AD-A159 827 STOCHASTIC MEASUREMENTS AND SYSTEMS IMPLICATIONS(U) 1/1
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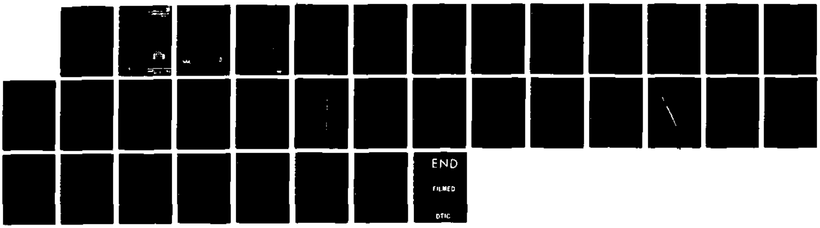

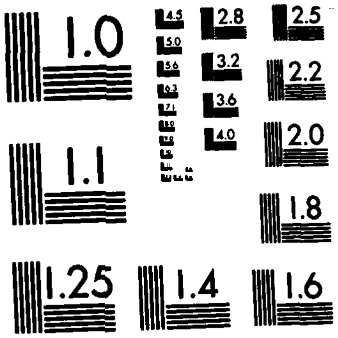

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STOCHASTIC MEASUREMENTS AND SYSTEMS IMPLICATIONS

SAIC/85-1748

June 1985

Contract No. N00014-85-C-0084

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER SAIC-85/1748	2. GOVT ACCESSION NO. AD-A159 827	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Stochastic Measurements and Systems Implications		5. TYPE OF REPORT & PERIOD COVERED Technical Report 6. PERFORMING ORG. REPORT NUMBER SAIC-85/1748
7. AUTHOR(s) J.L. Collins R.R. Greene		8. CONTRACT OR GRANT NUMBER(s) N00014-85-C-0084
9. PERFORMING ORGANIZATION NAME AND ADDRESS Science Applications International Corp. 1710 Goodridge Drive McLean, VA 22102		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Ocean Research and Development Activity NSTL Station, MS 39529		12. REPORT DATE JUNE 85 13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) Office of Naval Research Dept. of the Navy 800 N. Quincy Street Arlington, VA 22217		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE
DISTRIBUTION UNLIMITED

Unlimited

APPROVED FOR PUBLIC RELEASE
DISTRIBUTION UNLIMITED

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Environmental Acoustics, Fluctuations, Coherence, Spread, Sonar, System, Performance

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report addresses those Arctic specific acoustic transmission effects which affect system performance due to spreading and fluctuation of the acoustic field in space, angle, time, and frequency.

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Section 1

BACKGROUND

The U.S. Navy is defining the baseline performance of the current SSN ASW suite in the Arctic operating environment. This suite includes the AN/BQQ-5 sonar suit (including the Towed Array, the sphere and other sensor and processor sub-systems), communications subsystems and weapon systems (Mk 48 and ADCAP). An effective acoustic measurement program in the Arctic must support the evaluation of how well the different subsystems are able to carry out their assigned functions. Unique aspects of the operating environment in the Arctic include unusual noise properties, unusual transmission effects and an unusual "sea" surface. This report addresses those acoustic transmission effects which affect system performance due to fluctuations or spreads in the acoustic field in space, angle, time and frequency.

Additional keywords: Coherence; environmental acoustics;

Section 2

THE PROBLEM

Acoustic energy propagating over short, tactical ranges (less than 100 nm) and without interaction with rough boundaries, suffers little effect except attenuation. However, when the path scatters from a rough boundary the signal structure can change markedly. Both deterministic and stochastic mechanisms are acting which can modify the signal structure in the time, frequency and spatial domains. Table 1 summarizes these mechanisms.

Table 1

Summary of Deterministic and Stochastic Mechanisms

DOMAIN	CLASSICAL OR DETERMINISTIC	STOCHASTIC ACOUSTIC FIELD
Time	Multipath	Time Spread (single path) or Frequency Coherence
Frequency	Doppler	Frequency Spread or Time Coherence
Space	Arrival Angle	Angle Spread or Spatial Coherence

The objective of an acoustic experiment is to measure these mechanisms, along with the appropriate environmental properties, so that we can properly interpret the data and reconstruct how and why the ASW subsystems performed as they did. When this combination of measurements is of sufficient quality it can be the basis for developing acoustic and system performance prediction models.

The measurement of the deterministic values is reasonably straightforward. The important measurements are the multipath and arrival angle. Both vertical and horizontal arrays will be needed and the measurements must be made over the range of frequencies of interest. Short cw pulses may be appropriate for the deterministic measurements since doppler is of less interest.

