31. Passive acoustic monitoring

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Continuous monitoring in the ocean over prolonged periods of time is notoriously difficult, no matter what animal is in focus. Observers are generally restricted to the surface and must rely on cameras or other remote sensing tools to observe what is going on in the deep. Vision is often of little help, as visibility is poor compared to in air and light only penetrates to limited depth. Sound on the other hand travels well in water and many marine animals use sound for communication and orientation. This is exploited in various passive acoustic monitoring systems. These systems, when properly designed, can provide uninterrupted time series of animal activity over extended periods of time.

Data reduction

Recording of sound in the audioband (20-20.000 Hz) has never been easier than it is today, where digital recorders are cheap, reliable and easy to operate. Even wideband systems with bandwidths up to 200 kHz or more are now reasonably easy to find or construct. The main problem with sound recordings is no longer hardware, but information overload. The amount of data generated by digital recording systems are immense, illustrated by a few examples in *Table 1.*

Table 1

Application	Bandwidth	Data per second	Data per day
Fin whale single hydrophone	100 Hz	0.4 kbytes	33 Mbyte
Fish single hydrophone	500 Hz	2 kbytes	160 Mbyte
Baleen whale wide band single hydrophone	1000 Hz	4 kbytes	320 Mbyte
Dolphin audio range single hydrophone	20 kHz	78 kbytes	6.4 Gbyte
Porpoise wide band single hydrophone	200 kHz	0.8 Mbyte	64 Gbyte
Dolphins wide band array (4 hydrophones)	400 kHz	6.1 Mbyte	510 Gbyte

Note: Calculation of data amount per second: 2*BW*(bits/8)*channels, where BW is bandwidth in Hz (= half the sampling frequency), bits is the resolution (often 8, 12 or 16 bits) and channels is the number of hydrophones.

For low frequency applications, such as listening for baleen whales or fish, the amount of data generated is manageable and it is possible to have a simple digital recorder running continuously for many days before running out of storage space. This strategy has serious drawbacks however, as the time taken to process the many days of continuous recordings may be tremendous. The key to successful long term monitoring is data reduction. The more processing can be performed real-time, the easier the data analysis becomes afterwards.

Ultrasound detectors

Batdetectors (heterodyning and divide by 10) and porpoise/dolphin detectors (envelope detectors) were originally developed to make ultrasonic signals audible to the human ear. This has the side effect that ultrasonic signals can be recorded on an ordinary cassette tape recorder or a standard computer soundboard. Depending on type and signals in question, these detectors can provide compression rates up to 1:20, but always at the cost of complete or partial loss of information on frequency spectrum and intensity. Temporal information (signal durations and time of occurrence) is faithfully recorded, however.

Triggered recordings

If the signals one is interested in recording are comparatively rare occurring events, one will inevitably end up with endless recordings containing almost nothing of interest, when using continuously recording systems. In these situations it can be of tremendous advantage to use triggered recordings, where only the interesting bits are saved. This can be done through some circuit that continuously monitors the input and once the input exceeds a certain level, the recording mechanism is activated. Through this technique, very high compression rates can be achieved. The major advantage of triggered recordings is that (ideally) only the silent parts between signals are removed and complete information on the signals themselves are preserved with full bandwidth. Drawbacks include the risk of recording only a fraction of the sounds present, or alternatively record a number of irrelevant sounds, if the trigger level is not accurately adjusted. A further problem is of statistical nature, as one has incomplete information on what goes on when the system is not recording. This may or may not have implications in terms of how well recordings can be generalised to the entire period. An example could be a system, which automatically adjusts trigger level according to the background noise. This is a clever thing to do, if one wants to optimise the number of calls recorded, but it prevents one from concluding that animals are absent in periods where no sounds are recorded, as lack of recordings could also be caused by an elevated background noise level, which masks out the calls.

Filtering and event recording

If one is opting for maximal compression and can accept that only some information on the signals of interest are recorded, then it is possible to perform some intelligent filtering of the signals and extract only the relevant information. Some animals, such as harbour porpoises, have signals that are extremely stereotypic. One can then design a detection system with high selectivity towards this signal and instead of recording the entire signal retain only the most central information: time of occurrence. It is also possible to extract a limited number of other parameters characterising the signal, such as duration, peak intensity and perhaps a few points characterising signal envelope or frequency spectrum. Through this intelligent filtering compression rates of well above 1:1000 can easily be realised.

Types of systems

Three examples of acoustic monitoring devices are described below. Main focus is on the T-POD (porpoise detector), with additional comments on pop-up tags and towed arrays.

T-POD porpoise detector

For porpoise detection one can rely on the highly stereotypical nature of porpoise sonar signals. These are unique in being very short (50-150 microseconds) and containing virtually no energy below 100 kHz (*Figure 1*). Main part of the energy is in a narrow band from 120-150 kHz, which makes the signals ideal for automatic detection. Most other sounds in the sea, with the important exception of echosounders and boat sonars, are characterised by being either more broadband (energy distributed over a wider frequency range), longer in duration, with peak energy at lower frequencies or combinations of the three.

