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Passive Acoustic Monitoring from Fixed Platform Observatories

Lead beneficiary: UPC

Lead author(s): Mike van der Schaar (mike.vanderschaar@upc.edu),

Michel André (michel.andre@upc.edu)

Contributors: Eric Delory (PLOCAN), Doug Gillespie (USTAN), Jean-Francois Rolin (IFREMER)

Work Package leader: Jean-Francois Rolin (IFREMER) - jean.francois.rolin@ifremer.fr

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SEVENTH FRAMEWORK PROGRAMME

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1 Introduction

The development of fixed platform observatories provides an excellent opportunity to measure ocean noise and to acoustically monitor for marine mammals. The addition of passive acoustic monitoring equipment to such a platform observatory contributes to its scientific output and allows the use of these platforms to implement EU directives concerning anthropogenic noise. In general, it is very expensive to deploy acoustic recorders purely for marine mammal or noise monitoring purposes. Taking advantage of existing or planned observatories greatly reduces these deployment costs. The types of platform deployments considered here are fixed or moored platforms, either installed on a cabled platform providing external power and allowing high volume data transfer to shore and complex data processing; installed on a buoy that has the capability to generate e.g. solar or wind power allowing some local processing and possibly data transfer using a radio link; or installed in a battery powered housing where there is no possibility of real-time processing.

While this document concentrates on noise and marine mammal monitoring, it should be noted that geoscientists also use acoustic monitoring equipment for geological studies and there may be possibilities of combining / sharing infrastructure costs for some types of monitoring. For example Harris et al., 2013, present a study using data from bottom seismometers to study fin whale abundance in the Eastern Atlantic.

1.1 Noise Monitoring

Noise pollution has become a subject of interest in recent years, not only in relation to high intensity anthropogenic sounds (naval sonar, pile driving, seismic survey, etc.) that can cause direct harm to ocean species (see for example Balcomb and Claridge, 2001; Evans et al., 2001; Fernandez et al., 2005), but also with respect to the continuous sounds produced by e.g. shipping traffic or drilling platforms that can mask biological signals (Clark et al., 2009). Due to an increase in these activities over the last century the ambient sound levels especially at low frequencies have been slowly increasing (Hildebrand, 2009) raising environmental concerns. Marine mammals and many fish species depend on sound, and masking can reduce their exploration or communication range prompting behavioural changes or driving animals away from their habitat.

Of special interest is the European Marine Strategy Framework Directive - Good Environmental Status (http://ec.europa.eu/environment/marine/pdf/MSFD_reportTSG_Noise.pdf) that requires the monitoring of anthropogenic noise. Any platform that includes the capacity to collect acoustic data should consider including reporting of the acoustic indicators under this directive. There are two indicators (11.1.1 and 11.2.1) that are related to noise pollution. Indicator 11.1.1 is aimed at measuring the cumulative impact of high amplitude, low and mid-frequency impulsive sounds. It requires the reporting of the following descriptors for areas that may experience this type of noise:

"The proportion of days and their distribution within a calendar year, over geographical locations whose shape and area are to be determined, and their spatial distribution in which either the monopole energy source level (in units of dB re 1 $\mu Pa^2\ m^2\ s$), or the zero to peak monopole source level (in units of dB re 1 $\mu Pa^2\ m^2$) of anthropogenic sound sources, measured over the frequency band 10 Hz to 10 kHz, exceeds a value that is likely to entail significant impact on marine animals (11.1.1)."

This indicator almost always requires modelling the sound propagation since the level threshold for counting is placed on the source level of the sound, using sound level measurements to support the model. The hydrophone itself should never be placed directly close to the source. Calculation of this indicator is useful if the platform is moored in a location where there will be e.g. construction activities (pile driving) or seismic surveys (airguns).

The second indicator (11.2.1) is aimed at characterizing the continuous ambient sound level. It requires the reporting of:

"Trends in the annual average of the squared sound pressure associated with ambient noise in each of two third octave bands, one centred at 63 Hz and the other at 125 Hz, expressed as a level in decibels, in units of dB re 1 µPa, either measured directly at observation stations, or inferred from a model used to interpolate between or extrapolate from measurements at observation stations (11.2.1)."

The frequencies selected here are considered characteristic especially for shipping noise. Although only a yearly average is required, it is recommended to provide an overview of the distribution of all data over the year or per month to be able to interpret the average; the shape of the distribution for example shows if the average value is close to the median or if there are multiple modes. The measurements themselves do not have to be made continuously to calculate the indicator. A recording duty cycle can be used that should cover each moment of the day during the year. For this indicator the use of a calibrated hydrophone and avoidance of self-noise is essential to be able to relate changes in levels to changes in the background noise.

1.2 Marine Mammal Monitoring

While the MSFD is less prescriptive about marine mammal monitoring than it is about noise, monitoring long term trends in marine mammal occurrence can contribute directly to the reporting of "Good Environmental Status" under the MSFD, particularly Descriptor 1 - Biodiversity.

Globally, there are around 125 known species of marine mammal in the world, comprising 84 cetacean species (whales, dolphins and porpoises), 33 species of pinniped (seals and sea lions), five sirenia (Manatees, Dugongs and Sea Cow), plus otters and polar bears (three species). At least 28 species of cetaceans are known to be present in European waters (Macleod, 2004). Between them, they produce a diverse array of sounds, ranging from the low frequency (10 – 15 Hz, ~15 s duration) moans of blue whales to ultrasonic (130 kHz, ~100 µs duration) echolocations clicks of porpoises and some dolphin species. Between these extremes, cetacean calls can be found in all parts of the spectrum. Some species, such as the harbour porpoise and most beaked whales, appear to produce highly stereotyped clicks with little variation between individuals, other species, such as blue whales have stereotyped but region specific calls, with different populations and sub species producing different call types. Other species produce highly variable call types and demonstrate strong evidence of social learning, changing the calls they make over periods of months and years. The classic example of this behaviour is humpback whales, which exchange and learn different songs during their annual migratory cycles.

It should also be noted that several species have not yet been recorded and for some species, recordings come from a small number of individuals and may not be at all representative of the species as a whole. It is not uncommon to hear sounds during acoustic monitoring programs which are clearly marine mammal like, but cannot be assigned to a species.

Most sounds from marine mammals fall into two main categories, biosonar signals and tonal vocalisations.

Biosonar signals, which it is believed are primarily used for echolocation by toothed whales and dolphins, are short duration impulsive sounds, generally less than a millisecond duration. The detection bands of interest depend on the species of interest, which is often a function of deployment location. Sperm whales produce broad band clicks (e.g. Madsen et al., 2002), mostly at frequencies below 15 kHz. Most dolphin clicks are also broadband, but with most of the energy above 20 or 30 kHz. A special biosonar case is if there is interest in the detection of harbour porpoises. This can be especially relevant for deployments in Northern Europe shelf waters. This species produces biosonar in a narrow band centred at around 130 kHz (Au et al., 1999). Beaked whales are also of interest in deeper offshore areas due to their known sensitivity to anthropogenic sound

(Evans et al., 2001). Beaked whales produce narrow band clicks at frequencies between 25kHz and around 70kHz (Baumann-Pickering et al., 2013)

There are two main classes of tonal vocalisations. The first are whistles produced by most dolphin species. These are narrow band in frequency (but can be modulated and include harmonics) and can have a duration of a several 10ths of seconds. Large baleen whales, such as the fin whale also produce tonal vocalisations, but at lower frequencies of between around 10Hz and 4 kHz depending on the species. Tonal vocalisations are generally believed to play a role in communication.

There are biological signals that fall between or outside the two broad categories described above because they contain energy that is not especially focused in time nor in energy. Many fish sounds fall into this category, but also some baleen whale vocalizations. It is not easy to prepare detectors or classifiers for these signals beforehand if there is no information on other sources that could produce these kinds of time-frequency energy blobs. The required processing power to classify each acoustic event may not be available on the buoy and preference can be given to the analysis of better defined events (impulsive or tonal). In the case of fish (and shellfish), their presence may be assessed from noise measurements in the low frequency third octave bands. It is important to have raw data recordings available to ensure that energy in low frequency bands can be related to biological sources and to be able to exclude shipping contributions.

2 Monitoring hardware

A typical acquisition system will consist of a hydrophone, connected to a preamplifier and an analogue to digital converter, which transfers the data to an embedded processing board. The exact hardware will always be a balance between the studies primary objectives, physical space, power availability, and budget. In some cases, real-time measurements can be performed (noise measurements, and some sound detection or classification) directly on the platform, transmitting the results and storing the raw data on a local device. This is essential when real time data are required on-shore. In other cases, the platform will only store raw data requiring a minimum amount of electrical and processing power. This is sufficient to perform the MSFD reporting.

2.1 Hydrophones

A typical preamplified hydrophone has a sensitivity of around -170 dB re 1 V/μPa and, depending on preamplifier gain, saturates at a level of around 180 dB re 1 μPa. These characteristics are sufficient in most cases to both detect animals at a few kilometres distance and to properly measure moderate noise sources (passing ships). When there is an interest in recording activities that produce high level noise (pile driving, air gun shots) then a less sensitive hydrophone may be required which does not saturate below 200 dB re 1 μPa, depending on the distance to the source. If there is an interest in tracking sources then a minimum of two hydrophones is needed to track the source bearing. Performing localization in two or three dimensions requires at least 3 or more hydrophones. The optimal configuration of such a hydrophone array depends on the local bathymetry and species of interest. Especially the frequency of the target signal should be considered in relation with the hydrophone spacing, where localization of lower frequencies may require hydrophone spacing from tens to hundreds of meters.

For marine mammal detection, the analogue to digital converter should be able to sample at a frequency of at least 48 kHz to capture calls, whistles and the low part of most biosonar. Ideally, to capture most biosonar a frequency of 96 kHz or higher is used. There are a few cetacean species that exclusively use high frequencies outside this band. If there is a special interest in dolphin sonar or to properly record beaked whales, a sampling frequency of at least 192 kHz needs to be used. For harbour porpoises, the frequency has to be at least 300 kHz (Table 1). In most cases there is no requirement to favour a 24-bit system over 16-bit (except if e.g. low level signals need to be recorded in a very quiet environment, together with high level signals). The quantization voltage range can be matched with the saturation level of the hydrophone, although if it is known that the deployment location is relatively quiet, the quantization can be performed in a lower voltage range allowing occasional saturation when marine mammals are close by. It is important that no hardware filtering is done that might remove useful signals: all filtering can be done in software offline. Only if very low frequency wave induced noise is expected (which can occasionally reach high levels), a high pass filter with a cut-off frequency below 10 Hz can be used for removal. Higher cut-off frequencies will start removing baleen whale calls and fish sounds.

Sampling Frequency (Hz)	Bandwidth (Hz)	Gigabytes per Day	Gigabytes per Week	Gigabytes per Month	Gigabytes per Year	Species Accessible
250	125	0.04	0.3	1.2	15	Blue and some other large baleen whales
2000	1000	0.32	2.2	9.7	117	Baleen whales
48000	24000	7.7	54	232	2820	Sperm whales, most dolphin whistles and some clicks

192000	96000	30.9	216	927	11278	Most dolphin and beaked whale echolocation clicks
500000	250000	80.5	563	2414	29370	Porpoises, Kogia, (all known species).

Table 1 Overview of data storage requirements for a 16-bit recorder at various sampling frequencies.

If the system is to be used for precise sound level measurement, for example to report the MSFD noise indicators, then the entire hydrophone acquisition chain should be calibrated. In addition, the self-noise of all the hardware in the deployment has to be measured. The self-noise should be at the level of sea state 0 or below.

The choice of the embedded processing board depends largely on the availability of power. When possible, the ability to run Linux on the board will open the platform to a greater number of researchers who can deliver code in languages such as Python or C, making use of many existing data processing libraries to obtain processing results in real-time. However, if an ultra low power system is required, then DSP technology can be used. Typical power consumptions of Linux based systems are between 1 and 5 Watts. DSP based systems can consume as little as 45 mW but are less capable of running complex processing algorithms.

2.2 Hydrophone calibration

Hydrophones are a highly critical component of the measurement system, hydrophone calibration values shall be provided by a calibration laboratory or by the manufacturer, and not merely be indicative or nominal values indicated by the manufacturer's design specification. The hydrophone calibration should be updated at least every 24 months over the specified frequency range in accordance with IEC 60565.

Note: It is recommended that the self-noise floor of the hydrophone and sound measurement system be assessed during this calibration.

If the data acquisition system is not integrated with the hydrophone, then the system should be checked by an accredited laboratory at least every 24 months.

During acoustic measurements, the complete sound measurement system should be calibrated immediately before and after the measurement session at one or more frequencies using an acoustical calibrator on the hydrophone. The calibrator should fulfill the requirements of IEC 60565 and should be used within its specified environmental conditions.

Applicable standards:

ANSI/ASA S1.20-2012, *Procedures for Calibration of Underwater Electroacoustic Transducers*, American National Standard Institute, USA, 2012.

