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Correlation

New Title: (6) A Pseudorandom Signal [redacted] Method for Underwater Acoustic [redacted] Studies, (1)

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(10) J. L. Stewart [redacted] W. B. Allen (11) 1966 (12)
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A Pseudorandom Signal Correlation Method for Underwater Acoustic Studies,

It is the purpose of this paper to present the method of pseudorandom signal (pseudonoise) correlation measurements and to demonstrate theoretically and experimentally that the results are different from and unpredictable from those obtained by employing the usual filtering and detection of impulsive (explosive) or single frequency signals. Since the crosscorrelation of the received underwater acoustic signal with that transmitted is a measure of the feasibility of signal processing techniques employing coherent time averaging, these measurements are of practical importance. A study of such correlation coefficients as a function of the averaging time frequency, and bandwidth of the signal and of the locations and motions of the source and receiver will lead finally to a determination of those properties of the medium and its boundaries which perturb underwater acoustic propagation.

Two earlier experiments of a similar nature should be mentioned. In air acoustics, Goff[1] crosscorrelated the signals received at one point in a machine shop with the signal recorded next to a particular machine to identify the component due to that particular machine at the distant point. In radar, Lincoln Laboratory's Venus ~~shoe~~ echo ranging experiment[2] employed a series of single frequency pulses 'interval modulated' by a pseudorandom sequence generator and correlated the envelopes of the transmitted and returned pulse trains to suppress the range ambiguity.

[1] K.W. Goff, J. Acoust. Soc. Am. 27, p. 223-246 (1955).

[2] R. Price, Science 129, p. 751-753 (1959).

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383 550

Since the system being presented determines the input-output cross-correlation of the ocean with a broadband pseudorandom signal as input, one might expect by the theorem of Weiner, Lee and Wiesner[3] that the result would be identical with the impulsive response of the ocean obtained by firing explosives and analyzing the received impulses in the same bandwidth. This would be correct if everything were stationary but when reflections from a moving surface or motions of the source or receiver in a nonhomogeneous medium are involved the results may be quite different. That is, the shot measures one sample of the changing impulsive response while the correlation measures its time average. Since the time averaged impulsive response is the Fourier transform of the single frequency response of the medium, one might also expect that the result of the pseudorandom signal correlation might be predictable from propagation studies made with long pulses of different single frequencies. This would be correct even if the situation of medium, boundaries and terminals were nonstationary; if all the different frequencies in the band could be observed simultaneously and if the phase spectra of the different frequencies were measured as well as their amplitude spectra. Since in practice only the power response at a few frequencies are measured and these at different times, the single frequency results cannot predict the correlation responses or coefficients for the broadband signals.

Woodward's signal ambiguity function[4] is the squared magnitude of the autocorrelation function with respect to both time and frequency displacement. From a study of the ambiguity functions of available waveforms,[5] it is easily seen that the pseudorandom (PR) signals of large time-bandwidth product are much superior to all other waveforms for our purposes. They alone permit

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[3] Y. W. Lee, Statistical Theory of Communication (John Wiley & Sons, 1960) p. 341-348.

[5] J. L. Stewart and E. C. Westerfield, Proc. IRE 47, p. 872-881 (1959).

4 PM Woodward Probability and Information Theory, with Applications to Radar, (McGraw Hill 1953) pp. ... 125

simultaneous high resolution of the received signals both in range and in Doppler. The PR waveforms, which are generated by shift register encoders[6] are even superior to sample signals from a real noise generator because all possible sequences of the shift register length occur once and only once before the whole sequence repeats. The PR signals can be completely reproduced with any desired time delay and time compression by a similar shift register encoder.

The correlator employed must be capable of continuous search over the region of uncertainty in both range and Doppler of the source. Two possibilities presently exist, a matched filter or a time compression correlator. The delay line time compressor (Deltic[7,8]) correlator system we employ uses infinite peak clipping. Clipping has been found to have many practical advantages such as eliminating dynamic range problems, permitting digital storage and shift register time delay techniques. The differences between polarity correlation and complete amplitude correlation are well known[9]. The variations in correlation output due to clipping, sampling, and lack of precise Doppler matching have been observed in the laboratory to be much less than the variations observed in the field which are thus presumably due to the motion of the source or of the medium.

The experiments are conducted by employing an experimental broadband transducer mounted on a submarine operating at sufficient depth to be out of surface wave action and running slowly at right angles to the sound path to produce a low and very constant range rate. The receiving hydrophone is

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[6] S.W. Golomb, L.R. Welch, and R.M. Goldstein, Jet Propulsion Lab Progress Report 20-389 (1959).

[7] V.C. Anderson, Harvard Acoustics Research Lab TM-37 (Jan 5, 1956).

[8] W.W. Scanlon and G. Lieberman, Proc. IRE 47, p. 910-920, (May 1959).

