INVESTIGATION OF THE PULSE REFLECTED FROM BOTTOM SEDIMENTS

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The paper describes method of determining time proceeding of the echo pulse arising as an effect of reflection of sampling pulse given with the known form from layered sea bottom. The main goal of presented model is to afford theoretical data that could be used as a point of reference for the experimental data obtained with SES 2000 Standard parametric echosounder. Basic formulas, computation algorithm with its implementation in Matlab language and examples of obtained results are described. Numerical simulations results are compared with experimental data. The laboratory station enabling computing acoustic impedance of sediments and parameters of sampling and echo pulse in different distances from antenna is presented.

INTRODUCTION

The mathematical model described in this paper and simulation program based on it were created to deliver data, that could be compared to the experimental results, obtained with SES-2000 Standard parametric echosounder. The computation algorithm takes into account specification of the problem to be solved and focuses on most important issues in terms of deriving results. The parametric echosounder used for experimental investigations has very narrow main lobe and side lobes low enough to be skipped in described considerations. During measurements the beam is pointed vertically and the sounding pulse frequency is lower than 15 kHz – wavelength is much longer than mean height of typical seafloor roughness. Taking into account facts described above, the considerations will be limited to plane wave reflecting perpendicularly from flat-parallel layered media.

It is assumed, that propagation environment is linear (this assumption does not take into account parametric effects responsible for creating the low frequency pulse – those effects are not important for further considerations, only the shape of the pulse matters) and its physical parameters are constant in time periods involving modeling processes. Due to those assumptions it is possible to treat propagation media as a system characterized with given transmittance and to compute reflected pulse as response of this system for the excitation with known sampling pulse.

Real pulses were recorded during experimental measurements and used in computer simulations. The pulses have wide spectrum, so it is necessary to compute transmittance in wide range of frequencies. Resolution of the computations is delineated with the sample frequency of the recorded data.

It is necessary for the simulations to know acoustical parameters of the sediments, that are assumed to create the sea bottom layers. To limit the number of input parameters needed for every simulation acoustical properties of bottom sediments are calculated using empirical relations connecting acoustic speed, density and attenuation coefficient of each sediment with mean diameter of its particles. Thanks to implementation of such procedure amount of the input data is limited to minimum.

The main goal of computer simulations is to find such structure and acoustical properties of the propagation enviroment, for which results of the numerical computations will be as similar as possible to the results of experimental measurements. Achieving good covergence of the data allows to expect, that assumed bottom properties correspond to experimental enviroment conditions.

1. THEORETICAL BACKGROUND

Situation ilustrated on figure Fig.1. is considered. On the top of the stack of n flat, parallel layers, each of which has given thickness ($d_1 \ldots d_n$), density ($\rho_1 \ldots \rho_n$), acoustic velocity ($c_1 \ldots c_n$) and acoustic impedance ($z_1 \ldots z_n$) incidents an acoustic wave transmitting from half-infinite medium with parameters given with, respectively, ρ_0, c_0, z_0. On the other side the stack of the layers is limited with another half-infinite medium, described with parameters $\rho_{(n+1)}$, $c_{(n+1)}$, $z_{(n+1)}$.

