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Transverse Coherence of Low-Frequency Acoustic Signals

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Results are reported for a long-range deep-ocean experiment in which a 15-Hz CW source was towed transverse to the line of propagation to a single receiver. Reciprocity between transmitter and receiver roles is used to interpret the aperture formed by the moving source as a large receiving aperture. For the shallow source and bottom-suspended SOFAR-axial receiver employed, we observed the largest physical broadside apertures yet reported over which the received signal was coherent. The maximum observed coherent interval corresponds to a broadside aperture of 14 km at 1600 km range. The measured array gain for this aperture was 1.2 dB less than the maximum possible.

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TRANSVERSE COHERENCE OF LOW-FREQUENCY ACOUSTIC SIGNALS

INTRODUCTION

Determination of the size of the largest array whose performance is not seriously degraded by the medium is of significant naval interest. For low-frequency signals sufficiently large arrays have not been available for this purpose. We have attempted to interpret the signals emitted by towed CW sources and received at single fixed hydrophones so as to determine the limiting factors on the size of a low-frequency array. Reciprocity permits the roles of a source and a point receiver to be interchanged in the analysis. Once the factors controlling broadside and endfire array performance have been determined, the limitations on performance at any other bearing can be calculated [1]. A previous paper [2] considered the signals received from a 14-Hz CW source towed along the line of acoustic propagation. It suggested that the limiting factor on signal coherence in the direction of propagation was the deterministic multipath structure and not medium temporal and spatial variability. This report interprets the signals from a CW source towed transverse to the direction of propagation.

DESCRIPTION OF THE EXPERIMENT

In the final phase of a larger experiment a stable low-frequency CW source operating at 15 Hz was towed at a depth of 140 m and a speed of 7 knots for 46 hours (2766 min). The signals were received on an omnidirectional hydrophone of the Pacific Missile Impact Locating System near Midway Island. This SOFAR-axial hydrophone is suspended up from the bottom in deep water. The ship's track began 1650 km from the receiver and ended 1550 km from the receiver and the distance traveled along the track was 605 km (Fig. 1). The average water depth in the triangular area of Fig. 1 was about 5500 m. A typical sound-speed profile for this region showed a single channel (the SOFAR channel) with an axial depth of 850 m and a depth excess of a few hundred meters.

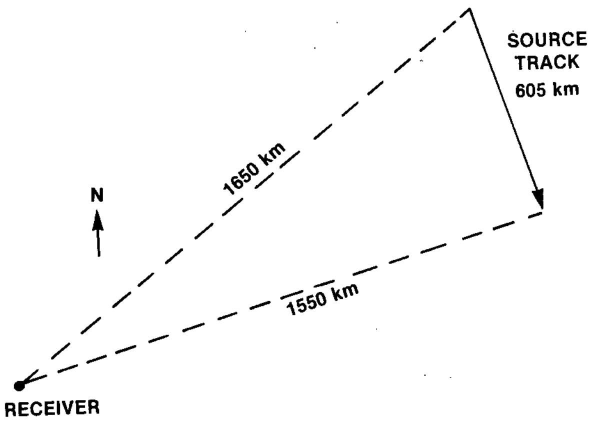

Fig. 1 — Source-receiver geometry

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The received signal was bandpass filtered, heterodyned to low frequency, low-pass filtered, and digitized at 30 samples per minute. The Hilbert transform of the digital signal was computed, and phase and amplitude were obtained every minute. If the signal at the hydrophone is represented in terms of phase and amplitude as $A(t)e^{i\phi(t)}$, then the digitized signal is

$$Re\left\{ A(t)e^{i[\phi(t)-\omega_0 t]} \right\} , \tag{1}$$

where ω_0 is the angular heterodyne frequency.

ANALYSIS

If the amplitude and phase of the received signal were known as a function of position, various statistical parameters could be computed which would characterize signal coherence and broadside array performance. To obtain a valid characterization, it is necessary to control, in particular, the error in received signal phase to a small part in π radians. This implies that at least the relative range error should be much less than 50 m for a 15-Hz signal. The Navy Navigation Satellite System available in this experiment did not meet this requirement.

Additional difficulties degraded the data. In the field, only one quadrature component (the real part in (1)) of the synchronous detector (lock-in amplifier) output was digitized. This is perfectly acceptable and causes no loss of information, provided the input reference frequency ω_0 never lies within the frequency bandwidth of the received signal. Unfortunately the ship's course and speed were not maintained to within the design tolerances of the experiment. The doppler shift varied sufficiently to move the frequency band of the received signal through the nearby reference frequency ω_0. More than half the data were seriously affected because of this.

