SILENT SONAR FOR MARITIME SECURITY APPLICATIONS

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1 INTRODUCTION

The disadvantage of active echolocation systems (radar, sonar) from the standpoint of military applications, is that they do not ensure secrecy of operation and can be intercepted over long distances exceeding the range of these systems. This disadvantage can be limited by reducing the sounding signal power (which reduces the enemy's range of interception) and in exchange for this increasing its duration. This method has been implemented in silent radar with frequency modulated continuous wave FMCW [1,2,3,4]. Silent sonar is not manufactured anywhere in the world yet. There are no scientific reports on the theoretical issues relating to this topic.

A research project on silent sonar is currently underway at the Gdansk University of Technology [7,8,9,10,11]. The results indicate clearly that it is possible to build a silent sonar for detecting underwater objects and determining their location. The sonar can be successfully used on submarines for navigation and collision avoidance and on other ships and underwater vehicles to search for mines and detect and track divers, underwater vehicles and submarines. In each of these applications the range of intercept of sounding signals can be reduced from several to tens times, compared to the conventional pulse sonar. At the same time silent sonar parameters such as detection range and resolution are the same as for the conventional sonar.

2 BASIC PRINCIPLE OF FMCW SONAR OPERATION

The transmitter of a FMCW silent sonar emits a continuous periodic acoustic signal of T duration into the water medium. The signal emitted in each period has linear frequency modulation with mid frequency f_0 and bandwidth B as shown in Fig. 1. [4,7].

The instantaneous value of the signal frequency emitted in time interval $(0,T)$ is described with the following relation:

$$f(t)=f_0-B/2+B\frac{t}{T}, \qquad (1)$$

and all subsequent periods emit copies of the above relation delayed by nT.

Let us assume that the sounding signal propagates in an ideal unlimited medium and reflects off a point object at distance R from the transmitter. If the ultrasound transmitting transducer and receiving transducer are in the same location, the echo signal received is a delayed and reduced copy of the signal originally emitted. Delay τ is equal to:

$$\tau=\frac{2R}{c}, \qquad (2)$$

where c is the velocity of sound in water.

As a result, the instantaneous frequency of echo signal $f_e(t)$ will be equal to:

$$f_e(t) = f_0 - B/2 + B\frac{t-\tau}{T}. \tag{3}$$

The receiver continuously determines the differential frequency between the frequency of the signal emitted and the frequency of the echo signal received $F(t) = f(t) - f_e(t)$. As a result, differential frequency can be determined from this relation:

$$F = B\frac{\tau}{T}. \tag{4}$$

When the target is motionless, differential frequency will be constant.
The above formula is right for time interval $\tau < t < T$ and subsequent analogous time intervals. For time interval $0 < t < \tau$ and periodically repeated intervals, the difference in frequency is equal to $F - B$, as shown in Fig. 1.

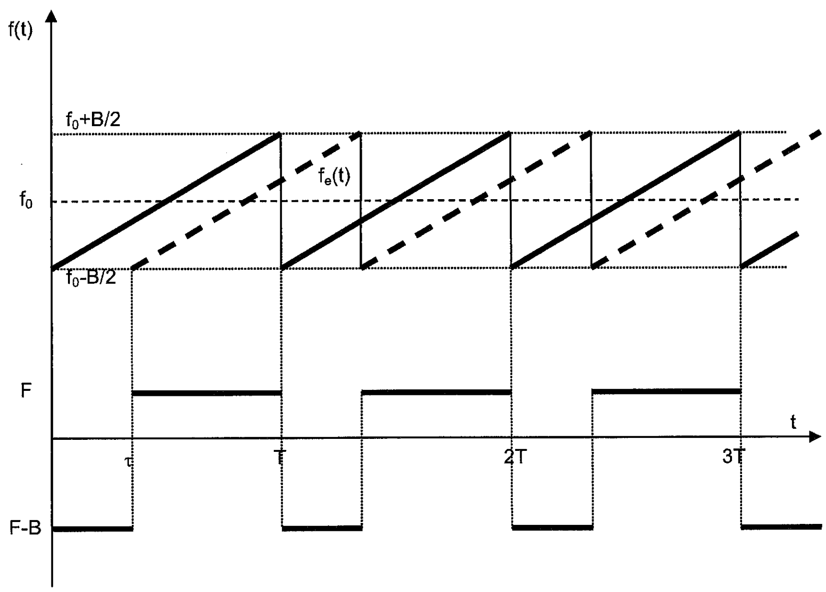

Fig. 1. The frequency of the emitted signal, frequency echo signal and differential frequency in a FMCW silent sonar.

