

LOCATION OF THE HYDROACOUSTIC NOISE SOURCES PERFORMED BY DISTRIBUTED PASSIVE SONAR

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Hydroacoustic location of underwater sound sources is commonly used to protect naval bases or military sea areas from various threats. Sonar technology applies hydrophones to detect sources of underwater noises. DOA estimation method based on the high angular resolution MUSIC algorithms are commonly used for small size antennas composed of hydrophones. The article proposes another approach to this problem. Additional equipage of the hydrophone with the GPS receiver and radio transceiver enables construction of the distributed antenna. The size of such antenna can be significantly higher in comparison to the classical passive antenna. The article describes the algorithms of the sound sources location, results of the computer simulation and possibilities of hydrophone manufacturing as well its practical usage.

INTRODUCTION

In scope of the 7FP the passive sonar composed of 4 digital hydrophones was manufactured in OBR CTM S.A. It estimates narrowband DOA in frequency range from 300 to 500 Hz. Many technical problems associated with technology of the underwater connectors, complex cabling resulting from star topology and synchronous signals processing provided the designing staff to elaborate the new concept. The first approach was the Precision Time Protocol Hydrophone applying the IEEE1588 standard to synchronize hydrophones network. In this case the antenna can be considered as the network of bus topology using the real time Ethernet protocol (EtherCAT). This network enables acquisition of raw or processed data in the single Ethernet data frame. From mechanical point of view it is a uniform circular array (UCA). To obtain DOA in regards to the geographical North the antenna should be equipped with compass. The geographical location of directionally detected target is also possible. However the triangulation requires minimum two antennas of known geographical positions. So each antenna should be equipped with GPS and radio module.

The [9] article suggested another method of sound source location. Instead of mechanically complex antennas equipped with GPS, compass and five network hydrophones [3] the distributed antenna is proposed. It is composed of several autonomous hydrophones incorporating batteries, GPS, microcontroller and radio module. The hydrophones be can be independently distributed over a large sea area. GPS except primary geographical location of the hydrophone enables also precise and synchronous acquisition of data. The data integration is carried out via radio network. Determination of the so called pseudo-ranges makes possible location of the sound sources.

1. MEASUREMENT OF THE PSEUDO-RANGES

The determination of acoustic wave propagation time on the way from source to the particular hydrophone is essential for all directional and location algorithms. It requires synchronous acquisition of acoustic pressure samples received from all hydrophones. At the input of the pseudo-range algorithm they are the signal samples of common time base. The cross-correlation function for two independent hydrophones allows only the calculation of the propagation time differences i.e. the individual propagation time from source to particular hydrophone remains unknown (figure 1).

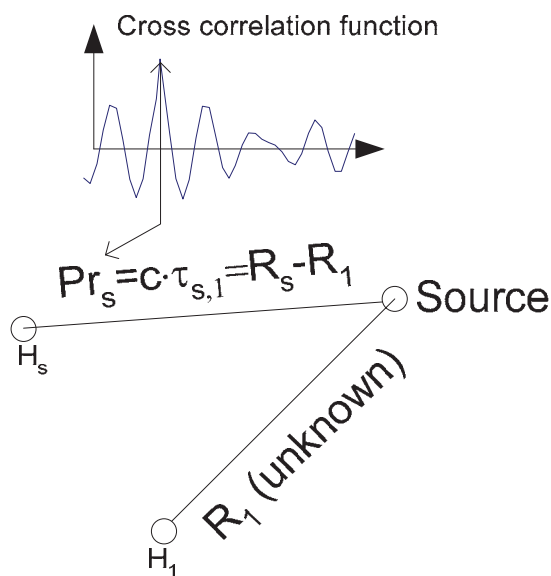


Fig.1. Pseudo-ranges measure.

