

## Data Post-Processing Algorithms for Active Forward-Looking Sonar System

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### Introduction

This paper focuses on data processing for an active forward-looking sonar (FLS). Digital sonars, in general, are concerned that are transmitting different waveforms on the elements of a uniform linear array. The FLS enables row data processing that extracts target locations used for navigation safety purposes on large ships and vessels. The FLS images represent overlapping areas that can be combined to one image. Numerous different techniques have been developed for the object classification and interpretation of those images. However, many image processing algorithms consider images simply as a collection of points and do not associate them with physical sensors.

The FLS structure previously discussed [1] allows us to run beamforming and image post-processing algorithms automatically. Nevertheless, not only range data should be processed, the angular object information will be important as well. In particular, in the case of limited visibility the real time processing would improve the whole system performance. In practice, detailed information about the location and type of threat in shallow waters, which could not be determined by radar, is safety-critical. FLS applications would provide this information on a long distance. The redundant information in the raw data will be effectively used for data extraction necessary for navigation, image enhancement techniques and for the decrease of an output data stream. For a cost-effective solution wide beam transducers or multichannel reception modules with similar characteristics could be used as an alternative to narrow ones. In this case, an additional beamforming should be implemented. Moreover, the performance of the different beamforming algorithms should be modeled with the real sounding signals. This paper illustrates the efficiency of the proposed beamforming and post-processing algorithms in terms of angular aperture and target detection. Focus will be on the post-processing details and some of the algorithms implemented in FLS software applications.

### Angular resolution in the case of spread spectrum signals

The angular resolution of a sonar system is determined by the width of the beam pattern – the narrower it is the better. In the case of electrical scanning (classical phased array) [2], the width of the beam pattern is determined by the spatial length of the sensor array, and the far-field beam pattern of the array when it is complex weighted is given by

$$D'(f, f_x) = \sum_{n=-N}^N a_n(f) \exp\{j[2\pi f_x n d + \theta_n(f)]\}, \quad (1)$$

where  $a_n(f)$  is an amplitude window of the array,  $N$  – amount of sensors and  $d$  – distance between the sensors [4]. We know that a phase shift  $\theta_n(f)$  in radians is equivalent to a time delay  $\tau_n$  in seconds, that is

$$\theta_n(f) = 2\pi f \tau_n, \quad \tau_n = \frac{\theta_n(f)}{2\pi f}. \quad (2)$$

In the case of long duration signals, the use of time-delay circuits to do beam steering is really not necessary, since beam steering can be accomplished via phase weighting, which can be implemented by using digital signal processing (digital beamforming). For signals with a spread spectrum, the directional diagrams of the sensor array may vary dynamically in time and we must directly compensate all the delays  $\tau_n$ . It is possible to perform delay compensation and formation of the beam pattern in the frequency domain. In principle we must compute the complex frequency spectrum from the signal in each channel of the array, then multiply all given spectrum values in each channel with the expression  $\exp[-j\theta_n(f)]$ . From the results we must take the inverse Fourier' transform and then obtain a delayed signal as a final result.

Several advanced digital algorithms may be used for delay compensation [2]. Instead of computing intensive FDFIB (Frequency Domain Frequency Invariant Beamformer) described before, an advanced Block-Phase

(BP) method could be used [3, 4]. This method solves many problems related to beamforming and we can obtain good results in the output of the array. But the question is how to calculate and check the beam pattern in the case of spread spectrum signals. Assume that the output signal of the array in different partial directions  $\beta_\gamma$  is represented as  $y^\circ(t, \beta_\gamma)$ . For a beam pattern we can calculate the output signal for each discrete direction as follows:

$$LX_{t,d_g} = \text{Re} \left( y^\circ \left( t, \frac{d_g \cdot \pi}{p_a} \right) \right), \quad (3)$$

$$\beta_\gamma = \frac{d_g \cdot \pi}{p_a}, \quad (4)$$

where  $p_a$  – amount of points in the direction diagram,  $d_g$  – sampled partial directions  $d_g = \overline{0,1,\dots,p_a}$  [4].

