# ACOUSTIC SIGNAL PROCESSING IN PASSIVE SONAR SYSTEM WITH TOWED ARRAY

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*The aim of this document is to introduce acoustic signal processing in passive sonar system with towed array. The concept of the „acoustic signals processing" includes all possible operations on analogue signals such as amplifying, filtering, sampling and most importantly - operations on digital signals obtained in the sampling process. Digital operations executed in the system include: synchronizing, conversion, sorting, creating deflected beams sets, plotting the power density spectrum received signals and imaging the results. Apart from digital signals processing, we focus on reciprocal connections between microcontrollers and processors in which processing is performed. At the end of this document some exemplary imagings of the output are presented, obtained at the marine testing of this system.*

## INTRODUCTION

The main task of passive sonar systems is detection and positioning underwater objects transmitting acoustic signals. This complies of detection of the transmitted signal within the background noise of the sea and determining the bearing of the distant sound source. Because the transmitted signal is unknown, detection is performed by monitoring the power density spectrum of the signals received in the wideband of acoustic frequency. To identify the ranging, multibeam spatial filters are used (beamformers), and to enhance the accuracy of radio location – the mono-impulse method and/or the spatial spectrum estimation methods. Contemporary passive sonar systems are very complex instruments. They are confronted with more and more demanding tasks which create the need for their constant development. In these instruments, apart from the above mentioned, there are also processed other signals and information obtained from the system itself as well as from on-board monitoring and command systems. The first group comprises of mainly non-acoustic measuring signals supporting the positioning and evaluation of hydrological conditions, the second group includes signals from supporting systems such as navigation systems or radar systems ARPA – *Automatic Radar Plotting Aid*.

The results of the detection and positioning need to be presented gradually when receiving the acoustic signals or with a possibly small delay that cannot cumulate. Thus acoustic signal processing and the other data processing must take time in the real-time mode as well as the simultaneous processing in the system processors. Fulfilling the above mentioned requirements implies the necessary division of the whole acoustic signal processing concept to many simultaneous processes. As a result of such approach, there is a need to use a few microcontrollers and industrial hardware connected in one integrated system.

## 1. ACOUSTIC SIGNAL PROCESSING IN PASSIVE SONAR SYSTEM

Acoustic signal processing is a multistage process. It is directly determined by the idea of the system which transforms simultaneously signals from four frequency ranges and is based on the algorithm of the delay-and-sum beamformer operating in the frequency domain. Both the analogue acoustic signals are being processed but most of all, the output of the digital data. These processes take place in the towed array and in the processing digital signals and imaging unit in the deck part of the system.

In a shortcut, operating of the acoustic signal processing system can be described in a following way: acoustic signals transformed to electrical form in the hydro acoustic converters (hydrophones) located in the array, after preliminary filtration and amplification, are subject to analog-digital conversion and in the form of digital data are being transmitted to the on-board data transmission set, where proceeds – due to significant electromagnetic interference at the ship – conversion of the transmission medias from the coaxial cable to the optic fibre line. Digital data from the towed array are delivered through the optic fibre line to the signal processing and imaging unit, where their detection, positioning estimation and results of the operations are presented.

### 1.1.PROCESSING IN THE TOWED ARRAY

Figure 1 shows block diagram of the towed hydro acoustic array. It is composed of dozens of elements. These vary from stabilizing elements, modules including electronic configurations to acoustic modules made of hydro acoustic converters.

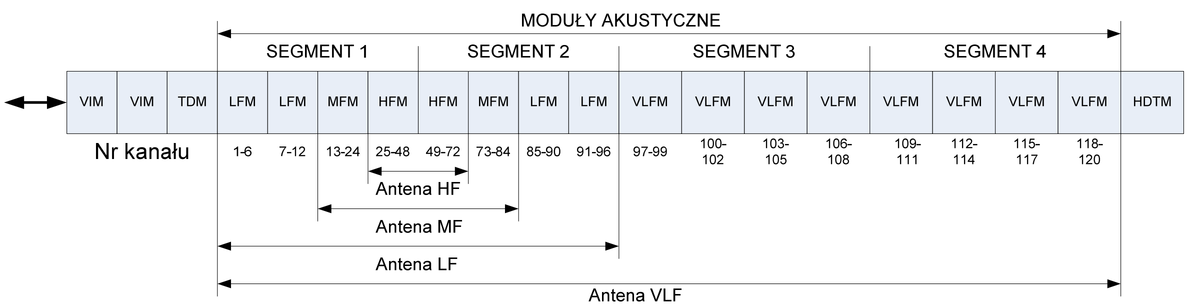


Fig.1 Block diagram of the towed array

The purpose of particular acoustic modules is:

- VLFM – 8 very low frequency modules, containing hydrophones used for acoustic signal monitoring only in the lowest frequency band from 10 to 175 Hz,

- LFM – 4 low frequency modules, containing hydrophones used for acoustic signal monitoring in the low frequency band from 176 to 350 Hz and very low frequency bands,
- MFM – 2 medium frequency modules, containing hydrophones used for acoustic signal monitoring in the medium frequency band from 351 to 700 Hz, low and very low frequency bands,
- HFM – 2 high frequency modules, containing hydrophones used form acoustic signal monitoring in the high frequency band from 701 to 1400 Hz and the remaining frequency bands.

The total number of independent acoustic channels in the array that are used in the date processing, equals 120, divided to bands as follows:
- very low frequency VLF – 24 channels,
- low frequency LF – 24 channels,
- medium frequency MF – 24 channels,
- high frequency HF – 48 channels.

The array, as a data acquiring instrument, is divided into two parts. Modules with electronic configurations that take part in the complex sampling process are located at the front part of the array, in the TDM module as well as in the back part of the array, the HDTM module. The function of the electronic configurations in the above mentioned modules is transforming the acoustic signals received by the group of hydrophones as well as signals received from the water temperature and depth sensors and the compass into the form transferable through the cable line to the on-board data transmission set. The processing is performed with the help of a few microcontrollers and complies of following stages:
- processing of the received acoustic signals to electric signals in the hydrophones,
- amplification and appropriate restriction of the band of these signals in the preamplifiers with filters and variable gain amplifiers,
- sequential connecting the signals from following groups of hydrophones (acoustic channels) to the analog-digital converters,
- transforming the measured water temperature, depth and compass data to the digital form in the navigation data transmission module HDTM,
- acquisition of sampled data in the FIFO buffers,
- synchronization and connecting the data from two locations (TDM and HDTM) to the one ethernet frame,
- transmission of the processed data through the VDSL connection line – *Very High Speed DSL* through the TDM data transmission module (through the switch and matching circuits) to the cable line.

When considering the practical side of the data acquisition concept, the most difficult stages among the mentioned above are: controlling the sampling process and preparing the data to be transmitted which means synchronization and linking the digital data into one ethernet frame. The sampling process is complicated by the necessity of synchronization of the gathering samples in two different locations, TDM and HDTM in range of 200 meters from each other. Due to this distance, the timing of the signal propagation in the internal data transmission system influences significantly the sampling sets operations.

The data acquisition is performed as follows. Acoustic signals received by the hydro acoustic converters are preliminarily filtered and amplified, then sampled in the above mentioned modules in the fixed sequential order of gathering the samples. Such big number of acoustic channels enables the signals from particular hydrophones of the array to be transmitted to the analog-digital converters in this fixed sequential order through the built-up multiplexer system. Acoustic channels have been divided into twelve groups, from which each one contains 10 channels. The channels in groups divide into: 8 from 10 sampled channels is located in the TDM section, the other two in the HDTM section. The order of sampling is fixed so that the signal from each hydrophone is being sampled with the frequency meeting the Nyquist criterion. The frequency of a single channel sampling is fixed at 4096 Hz. This results in frequency of S&H – *Sample and Hold* sets tacting equals 49 kHz, whereas the tacting frequency of the analog-digital converter which is sampling, equals in the TDM section 393 kHz and in the HTDM section 98 kHz.

The process of data acquisition, in each of the locations, is being steered by two fast microcontrollers from which one is responsible for sampling from the A/C converter and steering of the synchronization signal generator and the amplifiers, the other one presents the sequence of the acoustic channels addresses and generates the tacting signal for the A/C converter and clock impulses for the S&H systems. At the location given, microcontrollers work simultaneously and are systems equivalent to each other. To synchronize the sampling moments in both locations, microcontrollers from the TDM section produce the address sequence to their equivalents from the HDTM section.