If we measure differential frequency F then using formulas (2) and (4), we can determine the distance to target R:

$$R = \frac{cT}{2B}F. \tag{5}$$

Because differential frequency F will not be greater than bandwidth B, the maximal sonar range R_{MAX} is defined in this relation:

$$R_{MAX} \le \frac{cT}{2}. \tag{6}$$

As delay τ becomes longer, the time interval for measuring differential frequency becomes shorter which significantly reduces the actual maximal sonar range. In an effort to limit this, frequency $F - B$ which appears in time intervals $nT < t < nT+\tau$ can be used in the calculations. Silent radars, on the other hand, can achieve this through frequency modulation by alternating linearly ascending and linearly descending frequency.

Where systems of silent radar and sonar receivers are built based on the above concept, the sounding signal is multiplied by the echo signal and the result is analysed using FFT spectral analysis. The frequency of each line in the spectrum depends on the echo signal returning from a definite distance as stated in relation (5).

The above system solution works perfectly well in silent radars. If we analyse the effect the target's motion has on detection and accuracy of a silent sonar, we will find [5,6,7] that the signal amplitude after FFT drops rapidly as the target increases its speed and the distance to target reading is highly inaccurate. It should be stressed that even though the Doppler effect has a similar impact on detection and accuracy, it is negligible in silent radars which operate to the same principle. This is because the relation between the speed of the target (e.g. a submarine v = 30 kt) and the speed of acoustic wave propagation in a sonar is some 2000 times higher than in the case of the relation between the speed of the target (e.g. a fighter v = 1500 km/h) and the speed of electromagnetic wave propagation in silent radar.

In the concept of silent sonar stated above, the same echo signal parameter, i.e. instantaneous frequency, depends on a target distance as well as a target velocity. This observation has inspired a search for other sounding signals which could be used in silent sonar. The possible signals are non LFM signals with a long duration and a narrow autocorrelation function with small side lobes. Signals like these cannot be used in simple silent sonars with FFT algorithms as described above. What can be used, however, is digital matched filtration.

3 SILENT SONAR WITH MATCHED FILTRATION

A receiver with matched filtration is a filter [8,9,10], whose pulse response *k(t)* is the reversed copy of the emitted signal *s(t)*. As you know, signal *y(t)* at filter output is a combination of input signal *x(t)* and pulse response *k(t)*, namely:

$$y(t) = \int_{-\infty}^{\infty} x(\tau)k(t-\tau)d\tau = k(t) * s(t)\,. \tag{7}$$

The pulse response of a matched filter is equal to:

$$k(t) = x^*(-t)\,, \tag{8}$$

where symbol (*) is used to denote the conjugate value of the complex signal.
When the relation is inserted into formula (7) and the symbols of variables are changed, we obtain:

$$r_{xx}(\tau) = \int_{-\infty}^{\infty} x(t)x^*(t-\tau)dt\,. \tag{9}$$

This is the autocorrelation function of signal x(t), which means that a matched filter whose pulse response is described with relation (8) is equivalent to a correlation receiver. It is optimal for detecting the known signal against Gaussian noise [3]. Thus we can take that pulse response is equal to a time scale inverted emitted signal: *k(t) = s*(-t)*. The signal received with no noise *x(t)* can be written down in a simplified form as:

$$x(t) = K_o s(t-t_o)\,, \tag{10}$$

where K_0 is a coefficient of the scale of echo signal amplitude versus the emitted signal amplitude, t_o – its delay versus the transmitted signal *s(t)*.
We insert the above relation into formula (7) and obtain:

$$y(\tau) = K_0 \int_{-\infty}^{\infty} s(t-t_0)s^*(t-\tau)dt\,. \tag{11}$$

By substituting $t' = t - t_0$ we obtain:

$$y(\tau) = K_o \int_{-\infty}^{\infty} s(t') s^*[t' - (\tau - t_o)] dt' . \tag{12}$$

