many possible sources of uncertainty in a measurement, including:

- incomplete definition of the measurand
- imperfect realization of the definition of the measurand
- nonrepresentative sampling — the sample measured may not represent the defined measurand
- inadequate knowledge of the effects of environmental conditions on the measurement or imperfect measurement of environmental conditions
- personal bias in reading analogue instruments
- finite instrument resolution or discrimination threshold
- inexact values of measurement standards and reference materials
- inexact values of constants and other parameters obtained from external sources and used in the data-reduction algorithm
- approximations and assumptions incorporated in the measurement method and procedure
- variations in repeated observations of the measurand under apparently identical conditions.

The results of the continuous underwater sound monitoring, which are assessed by the measurement, should consist of, as stated previously, numerical value, which is the estimate of the measured sound level, and the measure of the uncertainty associated with this estimated value. The uncertainty components of the continuous underwater sound measurement would be of the type B uncertainty as continuous underwater sound is a random process. Therefore, it makes no sense to repeat measurements as the source levels during the new measurement will differ from the previous ones.

For assessing measurement uncertainty, a list of all the components specifying for each method used to obtain each numerical value should be produced.

There is a significant knowledge gap in defining and quantifying the comprehensive list of uncertainty components of continuous underwater sound measurement.

According to our best knowledge, possible sources of uncertainty in measurement are proposed and include some of the following:

- Equipment calibration
- Processing of raw data recorded
- Validity of any assumptions made
- Temporal sampling of the continuous underwater sound
- Spatial position of the hydrophone
- Platform and/or deployment induced (unwanted) sound.
- Environmental parameters.

4 Analysis and the assessment of measurement uncertainty in continuous underwater sound measurements

The uncertainty of each identified possible source will be analyzed and explicitly assessed as implemented in the measurement of the continuous underwater sound levels in the Soundscape project.

4.1 Uncertainty of equipment calibration

Figure 1 shows that equipment specifications that influence the underwater sound levels measured are hydrophone sensitivity and the gain of signal conditioning electronics.

4.1.1 Uncertainty of hydrophone sensitivity calibration

The hydrophone used is Neptune Sonar D60. The calibration sheet is shown in Figure 3. The hydrophone was calibraed by using calibrated reference projector which is calibrated using free-field three-transducer reciprocity calibration, with both procedures according to IEC 60565-1:2020 international standard

The receiving sensitivity *M* in dB/V/µPa and expanded uncertainty *U* in dB are shown for frequencies from 2 to 23 kHz in 0.5 kHz steps. Expanded uncertainty is for k=2 (95% confidence level).

For lower frequencies (which are of interest), the expanded uncertainty is ± 2.4 dB, and for k=2, standard uncertainty will be ± 1.2 dB.

NEPTUNE SONAR LTD

ACOUSTIC CALIBRATION LABORATORY

CALIBRATION DATE:	3 December 2019 at 15:14	**PROJECT No.:**	6962/A
TRANSDUCER TYPE:	T437	**DESCRIPTION:**	D/60/H
SERIAL NUMBER:	41538-41547	**TEST SPECIFICATION:**	T437 10-01-02
CALIBRATED BY:	I. Griffiths	**WATER TEMPERATURE:**	7°C (±0.5)
1kHz CAPACITANCE:	3.302 nF (±86pF)	**CABLE:**	10m
REMARKS:	Tested at end of 10m cable		

F (kHz) (±0.005%)	M(±U) (dBre1V/µPa)	Calculated S(±U) (dBre1µPa/V@1m)	U (dB)
2.000	-196.4	76.2	±2.4
2.500	-195.8	80.6	±2.2
3.000	-195.6	84.0	±2.2
3.500	-195.8	86.5	±2.2
4.000	-196.1	88.6	±2.2
4.500	-196.4	90.3	±2.2
5.000	-196.2	92.3	±2.2
5.500	-196.4	93.8	±2.2
6.000	-196.7	95.0	±2.2
6.500	-197.2	95.9	±2.2
7.000	-197.0	97.4	±2.2
7.500	-197.7	97.8	±2.2
8.000	-197.9	98.8	±2.2
8.500	-197.3	100.4	±2.2
9.000	-197.3	101.5	±2.2
9.500	-196.9	102.9	±2.2
10.000	-197.2	103.4	±2.2
11.000	-196.6	105.6	±2.2
12.000	-197.4	106.4	±2.2
13.000	-198.1	107.1	±2.2
14.000	-198.4	108.1	±2.2
15.000	-198.7	109.0	±2.2
16.000	-199.3	109.6	±2.2
17.000	-199.0	111.0	±2.0
18.000	-199.8	111.2	±1.9
19.000	-200.5	111.4	±1.9
20.000	-201.4	111.4	±1.9
21.000	-201.3	112.5	±1.9
22.000	-201.3	113.3	±1.9
23.000	-200.8	114.5	±1.9