There are four address lines A0-A3 used in the system, which are needed to address 10 acoustic channels. There is an interesting solution to the address signal generation issue, where – in opposition to standard solution in which the following addresses are being changed with the two times lower frequency – the frequency of the address lines A1-A3 states is three times lower than the A0 line and the signals are dephased for 1/3 of the period. This gives the possibility of addressing all of the acoustic channels in the chosen group.

Before being sent to the on-water system section, the digital data from two locations must be synchronized and linked together into one ethernet frame. For the purpose of digital data transmission between TDM and HDTM locations we use internal transmission system based on the ADSL connection - *Asymmetric Digital Subscriber Line* with capacity of 2 Mb/s. Digital data gathered in the sampling process in the HDTM module are transmitted through this line to the TDM module where the data is being attached in a specific way to the digital data from this location, filling in the data field of the ethernet frame. The complete ethernet frames are transmitted to the on-board section through the VDSL connection – *Very High Speed DSL* with capacity of 10 Mb/s. To perform a correct synchronization and combine the measuring data, the structure of this data in both locations contain modulo counters and fields of byte numbers gathered in specific locations. The data in the ethernet frame is considered correct if all of the modulo counters are consistent and there is a correct number of bytes in each location. Because the system works synchronically, all of the frames are being sent and the rejection of the erroneous frames takes place in the digital signal processing and imaging unit.

## 1.2.PROCESSING IN THE DIGITAL SIGNALS PROCESSING AND IMAGING UNIT

Digital signals processing and imaging unit is composed of five computers. One of them, considered the measuring computer, performs all of the arithmetic operations while the other four are used as the imaging hardware and are responsible for visualization of the received data. Industrial computers used in the system are located at the VMEbus. However, to avoid the overload of the bus and the interruptions within the measuring process control by the data used in the process of presenting the measurement results, the hardware responsible for the imaging is connected in one ethernet network. The measuring computer communicates and exchanges the data with only one specific imaging computer which at a particular moment serves as a main computer controlling the measuring. The other three receive the data from this computer. To avoid unexpected problems, the specific organisation of the system allows every other imaging computer to be a measuring controlling substitute.

The measuring computer has a real-time operating system QNX4.2x. Processing in this part of the system has a few stages. The results of all possible operations are presented to the system operator in the form of different imagings, illustrated in the next sections.

### 1.2.1 Data sorting.

The first phase of processing includes the analyse of the ethernet frames according to accuracy of the data received; the accuracy of the modulo counters and byte counters of the data collected from particular locations.

The underwater section digital data that has been sent correctly, is then sorted in order resulting from sampling process so if the data is to be a subject to some other operations, it must be put in a specified order again. It is important to notify that the order of the data from the TDM and HDTM is different and it is necessary to use different methods of putting them in order.

As a result of this operation we obtain 120 measurement series appropriate to specific acoustic channels. The amount of data in a single series depends on the monitoring time so that for 1, 2 and 4 s equals respectively 4096, 8192 i 16384.

### 1.2.2. Beamformer algorithms.

Digital data put in a desired order is a subject to calculation by the beamformer delay-and-sum algorithm that operates in the frequency domain.

The goal of the beamformer is to produce the receiving beams that cover full monitored sector. The described beamformer produces simultaneously 91 beams in each of the frequency bands: very low, low, medium and high.

The angle configuration of the beams in each band is identical. The beams are deflected in range of $-90^0$ to $+90^0$ at an angle interval of $2^0$. The angle positions of the beams are: $-90^0$, $-88^0$, $-86^0$, $-84^0$,..., $-2^0$, $0^0$, $+2^0$,..., $+84^0$, $+86^0$, $+88^0$, $+90^0$. The beam with the $0^0$ deviation is perpendicular to the pivot of the towed array, the beam with a $-90^0$ deviation is pointed along the pivot in the direction of the ship, the beam with a $+90^0$ deviation is pointed along the pivot in the opposite direction.

