Suppression of side lobe level on the cone characteristics of the directivity pattern of an antenna as an important factor in its directivity index and effective aperture

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Abstract: This paper presents a universal procedure of precise de-embedding of directivity index and effective aperture dependent of the suppressed side lobes on measured cone directivity pattern of sonar antenna. The procedure is derived on an idealized model of cone directivity pattern characteristic of antenna. It is directly and universally applicable on any contemporary sonar or hydroacoustic communication system with cone directivity pattern. In accordance with given expressions of directivity index and effective aperture of hydroacoustical ring antenna, this paper gives graphical presentation of the impact of total transmission losses in dependence on directivity index and suppress of side lobes level on the sonar range. Presented graphs of functional behavior in a two-dimensional system and especially in a three-dimensional coordinate system are an excellent base for standardization, unification and quality evaluation of sonar or radar systems and also medical scanners.

Key words: directivity index of sonar antenna, idealized model of cone directivity pattern, level of suppressed side lobes, effective aperture

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1 Introduction

Directivity index DI is one of the important parameters of sonar equation for hydrolocation. *DI* is especially and repeatedly significant via level of the signal/noise relation in presenting its influence on the range and resolution of underwater targets with the same conditions at all sonar systems.

Therefore, from the level of the system analysis through the sonar equations there can be additional requirements for antenna manufacturers in the phases of constructions. Keeping in line with the construction and conditions of sonar antenna, we have many expressions in theory as unusable in practical applications. It is especially important for directivity index DI_R in receive. It is the same equation for active and passive systems to the given expressions in literature in the end of the paper. There we have equations for the systems in general:

$DT=SL+TS-NL+DI_R-TL_{TT}-TL_{TR}$ (1.1)

$TL_{TT} = 20\cdot\log(r_{TT}) + \alpha\cdot r_{TT}$, (1.2)

$TL_{TR} = 20\cdot\log(r_{TR}) + \alpha\cdot r_{TR}$, (1.3)

$SL = 10\cdot\log P_e + 10\cdot\log\eta_{ea} + DI_T + 171.5$ (1.4)

$NL=N+10\cdot\log B$, (1.5)

If we have a monostatic system, then is

$2TL=SL+TS+DI_R-NL-DT$ (1.6)

where is:

α(dB/m) – absorption coefficient in sea water (defined by parameters of the sea, [13]),

SL(dB re 1μPa//1m) – Sound Level on 1 m of surface of antenna, to equation (1.4) Fig. 1.1,

DI_T(dB) – Directivity Index in the Transmit,

η_{ea}(1) – efficiency power factor of the sonar antenna $\eta_{ea}=P_a/P_e$,

P_e(W) – electrical power on the electrical input of sonar antenna,

P_a(W) – acoustical power produced in the acoustical parts of the antenna system,

TL_{TT}(dB) – Transmission Loss of sound in the sea from transmitting antenna to target as function of range r_{TT} and α(dB/m),

r_{TT}(m) – range of sonar systems in transmit, distance from the transmit antenna to target,

TL_{TR}(dB) – Transmission Loss of sound in the sea from target to the receive antenna as function of range r_{TR} and α(dB/m),

r_{TR}(m) – range of sonar (hydroacoustical) systems, distance from target to the receive antenna, Fig. 1.1,

B(Hz) – band width of frequency, (defined with conditions of filters, input of electrical preamplifiers and duration of hydroacoustical and electrical impulse τ),

τ(s) – duration time of hydroacoustical impuls, (defined with detection conditions of the hydroacoustical targets),

DI_R(dB) – Directivity Index in the Receive, its character and value we have given in (1.1)

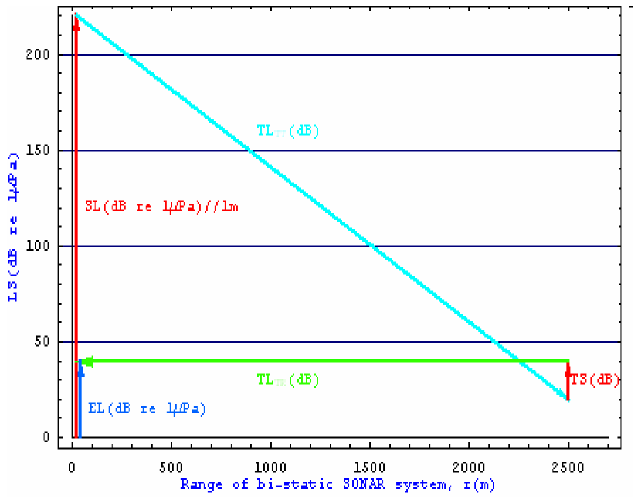

Fig. 1.1 The symbolical presentation of the importance levels with sonar systems in the sea, from the transmit antenna to the target and back, from the target to the antenna in receive.

