Counterintuitive Results in Underwater Acoustic Communications

Daniel Rouseff

Abstract Underwater wireless communication using acoustic signals is a difficult problem and progress in finding robust solutions has been disappointing. Methods employed successfully in terrestrial wireless communications have not always transitioned successfully to underwater scenarios. An engineer's intuition developed in solving the terrestrial problem may actually become a hindrance to solving the underwater problem. In the present work, several seemingly counterintuitive experimental results are examined: communications performance can be better when the range is longer rather than shorter, when the sea surface is rough rather than calm, when the bathymetry is undulating rather than flat. Physics-based explanations for the observed results are developed. A physicist's intuition, however, also may fail when trying to develop useful models. A seemingly counterintuitive fact is that acoustic paths that undergo incoherent reflection from a rough sea surface can be shown experimentally to be useful for coherent communications. The requirements for a proper physics-based model are sketched.

Keywords Underwater acoustic communications · Rayleigh parameter · Equalization

1 Introduction

In 2000, Kilfoyle and Baggeroer [1] published a comprehensive review of progress in underwater acoustic communications since 1982. They noted how early work had concentrated on incoherent methods, but since the early 1990s there had been

D. Rouseff (✉)
Applied Physics Laboratory, University of Washington, Seattle, WA 98105, USA
e-mail: rouseff@apl.washington.edu

D. Rouseff
Northwest Electromagnetics and Acoustics Research Laboratory,
Department of Electrical Engineering, Portland State University,
Portland, OR 9720, USA

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numerous publications on coherent systems. Coherent systems make better use of the available bandwidth and so are capable of much higher data rates. With coherent modulation and complex receiver structures, systems deployed at sea had achieved a data rate time's range product of nearly 40 km $\times$ kbit.

While research in underwater acoustic communications has certainly advanced since 2000, it is not unfair to say that the results have been somewhat disappointing. This is not to say that there has not been progress in equalizer design, or that there have not been several high quality scientific experiments. What has been lacking, though, is robustness; a prototype system might work well on one day or at one location, but then fail on another day or at another location. This lack of robustness has hampered transition from prototype systems used in demonstration experiments to viable commercial products.

The reasons why underwater acoustic communication is so difficult are well known: the communications channel is lossy, inhomogeneous, rapidly varying, and vulnerable to Doppler shifts [1]. While these difficulties are well known in the abstract, when they actually manifest themselves in experimental data the results are still often surprising, seemingly counterintuitive: communication performance can get better and be more stable as the source–receiver distance is increased, small changes in source or receiver depth can have a major effect on performance while changing the transmission power can have no effect at all, acoustic paths that are incoherently scattered by a rough sea surface can still be useful for coherent communication.

The premise of this paper is that many of these seemingly counterintuitive results have well-understood physical bases and can be adequately modeled. By understanding these bases, one can develop a better intuition, develop better performance prediction models, and perhaps, ultimately design better communications systems.

This paper reviews seemly counterintuitive results from three experiments in which the author participated: the 2000 Puget Sound Passive Phase Conjugation Experiment [2–5], the 2003 Kauai Experiment (KauaiEx03) [6–8], and the 2009 Cooperative Array Performance Experiment (CAPEx09) [9, 10]. In each case, relatively simple, physics-based models can reproduce the experimental results. Even seemingly complicated effects like scattering from the spatially rough and temporally varying sea surface can yield to fairly simple modeling efforts.

2 The Rayleigh Parameter

Oceanographic processes operate over a wide range of spatial and temporal scales. The oceanographic process with particular relevance for acoustic communication is waves on the sea surface. This is true for two interrelated reasons. First, the height of the waves can be large compared to the acoustic wavelength. As a result, the phase of a surface-reflected path will depend strongly on where the sea surface wave is in its cycle. This is important for coherent communications techniques where a signal's information is encoded in its phase. Second, the period of the surface wave is often comparable to the duration of a communications packet. The acoustic channel cannot therefore be regarded as stationary over time scales on the order of the wave period. To develop an intuition for representative numbers, a fully developed sea driven by a 10 m/s wind has waves with a dominant period of about 7 s. An equalizer would have to adapt to an environment changing at these time scales.