Measurement of the stochastic acoustic field will require a more sophisticated and careful selection of instrumentation and procedures. At short ranges and lower frequencies each arrival of the multipath structure will be modified by stochastic effects and can be observed individually. At higher frequencies and longer ranges, the deterministic multipath structure may be totally swamped by stochastic scattering from ice structures. The trade-offs in measurement planning with respect to stochastic effects in the time, frequency, and spatial domains are discussed in the following sections.

Section 3

THE STOCHASTIC ACOUSTIC FIELD

During the past few years, several acoustic systems have experienced unexpected performance degradation due to stochastic mechanisms. These effects were recognized when the "systems" were operating in the bottom-bounce mode where the bottom was somewhat rough and platform motion was present. Analysis indicated that the received signals experienced spreading due to the usual multipath arrival structure, but also each single path was spread in time and frequency.

The Arctic ice cover is expected to cause similar effects because it is somewhat rough, the transmission paths involve multiple reflections due to the upward refracting environment, and relatively long range performance is desired.

A brief description of the nature of each stochastic effect follows, along with suggested measurement procedures. Measurement details will require considerable additional analysis. These discussions assume that the bandwidth is less than about 15% of the carrier and the RMS slope is < 10°.

Section 4

TIME DISPERSION

4.1 TIME SPREAD

Time spread is differentiated from multipath in that time spread is unresolvable multipath on a single path. It can be due to sub-bottom structure (layering) or bottom roughness. In the Arctic, the principal cause is expected to be ice roughness.

Figures 1(a) and 1(b) define timespread and indicate the effects. The effects become more pronounced as the time spread, L, approaches the pulse length, T. The consequences are that the signal is distorted and lengthened: L defines the limit on time resolution.

The coherent bandwidth or frequency coherence is given by L^{-1} and defines the minimum frequency separation between two signals to insure independence of the signals. This means that there is no correlation between two signals which have more than L^{-1} Hz separation. Independence of two signals gives diversity which helps insure the successful transmission of the signal (or pulse) with minimum distortion or frequency selective fading.

If the original signal is T seconds long, the received signal will be T + L seconds long. If multiple measurements are made, an ensemble of values is formed and a statistical definition of L can be developed, which makes possible the estimation of the statistical coherent bandwidth.