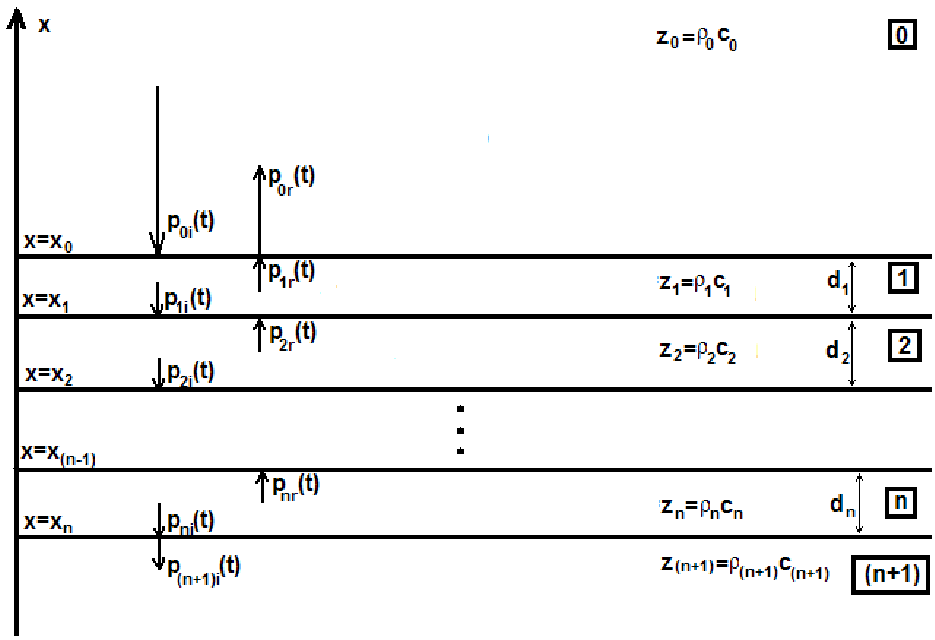

Fig.1. Acoustic wave reflecting perpendicularly from flat-parallel layered medium

It is assumed, that incident acoustic wave is plane, it has infinitely low amplitude and that it reflects perpendicularly from the layered medium. All of the layers are considered as linear, uniform and isotropic fluids. The limiting planes are perfectly flat. Every layer is described with given exponential attenuation coefficient $(\alpha_0,...,\alpha_n)$.

Relations between acoustic pressures of waves incident, transmitted and reflected from boundary between layers *l* and *l+1* are given with:

$$\frac{p_{lr}}{p_{li}} = \beta_l \quad , \qquad \frac{p_{lt}}{p_{li}} = 1 + \beta_l \quad , \tag{1}$$

where β_l is reflection coefficient, given with:

$$\beta_l = \frac{\rho_{(l+1)}c_{(l+1)} - \rho_l c_l}{\rho_{(l+1)}c_{(l+1)} + \rho_l c_l} = \frac{z_{(l+1)} - z_l}{z_{(l+1)} + z_l} \, . \tag{2}$$

Reflection coefficients describing acoustic waves that incident from layer *l* on *l+1* and on the opposite direction are described with following relation:

$$\beta_{l\to(l+1)} = -\beta_{(l+1)\to l} \, . \tag{3}$$

Propagation time in each sediment layer depends on the thickness of the layer and acoustic velocity in the sediment. For layer numbered *l*, with given thickness d_l and acoustic velocity c_l propagation time is described with following relation:

$$\tau_l = \frac{d_l}{c_l} \, . \tag{4}$$

Acoustic waves propagated in real (dissipative) media are attenuated. Attenuation of the wave depends on the physical properties of the medium and on the length of the propagation path. In presented considerations it is assumed, that acoustic pressure of wave before and after its transmission through layer numbered *l* is given with transmission coefficient, described with following relation:

$$\frac{p_{li}}{p_{(l-1)i}} = T_l = 10^{\left(\frac{-\alpha_l d_l}{10}\right)} \, , \tag{5}$$

where α_l is exponential attenuation coefficient of the layer expressed in [dB/m].

Implementation of the equations (1) – (5) requires inputting four parameters describing acoustic properties of each of the layers: its density, acoustic velocity, exponential attenuation coefficient and thickness. Inputted data should refer to values describing sediments that create sea bottom. In simulation program empirical relations connecting all of the necessary parameters of each sediment with mean diameter of its particles are used. Corresponding equations are described in paper [1].

Time dependence of the acoustic pressure of the reflected wave – $p_{0r}(t)$ - is sought. Finding solution of the problem in time domain, basing on equations (1) – (5), is complicated, due to the time delays between waves reflected from different boundary planes [2]. Using Fourier transform to the equation set describing time dependence of acoustic pressures of waves incident, transmitted and reflected from each of the layers allows to skip those complications. Final equation set that is solved is given with:

$$
\begin{aligned}
&p_{0r}(j\omega)=\beta_0 p_{0i}(j\omega)+(1-\beta_0)p_{1r}(j\omega)\\
&p_{1i}(j\omega)=(1+\beta_0)T_1D_1p_{0i}(j\omega)-\beta_0T_1D_1p_{1r}(j\omega)\\
&p_{1r}(j\omega)=\beta_1T_1D_1p_{1i}(j\omega)+(1-\beta_1)T_1D_1p_{2r}(j\omega)\\
&p_{2i}(j\omega)=(1+\beta_1)T_2D_2p_{1i}(j\omega)-\beta_1T_2D_2p_{2r}(j\omega)\\
&p_{2r}(j\omega)=\beta_2T_2D_2p_{2i}(j\omega)+(1-\beta_2)T_2D_2p_{3r}(j\omega)\\
&(\ldots)\\
&p_{li}(j\omega)=\left(1+\beta_{(l-1)}\right)T_lD_lp_{(l-1)i}(j\omega)-\beta_{(l-1)}T_lD_lp_{lr}(j\omega)\\
&p_{lr}(j\omega)=\beta_lT_lD_lp_{li}(j\omega)+(1-\beta_l)T_lD_lp_{(l+1)r}(j\omega)\\
&(\ldots)\\
&p_{(n-1)i}(j\omega)=\left(1+\beta_{(n-2)}\right)T_{(n-1)}D_{(n-1)}p_{(n-2)i}(j\omega)-\beta_{(n-2)}T_{(n-1)}D_{(n-1)}p_{(n-1)r}(j\omega)\\
&p_{(n-1)r}(j\omega)=\beta_{(n-1)}T_{(n-1)}D_{(n-1)}p_{(n-1)i}(j\omega)+\left(1-\beta_{(n-1)}\right)T_{(n-1)}D_{(n-1)}p_{nr}(j\omega)\\
&p_{ni}(j\omega)=\left(1+\beta_{(n-1)}\right)T_nD_np_{(n-1)i}(j\omega)-\beta_{(n-1)}T_nD_np_{nr}(j\omega)\\
&p_{nr}(j\omega)=\beta_nT_nD_np_{ni}(j\omega)
\end{aligned}
\tag{6}
$$

, where D_l is delay coefficient and it is given with the following equation:

$$D_l = e^{j\omega\tau_l}\ . \tag{7}$$

Set of equations (6) can be expressed as one matrix equation:

$$Ax = b\cdot p_{0i}(j\omega), \tag{8}$$

where matrix A is coefficients matrix, given with:

$$
\begin{bmatrix}
-1 & 0 & (1-\beta_0) & 0 & 0 & 0 & 0 & 0 & 0\\
0 & -1 & -\beta_0T_1D_1 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & \beta_1T_1D_1 & -1 & 0 & (1-\beta_1)T_1D_1 & 0 & 0 & 0 & 0\\
0 & (1+\beta_1)T_2D_2 & 0 & -1 & -\beta_1T_2D_2 & 0 & 0 & 0 & 0\\
\ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots\\
0 & 0 & 0 & \left(1+\beta_{(n-2)}\right)T_{(n-1)}D_{(n-1)} & 0 & -1 & -\beta_{(n-2)}T_{(n-1)}D_{(n-1)} & 0 & 0\\
0 & 0 & 0 & 0 & 0 & \beta_{(n-1)}T_{(n-1)}D_{(n-1)} & -1 & 0 & \left(1-\beta_{(n-1)}\right)T_{(n-1)}D_{(n-1)}\\
0 & 0 & 0 & 0 & 0 & \left(1+\beta_{(n-1)}\right)T_nD_n & 0 & -1 & -\beta_{(n-1)}T_nD_n\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \beta_nT_nD_n & -1
\end{bmatrix}
$$

(9)

Matrixes x and b are given with:

$$\mathbf{b} = \begin{bmatrix} -\beta_0 \\ (1+\beta_0)T_1 D_1 \\ 0 \\ 0 \\ 0 \\ \ldots \\ 0 \\ 0 \\ 0 \end{bmatrix}, \qquad \mathbf{x} = \begin{bmatrix} p_{0r} \\ p_{1i} \\ p_{1r} \\ p_{2i} \\ p_{2r} \\ \ldots \\ p_{(n-1)r} \\ p_{ni} \\ p_{nr} \end{bmatrix}. \tag{10}$$

Elements of x matrix are described with following relations:

$$\begin{gathered} p_{0r} = p_{0r}(j\omega) = \Im\{p_{0r}(t)\} \\ p_{1i} = p_{1i}(j\omega) = \Im\{p_{1i}(t)\} \\ \ldots \\ \ldots \\ \ldots \\ \ldots \\ \ldots \\ p_{ni} = p_{ni}(j\omega) = \Im\{p_{ni}(t)\} \\ p_{nr} = p_{nr}(j\omega) = \Im\{p_{nr}(t)\} \end{gathered} \tag{11}$$