Therefore, the value of directivity index in the receive DI_R is one of the important parameters in all sonar systems. In accordance with the specification and technical conditions on the sonar systems, the range as parameter is directly dependent of DI_R and we can point out it as a centre of our analyses and activity. Therefore, the value of this parameter we need to de-embed very safely and calculate very precisely.

2 Hydroacoustical measurements of directivity patterns of antenna

De-embedding of DI_R of antenna on the idealized model of its measured directivity pattern can give better access in good detection of targets. On the other hand, this model will give better comparison of quality of different sonar systems with the higher range. In accordance with the specification and technical conditions on the sonar systems we need to point out the range as a parameter in a very direct dependence of DI_R.

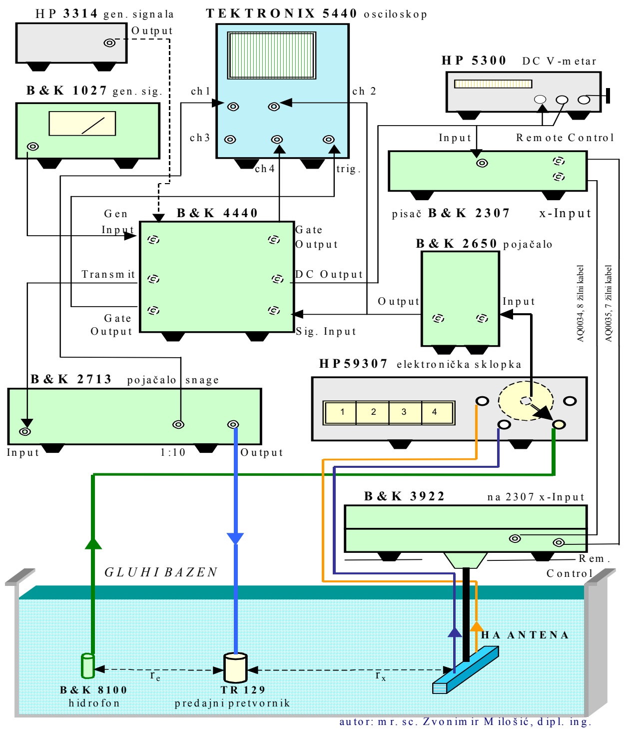

Fig. 2.1 Block scheme for measurement of directivity pattern characteristic $R_I(\theta_{-3dB}, SoS)$ of hydroacoustical antenna in the receive.

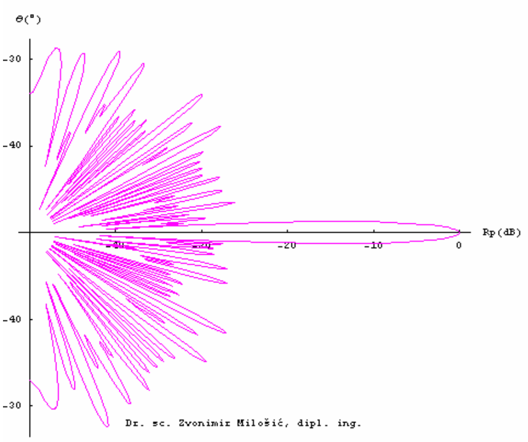

Fig. 2.2 Measured or simulated directivity cone patterns of sonar antenna in one plane, if we have angle θ_{-3dB}=1° with suppress of side lobes SoS=−25 dB we have DI_{SoS}=+25 dB.

Therefore, we have one choice and the solution in the hydroacoustical measurements of the receive cone pattern characteristics, Fig. 2.2. Mainly, many expressions in literature based on standard theory are unusable in practical applications. Using the expressions of idealized model on measured directivity pattern of antenna of measured data, Fig. 2.2, we can precisely calculate the value of DI_R and de-embed minimal conditions for maximal range. It is very important as usable operative data for underwater security and sonar monitoring.

