IMPLEMENTATION OF CONTEMPORARY TECHNOLOGIES IN THE MODERNISATION OF NAVAL SONARS

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Today's fast technological advancement in electronics and signal processing methods makes electronic systems, including sonars, obsolete very quickly. The Polish Navy seems to be particularly affected as its ships were built in the 1970s and 1980s. Researchers at the Gdansk University of Technology have developed a methodology for modernising Navy sonars which involves the use of new electronic sub-systems and modern, bespoke methods of digital signal processing. Thanks to that, the existing large and expensive ultrasonic transducers and their systems for deployment and stabilisation remain unchanged. Between 2001 and 2013 this methodology was used by the Gdansk University of Technology to modernise 26 sonars of different types for the Polish Navy. The projects have significantly improved the technical and utility parameters of the sonars, while keeping the expenditure at about 20% of the value of new equipment.

INTRODUCTION

One of the main tasks of the Navy is to track submarines (Anti Submarine Warfare ASW) and search and destroy naval mines (Mine Counter-Measure MCM). Anti submarine warfare is handled by specialised ships equipped with low frequency long-range sonars and by helicopters with dipping sonars and sonobuoys. Naval mines, on the other hand, are searched for and destroyed by minesweepers and mine destroyers fitted with high-resolution short-range sonars. The quality of the performance depends largely on the efficiency and quality of on-board sonar.

Entering the 21^{st} c. the Polish Navy's fleet (including the ships discussed here) was mainly built in the 1970s and 1980s. With the majority of the ships built in Polish shipyards, the most recent ones included a corvette project 620 ORP Kaszub built in 1987 and a series of

17 minesweepers project 207 with hulls made of polyester and glass laminates built between 1982 and 1994.

Anti submarine warfare was the task of the corvette ORP Kaszub, 11 submarine chasers stationed at Kolobrzeg and eight Mi-14Pl helicopters from Darlowo. The ships' and helicopters' main sonar equipment was a Soviet dipping sonar MG-329 (known as the OKA-2M if used in helicopters) and hull-mounted sonars, the MG-322 on the ORP Kaszub and MG-11 TAMIR on submarine chasers. In 2000 the US presented the Polish Navy with an Oliver Hazard Perry class frigate, the ORP Pulaski (built in 1980), and the ORP Kosciuszko in 2002 (built in 1978). Both had hull-mounted SQS-56 sonar and passive towed array sonar, the SQR-19. With the exception of the hull-mounted sonar SQS-56 on the ORP Pulaski, the sonar equipment was not operational. In 2006 the 16th Submarine Chasers Division in Kolobrzeg was dissolved and in consequences only 3 out-dated ships left in Polish Navy to serve as ASW.

The naval mines search and destroy function on the west coast of Poland was performed by 12 minesweepers project 207 stationed at Swinoujscie. Their equipment included Soviet sonars of the MG-79 and MG-89 type. The area of the Bay of Gdansk was covered by 5 minesweepers project 207M and 3 mine destroyers project 206FM (built in 1967 and modernised in 1999 - 2001). Although originally stationed at Hel, they were moved to Gdynia after a reorganisation in 2006. Gdynia-based ships were equipped with side scan sonars SHL-200 designed at the Gdansk University of Technology in the mid 1980s. First produced by Telkom-Telmor, they were later taken over by AKMOR. The ships also had hull-mounted sonar, the SHL-100, designed at the Gdansk University of Technology in the late 1980s to be later produced by the R&D Marine Technology Centre in Gdynia. The only exception is the ORP Wdzydze (646), which was given a more recent sonar, the SHL-101/T, manufactured by the Marine Technology Centre in cooperation with Thales Underwater Systems, France.

Designed twenty years ago, the ships' sonar systems were in poor condition, inoperable and no match for modern technology both in terms of the equipment itself and its signal processing and imaging capacity.

