Acoustics in halieutic research

The propagation of sound through water is a phenomenon widely used by aquatic fauna to locate fellow individuals, prey and predators (the lateral line in fish, for example), to situate them precisely (dolphins, pilot whales) or even as a weapon to disorient prey (certain shrimp and mammals).

In humans, it seems that Leonardo da Vinci was the first to make use of the propagation of sound in water in 1490. At the time, he wrote, “If you cause your ship to stop and place the head of a long tube in the water and place the outer extremity to your ear, you will hear ships at a great distance from you.”

In 1870, Jules Verne as well brilliantly described this capacity in his book, *20,000 Leagues Beneath the Sea*, “The slightest sounds were transmitted with a speed to which the ear is unaccustomed on the earth. Indeed, water is a better vehicle for sound than air, and it travels through it four times as quickly. [...] Deep sounds, clearly transmitted by this liquid medium, reverberated majestically.” This property was widely used during the First World War, simply by improving Leonardo da Vinci’s experiment, first by the use of a second tube at a distance from the first, sometimes directional, and placed near the other ear: the stereo effect allowed a rough approximation of the direction of origin of the sound.

A bit later the system was improved upon once again by assembling two systems of a dozen tubes set starboard and port in the holds of ships: this system improved considerably the localization of sound sources, precise to the order of ½ a degree.

And the story goes on...

Later in the XIXth century, many physicians were interested in the problems of “transduction”, the phenomenon of the conversion of electrical energy into sound energy and vice versa. Magnetostriction, or the aptitude of certain materials to change form when submitted to a magnetic field, was discovered around 1840, a discovery which led to the invention of the telephone, first attributed after lengthy deliberations to Alexander Graham Bell in 1876, before the just, if belated, recognition in 2002 of Antonio Meucci as the true inventor of the telephone in 1860. The counterpart to magnetostriction is the piezoelectric effect, discovered by Jacques and Pierre Curie in 1880. The piezoelectric effect is the capacity of certain crystals to electrically charge their surfaces when subjected to a mechanical constraint. Thus prior to the end of the XIXth century, two effects had been discovered which would be used to transmit and to receive sound in water, bringing partial answers to the question of how to “see underwater”.

The collision of the Titanic with an iceberg in the night of April 14-15, 1912, resulting in the loss of hundreds of lives, had a huge impact on public opinion and probably triggered the urgent need to find ways of underwater detection. The same month, L. R. Richardson patented an acoustic telemetry procedure in England, capable of detecting large submerged objects through their echo. On January 29, 1913, R. A. Fessenden who was working on the same problem filed a patent in the United States for an underwater electroacoustic source prototype, and succeeded in locating an iceberg two miles away on April 27, 1913.

Meanwhile in Europe, the eruption of World War I made clear the absolute necessity of being able to detect enemy military submarines. The French physician P. Langevin developed a transducer powerful enough to send a sound wave across the Seine to Paris in the winter of 1915-1916. The British allies, thanks to R.W. Boyle, were able to reproduce the same result in the summer of 1916.

Major progress was made in 1917 by P. Langevin who had the idea of constructing a sound source made of sandwiching piezoelectric material (quartz) between two metal plates and using the brand-new tube amplifiers. The strength of this sound source ranged up to 8 km and in 1918, allowed for the first detection of a submarine 1500 m away.

During the period between the two wars, progress in the electronics field was very significant and found important applications in the domain of underwater acoustics, with in particular amplifiers and visualization systems of echo sounders/sonar for users. Ultrasonic frequencies permitted increased systems directivity while reducing apparatus size.

It was necessary nevertheless to wait until 1925 for the commercialization in England and the USA of “fathometres” for measuring the depths of the seas. In 1929, Kimura showed that a transducer could detect fish in an enclosure. In the early 1930s, the English captain R. Balls used an “echometre” to detect schools of herring in the North Sea. In 1935, the Norwegian O. Sund published an article in *Nature*, “Echo Sounding in Fisheries Research” in which he showed echograms of codfish concentrated in a layer 10 metres thick above the seafloor. He was probably the first to establish codfish abundance maps and to inform fishers of the zones and depths where cod was most abundant. Still in 1935, several types of sonars/echo sounders were in operation, and in 1938, in anticipation of the Second World War, the
The simplest way of producing an acoustic wave is to make a surface vibrate alternately from front to back. When a
sounder transducers were perfected in the USA by Biosonics in order to complete and refine the results of echo
integration campaigns by *in situ* measures of the index of acoustical reflection (TS: Target Strength) of fish. Standard
transducer calibration spheres came into being, and standardized calibration protocols were adopted by the scientific
community. Simrad in Norway perfected the split beam technique, bringing in addition to the TS measurement the
possibility of precisely locating fish position in the acoustic beam and consequently of following their trajectory
(tracking). Transducer data became digital and the transition between analogical and digital integrators became
irreversible.