3 Impact of the idealization of cone directivity pattern characteristic of antenna on the range of monitoring and communication systems

Keeping in line with the given illustration in Fig. 3.1 basic elements should be set for the procedure of conducting correct integration as the basic factor of a mathematical definition of directivity index of hydroacoustic transducers and antennas. It follows that

$$S_I = \int_S R_I(\theta) dS \qquad (3.1)$$

where we have

dS (m^2) – elementary surface according to Fig. 3.1 is defined by the expression (3.2) in accordance with [7]

$$dS = 2\pi r^2 \sin\theta \, d\theta \qquad (3.2)$$

$R_I(1)$ – directivity size of sound intensity in the spreading media (water) as a dimensionless figure, which is by θ=0 (rad) in relation to +z axis

$$R_I(\theta=0, SoS)=1 \qquad (3.3)$$

S_I(m^2) – the sphere surface which is under the weight activity of the sound directivity characteristic $R_I(\theta, SoS)$ and sound intensity $I(\theta, SoS)$.

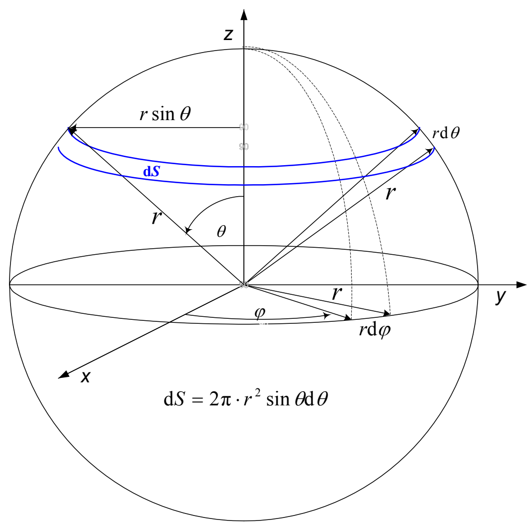

Fig. 3.1 Model of the coordinate system for de-embedding of any parameters the new modern sonar antennas with the cone directivity pattern characteristics.

By using the given coordinate system in Fig. 3.1 and the idealized characteristics of the measured directivity patterns as in Fig.2.2 and to the models in Fig. 3.2 or Fig. 3.3, we can give a relatively simple mathematical expression of directivity index. The conditions for process of integration to the general definition are given in expressions (3.4) and (3.5), what is in accordance with so called '*squared approximation of directivity pattern of antenna*' by Sverdlin in literature [12].

$$R_I\left(\begin{array}{c}-\dfrac{\theta_{-3\mathrm{dB}}}{2}>\theta>+\dfrac{\theta_{-3\mathrm{dB}}}{2}\\ \text{sphere with cone hole}\end{array}\right)=R_{SoS} \qquad (3.4)$$

$$R_I\left(\begin{array}{c}-\dfrac{\theta_{-3\mathrm{dB}}}{2}<\theta<+\dfrac{\theta_{-3\mathrm{dB}}}{2}\\ \text{calotte base of cone}\end{array}\right)=1 \qquad (3.5)$$

In practice, the term of suppressing level of minor lobes SoS (dB) is often used and it often shows the level of the maximum of suppressed minor lobes below the maximum of the major lobe on the directivity characteristic. The connection of numerical data of the minor lobe amplitude, the sign R_{SoS} and the value of suppressing level are determined by the expression

$$R_{SoS}=10^{\frac{SoS}{10}} \qquad (3.6)$$

where is

$\theta_{-3\mathrm{dB}}$ (rad) – sensitivity angle of hydroacoustic antenna on the $+z$ axis,

R_{SoS} (1) – amplitude size of suppressed minor lobes, that is, of secondary lobes on the directivity characteristic of sound intensity; this size is a dimensionless number.

SoS (dB) – suppression of minor lobes size in relation to the peak of the major lobe which lies in the acoustic axis of an antenna with $R_I(\theta=0)=1$, level of suppressing SoS comes as a negative value in relation to 0 dB in the axis, so we write $SoS=-30$ dB or on example −50 dB, so that is $R_{SoS}\leq 1$.

$R_I(1)$ – direction of sound intensity is a dimensionless number in the integrational equation of the directivity index definition and if it is shown in the form of the level of directivity pattern characteristic then it has a decibel dimension (dB).

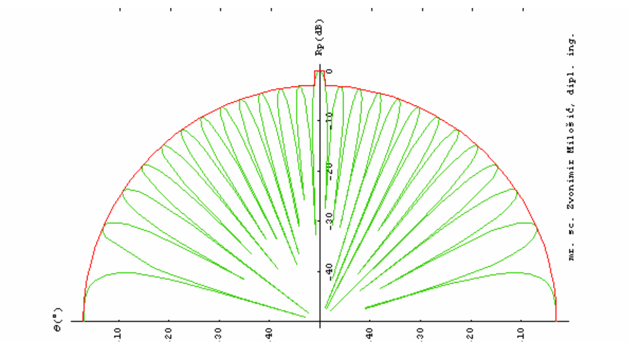

Fig. 3.2 Directivity patterns of the theoretical concentric ring antenna, with sensitivity angle $\theta_{-3\mathrm{dB}}=1°$ related to $+z$ axis and with parameter $SoS=-3$ dB, we have $DI=+3$ dB.

