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Efficient Use of AUVs in the Maritime Environment

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Abstract. Autonomous underwater vehicle (AUV) a.k.a. underwater drones are subsea vehicles which operate in the underwater environment independently of direct human input. There is a growing interest in underwater data collection by using autonomous underwater vehicles within the oceanographic research community. In this paper, the Iver 2 AUV is examined to accomplish accurate side-scan data while executing well planned missions. Therefore, this papers goal is to establish the optimal use conditions for the AUV that RCN has so that we maximize the detection probability of sea bottom objects that can be risk factors and at the same time to cover a surface as large as possible during a single mission.

1. Introduction

The capability of protecting marine areas and important objectives situated near the shore against dangers associated with surface or underwater threats is critical for providing security in marine activities. Significant categories of threats are ships, small crafts and divers – these can either transport terrorists or various dangerous substances and materials in the protected area or can deposit such items on the sea bottom in the area, or can even conduct terrorist action themselves.

This is the reason that the mission profile for a SIROLC-type system (System for detection, localization, tracking and identification of risk factors addressing important strategic objectives in littoral areas) should focus on two main objectives. The first one is to detect, locate and identify, through regular inspections and post-mission analysis the presence on the sea bottom or near it of objects that can become dangerous to the shipping activities in the area and for the protected objective.

For this purpose SIROLC will have in its configuration an AUV-type subsystem for underwater surveillance [1] and which is fitted with specific sensors for orientation and determination of its own position and for determining the conductivity and salinity parameters, needed for calculating the sound speed profile at depth (information needed for increasing the performance of sonar systems). For observing the objects situated on the sea bottom the AUV subsystem is fitted with a high resolution side scanning sonar.

A second objective is that of signaling the presence near the protected area of small ships or divers. There are various systems that can detect and track targets that move on surface or underwater, the most often used being of the active type (sonar and radar) [1].

The AUV has a main role in the missions of detection, localization, tracking and identification of risk factors situated on the sea bottom as it can be deployed in relatively large areas with a high coverage degree with spatial and temporal resolutions that can not be achieved through other means. At the same time, the AUV efficiency is very high when compared to the costs and duration of measurements [3].

After analyzing the answers provided by the potential beneficiaries to a requirements form, the operational requirements for the SIROLC system have been defined and a part of these also cover the AUV subsystem:

- surveillance of the underwater environment in the harbor area and other coastal objectives, ship anchorage ranges and mandatory pass points;
- warning about presence of underwater danger (explosive devices – mines, improvised devices, etc.) in the interest areas.

The main operational characteristics of the AUV of type IVER 2 that RCN has are:

- autonomy: min. 8 h / 2 – 2.5 kts (depending on sensor package used)
- speed: max. 4 kts
- maximum immersion depth: 100 m

The fitted side scanning sonar has the following characteristics:

- frequency: 450 kHz center (430 – 470 kHz)
- pulse duration: 400 μs
- signal processing: pulse compression (CHIRP pulse)
- hydro-acoustic antennas: 2 pieces, width of the directivity characteristic (VxO): 60° x 0,5° (-3 dB);

2. Factors that affect the AUV capabilities of discovering underwater targets

The AUV capabilities of discovering underwater targets are affected by the following factors:

- side scanning sonar performance: angle and distance resolutions, frequency, type of signal used, emission power, etc.
- environmental conditions: profile of the sound speed on depth, ambient noise;
- sea bottom type;
- AUV evolution parameters as defined through the mission profile (path, speed, depth), and the oscillations of the platform (due to the influence of the environment or to the mission profile – points of direction change);
- own noise level at different evolution speed;
- target characteristics: target strength depending on dimensions, geometry, etc.;
- operator ability: experience in analysis of sonar images.

2.1. Side scanning sonar performance

Accounting for the side scanning sonar characteristics (signal processing with pulse compression, using pulses with linear frequency modulation) we can calculate the resolution in range (perpendicular to the path traveled) with the formula [4]:

$$\Delta r_y = c/(2\times B) \tag{1}$$

where B is the bandwidth of the pulse (40 kHz in our case).

Considering an average value for the speed of sound in a marine environment of 1500 m/s, this gets us a range resolution of Δr_y = 18,75 mm.