IEC60565: 2006 *Underwater acoustics-Hydrophones - Calibration in the frequency range 0.01 Hz to 1 MHz*, IEC 60565 - 2006 (EN 60565: 2007, BS60565:2007), International Electrotechnical Commission, Geneva, 2006.

An annexe on hydrophone calibration, best practices and an example of a laboratory where to perform a standard caliration.

2.3 Data storage

Raw data volumes from an acoustic monitoring system tend to be quite high (Table 1). Unless an observatory can be cabled to shore, raw data need to be stored on local hard drives or SD cards. All types of drive have their advantages and disadvantages. Spinning hard drives can introduce mechanical tonal noises into the water, a number of solid state drive manufactures have produced drives that can be “bricked” on sudden power loss. In addition to corrupted file systems, which can happen with mechanical drives as well and which can be solved by using e.g. a journaling file system, the SSD internal metadata can become corrupted making the entire drive inaccessible. A low level format may be the best solution. It is advised to look for drives that carry an extra “power-loss” capacitor to lower the chance of losing all data.

Compression of audio data is an option to increase the amount of stored data. One of the most efficient readily available loss-less compression algorithms is FLAC which can typically reduce audio file with a compression ratio of 50% to 70%. Johnson et al., (2013) describe a lossless compression algorithm (known as X3) specifically designed for passive acoustic monitoring data which can achieve compression rates of between 3 and 4 times. The compression rate will depend on gain settings and the quantization range and the amount of noise in the data. A high compression ratio may indicate that the system is not recording a lot of information, i.e. it is running with a too low gain which might prevent detection of acoustic events. In general, lossy compression algorithms, such as MP3, are not suitable for scientific data collection since they deliberately discard components of the sound which are not considered important to the human ear. Lossy algorithms should only be used if the data are only to be used for human listening, for instance in an outreach project. **Error! Reference source not found.** lists some commonly used compression algorithms and typical compression ratios achieved with acoustic monitoring data.

Storage format (default parameters)	Size	%	Description
Lossless			
PCM WAV File (uncompressed)	1.3 GB	100	Most universal support, can be handled directly by any software that processes audio.
FLAC	797 MB	61	Free codec that has support in most audio processing tools, including e.g. recent Matlab versions.
BZIP2	862 MB	66	Universally available compression utility; data processing software will need to uncompress the file before being able to handle it.
GZIP	1 GB	77	Usage not adviced.
X3 (not tested on the same data set)	300 to 700MB	25 - 50	Bespoke development for passive acoustic data. Code available on request.
Lossy			
MP3	55 MB	4	Most patents covering this format have expired; universal audio software and browser support.
OGG/Vorbis	68 MB	5	Patent free alternative of MP3 format with broad support, including most browsers.
OGG/Opus	51 MB	4	Successor of OGG/Vorbis with currently limited support.

Table 2. Commonly used compression algorithms.

Sometimes a large storage drive cannot be used or the system will be deployed for a much longer time than there is storage space. In that case the recordings can be made in a duty cycle mode while continuously processing data. Even when all analysis is performed on the system and the analysis results are stored it is still important to take raw data samples to be able to validate the results offline, especially to check detector or classifier results. Without raw data it will be very difficult to establish true and false positive detection rates, or to assess system self-noise that might have appeared during deployment. If the entire acoustic system is operated in a duty cycle, it should be programmed such that measurements are taken covering each minute of each hour of the day over time. Raw data samples can be selected randomly, or triggered based on a measurement or detector output (but for both high and low scores of the detector).

2.3.1 Acoustic Meta-Data

All audio formats preserve basic information such as sample rate and number of hydrophone channels within the audio files themselves. However, there are several bits of meta data which are required for the interpretation of acoustic monitoring data. This includes hydrophone and other hardware types, calibration information, deployment methods and positions. It is also important to store the configuration of any automatic detecotors running within a monitoring system and information on how any duty cycling process is controlled.

Meta data are small compared to raw acoustic data and can be stored in XML or similar formats. Some teams have packaged essential meta data into additional data “chunks” in the header of PCM wav files.

An ANSI standards working group S3/SC1/WG7 is currently discussing acoustic monitoring Meta-Data and will provide useful guidelines which will be suitable for both noise and marine mammal monitoring when it reports in 2018.

3 Equipment deployment

Key to successful acoustic data collection on any platform is the avoidance of noise. Platforms can produce three types of noise which might affect an acoustic monitoring system:

1. Intentional noise: Several oceanographic instruments such as SONAR and ADCP’s work by emitting sound and then monitoring reflections from objects in the water column. Clearly if these sound emissions are in the same frequency band as is being monitored acoustically, interference will occur. It should be noted that many instruments which specify operation at a particular frequency often also produce energy at numerous side bands, so a device operating at 1MHz, which would not normally interfere with acoustic monitoring equipment may also be producing energy at much lower frequencies. Many platforms also use acoustic modem technology to communicate between sensors, which may also interfere with a passive monitoring system.
2. Mechanical noise: Most mooring systems contain chain and shackles which clank and produce impulsive noises as the system moves due to current and waves.
3. Electrical noise: This can come from the platforms power regulation system or may be introduced into the platform by other system components. It is also possible to pick up noise from Ethernet and serial communications systems between platform sensors, particularly if acoustic cables are run close to these other communications cables.

Obviously, it is best to maximise the separation between the hydrophone and any equipment that uses acoustics to make measurements (e.g. ADCP devices). If the platform itself operates in duty cycles then noisy equipment could be operated while the acoustic acquisition system is sleeping. Two often encountered noise sources are chain noise from the mooring cable and cable strumming in strong currents. In some cases it might be practical to tape the chain or to enclose it in hose pipe to prevent noise. At low frequencies below 1 kHz some special care should be taken to avoid impulsive noise from cable strumming. Cable fairings can help to reduce the strain and strumming on the cables if they cannot be fixed or shielded from the current.

The hydrophone should be installed at least 10 m below the surface and preferably in the middle of the water column in shallow water. The placement of the hydrophone can depend somewhat on the objective for the acoustic measurements. For the measurement of local ambient noise (as under the MSFD), the hydrophone should not be in a sound channel and not in a shadow zone relative to fixed sources of interest (e.g. exploration platforms, harbour construction). There is no recommended distance to shipping lanes; if a direct relation between shipping traffic and noise level is sought, then installing within a kilometre from the lane will most likely record all passing ships without causing saturation. If there is no specific interest in anthropogenic contributions but rather in long term changes in background noise, then deploying at least 10 kilometres from anthropogenic sources will greatly reduce their contribution; the ideal distance would have to be computed by modelling the propagation taking into account the effects of the local bathymetry and acoustic environment.

The acoustic processing module should be placed as close as is possible to the hydrophone in order to avoid long cable runs. If cable runs (for example from a hydrophone at 10m to a processing module in the platforms hull) are used, then care should be taken to ensure that these are shielded from any digital communications cables.

If the primary objective is to record marine mammals then installation in a sound channel might increase the detection range of the system. A distance of at least 10 kilometres from anthropogenic sources reduces masking of biological signals.

4 Data Processing

As explained in the introduction, there is a requirement for the measurement of ambient noise levels around the EU coastline under the Marine Strategy Framework Directive. If a project is funded with environmental objectives then both noise level measurements and biological contributions are important to measure.

4.1 Noise

The minimum noise measurement that should be computed under the MSFD directive is the sound pressure level in the third octave bands centred on 63 and 125 Hz. The time interval over which to compute this level has not been standardized, other than that the MSFD requires a yearly measurement. However, a single value is not very informative if there is interest in sound contributions from transient sources. In practice the SPL is computed over shorter time intervals (the snapshot time) and the sound pressure values are averaged to compute the yearly value. A long snapshot time, e.g. computing one average sound level every day, will 'hide' some sources, while a short interval, e.g. computing a level every second, will generate a lot of data. Under ESONET (http://www.esonet-noe.org/) it was suggested to use 10 second SPL snapshots as a compromise. This duration also allows to compute a meaningful median SPL level over longer time intervals that is not as influenced by outliers as taking the (arithmetic) average over the sound pressure values. Especially the arithmetic averaging of SPL values can be heavily influenced by occasional high intensity transient sounds. It is important during the analysis to determine whether these are genuine sound sources or self-noise from the platform. This is generally achieved by a human analysist examining samples of raw data.

In addition to the required third octave band levels it is useful to compute additional noise levels to characterize the ambient noise outside of "shipping frequencies", for example up to 1000 Hz in third octaves and in octaves beyond that to reduce the number of sound levels while covering the full acquisition band. This will provide more detailed acoustic descriptions of different acoustic sources that will be recorded during the deployment period and it may allow correlating between the presence or absence of particular species and anthropogenic activities.

4.2 Marine Mammals

Obviously, it is of great interest to identify the presence of marine mammals and to quantify the biological contribution to the ambient sound. It is rarely possible to classify all the species that may be present, but processing can be done in different stages of precision starting from assigning broad category labels to specific classes. Under ESONET the first distinction was made between biosonar- and whistle-like signals – which can be detected and distinguished by most available software packages.

The main anthropogenic source that is picked up by an impulse detector is shipping noise, which impulses mostly stay below 20 kHz. These signals can be mixed with sperm whale sonar, which is normally detected below 15 kHz (depending on a number of factors). Above 20 kHz, most impulse detections will belong to dolphins, porpoise or beaked whales. If the system is deployed in shallow water then many broad band impulses can be present from shrimp (Au and Banks, 1998) and other shellfish. It is important to always store raw data samples to be able to confirm these assumptions.

Depending on the deployment location most tonal vocalisations would be produced by dolphins, but mooring chains can also produce tonal signals which may be picked up by a detector. In some cases ships can produce constant tonal signals of a few second duration, which can be separated from biological noise with the constant characteristic. Dolphins will mostly produce these signals between 1 and 24 kHz. Baleen whales can produce calls up from 10 Hz and generally below 4 kHz while fish species produce modulated sounds mostly below 1 kHz (e.g Ladich, 1997).

Once impulse and tonal sounds have been detected, a number of techniques are available to attempt to classify them to species (e.g. Oswald et al., 2007; Baumgartner and Mussoline, 2011; Gillespie et al., 2013; Rankin et al., 2016). These classifiers are imperfect often due to high levels of overlap in the types of calls produced by closely related species. As always, the ability to check raw data is often an essential part of data analysis. While it is possible to implement detectors for impulsive and tonal sounds on a real time embedded processor, it is generally not possible, or even desirable, to run high level classifiers on board, classification generally being conducted back on shore.

In the case of a cabled and powered installation, it may be possible to stream raw data to shore in real time, in which case detection, classification and data archiving can all take place on shore. Analysis results can also be presented in real-time to the environmental agencies and the public. All raw data should be stored to allow processing by interested scientists.

If the buoy is not cabled but has a way to generate its own power then it can be of interest to present a few real-time results that are transmitted through a radio link (e.g. WiFi, 3G, satellite). There is likely enough physical space on the buoy for hard drives to store a large amount of raw data, otherwise at least all analysis results together with samples of raw data or spectrogram should be stored. The acoustic duty cycle can be automatically adapted depending on the current battery status. For example, when solar panels are used, the acoustic system can run longer during the day if there is excessive solar power and shorter during the night to save battery power.

In the case of a battery installation there is no real-time requirement and as much raw data as possible should be stored, choosing a duty cycle that allows acoustic sampling during all hours of the day. If there is little available storage space then the basic analysis should be stored with a spectrogram, combined with some randomly sampled raw data as described under section 5 “Considerations for power and duty cycling” below.

5 Considerations for power, storage and duty cycling

The need for duty cycling the measurements is generally based on the available power, whether only from a battery or from a combination of battery and wind/solar power generation. The largest power consumption comes from the processing board if on-line data analysis is needed. When there is no requirement for this then the consumption can be drastically reduced. A limitation in storage space can sometimes be resolved by storing a combination of processed results and a selection raw data.

For noise measurements in the MSFD framework there is no need to record long continuous time periods. The primary interest here is in long term changes in the background noise, which only require a short recording, e.g. 2 minutes every half hour. The recording time should be distributed over all hours of the day to have fully sampled both day and night times at the end of the measurement period. If there is an expectation that short transient sounds will be present and that these sounds should be recorded for noise regulation purposes, then the duty cycle does need to be configured such that these sounds will be included in the recording. If it is known that the source is not present at night or during weekends, then these moments can be sampled at the lowest duty cycle rate.

For the detection of cetacean presence a short recording interval is not useful as the chance is too big that cetaceans will be missed. In that case it is preferred to have at least a 5 minute continuous recording with an off-time since it is often required to detect multiple calls from an individual to confirm species identification. The duty cycle should again be programmed such that recordings are made covering all hours of the day.

In both cases and when possible, the acoustic duty cycle should be timed such that it does not coincide with the use of other noisy equipment. This type of self-noise could be removed in post-processing, or even on-line, but reduces the use of the already limited recording time. The operation times of such noisy equipment should be logged to facilitate the removal of their contribution to the recordings.