The size R_{SoS} shown in expressions (3.4) shows the directivity values of sound intensity R_I outside the sensitivity angle. The graphical illustration of this condition is in Fig. 3.2. and Fig. 3.3, which from definition (3.6) passes over into a form of influencing the suppressing level of minor lobes on D_f. According to that, we have that the directivity factor D_f according to definitions from literature [9, 11, 12] is shown in dependence of two variables as follows

$$D_\mathrm{f}=\frac{I(\theta,SoS)}{I_0} \qquad (3.7)$$

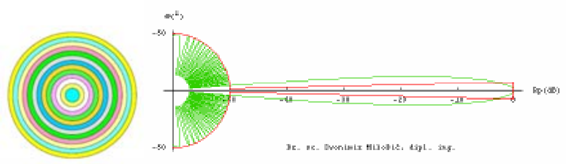

Fig. 3.3 Cone directivity pattern characteristic of ring antenna with the angle $\theta_{-3\mathrm{dB}}=1°$ relative to $+z$ axis, with suppression of lobes $SoS=-50$ dB we have $DI=+45.4$ dB.

$$I(\theta,SoS)=\frac{P_\mathrm{a}}{S_I(\theta,SoS)}=\frac{P_\mathrm{a}}{\iint\limits_S R_I(\theta,SoS)\mathrm{d}S} \qquad (3.8)$$

$$I(\theta,SoS)=\frac{P_\mathrm{a}}{\iint\limits_S R_I\left(\frac{\theta_{-3\mathrm{dB}}}{2}\right)\mathrm{d}S+4\pi r^2R_{SoS}-\iint\limits_S R_{SoS}\left(\frac{\theta_{-3\mathrm{dB}}}{2}\right)\mathrm{d}S}$$

$$D_\mathrm{f}=\frac{\dfrac{P_\mathrm{a}}{\iint\limits_S R_I(\theta,SoS)\mathrm{d}S}}{\dfrac{P_\mathrm{a}}{4\pi r^2}} \qquad (3.9)$$

and

$$D_\mathrm{f}=\frac{4\pi r^2}{\iint\limits_S R_I(\theta,SoS)\mathrm{d}S} \qquad (3.10)$$

Applying conditions (3.4) and (3.5) we can write that is

$$D_\mathrm{f}=\frac{4\pi r^2}{\iint\limits_S R_I\left(\frac{\theta_{-3\mathrm{dB}}}{2}\right)\mathrm{d}S+4\pi r^2R_{SoS}-\iint\limits_S R_{SoS}\left(\frac{\theta_{-3\mathrm{dB}}}{2}\right)\mathrm{d}S} \qquad (3.11)$$

With the given conditions and the application of mathematical analysis of expression (3.1) we reach the understanding that the directivity value, according to the conditions (3.4) and (3.5) as the first member of subintegral function in the denominator is equal to $R_I=1$ and the value of the first factor of the sub-integral function of the third member in the denominator equals to R_{SoS}. If we insert the value of differential surface $\mathrm{d}S=2\pi r^2\sin\theta\mathrm{d}\theta$ into expression (3.11) and if we shorten it with $2\pi r^2$, we can write

$$D_\mathrm{f}=\frac{2}{\int\limits_0^{+\frac{\theta_{-3\mathrm{dB}}}{2}}\sin\theta\cdot d\theta+2R_{SoS}-R_{SoS}\int\limits_0^{+\frac{\theta_{-3\mathrm{dB}}}{2}}\sin\theta\cdot d\theta} \qquad (3.12)$$

After addition of two integrals, we have

$$D_\mathrm{f}=\frac{2}{\left(1-R_{SoS}\right)\cdot\int\limits_0^{+\frac{\theta_{-3\mathrm{dB}}}{2}}\sin\theta\cdot d\theta+2R_{SoS}} \qquad (3.13)$$

Finally, we have

$$D_{\mathrm{f}} = \frac{2}{\left(1 - R_{SoS}\right)\cdot\left(1-\cos\dfrac{\theta_{-3\mathrm{dB}}}{2}\right)+2R_{SoS}} \qquad (3.14)$$