As shown by Fig. 1, the ship closed in range by about 100 km during the experiment. Signal variability due to the deterministic range-dependent multipath structure was thereby inseparably mixed with the azimuthal variability under investigation.

Finally, some of the Musicians Seamounts lay in the triangular region of Fig. 1 and at times produced significant blockage. Such singular topographic effects, it was felt, should not be included in a description of the medium-induced limitations on aperture size.

As a result of these problems, it was decided that to attempt a statistical description of the field from these data would be fruitless. Instead, given that the ship was attempting to steer a straight course (no maneuvers were planned), it was decided to search for intervals in the data over which the signal appeared coherent. Such intervals probably correspond to spatial regions and temporal intervals over which the field was coherent and through which the ship steamed with constant velocity (speed and direction). By reciprocity these spatial regions can be interpreted as receiver apertures.

As will be shown, a simple indicator of coherence is phase linearity. The field of a simple harmonic point source whose position is fixed in a temporally stable but otherwise randomly inhomogeneous medium can be expressed as

$$A(\mathbf{x})e^{i[\phi(\mathbf{x})-\omega t]} ,$$

where the amplitude A and phase ϕ are functions of only position and ω is the angular frequency of the source. A distribution of N omnidirectional point receivers in a region with average sound speed c can be used to beamform by entering time delays and coherently summing the outputs [3]. Modeling the incoming waves as plane waves leads to time delays which are linear functions of the projected receiver position on the line of propagation. The signal crosscorrelation between hydrophones, which is needed to compute array gain, is

$$\rho_{ij} = \frac{1}{2} A(\mathbf{x}_i)A(\mathbf{x}_j)e^{i[\phi(\mathbf{x}_i)-\phi(\mathbf{x}_j)-(\xi_i-\xi_j)\omega/c]},$$

where ξ_i measures the projected position of a hydrophone on the line of propagation. When the departure of the phase from linearity is written as

$$\theta_i = \phi(\mathbf{x}_i) - \xi_i\omega/c + \phi_0 ,$$

where ϕ_0 is a constant, the signal crosscorrelation becomes

$$\rho_{ij} = \frac{1}{2} A(\mathbf{x}_i)A(\mathbf{x}_j) \cos (\theta_i - \theta_j).$$

If we assume that the amplitude is the same at each receiver and that the noise is uncorrelated between receivers, we obtain array gain as

$$AG = 10 \log \frac{1}{N} \sum_{i,j=1}^{N} \cos (\theta_i - \theta_j) . \qquad (2)$$

If the phase is a linear function of position, then θ_i is zero for all i and the array gain takes on its maximum value: 10 log N.

To calculate the extent of the phase linearity, a computer program was employed which determined the largest time interval centered at a given minute such that

$$\theta_i - \theta_j < \pi/2 \qquad (3)$$

for all i and j in the interval. Choosing $\pi/2$ as the maximum allowed nonlinearity guarantees that every term in the double sum of (2) has a positive sign. In determining θ_i in a time interval, that time-linear component optimum for the time interval under consideration was subtracted from the phase, as would be the case in an unfocused beamformer. Because no correction is made for the nonlinear phase variation inherent in an unfocused beamformer, the size of the largest interval over which the phase is linear is limited to 18 km for a constant-velocity ship track in this experiment. Although the array gain depends on the actual distribution of $\theta_i - \theta_j$, we can take the distribution to be uniform in the range 0 to $\pi/2$ radians and obtain an estimate of array gain from (2) as 10 log $2N/\pi$. This is down from the maximum possible array gain, 10 log N, by 2 dB.

RESULTS

The signal amplitude has been plotted in Fig. 2 as relative transmission loss versus time. Although intervals of high transmission loss may result from any of the aforementioned problems, intervals showing good signal level and low transmission loss correspond to periods in which topographic blockage was absent and the received signal was suitably located in the frequency bandwidth of the detector. Figure 3 is a plot of the largest time interval centered at a given minute over which the condition of (3) is satisfied. The interval is plotted as a function of its midpoint. The ordinate scale in Fig. 3 is in minutes on the left-hand side and in kilometers on the right-hand side. That is, the interval in minutes has been converted using the geometry of Fig. 1 into a broadside-aperture arc length in kilometers at 1600 km range. The maximum observed coherent interval was 69 min long. This corresponds to a broadside aperture of 14 km at 1600 km range. Figure 4 is a plot of phase minus a linear component selected for display purposes. The data of Fig. 4 contain the time interval which includes the largest peak in Fig. 3. Figure 4 shows that the interval from 504 min to 572 min is coherent in the sense of (3). Using the measured amplitude and phase, normalizing with respect to the mean intensity in the aperture, and assuming the noise is uncorrelated between hydrophones, we obtain the measured array gain for this 14-km aperture as 10 log 0.76 N, which is 1.2 dB less than the maximum possible.