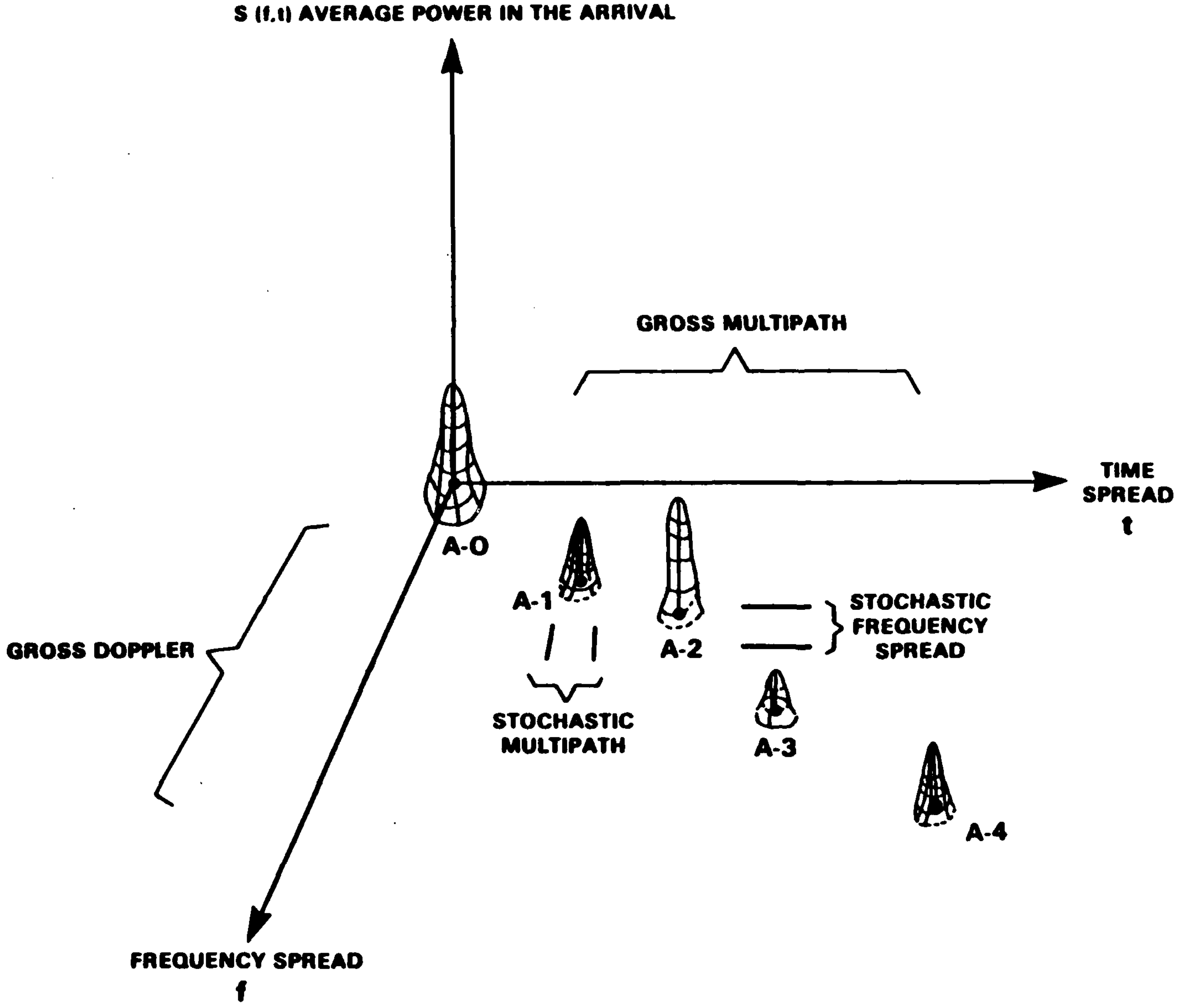


Figure 4. A Two-Dimensional Representation of Joint Time-Spread/Frequency-Spread Effects

Section 7

JOINT EFFECTS

With any propagation channel, time, frequency and spatial spreads may occur at the same time. This is more likely when platform motion is involved. The joint time-frequency spread channel presents some unusual effects which must be recognized when the measurement system is being designed. Spatial spread and frequency spread are not independent, but closely related.

The propagation channel which is dispersive in both time and frequency is doubly dispersive: the channel will have both time selective and frequency selective fading and is neither time flat nor frequency flat. Figure 4 shows the response of a multipath channel which is doubly dispersive.

In the doubly dispersive channel, if the product of the coherence time and coherence bandwidth (L•B) is much larger than one, the channel is underspread. This implies correlated fading in both time and frequency and provides a basis for adaptive methods for signaling and measuring the channel. Replica correlators and wideband signals can be used effectively.

If the coherence time and coherence bandwidth product (L•B) is much less than one, the measurement of the channel response is difficult. Large W•T signals are useless and therefore replica systems perform poorly. Our measurement system would be restricted to long CW and short impulsive signals.

