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TRAVEL-TIME DIFFERENCES FROM A BROADBAND SOURCE FOR PAIRS OF SE--ETC(U)
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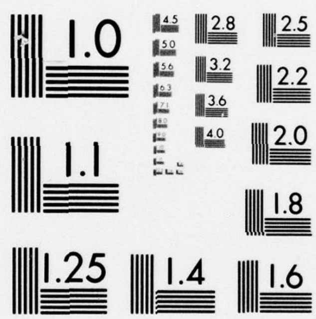
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Travel-Time Differences from a Broadband Source for Pairs of Sensors

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Section 1

INTRODUCTION

Given signals from two spatially separated hydrophones which receive energy from the same broadband source, it is possible to measure the travel-time difference from the source to those phones. The success in doing such a measurement is dependent on several practical factors:

- the extent to which the signal on the two phones is spatially coherent, and

- the bandwidth of the signal.

For the problem of interest here, the source will be within direct path range of the two receivers (which are no more than a few thousand feet apart) and so it will be assumed that the same signal is received on both phones and lack of coherence is not a problem. The significance of bandwidth will be discussed below.

The problem of interest, alluded to above, is that of establishing the travel-time difference as a function of time for a surface ship transiting past bottomed hydrophones. A formalism is developed in the next section which permits establishing this time difference from an analysis of the normalized cross covariance of the data from pairs of phones.

Section 2

RELATIONSHIP OF TRAVEL-TIME DIFFERENCES TO CROSS COVARIANCE

2.1 Some Basic Relationships

We begin by expressing the signal as received on a single phone from some number, M, of discrete sources as

$$x(t) = \sum_{i=1}^{M} a_i(t) \tag{1}$$

where $a_i(t)$ is the signal from the i^{th} source. The signal received by a second phone some distance from the first is, then,

$$y(t) = \sum_{i=1}^{M} a_i(t-\tau_i) \tag{2}$$

where the signal from the i^{th} source is delayed by some time τ_i from its arrival at the first phone. Several assumptions are implicit in Eqs. (1) and (2):

- there is perfect coherence between the two phones;

- all the sources of significant energy are discrete (we are interested in that part of the spectrum which is dominated by broadband noise from surface ships).

It will further be assumed that signals from two different sources are uncorrelated, which can be expressed here as

$$\langle a_i(t)a_j(t+\Delta)\rangle = \delta_{ij}R_i(\Delta) \tag{3}$$

where $R_i(\Delta)$ is the autocorrelation of the signal from the $i^{\underline{th}}$ source and the brackets denote statistical expectation.

It follows from Eqs. (1), (2) and (3) that the autocorrelation for x(t) and y(t) and the cross correlation between them are (assuming the processes are stationary)

$$R_x(\Delta) \equiv \langle x(t)x(t+\Delta)\rangle$$

$$= \sum_{i,j} \langle a_i(t)a_j(t+\Delta)\rangle$$

$$= \sum_i R_i(\Delta) \tag{4}$$

$$R_y(\Delta) \equiv \langle y(t)y(t+\Delta)\rangle$$

$$= \sum_{i,j} a_i(t-\tau_i)a_j(t-\tau_i+\Delta)$$

$$= \sum_i R_i(\Delta)$$

$$= R_x(\Delta) \qquad (5)$$

$$R_{xy}(\Delta) \equiv \langle x(t)y(t+\Delta)\rangle$$

$$= \sum_{ij} \langle a_i(t)a_j(t-\tau_j+\Delta)\rangle$$

$$= \sum_i R_i(\Delta-\tau_i). \qquad (6)$$

Because the signals, x and y, are acoustic pressures, they have zero mean and so the normalized cross covariance can be written directly as[1]

$$\rho_{xy}(\Delta) = \frac{R_{xy}(\Delta)}{(R_x(o)R_y(o))^{\frac{1}{2}}}$$

$$= \frac{\sum_i R_i(\Delta-\tau_i)}{\sum_i R_i(o)} . \qquad (7)$$

It will further be assumed that the processes, x and y, are ergodic so that the various correlation functions can be estimated from a sample time series:

$$R_x(\Delta) \simeq \frac{1}{T} \int_o^T x(t)x(t+\Delta)dt \tag{8}$$

$$R_y(\Delta) \simeq \frac{1}{T} \int_o^T y(t)y(t+\Delta)dt \tag{9}$$

$$R_{xy}(\Delta) \simeq \frac{1}{T} \int_o^T x(t)y(t+\Delta)dt. \tag{10}$$

For the case where $\Delta << T$, it follows from Eqs. (8), (9) and (10) that the correlation functions also can be estimated[1] from the Fourier transform of either a power density spectrum or a cross spectral density:

$$R_x(\Delta) \simeq F^{-1} [|S_x(\omega)|^2] \tag{11}$$

$$R_y(\Delta) \simeq F^{-1}[|S_y(\omega)|^2] \tag{12}$$

$$R_{xy}(\Delta) \simeq F^{-1}[S_x(\omega)S_y(\omega)^*] \tag{13}$$

where

$$S_x(\omega) \equiv F[x(t)]$$

$$S_y(\omega) \equiv F[y(t)]$$

F, F^{-1} and * denote the Fourier transform, the inverse Fourier transform and complex conjugation, respectively. Finally, note that the auto correlation functions $R_x(\Delta)$, $R_y(\Delta)$ and $R_i(\Delta)$ when evaluated for $\Delta = 0$ are estimates of the total intensity for the signals x(t), y(t) and $a_i(t)$, respectively.

For a broadband signal with an essentially flat spectrum of width Ω, the auto correlation function $R_i(\Delta)$ will be a function which peaks at $\Delta = 0$ and has a nominal width of $2\pi/\Omega$. So the expression $\sum_i R_i(\Delta-\tau_i)$, from the numerator of Eq. (7), might appear as shown in Fig. 1. In this stylized picture, it has been assumed that the widths of the R_i functions are comparable and the time delays are such that most of these peaks are separable. If the $i^{\underline{th}}$ peak is, indeed, distinguishable from the rest, then Eq. (7) evaluated at $\Delta = \tau_i$ is, approximately,

$$\rho_{xy}(\tau_i) \simeq \frac{R_i(0)}{\Sigma R_i(0)} \tag{14}$$

from which it is clear that at the time delay τ_i, the cross covariance is just the ratio of the intensity of the $i^{\underline{th}}$ signal to the total intensity on either of the phones. It is intuitively clear at this point that for the case of one nearby broadband source and many at substantially greater distances (and varied time delays), the nearby source should show up as a distinct peak in the covariance at a time delay which can be measured with some accuracy equal to or less than $2\pi/\Omega_i$. In section 2.3 below an estimate of what could be expected is made for a typical case of interest.

2.2 Compensation for Doppler Shift and Discrete Lines

Because of the short ranges involved for ships within direct path range of the phones, it is likely that a relative Doppler shift will exist which must be compensated before computing the cross correlation of the two phones. Because the cross correlation is computed from the cross spectral density, it is convenient to adjust for the relative Doppler shift in the frequency domain. Fig. 2 illustrates the way this shift has been implemented. Since the data are processed in digital form, one has N sample points of each spectrum which is bandpass filtered as shown. This spectrum is resampled by linear interpolation of the amplitude and phase to obtain N samples on the frequency shifted axis where

$$\omega = (1+\delta)\omega' .$$

The unshifted frequency is ω, the shifted frequency is ω' and δ is the fractional shift in frequency. To obtain the necessary out-of-band values along the ω' axis which extend beyond the last value on the ω axis, the unshifted spectrum is zero-filled as necessary. By shifting either $S_x(\omega)$ or $S_y(\omega)$, the two possible relative Doppler shifts (up or down) can be compensated.

The actual spectrum of a ship will look as shown in Fig. 3, containing both a broadband background and discrete lines. If a significant fraction of the total intensity is in the lines, then they can complicate the cross correlation function by the addition of discrete sinusoidal components, one for each line in the spectrum and having the frequency of that line. Accordingly, the formalism for constructing the cross correlation, $R_{xy}(\Delta)$, includes the capability to eliminate any strong line components from $S_x(\omega)$ and $S_y(\omega)$ prior to computing the cross correlation. This is accomplished by a sliding window which compares the amplitude value at its midpoint with the median value for the window (exclusive of the point being compared); if the amplitude of the tested point exceeds the median amplitude by more than a specified amount, it is replaced by the median amplitude.