Substituting the expression (3.6) for R_{SoS} with a computing of the decadal logarithm of directivity factor, we can as well determine and scientifically analyze the behaviour of the directivity index function on the most important parameters of modern hydroacoustic antennas. But if we substitute expression in brackets as in form of function of sinus, we have

$$\sin\frac{\theta_{-3\mathrm{dB}}}{2} = \sqrt{\frac{1-\cos\theta_{-3\mathrm{dB}}}{2}}$$

and then we get directivity index of conical directivity pattern of the antenna as follows

$$DI = 10\cdot\log\frac{1}{\left(1 - R_{\mathrm{SoS}}\right)\cdot\sin^{2}\left(\dfrac{\theta_{-3\mathrm{dB}}}{4}\right)+R_{SoS}} \qquad (3.15)$$

Finally, we have graphical presentations in Fig. 3.4 and in three-dimension on Fig. 3.5.

Introducing the condition of a small angle in azimuth and elevation, mathematically sensitivity angle $\theta_{-3\mathrm{dB}}$, it is valid that the size $\sin(\theta_{-3\mathrm{dB}}/4)\approx(\theta_{-3\mathrm{dB}}/4)$ and the expression (3.15) is simplified so that we have

$$DI = 10\cdot\log\frac{16}{\left(1 - R_{SoS}\right)\cdot\left(\theta_{-3\mathrm{dB}}\right)^{2}+16R_{SoS}} \qquad (3.16)$$

Using expression (3.15) with the condition with ideal model of minor lobe suppressing when is $SoS=-\infty$ dB, then we have $R_{SoS}=0$. With the substitution of this value of R_{SoS} in (3.15) we get a very simple expression

$$DI = 20\cdot\log\frac{1}{\sin\left(\dfrac{\theta_{-3\mathrm{dB}}}{4}\right)} \qquad (3.17)$$

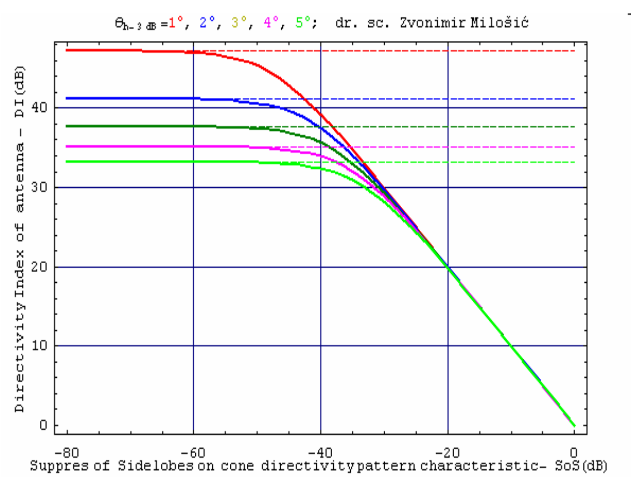

Fig. 3.4 Graphical presentation $DI(\theta, SoS)$ of conical directivity pattern of concentric ring antenna as function of sensitivity angles $\theta_{-3\mathrm{dB}}$ and level of suppression of side lobes SoS.

In the same way, by using (3.16) we get the simplest expression (3.18), which is usable only in above mentioned unreal (ideal) conditions.

$$DI = 10\cdot\log\frac{16}{\theta^{2}_{-3\mathrm{dB}}(\mathrm{rad})} \qquad (3.18)$$

$$DI = 10\cdot\log\frac{52525}{\theta^{2}_{-3\mathrm{dB}}(^{\circ})} \qquad (3.19)$$

$$DI=47.2 - 20\log\theta_{-3\mathrm{dB}}(^{\circ}) \qquad (3.20)$$

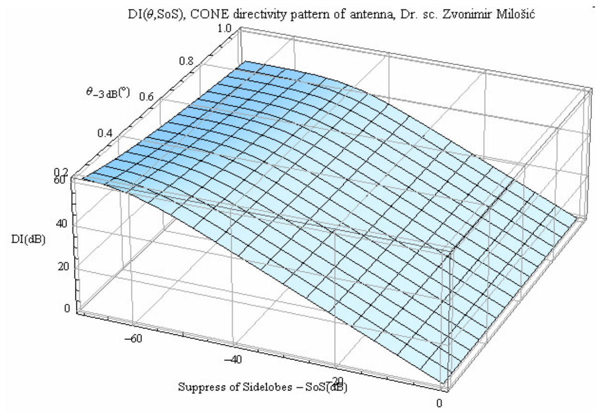

Fig. 3.5 Graphical presentation $DI(\theta, SoS)$ of measured conical directivity pattern of ring antenna.