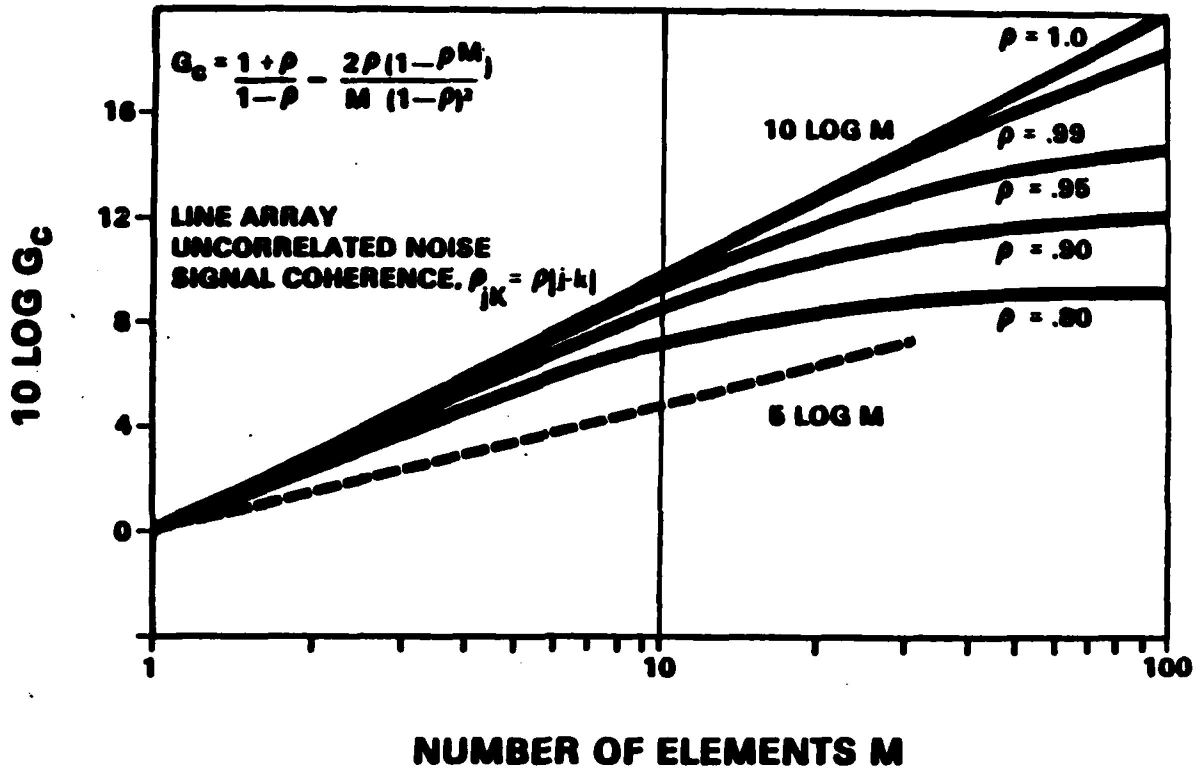


Figure 3. Gain of a Conventional Beamformer (after Cox)

Section 6

ANGLE DISPERSION

6.1 ANGLE SPREAD

In the same manner that the rough boundary interaction distorts the signal structure in both time and frequency, the received signal may also be spread in spatial arrival angles. The signal can be spatially spread just the same as it is lengthened in time or widened in frequency.

A single path propagation channel which is dispersive in arrival angle is one in which a single deterministic acoustic ray path is stochastically perturbed to produce simultaneous arrivals from a cluster of directions. The expected locally plane wavefront is instead dispersed in arrival angle, both horizontally and vertically.

Arrival angle dispersion produces an interference pattern in space and can be described as spatially selective fading. This is the spatial equivalent to the fading, dispersive channel in time and frequency.

Because beamforming is the equivalent of correlation with a stored replica plane-wave, the beamformer output is degraded when the array length exceeds the spatial coherence length. In other words, the spatially spread signal components will act like "coherent" noise to the beamformer. In another view, if the beamwidth is smaller than the angle spread over which the signal energy is arriving, the energy outside the beam is lost and the output $\frac{S}{N}$ ratio may be reduced.

5.2 MEASUREMENT CONSIDERATIONS

As opposed to the high resolution requirements to measure time spread, a narrowband frequency resolution is required to measure frequency spread. This implies a long C.W. signal transmitted from a moving platform where the relative velocity between source and receiver is well known. Spatial resolution will be important and therefore the correct array must be employed. Several different center frequencies should be selected to insure coverage for the systems of interest. Frequency spread and spatial spread (arrival angle) are closely related measurements, because of the common scattering multipath issues.

Table 5

Examples of Frequency Spread from MACS/AFAR Data

PATH	FREQUENCY SPREAD - B	COHERENCE TIME 1/B sec (1/2 AMPLITUDE VALUE)
Direct Path	~ .1 Hz	~ 9 sec
Smooth Bottom Bounce	~ .21 Hz	~ 4 sec
Rough Bottom Bounce	~ 1.0 Hz	~ .9 sec

Table 4

Effects of Frequency Spread R in Relation to Pulse Length T and Bandwidth W

PULSE LENGTH - T	BANDWIDTH - W	WAVEFORM DISTORTED	FREQUENCY DISPERSION	COMMENT
T << 1/B	B << W	No	No	------
T >> 1/B	B << W	Yes	No	Waveform distorted No Dispersion
T >> 1/B	B >> W	Yes	Yes	Waveform Distorted Dispersion Present

Frequency dispersion B helps define the limit on frequency resolution for a processor (i.e., how narrow the filter can be without performance loss). The coherence time is 1/B and defines the longest coherent integration time or pulse length that can be used without performance degradation.

