Acoustics'08 Paris
June 29-July 4, 2008
www.acoustics08-paris.org

On the consideration of motion effects in underwater geoacoustic inversion

Nicolas Josso[a], Cornel Ioana[a], Cédric Gervaise[b] and Jérôme Mars[a]

[a]GIPSA-lab, dep. DIS, 961, rue de la Houille Blanche, 38402 St Martin d'Hères, France
[b]E3I2 - EA3876, 2 rue François Verny, 29806 Brest Cedex, France
cedric.gervaise@ensieta.fr

The estimation of an impulse response (IR) of a propagation channel is necessary for a large number of underwater acoustic applications : underwater communication, sonar detection and localization, marine mammal monitoring, etc. Basically, it informs us about the distortions of a transmitted signal in one underwater channel. This operation is usually subject to additional distortions due to the motion of the transmitter-channel-receiver configuration.
This paper points on the effects of the motion while estimating, in shallow water environments, the IR by matching filtering between the transmitted and the received signals. We propose a methodology to compare between the IR estimation in motionless and motion contexts, respectively. Using this methodology a method for motion effect compensation is proposed in order to reduce the distortions due to the motion phenomena.
The proposed methodology is applied to real data sets issued from BASE07 campaign (SHOM, South of Sicilia, 2007) proving also its interest for motion effect analysis.

1 Introduction

The knowledge of the IR of one propagation channel is necessary for a large number of underwater acoustics applications such as underwater communication, sonar detection and localization, marine mammal monitoring, etc. If the Ray theory applies [1], a well know and effective method to compute the IR is the matching filtering [2] where the received signal is correlated with the transmitted one. In the following, it is considered that the Ray theory applies and the case of Modal propagation is not discussed.

The purpose of this paper is to point out the effects of the motion that often exists in an operating transmitter-channel-receiver configuration. Doppler effect consequences on the estimation of the IR are shown and explained for shallow water environments with matching filtering between the transmitted and received signals in the very low frequencies bandwidth. For feasibility purposes, it is considered that the relative motion existing between the transmitter and the receiver is rectilinear with a constant speed.

As linear frequency modulations (LFM) are well adapted to geoacoustic inversions purposes, this study focuses on LFM emitted signals but it could be applied for other emissions. The received signal is characterised using different time axis for the emission and the reception [3]. This allows modeling the broadband Doppler effect for LFM which is different from the carrier frequency shift usually used to model the narrow-band case. Once the received signal is characterized, the effect of the motion on the IR are pointed out and explained. Techniques improving the IR on Doppler effect scenarios are then presented on simulations and real data sets.

The paper is organized as follows. Sections 2 presents the characterization of the received signal in a multipath environment with a rectilinear and a constant speed motion. Section 3 describes the effects of the motion on the estimation of an IR computed with matching filtering. Section 4 introduces and explains the Doppler effects removal technique on the IR and its applications on simulated data. The real data sets results are presented in Section 5. We close in section 6 with Conclusions.

2 Characterization of the multipath received signal

A way for introducing the broadband Doppler effect in an underwater multipath is presented in this section.

2.1 Signal received for one ray

In this paper, we consider that the receiver is fixed and the source is moving with a constant speed motion. Analysing a multipath propagation with a moving source and a fixed receiver implies to identify each ray and define the equations it follows.

We define a time axis *u* for the emission and *t* for the reception following a relation of the form

$$u + T_i(u) = t, \tag{1}$$

where $T_i(u)$ refers to the time of propagation of the *i*th ray. This relation means that a signal transmitted at the time *u* is received on the *i*th ray at the time *u* plus the propagation time along the *i*th ray. $L_i(u)$ is defined as the length in meters of the *i*th ray. With a source moving at constant speed motion along axis *x* we can write

$$u + \frac{x_0 + L_i(u) + v_i u}{c} = t, \tag{2}$$

where x_0 is the position of the source when $u = 0$ and c is the speed of the sound in the medium (considered constant). To clarify notations, we introduce

$$\tau_i(u) = \frac{x_0 + L_i(u)}{c}. \tag{3}$$

Some manipulations with (1), (2) and (3) yields to:

$$u = \left(t - \tau_i(u)\right)\left(\frac{1}{1 + v_i / c}\right), \tag{4}$$

this relation means that the signal received at the time *t* for the path number *i* was emitted at the time $(t - \tau_i(u))(1/(1 + v_i / c))$. The term $\tau_i(u)$ represents the time of propagation from the source to the receiver. It depends on the time of emission (*u*) and cannot be expressed with the time of reception (*t*) for all cases. The term $1/(1 + v_i / c)$ is the classical compression or expansion in the time domain of the broadband Doppler effect.