The common time base makes possible generation of the cross-correlation function. Following symbols are used in figure:

- s - hydrophone index
- $\tau_{s,1}$ - maximum of the cross-correlation function between sensors of 1 and s indexes
- PR_s - pseudo-range for sensor of s index
- R_s - unknown distance from sound source to sensor of s index
- Cr - „clock error” correction for all pseudo-ranges

To simplify further calculation the rectangular coordinate system of X, Y axes is used instead of more complex geographical latitude and longitude.

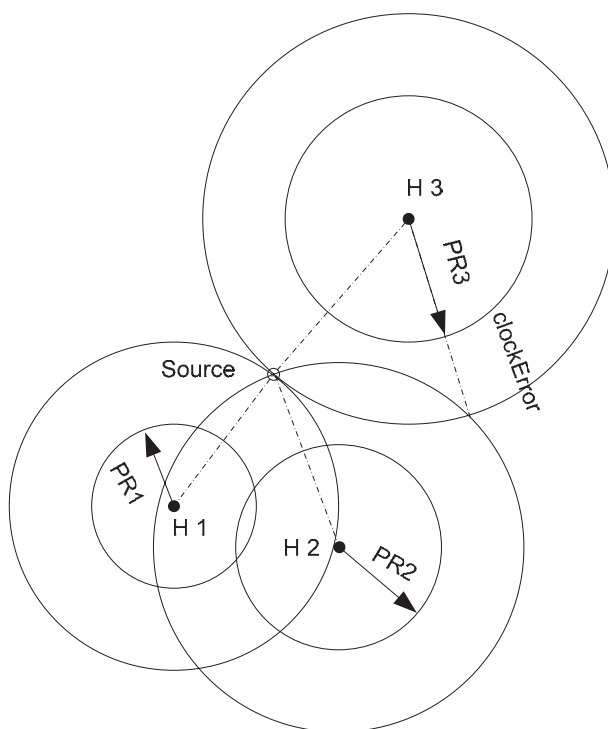


Fig.2. Calculating of position using pseudo-ranges.

Figure 2 shows the common „clock error” enabling calculation of the distance on the basis of pseudo-ranges.

$$Pr_s + Cr = \sqrt{(Xr - X_s)^2 + (Yr - Y_s)^2} = Rr_s \quad (1)$$

In the above (1) expression unknown are the position of the source (Xr,Yr) and „clock error” Cr.

The next steps assume the approximate knowledge of the source position (Xr,Yr). The errors of this position are marked as (dX, dY). It conducts to below approximate dependence:

$$Pr_s + Cr \approx Rr_s + dX \cdot \frac{Xr - X_s}{Rr_s} + dY \cdot \frac{Yr - Y_s}{Rr_s} \quad (2)$$

The three variables Cr, dX and dY are common for all s indexes. Usage of the least square method for system of equations (2) provides to following criterion:

$$f(dX, dY, Cr) = \sum_s \left(\left(dX \cdot \frac{Xr - X_s}{Rr_s} + dY \cdot \frac{Yr - Y_s}{Rr_s} - Cr \right) - Pr_s + Rr_s \right)^2 \quad (3)$$

Minimum of criterion function leads to dependence:

$$\frac{\partial f}{\partial(dX)} = \frac{\partial f}{\partial(dY)} = \frac{\partial f}{\partial(Cr)} = 0 \quad (4)$$

These dependences conduct to linear equation with symmetric matrix:

$$\begin{bmatrix} \sum_s \frac{Xr - X_s}{Rr_s} & \sum_s \frac{Xr - X_s}{Rr_s} \frac{Yr - Y_s}{Rr_s} & \sum_s \frac{Xr - X_s}{Rr_s} (-1) \\ \dots & \sum_s \frac{Yr - Y_s}{Rr_s} \frac{Yr - Y_s}{Rr_s} & \sum_s \frac{Yr - Y_s}{Rr_s} (-1) \\ \dots & \dots & \sum_s (-1) \end{bmatrix} \begin{bmatrix} dX \\ dY \\ Cr \end{bmatrix} = \begin{bmatrix} \sum_s (Pr_s - Rr_s) \frac{Xr - X_s}{Rr_s} \\ \sum_s (Pr_s - Rr_s) \frac{Yr - Y_s}{Rr_s} \\ \sum_s (Pr_s - Rr_s) (-1) \end{bmatrix} \quad (5)$$

