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Conditions for Multiple Acquisition of Echoes from Stationary Targets in Successive Transmissions of Active Sonars

Lech KILIAN , **Aleksander SCHMIDT** , **Mariusz RUDNICKI**

Gdańsk University of Technology Faculty of Electronics, Telecommunications and Informatics,
Department of Sonar Systems, ul. Narutowicza 11/12, 80-233, Gdańsk, Poland

Corresponding author: Lech KILIAN, e-mail: kilian@eti.pg.edu.pl

Abstract: In echolocation, the highest possible number of contacts with a detected target is clearly decisive on the possibilities of echo processing to optimise the estimation of distinctive characteristics of the observed target. In hydrolocation, the slow propagation of acoustic waves in water reduces the number of contacts of echosounders and sonars with detected targets. The article considers model conditions for acquiring multiple contacts with stationary targets detected by various sounding methods - with echosounders, classic active sonars and side looking sonars. Appropriate formulas explicitly linking the possible number of echo signals from the target in a specific geometry of the survey performed at the assumed speed are presented. These formulas are intuitively clear and not very complicated, but their value lies in the ability to instantly combine the vessel speed with the sounding effects, and may be a clear argument for imposing a low sounding speed, which make it difficult to steer the vessel.

Keywords: echosounder, sonar, side scan sonar, multiple echoes, beam geometry, scanning speed.

1. Introduction

The basic method of increasing the credibility of obtained information in every field is, as is commonly known, repeating simple measurements or complex observations, and further, intelligently comparing as many as possible of the results of these observations, e.g. echo signals from an interesting target obtained from possibly multiple successive sonar transmissions.

There are now powerful hardware and software tools for improving the detection conditions. They are based on image processing technologies.

These tools are of course less effective when less information is provided to them, e.g. in echolocation – due to a smaller number of acquired echoes from the observed target. And here we can recall the complaints of designers and sonar operators who have to fight the slow transmission of sound in the water (as a reminder: 200.000 times slower than electromagnetic radar waves. The number of contacts is not included in the sonar range equations that are the basis of sonar design [1-3]. This is probably why it is rarely discussed in specialist literature but should be discussed during the trainings of sonar operators.

The beamforming technique [1-3] was invented especially for hydrolocation (and not transformed from radiolocation), i.e. the simultaneous production of many narrow horizontal cross-sections of beams (usually receiving), providing sonars with good horizontal angular resolutions in wide observation sectors and by this creating the possibility of multiple observations of targets located in these sectors in successive transmissions. The slow propagation of waves in water, however, still limits the number of sonar contacts with detected targets in the vertical cross-section of the transmitting-receiving beam, and the possible improvement of the situation by reducing the speed of the sounding vessel is limited by the loss of steering or the danger for the battleship as a slowly moving target.

Different survey conditions of water spaces and their bottoms exist for side-scan (looking) sonars [4, 5], where problems connected with the necessarily very narrow horizontal section of the sonar beam predominate, where "simple" beamforming cannot be used, but only the synthetic aperture of the receiving antenna (this time unfortunately coming straight from radiolocation)[1-3].

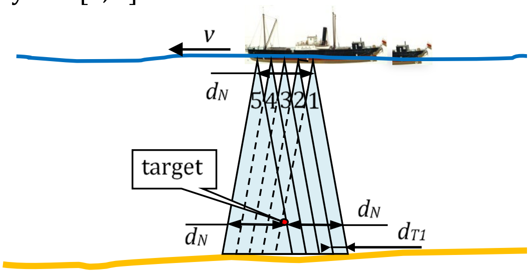
The conditions for acquiring and estimating the number of multiple contacts with stationary targets as detected by various sounding methods with echosounders, forward-looking (standard) active sonars and side-scan sonars will be discussed below.

In the case of moving targets, their detection and tracking generally requires greater operator efforts and leads to attempts to retrieve an echo from each transmission for as long as possible [1-3].