A useful quantity for describing acoustic paths that interact with the sea surface is the Rayleigh parameter. Assume that there are multiple acoustic paths between a source sending a communications signal with center frequency f and a receiver. The Rayleigh parameter for a path incident on the rough sea surface at grazing angle θ is

$$P = 2k\sigma \sin(\theta) \quad (1)$$

where $k = 2\pi f/c$ is the acoustic wavenumber with c the sound speed in the water at the air–sea interface, and σ the standard deviation of the height of the waves.

As observed by Eckert, a Rayleigh parameter $P = 2$ is sufficient to cause a loss in the coherent reflection of 15 dB [11]. This energy is not actually lost, but rather redistributed into the incoherent field scattered off the sea surface. Figure 1 is an example showing the effects of incoherent reflection off the sea surface. Shown is the time-evolving channel impulse response (CIR) for the KauaiEx03 experiment at a range of 1 km. Specifically, linear frequency-modulated chirp signals, 50 ms in

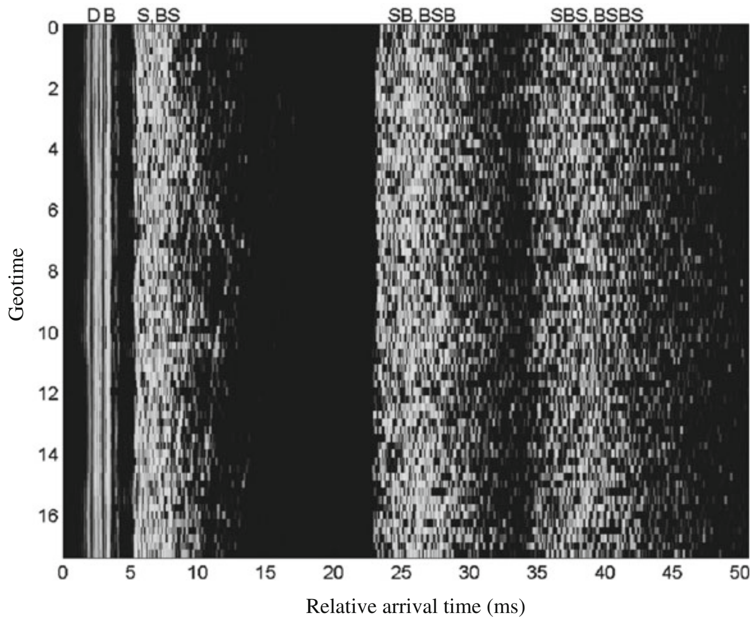

Fig. 1 Time-varying channel response. Example is from KauaiEx03 at 1 km range from transmitter [2]. Direct (*D*), bottom-bounce (*B*), surface-bounce (*S*), and multiple-bounce paths are labeled. The time spread for each path reflected off the sea surface is consistent with that having a Rayleigh parameter greater than one. The dynamic range is 25 dB

duration and spanning the 8–16 kHz band of the communications sequences, were transmitted every 250 ms for 20 s. The output of a matched filter for consecutive chirps is then stacked and displayed as shown. Because the acoustic source was located near the seabed, the acoustic arrivals come in pairs. The first pair, with the direct (D) and bottom-bounce (B) paths, does not interact with the sea surface. These paths show little time spread and are stable over the 20 s. The second pair has the surface-bounce path (S) and the path that reflects first off the bottom and then the sea surface (BS). This second pair of arrivals is less distinct than the first. Using environmental data collected concurrently, the Rayleigh parameter for this pair was shown to be 4.4 [8]. The interpretation is clear: acoustic paths that get reflected off the sea surface and have a large Rayleigh parameter get smeared out in time. It follows that the larger the Rayleigh parameter, the more pronounced this smearing becomes. This can be observed in Fig. 1 for later arriving paths labeled as the (SB, BSB) pair and the (SBS, BSBS) pair. Note that beginning with the latter pair, the paths have multiple reflections from the sea surface. From the standpoint of Eq. (1), later arriving paths reflect off the sea surface at a steeper angle and so have larger Rayleigh parameters. For the (SB, BSB) pair, $P = 8.3$ and for the (SBS, BSBS) pair, $P = 10.6$.

