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Saclant ASW Research Centre contributions to underwater acoustics during the first sixteen years of its existence: Personal records

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In less than one year the NATO Undersea Research Centre, previously called Saclant ASW Research Centre, will celebrate its 50th anniversary. I had the great privilege to be one of the first scientists joining the Centre in 1959 and to work there until 1975. The main purpose of the research conducted in underwater acoustics was to reach a physical understanding of the different processes of sound propagation, including multipath effects, transformations introduced by a multilayered bottom and random scattering by the volume in homogeneities and by the surface and bottom roughness. Experiments at sea first conducted from the research ships Aragonese and then Maria Paolina used explosives charges and active sonars FM pulses as sound sources. The digital analysis equipment, which had been designed to record, process and facilitate the interpretation of the received signals, had no equivalent at the time. The Centre has been a very active platform of intercommunications for most of the civilian and military organizations, which were involved in this discipline. The result of this continuous exchange of ideas has facilitated the harmonization of the research programs in the different NATO countries and has greatly contributed to the creation of a large international research community in underwater acoustics.

Introduction

In less than one year the NATO Undersea Research Centre, previously called SACLANT ASW Research Centre, will celebrate its 50th anniversary. The Centre was created at a critical period of the cold war, when the Western World became more and more concerned about losing its superiority, in space after the launching of the first Sputnik, and in the depth of the sea with the threat of a huge Soviet submarine fleet. The Centre's fundamental mission was to help the NATO nations to improve the performance of anti-submarine warfare systems.

I had the great privilege to be one of the first scientists joining the Centre at its very beginning, and to work there until the summer of 1975. During my previous work at Alcatel Society in Paris I had been in charge of designing an acoustic passive range estimator for submarines (called DUUX2). The principle was to measure the curvature of the acoustic wave front by comparing the phases of the signals received by three arrays of hydrophones distributed along the length of the submarine along a perfect straight line. The problems of signal processing to be solved were extremely interesting, but the first trials at sea of the experimental prototype revealed that the wave front curvature measured by this system presented large fluctuations and that it was necessary to average the results over sufficient time to get the exact value. These fluctuations were attributed to "wave front corrugations," but nobody at that time could explain the cause of this phenomenon, and I became curious to know more about the mysterious properties of the underwater acoustic medium.

When I learned about the creation of the SACLANT Centre, I saw the opportunity to extend my field of activity from purely engineering aspects to a more physical approach to solving the problems. My candidature was accepted by Dr. Booth and Dr. Wood, respectively the first director and deputy director of the Centre, after a meeting in Paris in April 1959. I arrived at the Centre on 16 August 1959 with a two years contract, and the written promise that I should return to Alcatel at the end of that period. On request of the French representative to the SCNR (Scientific Committee of National Representatives), I was released from this promise and my contract was renewed for a new period of three years, with the warning that it would probably be the last time. In reality, with the support of successive directors, my contract was renewed five times, until the summer of 1975 when my last request was rejected on the basis of a new "principle of rotation."

In early 1963 the Centre was transferred from SIRIMAR to NATO. In 1967, after the French withdrawal from NATO, France was no longer represented at the SCNR and the seven French scientists present at that time received a letter of revocation. After lengthy discussions, however, it was agreed that the French could remain and I decided to stay.

In spite of the permanent uncertainty about contract renewals, I remember the time I spent at the Centre as the most exciting period of my professional life, as I was given the opportunity to carry on with continuity and serenity all the projects which were close to my heart.

In his welcoming speech, Dr Booth expressed the hope that, within the very general scope of research that SACLANT and the SCNR would define the Centre scientists would give proof of creativity and develop original ideas. I shall try to show, in this brief presentation, that this opportunity has really been seized. It is not my intention to present a summary of the many different studies conducted by the Centre during this period. My comments will be limited to the domains in which I was closely involved, and which are still present in my memory after such a long time. They concern essentially the studies in Underwater Acoustics, in Target Classification and in New Sonar Concepts, leaving apart the important work conducted in Oceanography, Operations Research and Non-Acoustic ASW.

Underwater acoustics research

The basic purpose of the research conducted in underwater acoustic was to reach a physical understanding of the different processes of sound propagation, including multipath effects, random scattering by the volume inhomogeneities and by the surface and bottom roughness, and the effects of reflection from a multi-layered bottom. Experimental and theoretical works on all these different aspects were conducted in parallel.