2.3 An Estimate of What to Expect for a Case of Interest

Consider a case where the ambient spectral background has a level of 80 dBμPa/Hz in the absence of nearby ships. Given a nearby ship which has a radiated spectral level of 160 dBμPa/Hz, how far away (assuming spherical spreading along the direct path) could this ship be and still yield a peak in the normalized cross spectral density of at least 0.4? Assuming Eq. 14 to be an appropriate approximation for this case, we require

$$\frac{I}{N+I} \geq 0.4 \qquad (15)$$

where

$$10 \log I = 160 - TL$$

$$10 \log N = 80$$

and we want TL such that Eq. (15) is satisfied. This implies

$$TL \leq 81.4$$

or, assuming spherical spreading, that the range satisfies

$$r \leq 11 \text{ km}$$

Since the direct path range for a bottomed phone at a depth of 2 - 4 km is generally less than 11 km, this analysis suggests that any ship within direct path will result in an obvious peak in the cross covariance under the representative conditions given above.

Section 3

SUMMARY

As a step in tracking surface ships, a formalism has been developed to measure the time history of travel-time differences between pairs of phones by cross correlating on the broadband output of ships within direct path range of the phones. Provisions have been made for compensating relative Doppler shift and eliminating (when necessary) strong line components prior to computing the cross correlation. By assuming typical values for the ambient noise and the ship radiated level, it was shown that a ship within direct path range could be expected to yield a peak in the normalized cross covariance of at least 0.4. These algorithms have been incorporated in a computer code, as described in Reference 2.