Due to the reduced width of the directivity characteristic in a horizontal plane, this theoretical range resolution, parallel to the direction of movement, is extremely good. Also, considering the horizontal swath width of the directivity characteristic and the distance from AUV to target, we have determined the following values for the range resolution:

Table 1. Range resolution, parallel with the AUV movement path.

r [m]	10	20	40	60	80	100
Δr_x [m]	0.14	0.28	0.56	0.84	1.12	1.40

We can affirm that:

- at small distances from the AUV, the range resolution perpendicular on the path traveled is reduced and the one parallel with the traveled path is very good;
- at large distances from the AUV, the range resolution perpendicular to the path traveled is good but the one parallel to the traveled path is reduced.

Considering the dimensions of the sonar antennas and the maximum range of these (adjustable between approx. 10 and 150 meters) we have to define a maximum upper speed limit for the AUV so that during the pulse repetition interval there should be enough time for the emitted signal to reach a possible target, be reflected and reach back to the sonar antenna [5]. This condition is represented by the following equation:

$$v_{\max} = L \cdot f_p = \frac{L \cdot c}{2 \cdot R} \quad (2)$$

where:

- v_{max} = maximum AUV speed;
- L = antenna length;
- f_p = pulse repetition frequency;
- c = speed of sound in the environment (assumed 1500 m/s);
- R = maximum sonar range.

We have calculated the maximum AUV speeds for different sonar ranges with the current antennas.

Table 2. Maximum AUV speed vs. side scanning sonar range.

R [m]	10	20	30	50	100	150
v_{max} [m/s]	32.4	16.2	10.8	6.48	3.24	2.16

Considering that the maximum speed that the AUV can reach is about 2.057 m/s we conclude that in any navigation conditions the underwater targets, even those situated at the extreme limit of the detection range, will be "illuminated" and seen by the side scanning sonar.

In figure 1 below we present the results of a simulation of the propagation loss for the side scanning sonar, for a single side of the directivity characteristic, at a depth of 30 meters and using real data for the sound velocity profile (SVP).

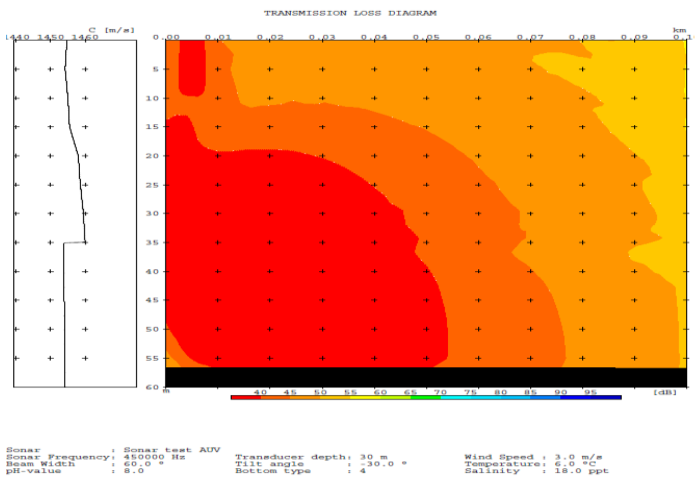

Figure 1. Propagation loss (TL), f = 450 kHz, real SVP Black Sea, across Mangalia, February (winter).

We find that the working frequency of the side scanning sonar is low enough so that it reduces propagation loss.

From the global analysis of the side scanning sonar characteristics we can conclude that this one has good performance (very good resolution, relatively low working frequency, etc.).

2.2. Influence of the AUV mission parameters

In regular use, the recordings provided by the side scanning sonar can also contain distortions caused by the AUV oscillations while it travels the mission path (these are presented in figure 2) and also due to variations of the vehicle speed.