Considering relation (9) after the transformation we obtain:

$$y(\tau) = K_o r_{ss}(\tau - t_o) . \tag{13}$$

What this means is that the signal at matched filter output has the shape of the autocorrelation function of the emitted signal and is delayed by time t_0. When the sounding signal has a narrow autocorrelation function with a single maximum and a low level of side lobes, echo signal will be detected when output signal $y(\tau)$ reaches its maximum. As shown in formula (13) it occurs at $\tau = t_o$. At this moment of time which is equal to the echo signal delay, the matched filter output signal is:

$$y(t_o) = K_o E_t , \tag{14}$$

where E is the energy of the transmitted signal equal to:

$$y(t_0) = \int_{-\infty}^{\infty} | s(t) |^2 \, dt . \tag{15}$$

If the useful signal is received together with Gaussian noise whose power spectral density is N, the output signal to noise ratio is [3]:

$$SNR_m = \frac{K_o E_t}{N} , \tag{16}$$

where E_t is the energy of the sounding signal.

To meet the needs of detection, the energy of the signals should be as high as possible. In terms of range resolution and its needs, the autocorrelation function of the transmitted signal should be narrow and have a low level of side lobes.

Both criteria are met by signals with linear frequency modulation. If matched filtration and LFM signal are to be used to build a silent sonar, the power of the transmitted signal must be maximally reduced. This postulate is based on the assumption that the enemy does not know the sounding signal and cannot use a matched filter to intercept it. If the sounding signal is to be intercepted in the enemy's intercept receiver, the signal to noise ratio must be equal to:

$$SNR_{um} = \frac{P_r}{\sigma^2} , \tag{17}$$

where P_r is the power of the signal intercepted and σ^2 is a variance of noise in the intercept receiver's frequency band.

The power of the intercepted signal is equal to:

$$P_r = \frac{K_r E_t}{T} = K_r P_t , \tag{18}$$

where T is the duration of the sounding signal with energy E_t, P_t – the power of the signal, and K_r – the coefficient of power reduction as a result of propagation loss. Because $\sigma^2 = NB$, where B is the receiver's transmission band, hence:

$$SNR_{um} = K_r \frac{P_t}{BN} . \tag{19}$$

As you can see, when we reduce the power of the sounding signal, we deteriorate the signal to noise ratio in the enemy's passive intercept receiver making the detection of the sounding signal more difficult. We can achieve the same result by increasing the width of the sounding signal spectrum. The width of the listening band B in the formula above is equal to the width of the sounding signal spectrum. If the enemy uses a wider listening band because he does not know the location or width of the sounding signal spectrum, noise level goes up and the signal to noise ratio deteriorates. If, however, the enemy chooses an overly narrow listening band (or if the band misses the spectrum of the sounding signal), power P_t drops leading to a drop in SNR_{um}.

When the power of the sounding signal is reduced and its duration stays the same, energy E_s drops and the performance of our own sonar deteriorates. This can be seen in the quotient of both signal to noise ratios which is equal to:

$$\frac{SNR_m}{SNR_{um}} = \frac{K_0 E_s}{N} \frac{BTN}{K_r E_s} = BT \frac{K_o}{K_r}. \tag{20}$$

The above relation shows that the enemy's intercept receiver detection performance deteriorates compared to the matched filtration sonar, as duration T of the sounding signal is longer and its spectrum width B is greater. The fact that there is no relation to power in the formula above, is not to say that power should be kept as low as possible. For a high power P_t the signal to noise ratio SNR_{um} can be sufficiently high to perform detection even though it is much lower than SNR_m.

