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DETECTION OF COMPLEX SIGNALS AS A FUNCTION OF SIGNAL BANDWIDTH AND DURATION

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By: C. D. Creelman

Approved by: A. B. Macnee

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ABSTRACT

An experimental examination of the efficiency of human observers in detecting a stimulus waveform which consists of a train of damped sinusoids is reported. The signal duration and degree of damping (or spectral bandwidth) were varied, with the energy of the signal held constant. Bandwidth is shown to affect human detection more at long than at short durations.

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1. INTRODUCTION

The Theory of Signal Detectability has had considerable success in characterizing human auditory processes. Tanner, Swets, and Green[1] report results of extensive experimentation supporting the applicability of the theory, and Licklider[2] has presented an excellent critical review of this work. Most of the developments to date have been based on the theoretical work of Peterson and Birdsall[3], particularly their case of an ideal observer detecting a signal known exactly. The observer, a mathematical abstraction, is assumed in this case to have an exact replica of the signal to be detected, and to know the starting time and duration of the signal. Both on intuitive and empirical grounds it is clear that human observers do not perform as well as the ideal. Evidence is accumulating on how humans do behave compared to the ideal, and a current experimental aim is to specify the kinds of limitations to impose on the ideal which will produce performance like that of human observers. Peterson and Birdsall work out predictions of performance for a number of cases in which the observer has less than perfect knowledge of the signal, and Green, Birdsall, and Tanner[4] discuss the effects of less than optimal receiver bandwidth on performance. On the basis of experiments reported in the later article it is argued that no single model thus far developed will fit all the available data.

The frequency composition of the signal has no effect on detection in the theoretical ideal observer, but it may have considerable effect on human detection. The ways in which spectral complexity is found to affect human detection will place restrictions on the sorts of general models eventually developed. Since much of the work to date on psychoacoustic applications of detectability theory has used sine-wave signals as stimuli, it was felt that some comparison experiments using more complex stimuli were in order.

The stimuli used in this study were trains of damped sinusoids produced by a recurrently excited variable resonator designed and built at the University of Michigan Speech Research Laboratory.[5] The particular form of the signals used in this experiment was chosen for similarity to speech signals, and as such the data show a direction in which theory must move if it is to encompass this very important aspect of human auditory experience.

2. PREVIOUS RESEARCH

Green[6] and Marill[7] have published results concerning the sensitivity of human observers to complex auditory signals. The stimuli in these studies were mixtures of two equally detectable sine waves, and the independent variable was the separation in frequency between the two components. Unfortunately, the two studies yielded contradictory results. Green found an equal contribution to detectability from both components in all cases. Marill, on the other hand, found that when the frequency separation between the two components was large, in the order of 500 cps, it appeared that observers were sensitive to only one of the two component tones; detection was the same as of one tone alone. When the two frequencies were only 40 cycles apart, however, detection of the complex was increased. Marill's results are consistent with the critical band model of Fletcher[8] if we assume that an observer is able to listen at one time only within a single critical band. Green's results are interpreted as showing that observers can listen to at least two critical bands at the same time. The answer to the paradox posed by these conflicting results is a challenge that must be met if such models are to be extended to encompass human perception of complex signals.

A comprehensive and careful review of the experimental literature relating to the critical band hypothesis has been presented by Green[9], and the reader is referred to this report for further discussion of the area.

Study of the effect of signal duration on detection has had a long and venerable history in psychoacoustics. Licklider[10] has summarized much of the earlier relevant experimental data. The generally accepted notion has been that over a range of signal durations a "time-intensity trade" may be effected; constant detectability can result from a decrease in signal power if duration is increased. Green, Birdsall, and Tanner[4] have shown this relationship over a narrow range of durations. Detection decreased, however, with signals shorter than about 0.01 second or longer than about 0.1 second.

In the present experiment more complex signals were employed. The objective was to study the combined effects of duration and of increased signal bandwidth on detection, and to compare the results to previous data collected with sine-wave stimuli.

3. EXPERIMENTAL DESIGN AND PROCEDURE

3.1 Stimuli

The stimuli used were the gated output of a recurrently excited series RLC resonant circuit which produced a train of damped sinusoids. The resonant frequency of the circuit was fixed at 500 cps, and five different damping rates were used. The stimuli are represented schematically in Fig. 1 for three degrees of damping, at a signal duration of 0.05 second.