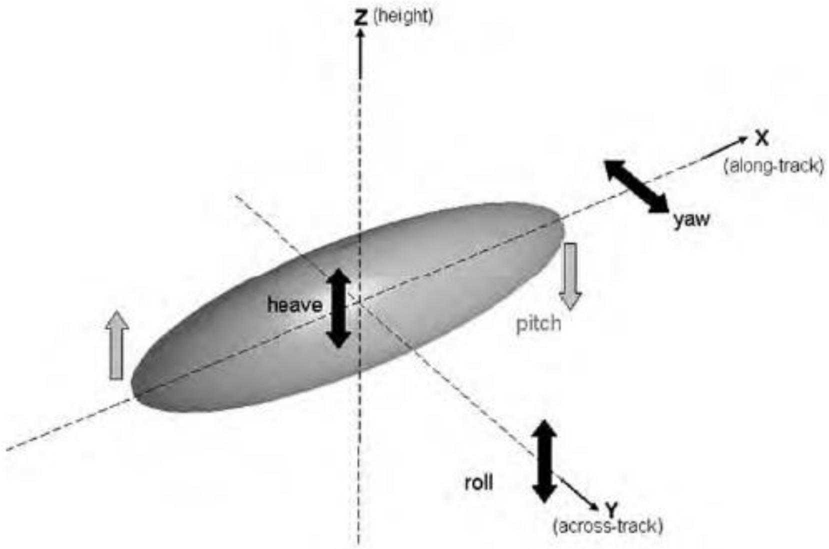

Figure 2. Variations of the AUV attitude that can degrade the side scanning sonar performance [5].

During experiments conducted in 2015 and 2016 we have recorded data about roll, pitch, depth and track variation - a graphical representations of these are in figure 3, figure 4 and figure 5.

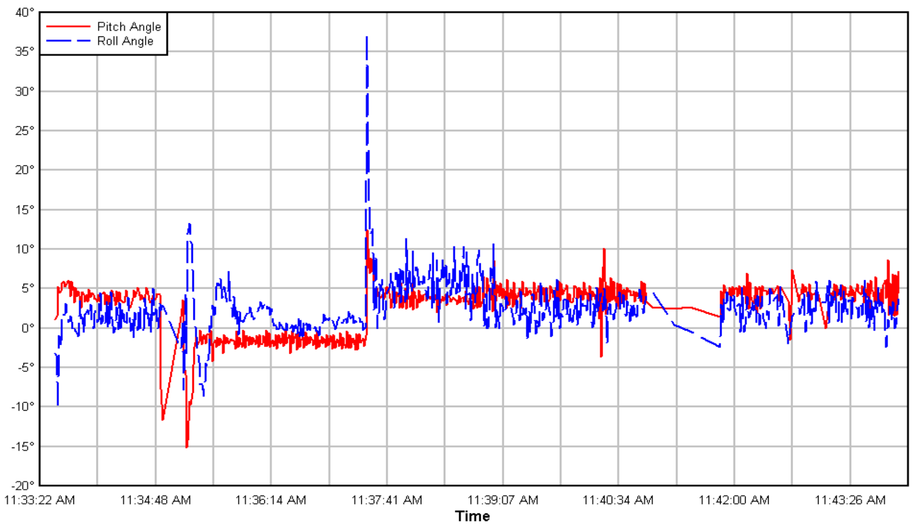

Figure 3. Oscillations of the pitch (red) and roll (blue) of the AUV while in immersion.

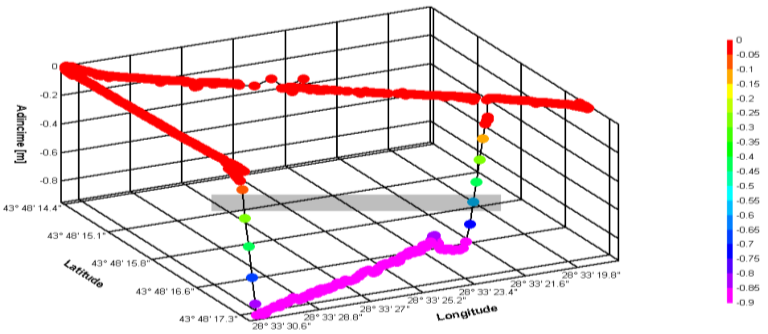

Figure 4. Vertical oscillations (depth) of the AUV while sailing at surface and immersed.