2. Standard vertical sounding

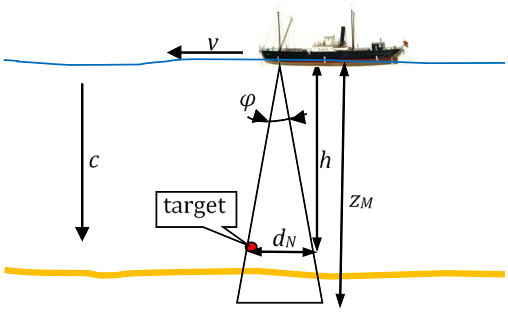
The simplest, model, geometric conditions for calculating the number of contacts with the fixed target occur for a typical single-beam echosounder sounding. On their basis, it is possible to determine the number of contacts n depending on the speed v of the sounding vessel and the depth h at which the target is immersed. This situation is illustrated in Figs. 1 and 2, below.

The adopted model neglects the real shape of the cross-section of the transmitting-receiving beam, approximating it with a triangle. In the drawn example, the number of contacts with the target within one beam n = 5. Due to the significant beam width, usually over 7° for single-beam echosounders, the problem of beam escaping from the target was abandoned in the presented model. This fact is treated further when analyzing the movement of side looking sonars, where the horizontal cross-section of the beam must be extremely narrow and therefore contacts with targets in sonars without synthetic antenna aperture are especially few [4, 5].



v – sounding vessel speed [m/s]
d_{T1} – distance traveled in the period T_1 of one transmission from the currently set maximum echosounder range
d_N – distance where the target is inside the beam ("visibility" of the target N times) [m]

Figure 1. A simple model of the geometry for the vertical cross-section of a single-beam echosounder.



c – speed of sound in the water area [m/s]
z_M – currently set (nominal) maximum echosounder range [m]
h – target depth [m]
φ – angle of opening of the transmitting and receiving echosounder beam [rad]

Figure 2. Geometric conditions for determining the number of contacts with the target for a single-beam echosounder.

The minimum duration of a single transmission (usually extended for various reasons) is:

$$T_1 = \frac{2z_M}{c}, \tag{1}$$

and the dimension of the space d_N determines the target depth h and the spread angle φ of the sonar beam:

$$\frac{d_N}{2h} = \tan\left(\frac{\varphi}{2}\right), \text{ i.e. } d_N = 2h\tan\left(\frac{\varphi}{2}\right). \tag{2}$$

For narrow (usually) sonar beams, this can be approximated by a simplification:

$$d_N \approx h\,\varphi. \tag{3}$$

The number n of single transmissions during the distance d_N is determined by its length, vessel speed and duration of a single transmission:

$$nT_1 = \frac{d_N}{v}. \tag{4}$$

So, the number n can be roughly calculated from the relationship:

$$n = \frac{d_N}{vT_1} = \frac{c\,d_N}{2vz_M} = \frac{c\,h\,\varphi}{2vz_M}, \tag{5}$$

and for example, for moderate conditions: z_M = 100 m; h = 50 m; φ = 12° = (3.14 · 12/180) rad = 0.21 rad; v = 5 kn ≈ 2.6 m/s; the number of contacts n ≈ 15. It is number sufficient to detect target but it is clearly not enough for use in statistical methods of echo signal processing. However, it is enough to set too long the measuring range of the echosounder (repetition time of sounding signal transmission z_M) and the number of contacts will decrease proportionally. The same thing happens when increasing the speed of the vessel.

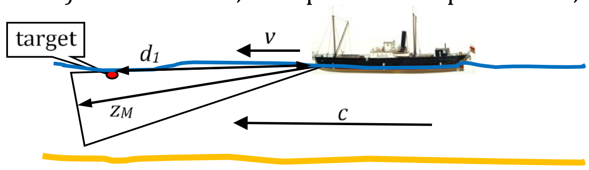
Formula (5) is intuitively obvious and indicates that when sounding, it is worth sailing as slowly as possible, to make sure that the minimum possible range of the sonar is set and that it is good for the transmitting-receiving beam to be as wide as possible from the point of view considered here. All sonar operators, even the inexperienced ones, know this. They also know, of course, that they have no influence on the speed of sound propagation in the water as well as on the depth of the targets.

The treatment of the precision of the presentation of the geometric situations and of the accuracy of the calculations presented above is slightly disrespectful. This is, in general, due to the lack of clear consequences of such simplifications in relation to possible changes resulting from the physical inconvenience of the conditions of echo formation and transmission (echo interference with reverberations, incompletely compensated unit trims, uncontrolled echoes from side lobes, channel delamination, etc.).

3. Inclined observations (classical sonars)

With typical oblique observations – e.g. detecting bottom or anchor mines, the geometric conditions sometimes simplify and sometimes become a bit more complicated.