The character of the array is a non-direction one in the plane perpendicular to it. This results in the beamformer disabled to set the sound source elevation angle which means to recognize the side that generates received signals. Thus, when imaging the position in relation to the array, two positions are given – symetrical to the array.

3-decibel beam widths depend on the frequency of the received signal - the bigger the angle of deviation, the wider the beam.

Processing the data by the beamformer algorithm has for following stages:

- digital signal weighting with the Hamming window,
- calculating the fast Fourier transformates FFT – depending on the band, the number of transformates is 120 from N for VLF, 96 from N for LF, 144 from N/2 for MF, 192 from N/4 for HF, where N = 4096, 8192 or 16384,

– delay correction – multiplying the complex samples of the spectrum by complex correction factors fixed during the system starting time and kept in the RAM of the computer responsible for the aritmethic operations.

– sorting and summing up the signals in the frequency domain, using the method presented in the table below,

Tab.1 Numbers of the array components used to produce the beams in the chosen beamformers

| Numbers of the arrays components | Elements used in beamformers | | | |
|---|---|---|---|---|
| | **HF** | **MF** | **LF** | **VLF** |
| **HF** | 27:72 | 27:72 summed as 2-s | 27:72 summed as 4-s | 27:72 summed as 8-s |
| **MF** | - | 13:24; 72:84 | 13:24; 72:84 summed as 2-s | 13:24; 72:84 summed in 4-s |
| **LF** | - | - | 1:12; 75:96 | 1:12; 75:96 summed as 2-s |
| **VLF** | - | - | - | 97:120 |
| **Total** | 48 | 48 | 48 | 48 |

After summing up the value of the stripes, the sum is divided by 2, 4 or 8, depending on the number of the signals summed up,

– determining the beamformers matrix as stated in the formula below:

$$B(m,f) = \left| \sum_{m=1}^{48} a(m) w(n,m,f) S(n,f) \right|^2 \quad \text{m=1,2,...., 175 (350 lub 700)} \qquad (1)$$

where:
*m* – beam number (1:91)
*f*- spectrum stripe number (1:175 lub 350 lub 700)
*n* – virtual array element number (1:48)
*a(m)* – amplitude weighting function (the Hamming window)
*w(n,m,f)* – phase correction factors
*S(n,f)* – signals spectrums (data)

## 2. ILLUSTRATION OF THE MEASUREMENT RESULTS

The fixed beamformer tables are transmitted to the imaging computers which present data as the various imagings shown in the beneath images. The high diversity of the imagings results from the big number of tasks given to passive hydro location system and above all from the complexity of the detection process and defining the location of the searched target.

On the basis of the presented imagings the system operator must at first detect the target, then find its position, then, if the conditions are convenient, track it manualy or use the auto-tracking mode available in the system.

Figure 2 shows some basic imaging, bearing-frequency type, of the described passive hydrolocation system used in the preliminary target detection and positioning phase. The imaging is divided into 4 sections illustrating the measurement results from specific bands. Starting from the very bottom, we may find the data from very low frequency band and above from the other bands, respectively low, medium and high. At the left, the vertical axis illustrates the frequency scale, the horizontal one – the positioning axis.