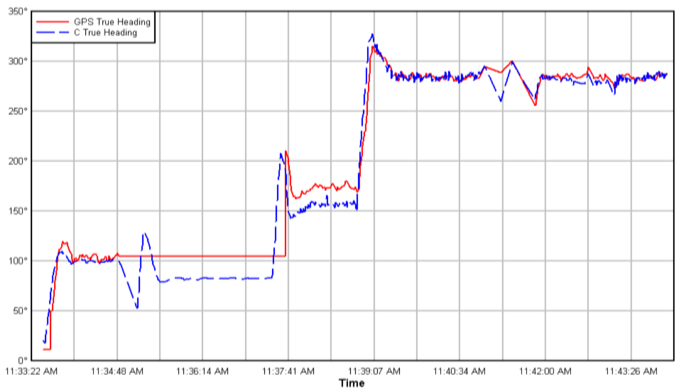

Figure 5. Variations of the AUV direction (yaw) while sailing at surface and immersed.

From the analysis of the data about the oscillations of this platform and without insisting too much on the characteristics of the area where the AUV has collected the direction or depth changes data, the following conclusions can be drawn:

- in the case of surface navigation the roll and pitch are quite large in amplitude as they are influenced significantly by the sea state and the direction of movement (the attack angle of the waves);
- in the case of underwater navigation the roll of the platform is larger than the pitch, this is mainly because the AUV attempts to correct its attitude in the presence of underwater currents, especially at slow movement speeds of around 2 kts;
- the variations of depth and path, especially when moving underwater, are reduced.

In missions where it is required to move only at surface, the vehicle can follow accurately the programmed path, using data from GPS, magnetic compass and accelerometers to compensate for the possible deviations caused by waves, currents and so on.

In underwater missions, as the vehicle does not have a Doppler velocity loch (DVL) or an inertial navigation system, compensating for the path deviations caused by the currents could not be done accurately. Later on, this causes errors in geo-referencing the images obtained from the side-scanning sonar.

Diving/ surfacing of the underwater platform can be done very suddenly, without large variations of the geographic position and this allows for a relatively easy mission planning but for obtaining relevant data that is as close to reality as possible the sonar recordings must be started only after the AUV stabilizes at the scheduled depth.

2.3. Acoustic characterization of underwater targets

For cylindrical bodies, the target strength is calculated with the formula [4] below:

$$TS = 10\lg\left[\frac{rL^2}{2\lambda}\left(\frac{\sin(k\cdot L\cdot\sin\theta)}{k\cdot L\cdot\sin\theta}\right)^2\cdot\cos^2\theta\right] \tag{3}$$

where:

- r – cylinder radius;
- L – cylinder length;
- λ – wave length (ratio between the sound speed underwater and the sonar working frequency);
- k – wave number (2π/λ);
- θ – incidence angle of the probing signal, considered relative to the normal vector on the cylinder surface generator.

For a marine mine (MMA – a cylinder of 1.96 meters in length and diameter of 0.45 meters) and for a heavy torpedo (caliber 533 mm and length of 7.8 meters), when considering a sonar that works on a central frequency of 450 Khz, the target strength data is presented in figure 6.