**The astounding evolution of echo sounders and sonars**

The 1990s saw enormous progress in techniques and methods of analysis of acoustical signals. The analytic processes
of TS became more refined, the morphological and energetic parameters of schools of fish became accessible automatically.
The use of omnidirectional sonar become common in abundance evaluation campaigns, as much for evaluating biomass
very near to the surface undetectable by transducers as for studying avoidance phenomena of schools upon approaching
vessels. The techniques of spatial statistics (geostatistics) developed for mining were adapted to the needs of acoustics
both for determining confidence intervals of estimates by taking into account the effects of spatial distribution of
biomass, and for studying the behaviour of populations (size and geographical distribution of aggregations).

From 2000 on, a growing interest in the classification and identification of acoustic reflectors (fish, plankton...) through
the use of multifrequency analyses, or the observation and analysis of synchronous acoustical measures taken by
transducers operating on different frequencies. The use of “wide band” techniques, where an acoustic wave sweeps a
wide range of frequencies, is developing as concerns echo sounders and sonars, with among other purposes the better
identification of detections.

**Frequency, amplitude, pressure, speed… All the secrets of the acoustical wave**

The principle of echolocation is simple: a sonar impulse is emitted in water, propagates through the water, reflects on an
object (sea-floor, fish, plankton, etc.), and is sent back to the emitter. The speed of propagation of sound being known,
the time elapsed between the emission and the reception of the signal allows for the calculation of the distance at which
the reflector is situated. If the emission is directive, an indication of the direction to which the target is located in relation
to the emitter is also obtained. If the sonic impulse is directed downwards, an echo of the seafloor is obtained, making it
possible to precisely locate fish position in the acoustic beam and consequently of following their trajectory.

On both sides of the Atlantic, the period of the Second World War was marked by intense research activity focused on
the properties of sound in water. Thus the National Defense Research Committee (NDRC) in the United States financed
a large number of scientists to investigate all aspects of the propagation of sound in water. The Americans replaced the
name ASDIC by the more comprehensible term of SONAR (Sound Navigation And Ranging). A great many present-day
concepts and practical applications have their origins in this period.

Although it was possible to detect fish with echo sounders thanks to their echoes, these echoes had yet to be quantified,
that is to say, scientists were still unable to estimate the quantity of fish they represented. Middtun and Seatersdal in 1957
proposed the first attempts at estimating abundance by counting the number of individual fish echoes on a paper
echogramme recorded in the Baring Sea. Richardson et al. in 1959 refined this method by taking into account the
amplitude of the echo, which is linked to fish size, measuring it on a cathode tube. In the 1960s, several automatic echo
counting devices coupled to a transducer were proposed: the impulse counter (Mitson and Wood, 1961) and the cycle
counter (Dowd, 1968) ; it was not until 1965 that Dragsund and Olsen invented the echointegrator which put to use the
relation between fish density and the voltage of their echo squared, a technique still widely used today.

In the 1980s, echo integration became a widely used technique for the evaluation of biomass. Dual beam echo
sounder transducers were perfected in the USA by Biosonics in order to complete and refine the results of echo
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adjacent particles and so forth, since the medium (air) is compressible. This generates an acoustic wave.

One of its characteristics is its frequency. When the surface of a gong is struck, the surface leaves its zero position to attain a maximum deformation, then goes back through the zero position to reach a maximum on that side, then comes back again through the zero position: a new cycle then begins... The number of cycles effectuated per unit of time is called the frequency \( f \) of the vibration, expressed in Hertz (Hz), the number of cycles per second. The range of frequencies used in underwater acoustics goes from 10 Hz to 1 MHz, and in halieutic applications from 10 kHz to 500 kHz.

A second characteristic is its amplitude, characterized by the extension of the displacement of the surface of the gong, in other words by the distance separating its two postions of maximum displacement. This amplitude is transmitted to particles of the medium from one to another; the greater the amplitude, the louder the sound. This amplitude represents a stationary movement around the initial position, movement characterized by a particular speed. It is intuitively understood that the vibrations of the surface of the gong alternately exert an increase in pressure when the the surface comes closer to particles and a decrease in pressure as the surface recedes from them. This variation in pressure is another characteristic of acoustic waves, and in practice, it is the largest measure used in underwater acoustics; it is expressed in Pascals (1 Pa = 1 Newton per m²).