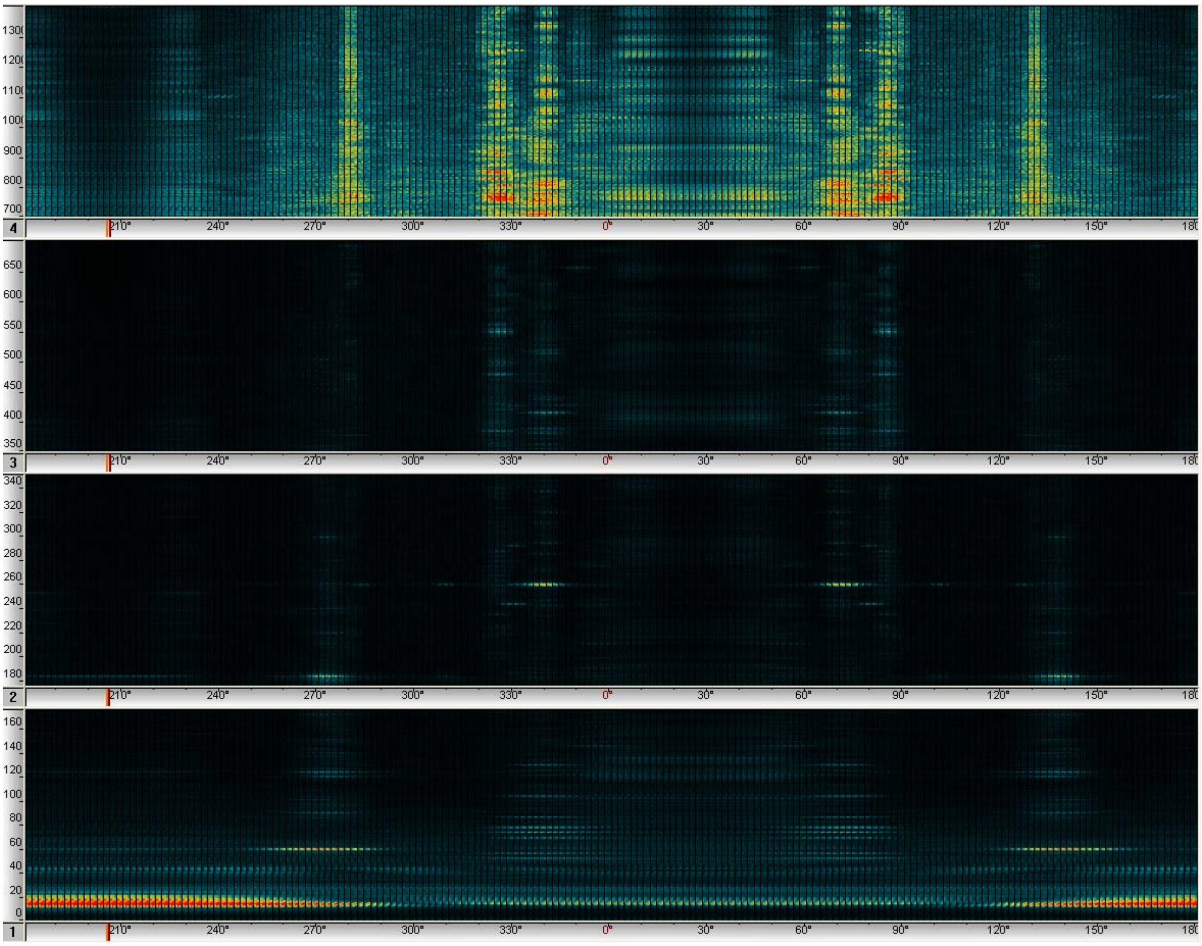

Fig.2 The basic imaging of the bearing-frequency type of the four bands

Figure 3 presents the bearing-frequency type imaging of one frequency band together with the auxiliary imagings. On the left side we can see the spectral energy density in the function of frequency and underneath – the spectral energy density in a given bearing. The stripes on the left side of the imaging are, in fact, the sum of the stripes of all the bearing. However the stripes in the imaging beneath illustrate the sum of all stripes in one particular bearing. The system operator can choose the required frequency range as well as the bearing range using the appropriate selection tools.