On the purely theoretical side, the *coherence studies of ocean acoustic paths* intended to analyze the random transformations introduced on the transmitted signals by the temperature inhomogeneities of the medium and by the surface and bottom roughness. The final purpose was to predict the degradation that these effects would introduce on the performance of advanced signal processing techniques and on the directivity of large arrays. The concept of a time-frequency-space scattering function was introduced as an extension of the simple time-frequency scattering function commonly used to characterize the multi-dimensional dispersion of the information transmitted through the acoustic communication channel. Theoretical models were developed for sound propagation in deep and shallow waters, for the reflectivity of layered bottoms and for volume, surface and bottom reverberation. Most of these models were implemented into computers codes.

Experiments at sea were first done from the research ship Aragonese which was chartered by the Centre in early 1960 and then replaced by Maria Paolina in 1964. These ships were progressively transformed into advanced floating laboratories thanks to the many electronics, acoustics and mechanical equipment pieces which, for the most part, were developed by the Centre's engineering support team.

Sound propagation experiments were conducted by using explosive charges as sound sources. The so-called "bombettas" originally designed for the Italian Navy, were produced for us in large quantities by a local supplier. They could be programmed to explode at any predetermined depth. The shock wave produced by the explosion covers a very large frequency band. By using a rather simple compression filter one could obtain the effective impulse response of the medium with the highest possible time resolution, the limit just being due to the physical absorption of the high frequencies by the medium itself. The charges were generally launched from an assist ship and the propagated signals were received by several hydrophones suspended at various depths from the Centre ship; they were recorded on board and were analyzed and interpreted later at the Centre. The first applications were concerned with sea floor reflectivity in order to evaluate the performance of bottom-bounce sonars. In the beginning the experiments were carried out in a rather primitive way, using just one or two hydrophones suspended individually from the ship, recording the signals on a double-track magnetic tape recorder and displaying the results on paper curve tracers. This experimental technique appeared promising and applicable to study all aspects of sound propagation in the sea.

After a first series of experiments, however, serious difficulties arose for the analysis and interpretation of the very large quantity of data which were collected during the sea trials. The processing of the recorded data was extremely slow, and unanalyzed results started to accumulate. The performance limitations of the analogue tape recorders were also creating big problems (insufficient number of tracks, limited dynamic range, poor signal-to-noise ratio, imperfect synchronization between the different tracks, etc.). In order to overcome these difficulties, it was concluded that the data processing problem required the use of digital computers and that digital recording techniques should replace the unsatisfactory analogue tape recorders. A new project on *digital techniques of data analysis* was created for this purpose in 1963. From this date one of the most important efforts of the sound propagation group was to develop the necessary techniques and equipment for the experiments conducted with explosive sound sources, in such a way that they became a powerful method of investigation for underwater acoustics. This required simultaneous developments in different directions: in the electronic domain for the reception and recording of the received signals, in the acoustic technology for the construction of the hydrophones and their assembly in various types of arrays, in mechanics for the handling of these arrays on the ship, and in computer programming for the analysis and interpretation of the collected data.

On the electronics side, the SPADA system developed at the Centre was composed of four different subsystems:

- A 20 channel broadband amplifier with gain settings adjustable in steps of 6 dB, and peak levels monitors, which could amplify separately the signals coming from the different hydrophones of large arrays.
- A bench of 20 analogue-to-digital converters, which were translating in floating-point binary form the analogue signals delivered by the receiving system.
- A high density digital tape recording system, which could record simultaneously the signals delivered by the AD converters. The principle which was adopted for its construction was entirely new at the time and it was patented. It employed a 14 track analogue recorder, of which 10 were used for the digital signals and 4 for the information relative to the conditions of the experiment (time, location, range and depth of the explosive charges, etc.). The sequence of bits resulting from the digital conversion of a given channel was recorded in series on one track and the total system was capable of recording about 3000 kilobits/sec, which at that time was several orders of magnitude higher than any commercially available system.
- An interface system to transmit the data to the Centre computer together with a set of special programs to process and display the data collected during the sea trials. The system was completed in 1968 for the Elliot computer. A new version was then developed for the Hewlett-Packard mini-computer which was acquired for this special application. A second identical computer was installed on the ship, thus permitting the processing of the collected data to be initiated on board during the sea trial.