Figure 3 The calibration sheet of Neptune Sonar D60 hydrophone

4.1.2. *Uncertainty of gain calibration*

Each SonoVault recorder was individually calibrated for self noise level and gain. The example of the test protocol is shown in Figure 4. The values in the table are signal levels below maximum (in dB) for the calibration signal level on 1031 Hz frequency. The calibration data are for 16-bit sampling, which was used throughout the Soundscape project.

Sono.Vault Electronic Test Protocol

develogic subsea systems

Serial Number:	1350	1319	1371
Revision:	**Interface**	**Analog Frontend**	**SDHC_0-4**
Hardware:	4.2	4.2	1.5
Software MSP:	4.13e	V4.13a	V4.13a
In-Circuit Voltages :			
3,5 V LDO (3V8_LDO):	3,50		
3,5 V LDO Sense(U_3V8_LDO_Sense):	1,40		
3,3 V MSP SVI (3V3_SVI):	3,30		
3,5 V DCDC (DCDC_C_OUT):	n/a		
3,3V Ethernet Sense (U_3V8_ETH_SENSE):	n/a		
5,5V LDO SVA (5V5_LDO):		5,28	
3,5V LDO SVA(3V8_LDO):		3,50	
5,0V Analog (5V_A)		4,99	
5,0V Analog Sense (U_Sense_5V_Analog)		1,60	
3,3V Analog (3V_A)		3,30	
3,3V Analog Sense (U_Sense_3V3_Analog)		1,32	
5,0V Generator (5V_Gen)		n/a	
5,0V Generartor Sense (U_Sense_5V_Gen)		n/a	
Operating Voltage (V):	25,2		
Standby Current (mA)	2,21		
Operating Current (mA)	8,55 (96kS/s - 16bit)		
Hardware Components:			
Interface			
SD-Card:	OK		
FRAM:	0x40000		
Precision Clock Calibration:	39602		
Real-Time Clock:	UTC		
RS232 Port1:	OK		
RS232 Port2:	OK		

	1	2	3	4	5	6	7
SDHC_0 SD-Card write test:	OK	OK	OK	OK	OK	OK	OK
SDHC_1 SD-Card write test:	-	-	-	-	-	-	-
SDHC_2 SD-Card write test:	-	-	-	-	-	-	-
SDHC_3 SD-Card write test:	-	-	-	-	-	-	-
SDHC_4 SD-Card write test:	-	-	-	-	-	-	-

Analog Frontend Calibration

Amplification level (gain setting)	0	1	2	3	4	5	6	7
Noise Level 24bit sampler (dB) *	-75,74	-70,42	-64,50	-61,64	-58,26	-55,62	-49,55	-43,47
Noise Level 16bit sampler (dB) *	-71,28	-70,39	-66,32	-63,23	-61,22	-57,55	-51,75	-46,27
Maximum Signal Level 24bit sampler (dB) **	-53,24	-47,25	-41,19	-35,14	-29,21	-23,17	-17,08	-11,02
Maximum Signal Level 16bit sampler (dB) **	-58,07	-52,48	-46,52	-40,43	-34,70	-28,65	-22,52	-16,40

08/12/2019 Al Rel
Date/Sign

Date/Sign

* The noise level was determinated by connectiong the positive and negative the hydrophone input to ground.

** The calibration was performed with a waveform generator, sine signal with an amplitude of 5mV (10mVpp between differential inputs), f = 1031,25 Hz.

Figure 4 The example of SonoVault test protocol

According to the manufacturer's data, the signal levels in the table are within ± 0.1 dB.