Table 3 gives an example of duty cycles assuming a standard high frequency recording hydrophone and single board computer combination (5 W), a standard recorder (1 W) and a low power DSP recording solution (100 mW). A power capacity of 12 V/ 200 Ah (2400 Wh ignoring the battery discharge characteristics under different loads, temperatures, etc.) is assumed. Such batteries are easily commercially available or the capacity can be reached with a small battery and solar panel. With large SSD drives available, the limiting factor tends to be battery power, unless the system has reliable power generation. In that case compression can be used to maximize the running time.

The same table provides an example of a storage limited system with a 1 TB drive. If compression is used then the drive size can be multiplied by its compression factor to simulate the larger drive. A Microsoft Excel sheet is available to compute duty cycle times for both power and storage space limited scenarios.

Power Limited (2400 Wh)					
Deployment period	Primary objective	Duty cycle	Sampling rate (16 bit)	Power	Storage
1 year on-line processing (5 W)	MSFD Sound levels	2 m on / 35 m off	48 kHz	2395 Wh	149 GB
	Cetacean presence	5 m on / 88 m off	128 kHz	2395 Wh	398 GB
1 year recording (1 W)	MSFD Sound levels	2 m on / 5 m off	48 kHz	2372 Wh	745 GB
	Cetacean presence	5 m on / 13 m off	128 kHz	2374 Wh	1986 GB
1 year recording DSP system (100 mW)	MSFD Sound levels	continuous	48 kHz	864 Wh	2781 GB
	Cetacean presence	continuous	128 kHz	864 Wh	7416 GB
Space Limited (1 TB)					
1 year recording (1 W)	MSFD Sound levels	2 m on / 3 m off	48 kHz	3154 Wh	1001 GB
	Cetacean presence	5 m on / 32 m off	128 kHz	658 Wh	1000 GB

Table 3 Duty cycle configurations for different monitoring objectives.

6 Data access and transfer

The three main consumers for the data and results will be the general public, environmental agencies or organizations and scientists. While general public interest tends to be limited, the public outreach is often an important component for EU funding. To reach the public some of the most interesting sound files can be made available for playback from the project website. Generally these will be marine mammal sounds and some of the noisier human activities.

For environmental impact assessment a noise level and cetacean presence report should be presented. In addition to the summary third octave SPL levels required under MSFD descriptor 11, an overview should be presented including the levels over time and the distribution. Ideally, an interface allows the selection of the monitoring time period of interest from the available to provide the sound report. If real time detections are being made, either on the platform or on shore (for cabled systems) then the detection data should also be made available in real time.

Scientific interest will be mostly in accessing the raw acoustic data to perform additional offline analysis or to test new algorithms. As indicated by Table 1, the space that is required to store multiple years of data from multiple platforms and channels grows quickly into tens of terabytes or an order of magnitude larger when high frequency information needs to be stored. Analysing such data sets will require not only space and bandwidth, but also a processing cluster to be able to run new or adapted algorithms over the full set. These requirements need to be taken into account in future projects.

It can be helpful to distribute the raw acoustic data in (pcm) wav files, including Meta data such as the overall hydrophone sensitivity, gain, quantization range, and recording location, which can either be stored inside the wav file metadata (e.g. the LIST-INFO chunk) or as a separate XML file. The recording time can be inside the filename itself following the ISO 8601 standard with the date time in UTC (e.g. “2016-02-12T14:12:21Z”). Most available monitoring software packages will allow an export of analysis results in an OGC SWE format; if not an encapsulation of the data in a suitable OGC format can normally readily be created.

The availability of data access depends on the transmission rate that is available. The table below lists a few typical transmission rates. Note that bandwidth and communication range are strongly related and dependent on antenna height (which usually are relatively close to the water) and that these values were **not** obtained from experiments at sea. In the case of a cabled system, analysis results can be transferred in real-time while raw data can be transferred in the background when there is low traffic. The same can be done with radio linked systems that have a high enough bandwidth. It is difficult to predict in advance if it will be possible to reliable transfer raw data over the link. As mentioned before, a minimum of raw data should either be stored or transferred to allow a review of the analysis.

	Bandwidth (order of magnitude)	Typical range	Usage
Satellite	2400 baud	--	Alert messages only
Zigbee	20 kbit / s	< 100 m	Alert messages
LoRa	1 kbit / s	4000 m	Alert messages only
3G/4G	1 Mbit /s	10000 m	Full analysis
WiFi	1 Mbit / s	< 1000 m	Partial analysis
WiMAX	10 Mbit/ s	5000 m	Full analysis

Table 4 Common transmission rates and ranges of widely available radio communication links.

7 Practical Monitoring

Passive Acoustic monitoring systems can be added to observatory platforms both to measure noise and to detect and monitor marine mammals. Member states are now required to monitor for noise under the MSFD. Monitoring for marine mammals is not stipulated, but can assist member states in the reporting of "Good Environmental Status" under MSFD.

If marine mammal monitoring is being undertaken, particularly in coastal waters, high data rates are required which are often several orders of magnitude higher than data rates of other oceanographic equipment such as temperature sensors and CTD's. This can mean that acoustic monitoring packages do not always fit easily into the architecture of existing platforms, often requiring considerable additional data storage capacity and power to process large quantities of data.

A wide range of self-contained battery powered acoustic monitoring devices are now available for purchase or hire, some of which could potentially be strapped to a mooring. These are reviewed in detail in Sousa-Lima et al., (2013). An example of a high-quality stand-alone acquisition and recording device produced in the EU that can accommodate very low-noise reference hydrophones can also be found in Annexe. However, even if all raw data cannot be sent to shore in real time, there is always a strong interest in returning at least some data, so generally, smart devices integrated into a platforms infrastructure are preferred over these simple recording devices.

As with many oceanographic instruments, there is the possibility that other sound producing devices may interfere with a passive acoustic monitoring system and self-noise generated by many moorings can be a significant problem. However, those issues aside, a number of systems are available which are suitable for inclusion on remote observatories. The following Annexes detail the LIDO system, which has been developed for the processing, storage and display of long term acoustic monitoring data and a new monitoring hardware system under development at PLOCAN.

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A Data management through LIDO (ESONET)

The Laboratory of Applied Bioacoustics (LAB) of the Technical University of Catalonia, BarcelonaTech (UPC) is currently leading an international programme titled ''Listen to the Deep Ocean Environment (LIDO)'' to apply and extend developed techniques for passive acoustic monitoring to cabled deep sea platforms and moored stations. The software framework, called SONS-DCL, is currently active at the ANTARES (http://antares.in2p3.fr/) neutrino observatory, the OBSEA (http://www.obsea.es) shallow water test site, the NEPTUNE Canada (http://www.neptunecanada.ca/) observatory, the JAMSTEC (http://www.jamstec.go.jp/e/) network of underwater observatories and at the NEMO (http://nemoweb.lns.infn.it/) site after the observatory was redeployed, as well as through a zero-cost contract with the CTBTO (Comprehensive Nuclear Test Ban Treaty) hydroacoustic stations. Part of the system was also tested for suitability on autonomous gliders in collaboration with the NURC (NATO Undersea Research Center) and on wavegliders (Jupiter Research Foundation) to track humpack whales. Applied solutions have been also deployed in the Arctic in collaboration with STATOIL to measure and mitigate noise sources associated to Oil & Gas operations. Recognizing the technically advances of the software package has lead to a partnership between SONSETC (http://sonsetc.com), a spin of the UPC, and CSA Ocean Sciences Inc. (http://csaocean.com) aimed at providing advanced sound solutions to the offshore industry, government bodies, port authorities, and engineering firms. The vision is to deliver solutions that far exceed current acoustic monitoring technology, increase and highlight the benefit of acoustic measurements and demonstrate industries concern for the marine environment.

The development and implementation of the real-time component of SONS-DCL in existing observatories has offered a unique opportunity to monitor noise at a spatial and temporal scale never before realized. Access to the continuous flow of data has allowed the development of an exclusive database of sound sources that are permanently updated and used to calibrate the algorithms. These are applicable to almost any scenario, sea state, geographic location and noise level.

The system can be implemented on cabled observatories, autonomous radio-linked buoys, moored antennas, autonomous vehicles (including gliders), towed arrays and, existing data sets.

The software package contains several independent modules to process real-time data streams. Among these, there are dedicated modules for noise assessment, detection, classification and localization of acoustic events, including marine mammals and fish vocalizations. To summarize the LIDO system, it takes as input an acoustic data stream and produces as output the characterization of the acoustic events that were detected in the data (written to an XML file), spectrograms for quick visualization and compressed audio. These outputs are then made available on the Internet where they can be viewed with a specific application. A custom alert service is also available warning the user of the presence of acoustically sensitive species in the area of activity. SONS-DCL is designed to be modular and dynamic (allowing the choice of detectors/classifiers), depending on the objectives and geographical areas. SONS-DCL is conceived for ease of operation (non-expert) and provides a monitoring system that automatically operates 24/7, without the need of post processing.

A.1 Real-Time Monitoring

A.1.1 Cetacean Monitoring

The purpose of cetacean monitoring in real-time is especially to guard against direct acoustic impact. Animals close to the source may be exposed to sound levels sufficiently high for temporary or permanent hearing loss. The cetacean detection and localization range of interest is then up to around 2000 metre from the source, depending on the source levels, frequencies, and environmental parameters.

The vocalizations of cetaceans can be broadly separated into two main types. Impulsive signals, which are broadband and of short duration – in the order of milliseconds. These signals are commonly used for biosonar and are emitted by toothed whales. In many cases the detection of a biosonar signal means that the animal is within 2000 metres. The exception is the sperm whale which has a lower frequency sonar signal that can be received up to 15 km from the animal.

A second type of signal (whistle or call) is well defined in frequency and of longer duration – in the order of seconds. Dolphin whistles (1 – 30 kHz) and many types of baleen whale calls (generally 1 – 6000 Hz) fall into this class. When dolphin whistles are received the animals are generally within 5 km range, but low frequency baleen whale calls (below 1000 Hz) may travel long distances through underwater sound channels. It is not expected that the noise source will be inside a sound channel which could have an environmental impact at very large distances. For short range impact assessment it is not useful to monitor sound inside a channel and care should be taken to place the hydrophone outside a channel.

Figure 1 and Figure 2 give examples of cetacean detection using the software described in Section A.3.

Localization of the source (especially range estimation) should be precise up to 5 km and its performance can be allowed to deteriorate beyond that range. Ideally the tracking method provides probabilities of the presence of cetaceans within a certain zone with the zone shrinking at shorter ranges to the noise source.

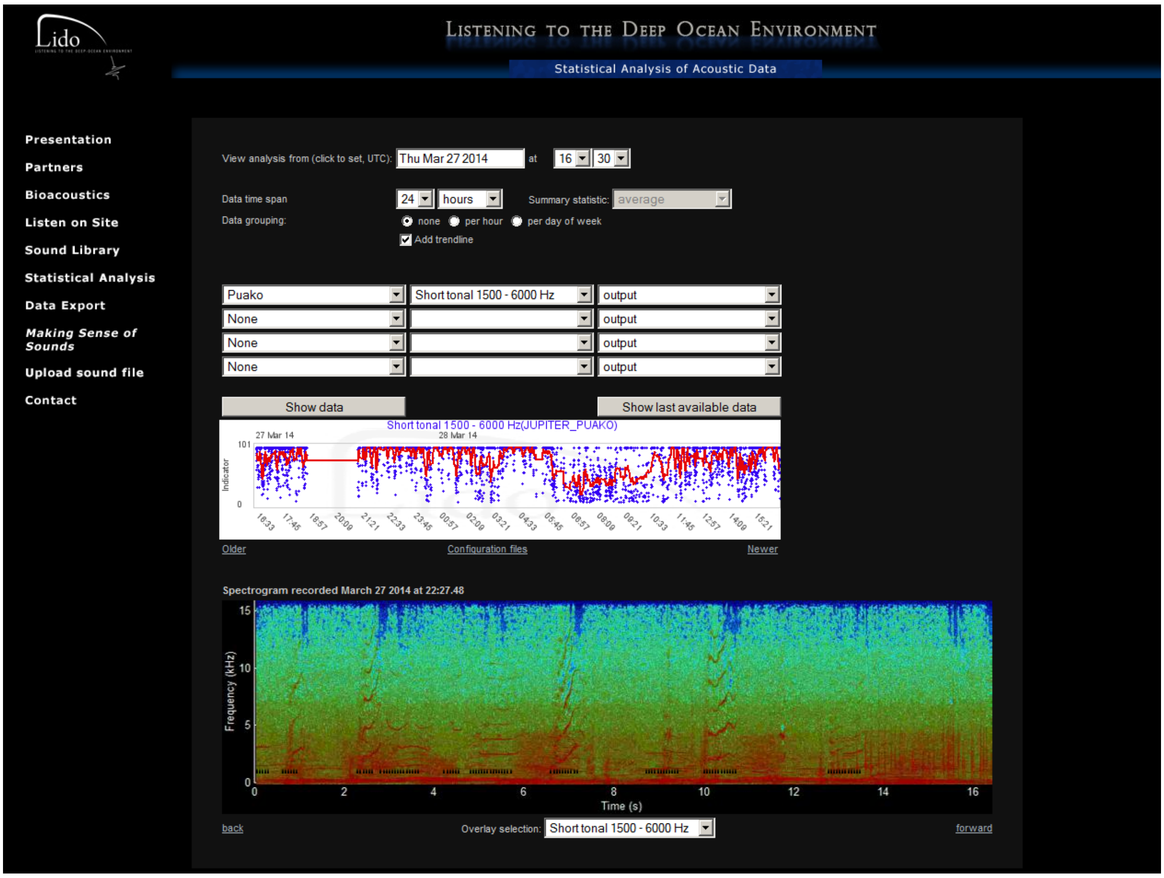


Figure 1 Example of harmonic Humpback call detection at Puako, Hawaii (data provided by the Jupiter Research Foundation).