2.2 Signal received with multipath propagation

In (2), it has been assumed that the speed of the source appears to be different for each ray. The projection of the source's speed on the sight line between the transmitter and the receiver is called *v*. It is assumed that *v* can vary with time as the line defined by the source and the receiver changes. As shown in fig. 1, the motion vector v is projected on the path of the *ith* ray with the declination angle θ_i what leads to

$$v_i = \left\|\vec{v}\right\| \cos(\theta_i). \tag{5}$$

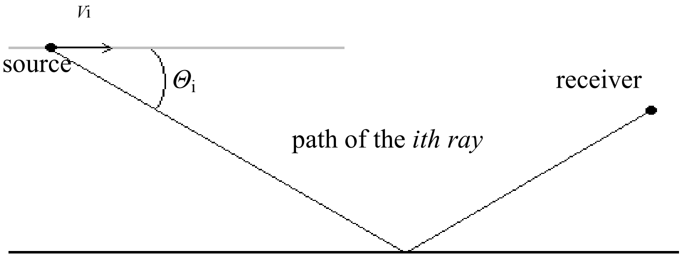

Fig. 1 Scheme explaining how v_i is computed from the motion vector v. For simplicity, here it is assumed that the speed is constant.

We consider that the received signal is composed of several rays, the ith ray is an amplitude-attenuated (a_i), time delayed and Doppler-transformed version of the transmitted signal *e(t)*. With (4) and adding a change in amplitude to conserve energy yields to the expression of the signal received at the time t for the ith ray

$$s_i(t,u) = a_i \left(\frac{1}{1+v_i/c}\right)^{1/2} e((t-\tau_i(u))(\frac{1}{1+v_i/c})). \tag{6}$$

The received signal *s(t,u)* is the sum of all the $s_i(t,u)$ received from each ray which leads to the following expression

$$s(t,u) = \sum_i s_i(t,u). \tag{7}$$

From now on, the propagation time is considered to be constant during one emission. This hypothesis is valid when the distance made by the source during the transmission can be neglected compared with the distance source-receiver. By using the complete formulations of the signal received for each ray (6) and of the apparent speed v_i, (7) can be rewritten

$$s(t) = \sum_i a_i \left(\frac{1}{1+\left\|\vec{v}\right\|\cos(\theta_i)/c}\right)^{1/2} e\left((t-\tau_i)(\frac{1}{1+\left\|\vec{v}\right\|\cos(\theta_i)/c})\right). \tag{8}$$

3 Estimation of an IR with a source motion

In the previous section, the multipath signal received has been characterised. The problem of the estimation of an IR with matching filtering is formulated and analysed in this section.

3.1 Correlation receiver

In section II, it has been explained that the received signal is defined as the sum of amplitude-attenuated, time delayed and Doppler-transformed version of the transmitted signal. Assuming the emitted signal is known, the propagation time and the velocity associated to each ray can be estimated by cross correlating the received signal with a set of reference signals. The set of reference signals is composed of time-delayed and Doppler-transformed versions of the transmitted signal for all the range of time delays and speeds expected [4]. The factor of contraction or expansion due to the Doppler transformation η satisfies

$$\eta = \frac{1}{1+v/c}. \tag{9}$$

The Doppler transformation factor of the *ith* ray is introduced as η_i and satisfies (9) with the speed v_i associated to the same ray. For each reference signal, the cross correlation is computed by

$$R(\tau,v) = \int_{-\infty}^{\infty} s(t+\tau)\eta^{1/2} e^*(\eta t)dt, \tag{10}$$

where * denotes the complex conjugation, *s(t)* the received signal and *e(t)* the transmission.

Using the expression of the received signal in a multipath environment (8) in (10) yields

$$R(\tau,v) = \sum_i a_i (\eta_i \eta)^{1/2} \int_{-\infty}^{\infty} e(\eta_i(t+\tau-\tau_i))e^*(\eta t)dt. \tag{11}$$

Local maxima of this correlation function are reached for each ray. For the *ith* ray, the maximum is reached when the reference and the propagated signal are exactly aligned in time delay and Doppler. It is assumed that rays are well separated in time in the motionless case so there is no interferences between local maxima. The interferences that could occur between local maxima are studied in [4] and are not the purpose of this paper. The time of propagation and the apparent speed of the *ith* ray can be estimated once the local maximum is detected.