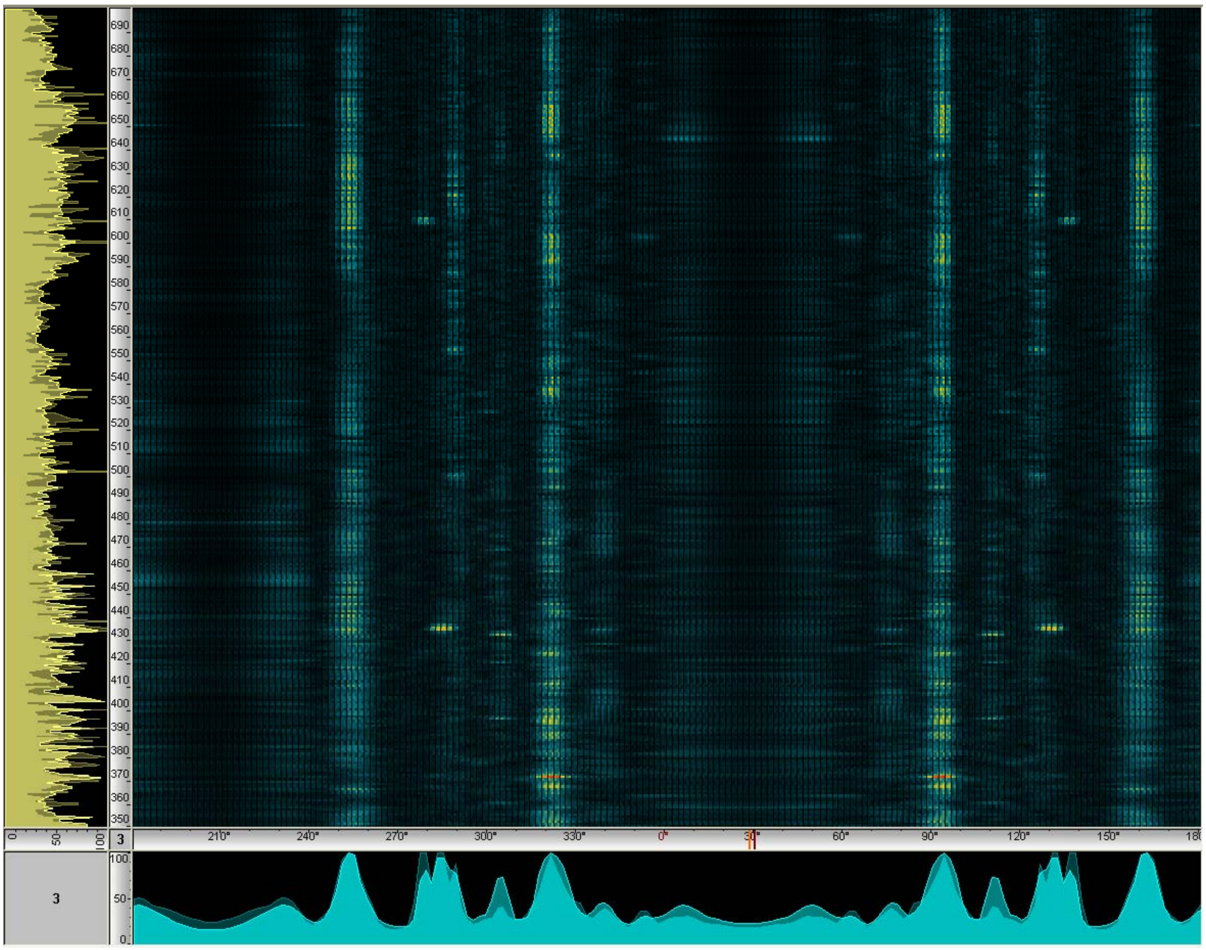

Fig.3 Bearing-frequency imaging of one frequency band together with the auxiliary imagings. On the left side, the spectral energy density in the function of frequency; underneath – the spectral energy density in a given bearing

Figures 4 and 5 show the imaging used in the tracking process. In fact it is not the single imaging but an imaging set. Looking from the top left corner of the fig. 4 we can observe a spectral energy density in the function of the frequency in a selected band. The same parameter is shown underneath as a colour spectrogram. The horizontal axis presents the frequency scale, the vertical axis is a time scale and the colour indicates the signal level. In the middle of an imaging in its upper part the spectral energy density is shown in the function of bearing and the same imaging exists beneath as a „waterfall" (radio location on the horizontal axis and the time scale on the vertical one). At the bottom of the imaging we can find the illustration of the bearing-frequency of the selected frequency range. On the top right side of the imaging there is the bearing-frequency type imaging presented as the polar coordinates and similarly the "waterfall" type imaging at the bottom.