The actual detection of porpoise signals is performed by comparing signal energy in a narrow filter centered at 130 kHz with another narrow filter centered at 90 kHz. Any signal, which has substantial more energy in the high filter relative to the low and is below 200 microseconds in duration, is highly likely to be either a porpoise or a man-made sound (echosounder or boat sonar).

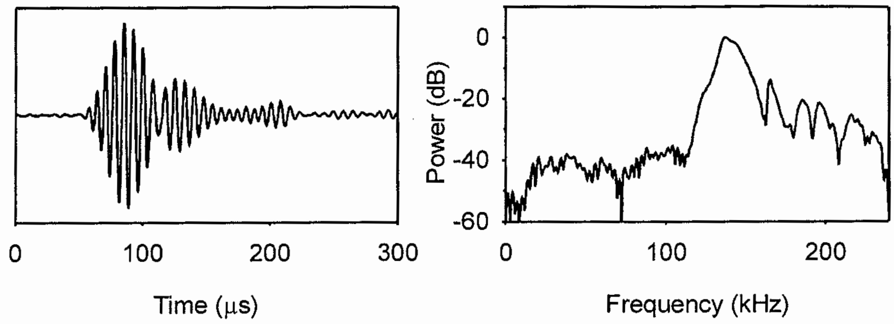

Figure 1 Porpoise click time signal (left) and power spectrum (right). There is virtually no energy present below 100 kHz (the curve below 100 kHz represents background noise of the recording).

Some spurious clicks of undetermined origin (e.g. background noise and cavitation sounds from high-speed propellers) may also be recorded. These, as well as boat sonars and echosounders can be recognised by analysing intervals between clicks. Porpoise click trains are recognisable by a gradual change of click intervals throughout a click sequence, whereas boat sonars and echosounders have highly regular repetition rates (almost constant click intervals). Clicks of other origin tend to occur at random, thus with highly irregular intervals.

No other cetacean regularly found in European waters has sonar signals that can be confused with porpoise signals. Dolphins (with the exception of the genus *Cephalorhynchus*, which does not occur in European waters) use broadband sonar clicks, i.e. energy distributed over a wide frequency range, from below 20 kHz to above 150 kHz (Au, 1993). It is thus highly unlikely that they will trigger the T-POD, when settings are adjusted to detect porpoises.

Porpoise detectors deployed over longer periods provide excellent opportunities to study temporal variation in porpoise abundance, either on a daily or yearly basis. If sufficiently good baseline data are recorded, the T-POD may also provide good indications of the magnitude of disturbance to porpoises inflicted by short-term or long-term changes in the environment. This includes, but is certainly not limited to, the study of disturbance by offshore construction activities, seismic surveys, explosions etc.

The greatest challenge in analysing porpoise detector data, whether from a T-POD or other type, is the weak link between what are recorded (individual clicks) and what information is sought (porpoise abundance). Click data can be summarised in various ways as average number of clicks per minute, average clicks per minute for non-zero periods (sometimes somewhat misleadingly referred to as *click intensity*), fraction of day with click activity (also somewhat misleadingly referred to as *click frequency*), but also grouped into encounters, i.e. groups of clicks presumed to represent visit by one animal (or group of animals). Encounters can be further described through their average duration, encounter counts per day and average interval (waiting time) between encounters. Through appropriate transformations these parameters can be used to test statistical hypotheses regarding changes in abundance and behaviour of the animals. There are however, two central and largely unsolved questions in this context:

- Does a decrease in one or more of the parameters reflect a decrease in abundance of porpoises, or does it merely signify that the behaviour of the animals changed in a way that causes fewer clicks to be recorded by the POD?
- Even if we assume that behaviour is unaffected, does a decrease in a parameter of e.g. 20% signify that there are 20% fewer porpoises in the area?

The first question probably cannot be answered from the data themselves, but must be answered through collection of additional data by other means (visual observations, satellite telemetry, tracking of animals by hydrophone arrays etc). The answer to the second question is almost certainly that there isn't a 1:1 correspondence between parameters and animal abundance. These two issues should be a main focus for T-POD investigations in the coming years, as they are central for maturing the T-POD technology into a more quantitative tool in monitoring. The situation today is that we can conclude from T-POD data that animals are present, with some qualitative index of density and that one or the other event (e.g. a construction activity) causes a change in abundance (either up or down), but we are unable to relate these changes to actual number of animals.