The solution of this system of equations delivers X_r , dX and dY variables. Updated position is described by following expression:

$$\begin{aligned} X_r &\leftarrow X_r + dX \\ Y_r &\leftarrow Y_r + dY \end{aligned} \quad (6)$$

The (5) and (6) equations create the iteration algorithm. After few iterations the dX and dY values decrease to zero.

2. MUSIC METHOD

The MUSIC (Multi-source Signal Classification) method relies on the narrowband analysis of the covariance matrix. The steering vectors corresponding to the sound source are calculated in manner presented in the figure 3. It incorporates I/Q detection and low-pass filtering.

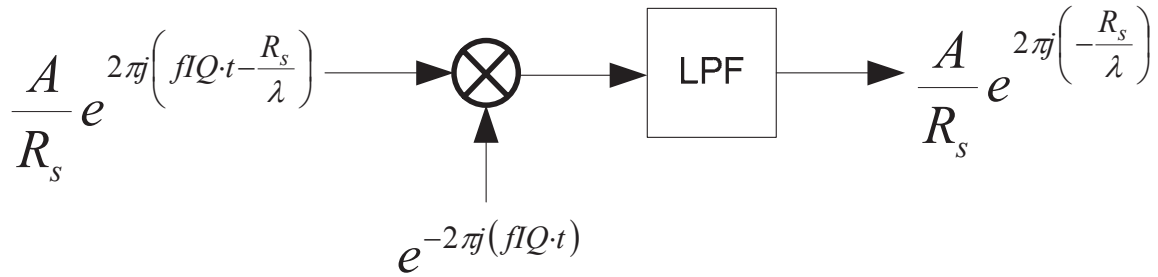


Fig.3. Generation of steering vector.

The number of vector components equals to the quantity of the hydrophones. The spectral decomposition of covariance matrix provides to the eigenvectors. The steering vector is the linear combination of eigenvectors subset. Remaining eigenvectors defining the noise subspace are orthogonal to the steering vector. The MUSIC algorithm relies on searching for the steering vector “the best orthogonal” to the noise subspace.

The manner of searching is decisive for calculation time and accuracy of solution. The classical DOA estimation [1] assumes antenna of dimensions much smaller than the distance to the sound source R_s . The omnidirectional searching for optimal steering vector is done with assumed angular resolution. The DOA is the result of this process. In case of the distributed system the searching for maximum can be additionally parameterized. One of the possibilities is the searching for maximum along the circle of R_0 radius and (X_r, Y_r) center as presented the figure 4. This leads to following components of the steering vector:

$$\bar{P} = \begin{bmatrix} X_p \\ Y_p \end{bmatrix} = \begin{bmatrix} X_r + R_0 \cdot \cos \Theta \\ Y_r + R_0 \cdot \sin \Theta \end{bmatrix}, \quad \Theta = i \cdot \frac{2\pi}{N}, i = 0..N-1 \quad (7)$$

$$\begin{aligned} R_s &= \sqrt{(X_s - X_p)^2 + (Y_s - Y_p)^2} \\ \Theta_s &= \arctan 2(Y_s - Y_p, X_s - X_p) \end{aligned} \quad (8)$$

$$a_s(\bar{P}) = \frac{R_0}{R_s} \left(e^{2\pi j\left(fIQ \cdot t - \frac{R_s}{\lambda}\right)} \cdot e^{-2\pi j(fIQ \cdot t)} \right) = \frac{R_0}{R_s} e^{2\pi j\left(-\frac{R_s}{\lambda}\right)} \quad (9)$$