3.2 The LFM case

From now on, the transmitted signal is assumed to be a LFM with known parameters

$$e(t) = rect(\frac{t}{T})\frac{1}{\sqrt{T}}\exp(j2\pi(f_0 t + \frac{k}{2}t^2)), \tag{12}$$

where f_0 the beginning frequency of the sweep, k is the chirp rate or sweep rate and the *rect* function is defined by

$$rect(t) = \begin{cases} 1, & if \ |x| \le 1/2, \\ 0, & otherwise. \end{cases} \tag{13}$$

Some algebraic manipulations [4,5] with (11) and (12) leads to the analytic expression of the cross correlation defined previously if v is different from v_i

$$R(\tau,v)=\sum_i \frac{C_i D_i E_i}{2\sqrt{|\beta_i|}} \int_{X_i}^{Y_i} \exp(\gamma \frac{\pi}{2} jt^2)dt, \quad (14)$$

where

$$C_i = \frac{\eta_i^{1/2}\eta^{1/2}a_i}{T}\exp(\pi j(f_0 \Delta\tau_i(\eta+\eta_i)), \quad (14a)$$

$$D_i = \exp(\pi \frac{k\Delta\tau_i^2}{4} j(\eta_i^2-\eta^2)), \quad (14b)$$

$$E_i = \exp(-\gamma 2\pi j(\frac{\alpha_i}{2\sqrt{|\beta_i|}})^2), \quad (14c)$$

$$\beta_i = \frac{k}{2}(\eta_i^{\ 2}-\eta^2), \quad (14d)$$

$$\alpha_i = f_0(\eta_i-\eta)+k\Delta\tau_i(\eta^2-\eta_i^{\ 2}), \quad (14e)$$

$$\Delta\tau_i = \tau-\tau_i, \quad (14f)$$

$$X_i = \frac{\gamma\alpha_i}{\sqrt{|\beta_i|}}+2\sqrt{|\beta_i|}t_{i,1}, \quad (14g)$$

$$Y_i = \frac{\gamma\alpha_i}{\sqrt{|\beta_i|}}+2\sqrt{|\beta_i|}t_{i,2}, \quad (14h)$$

$$\gamma = \mathrm{sgn}(k(\eta_i-\eta)). \quad (14i)$$

The result of (14) can be expressed and simplified with a complex form of the Fresnel integrals if v is different from v_i

$$R(\tau,v)=\sum_i \frac{C_i D_i E_i}{\sqrt{|\beta_i|}}(Z(X_i)-Z(Y_i)), \quad (15)$$

where

$$Z(u)=\int_0^u \exp(\frac{\pi}{2}jt^2)dt. \quad (15a)$$

When the Doppler transformation of the reference signal matches exactly the Doppler transformation of the *ith* path, the expression (15) is no longer valid and the *ith* term of the sum, $r_i(\tau,v)$, becomes

$$r_i(\tau,v)=C_i(|\Delta\tau_i|-\frac{T}{\eta_i})\frac{\sin(\xi_i)}{\xi_i}, \quad (16)$$

where

$$\xi_i = \pi k\Delta\tau_i\eta_i(\eta_i|\Delta\tau_i|-T). \quad (16a)$$

When the reference signal matches exactly the ith path, the expression (15) reaches it maximum as predicted. It is interesting to notice that (16) is a sine cardinal multiplied by a constant what can be compared with the classical LFM ambiguity function. A representation of the cross correlation result is introduced and studied in the next section.

3.3 The wideband ambiguity plane

The wideband ambiguity plane introduced here is the square magnitude of the result of the correlation (11). This representation can be compared with the classical ambiguity plane except the Doppler effect is modelled as a compression or expansion in time and not as a frequency shifting. As shown fig.2, the representation of a time delayed and Doppler transformed LFM is ambiguous in the wideband ambiguity plane.
Although the LFM is ambiguous in the ambiguity plane, the maximum is reached when the parameters of the reference signal match exactly with the parameters to estimate. The amplitude of the correlation stays high for time delays close to the simulated one and correlation broadens the farther from the simulated speed.