Figure 2 Example of Sperm Whale biosonar detection at Antares.

A.1.2 Noise Monitoring

Noise monitoring on location should at least follow recommendations for the MSFD indicator 11.2 concerning ambient noise and measure the sound levels in the 63 Hz and 125 Hz third octave bands. In order to provide a full overview of the sound levels in these octave bands it is suggested to present the results with a distribution graphic as shown in Figure 3 (top), in addition to reporting averaged levels. The top left and right images show the distribution of the measured sound levels (third octaves centred on 63 and 125 Hz and full bandwidth RMS) during April and October 2013 and they give an idea of the minimum and maximum levels, commonly encountered levels, and anomalies. For example in Figure 4 which shows the distribution of the same noise levels during September a small peak is seen for the RMS at a high level. These RMS peaks were due to an increased intensity of the 40 kHz noise band. A monthly summary statistic would have hidden this information, possibly leading to a too high estimate of a monthly RMS. Noise levels have been recorded for several years at the OBSEA and e.g. MSFD reports are generated automatically to provide information such as shown in Figure 5.

The MSFD indicator 11.1 concerns low and mid frequency impulsive sounds. The indicator requires a yearly summary on the days and locations that these impulses were produced. While not strictly necessary to measure impulses in real-time, it would be very useful to do so both to present data to validate modelling that was done in relation to this indicator and to be able to assess the impact on the environment directly. Representation of the peak level is shown in Figure 3 (bottom). Assessment of the number of days where a peak level exceeded the threshold is easier in a time plot than when displayed as a distribution. Ideally, the source (peak) level is known and the transmission loss of the acoustic path can be estimated from the recording. Otherwise a calibrated source can be used or a propagation model suitable for the environment.

Apart from measuring the MSFD acoustic indicators it can be useful to measure in frequency bands that may contain animal vocalizations. The exact bands depend on the monitoring location. A high noise level in the band may indicate that the bioacoustics signals will not be detected, or only detect from closer ranges. This should be taken into account in mitigation procedures. If high noise levels in these bands are produced by a near-by source then the monitoring station should be moved further away.

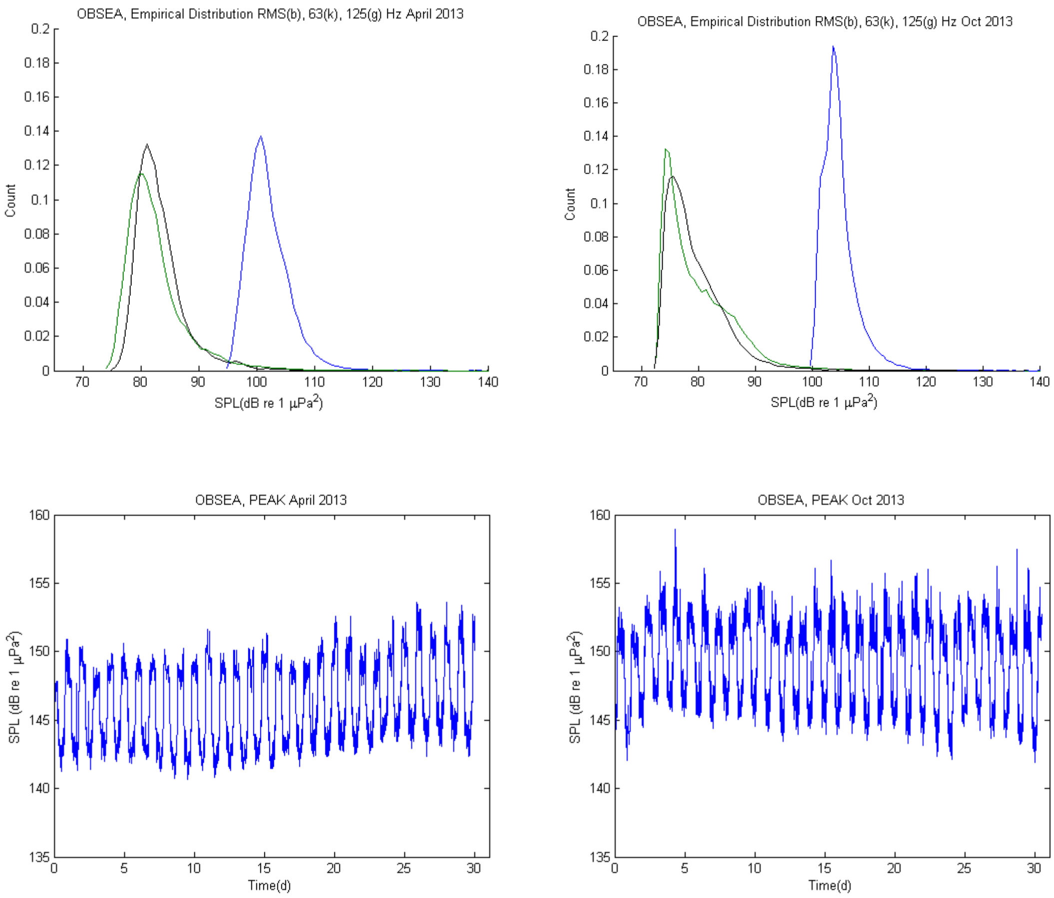


Figure 3 Top: Distribution of noise in two third octaves (centred on 63 and 125 Hz) and the full recording bandwidth (up to 48 kHz) at the OBSEA platform during April and October. Bottom: Evolution of peak levels at the OBSEA platform during April and October 2013.

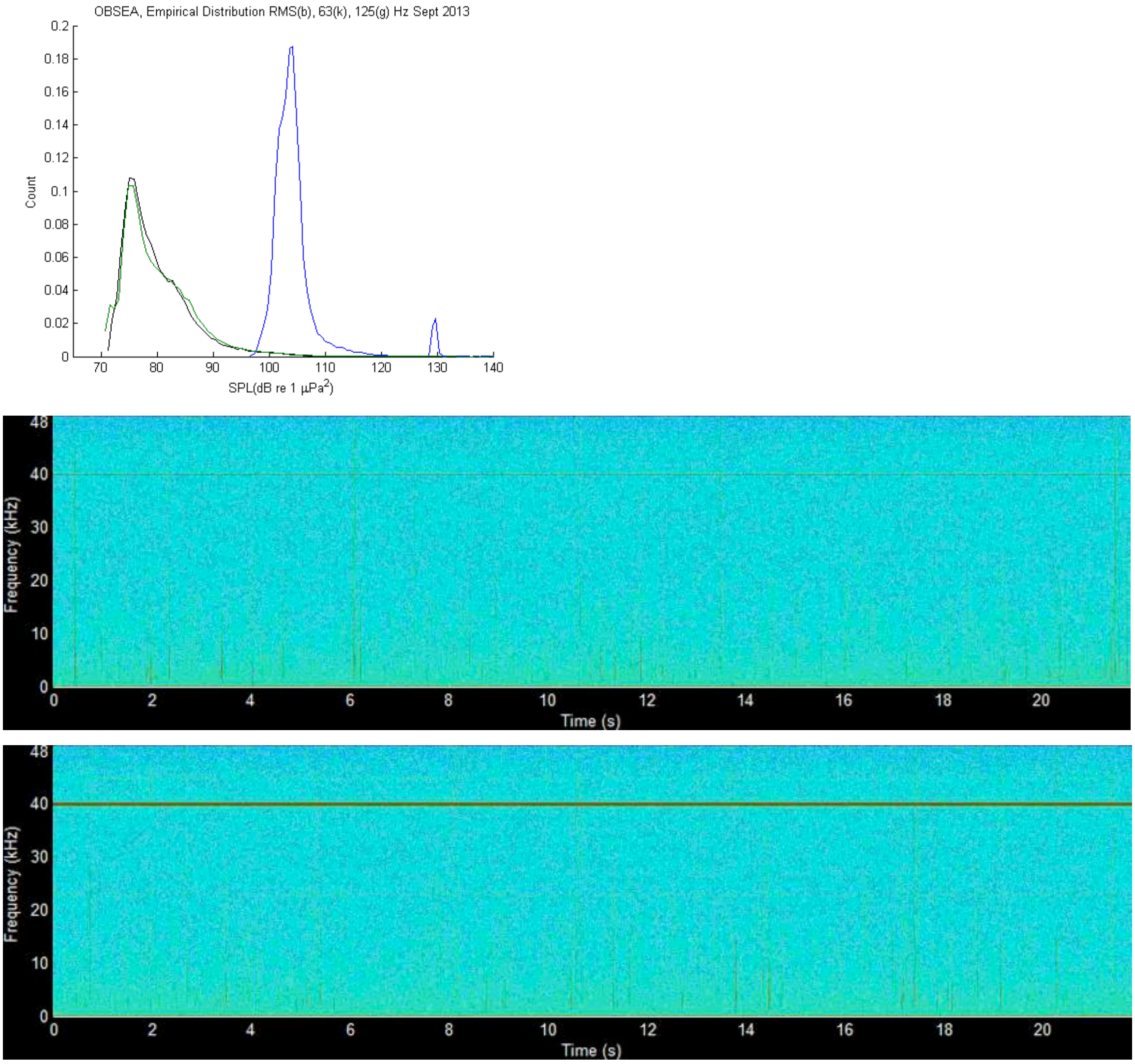
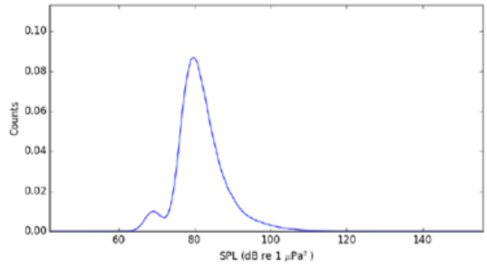


Figure 4 Top: Distribution of energy in 63 and 125 Hz third octaves and full bandwidth RMS at the OBSEA platform (as in Figure 3) in September 2013. The two following spectrograms show the cause of the isolated RMS peak.

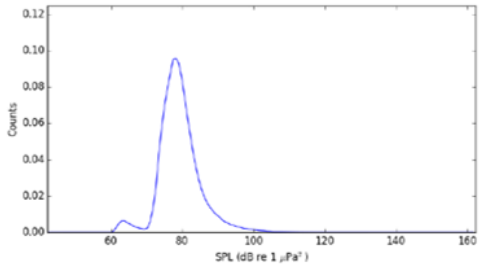
2011

Sound Pressure Level [MSFD D11.2][1]	86.92 dB-RMS
Mean Sound Pressure Level[2]	82.09 dB-RMS
Median Sound Pressure Level	81.31 dB-RMS
Maximum Sound Pressure Level	141.73 dB-RMS
Minimum Sound Pressure Level	59.81 dB-RMS



2013

Sound Pressure Level [MSFD D11.2][1]	83.41 dB-RMS
Mean Sound Pressure Level[2]	79.65 dB-RMS
Median Sound Pressure Level	79.08 dB-RMS
Maximum Sound Pressure Level	147.57 dB-RMS
Minimum Sound Pressure Level	60.21 dB-RMS



2015

Sound Pressure Level [MSFD D11.2][1]	84.16 dB-RMS
Mean Sound Pressure Level[2]	81.49 dB-RMS
Median Sound Pressure Level	80.78 dB-RMS
Maximum Sound Pressure Level	140.35 dB-RMS
Minimum Sound Pressure Level	71.1 dB-RMS

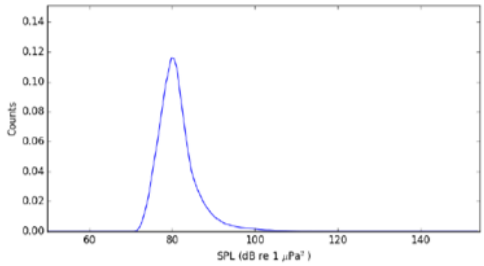


Figure 5 Automatically reported processing results from the OBSEA, in this case showing sound level measurements.

