Computer Derivation of Some Dolphin Echolocation Signals

Abstract. *Recent advances in radar theory have given rise to a straightforward method of sonar signal design. The method involves computer maximization of a signal-to-interference ratio. The procedure has been used to derive sonar signals that can accurately measure target velocity. When two dolphins were placed in a situation conducive to the utilization of such signals, their waveforms were similar to those that had been theoretically derived.*

In active sonar and radar systems, information about a reflecting object is obtained by investigating the effect of the target upon transmitted waveforms. For many situations, it has been found that echoes can be adequately described as delayed, doppler-distorted versions of the transmitted signal. Such a description is analytically convenient, since the returned waveform is easily represented in terms of range and target velocity.

An autocorrelation process is generally used to test for the presence of a target with specific range and velocity. A correlation process can be defined as the product of two waveforms, integrated over time. For autocorrelation, an echo is multiplied by a signal identical to itself, and the product is integrated over the time duration of the signal. Since echo delay and doppler distortion are unknown a priori, the receiver must hypothesize them. For a correct hypothesis, the receiver experiences its maximum possible response. If a sonar signal is very sensitive to the range (or velocity) hypothesis, an incorrect guess about delay (or doppler distortion) will result in a comparatively small receiver response.

When received echoes are immersed in additive white noise, the autocorrelation process is optimal in the sense that it maximizes the ratio of output signal power to expected output noise power (for correct hypotheses). Correlation processors are usually implemented either by multiplication of stored (hypothetical echo) waveforms with an echo, followed by time integration, or by passing received signals through a bank of linear, time-invariant filters with appropriate impulse responses.

$$\mathrm{SIR} = \frac{E_s\,[\chi_{vu}{}^{\mathrm{WB}}\,(0,1)]^2}{\left(\frac{N_0}{2}\right)\int [v(t)]^2 dt + E_c \int\limits_0^{\infty} \int\limits_{-\infty}^{\infty} p(\tau, s)\,[\chi_{vu}{}^{\mathrm{WB}}\,(\tau, s)]^2 d\tau ds}$$

Fig. 1. Signal-to-interference ratio.

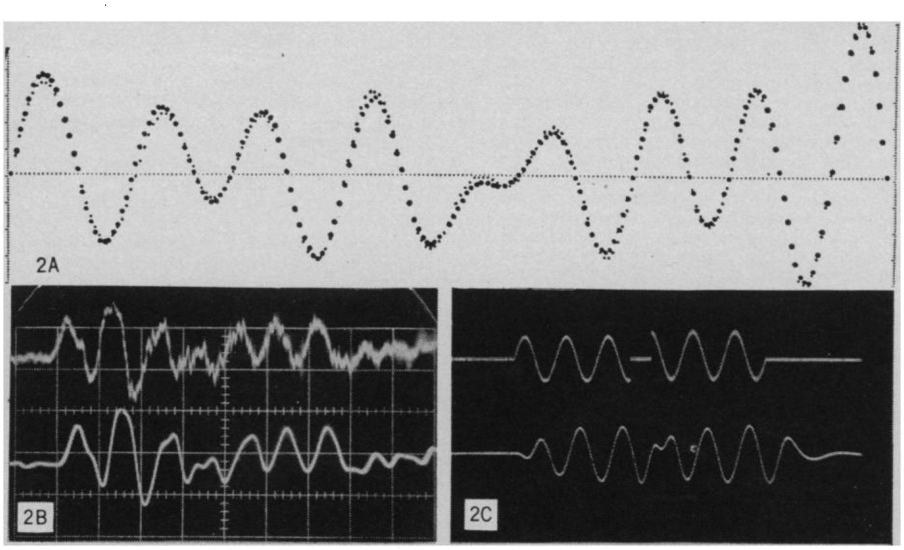

Fig. 2. (A) A computer-derived signal-filter pair for optimal velocity resolution. Heavy dots denote the signal function $u(t)$; small dots denote $v(t)$, the time-reversed filter impulse response. Note that the two functions almost coincide. (B) Top signal is an 8-msec signal used by one of two dolphins that had been newly introduced to a tank. Time scale is 1 msec per large division. Bottom signal is the same signal as above, low-pass filtered with high-frequency cutoff at 3 khz. (C) Top signal is a sinusoid with discontinuous amplitude. Bottom signal is a band-pass version of the above waveform.

It is sometimes advantageous to perform *cross* correlations rather than autocorrelations. An echo can be correlated with waveforms other than delayed, doppler-distorted versions of itself in order to obtain more accurate information about target motion or to better separate the target from a reverberatory environment. Cross correlation sacrifices signal-to-noise ratio for the sake of other benefits. For example, a slight decrease in maximum receiver response can sometimes be traded for better velocity resolution. The trade-off between maximum receiver response and other desirable system properties can be expressed by the formation of a signal-to-interference ratio.