With the arrival of the new century a number of initiatives were launched to build new ships both ASW class and mine destroyers. 2001 marked the start of construction of the first of a series of 7 multi-task corvettes project 621, the GAWRON. As we know, 12 years into the process the ship was never completed. Plans to build mine destroyers remain on paper and the dream of Navy commanders.

Faced with these problems and the continuous lack of funds for research and development of new sonar systems, already in the late 1990s a team from the Gdansk University of Technology, Faculty of Electronics, Telecommunications and Informatics, Department of Marine Electronic Systems started work on modernising helicopter systems for detecting submarines. Initially, it was meant as a continuation of work on new sonobuoys which helped modernise Soviet RGB-NM-1 sonobuoys and then develop an acoustic analyser using digital signal processing for conducting spectral analysis of the signals received. With the success of this project, modernisation efforts continued focussing on upgrading a helicopter dipping sonar, the OKA-2M. Its qualification tests conducted in 2001 went very well.

Once modernised, the OKA-2M sonar offered much better technical and functional parameters whilst keeping the cost relatively low. This had opened up more possibilities for modernising other sonar systems on Polish Navy ships. The main idea of the modernisation projects was for the sonars to keep their original ultrasonic transducers and mechanical systems for deployment and stabilisation, and provide new electronic sub-systems:

transmitters, receivers, signal processing and imaging systems. Those were designed anew using cutting-edge technology and signal processing methods [1]. With this approach, old sonars could be transformed into modern sonars at just 20% of the cost of new systems.

As a result, from 2001 to 2013 the Gdansk University of Technology modernised 26 sonars of different types significantly improving the performance of timeworn Navy ships. The modernisation projects were happening on the sidelines of never-ending futile discussions about Navy development programmes and were frequently funded from ship repair and maintenance budgets rather than from development funds. Table 1 lists sonars modernised by the Gdansk University of Technology in the years 2001 - 2013.

The scope of the modernisation projects by the types of sonar is discussed in the chapters below.

Tab.1. List of sonars modernised at the Gdansk University of Technology in the years 2001 - 2013.

No.	Sonar type	Country of origin	Symbol after modernization	Purpose	Number of sonar	Year of modernization	Installation site
1.	OKA-2M	USSR	OKA-2M/Z	Helicopter ASW Dipping Sonar	8	2001- 2006	helicopters Mi-14Pł Darlowo
2.	MG-329	USSR	MG-329M/Z	ASW Dipping Sonar	1	2003	corvette Kaszub Gdynia
3.	MG-89	USSR	MG-89DSP	MCM Hull-mounted Sonar	8	2002 - 2013	minesweepers project 207 Swinoujscie
4.	SQR-19	USA	SQR-19PG	ASW Towed Array Sonar	2	2007	OHP frigates Pulaski, Kosciuszko
5.	MG-322	USSR	MG-322DSP	ASW Hull-mounted Sonar	1	2007	corvette Kaszub Gdynia
6.	SQS-56	USA	SQS-56PG	ASW Hull-Mounted Sonar	1	2010	OHP frigate Kosciuszko
7.	SHL-200	Poland	SHL-200DSP	MCM Side Scan Sonar	5	2009 - 2012	minesweepers project 207 M Gdynia
8.	Total				26	2001-2013	Polish Navy

1. MODERNIZATION OF DIPPING SONAR OKA-2M

The OKA-2M dipping sonar is designed for detecting, localising and tracking submarines.

The OKA-2M is installed on ASW helicopters (Anti Submarine Warfare). The submarine search, localisation and tracking functions are performed while the helicopter is hovering. When installed on board a ship, the sonar is called MG-329M. It operates when the ship is drifting and the sonar's array set is lowered into the water on a cable.

Prior to the modernisation the OKA2-M was an analogue sonar with the transmitting and receiving array rotated mechanically. The sonar operated in the active and passive mode. Its operating frequency for both the active and passive mode was 15 kHz and the ultrasonic beam width was equal to 15˚. A narrow band sounding pulse was used in the active mode with duration 50 ms and power 1 kW.