[9] J. J. Faran and R.H. Hills, Harvard Acoustics Research Lab TM-27 (Sept 15, 1952).

mounted on the continental slope close to the depth of the deep sound channel axis, as in Sofar. The PR signals transmitted are accurately clock driven and repeat every 41 seconds which is much longer than the duration of the sequence of significant arrivals observed. The received and reference signals, which have been heterodyned down to be close to zero frequency, are sampled at twice the signal bandwidth. The receive Deltic compresses and stores the latest 5000 samples of the received signal and correlates it continuously with a similarly compressed fixed set of 5000 samples of the reference signal in the reference Deltic. Since the two signals are heterodyned down with frequencies differing by 10 cps, the output of the correlator is an AC signal which is analyzed in a bank of eleven Doppler filters. The system thus searches continuously in range and Doppler with a time delay resolution which is the reciprocal of the signal bandwidth and a Doppler frequency shift resolution which is the reciprocal of the integration time, i.e. 0.01 seconds for the 100 cps bandwidth and 1/25 cps for the 25 second integration time we have employed. The reference PR signal generator is run faster or slower to match the Doppler of the received signal to center the display.

Figure 1 illustrates our records. It was made with a 760 cps carrier at a range of about 60 nautical miles in the middle of a storm with confused seas. Time is running from right to left. On the right are four unprocessed tenth-second pings which preceded the PR transmissions on the left. On the left are two adjacent Doppler output channels (#5 and #6) with the signal mostly in the central channel (#6) for the duration of the run. The records have been retraced to place the correlation peaks, which repeat every 41 seconds, adjacent to each other by omitting the blank parts of the record as indicated by the breaks in the base line. Thus the record represents about 20 minutes of PR transmissions. The linewidth resolution on the paper is about equal to the duration of one-tenth second pings but does not resolve the correlation functions with their 1/100th second resolution.

Since the Doppler channels are separated by 1/6th knot at 760 cps, the record indicates that the range rate of the source submarine was constant within 1/12 knot for 20 minutes which makes it an ideal platform for correlation studies. Of course, the surface, bottom, and thermal structure involved in the transmission path did change slowly during the experiment as the source submarine changed slowly in bearing and drifted slightly in range and to this must be attributed the observed variations.

We do not as yet know the calibrations or linearity of our system to any precision so we can not obtain absolute values but the relative values are of interest. When all of the power is in a single arrival, as happens occasionally in Figure 1, we obtain the highest correlation. The correlation of these main arrivals dropped slowly from the higher values to lower values in long periods of the order of several minutes. Most of this variation is to be associated with the build up of one or two other arrivals and is simply a clipper normalization effect. The curve of dots in Figure 1 is the sum of amplitudes of the two highest peaks of the observed multiple arrivals in the output of the correlator. The relative stability of the sum indicates that half of the time the total correlation is constant. Some of the residual variation is due to splitting between Doppler channels, but most of the variation must be due to perturbations of the medium or boundaries such as reflection off the surface or bottom.

The precursor about 1.2 seconds ahead of the main arrival is believed to have traveled by an almost purely refracted path with one less top to bottom skip than the main arrival, as is crudely suggested in the ray diagram at the top of Figure 1. It will be noted toward the end of the run that, while the main arrival appears frequently in the lower Doppler channel the precursor does so only once, although they both have comparable amplitudes in the central channel. This is evidence of a very small Doppler difference of the order of 1/12th knot between these two arrivals.

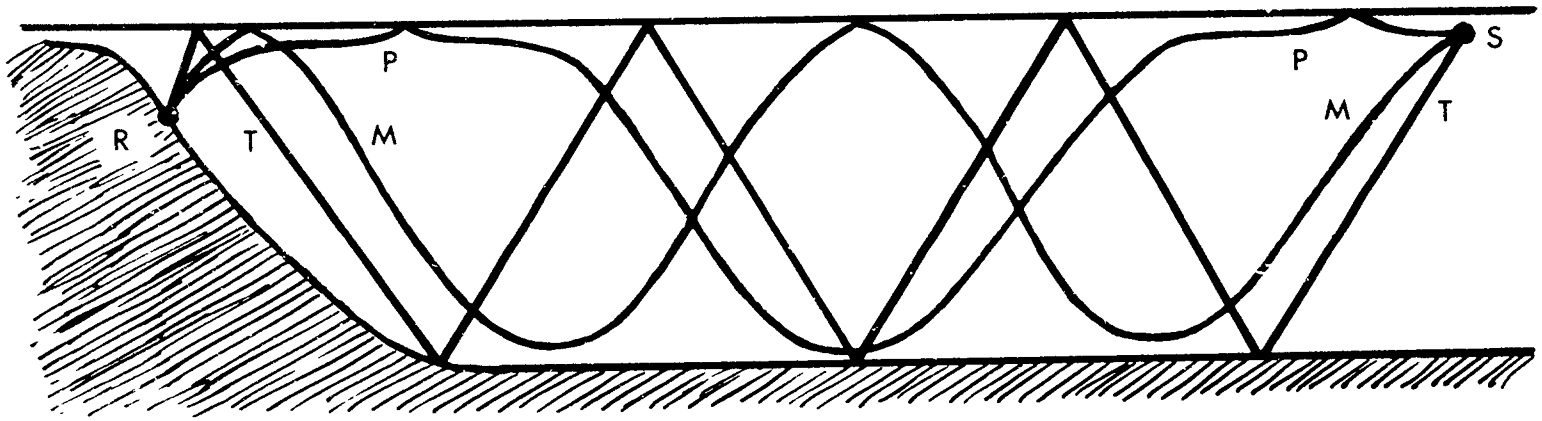
It will be noted that some tails marked T appear about 1.3 seconds after the main arrival in the pings. They presumably take one more top to bottom skip than the main arrival. While they appear with amplitudes comparable with the precursors in the ping records on the right; they do not appear in the correlator output on the left. Such uncorrelated tails can of course also explain why the sum of the correlator peaks is not conserved at all times.