Thus, standard uncertainty is $u = 0.2 / \sqrt{3} = 0.12$ dB.

As the results from all measurement stations (all SonoVault recorders) are processed in the same way, and no corrections are applied, it is also important to compare gains from the calibration sheets of all recorders and assess their uncertainty. The gain calibration of all recorders is displayed in Table 1 for all available gain settings.

	SonoVault S/N										
Gain	**1090**	**1092**	**1093**	**1095**	**1096**	**1097**	**1099**	**1101**	**1102**	**Average**	**StDev**
0	-57,98	-57,93	-58,05	-58,07	-58,12	-58,19	-58,08	-58,15	-58,05	**-58,069**	**0,076**
1	-52,34	-52,39	-52,48	-52,48	-52,54	-52,54	-52,48	-52,55	-52,43	**-52,47**	**0,068**
2	-46,4	-46,45	-46,51	-46,52	-46,58	-46,59	-46,58	-46,6	-46,47	**-46,522**	**0,067**
3	-40,32	-40,38	-40,4	-40,43	-40,49	-40,52	-40,43	-40,53	-40,39	**-40,432**	**0,066**
4	-34,54	-34,53	-34,81	-34,7	-34,74	-34,81	-34,67	-34,77	-34,67	**-34,693**	**0,098**
5	-28,48	-28,5	-28,74	-28,65	-28,69	-28,76	-28,61	-28,71	-28,59	**-28,637**	**0,095**
6	-22,38	-22,4	-22,6	-22,52	-22,55	-22,64	-22,49	-22,58	-22,46	**-22,513**	**0,084**
7	-16,29	-16,31	-16,49	-16,4	-16,45	-16,53	-16,39	-16,49	-16,36	**-16,412**	**0,079**

Table 1

In Table 2, the average signal level and standard deviation were calculated for each gain setting. The standard deviation is the greatest for gain setting four and will be, as the worst case, used in the uncertainty calculation.

If the standard deviation is s, then standard uncertainty is $u = s / \sqrt{n}$, where n is the number of signal levels observed.

Standard deviation $s = 0.098$ dB

Standard uncertainty $u = 0{,}033$ dB.

4.2 Processing uncertainty

Processing tool custom-tailored to the processing needs of the Soundscape project was developed, tested and implemented. All functions were tested against commercial or previously well-proven software tools. The first and most critical function is calculating SPL's in 1/3 octaves from raw sound pressure samples. This function was tested against well-known and proven commercial software. The one-hour recording was chosen from all nine recorders and processed with both software using the same main settings. The results in the form of standard deviations, standard and extended uncertainties of nine SPL values on the same frequency are shown in Table 2. The sample of SPL's obtained from both software (measurement site MS2 Azalea) is shown in Figure 5. As expected, the uncertainties are the greatest at low frequencies. Therefore, the lowest frequency of interest, 63 Hz, is used as the worst case, and uncertainties of the processing are assessed as:

Standard deviation *s* = 0.122 dB

Standard uncertainty *u* = 0,04 dB

Expanded uncertainty *U* = 0.081 dB and for k=2 (confidence level 95%).

f (Hz)	St.Dev (dB)	*u* (dB)	*U* (dB)
25	0,3387	0,1129	0,2258
31,5	0,2771	0,0924	0,1847
40	0,5590	0,1863	0,3726
50	0,1995	0,0665	0,1330
63	0,1217	0,0406	0,0811
80	0,0559	0,0186	0,0372
100	0,0770	0,0257	0,0514
125	0,1104	0,0368	0,0736
160	0,0470	0,0157	0,0314
200	0,0538	0,0179	0,0358
250	0,0169	0,0056	0,0113
315	0,0508	0,0169	0,0338
400	0,0406	0,0135	0,0271
500	0,0679	0,0226	0,0453
630	0,0466	0,0155	0,0311
800	0,0450	0,0150	0,0300
1000	0,0543	0,0181	0,0362
1250	0,0278	0,0093	0,0185
1600	0,0394	0,0131	0,0262
2000	0,0392	0,0131	0,0261
2500	0,0544	0,0181	0,0362
3150	0,0544	0,0181	0,0363
4000	0,0669	0,0223	0,0446
5000	0,1160	0,0387	0,0773
6300	0,1500	0,0500	0,1000
8000	0,1154	0,0385	0,0769
10000	0,1296	0,0432	0,0864
12500	0,1443	0,0481	0,0962
16000	0,1490	0,0497	0,0993
20000	0,1537	0,0512	0,1024