The modernisation involved leaving the original array with its cable, winch, electromechanical rotation elements and array stabilisation towards the north. All of the electronic systems in the transducer, receiver and imaging system were designed anew. Added to the array set was a new gradient passive array and a meter of speed velocity distribution in water [2, 3, 4, 5].

The new on-deck transmitter supports active mode operation using broadband sounding signals with frequency modulation. To generate these signals in the transmitter, the project applied a microprocessor controller and a DDS modulator with direct digital synthesis (DDS). The sonar receiver receives echo signals from a revolving ultrasonic transducer operating in the active mode and 4 signals from hydrophones of the passive array. Following filtration and gain, the signals undergo analogue-to-digital conversion. Once in the digital form they are sent to computers for digital processing and imaging. The computer and colour visualisation monitor together with power supply and array rotation control are placed in the newly designed operator console.

In the active mode on the receiving side, algorithms for digital processing perform matched filtration. This makes sure that for a broadband sounding signal with frequency modulation, the pulse is compressed and the signal-to-noise ratio improves at the same time. By using a broadband signal rather than a narrowband signal, we reduce the level of reverberation, which is particularly important for operations in shallow seas. As a result, the methods applied have significantly improved detection performance and increased the range for detecting and tracking submarines.

In the passive mode, signals from the gradient array are processed digitally to generate spectral characteristics and the bearing of acoustic signal sources from submarines.

Some of the modernised sonars are additionally equipped with a hydrotelephone block. It uses the sonar's array for communications with the submarine.

Figure 1 shows the modernised OKA-2M/Z sonar.

2. MODERNIZATION OF MCM SONAR MG-89

The MG-89DSP is the result of modernisation of a completely analogue sonar, the MG-89. It is designed for searching, detecting and localising bottom and contact mines, especially in shallow water with strong bottom reverberations and substantial deflections of acoustic wave propagation routes. It is a medium-range sonar operating at 43 kHz.

The modernisation involved exchanging all electronic systems. The only unchanged element was the multi-element ultrasonic transducer with a mechanical system of array