A three-dimensional image of the two-dimensional signal matrix  $LX$  is shown in Fig. 1. Here  $\beta_\gamma = 30^\circ$ . Horizontal axis represents the sampled partial directions  $d_g$  and the vertical axis (0–200) represents the signal samples. We can firmly distinguish the presence of the spread spectrum signal at the (sampled) directions where the beam is steered. Moreover, we notice that the spread spectrum signal at the output of the array is quite stable in time and thus we can use some well-known signal amplitude estimation techniques to derive the beam pattern in polar coordinates.

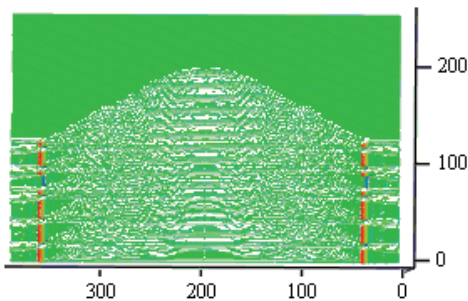


Fig. 1. Three-dimensional image of  $LX$  at  $\beta_\gamma = 30^\circ$

Fig. 2 shows the situation when the beam is steered to the end fire  $\beta_\gamma = 0^\circ$ .

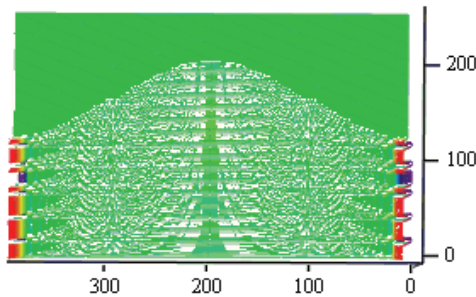


Fig. 2. Three-dimensional image of  $LX$  at  $\beta_\gamma = 0^\circ$

The results of modeling showed that the signals with spread spectrum at large angles would widen the main lobe of the beam pattern approximately 4 times less than the classical phase compensation size. Figs 3 to 6 present modeling results of the horizontal far-field beam patterns in case of  $\beta_\gamma = 30^\circ$  and  $\beta_\gamma = 10^\circ$  ( $N=81$ ) with conventional and Block-Phase methods.

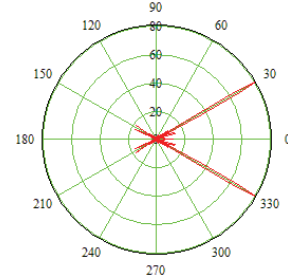


Fig. 3. Spread spectrum beamforming (BP)

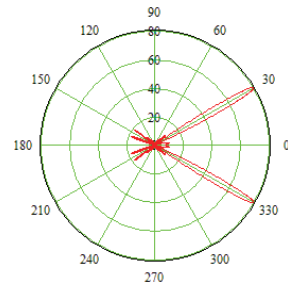


Fig. 4. Conventional beamforming

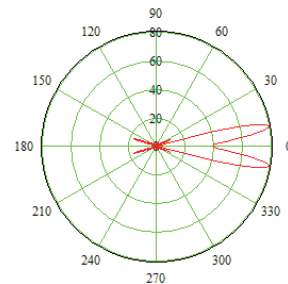


Fig. 5. Spread spectrum beamforming (BP)