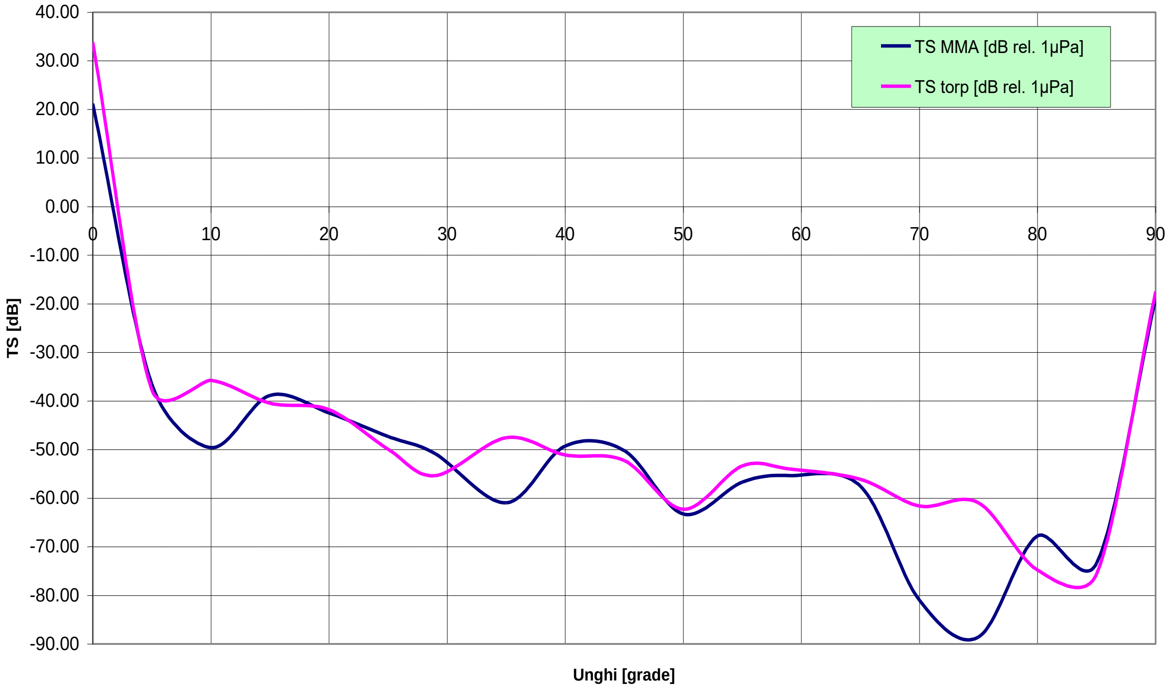

Figure 6. Target strength for a sea bottom mine (TS MMA) and for a heavy torpedo (TS torp).

It can be noticed that the TS varies across a large range of values which will have quite a large influence on the sonar discovery range. For the theoretical evaluation of the discovery capabilities of underwater targets by the side scanning sonar fitted to the autonomous underwater platform we'll consider targets with a TS = -20 and -45 dB rel. 1 µPa at 1 m, values considered adequate enough for the qualitative and quantitative evaluation of the system performance.

For the duration of the evaluation the AUV will operate in immersion, at depths of at most 5 – 20% of the depth of the area to explore. We'll only consider only modifications to the reflective properties of the sea bottom (rocky or muddy bottom) because the environmental noise level – generated by

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shipping traffic or sea state – has a very low influence on the general performance of the sonar in the frequency band that is used.

Theoretical evaluation of the discovery capabilities of underwater targets by the side scanning sonar fitted to the mobile autonomous underwater platform has been conducted for the scenarios presented in the following table.

Table 3. Scenarios in which we evaluate the performance of the side scanning sonar from the AUV.

Row	Target strength [dB]	Sonar immersion [m]	Water Depth [m]	Sound Velocity Profile	Specific characteristics
1.	-20	30	50	February	Sea state – SS 0 Bottom type – mixed rock and mud
2.	-20	40	50	July	Sea state – SS 0 Bottom type – mixed rock and mud
3.	-20	40	50	July	Sea state – SS 0 Bottom type – mixed rock and mud Bottom slope +10%
4.	-45	40	50	February	Sea state – SS 0 Bottom type – mud
5.	-45	40	50	July	Sea state – SS 0 Bottom type – mixed rock and mud Bottom slope +10%

Following the simulations run, we have evaluated the following relevant characteristics:

- acoustic rays distribution mode;
- propagation loss;
- target detection probability.

Results of evaluations for target detection probability for the scenarios presented in table 3 above are presented in figures 7 to 11.