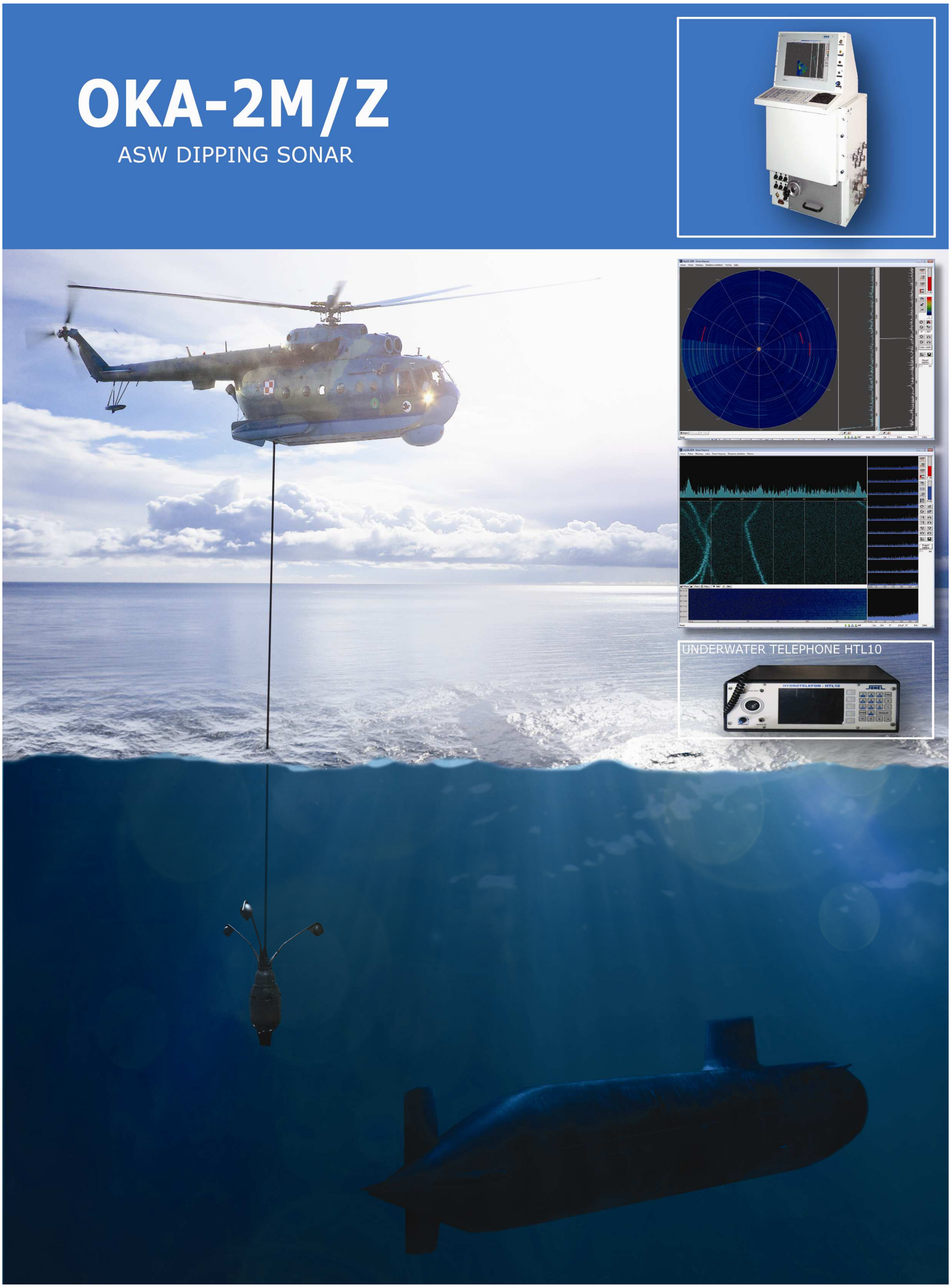

Fig.1. Dipping sonar, the OKA-2M/Z after modernization.

hydraulic stabilisation. On the transmitting side, the solution used was an electronically rotated beam (Rotational Directional Transmission RDT) [6, 7, 8]. Sounding signals and beam rotation are generated using DDS controlled by single-chip microprocessors. On the receiving side a multi-processor DSP system was used running the algorithms of a beamformer operating in the frequency domain with second order sampling and 14 bit resolution. When echo signals are processed digitally, the result is 61 receiving beams spaced every 1° and covering the entire sector of simultaneous observation.

Two LCD monitors were used for modern visualisation and help with detection, identification and tracking of objects. Information exchange between the sonar and other on-board systems was provided.

Following the modernisation, the result was a modern sonar with decent tactical and technical parameters. Getting the sonar ready for work is now significantly simpler, without having to continually fine-tune it and check sub-systems. As regards improvements to the most important detection parameters, there is a significant reduction of beam pattern side lobes both on the transmitting and receiving side. The resolution of the horizontal underwater image is improved up to one degree beam width. The images are now modern, ergonomic and panoramic, displayed on a colour monitor with additional images on an auxiliary monitor. Sonar setting is now much simpler thanks to ergonomic pictograms and messages. A procedure is now in place for classifying targets.

While no modernisation was conducted in the execution and array stabilisation sub-systems, its control and computational sub-systems were made in computer technology.

Figure 2 shows the modernised MG-89DSP sonar.

3. MODERNIZATION OF ASW TOWED ARRAY SONAR SQR-19

The SQR-19 is a passive long-range sonar with a long (about 250 m) towed array. It is designed for detecting and tracking submarines. Installed on Oliver Hazard Perry frigates (OHP), these sonars were designed in the late 1970s in digital technology.