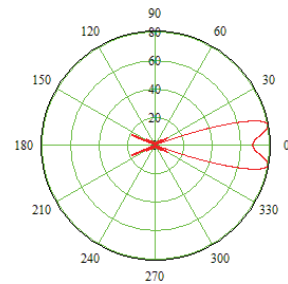


Fig. 6. Conventional beamforming

### Data post-processing algorithms

Synthetic aperture beamforming theory allows us to define location and the beamwidth of the main lobe of each channel [2]. However, the beamwidth depends on the number of physical sensors: the more sensors we use, the narrower the main beam. For example, the width of the synthetic aperture main lobe  $B_0$  of the sonar system with

equivalent distance antenna array with the number of array elements of  $N$ , distance between array elements  $d$  and with the sounding signals of wavelength  $\lambda$  could be calculated as

$$B_0 \approx \frac{2 \cdot \lambda}{d} \cdot \frac{1}{N}. \quad (5)$$

Therefore, to reduce the angular aperture and increase the angular resolution the number of array elements should be increased. In practice, this will give  $N$  squared increase in the number of calculations for conventional beamforming algorithm. Concerning the FPGA implementation this will result in algorithm complexity that could affect the cost of the equipment.

The sonar applications with wide beam array elements would need additional post-processing. Nevertheless, the proposed additional method does not increase the angular resolution of the system but gives an increase in object location accuracy [5].

The navigation would need real-time information about potentially dangerous underwater objects in shallow water areas. As the basic information acquired forms the prior area maps, so the main thread sources are single floating and unmarked bottom objects. The goal of the discussed sonar application is to detect and locate those objects on a maximum distance. Moreover, object location accuracy could be achieved as the post-processing of the synthetic aperture FLS sonar data. In fact, this allows us to achieve desired antenna array by applying additional beamforming methods.

Furthermore, the sonar system could use the array antenna, which consists of separate narrow beam transducers with known characteristics. In this case, antenna with  $N$  elements separated from each other by  $d$  would have the beam pattern  $F_v(\beta)$  and using a rectangular window could be formed as follows

$$F_v(\beta) = \frac{\sin(\pi N d (\sin \beta - \sin \beta_v) / \lambda_0)}{N \sin(\pi d (\sin \beta - \sin \beta_v) / \lambda_0)}, \quad (6)$$

where  $\lambda_0$  – wavelength of the sounding frequency,  $\beta_v$  – partial direction [2][6]. However, other standard windows (Hamming, Kaiser, Chebyshev etc.) reduce sidelobe levels at the expense of widening the main lobe. Consequently, if the synthetic channel location gives an overlap of the main lobes we could reduce the angular aperture using the signal levels in neighboring channels. Here we consider the case of a single point object observed from the distance [7].

Generally, synthetic aperture is done with channel overlapping (Fig. 7.) and the main lobe of each channel is in  $\pm\pi$ . So it could be represented as  $\sin x/x$  [5].

In this case, the signal levels of an object located at  $\alpha$  direction for 0 and 1 channels are:

$$x_0 = A \cdot \frac{\sin(\alpha)}{(\alpha)}, \quad (7)$$

$$x_1 = A \cdot \frac{\sin(-\pi + \alpha)}{(-\pi + \alpha)}, \quad (8)$$

where  $A$  – signal amplitude before the array processing. As a consequence

$$\alpha = \pi \frac{x_1}{x_1 + x_0}. \quad (9)$$

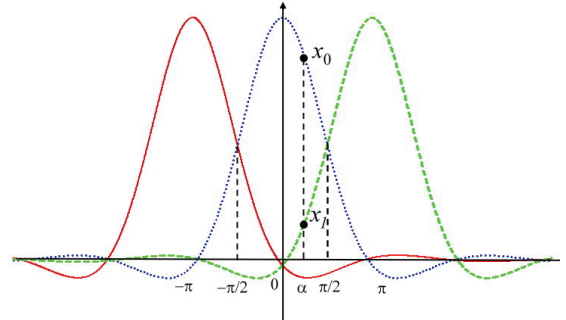


Fig. 7. Overlapping of the neighboring channels in FLS

What is more, this necessary object correction could be easily implemented in post-processing software application. The proposed post-processing algorithm was tested on the models and prototype application. The modeling includes real data from the 6-channel FLS sonar at 490 kHz frequency. Spread spectrum signals are with 32 periods per signal element. Fig.s 8–9 show modeled raw FLS data and post-processed object data. The modeling showed that the object seen in multiple neighboring channels could be successfully localized.