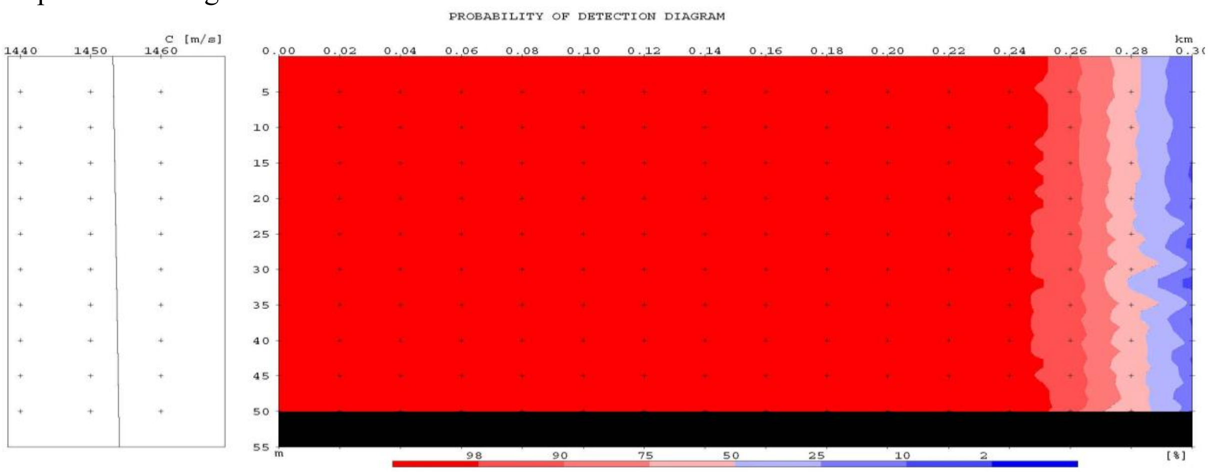

Figure 7. Detection probability distribution – scenario 1.

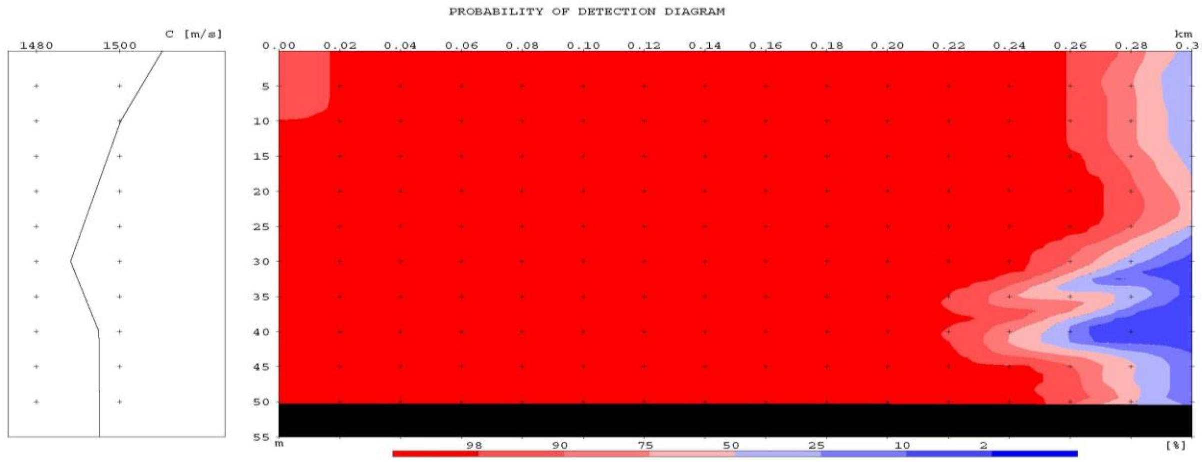

Figure 8. Detection probability distribution – scenario 2.