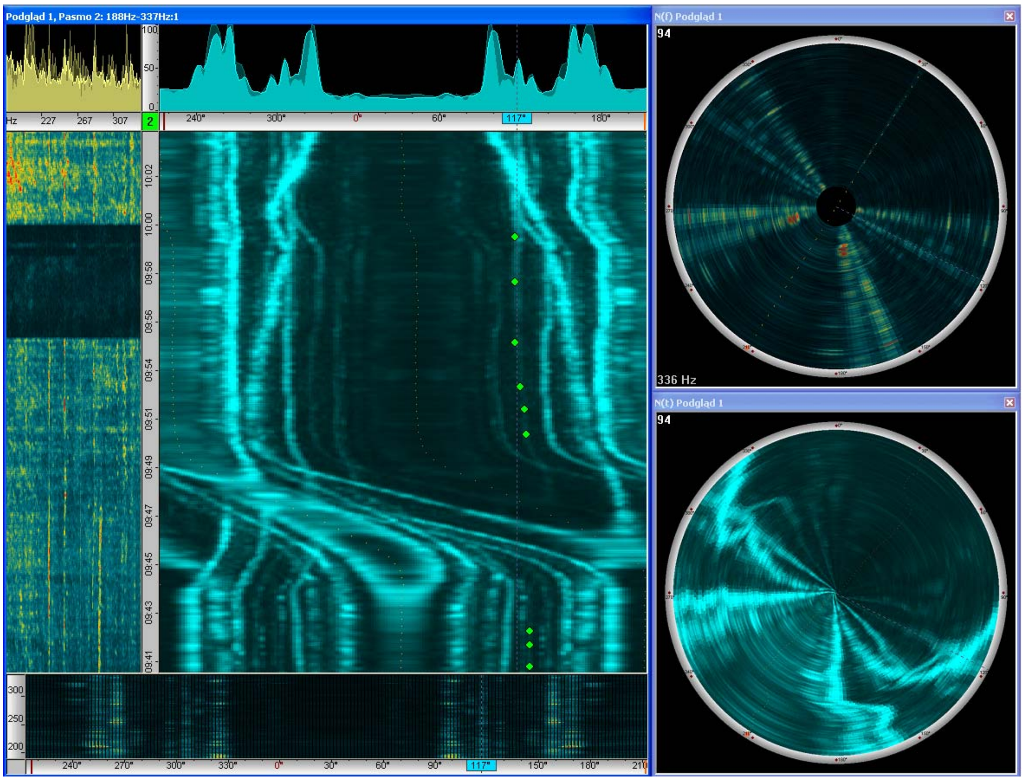


Fig.4 An exemplary imaging set used in the tracking process of the detected target