If the targets are shallow below the surface, they must be detected with a beam that is parallel (or almost parallel) to the surface of the water. In this case, in a model situation (without deflections of propagation rays, uncompensated trims of the vessel, etc.), many echoes reach the sonar receiver – as many as the transmissions that pass during the passage from the detection edge d_1, i.e. from obtaining the first echo (e.g. echo from the set of the the nominal sonar range z_M or when appropriate target detection conditions have been reached). The situation, with possible simplifications, is shown in Fig. 3.



v – sounding ship speed [m/s]
z_M - currently set sonar range [m]
d_1 – distance from which the first echo appeared from the target [m]
c – speed of sound in the water [m/s]

Figure 3. Geometric conditions for determining the number of contacts with a near-surface target for a regular sonar sounding.

Since, a single transmission t_1 invariably lasts as long as in relation (1) and the number of contacts with the target as in the initial form of relation (5), then further – without the non-existent angle of beam tilt:

$$n = \frac{c\,d_1}{2vz_M}. \tag{6}$$

It should be noted that it is very valuable to shorten the nominal ranges z_M, as much as possible, because if echoes appear from the edge of the range, the number n becomes the maximum number, inversely proportional only to the speed of the survey:

$$n = \frac{c}{2v}. \tag{7}$$

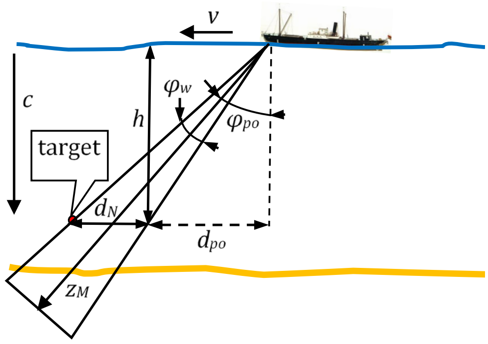
Formula (7) produces very optimistic results, as it indicates that at the speed of a ship equal to 5 knots, the number of contacts may reach 150. In practice, unfortunately, this is not encountered, because this number is greatly reduced by "losing" the echoes for numerous reasons, e.g. interference with reverberations from wavy water or bottom surfaces (which is the dominant cause of echo disappearance), but also deflections of sound propagation rays, local discontinuities and similar propagation misfortunes, especially in the subsurface layers. The condition $z_M=d_1$ is also not met (almost always $z_M>d_1$).

Therefore, in order to improve the transmission conditions, towed array sonars are constructed but operated with difficulty. They are towed under the keel waters, and even above or under the recessed thermoclines, under which submarines like to hide, like airplanes in the clouds.

For bottom or deep-water target detection, the geometry of the applicable model is shown in Fig. 4. It shows that formula (5) for the vertical survey becomes more complicated due to the geometry of the classic oblique observation, and more specifically, the inability to replace the tangent function directly with the value of the angles expressed in [rad]. While this could be done for a generally narrow vertical spread of the sonar beam (i.e. the angle φ_W), it is impossible to approximate the often considerable deviation from the vertical of the beam tilt angle (i.e. the angle φ_{PO}). The correct formula therefore takes on a somewhat clumsy form:

$$n = \left(\frac{c\,h}{2vz_M}\right)\left[\tan\left(\varphi_{po} + \frac{\varphi_w}{2}\right) - \tan\left(\varphi_{po} - \frac{\varphi_w}{2}\right)\right] \tag{8}$$

and if the above-presented conditions of echosounder sounding are repeated, but with the beam inclined φ_{po} = 45°, the number of contacts n more or less doubles – due to the elongation of the distance d_N after beam inclination.



c – speed of sound in the water [m/s]
v – sounding ship speed [m/s]
z_M – currently set sonar range [m]
h – target depth [m]
φ_W – spread angle of the transmitting-receiving sonar beam [rad]
φ_{PO} – beam inclination angle [rad]
d – distance where the target is inside the beam (target's "visibility") [m]
d_{po} – supplementary distance to the vertical beam inclination [m]

Figure 4. Geometric conditions for determining the number of contacts with a deeply submerged or bottom target for under-keel sonar.

Again, it is worth paying attention to the limited confidence in the accuracy of the calculated number of contacts, this time, apart from the factors mentioned in the vertical sounding, also due to the sometimes strong influence of deflections of sound propagation rays in the water area on the shape of the sounding geometry.