3 Communications Performance

Intuitively, one might expect that acoustic paths that have undergone incoherent reflection and have $P > 1$ could not then be used for coherent acoustic communication. The experimental observation is to the contrary: some paths that have undergone incoherent reflection are, in fact, useful for coherent communications. What limits communications performance is not necessarily the time spread in the CIR like what is evident by looking at a horizontal slice through Fig. 1. If the time spread was unchanging, an equalizer could be easily designed to compensate for it. Instead, it is the time variability in the CIR as is observed along a vertical slice in Fig. 1 that limits performance. The later arriving paths that have the largest Rayleigh parameters and are the most time spread are also the most rapidly varying. For the particular equalizer used in KauaiEx03, the best performance at range 1 km was observed when all paths with at most one reflection off the sea surface were retained and treated as useful signal rather than interference [8]. This optimal performance could only be achieved, though, when the parameters of the equalizer were updated sufficiently often. If an equalizer can adapt rapidly enough to changes in the environment, incoherently reflected paths can be used for coherent communications. If an equalizer cannot adapt rapidly enough, then the incoherently reflected paths act as inter-symbol interference.

Intuitively, one might expect communications performance to improve by transmitting louder and thereby increasing the signal strength. This is not necessarily correct. In this regard, it is important to distinguish between additive noise and inter-symbol interference. In principle, one could indeed combat additive noise simply by transmitting louder. Transmitting louder, however, does not defeat interference from incoherently reflected paths that are uncompensated. By transmitting louder, both the desired signal and the undesired interference are magnified with no resulting improvement in communications performance. For the linear equalizer used at CAPEx09, it was shown how doubling the transmit voltage had no effect on communications performance at range 1 km [10]. For the nonlinear equalizer used at KauaiEx03, individual surface-reflected paths were either signal or interference depending on the equalizer's adaptation rate [8].

It is sometimes possible to position a communications system in such a way as to have the ocean environment help rather than hinder operations. This was illustrated by data collected during the 2000 Puget Sound Experiment [2]. The source and receiver were separated by 1.6 km, both in water 30 m deep. The bathymetry in between was rugged with a crevasse 80 m deep. Communications performance was error free over 5 s without updating the equalizer. A ray trace suggested that the crevasse was serving to strip out the acoustic rays traveling with steep grazing angles and so large Rayleigh parameters. The result was an extremely stable communications channel.

Just as the bathymetry was important in Puget Sound, the sound speed profile had a significant effect on communications performance in CAPEx09. Warm surface-layer water overlaid much cooler water below causing a sharp sound speed gradient. Figure 2a shows the profile where the sound speed contrast between the top and bottom is almost 50 m/s. The result shown in Fig. 2b is strong refraction of the acoustic rays emanating from the source at a depth of 30 m. Figure 2b also highlights four ranges where the receiving arrays were positioned when communications sequences were transmitted: 100, 250, 500, and 1 km. The sharp sound