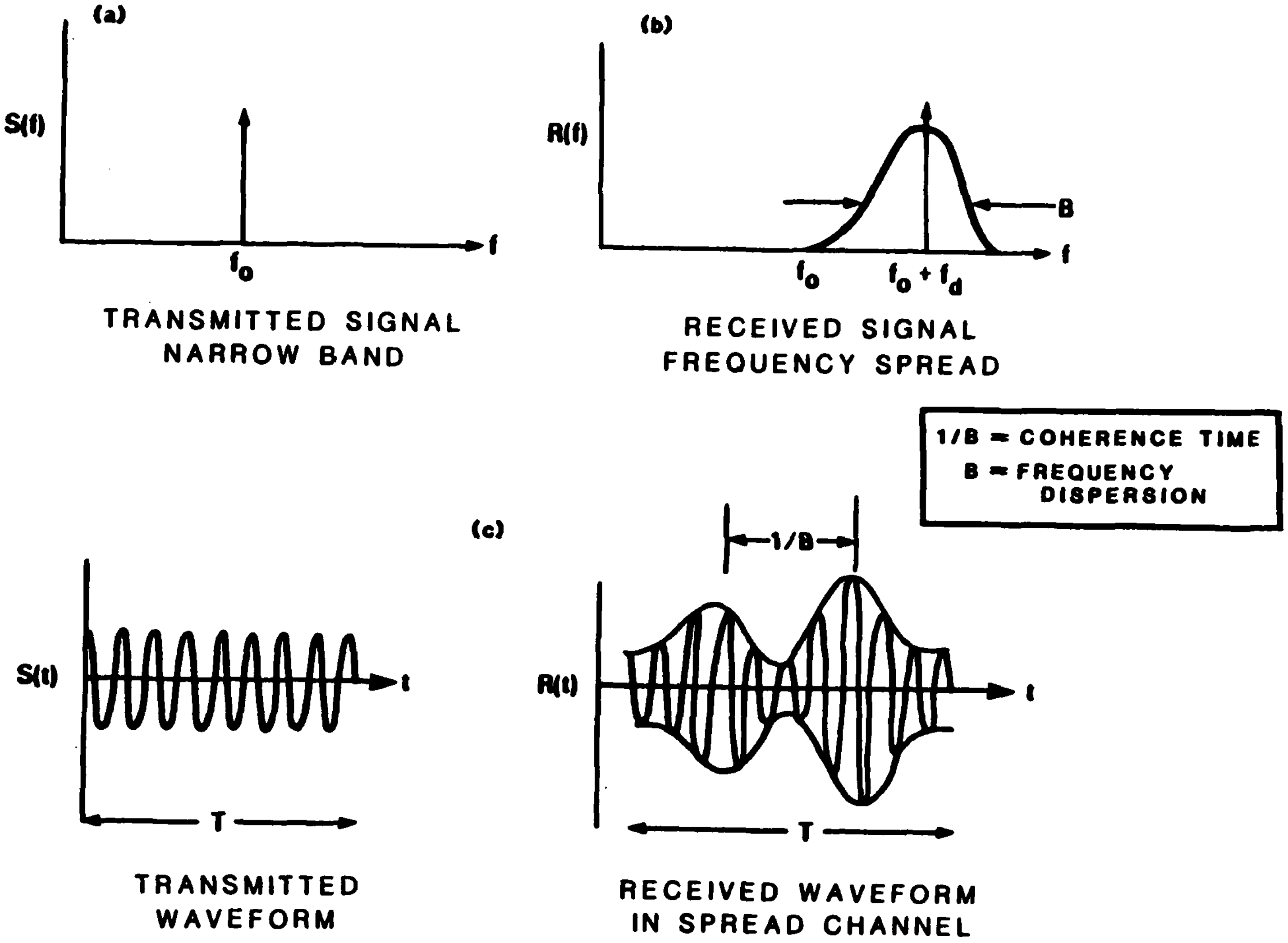
A realization of this process is shown in Figure 2(c), which is dispersive in frequency only, where $\frac{1}{B}$ represents the periodicity of the fade.

Frequency dispersion of the propagating signal is also dependent on certain signal parameters. These are primarily bandwidth and pulse length. Modulation format does not enter into the process to a major degree, except through influences on bandwidth.

Frequency enters into the process since doppler is frequency sensitive and frequency spread is related to relative velocity, wavelength and the boundary RMS slope.

The relationship between frequency spread B, pulse length T and bandwidth W, similar to the time dispersion case, indicates when problems can be expected. Table 4 outlines when frequency dispersion and/or waveform distortion may be present. B is a critical value, and its relationships to W and T set limits on the <u>waveform design</u> to minimize frequency dispersive effects.

Table 5 indicates nominal ensemble averages for three selected paths. These are included to provide guidance as to the "resolution" needed to measure frequency spread.