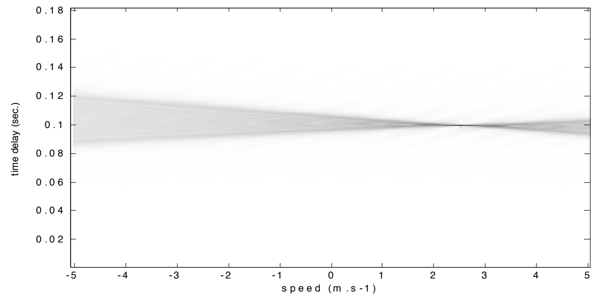

Fig. 2 Representation in the ambiguity plane of one LFM without multipath, with a central frequency of 1300Hz, a bandwidth of 2000Hz and a time duration of 4 seconds. The simulated speed is 2.5m.s^{-1} and the time delay is 0.1 seconds.

For multipath propagation as shown in fig.3, paths have different apparent speeds and different time delays. Each path is seen as a sweep-like shape which broadens with the distance between the reference and the simulated speed.

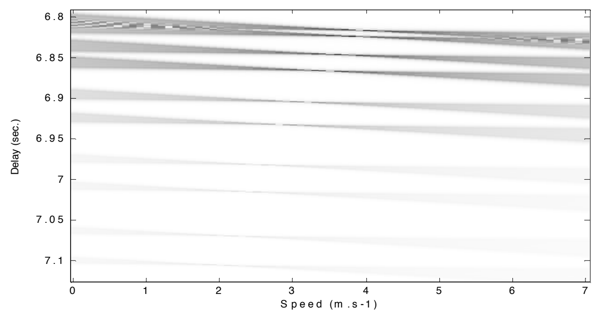

Fig. 3 Ambiguity plane of a simulated multipath propagation. The relative speed simulated is almost 8 knots and the distance source-receiver is 500 meters. The signal emitted is a LFM with a central frequency of 1300Hz, a bandwidth of 2000Hz and a time duration of 4 seconds.

A well known method of estimating the IR of one propagation canal is to compute the cross correlation between the time delayed transmitted signal and the received signal. This is equivalent to computing the expression (11) with a zero speed for all references and the result can be obtained by keeping the column at zero speed in the ambiguity plane. An example of the “zero speed” correlation is illustrated with solid line on fig.4 for the received signal introduced in fig.3. The two first paths are not resolved because the transmitted signal is transformed by the Doppler effect which is not taken into account during the processing. The amplitude of each peak is lowered and the time delay estimated are not exact. The exact values of amplitude and time delay of the *ith* path are located at the maximum value of the shape associated with the *ith* path. This explains the necessity of adding a speed parameter to the matched filtering processing so the motion of the source can be compensated.

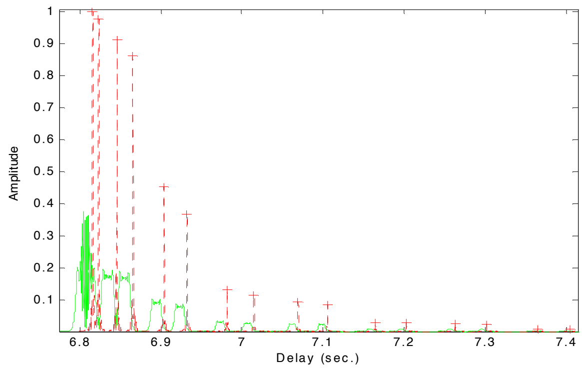

Fig. 4 Estimation of the IR of a propagation canal computed by keeping a column at zero speed in the ambiguity plane represented by solid lines. Dotted lines represents the IR estimated with a motionless source. The relative speed simulated is almost 8 knots and the distance source-receiver is 500 meters.

4 Doppler removal techniques

A computation method has been presented in the previous section to study the multipath propagation when a LFM is emitted. The wideband ambiguity plane was introduced as an adapted representation of the multipath propagation whenever the source is moving or not.