A.2 Real-Time Reporting

Noise measurements and detection data can be made available locally to ships operating in the vicinity or globally over the internet. The advantage of the latter may be that any environmental or government agencies can follow the operations and ensure that regulations are being followed, without the need to be physically present. Local access is provided by a WiFi radio link with the buoy acting as an access point if cabling of the buoy to a platform is not possible. In the case of WiFi, normally only one or two clients would connect to the buoy, but if there is more interest it is preferred to install a WiFi point-to-point bridge to an auxiliary vessel and provide data access from there, e.g. connecting to an AP on the vessel or provided wired access to observers on the vessel. This setup would be able to provide access to analysis results, spectrograms that allow human observers to identify the correctness of the automated process and a compressed audio stream.

Global access is provided through an Iridium satellite uplink. The available bandwidth will be much less than available for a WiFi link and at least the compressed audio stream would normally not be available while spectrograms could be transferred upon request. The data is transferred to a centralised storage location from where it can be further distributed.

A.3 Software Implementation

The software for the real-time analysis (SONS-DCL) is developed in C due to the availability of C-compilers on most embedded platforms. The design follows a modular approach that allows loading/unloading modules while the system is running. The modular design is especially needed to ensure that data from a hydrophone can be picked up without dropping samples. Additionally, analysis of data is not unnecessarily delayed due to a single module waiting for e.g. a network timeout. Some modules may make further use of multiple processor architectures with the OpenMP library (whether or not this gives a true advantage depends on the server specification). There are generally 3 types of modules:

- Data entry module: a SONS-DCL system normally has only 1 acoustic data entry module. This module cannot be replaced or restarted without stopping the data acquisition. Currently data entry modules are planned for data acquisition from e.g. Diamond Systems DAQ boards, SMID digital hydrophones, icListen or Naxys Ethernet hydrophones, and to read data from disk (files stored in pcm, wav, aiff, etc. format). Data files that are accessible through a network or the internet are often first stored to disk independently before passed through SONS-DCL. The system can have other modules that accept external data, such as AIS/GPS or other sensors connected through a serial or USB connection.

- Data analysis modules: analysis modules perform sound measurements, acoustic event detection, classification, localization, tracking etc.

- Data output modules: output modules provide (analysis) results in a format that can be read by other post-processing tools. There are e.g. XML and CSV output modules to export the analysis results; spectrogram creation for human analysis; mp3/ogg vorbis modules to allow listening to a compressed stream; a data recorder to record raw data allowing to recording based on triggers (e.g. only record data segments that contain short tonal signals).

The modules communicate using POSIX based IPC. It has been tested on FreeBSD (generally used for powered servers) and Linux (generally used for embedded systems) and is expected to run with minimal changes on other systems that have POSIX (.1-2001) support. It has been written for x86/x86-64 architectures and has not yet been tested on other architectures. On Windows a single executable version is available that does not depend on the POSIX IPC and cannot take advantage of the modular design. It is primarily used for analysis of large archived data sets.

The SONS-DCL system runs autonomously on a server or embedded board (not all modules are suitable for low power systems); once configured and started it generally does not require any supervision. One way to present the SONS-DCL output to a user is through the SONS-DCL client. The SONS-DCL client requires the standard software stack with Apache (or Nginx)/MySQL/PHP/JavaScript/XML and Flash for some parts. A part of the data interface can be installed directly on an embedded board to monitor its operation. However, it is advised to isolate the SONS-DCL system from the general public to avoid overloading the device. Data can be transferred automatically to another server where the public may access it.

A.4 Embedded Hardware

Currently the embedded version of SONS-DCL runs off a PC/104 stack based on Diamond Systems boards. The stack has the following components:

- Processing: DS - Aurora single board computer (Intel Atom Z530 1.6 GHz).
- DAQ: DS-MM-32DX-AT ADC board (optional).
- Ethernet port expansion: DS-Corona-Ethernet board (optional).
- Watchdog: proprietary board to power the Aurora and to monitor voltage, current, and the execution duty cycle.
- Power regulation board: proprietary board to switch on/off peripheral equipment through Aurora GPIO pins (optional).
- Main storage: solid state disk connected through SATA.

Common peripherals:

- GPS receiver
- AIS receiver
- Satellite modem
- 3G/WiFi modem
- WiMAX modem

The Aurora runs a 2.6 Linux kernel version which has complete Diamond Systems driver support. When a digital hydrophone is used the DAQ board is no longer necessary and a different hardware stack could be used.

A.5 Monitoring Protocol

1. Literature study: A list of all the species that may be found in the area during the time period of the operations should be compiled, especially cetaceans but also e.g. cephalopods and fish; vocalization frequencies should be separately noted. The area should also be inspected for other anthropogenic sound sources, such as existing platforms, shipping lanes, fishing grounds, etc.

2. Characterisation of the sound source: If possible the noise source should be measured in advance or its sound characteristics should be made available from the owner/supplier.

3. Premodelling: Based on information from the literature study, sound source and local propagation properties, modelling should be performed to find 1) the number of necessary hydrophones and 2) the optimal position of each hydrophone, taking into account that animals should be detected up to 5 km from the source.

4. Data acquisition configuration: The acquisition parameters should be chosen to allow recording of the full bandwidth of the source and cetacean vocalizations. Noise measurements should be made at least in the 63 and 125 Hz third octaves, but also in other bands where the sound source may have level maxima, especially if these fall inside a frequency range where they may affect cetaceans.

5. Real-time monitoring: A three stage alert protocol is suggested. At the first stage no animals are detected by the system. At the second stage animals have been detected beyond a 2 km range. If the animals move closer towards the operation a supervisor should be notified that mitigation routines may have to be initiated soon. At the third stage animals are within a 2 km range and may enter zones with dangerously high levels at any moment. Mitigation procedures should be effected immediately.

6. Final reporting: The final report should show the noise levels as described in Section A.1.2. This would not only provide information for the MSFD reporting but also show that the operator stayed at or below the sound levels that were provided for modelling (and possibly to obtain a permit). All cetacean detections should

be included in the report as well as the mitigation procedures that were followed.

A.6 Testing of real-time architecture

The software and hardware solutions described in Sections A.3 and A.4 have been implemented and tested during the ODEN-2013 campaign in the Arctic region. Buoys were deployed for cetacean detection and the measurement of ambient noise and ice breaker operations. The buoys were connected through satellite to provide information on the sound measurements. An overview of the sound measurements on two different deployment days is shown in Figure 6. The bimodal structure was caused by presence and absence of the ship. In parallel, a real-time monitoring system (BCUBE) was deployed from the ODEN itself; Figure 7 shows a screenshot of its interface. On board the ship WiFi was used to provide access to the monitoring system to everyone on board. The ODEN-2013 campaign is reported in Deliverable 2.45.

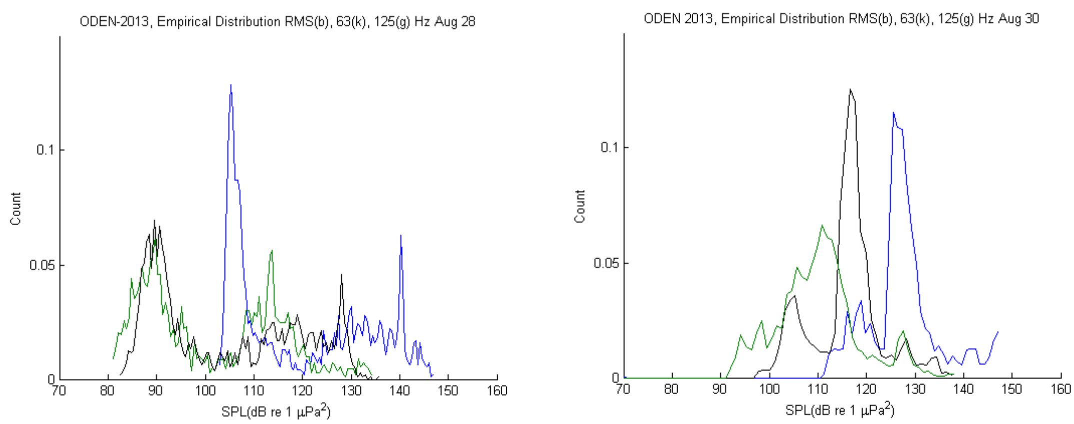


Figure 6 Measurement results from the ODEN-2013 campaign.

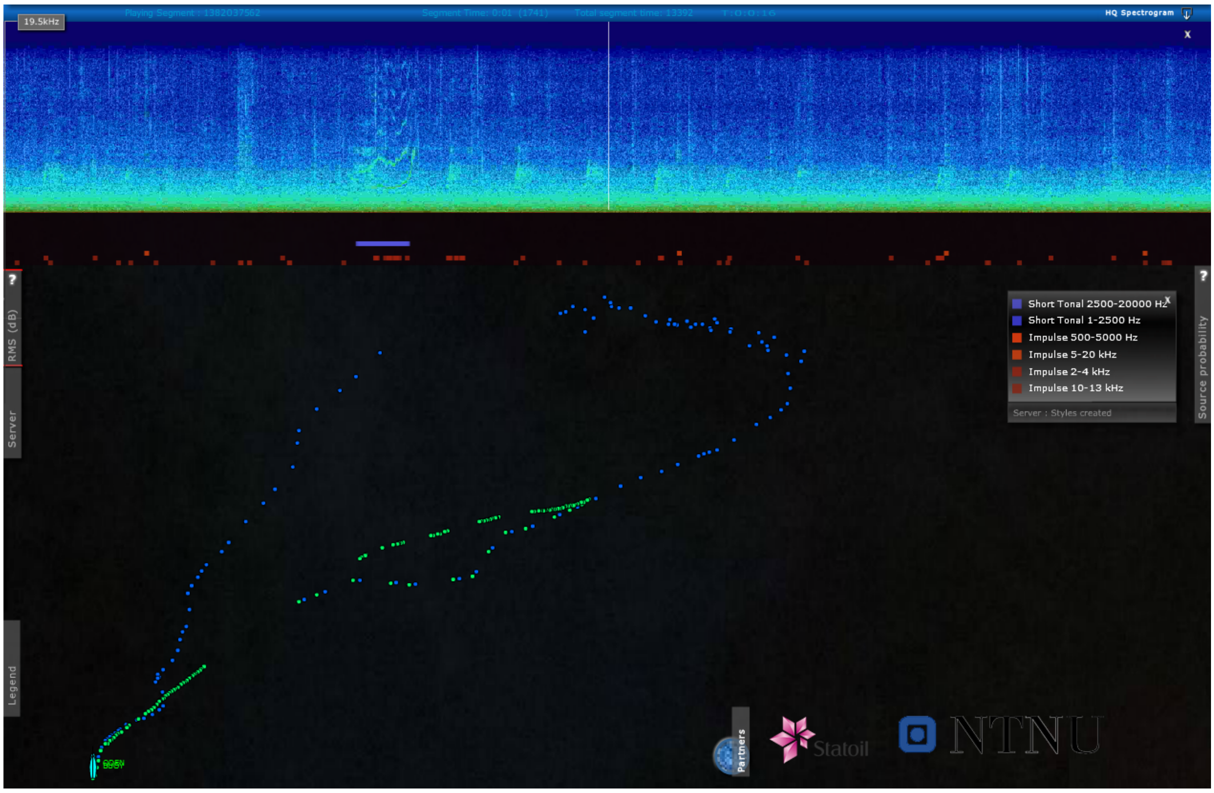


Figure 7 Detection of Narwhal whistle from the BCUBE on board the ODEN.

B Innovations for an end-to-end approach in passive acoustics sensors for moored stand-alone ocean observatories

Section contributor: Eric Delory, PLOCAN[1]

Current oceanic passive acoustic sensor systems generally include one or several transducers, signal conditioning, instrument interface with communication and control capability, and internal or external power supply. In stand-alone platforms, passive acoustic data are generally stored for later recovery and analysis, unless there is a direct and affordable RF link to shore. Hydrophones can also work in array configuration, needing synchronised acquisition (a.k.a simultaneous sampling), which is not trivial to implement in distributed systems and further increases costs. Most ocean monitoring platforms are still stand-alone with an RF link of limited bandwidth, and the growing use of autonomous platforms in global observation will continue to increase the use of RF transmission, mainly via costly and energy-demanding satellite links. Autonomous platforms are also now being increasingly considered for the monitoring of cetaceans via passive acoustics, as in (1). Current passive acoustic sensor systems also need to address the broad dynamic range of underwater sound intensity, which implies specific analog and/or specific digital design strategies, allowing for the measurements ranging from low-level ambient noise to high-level sounds produced by active sources, whether bioacoustic or anthropogenic, as presented in other sections of this deliverable. With respect to sensor metadata, internet connectivity and infrastructure interoperability, important functionalities are also desirable, such as discoverability of sensors, availability, accessibility of information, and usability through fully informed datasets with corresponding metadata. Machine readability is also desirable for future machine to machine information communication and automated processing, implying the use of standards wherever possible at sensor, host (platform), and user interfaces. Sensor characteristics and interoperability enhancements have followed recommendations from the ESONET consortium (2), a.k.a the scientific backbone of the European Multidisciplinary Seafloor and water column Observatory (EMSO).

For the development of a cost-effective and reliable solution, above-stated challenges can be turned into the following system engineering requirements:

- High dynamic range
- Compressed information
- Autonomous platforms compatibility
- Infrastructure interoperability
- Synchronised sampling for array configuration

Several innovations are presented in this regard in this section.