Table 2

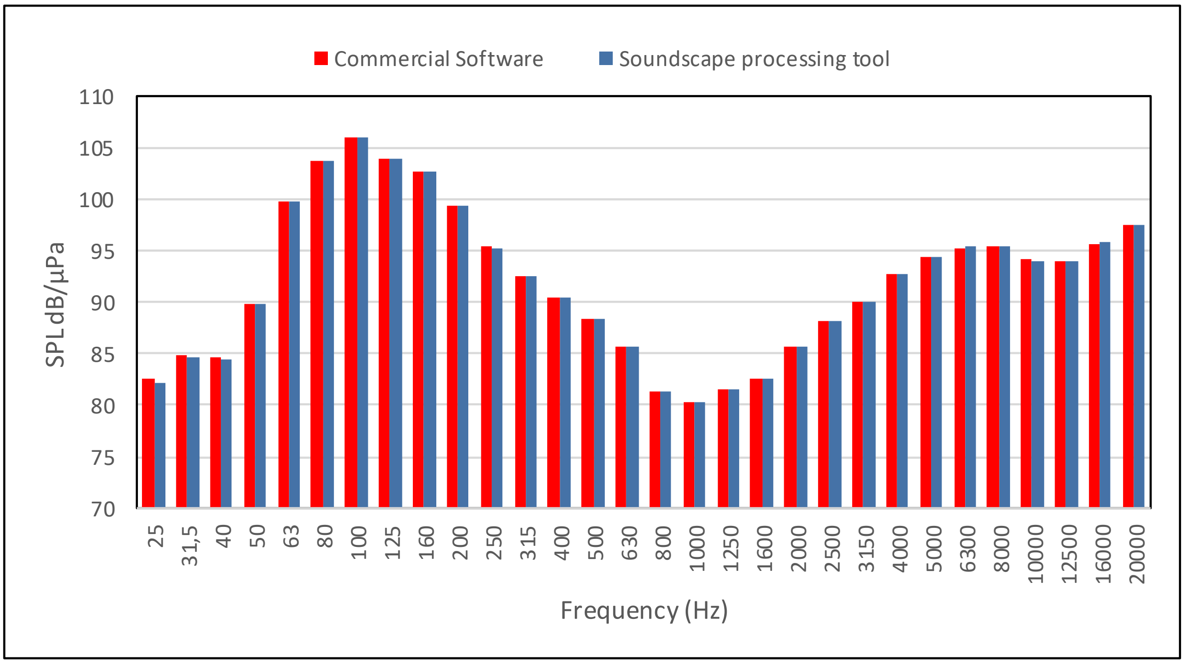


Figure 5 The sample of SPL's obtained from raw measurement data on measurement site MS2 Azalea with both processing software (commercial processing software and Soundscape processing tool)

4.3 Uncertainty in the validity of the assumptions made

4.3.1 Low-frequency hydrophone sensitivity

Hydrophone sensitivity was calibrated with the lower frequency of 2 kHz, as shown from Figure 3. Calibration below that frequency is not feasible due to the large wavelength compared to the dimensions of the calibration tank and some other physical and technical restraints. According to the theory of piezoceramic transducers, the sensitivity curve is flat in the low-frequency region, meaning that sensitivity on the lowest frequencies of interest (63 Hz, 125 Hz) is assumed the same as on the 2 kHz. The "flatness" of the sensitivity curve in the very low-frequency region is assessed by the manufacturer to be in the limits of ± 0.5 dB.

Thus, standard uncertainty is $u = 1 / \sqrt{3} = 0.58$ dB.

4.3.2 Uncertainty due to sensitivity differences between hydrophones

The calibration sheet shown in Figure 6 is generic as hydrophones used on nine SonoVault recorders were not calibrated individually. The assumption that all hydrophones have the same sensitivity was made, and recorded data from all recorders (hydrophones) were processed without individual corrections for the processing simplicity. According to manufacturers data, the difference in hydrophone sensitivity between individual hydrophones (repeatability), in the frequency band of interest (2 – 20 kHz), is in the range of ± 1 dB.