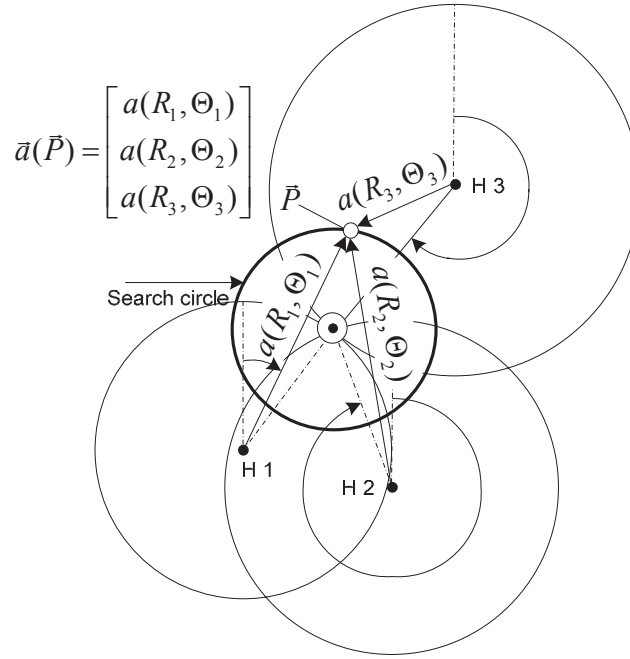


Fig.4. Searching for PMU minimum.

Another issue is the matching of parameters for searching method. The complete algorithm is described beneath. In case of single sound source the stream of random vectors appears at the algorithm input. The single random vector obtained from this stream corresponding to \bar{P} position is given by following formula:

$$\bar{s} = A \cdot \bar{a}(\bar{P}) + \bar{n} \quad (10)$$

The A parameter is the random variable whereas \bar{n} vector presents the remaining noise. The generation of the cross correlation matrix relies on calculation of the simple moving average according to dependence:

$$CCM = SMA(\bar{s} \cdot \bar{s}^T) \quad (11)$$

Eigendecomposition of this matrix is described by expression:

$$CCM = U \cdot \Lambda \cdot U^T \quad (12)$$

where U is the unitary matrix and Λ is the diagonal matrix.

Generation of the noise subspace is done through the separation of the eigenvectors subset corresponding to smaller values of the eigenvalues.

$$U = \begin{bmatrix} U_s \\ \text{-----} \\ U_N \end{bmatrix} \quad (13)$$

These vectors create to noise subspace U_N .

The Power MUSIC criterion is defined as:

$$\min_{\bar{P}} PMU = \min_{\bar{P}} \|U_N \bar{a}(\bar{P})\|^2 \quad (14)$$

The searching for this function minimum for selected subset of the steering vector enables determination of the sound source position. It can be done for single or several sound sources.

3. COMPUTER SIMULATION

To confirm the described hereinabove method the computer simulation program was developed. Program incorporates location algorithms based on embedded simulator of the environmental underwater acoustic signals. The figure 5 presents the location using pseudo-ranges method for four hydrophones. The pseudo-ranges are calculated on the basis of the cross-correlation function in regards to the H1 hydrophone. The smaller circles surrounding the hydrophones present the pseudo-ranges. The bigger circles correspond to distances from target to particular hydrophone. These circles are the result of the „clock error” correction for range of 149.7m. In case of sea area of 200×200m dimensions the real position of target is different from determined by antenna by about 5m.