4. Side scan sonars

Side scans are performed with other equipment than classical soundings, and there are different conditions for obtaining echoes from targets generally located at or near the bottom of water areas on the traverses of ships towing underwater antennas carriers. [4, 5]. The predominant task of surveys is to provide information for the creation of underwater maps or the recreation of the shapes of objects, e.g. wrecks. Therefore, the most important system parameter is resolution in the horizontal plane. For the first decades, "normal" long antennas (providing a horizontal resolution of 1°) were constructed on both sides of slender, stable, underwater towed carriers. The technology of synthetic antenna apertures, which has been introduced in recent years, which is difficult phenomenologically and in terms of hardware and software [1-3], is not of fundamental importance for the basic discussions on the conditions for performing side scans presented below, although the possible spectacular effects of using this technology will be indicated below.

A simple, geometric model of the search conditions is presented in Fig. 5. For the sake of clarity of further considerations, only one of the two symmetrical side-scan sonar channels will be shown, while for the sake of clarity of the drawings, the exaggerated horizontal cross-section of the beam, its projection on the bottom and the great height h of the carrier above the bottom are shown. In fact, usually the survey is carried out as close to the bottom as possible ($\varphi_M \approx 90°$) – only with the carrier safety conditions respected, and then the minimal differences in the width of the oblique section of the beam and its projection on the bottom can be neglected.

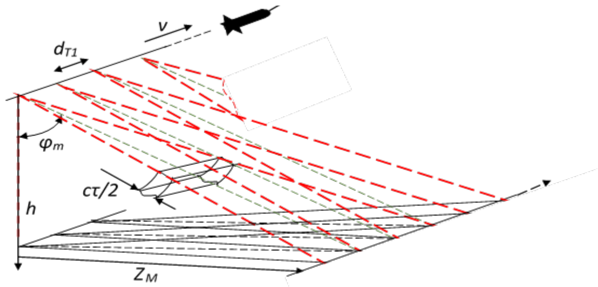


Figure 5. Geometric model of side-scan (sometimes: side looking) sonar sounding conditions.

When analyzing the side scans, one should take into account the previously neglected "escape" of the receiving beam from the area in which the sounding pulse was sent at the beginning of the transmission (within the transmitting beam). Due to the extremely narrow cross-section of the beams, the previously adopted simplifying omission here is untenable [4, 5].

The situation is shown schematically in Fig. 6. The antenna carrier is towed at the speed v and during a single transmission T_1 traverses the distance d_{T1}. The dashed area is indeed searched, Fig. 6a. At the limiting velocity v_G (distance d_{TG} traveled), no echo should appear due to the complete escape of the receiver beam from the transmission of the sounding pulse area in the water. With speed v_G, the scanned area decreases to zero, Fig. 6b.

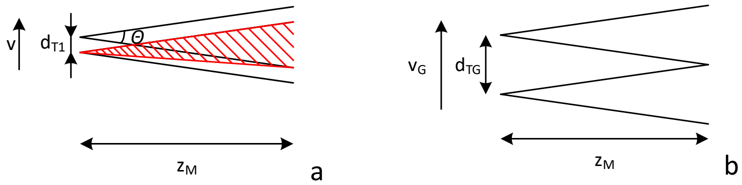


Figure 6. Movement of the horizontal cross-section of the side-scan sonar beam.

In the presented situation:

$$d_{TG} = v_G T_1 = 2 z_M \tan\left(\frac{\theta}{2}\right) \approx z_M \theta \tag{9}$$

and because:

$$z_M \approx \frac{cT_1}{2} \qquad\qquad v_G \approx \frac{c\theta}{2} \tag{10}$$

there is a simple formula linking the limiting speed of the sounding vessel with the angle of horizontal cross-section of the transmitting/receiving beam of the side scan sonar:

$$v_G[kn] \approx 25\theta_G[°] \tag{11}$$

and this means that if, for example, a sonar has a beam with a 1^0 cross-section at a speed of 25 knots, it unfortunately will not see anything (the case in Fig. 6b). The so-called dead zone - will not be searched in the entire range. It will be shown further that if one wants to minimise it, the carrier should be slowed down or the synthetic aperture antenna, mentioned above, should be used.