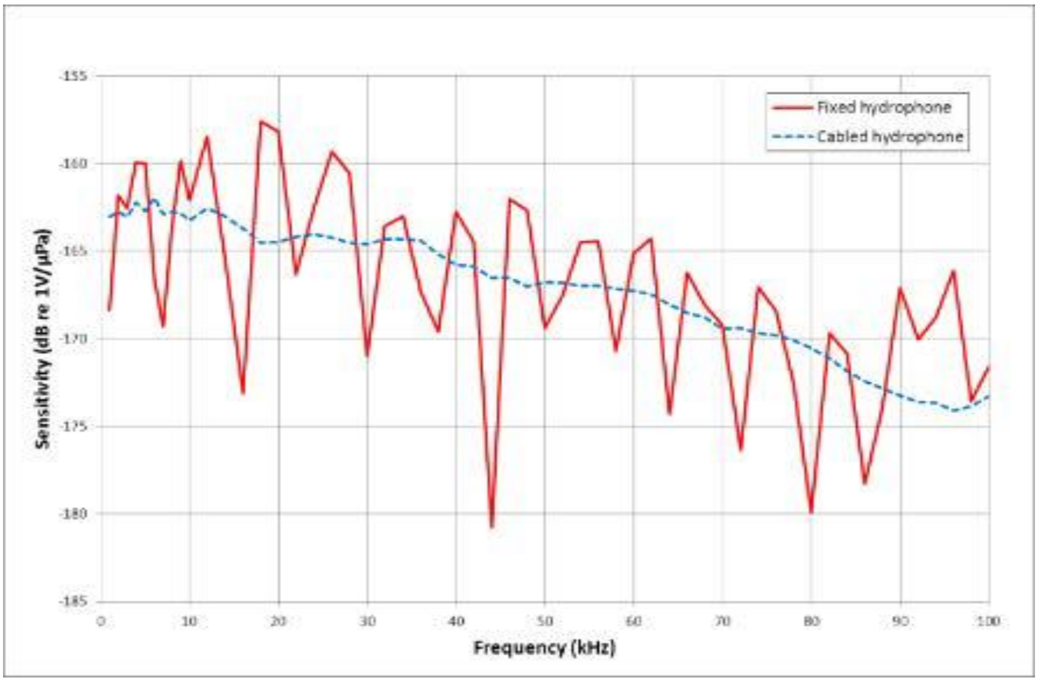
Thus, standard uncertainty is $u = 2 / \sqrt{3} = 1.16$ dB.

4.4 Uncertainty due to temporal sampling of the continuous underwater sound

Temporal sampling (on-off recording) of the continuous underwater sound was not used in the Soundscape project. Due to the increased memory and battery capacity of the SonoVault recorder used, the continuous underwater sound was recorded continuously throughout the whole deployment period of the recorder. Thus, this source was not considered as the component of the overall uncertainty.

4.5 Spatial position of the hydrophone

Depending on the measurement and/or deployment methodology, the hydrophone will be placed at different positions in the water column. All reflective surfaces in the hydrophone's environment will theoretically affect the reception of the direct sound signal. The reflected signal received by the hydrophone, together with the direct signal would produce interferences and changes in the received sound level. Also, parts of the deployment gear (e.g. flotations) or the case containing batteries and electronics can add to the diffraction or the shadowing of the sound waves also affecting the received levels. In the case of a bottom-based system where the hydrophone can be very close (2-3 m) to the eventually hard bottom, reflections from the bottom will surely have no negligible effect on the levels recorded. There are no scientific or engineering data of the possible uncertainties caused by the hydrophone position in different deployment settings, but as the illustration, Figure 6 shows the difference in sensitivity diagrams for the hydrophone close to the reflective surface (fixed) and away from it (cabled) in the case the sound incides from the direction parallel to the hydrophone.