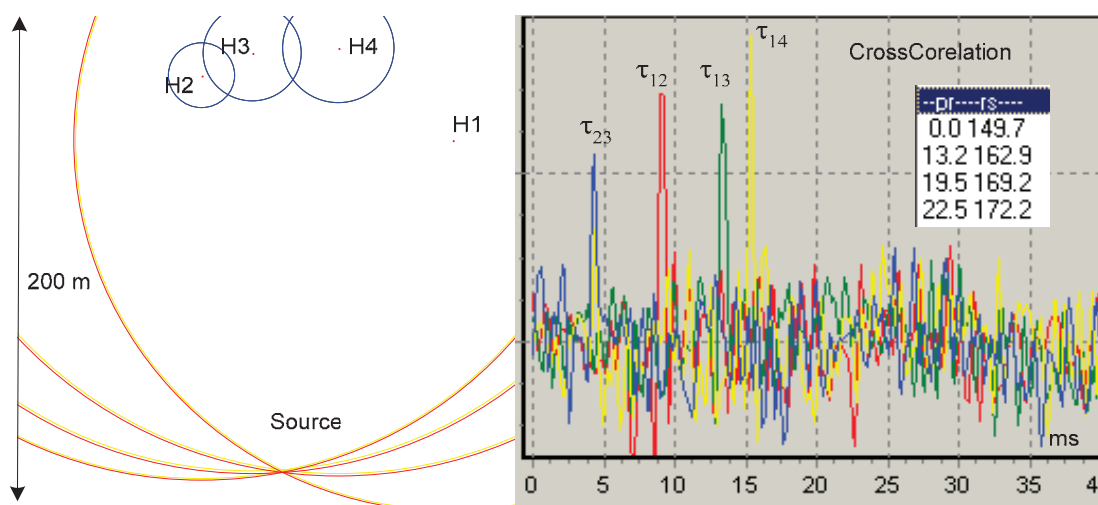


Fig.5. The simulation result for pseudo-ranges detection.

The figure 6 shows the simulation results for MUSIC method. The searching steering vectors were calculated for circle of 200m radius around the heptagon antenna. The antenna diameter equaled 40m whereas the frequency of the reference signal was 10Hz. The MUSIC method correctly determined the direction of the sound source.

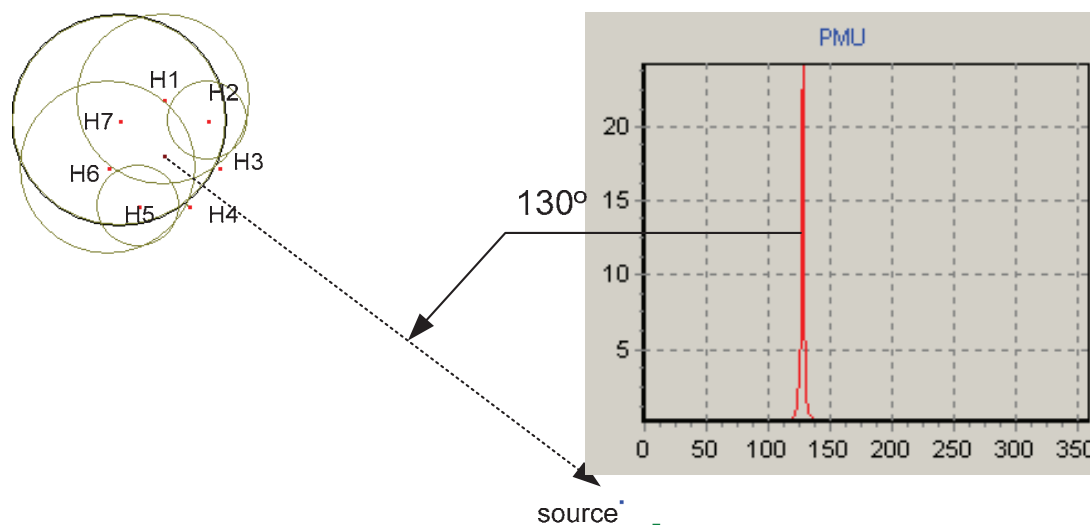


Fig.6. The results of the computer simulation for MUSIC method.