B.1.1 Technical requirements

We focus on platform and sensor needs in the following tables. For example 180dB re 1 µPa was set as maximum received level. This accounts for attenuation due to source-receiver distance, because

[1] Parts of this contribution build on the results of ESONET and the NeXOS European projects.

measurements are oceanic and not meant to be performed at close range. Resolution, dynamic range, accuracy, sampling frequency, special requirements, among other requirements are provided in Table 5 and Table 6.

Table 5 ***Proposed hydrophone requirements for noise and bioacoustics in the open-ocean***

Resolution	Dynamic Range (DR)	Directivity	Accuracy	Sampling frequency	Special requirements	Other1	Other2
16 to 24 bits, with different gains to fit DR	<SS0; 50 to 180dB re 1uPa	Omni-Directional	+-3dB	100kSps	Embedded noise and bioacoustics statistics	Store on detection, Solid-state storage	Low power for stand-alone systems *ESONET Label

Table 6 ***Example of fixed stand-alone observatory characteristics for integration of new sensors***

PLATFORMS:	Deep Observatory- stand-alone (ESONET label used or recom.)
Power available for new sensors	48VDC-15VDC- 20W min (>=4 ports)
Deployment Duration	6 months-1 year
Operating depth range	0 to thousands of m
Transmission	Iridium for world coverage, ORBCOMM, ARGOS 3. VHF, Wi-fi – AirMAx, GSM, GPRS, EDGE, UMTS, HSPA, WiMAX
Ports communication protocols	RS232-422-485 – Eth 100 base T (copper)
Ports Plug and play capabilities	PUCK protocol, zeroconf/bonjour, 1-wire
Other relevant sensors	CTD
Clock for sensors	NTP, PTP (IEEE1588), Underwater GPS emulation + NMEA (all from local clock reference)

B.2 Development

This section describes the development of a new hydrophone (NeXOS A1) with multi-platform integration capability, addressing firmware, preprocessing functionalities, interfacing and hardware, leading to assembly prototype production.

B.2.1 Firmware overview

A very compact and low-power board was chosen as main CPU for the hydrophone, yet allowing for the implementation of sufficient firmware capabilities to encompass interfacing, control and digital signal processing functionalities, where:

- The sensor-side interface is in charge of providing the communication with the on-board sensors such as temperature and clock, and the acoustic transducers after the digital conversion.
- The "plug and play" middleware is in charge of implementing a standard protocol and warranting sensor metadata traceability
- The host-side interfacing allows for serial or Ethernet-capable platforms communication.
- A self-configuration service decodes the sensor metadata encoded in a standard format at power-on, retrieving the parameters values and starting the hydrophone sensing functions.
- Data recording (.wav file format for acoustic data), synchronization, and data transfer between internal processes is taken care of by the mother board.
- User-selectable digital signal processing tasks are performed, such as: click detection, whistle detection, noise measurement algorithms may be executed sequentially on the acoustic raw data.
- Standard Commands for Programmable Instruments (SCPI) encode all instrument commands.

B.2.2 Functionalities

The resulting hydrophone implements signal processing algorithms in order to provide the capabilities required to cover MSFD[2] Descriptors 1 and 11 for "Good Environmental Status", ensuring respectively that "Biodiversity is maintained" and "introduction of energy (including underwater noise) does not adversely affect the ecosystem". For Descriptor 1, three different algorithms (Click Detector, Whistle Detector and Low Frequency Tonal Sounds) are implemented. The first two are based on the open-source software PAMGuard[3] , the third on (3), we invite the reader to consult (4-6) for more details on the algorithms development. This decision was taken after a study of applicable referenced passive acoustic monitoring software (see (7) for details). For Descriptor 11, four different algorithms have been developed. MSFD requirements regarding Indicator 11.2.1 and Indicator 11.1.1 have been taken into account. These requirements have been extracted from (8-10). The purpose of these indicators is to assess the pressure on the environment by making available an overview of all low and mid-frequency, impulsive sound sources over a period of one year throughout regional seas. This will provide the European Member States with an overview of the environmental pressures.

B.2.2.1 Click and Whistle Detectors

The click and whistle detector algorithms are based on the PAMGuard open-source code, a leading community-based software development used in the cetacean research community. These broadband detectors mainly work on specific acoustic features of the upper part of the spectrum and are fittest for detecting toothed whales in general, like dolphins, beaked whales and sperm whales. We invite the reader to consult the resource available on-line[3] for further details on the detectors. Most efforts in this work for this specific functionality have focused on optimising and porting the code to an embedded platform, while maintaining it open-source in its ported version. Functional integrity of ported algorithms was then checked by comparing algorithm behaviour on a well-known commercial technical computing software. Open code

[2] European Marine Strategy Framework Directive
[3] www.pamguard.org

repository is still to be selected at the time of writing. Performance of this functionality is under validation at the time of writing, particularly with respect to false-alarm and storage needs.

B.2.2.2 Low Frequency Tonal Sounds

The algorithm is based on the technique depicted in (3), using the quantification of the prominence of spectral peaks. The result of this metric is compared with a threshold defined by the user. This metric can be computed in different ways, the entropy metric was chosen with values ranging from 0 to -1, being -1 when the spectrum is perfectly flat and 0 when there is a single peak in the spectrum. The algorithm is generally adapted to signals produced to baleen whales. The most challenging aspect of the implementation consisted in porting the algorithm to our embedded system, due to the memory limitations (2048 samples) hindering efficient (i.e. real-time) processing of the relatively long time durations necessary to detect consistent spectral peaks. As for the above, performance of this functionality is under validation at the time of writing.

B.2.2.3 Impulsive sounds indicator in 10Hz-10kHz band

The measure was implemented in this new development as a contribution to MSFD Indicator 11.1.1. The latter is defined as follows: the proportion of days and their distribution within a calendar year over areas of a determined surface, as well as their spatial distribution, in which anthropogenic sound sources exceed levels that are likely to entail significant impact on marine animals measured as Sound Exposed Level (in dB re 1 $\mu Pa^2 s$) or as peak sound pressure level (in dB re 1 µPa peak) at one meter, measured over the frequency band 10 Hz to 10 kHz. Amount of data to be transmitted can be selected by the user.

B.2.2.4 Trends in third octave bands

The measure contributes to Indicator 11.2.1, defined as: trends in the ambient noise level within 1/3 octave bands 63 and 125 Hz (centre frequency) (re 1 µPa RMS; average noise level in these octave bands over a year) measured by observation stations and/or with the use of models if appropriate (11.2.1). Two digital filters are applied to the input signal. The filters are third-octave band filters, which fulfill with base – ten systems and class 0 filters according to IEC 61260 (1995) standard. While indicator 11.2.1 requires third-octave bands 63 and 125 Hz, recommendations have been expressed to extend the range of ambient noise level to (20 Hz – 20 kHz). The number of third-octave bands within this frequency range according to IEC 61260 (1995) being 30, a total of 30 filters are applied to the input signal in order to obtain the SPL_{rms} for each frequency band. Signal decimation stages were implemented to this aim. This was needed due to filtering implementation constraints of the processing platform, and consisted in the process of pre-filtering and decreasing the sampling frequency of a given signal, therefore after the decimation process by two different orders, two new sampling frequencies were obtained (1kHz and 16 kHz). Basic modules of this algorithm are the same as in the indicator 11.2.1 except for the decimation module.

B.2.2.5 Noise Band Monitoring

This algorithm calculates ambient noise level trends within a frequency band defined by the user. The general foundation is the same as for indicator 11.2.1. The structure defined for this algorithm is similar to indicator 11.2.1. Instead of two filters (63 and 125 Hz), the algorithm takes a user-defined filter.

B.3 Acoustic specifications

This section summarises overall characteristics of the new hydrophone, including acoustic specifications for three transducer types (D70, SQ26 and JS-B100) meant for different depth ratings, while maintaining similar characteristics.

Table 7 Transducer types and characteristics

Hydrophone type	**D/70**	**SQ26-01**	**JS-B100**
Sensitivity ChA	-138/-158 dB re 1µPa	133.5/-153.5 dB re 1µPa	-141/-161 dB re 1µPa
Sensitivity ChB	-178 dB re 1µPa	-173 dB re 1µPa	-181 dB re 1µPa
Frequency range (±1,5dB)	from 1Hz to 50kHz	from 1.15Hz to 28kHz	from 1Hz to 50kHz
Sea noise equalizer	HP filter one pole 3.2 kHz	HP filter one pole 3.2 kHz	HP filter one pole 3.2 kHz
Beam pattern	Omni-directional	Omni-directional	Omni-directional
Input equivalent noise (@5kHz G=60dB)	27dB re1 µPa/√Hz	22.5 dB re1 µPa/√Hz	30dB re1 µPa/√Hz
Full BW dynamic range	136dB using 2x16 bit ADCs and gains		

A1 Electrical / Mechanical characteristics

Supply voltage	4.6 to 42Vdc.
Power consumption sleep	30mW.
Power consumption min	350mW.
Max consumption(full CPU speed)	1W.
Connector	SubCon MCBH12M (ESONET label).
External coat	Polyurethane.
Size	Φ34 x 255mm.

Hydrophone type	**D/70**	**SQ26-01**	**JS-B100**
Working depth	up to 1500m	up to 2000m	up to 3600m
Weight	333 g	317g	333 g

Software Settings:

It is possible to set the following parameters, through software commands:

Sampling frequency: up to 100 ksps.

CHA sensitivity: -138 / -158 dB re 1 µPa.

Equalizer (HP filter): 1 Hz / 3200Hz.(one pole)

Channel selection: A&B - A - A with Equalizer - B.

Hydrophone type	**D/70**	**SQ26-01**	**JS-B100**
CHA sensitivity	-138 / -158 dB re 1 µPa	133.5/-153.5 dB re 1µPa	-141 / -161 dB re 1 µPa

B.4 Compliance and recommendations with fixed open-ocean moorings

The majority of FixO^3 observatories consist of fixed open-ocean moorings, powered by and communicating via a single point surface buoy (see example in Figure 8). Considering the main constraints are limited power and communication, importance must be given to the capability to communicate acoustic information via a bandwidth limited serial port (RS232), i.e. limited to a maximum bit-rate of 115200 bit/s, and ideally less than 1Watt power consumption in active mode, i.e. for acquiring, processing and communicating to a data logger. The preprocessing capability added to the low-power consumption and serial communication make the sensor compatible for fixed moorings power and communication constraints.

An important issue remains partly unresolved with passive acoustics on fixed open-ocean moorings. Mechanical vibrations transmitted to the mooring from the surface buoy movement and most significantly cable/rope tension variation affect the quality of the acquired signal if the transducer is physically attached. While these artefacts may be a minor issue for high sound levels application such as marine mammal acoustic detection, this is particularly relevant for ambient noise measurements and measurement or detection of low sound pressure levels. While there is no standard solution, a possibility consists in decoupling, partially or totally, the surface buoy movement from the hydrophone system. This can be done by different means with different degrees of complexity, success and costs, being the most effective yet costly the installation of a second mooring or lander communicating via modem with the surface buoy. Few FixO3 observatories provide such capability today.

Other considerations should be taken care of, where possible, such as reducing the impact of other communication or mechanical noise interferences. Acoustic modems communication and sensor pumps duty cycles should be adapted to the monitoring strategy, or reciprocally.