For what concerned the acoustic and mechanical equipment, an outstanding technical support team constructed and calibrated all the hydrophones, assembled them in long vertical and horizontal arrays and designed the complex mechanical systems to handle them on the ship. This team was a pioneer for the conception and engineering of towed horizontal arrays. Another creation of this team was a rigid horizontal array (called EXACT), which could be suspended from Maria Paolina by an elaborate system of two winches. A characteristic of this array was the logarithmic spacing between the different hydrophones. Through a special digital processing technique the highly directive beamwidth of this array was constant and independent of frequency over several octaves.

Extensive series of propagation experiments were carried out in the Ligurian Sea, in the Levantine Basin, in the western Atlantic, in the Strait of Sicily, across the so-called Maltese front, and in several shallow waters areas. Particular attention was dedicated to the properties of Reliable Acoustic Paths (RAP): By lowering the sound source to the critical depth for which the sound velocity equals that near the surface, a continuous coverage without shadow zones can be obtained. The different paths are well separated and the propagation is practically not affected by medium inhomogeneities. It has been suggested that the surface reverberation can be eliminated on most part of the range by placing the sonar slightly above the critical depth, thus creating a thin shadow zone below the surface.

The close connection between the theoretical and experimental work resulted in considerable progresses in the understanding of the principal mechanisms of sound propagation and reverberation. In homogeneous deep waters areas, a rather good agreement was observed between the experimental results and the prediction of available ray tracing models. For more complex environmental conditions the necessity of developing range dependent models was pointed out. The experiments conducted in shallow waters revealed that much work had still to be done before reaching a satisfactory understanding of the propagation in such media (this was effectively done in the following periods).

An original method was perfected to study the fine vertical structure of the deep scattering layer. By exploding "bombettas" below a deep vertical end-fired array one could get rid of surface and bottom reflections and obtain a precise measurement of the volume reverberation coefficient as a function of depth and frequency.

In addition to environmental applications, the explosive charges technique was used to study the echo structure of submarines as a function of its aspect angle, both for monostatic and multistatic conditions. Several experiments were done using horizontal and vertical arrays in order to evaluate the degree of coherence of the echoes received at two slightly different horizontal or vertical angles of observation. It was shown that by cross-correlating the echoes of submarines received by two hydrophones separated horizontally by some tens of meters, it was possible to recognize that the target had a long thin structure. In favorable propagation conditions, a very detailed image of the target was obtained showing its length, its aspect angle, and sometimes even the position of the conning tower. For these experiments several submarines were made available by different NATO nations. This type of measurement required an extremely delicate coordination of the trajectories to be followed by the submarine when Maria Paolina was just drifting. The spirit of collaboration of the submarine crews was always remarkable.

New sonar concepts and target classification

Since some NATO countries already had a research program on passive acoustic systems, the Centre was asked to concentrate its activities on active systems. The finality was to improve the techniques of detection, localization and classification of submarines.

The first work which was undertaken concerned the application of long, broadband FM pulses. An experimental sonar was developed for this purpose. Its principal originality consisted in the fact that the received signal was cross-correlated with the transmitted FM pulse. This correlation acted as an inverse filter which "recompressed" the received signal. The resolution resulting from this operation was identical to the one of a short pulse of equivalent bandwidth. The FM pulse could then combine the high resolution of a short pulse with the high energy of a long pulse. The high resolution resulted in a high signal to reverberation ratio, and, above all, it was expected that the information contained in the fine-structure of the echoes could be exploited for target classification. At the same time, the signal-to-noise ratio took advantage of the high energy of the long pulse. The price to pay was the range Doppler ambiguity inherent to the FM pulse, but this could be removed by alternating the transmission of FM and CW pulses. Another possibility to remove the ambiguity was to transmit a burst of two successive FM pulses of opposite slope.

The system which generated the waveform of the linear FM pulse to be transmitted, and the correlator (or inverse filter) which recompressed the received signals were entirely constructed with digital electronic components which just started to become commercially available. As far as we know, it was the first time that digital technology was applied to the processing of sonar signals.