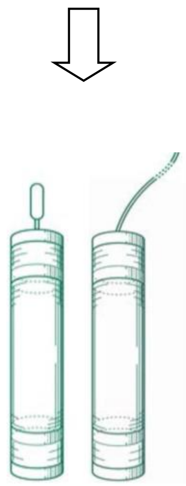
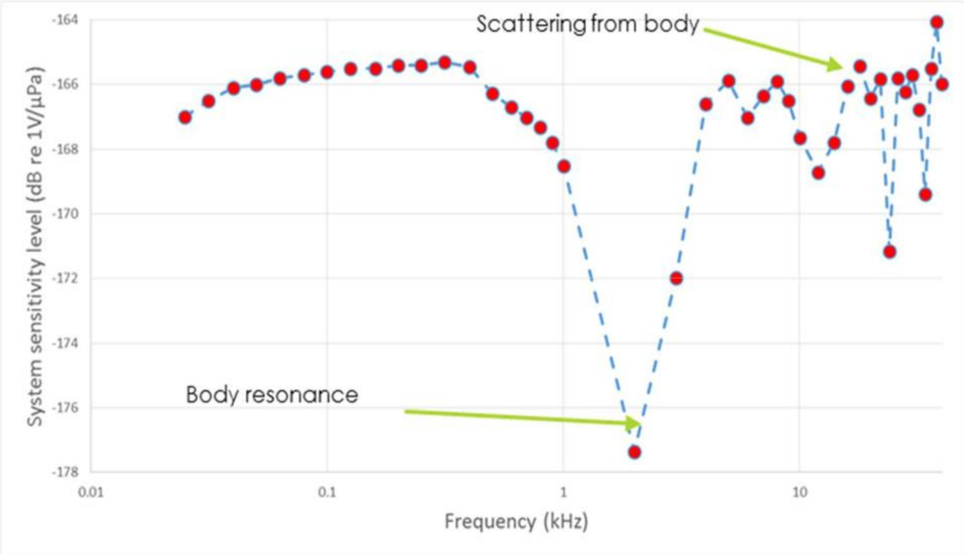


Figure 6 The difference in sensitivity diagrams for the hydrophone close to the reflective surface (fixed) and away from it (cabled)

Figure 7 illustrates the lower spectrum part that shows pronounced case resonances and scatterings for the hydrophone rigidly attached close to the recorder casing[3].



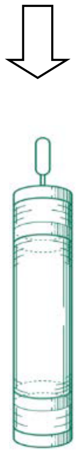


Figure 7 Lower spectrum part shows pronunced case resonances and scaterings for the hydrophone rigidly attached close to the recorder casing

The assessment of this uncertainty component is not an easy task as it is the case (deployment) as well as frequency-dependent. In the Soundscape project, hydrophone is elastically attached to the casing, avoiding case resonances (see Figure 8) but is relatively close to the casing.

Figure 8 Hydrophone elastically attached to the casing avoiding case resonances

Obviously, broadband and one-third octave measured levels will differ depending on the hydrophone placing and that this component may seriously influence the uncertainty of the measurement result.

As there are no quantified data available, this source of the uncertainty is considered as **a knowledge gap** in determining this measurement uncertainty component.

4.6 Uncertainty due to platform and/or deployment induced (unwanted) sound.

Every attempt to eliminate sources of unwanted sounds caused by platform and/or deployment gear, such are the fixtures of the anchor rope to the anchor, acoustic releaser and system container, which are usually stainless steel shackles and eyes, was made. However, although it can be considered the validity of the assumption, as none of such sounds with the levels to influence anthropogenic sound level recorded was reported, this source was not considered the component of the overall uncertainty.

4.7. Uncertainty due to environmental parameters

Environmental parameters (temperature and pressure) during the deployment were not found to differ significantly from those encountered during calibration. The hydrophone sensitivity calibrated is specified at 22°C and deployed in the sea whose temperature ranges from 14 to 25°C. The gain was calibrated at “room temperature”. The hydrophone was calibrated in a few meters’ depth, and the deepest deployment was at around 45 m. As the maximum depth of the hydrophone is 900 m, the manufacturer found no possibilities that sensitivity would change on the deployment depth, nor can provide any data on that. The signal conditioning electronics are within the container at atmospheric pressure, the same during the calibration.