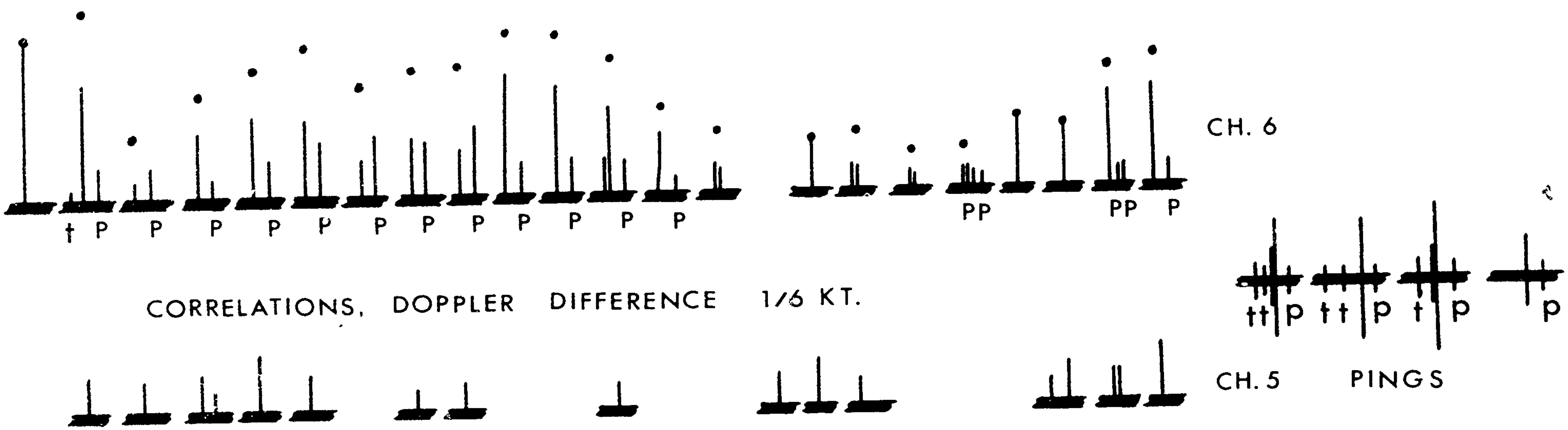
The obvious explanation of the missing tails is that they are more perturbed than the main arrival due to more reflections off the violently moving surface and at higher angles with the surface. Numerically the tails might have angles with the surface of 15° while the main arrivals have angles of 7°. Then the surface perturbation per reflection would be twice as much for a tail arrival as for the main arrival and could be greater than a half wavelength while the perturbation of the main arrival could be less than a half wavelength. Since the dominant period of ocean waves is known to be in the 5 to 10 second region[10] (continuous amplitude modulations of this period were observed on single frequency transmissions) and our integration time is 25 seconds, the tail correlations were wiped out. On this basis, we would

[10] H. O. Publication No. 603, "Practical Methods for Observing and Forecasting Ocean Waves," p. 48 (1955)

expect the tails to hold their correlation for integration times less than 5 seconds.

In our future plans, we hope to obtain the absolute calibration of the searching polarity correlator herein described. We also hope to employ it to synchronize the local PR generator with one of the arrivals. Then we can employ a nonsearching but completely analogue DC correlator to obtain absolute correlation coefficients as a function of averaging time. With these improvements, the pseudorandom signal (pseudonoise) correlation technique is expected to be a valuable tool for the study of the propagation of signals including those of underwater acoustics.





CORRELATIONS, DOPPLER DIFFERENCE 1/6 KT.