Signal filter design by signal-to-interference ratio maximization can result in sonar waveforms that resemble certain dolphin signals. The purpose of these dolphin waveforms can then be interpreted, and some tentative conclusions about dolphin signal processing can be deduced.

If a real, wide-band sonar signal $u(t)$ is reflected from a planar target traveling at velocity v_{T}, then the energy-normalized echo is written $s^{1/2}\,u[s(t+\tau)]$. The doppler scale factor s equals $(1 + v_{\mathrm{T}}/c)/(1 - v_{\mathrm{T}}/c)$, where c is the speed of sound. The translation variable τ describes the time delay experienced by the signal from transmission to reception (*1*). If the echo is processed by a linear filter with impulse response $v(-t)$, then the filter output is

$$\chi_{vu}{}^{\mathrm{WB}}\,(\tau, s) = s^{1/2} \int\limits_{-\infty}^{\infty} v(t)\,u[s(t+\tau)]dt \qquad (1)$$

$\chi_{vu}{}^{\mathrm{WB}}(\tau, s)$ is called the wide-band uncertainty function of the signal-filter pair $u(t)$, $v(t)$. $[\chi_{vu}{}^{\mathrm{WB}}(\tau, s)]^2$ is known as the wide-band cross-ambiguity function.

If a target is surrounded by an array of spurious planar reflectors (clutter) at various ranges and velocities, then the distribution of the unwanted reflectors can be written $p\,(\tau, s)$, where τ and s are measured relative to the desired echo. The target return is then written simply as $u(t)$, and $p\,(\tau, s)$ is a probability distribution function describing the clutter. If $p\,(\tau, s)$ were concentrated at $s = 1$ and $\tau = \tau_0$, for example, then the clutter would consist of a single unwanted reverberation received τ_0 seconds after the target echo.

The power of the filter response to the desired signal (the reflection from the target at $\tau = 0$, $s = 1$) is proportional to $[\chi_{vu}{}^{WB}(0, 1)]^2$, while the expected power of the response to clutter (2) is

$$\int_{0}^{\infty}\int_{-\infty}^{\infty} p(\tau, s) \cdot [\chi_{vu}{}^{WB}(\tau, s)]^2 d\tau\, ds$$

In addition to signal and clutter returns, there is always a certain amount of additive noise that would be received even if no signal were transmitted. If the expected noise power per unit frequency interval is a constant $(N_0/2)$ for all frequencies, then the expected filter response to the noise (2) is

$$(N_0/2) \int_{-\infty}^{\infty} [v(t)]^2 dt$$

By defining interference as the expected sum of system response to noise and to clutter, a signal to interference ratio (SIR) can be written (2–4) as shown in Fig. 1, where E_s is signal energy and E_c the total energy of clutter returns.

An optimal signal-filter pair is defined as one which maximizes SIR. Given a particular clutter distribution $p(\tau,s)$, along with E_s, E_c, and $N_0/2$, an optimal signal and filter can be found by using a computer (2–4). In order to utilize a computer, however, it is necessary to write the signal and filter functions in terms of a sum of orthonormal components,

$$u(t) = \sum_{i=1}^{N} a_i \phi_i(t)$$
$$v(t) = \sum_{i=1}^{N} b_i \phi_i(t) \qquad (2)$$

where

$$\int_{0}^{T} \phi_i(t)\phi_j(t)\,dt = \begin{cases} 1, & i = j \\ 0, & i \neq j \end{cases} \qquad (3)$$

In Eq. 3 it is assumed that the signal is time limited to the interval [0, T].

It is possible to simulate a clutter distribution $p(\tau,s)$ in order to design a signal with certain resolution properties (5). A velocity resolvent signal, for example, has a very small filter response for $s \neq 1$, compared with the maximum response $[\chi_{vu}(0, 1)]^2$. A velocity resolvent signal can be derived by placing clutter uniformly along the s-axis of the τ, s plane (except at the point $s = 1$).