It is worth noting that the inconspicuous form of formula (11) stands in opposition to its considerable usefulness, as it allows you to easily combine the most important operational parameters of side-scan sonars, i.e. horizontal resolution, permissible sounding speed and the dimension of the dead zone, regardless of the sonar design complication. For example, for sonars with synthetic antenna apertures, a somewhat wide (e.g. several degrees) opening of the physical "short" antenna cross-section should be inserted into the formula, and you can immediately see the possibility of a proportional acceleration of the sounding speed.

With a sufficiently slow sounding, conditions are created to minimize the search dead zone and to acquire echoes multiple times from single targets. This is explained in Fig. 7.

While maintaining the assumption of linearity of geometric dependencies in the situation from this figure, it can be seen that in order for the dead zone not to exceed e.g. 10% of the maximum range z_M, the sounding should be conducted at a speed just 10 times lower than the velocity v_G from the formula (11), i.e. at a speed slightly higher than 2 knots. This is a rather bad prognosis for the controllability of the navigation of the sounding vessel. Therefore, one should use sonar with a wider horizontal cross-section of the beam or accept longer zone that is poorly searched (and, according to the model presented above, completely not searched). In fact, as usual, there are no binary situations, because there is a chance, especially up close, for some echoes resulting e.g. from a softer shape of the beam than in the adopted criterion of its width or from its side lobes Finally, you can go into the construction of sonar with a synthetic antenna aperture that allows the use of much wider (several times) cross-sections of physical beams and thus the proportional acceleration of the scans.

The number n from Fig. 7 has a similar meaning as its counterpart in classical sounding – a single, small, distant target may be seen in several transmissions. This does not (and even helps) spot and track targets in front of or below a ship, but "smearing" distant small targets by multiple echoes is not beneficial for the normal needs of side scans. This is, unfortunately, a physical property of echolocators with a constant angular resolution of the antennas that can only be combated by constricting the beam. In practice, this can only be achieved by beamforming or synthetic apertures – both technologies being difficult to design, construct and program [1-3].

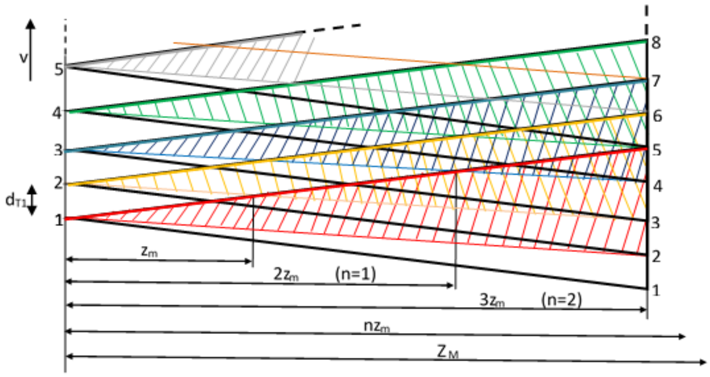


Figure 7. Side looking sounding . Dead zone z_m and further – areas searched *n* times.

Current side looking sonars with synthetic apertures, work a bit inaccurately in real-time, but are very suitable for autonomous underwater drones and, above all, they allow a significant improvement in the speed of the sounding, which is important especially on military minesweepers. At these increased speeds, the non-searched dead zone remains small, despite the ultimately very narrow "synthetic beam", because the primary information is collected from the "wide" physical beam of the antenna and is not lost during processing because the subsequent reduction of the beam due to the long aperture synthesis procedure no longer extends the dead zone, i.e. losing close targets.

5. Summary

The considerations presented above are not too complicated phenomenologically, and especially mathematically, and perhaps that is why they are not explicitly discussed in the literature on hydrolocation. For example, their omission in the manuals for echosounders and sonars may also be explained by the reluctance of the authors of these instructions to present the limitations of the described, commercial equipment. These limitations and the ways to deal with them are obviously known to experienced sonar operators, but rather intuitively. Explicitly showing a few non-confusing dependencies that determine the possible results of the survey in a compromise with speed limits, strengthens the negotiating role of operators against always hurrying ship navigators.

It should also be mentioned that the group of sonar images is supplemented with histograms, popularly known as "waterfalls", which consistently show the line under the line, echoes in subsequent transmissions. The target strength in the echo signals on each of the lines are marked with the color of the pixels. The combination - "integration" of a few slightly different images improves the consequences of possible "lost" echoes from targets in some transmissions.

Additional information

The authors declare: no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited and that appropriate permits are obtained.

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