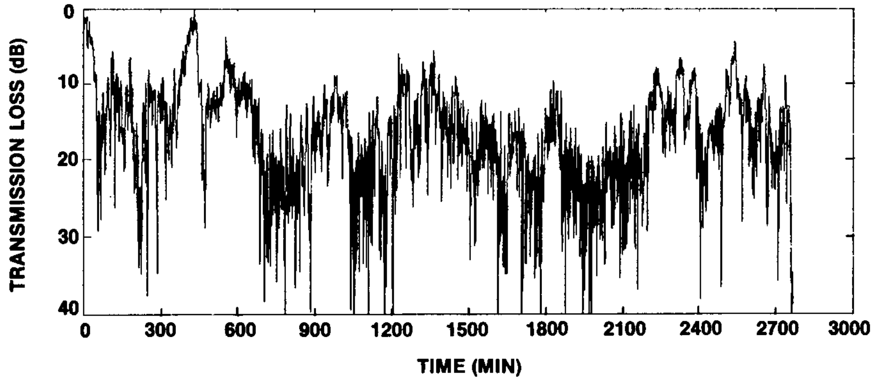

Fig. 2 — Transmission loss (dB relative to an arbitrary level)

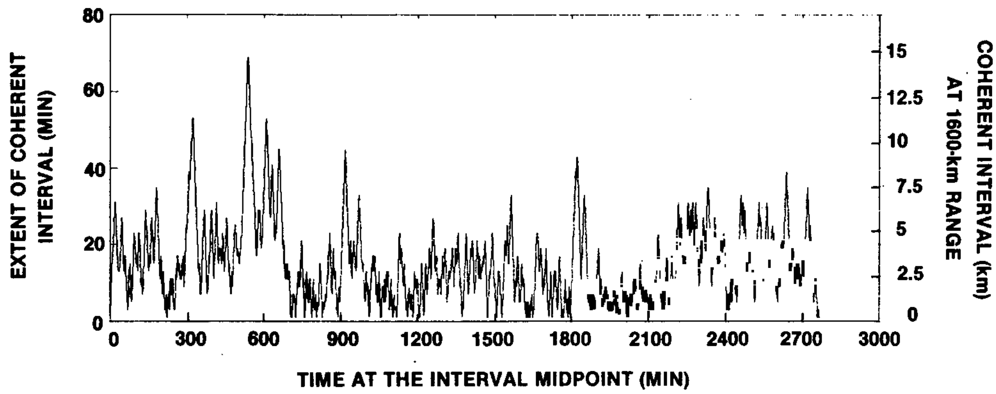

Fig. 3 — Largest interval, centered at a given minute, over which the signal is coherent in the sense of (3)

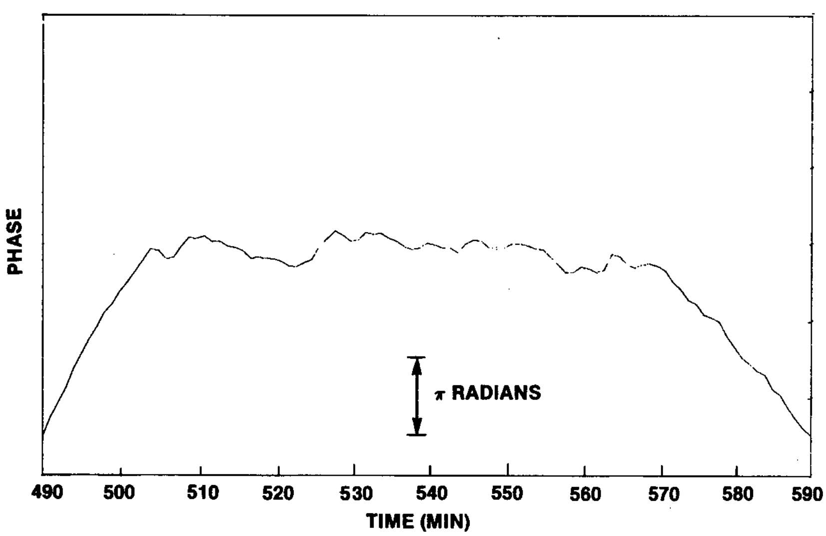

Fig. 4 — Phase of the digitized signal (radians) minus a linear function of time, plotted for a time interval that includes the largest peak in Fig. 3

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