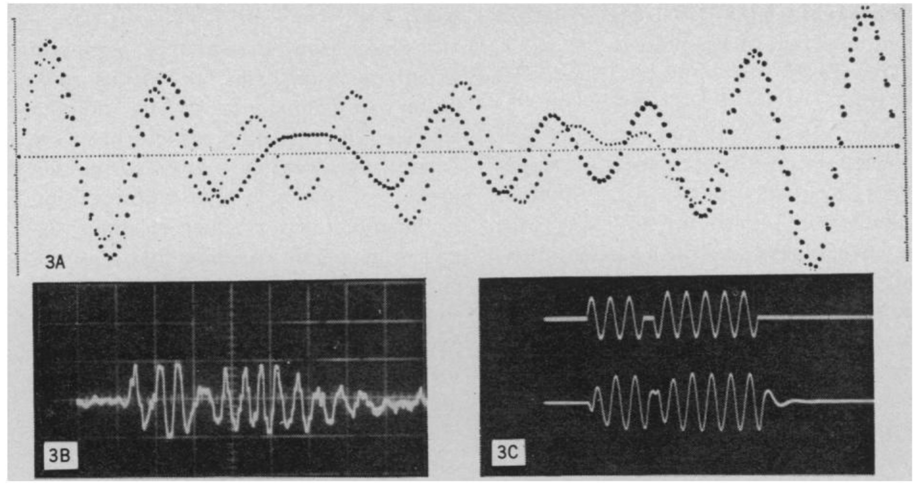

Fig. 3. (A) Another computer-derived signal-filter pair for optimal velocity resolution. Heavy dots denote the signal $u(t)$; light dots denote $v(t)$, the time-reversed filter impulse response. (B) A signal used by one of two dolphins that had been newly introduced to a tank. Time scale is 2 msec per large division. (C) Top signal is a sinusoid with discontinuous amplitude. Bottom signal is a band-pass version of the above waveform.

Maximization of the SIR for such a contrived clutter distribution would yield a signal-filter pair such that $[\chi_{vu}(0, s)]^2$ was small for most values of $s \neq 1$.

A computer maximization of SIR for clutter distributed uniformly in s has been accomplished. The orthonormal components $\{\phi(t)\}$ consisted of five time-limited sine functions (6). Two resulting signal-filter pairs are shown in Figs. 2A and 3A, and are associated with the same value of SIR. The existence of two solutions indicates that waveform pairs which maximize SIR are not necessarily unique. The problem is complicated by the existence of many waveform pairs that provide local maxima of the SIR. Out of several such solutions, the waveforms given here provide the largest value of SIR. There is no guarantee, however, that these waveforms represent a global maximum. The waveforms in Fig. 2A are plots on [0, T] of $u(t) = .172 \sin(3\pi t/T) + .408 \sin(11\pi t/T) + .544 \sin(15\pi t/T) + .608 \sin(17\pi t/T) - .373 \sin(18\pi t/T)$; $v(t) = .140 \sin(3\pi t/T) + .434 \sin(11\pi t/T) + .498 \sin(15\pi t/T) + .598 \sin(17\pi t/T) - .432 \sin(18\pi t/T)$. The waveforms in Fig. 3A are pictures of $u(t) = .483 \sin(13\pi t/T) + .129 \sin(14\pi t/T) + .595 \sin(15\pi t/T) - .243 \sin(16\pi t/T) + .581 \sin(17\pi t/T)$; $v(t) = .492 \sin(13\pi t/T) - .314 \sin(14\pi t/T) + .367 \sin(15\pi t/T) + .023 \sin(16\pi t/T) + .724 \sin(17\pi t/T)$ (7).

Since clutter is likely to be distributed in range as well as velocity, it would seem that range clutter, as well as clutter at $\tau = 0$, should be taken into account. The inclusion of range clutter, however, is not really necessary. The cross-ambiguity functions of the illustrated solutions reveal that for $0.98 \leq s \leq 1.02$,

$$\max_{\tau} [\chi_{vu}{}^{WB}(\tau, s)]^2 \approx [\chi_{vu}{}^{WB}(0, s)]^2$$

In other words, moving targets with velocities less than about 35 miles per hour are not likely to be confused with stationary targets at a different range. The signals' cross-ambiguity functions thus indicate that there is little to be gained by including range clutter at $\tau \neq 0$. If range clutter were added, different waveforms would result. Such waveforms would needlessly sacrifice signal-to-noise ratio and doppler resolution if targets of interest travel at speeds less than 35 miles per hour (30 knots) (8).

A narrated tape recording of dolphin (*Tursiops truncatus*) echolation signals was supplied by D. K. Caldwell (University of Florida, St. Augustine). The recording contained many different waveforms. Occasionally, however, a specific pulse shape was repeated many times with relatively little variation. One such situation was observed when two young females had been newly introduced to a tank. Typical waveforms are shown in Figs. 2B and 3B. The illustrated signals were produced as isolated waveforms (rather than in a train of closely spaced pulses). The signals have substantially longer time durations than are usually associated with dolphin echolocation (9, 10). Waveforms having such long duration have, however, been observed by Ayrapet'yants *et al.* (*11*), who classified them as echolocation pulses.