The resonator was pulsed continuously at 100 cps, and an electronic "sine zero" gate delivered signals to the observers starting at the beginning of a repeat cycle and continuing for a selected integral number of repeat cycles (see Fig. 1). Five signal durations were studied: 0.01, 0.02, 0.05, 0.1, and 0.2 second, or 1, 2, 5, 10, and 20 repeat cycles of the stimulus waveform.

3.2 Apparatus and Procedure

The experiments were conducted at the Psychophysical Laboratory, the Electronic Defense Group, The University of Michigan. The stimuli were mixed with continuous white background noise and presented to observers in the Psychophysical Laboratory's N. P. Psytar apparatus which has been described elsewhere[11]. A two-alternative forced choice procedure was used: after a red warning light two observation intervals separated by 0.5 second were marked by flashes of a white light. During a subsequent period the observers indicated which interval had contained a signal by pressing one of two buttons. The responses and correct answer information were recorded automatically on IBM cards, the observers were given information visually as to whether their responses had been correct or not, and the cycle was repeated. Each such cycle, or trial, took about 4.5 seconds (more when longer signals were used). The paid observers worked for two hours per day, five days a week. In a single day's session six or seven 100-trial runs could be completed with short rest periods after each run.

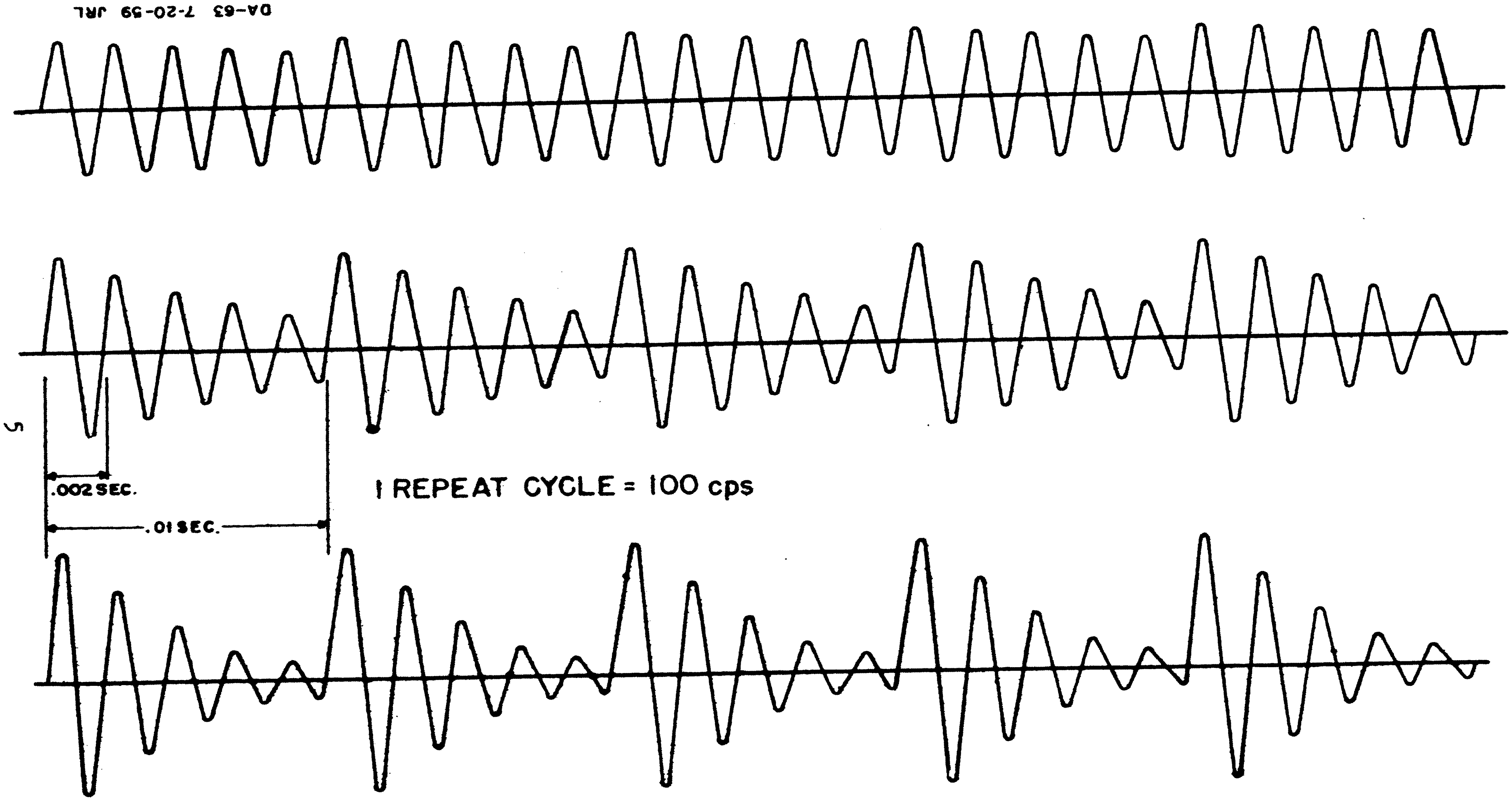

FIG. 1 SCHEMATIC REPRESENTATION OF STIMULI SHOWING THREE DEGREES OF DAMPING

All resonator damping values were presented at a single duration before a new duration was run. The order in which durations were run, and within each duration the order in which the damping values were presented were randomized. Two hundred observations were obtained for each combination of bandwidth and duration. Then the whole procedure was repeated with a new randomization of experimental values, yielding 400 observations for each data point. A constant background noise level was used throughout the experiment, and values of rms voltage were chosen for the signal at each duration such that the signal energy was nearly constant. The signal voltage values and the resultant values of $2E/N_o$ are presented in Table I. A somewhat different procedure was used with the 50 and 100 ms durations, which can be more easily explained after a discussion of the response measures used to analyze the data.