When a sound is produced, it is propagated in all directions around the source and forms a spherical wave of variation of acoustic pressure called once again a sonic wave: the result is that at each point of the medium, the acoustic pressure varies with time. Over time, this same pressure is spread over an increasingly large surface (surface of a sphere) and at each moment this pressure drops in function of the distance from the sound source.

This is attenuated pressure through geographical dispersion.

Another important characteristic is the speed at which the sound wave propagates in the medium or its celerity, \( C \). This is independent of both the frequency of the sound and its amplitude, and is affected only by the mechanical characteristics of the propagation medium, in particular its density and its elasticity module, \( k \) (the inverse of compressibility).

By way of illustration, the speed of propagation of sound in air is approximately 340 m/s, in seawater approximately 1500 m/s, in sediment from 1500 to 2500 m/s, and in steel from 5000 to 6000 m/s.

Since the density of a medium is not a constant but is variable according to temperature, among other factors, it is deduced that the speed of sound also depends on this parameter.

In fact, if greater precision is sought after, it must also be taken into account that while the celerity of sound in water increases with temperature, it also increases with salinity and pressure, which signifies that celerity changes with the time of day, the seasons, depth, geographical proximity of river mouths, etc.

Transmitting mediums are never perfect, and not only attenuation by geometric dispersion but molecular absorption are factors to be considered.

The direct consequence of this phenomenon is that the higher the acoustic frequency used, the lower the range. Thus, in a purely indicative manner, it can be roughly estimated that in good conditions of propagation in seawater, a 12 kHz transducer would have a range in the neighbourhood of 8 km, a 38kHz transducer a range neighbouring 1000 m, a 120 kHz transducer a range neighbouring 200 m.

For detection at the furthest distance possible, it is necessary to choose a low frequency, a large transducer (concentration of energy in a small beam), and a high power of emission.

Other losses of energy, more random and difficult to take into account, are the losses linked to the presence of air bubbles in seawater. These bubbles are generated naturally in the milieu by waves and biological activity, or by human activity (afterwake of boats, etc.). Due to their unpredictable nature, these losses are rarely taken into consideration in abundance calculations of sea organisms. They may however seriously weaken or even entirely mask the signal…

**Echo sounders**

In layman’s terms, an echo sounder is an apparatus used to emit sound waves vertically and to receive their echoes.

Broadly speaking, an echo sounder system consists of an emission stage, a reception stage, a transducer which emits the sound wave and receives its echo, and echosounding representation equipment (display screen, information recorder).

An echo sounder transducer is therefore used to measure depth of water (bathymetry) and to detect reflecting organisms (plankton, pelagic fishes, etc.) in offshore waters. They are accordingly of particular use in the field of fishing. In the scientific domain, echo sounders are used by biologists for ecosystemic studies, by ethologists for behavioural studies, by halieutic researchers for the evaluation of abundance of (principally pelagic) resources, but also in the marine geosciences and in geoseismsics which use specialized tools such as sediment echo sounders.

It must not be thought that echo sounders are capable of detecting everything. There are indeed “shadow zones” and “blind zones” whose volume depends upon the configuration of the seafloor and the shape of the beam.
Sonars
Sonars, in layman’s terms, present the same working principles as echo sounders but contrary to the transducer which works vertically, the emission and reception of sonars is done obliquely. They are hence adapted to the observation of the area surrounding a boat, either unidirectionally (frontally or laterally, for example), or omnidirectionally, or then again a combination of both.

The treatment of sonar data is more complex than that of data from echo sounders. In fact, the pathway of acoustic waves is no longer linear if the medium conditions are heterogenous, principally in the case of thermic gradients.

Multibeam halieutic echo sounders
Multibeam halieutic echo sounders are hybrid sonar-echo sounders in so far as they consist of beams working on both vertical and lateral axes.

These systems represent the latest generation of scientific echo sounders essentially used for resource evaluation. The first trials of the first model were undertaken in October 2005 on the Thalassa, Ifremer’s research vessel.

3D sonars and acoustic cameras
These are high-definition sonars which use a very large number of beams. The most elaborate among them produce images or films similar to those obtained using an underwater video camera. In principle, a sonic impulse is transmitted along an important angle using certain elements of the transducer and then upon reception the ensemble of transducer elements is used to receive the echoes along very fine angles. It is then possible to construct a 3D image of the acoustic reflectors. Their range is generally poor in seawater due to the high frequencies used to obtain good resolution. They have multiple applications in halieutics, with strong capability for behavioural analyses, the topographical study of fish schools, and shallow water observation.

Acoustic tags
Acoustic tags are small transmitters usually 15 mm to 150 mm in size and weighing 1 to 80 g. They are implanted either in the abdominal cavity of fishes, or attached to their backs. The smaller the tag, the fewer the sensors, and consequently, the lesser the capability of transmitting information on the surrounding environment (temperature, pressure) and the lesser their autonomy.