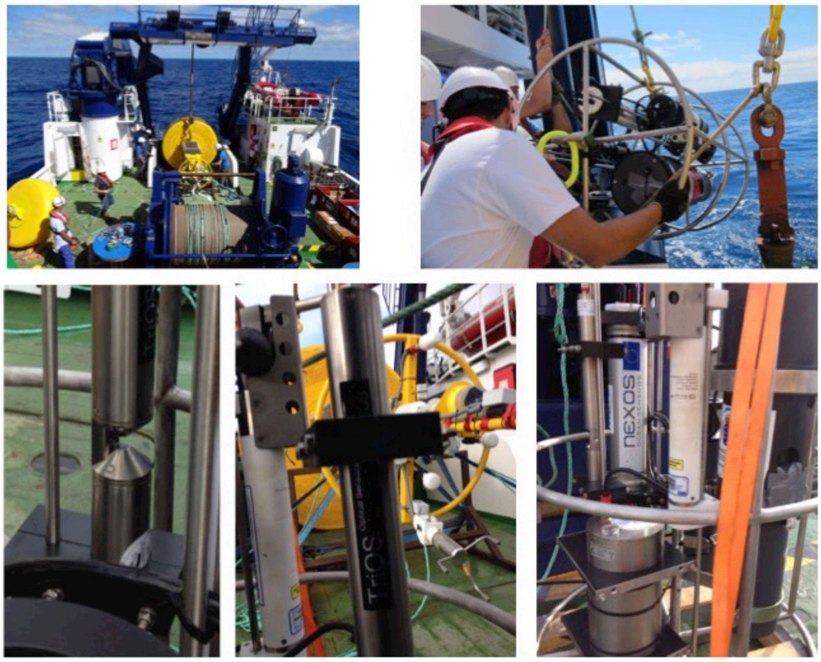


Figure 8 ***PLOCAN-ESTOC buoy (top left) on Spanish Insitute of Oceanography (IEO) RV Alvariño deck before deployment in 3630m water depth, 60 nautical miles North of Gran Canaria and frame (top and bottom right) with acoustic recorder, later positioned at 150m depth. Source: PLOCAN***

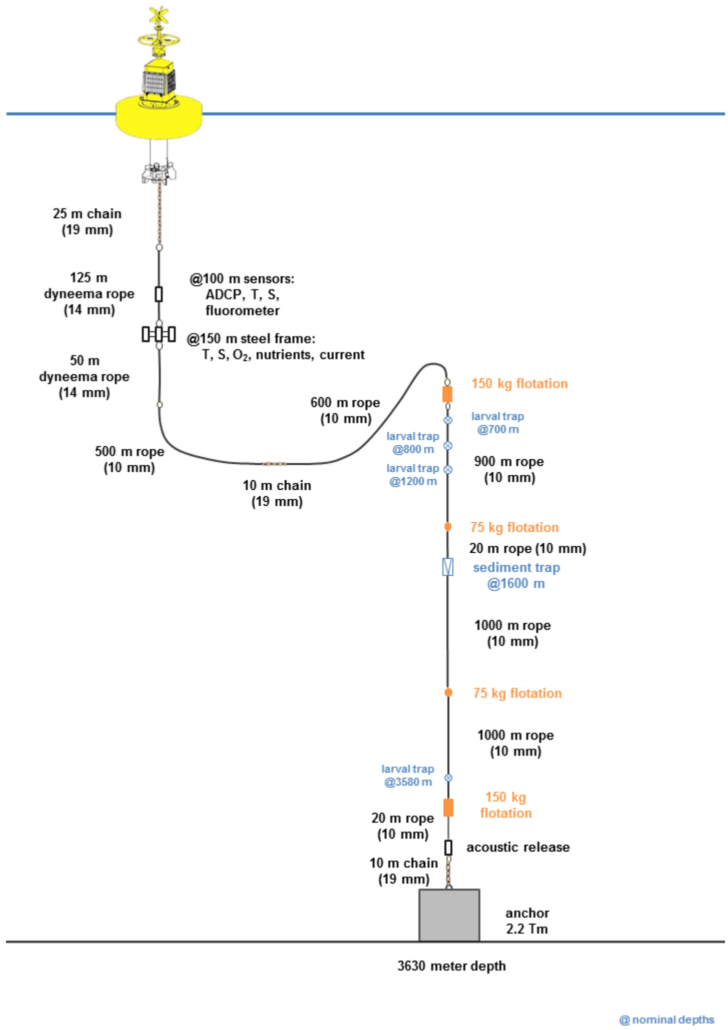


Figure 9 ***ESTOC Mooring design. Source: PLOCAN***

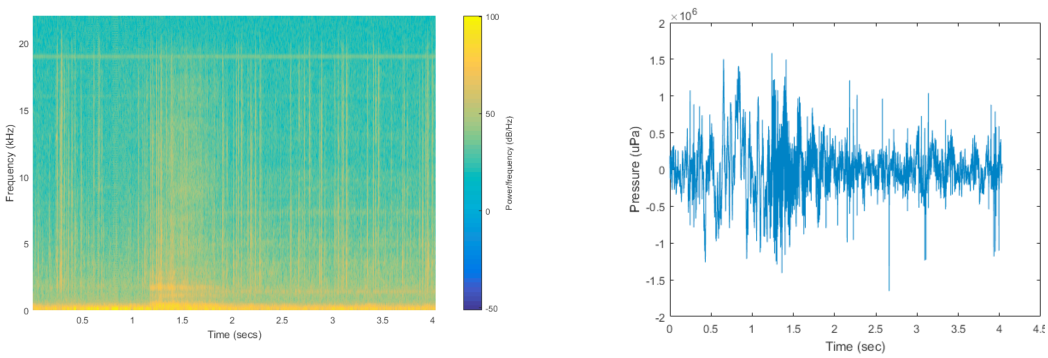


Figure 10 ***Mixture of Sperm Whale clicks and mechanical noises (cable-shackle rubbing noise and tonal pumping noise) on ESTOC, at 150m depth. Source : PLOCAN***

B.5 Sensor Web for Passive Acoustics

As proposed in (11, 12) for passive acoustics, innovation is also now underway to enhance interoperability of passive acoustic information and sensors, in a similar way as what has now long been promoted by the environmental and oceanographic data management community. This results in better usability, and sustainability of passive acoustic information and improved discoverability of sensors and sensor status. By encoding sensor metadata following common standards, a diversity of users and user clients (human or machines) can also connect to self-describing services independently of the technology. Examples of such encodings (here in XML, following the the SensorML 2.0 schema, an open standard) are:

Assignment of short description name and universal identifier:

```
<sml:Term>
    <sml:label>shortName</sml:label>
    <sml:value>NeXOS A1 Hydrophone</sml:value>
</sml:Term>
<sml:Term>
    <sml:label>UUID</sml:label>
    <sml:value>0fe65afd-4026-4754-b247-921299bb3b88</sml:value>
</sml:Term>
```

The data output type (here for 10 percentile level and dB as unit of measure):

```
<swe:field name="SPL_L10_63Hz">
    <swe:Quantity
definition="http://vocab.nerc.ac.uk/standard_name/sound_pressure_level_in_water">
<swe:uom code="dB"/>
    </swe:Quantity>
</swe:field>
```

The Instrument command that the service needs to implement to request a given functionality (here measuring noise):

```
<sml:input name="dataIn">
```

```
<sml:DataInterface>
    <sml:data>
        <swe:DataStream>
            <swe:elementType name="command"/>
                <swe:encoding>
                <!-- Define the text encoding -->
                    <swe:TextEncoding                tokenSeparator=","
blockSeparator="&#x000D;&#x000A;"/>
                </swe:encoding>
                <!-- Define the command string -->
                <swe:values>MEAS:NOISE?</swe:values>
        </swe:DataStream>
    </sml:data>
</sml:DataInterface>
</sml:input>
```


Figure 11 shows a schematic of the hydrophone low-level architecture to achieve plug and work capability and the protocols used for low-level communication, where the main innovating parts are the processing and the standard metadata embedded and hosted by the sensor itself, including self-description of how the host should communicate with the sensor.

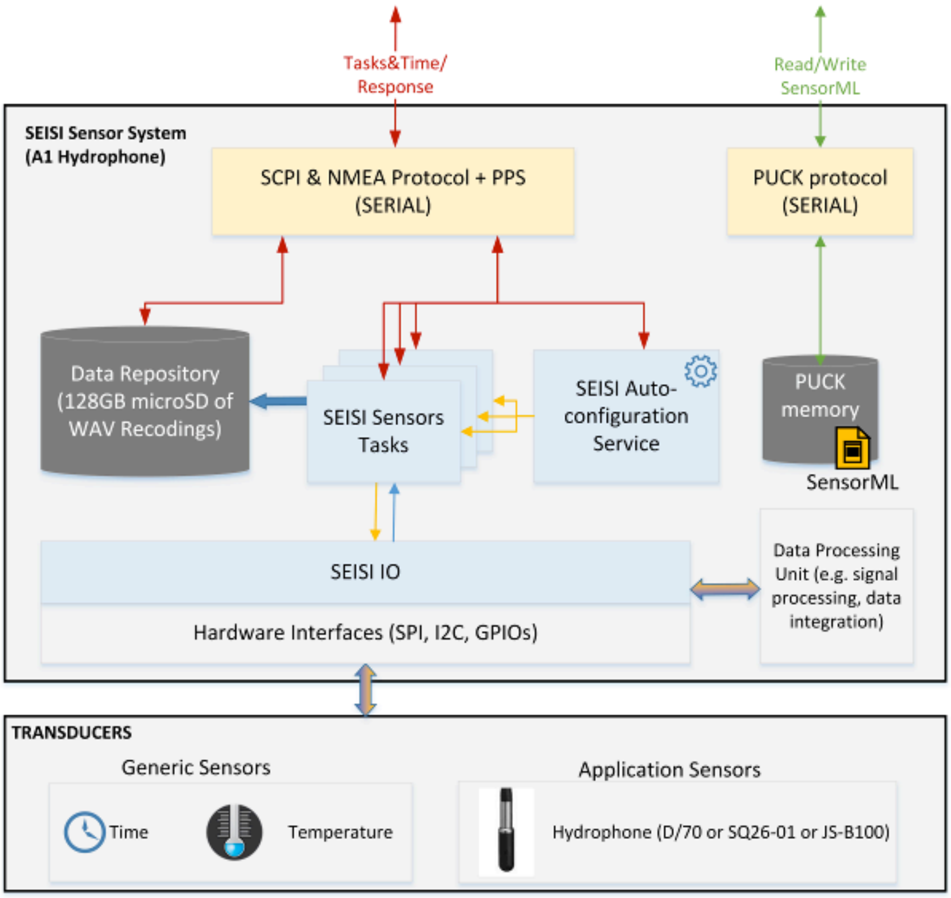


Figure 11 ***A1 Firmware Architecture showing the PUCK payload that holds the hydrophone unique SensorML instance, the low-level communication protocols, data processing, storage capability. Source: UPC-SARTI, NeXOS.***

Visualisation of processed data as transmitted through a RF link (here a noise statistical feature) is illustrated in Figure 12.

Figure 12 ***Visualization front-end of preprocessed noise level statistics for 125 Hz L90 transmitted to the sensor web. dB unit is referenced to 1uPa. Source: PLOCAN, 52N, UPC, CTN.***

B.6 Summary

In an attempt to summarise specifications, NeXOS A1 is a compact, low power, low noise digital hydrophone with embedded processing, consisting of one transducer and two A/D stages with different sensitivities to detect bioacoustics sources and measure acoustic source level spectral statistics from 50 dB to 180 dB re 1 µPa. Main innovations encompass:

- Smart integration with plug and work standard implementation (OGC-PUCK).
- Measurements of anthropogenic activities, nature sounds down to seismic events (sensitivity down to 1Hz).
- Standard web based availability of marine acoustic data.
- Open source for add-on programming.
- Stream / store raw data and/or processed data.
- Two Channels with different sensitivities for very wide dynamic range

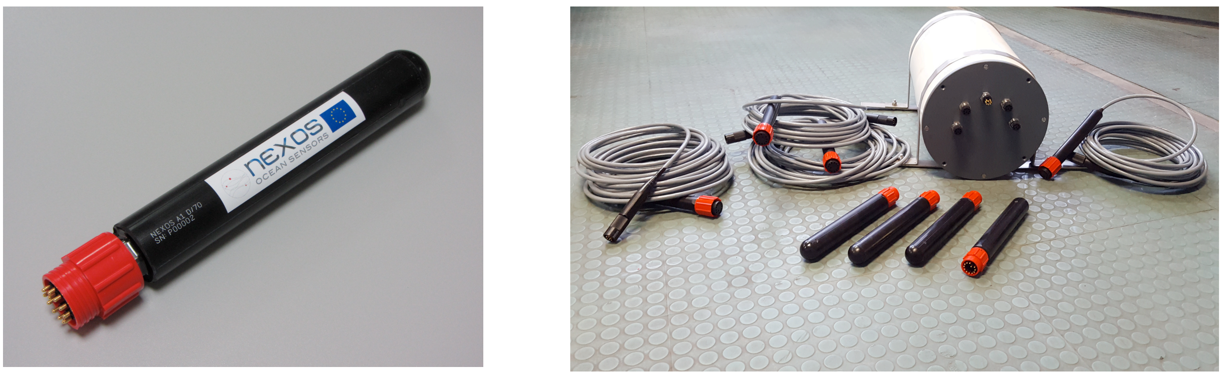


Figure 13 ***A1 and A2 (A1 array configuration with master unit and synchronised sampling) include preprocessing of acoustic raw data and interoperability standards for information flow to ocean observatories infrastructures. Source: NeXOS WP6 (PLOCAN, SMID,***

UPC, CTN).

The section has highlighted some current challenges and opportunities of passive acoustic monitoring from open-ocean stand-alone observatories. Satellite air-time costs being prohibitive for environment monitoring, on-board processing of acoustic data reveals to be a important functionality. The Internet of Things also calls for standard solutions and one has been presented where sensor metadata and services can be discovered and accessed with relative ease and allow for improved user experience.

B.7 References

1. Baumgartner MF, Fratantoni DM, Hurst TP, Brown MW, Cole TVN, Van Parijs SM, et al. Real-time reporting of baleen whale passive acoustic detections from ocean gliders. The Journal of the Acoustical Society of America. 2013;134(3):1814-23.
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C EMSODev D3.1 excerpt on specifications for hydrophone calibration

1.1. Metrological references and standards

Preliminary recommendation. The coexistence of acoustic applications such as passive acoustic hydrophones, data transmission modems and Acoustic Doppler Current Profilers may pose the problem of time-frequency overlap that must be addressed by synchronisation processes, spatial separation and software based-solutions. In some cases of acoustic interference, the use of frequencies from hydrophone and active acoustic device (ADCP and acoustic telemetry) will have to be shared by temporary stop of some equipment. Such acoustic sharing must be documented as a specification of the EGIM. It is also necessary to know the directivity of all acoustic systems in order to diminish interference.