TABLE I

Signal Duration	Signal Voltage*	$2E/N_o$**
.01	.018	43.04
.02	.013	44.85
.05	.008	42.51
.10	.0056	41.66
.20	.004	42.51

Signal voltages used at each duration, and the resultant values of $2E/N_o$.

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* Measured across the observers' PDR-8 earphones with Balentine Model 320 "True RMS" meter.

** N_o was constant at 1.51×10^{-7} watts per cycle per second. E is the signal energy in joules (or watt-seconds).

3.3 Response Measures

Tanner and Birdsall[12] have presented an excellent exposition and development of the measure of observer efficiency, η, which was used as a response measure. The basic idea behind the development is that an ideal receiver, built specifically for the particular signal used in an experiment, has a limit imposed on its performance by the environment. This limit was shown by Peterson and Birdsall[3] to be a function of $(2E/N_o)^{1/2}$, where E is the signal energy and N_o is the power per unit bandwidth of a white Gaussian masking noise. Given a performance measure in percent correct on a human observer we may easily find the value of $(2E/N_o)^{1/2}$ necessary for an ideal observer to produce the same performance. This value is defined to be d'. When a two-alternative forced-choice method is employed, percent correct is related to d' as is shown in Fig. 2. Tables of this relationship were calculated by Elliott. With the actual value of $2E/N_o$ used in the experiment we may calculate an observer efficiency measure, η:

$$\eta = \frac{(d'_o)^2}{(d'_I)^2}$$

where d_o is the observed d', as estimated from an obtained percent correct by means of Fig. 2, and d'_I is the value of $(2E/N_o)^{1/2}$ actually presented in the experiment, or the d' the ideal observer would obtain in the same situation.

In the cases of the 50 and 100 ms duration signals a range of signal voltages was presented rather than just one, and a psychophysical function relating $(2E/N_o)^{1/2}$ to d'_o was plotted for each observer at each damping rate. At least 200 observations were used to estimate each