Installed on frigates which the Polish Navy received from the US, the sonars were not operable. This is why the main objective of the SQR-19 sonar modernisation was to recreate the functional structure and software using today's technology and to keep to a minimum any interference with the existing mechanical structure or that of other ship's systems working together with the sonar.

The other objective of the modernisation was to improve the tactical and technical parameters of the SQR-19, make it user-friendly, increase reliability and reduce the size of the sub-systems by using modern technology both for the equipment and software [9, 10, 11].

The modernisation helped to increase the resolution of analogue to digital conversion of signals received by the towed array's hydrophones from 8 to 16 bits. With a higher resolution of analogue to digital conversion, the amount of data transmitted from the array to on-board devices was doubled. To ensure adequate transmission, modern data transmission methods were used, i.e. the VHDSL (Very High Speed Digital Subscriber Line).

With modern microprocessors and effective methods of digital signal processing, angular resolution could be increased by generating more receiving beams. New effective beamforming algorithms for broadband signals were developed as well as high resolution methods for spectrum estimation to ensure accurate measurements of the direction of an incoming acoustic wave. In addition, algorithms were used for automatic tracking of selected targets.

Figure 3 shows the modernised SQR-19PG sonar.

Fig.2. Mine countermeasure, the MG-89DSP sonar after modernization.

Fig.3. Towed array anti submarine warfare sonar, the SQR-19PG after modernization.

A new higher resolution visualisation computer set was designed, comprising two colour monitors with a wide range of images, display of settings, external data, messages, cursors, etc. Other improvements included data transmission between sonar elements and computer methods for signal and image recording.

To achieve these objectives, a complete change of the structure of all sonar systems was required, except the mechanical design of array hydrophones, winch and array cable line.

4. MODERNIZATION OF ASW SONARS WITH CYLINDRICAL ARRAY

Submarine detection is commonly conducted using active hull-mounted long-range sonars operating at low frequencies. They usually operate with a multi-element cylindrical array whose geometric size affects the sonar's angular resolution. The most popular arrays have a diameter of about 1 m and operating frequency from the range of 5 - 10 kHz. This type of sonar is installed on the ORP Kaszub corvette and on frigates – the OHP ORP Pulaski and ORP Kosciuszko.

The ORP Kaszub has a Soviet sonar, MG-322 type, while OHP frigates carry SQS-56 type sonars, made in the USA. Both types of sonar go back to the 1970s. The MG-322 was built entirely in analogue technology but the SQS-56 includes digital technology (obviously as it was in the 1970s). With very similar tactical and technical parameters (operating frequency, size of array, types of sounding signals), the sonars were modernised using the same methods and very similar modern systems and methods for signal processing. There are some differences due to slightly different operating frequencies and the number of elementary ultrasonic transducers in the cylindrical array. This translates into a different number of receiving channels, and as a consequence, a difference in beam number. The arrays, some of the high power transmitters with compensation systems remained unchanged in both types of modernised sonars.

The modernised MG-322DSP and SQS-56PG in the active mode use broadband sounding signals with linear or hyperbolic frequency modulation (LFM or HFM) [12, 13, 14, 15, 16]. On the receiving side, to generate a multi-beam pattern, second order sampling was used and beamformer algorithms operating in the frequency domain. Next, the signals from the beams undergo digital matched filtration with pulse compression and WT coefficient equal to 1600. The final result are multibeam patterns spaced every 4˚ for the MG-322DSP sonar and every 5˚ for the SQS-56PG. As a consequence, the MG-322DSP sonar generates 90 receiving beams (30 before modernisation) and 72 beams (36 before modernisation) in the SQS-56PG. In addition, a significant improvement was achieved in the submarine detection range under difficult propagation conditions, featuring a high level of acoustic noise and reverberation. Equipped with these features, the sonars perform best in shallow water.