Among others, issues to be addressed are:

- Calibration procedures:
    - **standardized tank calibration** (defined in this D3.1 document),
    - sea tests (see D4.1)
    - auto-calibration *in situ*
- standardization of raw and processed data format as standardized by ICES are recommended (to be addressed in WP4 and WP6);
- Bio-fouling protection will be addressed in WP3 design document.

The main standards to be used as references are:

- ANSI/ASA S1.20-2012, *Procedures for Calibration of Underwater Electroacoustic Transducers*, American National Standard Institute, USA, 2012.
- IEC60565: 2006 *Underwater acoustics-Hydrophones - Calibration in the frequency range 0.01 Hz to 1 MHz*, IEC 60565 - 2006 (EN 60565: 2007, BS60565:2007), International Electrotechnical Commission, Geneva, 2006.

Our recommendation is to stick to calibration protocol from Ifremer in lab at a first stage.

Standardization is very active under International Organization for Standardisation (ISO), within ISO Technical Committee 43, Sub-Committee 3 (ISO TC43 SC3) which has the title “Underwater Acoustics”. Note that an EMPIR call for project deals with the metrology associated with Marine Strategy Framework Directive marine noise parameter. Already, the EU Technical Sub-Group on Noise (EU TSG Noise), an expert committee which was set up to provide guidance on the implementation of the EU Marine Strategy Framework Directive (MSFD), has produced recent reports which partly cover the topic of guidance on *in-situ* noise measurement.

1.2. Calibration procedure

A calibration protocol is provided in the appendixes, directly copied and translated from ISO9001 accreditation of the Acoustic Subsea Laboratory of Ifremer (Yves Le Gall):

- appendix 6: Measurement procedure for electroacoustic transducers – Ifremer AS 2013-56
- appendix 7: Procedure for the reciprocity method – Ifremer AS 2013-57
- appendix 8: Procedure to use hydrophone calibrator B&K 4229 – Ifremer AS 2013-55

It is suggested to use these procedures or equivalent ones and keep track of the possible variations through the life of the hydrophones.

1.3. Best practice and recommendations

Among the recommendations, the environmental tests on hydrophones must include pressure test to validate the full range of depth required for the EGIM. A monitoring of the electrical characteristics during the pressure test helps to validate the *in-situ* operation behavior.

The calibration should cover the full frequency range of interest for the specific application at hand. It is possible to calibrate a hydrophone and recording system with an overall uncertainty of better than 1 dB (expressed at a 95% confidence level). It is recommended that a full laboratory calibration is undertaken before and after every major deployment or sea-trial

Key performance parameters are:

- Sensitivity
- frequency response
- directivity
- system self-noise
- dynamic range.

As EGIM will be used on the seafloor or on a mooring line or onboard a buoy, the mechanical design should include estimates of strumming noise of the mooring cable or hydrodynamic wave induced noises of a floating platform and try to minimize these noises.

1.4. Suggested calibration laboratory (non exhaustive)

Laboratory and small tank calibrations can be performed at Ifremer Brest Center by IMN/NSE/AS team (contact person Y. Le Gall)

1.5. References

ANSI/ASA S1.20-2012, *Procedures for Calibration of Underwater Electroacoustic Transducers*, American National Standard Institute, USA, 2012.

IEC60565: 2006 *Underwater acoustics-Hydrophones - Calibration in the frequency range 0.01 Hz to 1 MHz*, IEC 60565 - 2006 (EN 60565: 2007, BS60565:2007), International Electrotechnical Commission, Geneva, 2006.

UK National Physical Laboratory - Good Practice Guide for Underwater Noise Measurement - NPL Good Practice Guide No. 133 ISSN: 1368-6550

Operating procedure for Brüel&Kjaer type 4229 hydrophone calibrator

Ifremer

Département Infrastructures Marines et Numériques

History			
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Document Name:	Operating procedure for Brüel&Kjaer type 4229 hydrophone calibrator
Project Title:	Underwater acoustics
Summary:	This document specifies the procedure for measurement of hydrophone sensitivity in reception (S_h) at 251.2 Hz using the hydrophone calibrator B&K4229.
Keywords:	Quality; ISO 9001 Certification; Operating procedure; Calibrator; Hydrophone; Sensitivity

Author		
Yves Diascorn (IMN/NSE/AS)	*Date*: 29/11/2013	*Visa:*

Approved by		
Yves Le Gall (IMN/NSE/AS)	*Date*: 29/11/2013	*Visa:*
Marc Nokin (IMN/NSE/D)	02/12/2013	

IFREMER – *Centre de Brest*
Unité Navires et Systèmes Embarqués (PDG/IMN/NSE)
ZI de la Pointe du Diable – CS 10070 – 29280 PLOUZANE
Téléphone : 02 98 22 41 83 - Télécopie : 02 98 22 45 46

The Brüel & Kjaer type 4229 hydrophone calibrator is a precision, high sound pressure source, used for quick and easy calibration of Brüel & Kjaer hydrophones. Its operating principle is identical to that of a pistonphone, generating a perfectly defined acoustic pressure in the coupler or adapter cavity.

The Brüel & Kjaer type 4229 hydrophone calibrator is used at the Ifremer to verify the sensitivity in reception (S_h) of Brüel & Kjaer type 8100, 8101, 8103, 8104 and 8105 hydrophones, at a frequency of 251.2 Hz ± 0.1%, using the appropriate coupler for each of these captors. At this frequency, the sensitivity of Brüel & Kjaer hydrophones is virtually identical in air and in water. The calibration can therefore be done in air without affecting the accuracy.

An extension to the Reson TC4034 hydrophone, with construction of a specific adapter, has been implemented by the Ifremer.

The equipment required for the realization of a measurement (Figure 27) is the following:

- B&K type 4229 hydrophone calibrator
- Hydrophone(s) to be verified
- Adapter(s) or adapted coupler(s)
- Oscilloscope
- Power input in the case of pre-amplified hydrophone(s)

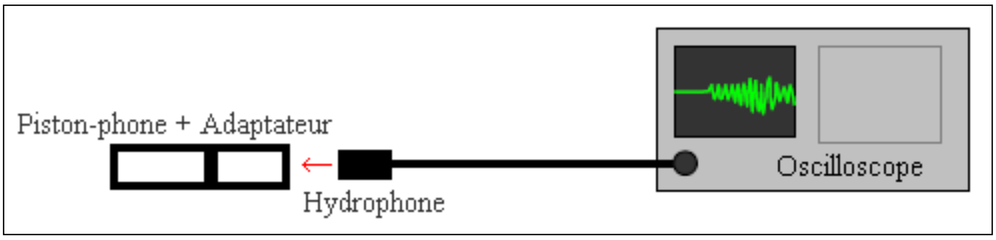


Figure 14: Assembly diagram

1. Check that the hydrophone calibrator is working correctly. When the switch is "On", the red LED should be lit and a very low frequency sound should be emitted.

2. Select the adapter depending on the hydrophone to be measured:

Hydrophone	B&K 8101/8105	B&K 8100/8104	B&K 8103	Reson TC4034
Adapter	UA 0546	UA 0547	UA 0548	IF 0001

3. Connect the hydrophone to the oscilloscope, do not forget to power it, in the case of a preamplified hydrophone, and measure the effective voltage received.

4. Spread some glycerol UA 0552 (provided in the hydrophone calibrator case) on the surface of the hydrophone.

5. Unscrew the adapter cap slightly to allow air to flow, screw the adapter onto the calibrator and insert the hydrophone, then rescrew the cap.

6. Turn the hydrophone calibrator on and check the frequency on the oscilloscope by using the measurement cursors. It should be about 251.2 Hz.

7. Next, read the effective voltage U_{eff} obtained on the oscilloscope (Fig. 28). If necessary, use the statistical function of the oscilloscope in order to obtain an average value.

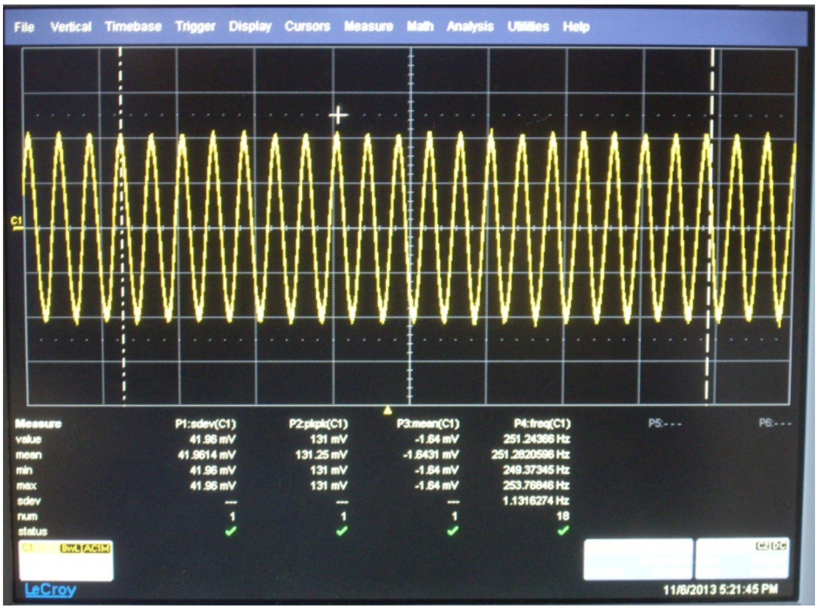


Figure 15: Visualization of the 251.2 Hz signal and the average value of the hydrophone voltage Ueff on the oscilloscope

8. Read the SPL_{doc} (*Sound Pressure Level* in dB ref. 1 µPa) corresponding to the tested hydrophone on the most recent calibration certificate (available in the hydrophone calibrator case, as well as on the intranet page “Parc Capteurs et Instruments” (Sensors and Instruments Park) and then use the formula:

$$S_h = 20\log(U_{\text{eff}}) - \text{SPL}_{\text{doc}}$$

where U_{eff} is in V_{rms}

9. Correct the calculated result for the ambient atmospheric pressure: the correction factor is indicated on the UZ 0004 barometer provided with the hydrophone calibrator (Figure 29).

Figure 16: Barometer UZ 0004 - here the correction to be made is

-0.1 dB

10. Fill in the tracking form for the hydrophone on the intranet page “Parc Capteurs et Instruments” (Sensors and Instruments Park) intranet page (date, operator, intervention, S_h value obtained, compliance).

D Example of a stand-alone recording system

EA-SDA14
Acoustic Recorder

Key features

- Autonomous and wired mode
- Until 4 hydrophones at the same time
- 24 bit data acquisition
- Selectable bandwidth acquisition
- Native 128 GB SD Card
- Programmable mission schedule
- Battery and attitude monitoring
- Calibration table for measurement accuracy
- 200, 700 or 3500 m operating depth

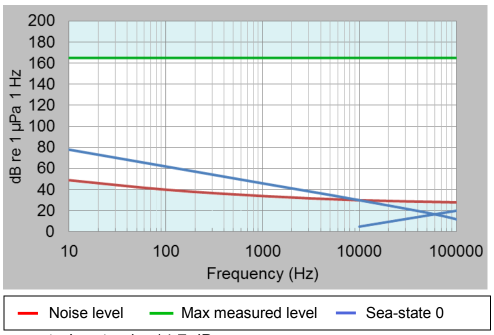
Options

- 1 or 2 TB HDD or 600GB SSD memory
- Additional battery for larger autonomy
- Additional temperature / pressure sensors
- Low frequency acquisition module

Fields of application

- Offshore and environment
- Scientific instrumentation
- Autonomous passive recording
- Hydrophone network

Typical application



- Input gain: 14.7 dB
- High quality hydrophone with Sh = - 174 dB re V/µPA

Description

The EA-SDA14 is a compact autonomous recorder that can simultaneously acquire the data of 4 wideband hydrophones.

The Acoustic Recorder accepts both passive and preamplified active hydrophones. Its wide band analog input allows until 1 MHz with a dynamic range greater than 100 dB which guarantees an efficient signal to noise ratio.

The embedded digital signal processor allows high speed acquisition, filtering and storage.

In autonomous mode, the data are stored on either a SD Card or a HDD.
In wired mode, the data ae stored then transferred with an Ethernet connection.

Its power consumption is between 0.6 to 2.5 W operating and less than 1 mW in standby.

The EA-SDA14 can be programmed with a mission schedule that includes the start date and the active / standby periods of the record cycles to improve battery life.

The configuration and monitoring are done through a web browser interface.

Short aluminum model characteristics:
Dimensions: Length 320 mm
Diameter 120 mm
Weight (air): 5 kg
Weight (water): 2 kg

Oct. 2015