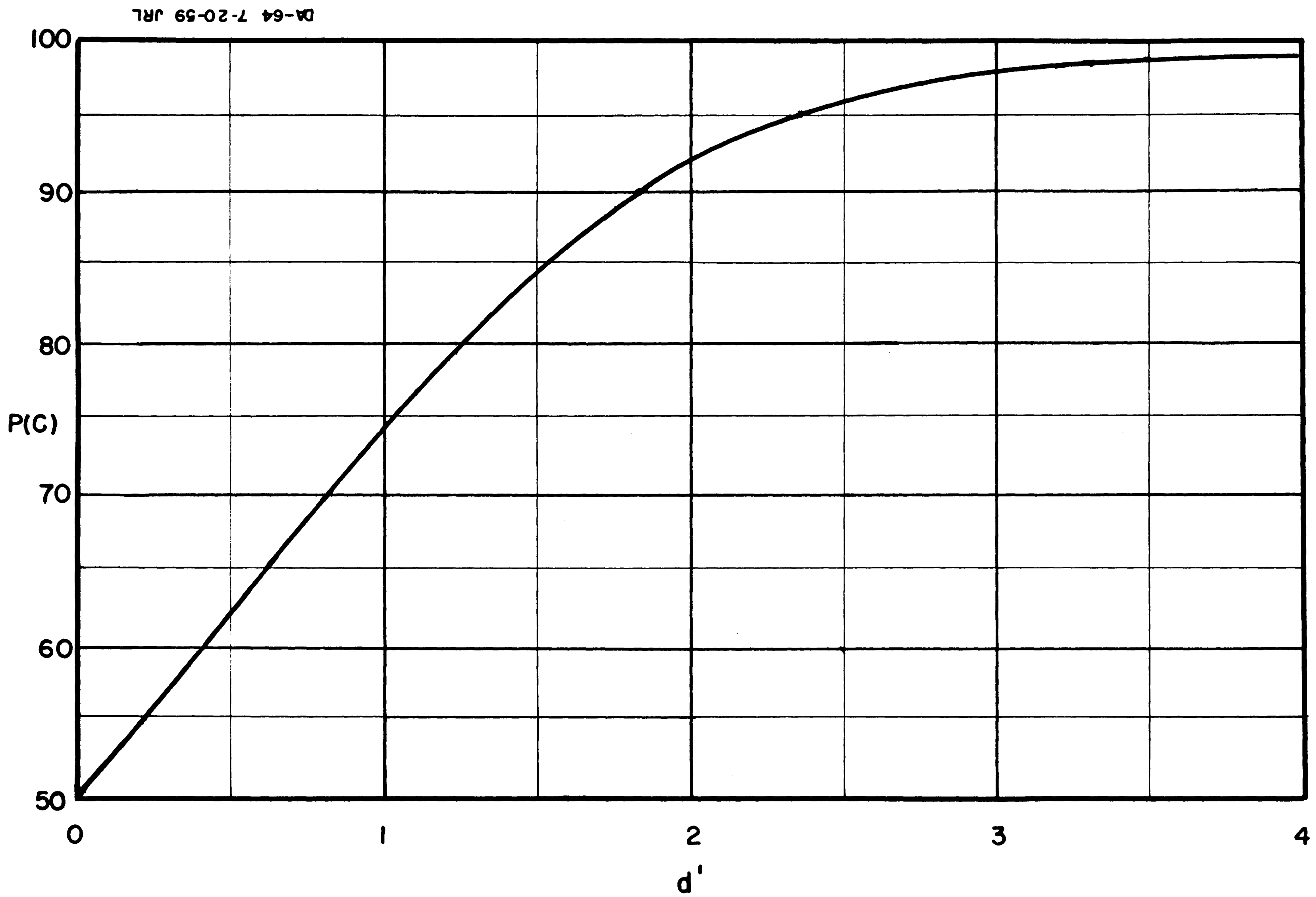

FIG. 2 THEORETICAL CURVE OF PERCENT CORRECT AS A FUNCTION OF d' IN A TWO-ALTERNATIVE FORCED-CHOICE EXPERIMENT

point on these plots. A best fit was drawn by eye to the points obtained and the reported experimental value of d' was that read from the curves for the appropriate $2E/N_0$ shown in Table I. No systematic differences between the shapes of these functions for the various resonator settings could be observed. Checking for any such differences was the primary reason for obtaining these extra data.

4. RESULTS AND DISCUSSION

On Figs. 3, 4, and 5 efficiency of the three observers is plotted as a function of signal duration. The value of resonator half-power bandwidth is the parameter. The missing data point in Fig. 4 at the 50 ms duration could not be obtained, since the psychophysical functions for 50 ms were collected at a time Observer II was not present. The data from observers I and II have essentially the same form. When only one repeat cycle of the waveform (0.01 second) is presented signal bandwidth has no systematic effect on detection. However, at longer signal durations highly-damped pulse trains are considerably less detectable than those signals which are essentially sine waves (10 and 30 cycle bandwidths). The results at narrow signal bandwidths support the conclusion by Green, Tanner, and Birdsall. Using 1000 cps gated sine-wave signals, they found constant detection over a range of durations with lower detection at longer durations. With wide bandwidth signals, on the other hand, the drop in detection in the present data is much like that predicted from the "radar case" observer discussed by Peterson and Birdsall[3]. The case is one in which a train of independent pulses of incoherent phase is to be detected, and it can be shown that detection is a decreasing function