TRANSMITTED SIGNAL NARROW BAND

RECEIVED SIGNAL FREQUENCY SPREAD

TRANSMITTED WAVEFORM

RECEIVED WAVEFORM IN SPREAD CHANNEL

Figure 2. Representative Effects of Frequency Dispersion (for $T > \frac{1}{B}$) on Signals

Section 5
FREQUENCY DISPERSION

5.1 FREQUENCY SPREAD

In frequency spread (or dispersion), a signal transmitted within a specified frequency band becomes spread over a wider band. This phenomenon is related to the simpler gross doppler shift, associated with source motion along a single path. In the complicated under-ice scattering environment, there are scattered paths which depart the source and arrive at the receiver from different directions in elevation and azimuth. Source and receiver motion with respect to this arrival structure produces a different doppler shift on each path, and spreads the frequency band of the overall signal.

Frequency dispersion causes the transmitted waveform to be amplitude and phase modulated. The propagation path may selectively alter certain time portions of the transmitted signal, producing the effect sometimes called time-selective fading. It is sometimes referred to as frequency-flat fading when all frequency components are modulated in the same manner.

In frequency space, Figure 2(a) represents the transmitted signal, S(f), and Figure 2(b) the received signal, R(f). The received signal has been shifted Δf Hz due to gross doppler and spread B Hz due to frequency dispersive effects during propagation.

Table 3
Examples of Time Spread from At-Sea Measurement Data

PATH	TIME SPREAD - L	COHERENT BANDWIDTH OR FREQUENCY CORRELATION (1/2 AMPLITUDE VALUE)
Direct Path	33 msec	30 Hz
Smooth Bottom Bounce	110 msec	9 Hz
Rough Bottom Bounce	900 msec	1 Hz

Table 2

Effects of Time Spread L in Relation to Pulse Length T and Bandwidth W

BANDWIDTH - W	PULSE LENGTH - T	DISTORTED	DISPERSED	COMMENT
$WL \ll 1$	$L/T \ll 1$	No	No	------
$WL \gg 1$	$L/T \ll 1$	Yes	No	Waveform Distorted Minimal Dispersion
$WL \gg 1$	$L/T \gg 1$	Yes	Yes	Waveform Distorted Dispersion Present

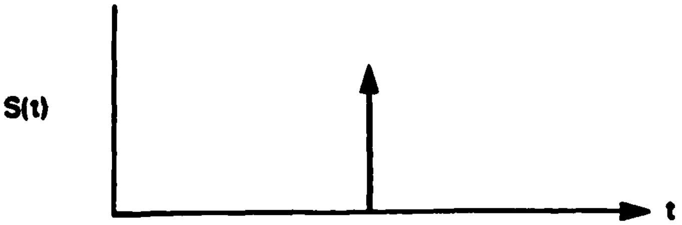
In sonar applications, time spread produces overlap of received signals, resulting in signal interaction much like passing a signal through a filter which is mismatched so that it alters the frequency components of the signal by different proportions. The impact of time spread (L) on the signal is dependent upon the value of L, the bandwidth (W) and pulse length (T). Table 2 shows the relationships between L, W and T in terms of distortion of the received waveform and time dispersion (extension) of the transmitted signal. In Figure 1(c) the received signal is both lengthened and distorted due to time spread, and both phase and amplitude are distorted. A magnitude estimate for three different channel boundary properties is shown in Table 3. These values represent "typical" ensemble averages and variations at different sites that should be expected.

4.2 MEASUREMENT CONSIDERATIONS

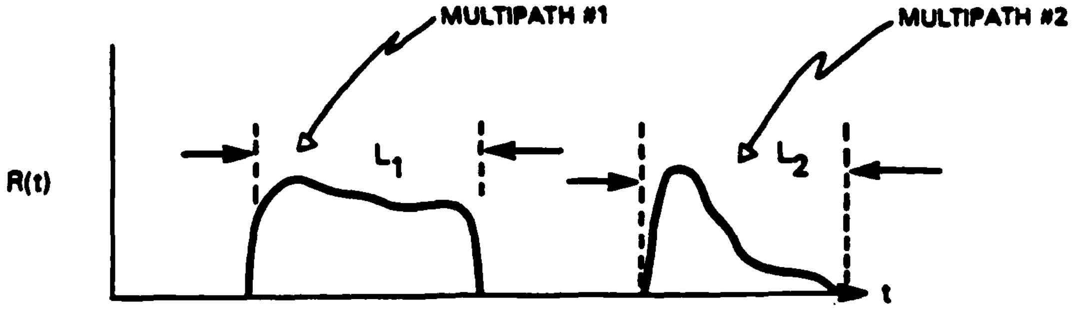
A measurement of time spread requires a "high" time resolution in order to resolve an individual path from the multipath structure and identify time spread values (L) on that path.

Suitable pulses include short impulsive signals (explosive sources), wide band coded signals (where $\frac{1}{W} < L$ for adequate resolution) and short, Gaussian envelope CW pulses with time resolution < L. Measurement distances of interest may dictate the pulse selected (total power) in order to generate an adequate S/N ratio at the receiver.