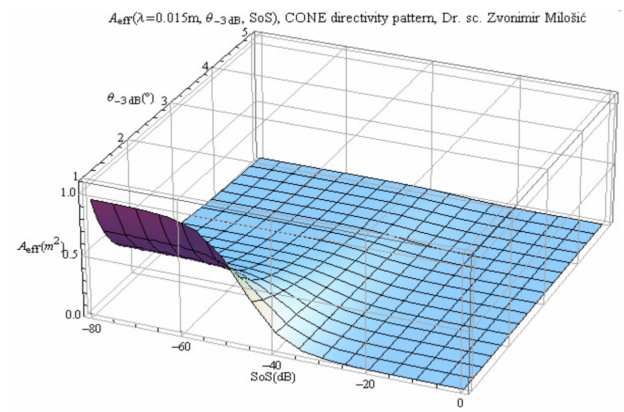

Fig. 3.6 Graphical 3D presentation of effective aperture area of conical directivity pattern of concentric ring antenna as function $A_{\mathrm{eff}}(D_{\mathrm{f}}, \lambda)$, to equation (3.14) and to literature [1, 2, 3, 10, 11, 12]

Keeping in line with the conditions in this theory of conical directivity pattern antenna, we can calculate and control the influence of mistake ΔDI_{R} (dB) on total transmission losses TL (dB) and range r (km) in the conditions with great absorption of sound.

$$TL_{1} = \frac{SL+TS+DI_{R1}-NL-DT}{2} \qquad (3.21)$$

$$TL_{2} = \frac{SL+TS+DI_{R2}-NL-DT}{2} \qquad (3.22)$$

$$\Delta TL = TL_{2} - TL_{1} = \frac{\Delta DI_{R}}{2} \qquad (3.23)$$

Total transmission losses difference ΔTL(dB) in different calculation of DI_{R}(dB) can have too big mistakes in the ranges of monitoring systems, showed on Fig. 3.7. Also, it is widely presented in references [8] and [9] in different conditions for contemporary sonars and radars.

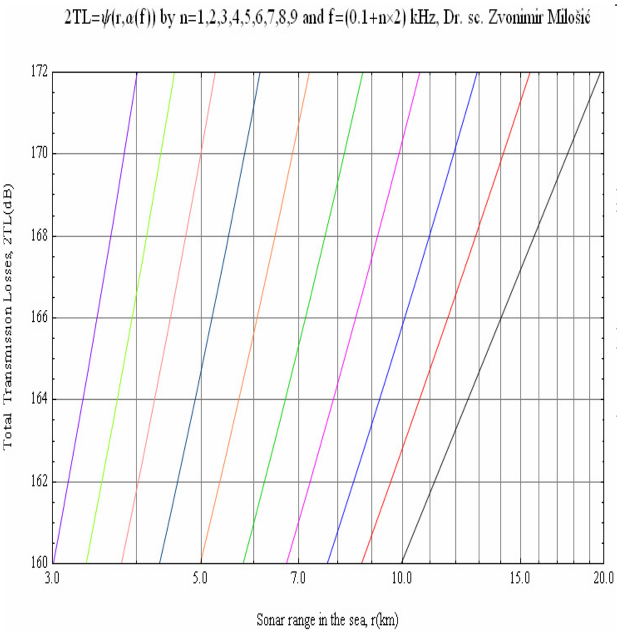

Fig. 3.7 The graphical presentation of the impact of change of total transmission losses $2TL(\alpha, r)$ on the change of sonar range r to Thorp in literature [13].

4 Conclusion

De-embedding of directivity index and effective aperture area in equations of hydrolocation ranges on undersea targets according to the conditions in this paper, makes possible a better evaluation of given parameters:

- *for buyers in contracts with specifications,*
- *in the research and development of R&D,*
- *in academies and*
- *by users.*

In accordance with the equations in this paper, de-embedding of directivity indexes of the receive antennas of sonar systems and ranges of detection of underwater targets are: SIMPLE, FAST, RELIABLE, ACCURATE and WIDELY USUABLE (sonars, hydroacoustics and radio communication systems, radars and also in medicine ultrasound scanners).

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Note: Keeping in line with given expressions in my paper [7], the places of the angle variables θ and φ on the presented figure of coordinate system must be exchanged.