4. CONCLUSION

Proposed method of target location is innovative. The algorithm correctly operates at very low frequencies (<10Hz). It is essential for detection of boats and other vessels. Presently our task is to design and manufacture the autonomous hydrophone. The OBR CTM S.A. has been providing such research and development works for many years. Application of the standard radio network is the optimal solution for freely disturbed hydrophones making up the antenna. Initially the standard IEEE 802.15.4 seems to be sufficient to setup connection [7]. Usage of this standard do not requires licenses. For signals acquisition the optimal shape of the antenna is the star – see figure 7. The complete data are gathered by node so called Personal Area Network Coordinator, the remaining node are named End Device.

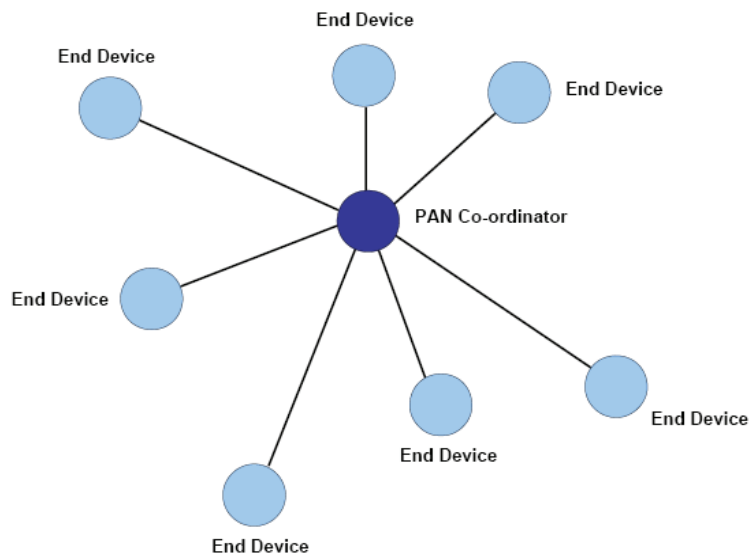


Fig.7. Star topology.

We have been using Jennic microcontrollers shown in the figure 8 for years. Such microcontroller not only the services the radio standard but also includes the interfaces to external peripheral devices.

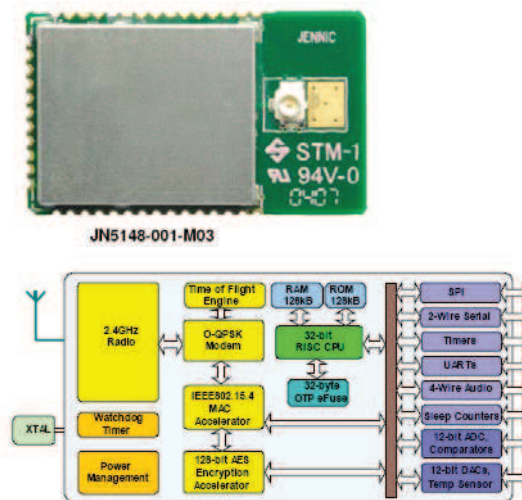


Fig.8. Microcontroller JN1548.

The most important interfaces of the microcontroller are following:

- UART acquiring the serial transmission data from GPS receiver
- Analog inputs to transform the analog hydroacoustic signal into 12–bits digital one
- Digital inputs to connect the synchronization signal (Pulse Per Second) from GPS receiver

The microcontroller contains some programmable timers useful for synchronous timebase generation.

The GPS receiver with serial data output and precise (1 μ s) PPS is available as the micro module. The figure 9 presents the satellite receiver servicing the GPS/GLONASS/Galileo systems.



Fig.9. Micro module of the satellite receiver.

Especially up-to-date standards and technologies are predisposed to construct the distributed systems frequently called the area systems. The system of the distributed antenna may find application in following fields:

- Detection and location of maritime threats such as underwater vehicles, ship's and boats
- The sea trials with explosives sound sources
- The remote monitoring of the environmental parameters

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