Solving equation (8) leads to relation connecting spectrum of acoustic pressure of wave reflected from layered sea bottom with spectrum of the incident wave. Due to the avowed assumptions which allow to consider propagation environment as a linear system with given frequency response $H(j\omega)$ described relation can be expressed as:

$$p_{0r}(j\omega) = H(j\omega)p_{0i}(j\omega). \tag{12}$$

Time dependence of the acoustic pressure of the reflected wave is computed using inverted Fourier transformation:

$$p_{0r}(j\omega) = H(j\omega)p_{0i}(j\omega). \tag{1.11}$$

Described algorithm takes also into account time delay and wave attenuation related with two-way propagation in water between sea bed and sonar head.

In simulations recorded time proceedings of true sampling pulses are used. Those pulses have wide frequency spectrum, that can be computed with resolution dependent on the time step between samples of the recorded pulses. To compute the reflected pulse it is necessary to solve equations (8) – (12) for all of the frequencies belonging to the considered spectrum.

2. IMPLEMENTATION

Described algorithm has been implemented using Matlab language. The simulation program - besides described computation process – performs many other functions connected with data storage, processing and ensures the user interface. It allows to load the text file containing samples of the recorded pulse, performing the simulation process and comparing the computation results with experimental investigations data.

The simulation program window with an example of simulation results is presented on figure Fig.2.

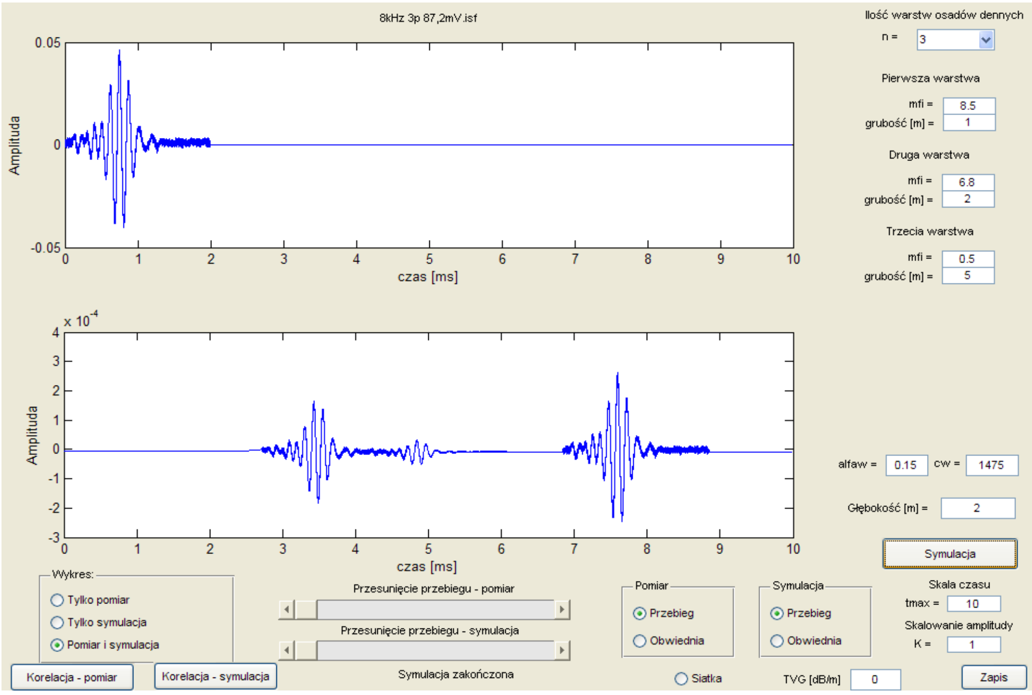

Fig.2. Simulation program window. Top graph ilustrates loaded sampling pulse, lower graph contains results of the simulation performed for the sea bottom composed with three sediment layers. Top layer – one meter thick – is clay, second layer is two meters of mud and the bottom layer is coarse sand. Signal frequency is f = 8 kHz

3. LABORATORY MEASUREMENT

During measuring acoustic impedance in laboratory conditions hydrophone ITC 1089D (Fig 3.) and model of different sediment layer (Fig 4.) were used.