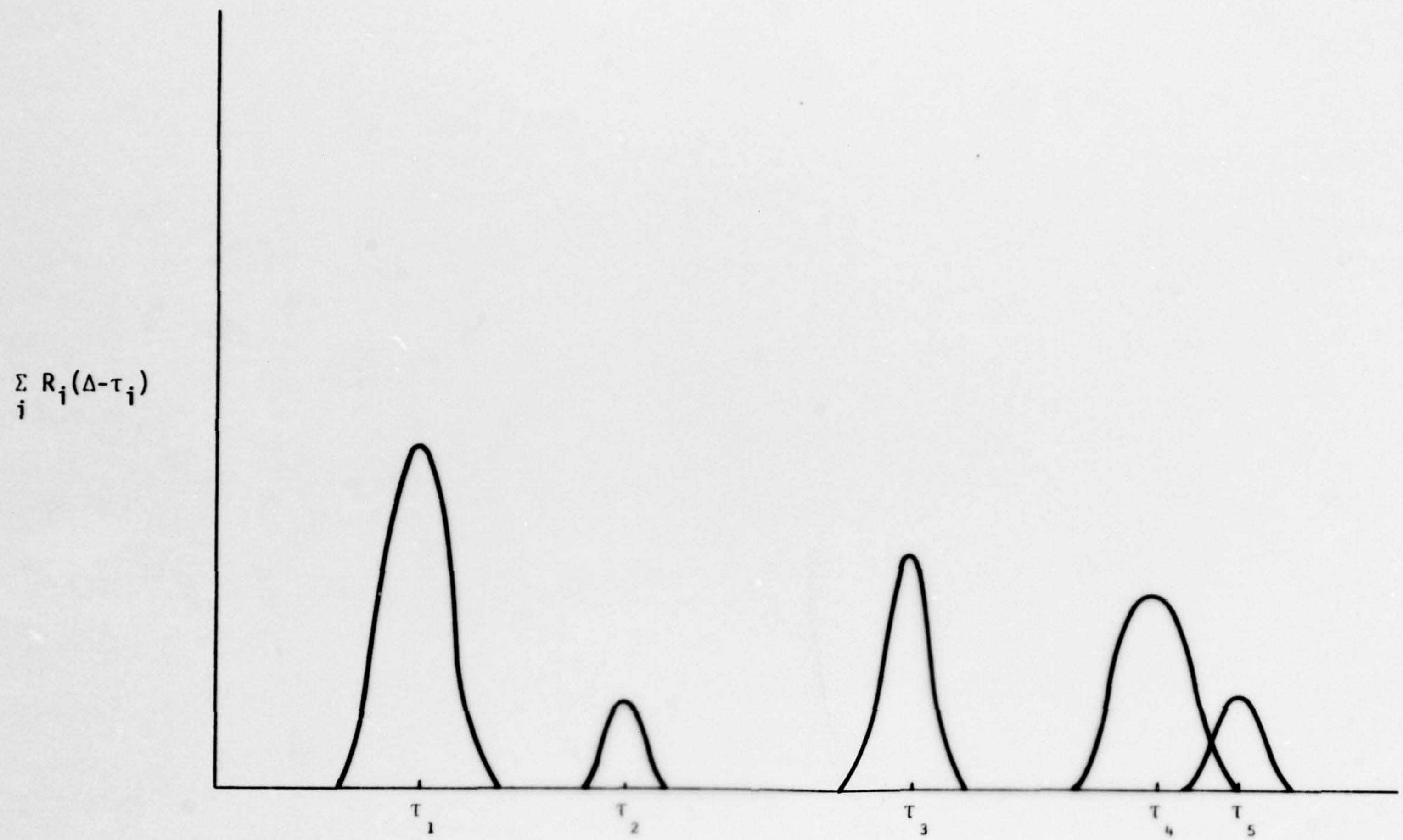

Figure 1. Stylized plot of numerator of cross covariance function

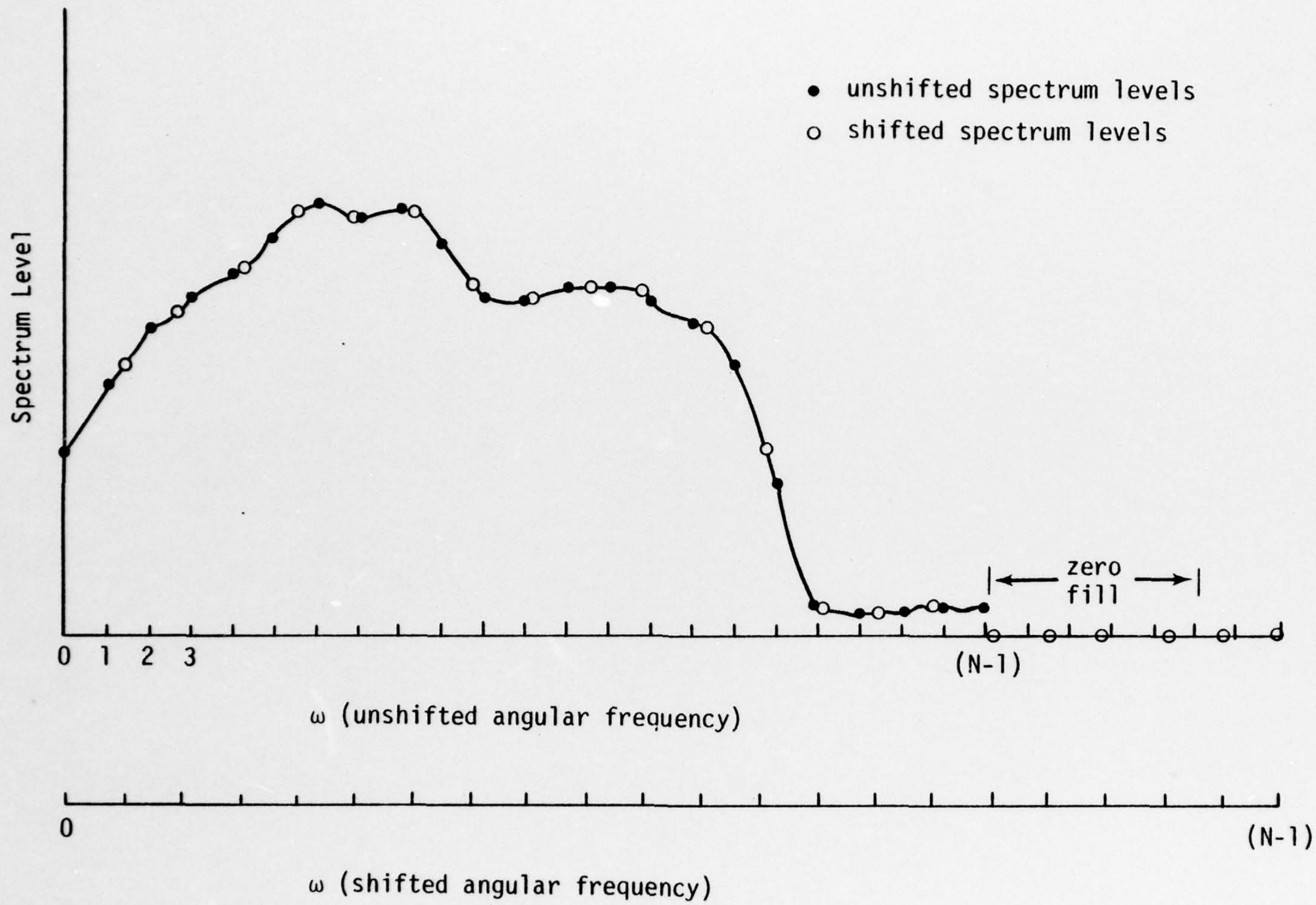

Figure 2. Relationship of shifted to unshifted spectrum levels

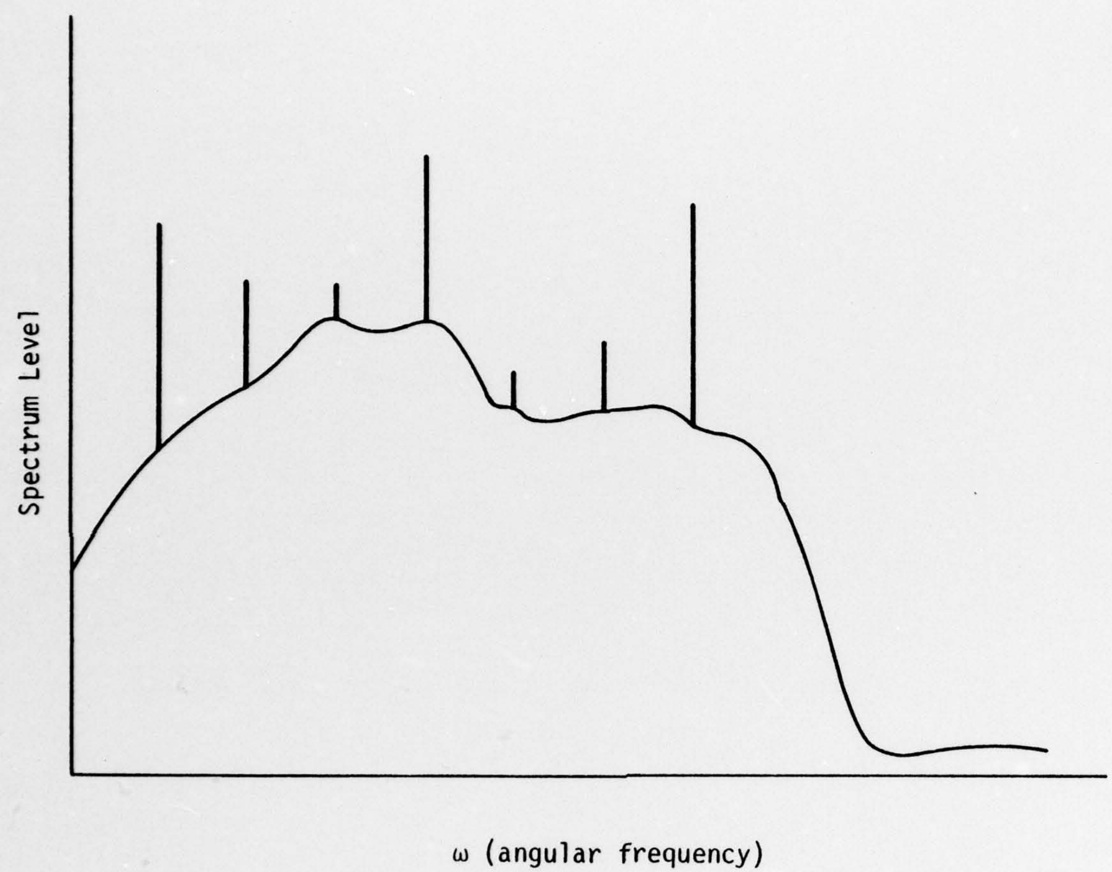

Figure 3. Example of surface ship spectrum

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1. J. S. Bendat and A. G. Piersol, <u>Random Data: Analysis and Measurement Procedures</u>, Wiley, New York (1971).

2. L. S. Blumen, "Documentation of PDP 11/70 Software for Determining Travel-Time Differences from Cross Covariance," SAI Report 78-713-WA, 23 December 1977.

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