The cross correlation between the time delayed transmitted signal and the received signal have been shown to give a poor IR if the motion is not taken into account. We propose here a new method to compensate the motion in the estimation of an IR of one propagation canal. Considering that the first arriving path is the direct path, its declination angle is very low and the expression (5) shows that the apparent speed of this path will be the projection of the motion vector along the receiver-source line. The amplitude of the direct path is higher than any other so the amplitude of its correlation with the reference signals is also higher than any other. The speed of the source, v, is estimated as the coordinates of the absolute maximum in the ambiguity plane. If the source is faraway from the receiver we can consider that received paths will have low declinations angle meaning an apparent speed close to v and (5) becomes

$$v_i = \left\| \vec{v} \right\|. \tag{17}$$

The uniform speed compensation is defined as keeping the line at constant speed v in the wideband ambiguity plane and is presented in fig.5.

The simulation presented in fig.5 was computed with a source moving at a constant speed of 2.5m.s^{-1}, distant of 3.5km from the receiver. The signal emitted is a LFM with a central frequency of 1300Hz, a bandwidth of 2000Hz and a time duration of 4 seconds. The star represented in fig.5.a shown the absolute maximum detected in the wideband ambiguity giving an estimated speed of 2.5m.s^{-1} as expected. The compensation of the motion on the estimation of the IR is made by keeping the column at the estimated speed and is represented with solid line on fig.5.a. The dashed line represents the IR estimated with “zero speed” compensation while the crosses represents the simulated IR. This compensation method is effective and allows to improve the estimated IR. Both amplitudes, time delays and peaks detection have been improved. It was not possible to distinguish the eleventh first paths before the compensation while they are clearly detectable with compensation. The Doppler effect lowers amplitudes and shifts time delays. The time delay shifting is clear on fig.5.b and can be explained by the sweep-like shape of each path on fig5.a.

a.

b.

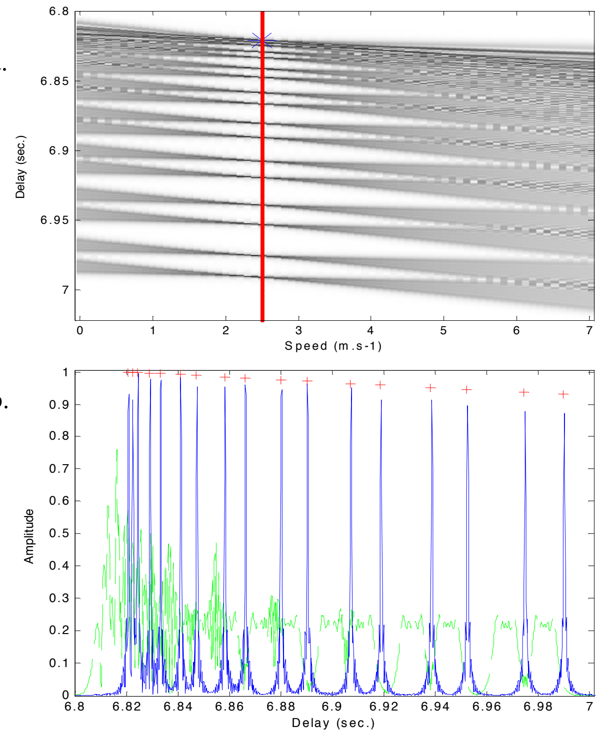

Fig. 5 The figure a. is the representation of the ambiguity plane with a relative speed of almost 5 knots, for a 3500 meters long multipath propagation. The star represents the detected absolute maximum. The picture b. shows the IR estimated with “zero speed” compensation in dashed lines, the IR estimated with uniform speed compensation in solid line and the crosses represent the ideal IR simulated.

The uniform speed compensation is a good way to compensate the motion of a source while estimating an IR. Though the hypothesis necessary to its validity can not always be met. A compensation method considering the speed of each ray is different one from another should lead to a more general results.

5 Application on real data

In this section, the presented methods are tested on real set of data from BASE07 campaign (SHOM, South of Sicilia, 2007) proving also its interest for motion effect analysis.

5.1 Experiment description

The BASE07 campaign was carried out by the SHOM (Service Hydrographique et Océanographique de la Marine) with the collaboration of the NURC (NATO Undersea Research Center) and the FWG (Für Wasserschall und Geophysik). The campaign lasted one week in 2007 and took place in shallow water (150 meters depth) of the South of Sicilia.

Underwater LFM were emitted by a source moving rectilinearly at constant speed from 2 knots to 12 knots and different depths. The source-receiver distance varied from 500 to 25000 meters and the emitted signals were recorded by an array of six hydrophones located at different depths (from 9 to 94 meters).