Introduced in the modernisation in the passive mode were digital filtration algorithms, broadband beamforming and spectral analysis using FFT algorithms. This helps to achieve periodograms of signals from each beam and BTR type images (Bearing Time Recorder). In addition, the active and passive mode use target tracking algorithms.

The modernised sonars are equipped with modern and ergonomic displays consisting of four colour monitors and control panels operated by two operators. With the new visualisation methods, the operators find it easier to detect targets, watch and track them. The monitors display target route and speed.

Figure 4 shows the modernised MG-322DSP sonar.

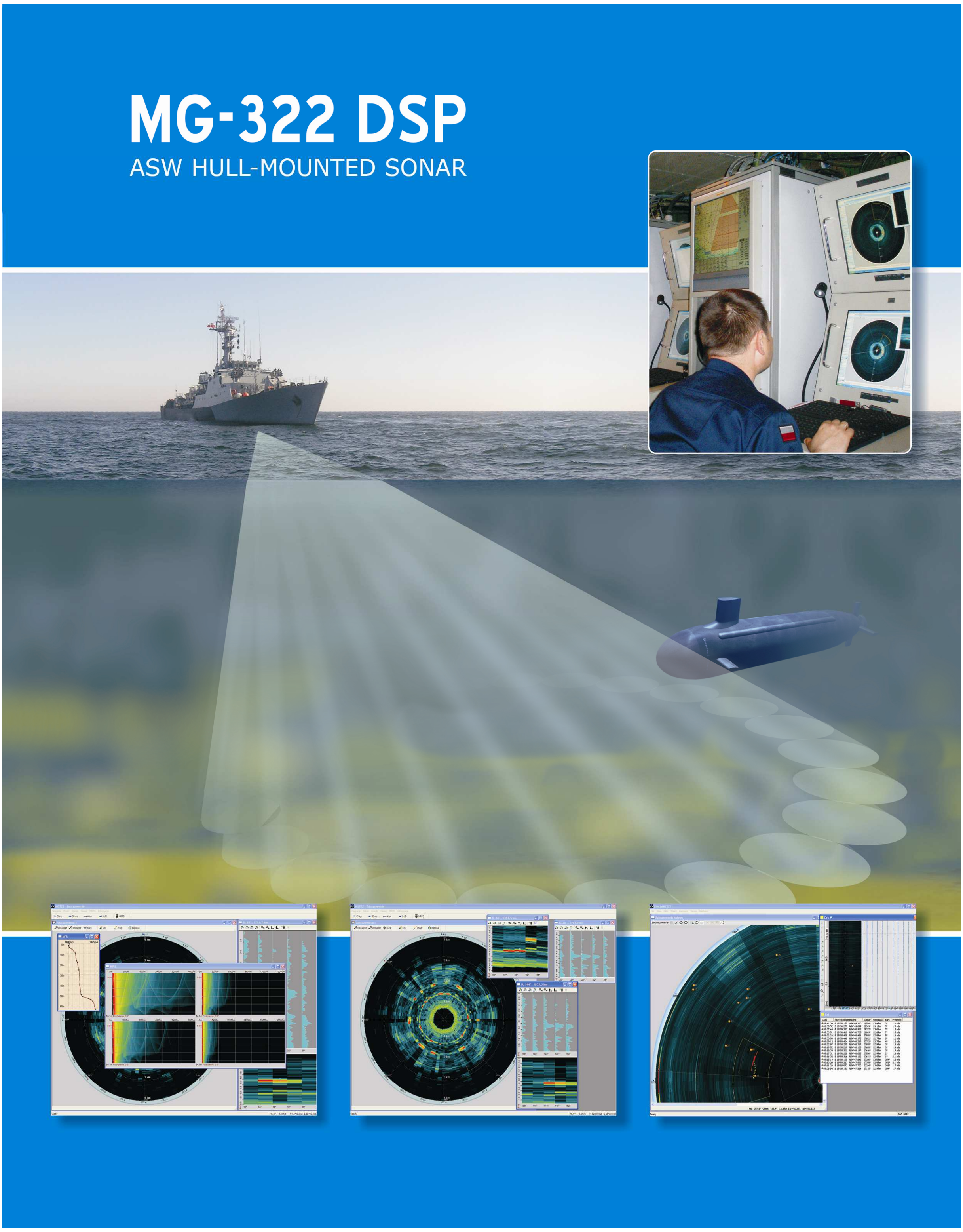

Fig.4. ASW hull-mounted sonar with cylindrical array, the MG-322DSP after modernization.