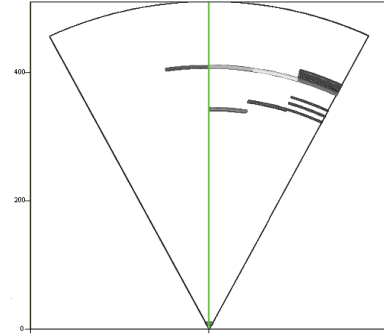


Fig. 8. Raw 6-channel FLS data

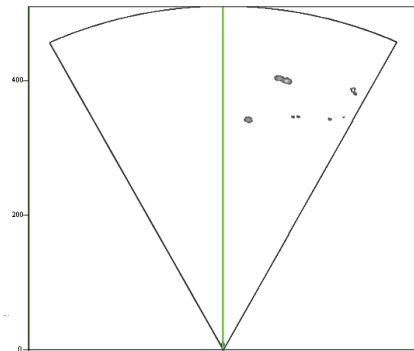


Fig. 9. The post-processed FLS data

Proposed post-processing is implemented in a software defined forward-looking sonar prototype [1]. So the signal processing includes sounding signal generation, data reception from sensors, beamforming, optimal filtering, data post-processing, and image representation (Fig. 10, Fig. 11).



Fig. 10. Raw data of the FLS application

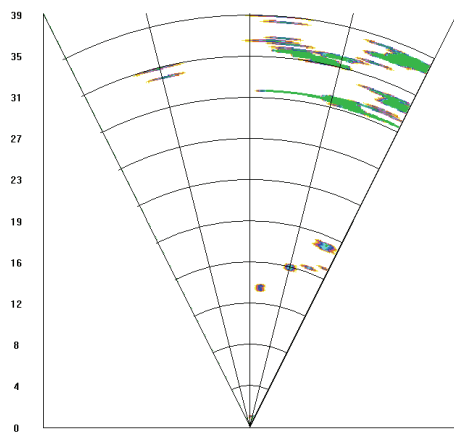


Fig. 11. The real-time post-processed FLS image

## Conclusions

Active digital forward-looking sonar could be implemented as a software defined application. The

redundant information in the raw data could be effectively used for data extraction necessary for navigation. Additional post-processing in cost-effective solutions could give an increase in object location accuracy. This method has some limitations. Processing of the signal levels in neighboring channels would increase noise sensitivity, especially for distant objects. In practice, array calibration coefficients should be applied at the beamforming stage. Furthermore, additional research of the target classification is required. Future work will extend the processing and data fusion capabilities [7, 8]. The data received should be combined with vessel motion, speed and depth at the measured point.

## References

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This paper introduces a new beamforming and received data post-processing method for forward-looking sonar applications with limited number of array elements. Applications like Sidescan or Forward Looking Sonars, used for area efficient sea floor imaging, collect large amount of raw data, which allows us to do both imagery and additional data processing. Moreover, object localization improvement could be accomplished by the post-processing of the received information collected with digital beamforming and beam focusing. Test results illustrate the efficiency of the proposed post-processing algorithms in terms of angular aperture and target detection. Ill. 11, bibl. 8 (in English; abstracts in English and Lithuanian).

**J. Berdnikova, V. Kozevnikov, T. Ruuben, A. Raja. Duomenų apdorojimo algoritmo taikymas aktyviosiose priešakinių hidrolokatorių sistemose // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 4(110). – P. 43–46.**

Aprašomas naujas duomenų apdorojimo algoritmo taikymas priešakinių hidrolokatorių sistemose. Tokios sistemos naudojamos jūros dugno vaizdai gauti ir dideliems grynosios informacijos kiekiams saugoti. Išsamiems vaizdams gauti duomenys gali būti papildomai apdorojami, įvertinamos kryptingumo diagramos. Pateikti rezultatai rodo duomenų apdorojimo algoritmo efektyvumą. Il. 11, bibl. 8 (anglų kalba; santraukos anglų ir lietuvių k.).