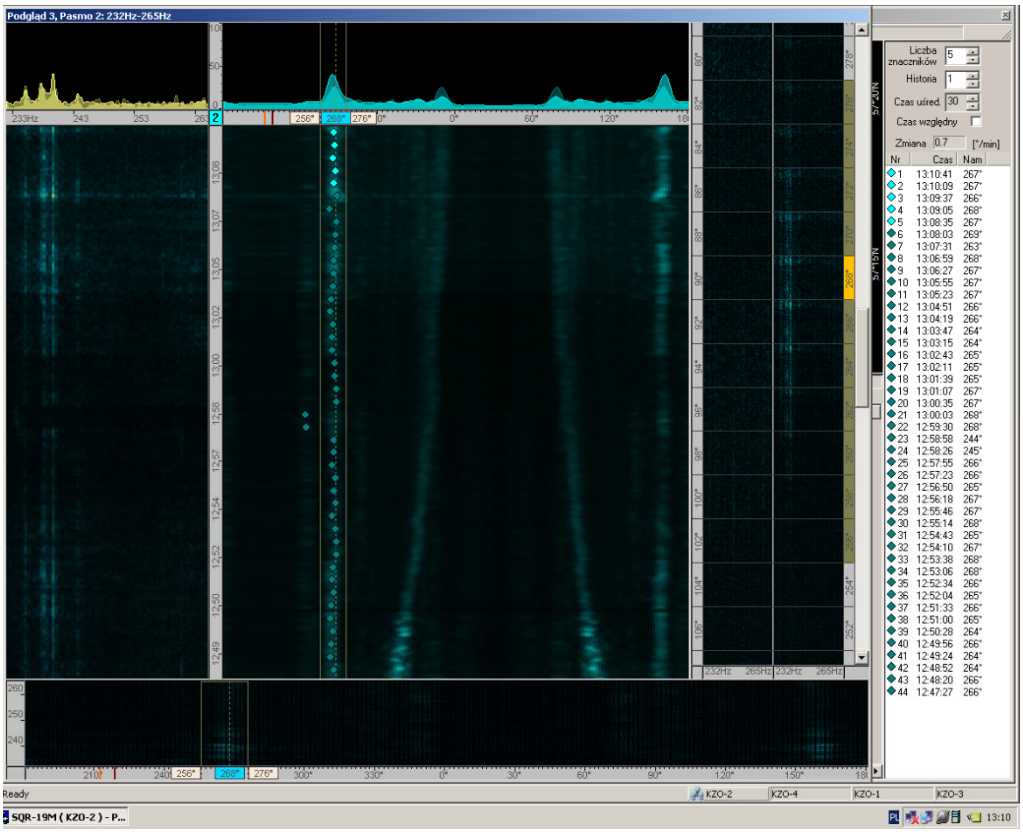


Fig.5 The imaging set used in the tracking process of the detected target

Figure 5 presents the imaging set with the signals spectrum illustration of the particular beams instead of the polar imagings mentioned earlier.

Figure 6 presents the next obtainable imaging variant in the tracking process. In the foreground, in the right bottom corner of the screen there is a tactical situation window where the following bearings of the tracked target are drawn. The application delivers the tools to enable an estimation of the position of the tracked target basing on the bearing history.

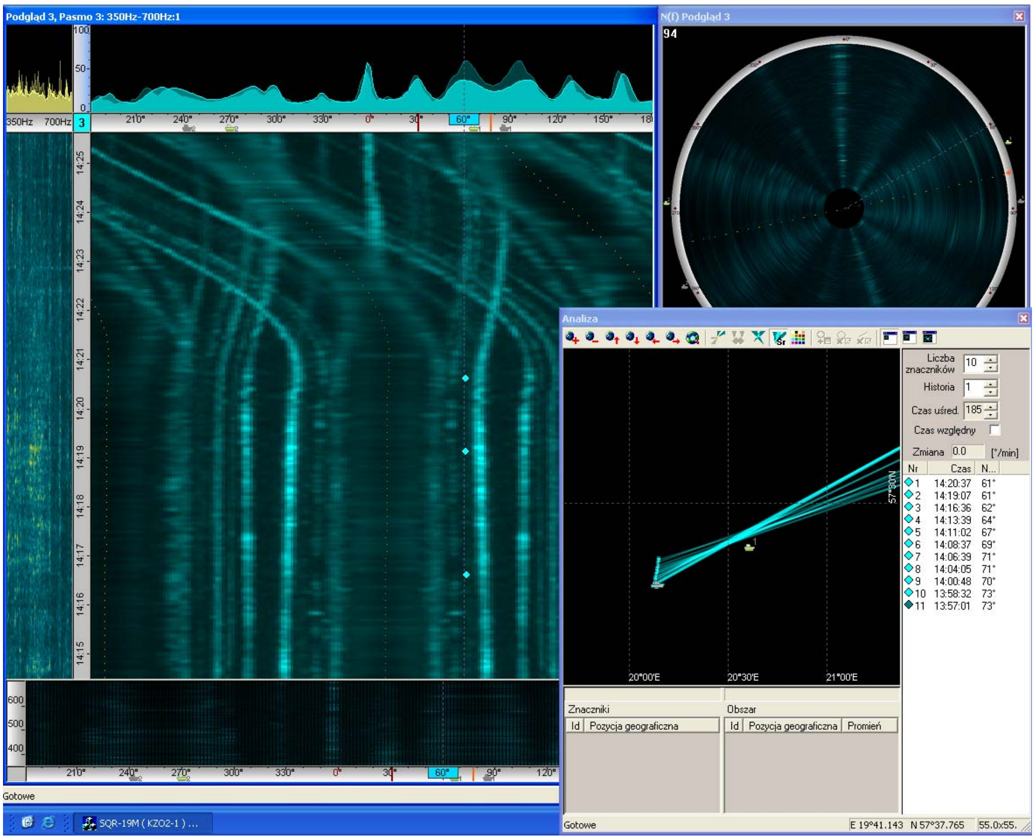


Fig.6 The set of the imagings used in the target tracking process. In the foreground in the right bottom part of the imaging there is the tactical situation window

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