Let us consider the effect of coefficients K_0 and K_t on detection. Coefficient K_0 (formula 10) refers to the amplitude of echo signal. What happens in an echolocation system is that if we leave out absorption, the amplitude is inversely proportional to r_0^2, where r_0 is the distance between the target and sonar. In addition, the amplitude depends on target strength TS and so coefficient K_0 can be written down approximately as:

$$K_0 \cong \frac{r_1^2}{r_0^2} 10^{TS/20}. \tag{21}$$

Coefficient K_r (formula 18) refers to the signal power, hence:

$$K_r \cong \frac{r_1^2}{r_r^2}. \tag{22}$$

When the above relations are inserted into formula (20) we obtain:

$$\frac{SNR_m}{SNR_{um}} \cong BT \left(\frac{r_r}{r_0} \right)^2 10^{TS/20}. \tag{23}$$

Let us assume as an example, that the minimal assumed target strength of the sonar is $TS = -20\ dB$ and that the same signal to noise ratio is sufficient for the sonar and interceptor receiver to detect:

$$\frac{r_r}{r_0} \cong \sqrt{\frac{10}{BT}}. \tag{24}$$

What the above relation allows us to do is determine the intercept system and target to sonar ranges relation for which the detection capacity of the sonar and interceptor system are identical. This relation can be identified with the relation of the ranges of both systems. As you can see, the relation improves for a higher BT product of the sounding signal.

4 SELECTION OF SOUNDING SIGNALS

The receiver of a silent sonar with matched filtration can also accommodate sounding signals other than LFM signals. As has been mentioned before, signals with a narrow autocorrelation function, a single maximum for time equal to 0 and a low level of side lobes are used in silent sonar on purpose. Such features are found in the following signals [10]:

- signal with linear frequency modulation (LFM),
- signal with hyperbolic frequency modulation (HFM),
- signal with phase modulation using pseudo-random codes such as Maximum Length Sequence (MLS).

A number of analyses and simulations were conducted to understand how the different sounding signals can be used in silent sonar [7,8,9,10,11]. The results did not always meet the expectations. There was a detailed analysis of the features of LFM signals. Because certain features were known to improve detection when Doppler effect occurs [5,6], the analysis focused on the hyperbolic frequency modulation signal HFM and its use in silent sonar. When the signal was used even for a very strong Doppler effect, detection quality deteriorated only slightly. Unfortunately, the accuracy of distance to target reading could not be improved. It is quite significant when Doppler effect is strong and can be worse than 10% of the sonar's maximal range, when the target moves at a speed of 30 Kt. In terms of motionless targets or slow moving ones the accuracy can be satisfactory.

When frequency modulation sounding signals (LFM and HFM) are used in silent sonar, the distance to target and target motion which causes Doppler effect affect the instantaneous frequency of the received signal. This is why signals using pseudo-random codes of the Maximum Length Sequence (MLS) type were tested. The codes were analysed for their direct application to phase-shift keying of the carrier signal with a wide enough band to ensure a good WT product, which is a precondition of stealth. Because the signal's autocorrelation function was particularly narrow, the results were very good for motionless targets, but unfortunately detection quality would rapidly decline even for a small Doppler effect [11].

The search for a good signal continued focussing on a combination of signals with frequency modulation and simultaneous use of MLS codes. The results were very good in the case of two elementary HFM signals with different adjacent frequency bands (different frequencies for a different sign of the code's element) and a relatively short duration in connection with the MLS code. The maximal error in distance reading as a result of Doppler effect can be estimated at $\Delta R \approx 10Tc/2$ [%], where T is the duration of the elementary signal and c is the velocity of sound in water. By using MLS codes we can extend the sounding signal and, by the same token the range of silent sonar. In this case the duration of the code element is long enough for Doppler effect to have a smaller impact than that in a broadband MLS signal with phase shift keying. It is worth stressing that the elementary HFM signal ensures good detection as well even when Doppler effect is significant.