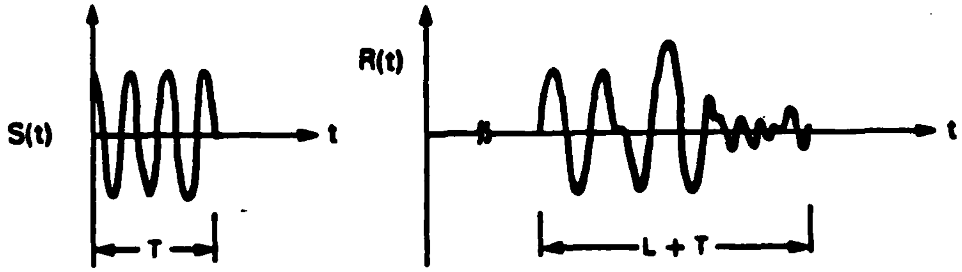
Spatial resolution is not critical although the receiving array should be able to resolve or reject bottom paths versus direct paths if needed.



(a) TRANSMITTED SIGNAL — IMPULSE IN TIME



(b) RECEIVED SIGNAL



TRANSMITTED SIGNAL **RECEIVED SIGNAL**

(c) TIME SPREAD EFFECTS: $WL \gg 1$, $L/T \gg 1$

Figure 1. Representative Effects of Time Dispersion on Signals

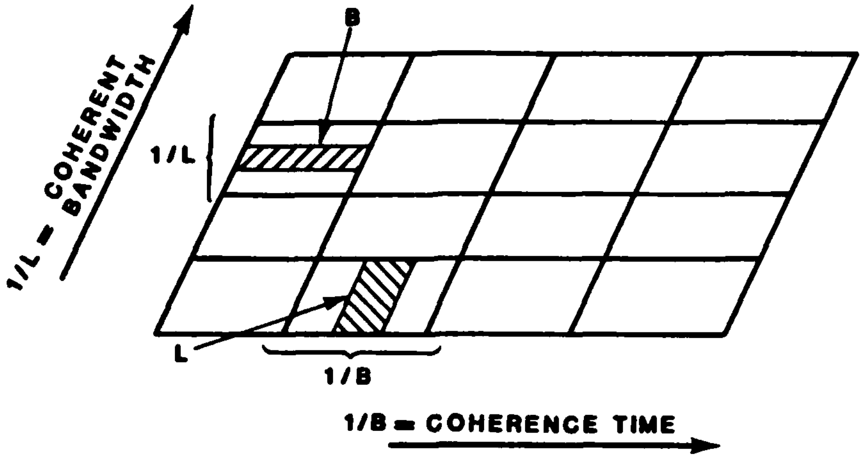
The transmitted waveform is defined in terms of the pulse length T and the bandwidth W. Time dispersion is measured as L (extension in pulse length) and frequency dispersion is measured as B (extension in bandwidth). The relationship between these four factors will help to explain why dispersion and distortion of the signal is present. If both time and frequency spreads are present at the same time, then the coherent bandwidth, originally 1/L, and the coherence time, originally 1/B, will generally be increased as follows:

- Real Coherent Bandwidth: $\Delta f_c \leq \max [\frac{1}{L}, B]$.
- Real Coherence Time: $\Delta t_c \leq \max [\frac{1}{B}, L]$.

The real coherent bandwidth is the minimum frequency separation between two signals that insures independence of the signals, an important result for estimating the diversity and thus reliability of communication channels. For sonar applications, the real coherent bandwidth is the maximum bandwith for coherent processing of signals.

The real coherence time is the minimum separation time between two signals to insure the independence of those signals, an important result for estimating the data rate for communication channels. For sonar applications, the real coherence time is the maximum integration time for the coherent processing of signals.

In a different presentation, the effect can be seen with a coherence 2-space graph:



L = Time Spread
$\frac{1}{L}$ = Coherent Bandwidth

B = Frequency Spread
$\frac{1}{B}$ = Coherent Time

In other words, the constraints placed upon systems and measurement designs in terms of resolution/integration times and frequency resolution/usable bandwidth must include consideration of the four aspects indicated. Coherent time and coherent bandwidth are dependent upon the relative values of L and B. Therefore, if L is much larger than $\frac{1}{B}$, then coherence time is influenced by that value, while if B is larger than $\frac{1}{L}$, the coherent bandwidth is modified.