The system originally designed for the processing of FM pulses was then adapted to build a highly sensitive Doppler analyzer for long CW signals. For this purpose, the received signal was first modulated by a sequence of FM pulses and then cross-correlated with the same pulse, using the inverse digital filter already built for FM application. At that time the principle of FFT's had not yet been invented and the frequency analysis by conventional filters was extremely heavy. Later on the principle of a similar frequency analyzer was discovered elsewhere, and we regretted not to have published it in time.

In order to get reliable experimental equipment and to reduce the extension of the shadow zones caused by the vertical thermal structure of the medium, the Maria Paolina was equipped with a deep panoramic sonar called MEDUSA, which could be suspended from the ship down to a few hundred meters. Later on the Centre was requested to evaluate the potential performance of RAP sonars. A new panoramic sonar equipment (MEDUSA 2000) which could reach the maximum critical depth of 2000 meters in western Mediterranean was installed on the ship. The digital processing techniques for FM and CW pulses designed for the first experimental sonar equipment was maintained in the following systems.

The various pieces of new sonar equipment were tested during a great number of trials at sea. Experiments of detection were conducted, first on artificial targets and then on real submarines. For detection, the advantage of using FM pulses recompressed at the reception was clearly demonstrated, in particular for the detection of targets presenting a low Doppler. On the other hand CW pulses processed with the fine frequency analyzer system often appeared superior for targets presenting a high Doppler, as the reverberation remains concentrated in the low Doppler frequency channels.

The fundamental task assigned to the new sonar concept group was to improve the technique of target classification. For this purpose, several campaigns of measurements of the fine-structure of submarine echoes as a function of aspect angle were carried out. Different signal processing methods were applied to differentiate the echoes of submarines from those coming from "false targets." A possible clue of identification was to recognize the fact that the length/diameter ratio of a submarine is fairly high (about 12). When high-resolution pulses are used, the echoes coming from a long thin target are identical on two different hydrophones separated horizontally by a distance of some tens of meters, except from a slight compression of the time basis of one with respect to the other. An adaptive correlation technique was developed to take advantage of this property. By using two hydrophone arrays, or a long towed array, it was then possible to decide by only one ping whether the target is one with a high length/diameter ratio and what aspect it has. As the method was demonstrated by using FM pulses it was given the name of *space-frequency* *target classification* owing to the complex interference pattern which could be observed between the two received signals, before they were recompressed by the inverse filter correlator. Later on it was shown that the need of using two separated arrays could be avoided by transmitting two successive pulses from a ship in motion. Doing this, the displacement of both the ship and the submarine between the transmissions of the two pulses could be assimilated by a synthetic array. In some cases, the turning rate of the submarine could also be evaluated.

Experiments with MEDUSA 2000 fully demonstrated the high potential performance of sonars using RAP, and some preliminary studies were conducted about their possible applications in ASW warfare.

Conclusion

It is clear that an important part of the experiments which were conducted by using explosive charges and experimental sonar systems were pursuing very similar objectives. Apart from the exciting competition between two teams, it can be considered that this partial duplication has been extremely positive. Experiments with explosive charges covered all frequency bands that the medium was able to transmit and offered the maximum possible resolution in time. They were ideally suited to conduct fundamental research on the acoustic properties of the ocean medium and the echoes from submarines. Experiments with sonar systems were limited to a more reduced frequency band but they were directly oriented toward the improvement of future operational sonars.

In conclusion, I would say that the fundamental mission which was assigned to the Centre, i.e. to help the NATO nations improve the performance of anti-submarine warfare systems, has been fulfilled. This has been done by combining theoretical and experimental work, by combining fundamental research with system oriented applications, and by introducing many technical innovations in the experimental procedures, in the associated equipment, and in the conception of future operational ASW systems.

I strongly believe, however, that the Centre’s contribution to the progress in underwater acoustic has not been limited to the work conducted internally. The Centre has been a very active platform of intercommunications for most of the civilian and military organizations which were active in this discipline. A large number of seminars have been organized. The Centre scientists made presentations outside and received many visitors. Most scientists returned to their home countries after some years at the Centre. The synergy resulting from this continuous exchange of ideas greatly helped to introduce better complementarities between the research programs of the different NATO countries and contributed to the creation of a prolific international research community.