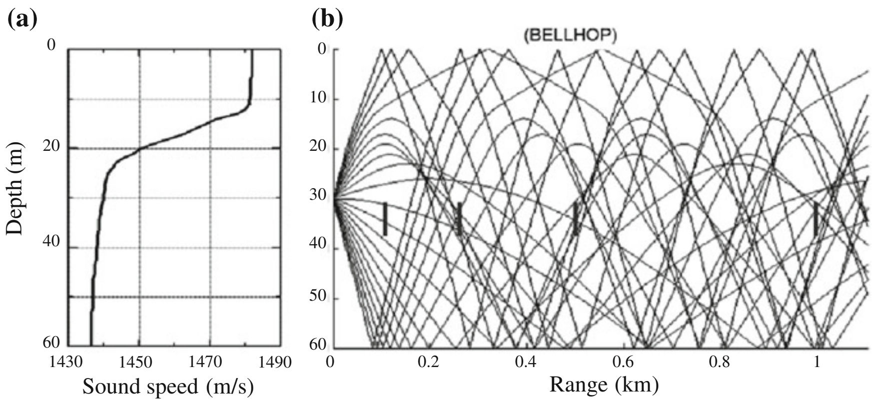

Fig. 2 CAPEx09 propagation environment [10]. **a** Measured sound speed profile; **b** Experimental geometry. Shown are the calculated acoustic rays from the transmitter at a depth of 30 m. Shown to vertical scale are the acoustic receiving arrays at the four ranges (100, 250, 500, 1 km) emphasized in the processing

speed gradient caused results to vary with range in ways that at first seem unexpected: performance at 250 m was better than at 100 m, and performance at 1 km was better than at 500 m. The performance also became more stable as the range increased with less frequent updating of the equalizer required.

The ray trace in Fig. 2 helps explain the range- and depth-dependence observed in communications performance. At 100 m, direct, surface-bounce, and bottom-bounce acoustic paths are observed while the array is positioned near a caustic at 250 m and many strongly refracted direct paths are incident. The strongly refracted paths avoid interaction with the rough surface above resulting in better communications performance. EigenRay calculations at a range of 500 m show that the bottom of the array will see a direct path while the top of the array will not. Evidently, the direct paths are better for communications as a two-channel receiver at the bottom of the array had a bit error rate of only 0.9 % while the top of the array had 2.3 % [10]. At range 1 km, there are no direct paths to any part of the array and each arrival has at least one reflection from the bottom. Rays get trapped in a duct and avoid the rough surface. The result is a stable channel where only infrequent updating of the linear equalizer is required.

4 Performance Prediction Modeling

Kilfoyle and Baggeroer [1] wrote "acoustic propagation models tailored to telemetry applications are sorely needed" and "captur[ing] the time variability of the channel is a necessary component of these models." While the detailed development of such a propagation model is beyond the scope of this short communication, certain key aspects can be outlined.

As argued above, the dynamic rough sea surface is responsible for the most rapid time variability in the acoustic channel. Capturing this variability in a model would seem a daunting task, but several factors make it easier than might initially be thought. For a communications channel, forward scattering from the sea surface is much more important than backscattering. Also, as observed at KauaiEx03, these forward-scattered paths are usually characterized by $P > 1$. Forward scattering configurations with large Rayleigh parameters fall into the regime where the classical Kirchhoff approximation for rough surface scattering is valid. Furthermore, experiments show that the update interval of an equalizer must be much less than the surface wave's dominant period when surface-interacting paths are to be retained as useful signal. Since it is necessary then to model the scattering process over only time scales short compared to the surface wave period, the calculation simplifies considerably. In the regime of interest, one can show that detailed features of the sea surface like capillary waves or those causing the wind direction are of little consequence. One finds that a simple criterion for the usefulness of an acoustic path that bounces off the sea surface is that

$$\frac{(\text{Rayleigh parameter}) \times (\text{total time spread})}{\text{surface wave period}} \ll 1 \tag{2}$$

In this context, the total time spread includes multi-path spreading, the update interval for the equalizer, and the time window over which the equalizer parameters are estimated. The total time spread is typically much less than the surface wave period implying that Eq. (2) can be satisfied even when the Rayleigh parameter is large compared to one. Detailed calculations of the mean-squared-error for an equalizer's soft demodulation output are in excellent agreement with KauaiEx03 observations at both 1 and 2 km [12].

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