The results of analyses and simulations are summarised in the table below. The following abbreviations are used for algorithms of digital signal processing: Fast Fourier Transform FFT, Digital Matched Filtration DMF and Double Digital Matched Filtration DDMF.

Table 1. Features of sounding signals used in silent sonar

Type of signal	Type of filtration	Advantages	Disadvantages
LFM	FFT	Simple design and easy algorithms. Good parameters for slow moving targets.	Detection and accuracy of distance measurement are very sensitive to Doppler effect.
	DMF	Good parameters for slow moving targets.	Detection and accuracy of distance measurement are very sensitive to Doppler effect. Complex algorithms.
HFM	DMF	Doppler effect has very little effect on detection.	Very poor distance accuracy for Doppler effect. Complex algorithms.
MLS	DMF	Highly precise with motionless targets.	Unacceptable detection and distance accuracy for Doppler effect. Complex algorithms.
MLS+HFM	DDMF	Acceptable detection and distance inaccuracy even for a strong Doppler effect.	Very complex algorithms.

5 HOW SILENT IS SILENT SONAR

To understand how silent the silent sonar is, let us compare the silent sonar with the classic pulse sonar without matched filtration [11].

Let for example, both sonars operate at the same frequency, the transmitter of the silent sonar emits HFM signals with spectrum width B = 20 kHz and duration T = 1s, and the transmitter of the pulse sonar emits signals with duration τ_{and} = 0.1 ms. As a consequence, the required bandwidth of the pulse sonar's receiver is $Bi = 1/\tau_{and}$ = 10 kHz. Let us assume that signal power at the pulse sonar's input is P_i, and P at the silent sonar's input. Let us assume further that the required output signal to noise ratio at the receiver outputs of both sonars is identical and ensures the same detection and false alarm probability. The receiver of the pulse sonar conducts envelope detection and so the output signal to noise ratio is almost equal to input signal to noise ratio, i.e.:

$$SNR_i \approx \frac{P_i}{NB_i} \tag{25}$$

where N is the spectral power of sea noise.

On the other hand, the output signal to noise ratio in silent sonar with matched filtration is equal to:

$$SNR \approx \frac{PT}{N} \tag{26}$$

As the above relations show the relation of signal power at sonar input is approximately equal to:

$$\frac{P_i}{P} \approx TB_i \tag{27}$$

For the values given above the quotient is 10^4, which means that the silent sonar has a range similar to that of the pulse sonar while it emits 10^4 less power. With a different power emitted by the sonars, signals intercepted by the enemy's receiver in the passive listening system can be intercepted at significantly different distances. Let us assume that in order to intercept the signal, its power at the receiver's input is identical for the pulse and silent sonar. For spherical propagation the following equation must be used:

$$\frac{P_i r_1^2}{r_i^2 \exp(0{,}23\alpha r_i)} = \frac{P r_1^2}{r^2 \exp(0{,}23\alpha r)} \tag{28}$$

where r_i means the distance at which the pulse sonar's sounding signal is intercepted, r – the distance of silent sonar interception, r_1 = 1 m, and α is the absorption coefficient of sound in water [dB/m]. Using relation (38), equation (39) can be written down as:

$$TB_i = \frac{r_i^2}{r^2} \exp[0{,}23\alpha(r_i - r)] \tag{29}$$

If the equation is solved numerically, we can estimate the pulse sonar's interception distance in the function of silent sonar interception distance. Fig. 2 shows the relation for TB_i = 10^4 and three values of the absorption coefficient for high frequency short range sonar. In ocean water at frequency f_0 = 120 kHz the coefficient is $\alpha \approx$ 35 dB/km, $\alpha \approx$ 5 dB/km in the Baltic, and $\alpha \approx$ 1.4 dB/km in fresh water. Because acoustic wave attenuation is very strong in ocean water, the difference between silent sonar and pulse sonar interception distance is small. It increases in the brackish water of the Baltic and even more in inland waters. Long-range sonars primarily designed for detecting submarines operate at low frequencies where sound absorption is much lower. As a result, the differences between silent sonar and pulse sonar interception ranges are greater as illustrated in Fig. 3. The value of the absorption coefficient for the ocean is now $\alpha \approx$ 0.42 dB/km, $\alpha \approx$ 0.08 dB/km for the Baltic, and $\alpha \approx$ 0.006 dB/km for fresh water.