When both time and frequency dispersions exist, care must be exercised to evaluate the joint effects. In fact, many of the simple models used here may not be applicable, but they give guidance and estimates of the singular and joint effects. The extension of the dispersion models to long pulses and wide bandwidths will require future research in signal physics and signal processing. But as stated earlier, when used with care, these existing methods will provide realistic guidance as to how dispersion can impact measurement system design.

Section 8

STOCHASTIC ACOUSTIC FIELD EFFECTS ON PROCESSOR PERFORMANCE

The random nature of the stochastic field can cause processor performance loss unless the design anticipates the effects on signal structure. These factors include:

- Time dispersion affects signal processing by:
  - Limiting time resolution
  - Placing bounds on the coherent bandwidth or minimum frequency separation
- Frequency dispersion effects signal processing by:
  - Limiting frequency resolution
  - Placing bounds on integration time or longest coherent pulse length
- Angle dispersion effects spatial processing by:
  - Limiting angle resolution (limiting usable D.I.)
  - Modifying the minimum spacing of phones to achieve independence

Basic processor performance is related to the waveform structure (including bandwidth) and array size. These factors are related to performance as shown below:

- Range resolution is related to bandwidth^{-1}
- Doppler resolution is related to $(\text{pulse length})^{-1}$
- Bearing resolution is related to $\left(\frac{\text{Aperture}}{\lambda}\right)^{-1}$.

The signal-to-noise ratio enters the analysis for accuracy:

- Range accuracy is proportional to: $\left(\frac{S}{N}\cdot(W)^2\right)^{-1/2}$
- Doppler accuracy is proportional to: $\left(\frac{S}{N}\cdot(T)^2\right)^{-1/2}$
- Bearing accuracy is proportional to: $\left(\frac{S}{N}\cdot\left(\frac{\text{Aperture}}{\lambda}\right)^2\right)^{-1/2}$.

The dispersion factors can be related to system processor loss by computing the loss in $\frac{S}{N}$ ratio, which indicates how accuracy can be degraded. These estimates are also related to the detection functional thru the sub-system ROC curves, where the false alarm and detection probability are related thru $\frac{S}{N}$ ratio changes.

The impact on sub-system or processor output signal to noise ratio can be estimated, in general, by the following:

Frequency Spread

- For a narrow-band processor, the loss in output $\frac{S}{N} = 10 \log \frac{\Delta f}{\Delta f+\sigma_f}$, where

Δf = processor bandwidth (Hz),

σ_f = frequency spread (Hz).

- For a coherent replica correlator, the loss in output $\frac{S}{N} = 10 \log \frac{W}{W + \sigma_f}$, where

  W = bandwidth of signal.

Time Spread

- For a matched filter C.W. power detector,

  the loss in output $\frac{S}{N} = 10 \log \frac{T}{T + \sigma_t}$, where

  T = pulse length or integration time,

  σ_t = time spread.

- For a cross-correlator, for example in a tracking system,

  the loss in output $\frac{S}{N} = 10 \log \frac{\Delta t}{\Delta t + \sigma_t}$, where

  $\Delta t = (B.W.)^{-1}$ of the receiver.

As an example, a split array tracker (as in a RAPLOC system) with a high signal to noise ratio, would estimate range by:

$R = \frac{L^2 \sin^2\theta}{C\Delta t}$, where

R = computed range,

L = effective array length (baseline),

θ = angle of incidence at array,

C = speed of sound,

Δt = arrival time differential between the two halves.

The range error equation is:

$$R_{error} = \frac{CR^2}{L^2 \sin^2\theta} t_{error}, \text{ where}$$

R_{error} = estimated error,

t_{error} = error in estimated differential time of arrival measurement.

The specific loss in tracker performance due to signal to noise is very system dependent, and is not estimated here. In the split beam tracker the time error, t_{error}, is also a stochastic function and both time, frequency and spatial spreads can have impact upon the tracking error values.

To illustrate, assume that for an array with effective baseline L, an error of 1 μ second (t_{error}) is caused by stochastic path variations at a range of 10 kyds.

Then:

L (ft)	R_{error}
100	450
300	50
1000	4.5

The principal of the invariance of difficulty seems to hold: for the smaller array, the signals are more likely to remain coherent; as the arrays get longer, a given t_{error} uncertainty causes less error but because the paths are more divergent, the signal coherence is more likely to decrease, which increases the probable range error. The balancing of these two effects implies an optimum array length for the environment.

These arguments are offered to help show how system performance is related to stochastic acoustic fields. It argues for the need to consider which Systems to be used in the Arctic, as well as New system requirements of the future, when a measurements program to support the Sonar Baseline definition effort is required.

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