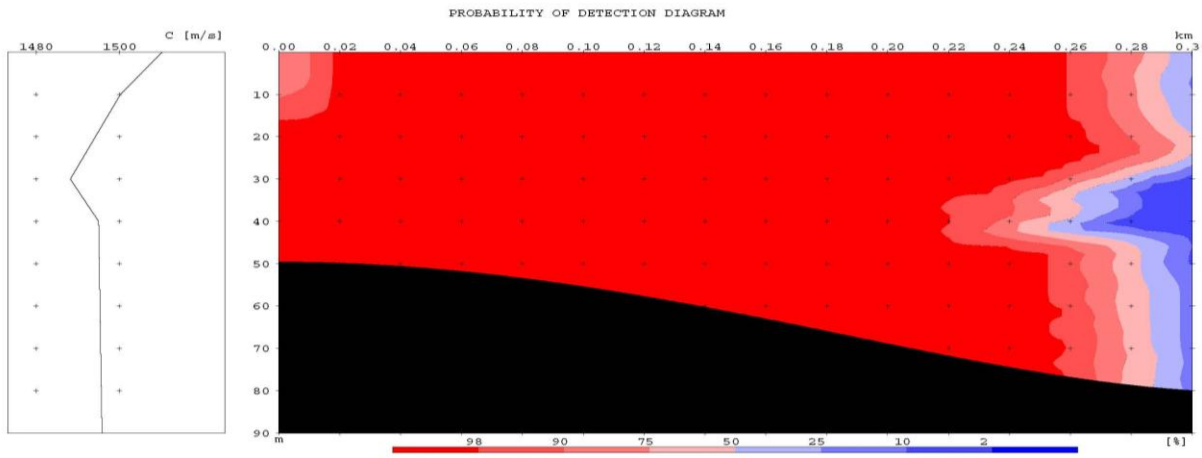

Figure 9. Detection probability distribution – scenario 3.

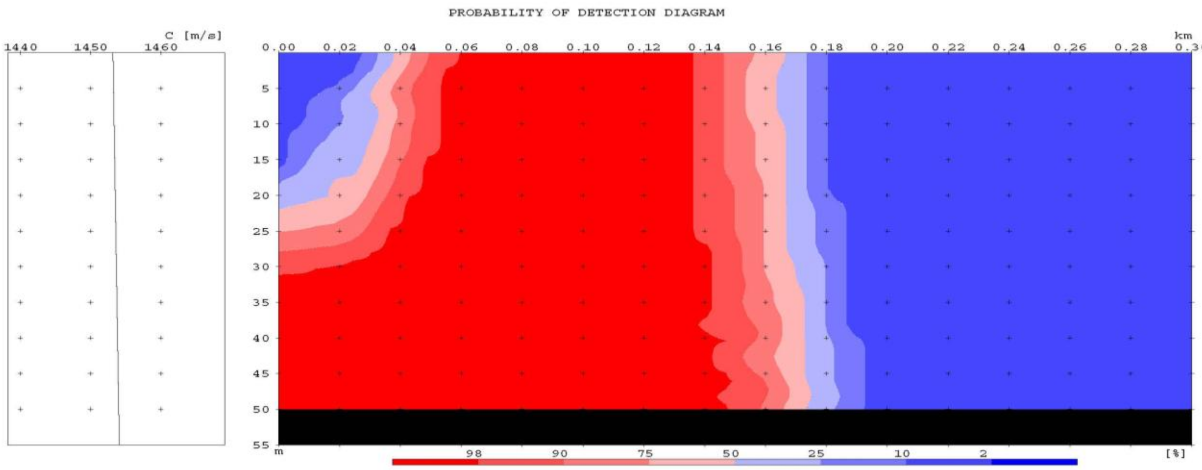

Figure 10. Detection probability distribution – scenario 4.

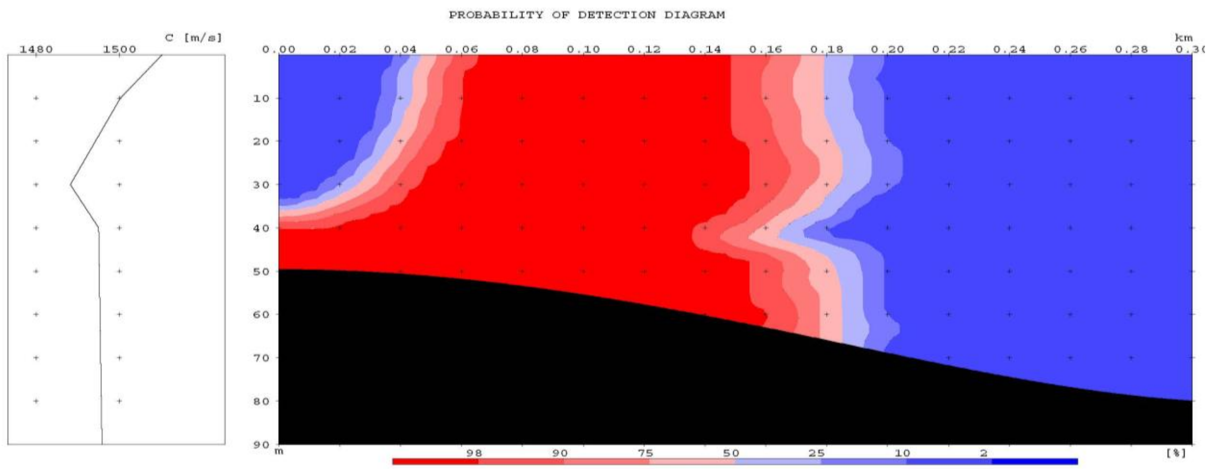

Figure 11. Detection probability distribution – scenario 5.