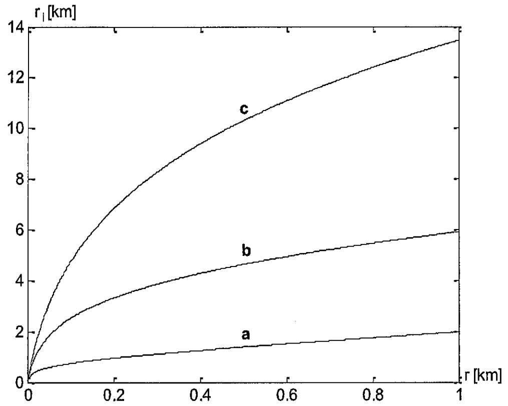

Fig. 2. Interception distance for a 120 kHz pulse sonar versus silent sonar (a - ocean, b – the Baltic, c – inland waters).

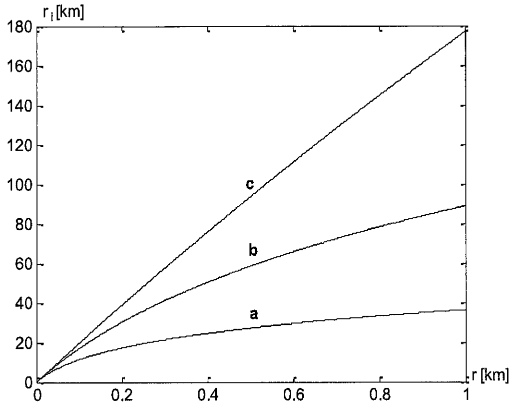

Fig. 3. Interception distance for a 8 kHz pulse sonar versus silent sonar (a - ocean, b – the Baltic, c - inland waters).

6 CONCLUSIONS

The Department of Marine Electronic Systems of the Gdansk University of Technology has developed the theoretical basis for the design of silent sonar whose parameters are comparable to those of classic pulse sonars. The theoretical assumptions will be tested shortly at an inland water test site using a model of the silent sonar.

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REFERENCES

1. K.L. Fuller, To see and not be seen. IEE Proceedings-F, 137(1), 1-10. (1990).
2. H.D. Griffiths, New ideas in FM Radar. Electron. Commun. Eng. Journal, 2(5), 185-194. (1990).
3. M. Skolnik, Radar Handbook. Second Edition. McGraw-Hill. (1990).
4. A.G. Stove, Linear FMCW Radar Techniques. IEE Proceedings-F, 139(5), 343-350. (1992).
5. S.A. Kramer, Doppler and acceleration tolerance of high-gain wide-band linear FM correlation SONAR. Proc. IEEE, 33, 627-636. (1967).
6. J. Yang, T.K. Sarkar, Doppler-invariant property of hyperbolic frequency modulated waveform. Microwave and optical technology letters, 48(8), 1174-1179. (2006).
7. J. Marszal, R. Salamon, K. Zachariasz, A.Schmidt, Doppler effect in CW FM sonar. Hydroacoustics, 14, 157-164. (2011).
8. R. Salamon, J. Marszal, J.Schmidt, M. Rudnicki, Silent sonar with matched filtration. Hydroacoustics, 14, 199-208. (2011).
9. R. Salamon, J. Marszal, I. Kilian, A. Jedel, A. Raganowicz, Z.Ostrowski, Signal selection for silent sonar with matched filtering, Proc. Open Seminar on Acoustics, Jurata Poland (2011).
10. J. Marszal, R. Salamon, Distance Measurement Errors In Silent FM-CW Sonar With Matched Filtering, Metrol. Meas. Syst., Vol. XIX, No. 2. (2012).
11. J. Marszal, R. Salamon, L. Kilian, Application of maximum length sequence in silent sonar, Hydroacoustics, Vol. 15. (2012).