The waveforms in Figs. 2B and 3B are similar to the velocity resolvent signals derived by SIR maximization.

Velocity-sensitive echolocation waveforms are well suited to a situation characterized by (i) unfamiliarity with the environment and (ii) a second (moving) animal in the tank. With no information about environmental reverberation, a reasonable way to detect a moving target in stationary clutter is to use a waveform that recognizes the target by its motion. In radar theory (*12*), such a strategy is commonly called moving target indication.

A laboratory simulation of the dolphin waveforms can be accomplished by band-pass filtering a time-gated sinusoid. The bottom signals in Figs. 2C and 3C were obtained by band-pass filtering the waveforms immediately above them. In order to simulate the waveform of Fig. 2B, the sinusoid of Fig. 2C (top signal) must have a frequency of $f_0 = 1$ khz and be band-pass filtered with high- and low-frequency cutoffs $f_H \approx 2$ khz, $f_L \approx 0.8$ khz, respectively. For Fig. 3C, $f_0 = 0.86$ khz, $f_H \approx 3.43$ khz, and $f_L \approx 0.62$ khz.

It is interesting to compare the above frequencies with the frequency range that dolphins actually have at their disposal. According to Johnson (*13*), *Tursiops* is capable of utilizing frequencies between $f_L \approx 0.1$ khz and $f_H \approx 150$ khz. Most of the signal energy in Figs. 2B and 3B is therefore restricted to a comparatively narrow band. It is the *ratio* of bandwidth to carrier (centroid) frequency, however, that is important to deciding whether a signal is narrow band or wide band (*6, 14*). By such a criterion, the dolphin signals are extremely wide band. Because of the large bandwidth-to-carrier frequency ratio, the doppler effect must be described by a compression factor s rather than by a frequency shift.

The reason for the dolphins' use of such a narrow frequency range is an open question. A possible explanation is that the signal is meant to detect objects at comparatively large distances. Because attenuation in water increases with frequency, a low-frequency waveform with small bandwidth is most likely to retain its structure and strength over long distances. Since the maximum output of a correlation processor is proportional to echo energy, a signal with comparatively long time duration is also to be recommended for long-distance propagation (if correlation is used).

It has been shown that optimum wide-band waveforms for velocity resolution are similar to certain dolphin signals. The optimum waveforms were derived by assuming a cross-correlation processor, that is, a filter whose output is the integrated product of input signals with a time function that may not be identical to the waveform that is sought. The resemblance between Figs. 2A and 2B, and 3A and 3B, would seem to suggest that *Tursiops truncatus* uses a generalized form of correlation processing. Similar evidence, for autocorrelation processing, has been found for the little brown bat (*Myotis lucifugus*) (*6, 15*) and the red bat (*Lasiurus borealis*) (*6*).

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References and Notes

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8. If constraints to an optimization problem are imposed one at a time (adding more constraints only when necessary), the solutions to a comparatively unconstrained problem will sometimes be satisfactory from the viewpoint of the unwritten constraints. Such situations can occur because of implicit constraints imbedded in the formulation, such as the description of all waveforms in terms of a given incomplete set of basis functions.
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Fate of Air Pollutants: Removal of Ethylene, Sulfur Dioxide, and Nitrogen Dioxide by Soil

Abstract. *The ultimate sink for many air pollutants is unknown. Data are presented here in support of the idea that reaction with soil, through microbial or chemical means, can remove ethylene, other hydrocarbons, sulfur dioxide, and nitrogen dioxide from the air.*

Large quantities of ethylene, an air pollutant and plant hormone, are produced in the United States each year. Table 1 presents data on the relative amounts of ethylene produced by natural sources and human activities. In

Table 1. Ethylene emissions from major sources in the United States, 1966.

Source*	Quantities utilized ($\times 10^6$ tons)	Emission factor†	Ethylene emission ($\times 10^6$ tons)
Coal combustion	486	0.001	0.5
Fuel oil combustion	235	.001	.2
Motor fuels			
Gasoline	280	.05	14.0
Diesel	27	.008	0.2
Jet	28	.001	.03
Refuse burning			
Good incineration	8	.000025	.0
Poor incineration	16	.015	.2
Open burning	56	.001	.06
Ethylene production from industrial leakage‡	11.2	.001	.01
Vegetation§	2000	.00001 ‖	.02

* Values for sources except leakage from industry obtained from (*8*). † Estimated values based on information from (*9*). ‡ From (*9*). § Assumes a ton of vegetation per acre and an area of 3×10^6 square miles for the United States. ‖ Calculated on the assumption of 0.5 nl of ethylene produced per gram (fresh weight) per hour, 24 hours a day, 365 days a year.