5. MODERNIZATION OF MCM SIDE SCAN SONAR SHL-200

Built in the mid 1980s, the SHL-200 sonar was manufactured until the mid 1990s. It is a sonar using side scan which is a very effective hydroacoustic method for detecting and localising motionless underwater objects. It works effectively in deep water and on the bottom (e.g. contact and bottom mines, shipwrecks, underwater structures), and helps with identifying the bottom topography (for hydrographic purposes – making seabed maps) on an area of several hundred meters in width, on both sides of the sounding vessel. A side scan sonar includes a tow fish with ultrasonic transducers. Their beam patterns are positioned diagonally towards the bottom, to the right and left of the direction of the tow. The underwater device is towed behind the ship, using a cable operated by a winch. Signals from the tow fish are sent to the on-board device and operator console.

Prior to the modernisation, all of the SHL-200 sonar's tow fish electronic systems, including data transmission systems were analogue. The on-board device converted signals to digital form and presented them on the computer screen. Thanks to the advances in computer technology, today there are better ways for processing and visualising the side scan sonar's signals. Thanks to that SHL-200 sonars are much more practical after the modernisation [17, 18].

Similar to the previous modernisations of sonars, the mechanical structure of the tow fish and cable line with the winch were left unchanged. All electronic systems were designed anew and modern computers were provided for signal visualisation. The tow fish was given new multi-element ultrasonic transducers and dynamic beam width control to ensure constant linear resolution (rather than the usual angular resolution) during the search. Echo signals from both ship's sides, tow fish draught and the distance to the bottom are converted into digital form directly in the tow fish and then transmitted to the on-board device using VDSL.

Now called the SHL-200DSP, the modernised version of the sonar has a significantly better quality of visualisation leading to improved target detection and classification. With the archaic computer operating system replaced with a modern one, survey results and other information can now be displayed on two monitors with useful functions such as zoom, short-term memory, dimensioning, multiple windows, etc.

A particularly useful feature is that the auxiliary screen displays on a grid and stores in memory the ship's current route and bottom sections already searched. This increases the precision of search operations by excluding areas that have not been searched. The ship (and the sonar's tow fish) can target objects already detected (and marked on the monitors) and generate target images from different aspects.

Figure 5 shows the modernised SHL-200DSP sonar.

6. CONCLUSIONS

The new systems and signal processing methods have effectively improved the parameters of the sonars and, as a consequence, the ships' warfare capability. Fitted with modernised sonars, Polish Navy ships and helicopters taking part in NATO international exercises can effectively engage in anti-submarine warfare and mine searches.

What needs to be emphasised is that the methods and scope of the modernisation are very cost efficient with all the work estimated at some 20% of the cost to purchase new sonars with similar parameters.