Continuing from this lies the perspective of developing analysis methods that will turn the T-POD or related systems into truly quantitative tools. This requires that a link is established not only to number of animals, but also densities (animals per unit area). T-POD data can be considered to originate from a special variant of a point sampling technique and quantitative methods exist for treatment of such data. The most powerful method is distance sampling, in which the distance from the observation point to each observed animal is determined and on the basis of these data a detection function is modelled. This function describes the probability of detection of animals with increasing distance from the observation point and allows for transformation of counts into animals per unit area. Several obstacles lie in the way before this goal can be achieved, however. First of all, a clear relation, even if only statistical, between clicks and group size must be established. This would probably rely on visual observations of animals concurrent with T-POD recordings or other, independently collected information. Secondly, reliable methods for determining distance to observations must be developed, in order to determine the detection function. This could either be visual methods (tracking by theodolit) or acoustic, via a smaller or larger array of hydrophones.

Even with all its limitations and current gaps in knowledge on interpretation of data, the T-POD has proved to be an extremely powerful way of analysing porpoise abundance and behaviour. The method is still in its infancy and the coming years will no doubt bring a wealth of new information on porpoise behaviour, achieved through carefully designed T-POD studies.

IFAW towed array

In terms of detection of harbour porpoise signals, the IFAW towed array is not principally different from the T-POD, although the physical realisation is different. It also relies on the small bandwidth of the porpoise signal and filters out signals with significant energy outside this band. In earlier versions of the system filtering was performed by hardware filters, but in recent versions all processing is performed by a PC.

The principal power of the IFAW array lies in the ability to detect harbour porpoises acoustically from a sailing ship and also determine their position relative to the ship. This approach holds many promises. First of all it allows line transect surveys to be conducted in areas of low porpoise abundance, where visual observations are inefficient. A towed array also allows for surveys to be conducted under conditions where visual surveys are impossible (e.g. at night and at sea states above 2 Beaufort). The array is able to detect porpoises out to distances of 100-200 meters from the ship.

A second powerful feature of the towed array is the ability to determine the position of animals, relative to the ship. This is done by repeated determination of bearing to the animal and taking advantage of the fact that the ship is usually sailing at significantly higher speed than the porpoises (*Figure 2*). Determination of the position of the animal first of all allows for visual confirmation of the observation and determination of number of animals travelling together. The second important possibility offered by the array and so far not exploited, is the application of *distance sampling* methodology to observations. Distance sampling is a set of tools developed for visual surveys, that allows

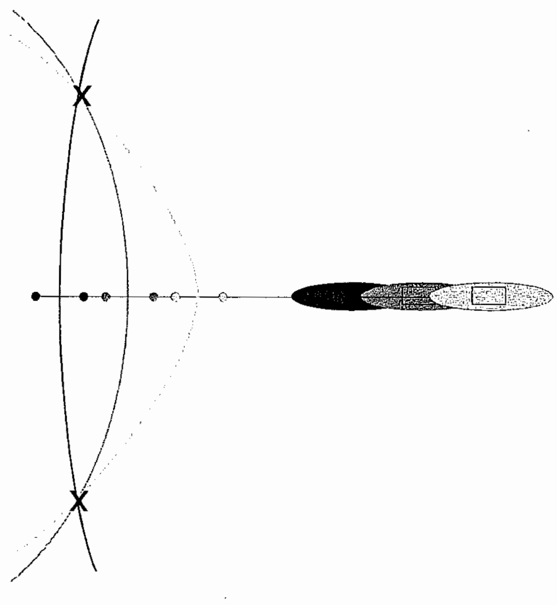

Figure 2 Localisation by the IFAW towed array. Shown is the situation at three different positions of the ship and the two-hydrophone array. At each position the porpoise can be positioned on a hyperbolic curve and by combining the three curves (assuming that the ship moves significantly faster than the porpoise) the position can be found (marked X). Due to the symmetry of the array, the animal can be on either side of the ship. Movement of ship greatly exaggerated.

calculation of absolute densities (animals per unit area), as mentioned above. A successful application of distance sampling methods to towed array systems raises large perspectives for conduction of surveys at regular intervals as part of a general monitoring effort on selected species, such as the harbour porpoise.

Pop-ups

The Autonomous Recording Unit (ARU), more commonly known as a Pop-Up, was developed by Cornell University in the late 1990's. It is a datalogger intended for long-term deployment in the oceans at depths up to 6000 m and specially designed for recording of baleen whale sounds. It is microprocessor-controlled and contains a hydrophone with associated amplifier and stores recordings on one or more hard disks. Recordings are uncompressed and recording time is thus principally determined by sampling rate and hard disk space, but may be extended by decreasing the duty cycle (percent of the time, the recorder is active). At present, continuous recordings up to 40 days at a sampling rate of 2000 Hz has been achieved.

The Pop-Ups are deployed with an anchor and remains attached to the bottom until transmitting a keyed acoustic sequence from the surface activates a release mechanism. On release, the unit floats to the surface and the build-in VHF-transmitter can facilitate recovery.

Pop-ups have great potential for long-term monitoring in remote oceans, also at times where these areas are inaccessible due to ice or weather. As they don't employ any other data reduction than through duty cycling they are however, limited to the low frequency range. They are well suited for baleen whales and may also hold promises for monitoring of vocal species of fish.

Suggested Reading

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