According to the results of the simulations we can affirm that:

- for a target strength with high values (above -20 dB rel. 1 μPa at 1 m) the probability of detection is over 98% at the maximum sonar range (adjustable between 10 – 200 m), no matter what the environment conditions are (sound speed profile specific for winter/summer, sea bottom type – muddy or rocky, water basin depth 20 – 50 m) and the AUV activity parameters (immersion between 10 to 45 meters);
- adaptation of the AUV immersion depending of the sound speed profile and the profile of the water basin bottom can lead to an increase of the target detection probability within the limit of the maximum sonar range;
- for targets with a low target strength (depending on the target viewing angle, dimensions, geometry or materials used for fabrication - under dB -20 dB rel. 1 μPa at 1 m) discovery can be done with a reasonable probability (> 90%) only at small distances, only when the AUV adapts its immersion very precisely and the maximum sonar range limit is adjusted for the sound speed profile and the sea bottom profile.

3. Conclusions

The major advantages provided by installing the side scanning sonar on the AUV are:

- excellent manoeuvrability;
- flexible development platform that can accept a wide range of sensor types and other instruments dedicated for specific missions;
- relatively long mission length;
- operating personnel can stay out the action range of dangerous items;
- significant economy of resources;
- possibility to conduct covert ops.

Experiences conducted in the previous stages have demonstrated that missions that require the platform to function on surface, it can follow accurately the programmed path, using GPS, magnetic compass and accelerometers to compensate for any path deviations due to waves, currents, etc.

The capabilities of the AUV fitted with a side scanning sonar are mostly influenced by:

- target strength (TS): the more this one has lower values, the higher that the probability of detection is at low distances only;
- knowing the precise profile of the sound speed with depth, sea bottom type and geometry: the sailing depth of the underwater platform and the maximum discovery range of the side scanning sonar depend on those two parameters in order to obtain a coverage rate as high as possible for the exploration area at a high detection probability

For determining the distance to target and target dimensions, knowing the precise sound speed in the current environment has a major importance. For this, assuming an error rate of 1% in the sound speed value, the calculations for targets and distances to the AUV path (position) are equally affected by the same 1% error.

In the context of mission definition, the main factors that affect the discovery capabilities of underwater targets are:

- quality of charts used for mission planning: the resolution of the chart determines the positioning precision of the waypoints, and the chart scale and detail level (depths of the area, sea bottom type, shipwrecks, etc) influences the mission depth plan for the AUV and thus the dimensions of the “blind spot” in the sonar data recordings, false targets, reflections from rock areas, and so on.
- planning the path of the autonomous underwater platform through immersion depth planning (usually 8% – 20% of the distance scale), overlaying the sonar swath image data, stabilization of the underwater platform on path before beginning to explore the interest area, and so on.

In missions at depth, as the vehicle does not have a Doppler velocity loch (DVL), compensating for the path deviations due to sea currents cannot be done accurately. This causes errors in geo-referencing the images obtained from the side scanning sonar. In order to decrease these errors the mission profile must be defined so that the platform returns to surface often and runs position correction calculations.

References

[1] Hanganu M and Slămnoiu G 2010 *Platformele de foraj marin româneşti şi securitatea acestora* (Bucureşti: Editura U.N.Ap. „Carol I”) 166-167 170-183
[2] Button R W, Kamp J, Curtin B and Dryden T 2009 A Survey of Missions for Unmanned Undersea Vehicles (Santa Monica, CA: RAND Corporation) 69 - 102
[3] Carfield S and Hillenbrand C 2002 Defence applications for unmanned underwater vehicles *Technology and applications of autonomous underwater vehicles* 161-178
[4] Waite A D 2002 *Sonar for Practising Engineers* **70-74** 192-200
[5] Blondel P 2009 *The handbook of sidescan sonar* **20** 56

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