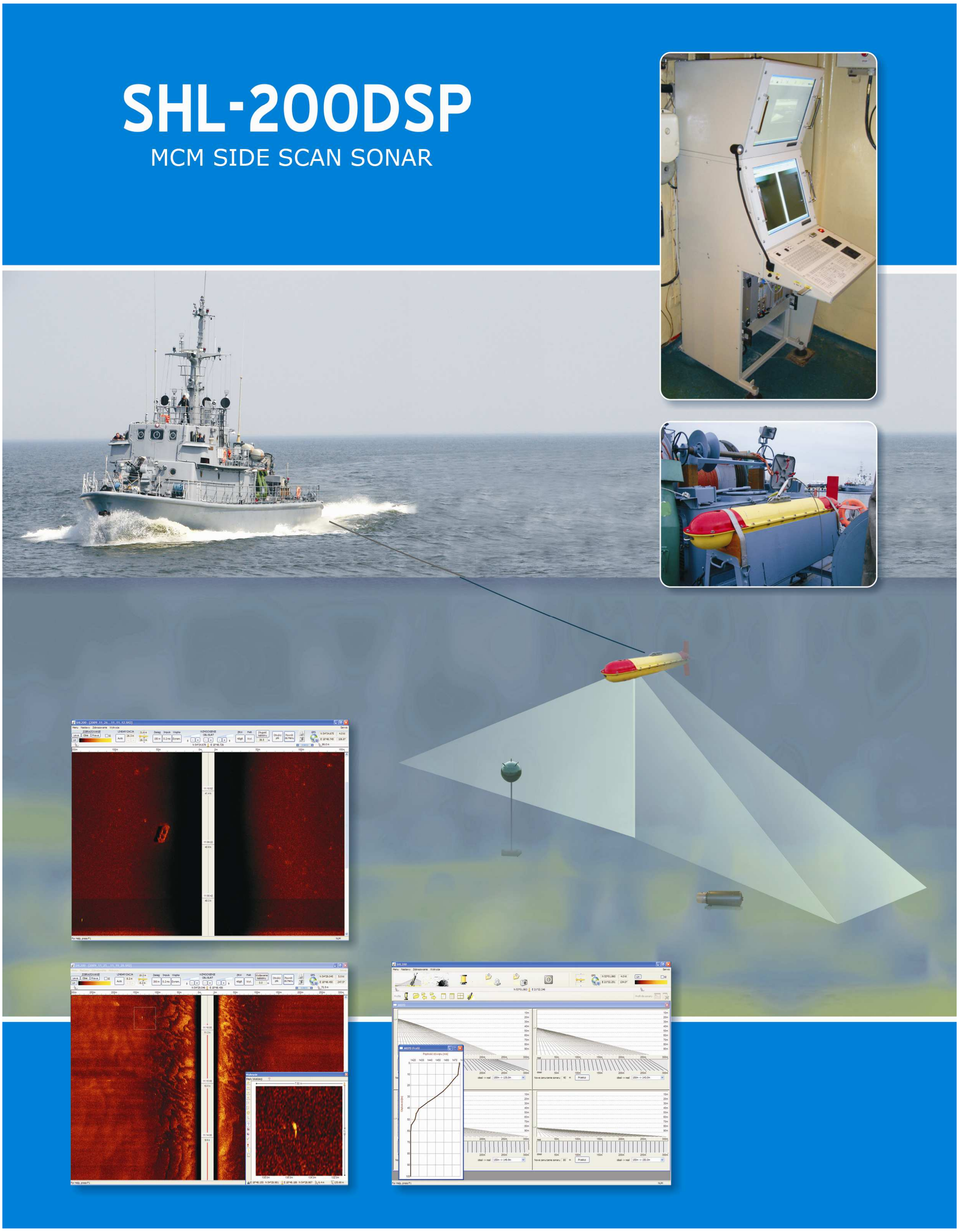

Fig.5. Side scan sonar, the SHL-200DSP after modernization.

Apart from these modernisation projects, in recent years the team of the Department of Marine Electronic Systems at the Gdansk University of Technology has been working on developing new hydroacoustic systems. The new designs include a unique silent sonar, which is difficult to detect by enemy intercepting systems [19, 20, 21, 22, 23]. Other on-going research focuses on Doppler systems [24, 25] and wireless underwater communications [26, 27, 28, 29].

With the new knowledge and experience gained by the Department of Marine Electronic Systems, the researchers are able to design and build other modern hydroacoustic systems for the Navy, including other multi-frequency and high resolution systems, sonars with synthetic aperture or systems of wireless underwater communications.

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