5.2 Results

The wide band ambiguity plane has been studied for more than 15 different scenarios on each of the six hydrophones of the array. The motion existing between the source and the receivers was clearly seen on all the wideband ambiguity planes. The uniform speed compensation method was then automatically carried out to get an estimation of the source-receiver relative speed.

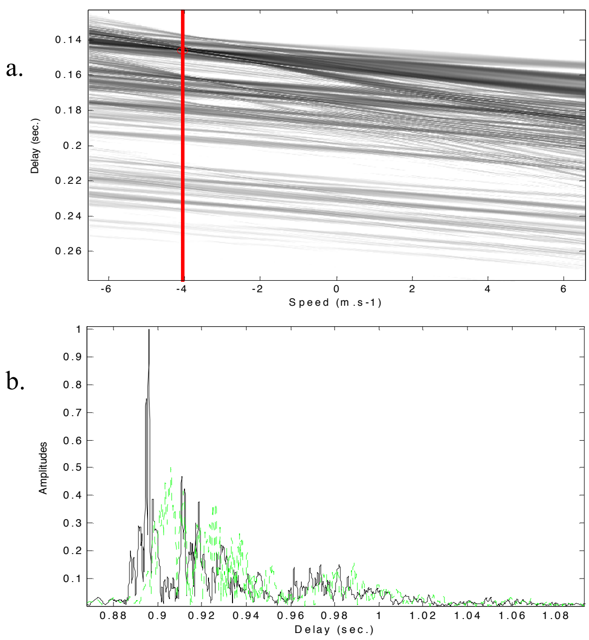

Fig. 7 Representation of the wideband ambiguity plane of real data from BASE07 campaign. The fig. 7.b represents the IR estimated with classical matching filtering in dashed line and a motion-compensated IR in solid line.

An example of the wideband ambiguity plane with its associated motion-compensated IR is presented on fig. 7. The scenario presented here was recorded with a relative speed of 8.5 knots and a 1920 meters long propagation canal. The speed estimated by the automatic process is 8.1 knots which appears acceptable. The ambiguity plane illustrated in fig. 7.a is close to the one obtained during simulations. The estimated IR is drawn with solid line on fig. 7.b and was computed with the uniform speed compensation method. The amplitude of each peak seems to be corrected and the time delays are shifted compared those of the IR estimated with classical matching filtering. Most of the estimated speed were correct and quite accurate but some were false. In most cases estimated speed were false because the absolute maximum of the ambiguity plane corresponded to a constructive interference existing between two paths arriving almost simultaneously.

6 Conclusion

The effects of the motion while estimating the IR for shallow water environments in the very low frequencies bandwidth must be taken into account. In this case, Doppler effect cannot be modelled by a carrier frequency shift usually used to represent the narrow-band case and broadband Doppler effect should be used instead.

The broadband Doppler effect is modelled as a compression or expansion in time. The wideband ambiguity plane is presented here as a convenient way of representing multipath environments in transmitter-receiver motion scenario. A method for motion effect compensation is proposed in the wideband ambiguity plane in order to reduce the distortions due to the motion phenomena when the transmitted signal is known. This compensation method was tested on real set of data from BASE07 campaign (SHOM, South of Sicilia, 2007) leading to realistic results.

Acknowledgments

This work is supported by research grant N°07CR0001 (SHOM, Service Hydrographique et Océanographique de la Marine).

References

[1] F.B. Jensen, W. A. Kuperman, M. B. Porter, H. Schmidt, *Computational Ocean Acoustics,* Ed. New York, Springer-Verlag, 2000.

[2] M. I. Taroudakis, G. N. Makrakis, *Inverse Problems in Underwater Acoustics,* Ed. New York, Springer-Verlag, 2001.

[3] J. G. Clark, R. P. Flanagan and N.L. Weinberg, “Multipath acoustic propagation with a moving source in a bounded deep ocean channel” J. Acoust. Soc. Am., vol. 60, pp. 1274-1284, Dec. 1976.

[4] J. P. Hermand and W. I. Roderick, “Delay-Doppler resolution performance of large time-bandwidth-product linear FM signals in a multipath ocean environment” J. Acoust. Soc. Am., vol. 85, pp 1709-1727, Nov. 1988.

[5] S. A. Kramer, “Doppler and Acceleration Tolerances of High-Gain, Wideband Linear FM Correlation Sonars”, Proceedings of the IEE, vol. 55, pp. 627-636, May 1967.