There are two large categories of tags, those which emit a signal at constant intervals and which are adapted to follow rapidly moving fish, and those which emit an identification signal which can be used in large numbers in the same zone and which are ideal for detecting the presence or absence of a particular fish in a given zone. The latter tags are particularly useful for studying the behaviour of fish around fish aggregation devices and are used for example in the European programme FADIO carried out in the Indian Ocean by IRD. They were also widely used in the ECOTAP programme of the late 1990s in French Polynesia, led by IRD, EVAM and IFREMER.

Halieutic acoustics in fishing and aquatic ecology
The domain of use of halieutic acoustics is extremely vast, including rivers, lakes, dams, estuaries, continental shelves, deep seas, etc.

It concerns milieux with waters only metres deep to those hundreds of metres deep, freshwater, saltwater, hypersaline water. It concerns organisms measuring in the millimetres (plankton), in the centimetres (mesopelagic fishes), in decimetres (fishes on the continental shelves), and in metres (offshore tunas and sawfishes).

ACAPPELLA - an IRD Service Unit, Unité de Service - is currently working in acoustics on shallow estuary environments such as the bolongs of Sine-Saloum and the Gambia River, or the dammed waters of Sélingué, Mali, and Manantali, Senegal, within the framework of the Research Unit known as RAP (Réponses Adaptatives des populations et des peuplements de Poissons aux pressions de l’environnement).

Applications of acoustics to the European continental shelves are historically older and directed towards the evaluation and charting of the biomass of exploited or exploitable fishes.

Many similar campaigns, principally in the framework of evaluation of resources, have been led by IRD. A few examples among the many include campaigns led by the oceanographic vessels, Capricorne in West Africa, the Laurent Amaro and the Louis Sauger in Senegal, the N’DIAGO campaigns in Mauritania, those of the oceanographic vessels the André Nizery and the Antéa in the Gulf of Guinea and in Venezuela, that of the Bawal Putih 1 in the Java Sea…

In an offshore pelagic milieu, the goals are more ambitious: to study the habitats of large offshore pelagics (tunas...
and sawfishes) in terms of their biotic and abiotic characteristics. Such was the case during the PICOLO campaigns undertaken by IRD in 1993-1995 in the equatorial Atlantic zone, the ECOTAP campaigns led by IRD in the EEZ of French Polynesia and more recently in the French EEZ of the Mozambique Canal during IRD’s ECOTEM campaigns led by the Research Unit THETIS, in collaboration with the Service Unit ACAPELLA.

In French Polynesia, the combined use of scientific echo sounders, acoustic tags and fishing (longliners and trawlers) has enabled the description of the habitat and feeding behaviour of tunas.

**Halieutic acoustics in full swing**

The use of acoustics continues its extraordinary growth in the scientific world, but also in civilian and military domains. It is at the moment the only easy way to explore the world beneath the seas because of the low constraints on the penetration of sound in water. Methodological and technological advances are rendering echo sounders and sonars more and more efficient, opening new paths of application for research, as in the case of multifrequency studies which are becoming widespread in the scientific world.

Halieutic acoustics is also more and more used in the world, especially for evaluating the biomass of fishes. This technology based on echo integration offers many advantages such as good bathymetric coverage, rapid production of results, and independance from commercial fisheries data; in addition, it is a non-intrusive method which destroys neither biotic or abiotic milieux, respecting the environment.

Due to the increasing concerns for environmental and ecosystemic protection, halieutic acoustics has extended its range of application to include the study of ecosystems and new approaches to ecosystemic fisheries management.

The necessity of such an approach, which takes into account the maximum number of parameters having an influence on ecosystems:

– human activities: pressure of fishing, other human activities (petrol, recreation, military, pollution, etc.)
– abiotic environment (substrates, physical chemistry, climatic change)
– biotic environment (primary and secondary production, predators from different trophic levels, whether invertebrates, fishes, birds, mammals, etc.),

is now largely integrated in scientific concerns and strongly desired by politicians and users. The stakes are many. This means improving the accuracy of abundance estimates for targeted and untargeted species alike, better quantifying the capacity of environments to tolerate aggression and to recover. It also means implementing fisheries management policy and regulations on the middle to long term, in opposition to the current practices of quota attributions year after year, which leave politicians and entrepreneurs alike no room for a sustainable view of their activities. These stakes which are taking on ever-growing dimensions in the north are evidently of even more crucial importance in countries in the south.

The stakes are many and of capital importance. There is no doubt that acoustics, especially halieutic acoustics, will have a growing place in the future, and IRD will continue to be a part of it.

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