Fig.3. Hydrophone ITC1089D

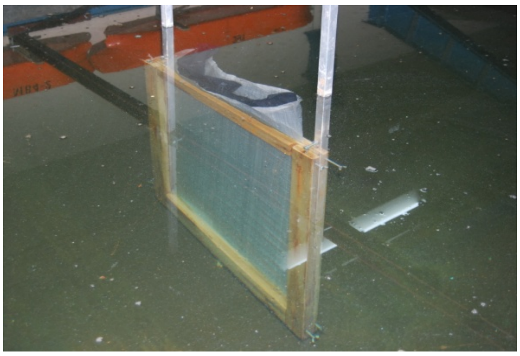

Fig.4. Sediment layer model

Laboratory measurements were made on 30 meters long, 3 m width and 1,5 m deep water tank Fig. 5. Center of antenna was placed 75 cm under water surface. First point during works was proper antenna direct. It was important to steer main lobe in axis parallel to tank walls and water surface.

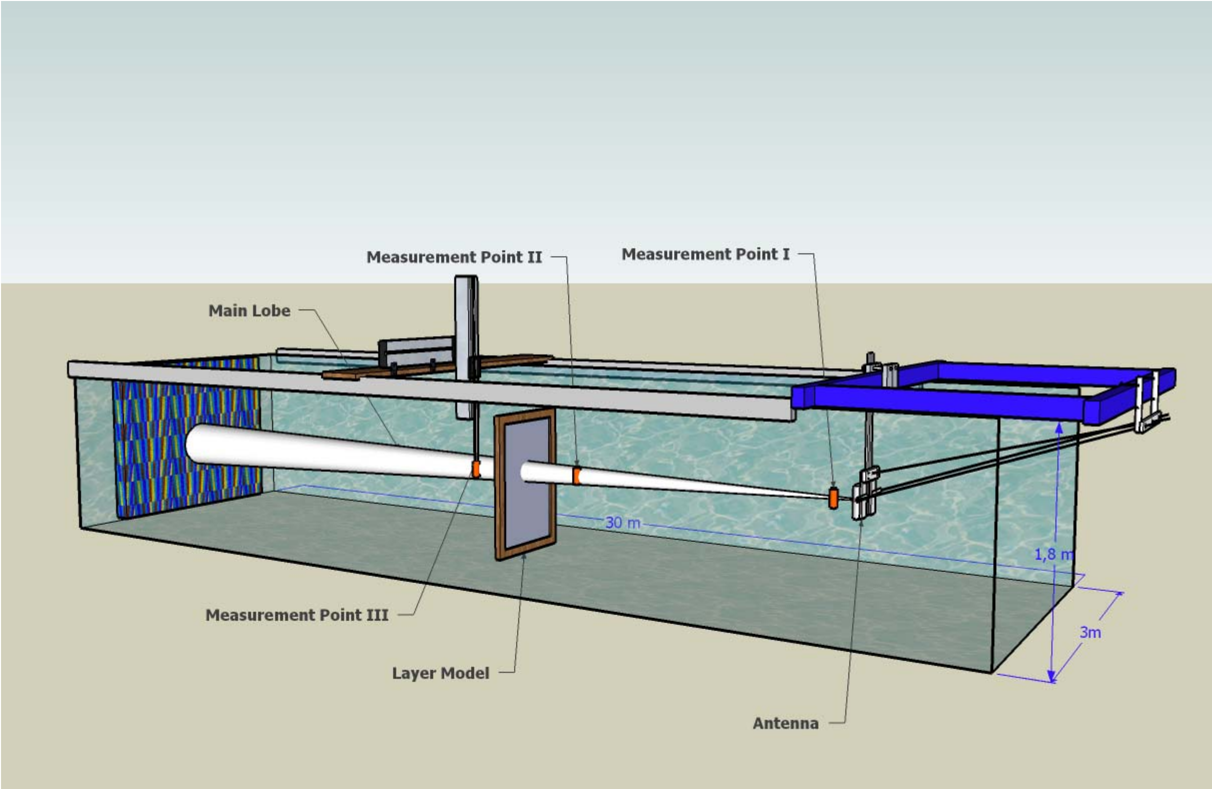

Fig.5. Configuration of measuring device in water tank

Data were stored in three measuring points after and behind sediment layer model and near echosounder's antenna. Set of measurements gives opportunity to calculate acoustic impedance of material and shows reflected pulse shape changes - what is very important during visualization sounding results on echogram Fig. 6.