For the reasons listed above, this source was not considered as the component of the overall uncertainty. Another possible source that can affect hydrophone sensitivity is biofouling. Weak or medium biofouling on hydrophone was reported in several cases, and some squid eggs laying on the container (partly on the hydrophone) was also observed. The possible effect on the hydrophone sensitivity is not known and present the knowledge gap. The hydrophone sensitivity was checked before and after each deployment with the pistonophone, but in order for that pistonophone to be put on the hydrophone, it has to be cleaned first; otherwise, mounting the pistonophone on the hydrophone is not possible. None of the partners has hydrophone calibration facilities to recalibrate the hydrophone with fouling still on, and the transport to manufacturers or any other facility would take time, and the fouling would dry and change properties. No relevant data on this issue was found in the literature. However, in the analysis of the recorded data, no sudden changes in sound pressure level were detected that could indicate a sudden decrease of the hydrophone sensitivity.
Therefore, the possible effect of biofouling on the hydrophone sensitivity and its contribution to the overall measurement uncertainty is considered as a knowledge gap.

5 The assessment of the uncertainty of the continuous underwater sound measurement and uncertainty budget

Based on the identified and assessed sources of possible uncertainties, the overall standard uncertainty (in dB) of the measurement of the continuous underwater sound pressure levels is estimated from the relationship[1]:

$$uSPL = \sqrt{(\delta^2_{HC} + \delta^2_{GC} + \delta^2_{GD} + \delta^2_{PR} + \delta^2_{ML} + \delta^2_{HD} + \delta^2_{R})},$$

where:

δ_{HC} – uncertainty of the hydrophone calibration
δ_{GC} – uncertainty of the gain calibration
δ_{GD} – uncertainty due to the difference in the gains of recorders
δ_{PR} – processing uncertainty
δ_{ML} – uncertainty due to the assumption on low frequency hydrophone sensitivity
δ_{HD} – uncertainty due to the difference between hydrophone sensitivities
δ_{R} - uncertainty due to the rounding of the SPL values

5.1 Uncertainty budget

Quantity X_i	Standard uncertainty (dB) $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution (dB) $u_i(y)$
δ_{HC}	1,2	Normal	1	1,2
δ_{GC}	0,12	Normal	1	0,12
δ_{GD}	0,033	Normal	1	0,033
δ_{PR}	0,04	Normal	1	0,04
δ_{ML}	0,58	Normal	1	0,58
δ_{HD}	1,16	Normal	1	1,16
δ_{R}	0,05	Rectangular	$(u(x_i)/\sqrt{3})$	0,03
uSPL				**1,77**

Expanded uncertainty is $U = k^* u(SPL)$ = 2*1,77 = **3,54 dB**

The reported expanded uncertainty of measurement is stated as the standard uncertainty of measurement multiplied by the coverage factor k = 2, which corresponds to a confidence level of approximately 95 % for a normal distribution.

From the uncertainty budget, it is obvious that the most significant contributions to the overall measurement uncertainty are δ_{HC} (uncertainty of the hydrophone calibration), δ_{ML} (uncertainty due to the assumption on low-frequency hydrophone sensitivity) and δ_{HD} (uncertainty due to the difference between hydrophone sensitivities). These contributions are linked to the quality of the hydrophone calibration (δ_{HC} and δ_{ML}) and the manufacturing of the hydrophone itself (δ_{HD}). This conclusion stresses how important it is to use high-quality hydrophone calibrated with a high-quality traceable calibration process in the measurement of the continuous underwater sound.

Important note: Overall uncertainty is assessed without the contribution due to the spatial position of the hydrophone. As stated before, the extent of this contribution is unknown and is considered the major knowledge gap. Also, as explained before, the effects of hydrophone spatial position in the water column and in the deployment rig are known (but not their extent in the form of any quantization), and according to that knowledge, its contribution to the overall measurement uncertainty is not expected to be a minor one.

References:

1. Evaluation of measurement data – Guide to the expression of uncertainty in measurement (ISO/IEC Guide 98-3); JCGM 100:2008

2. EA-4/02 M: 2013; Evaluation of the Uncertainty of Measurement in Calibration; Europian Acreditation

3. Crawford, N., Robinson, S. and Wang, L. (2018) Standard procedure for equipment performance, calibration and deployment. Report of the EU INTERREG Joint Monitoring Programme for Ambient Noise North Sea (Jomopans), August 2018

4. UNAC-LOW Underwater acoustic calibration standards for frequencies below 1 kHz; Final publishable report.