a) **b)**

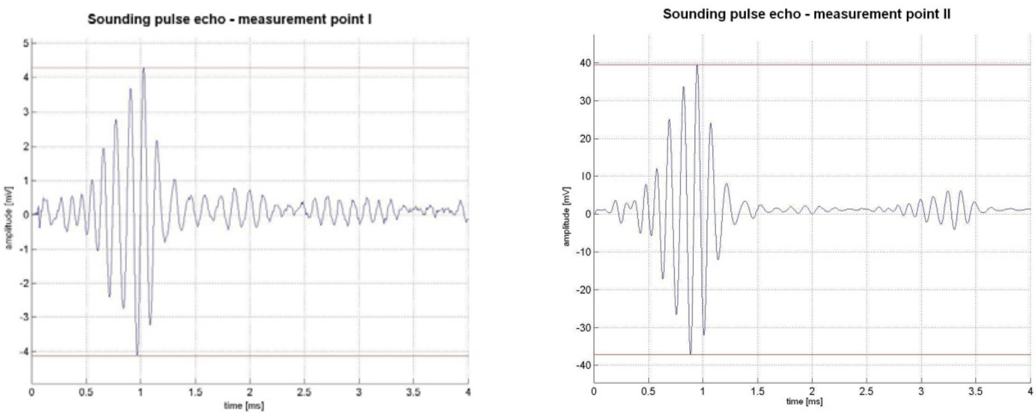

Fig.6. Sounding and reflected pulse recorded in a) first measuring point b) second measuring point

4. FINAL CONCLUSIONS

Numerical investigations performed using described simulation program lies in initial assumption of sea bottom layers properties and computation of the reflected pulse for those parameters and loaded sampling pulse. Computation results are compared to data obtained during measurements using the same sampling pulse. Model's input parameters are modified and the simulation process repeats until similarity between both results is good enough. Graphs illustrating described process are shown on figure Fig.7.

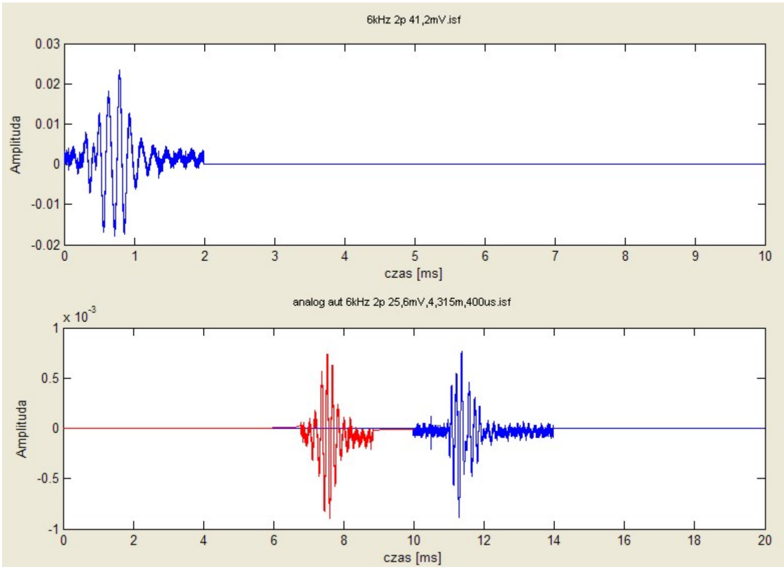

Fig.7. Part of the simulation program window. Top graph illustrates loaded sampling pulse, lower graph contains results of the simulation (red) and measurements (blue)

Computations performed with described algorithm – thanks to all the simplifying assumptions – are very fast. Using standard PC results are obtained in less than one minute, even for assumed complex sea bottom structure. Nevertheless, they seem to be accurate enough for the initial estimation of true sea bottom properties.

ACKNOWLEDGMENTS

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[2] Salomon R., Systemy Hydrolokacyjne, Gdańskie Towarzystwo Naukowe, Gdańsk 2006.