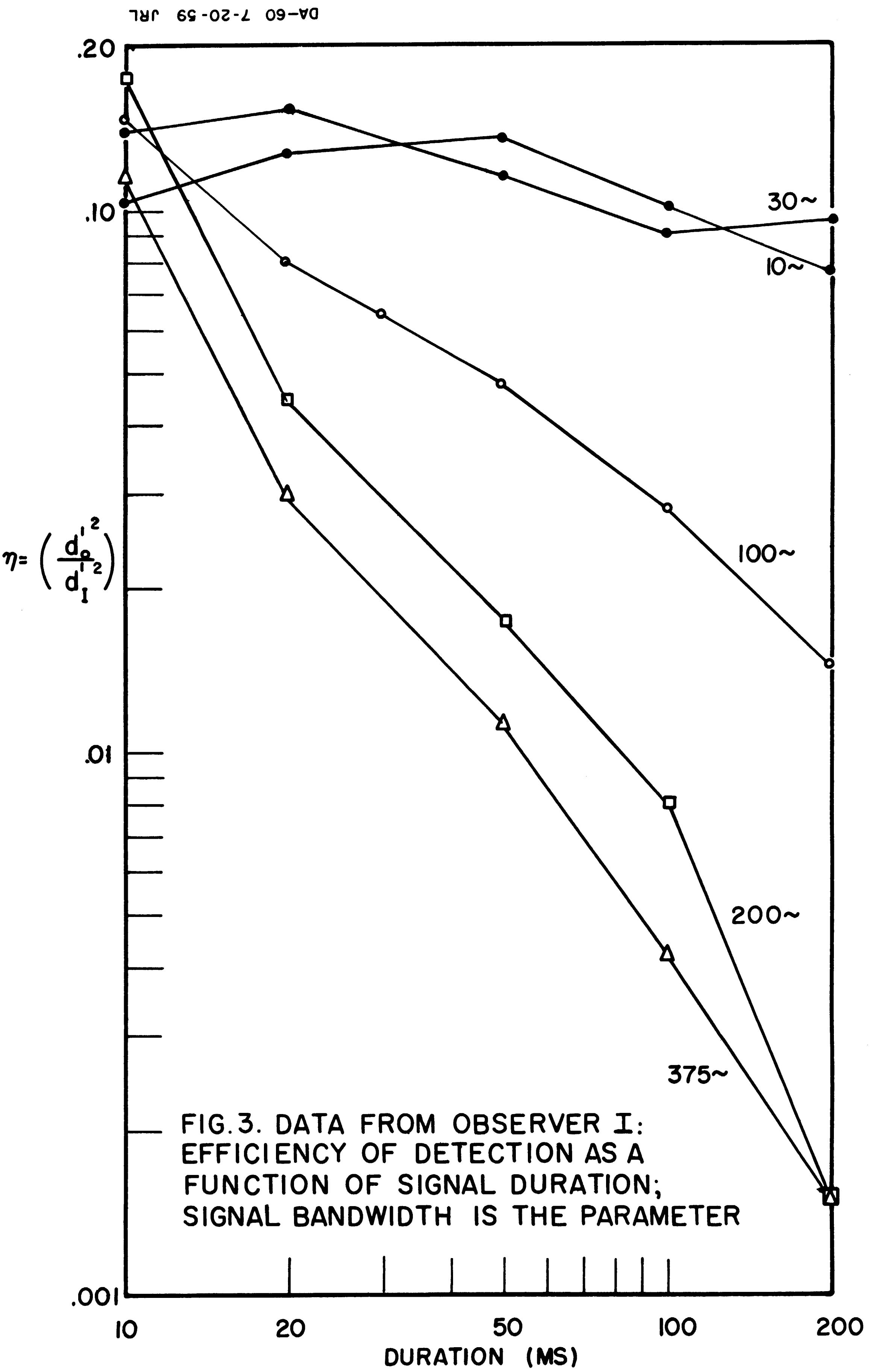

FIG. 3. DATA FROM OBSERVER I: EFFICIENCY OF DETECTION AS A FUNCTION OF SIGNAL DURATION; SIGNAL BANDWIDTH IS THE PARAMETER

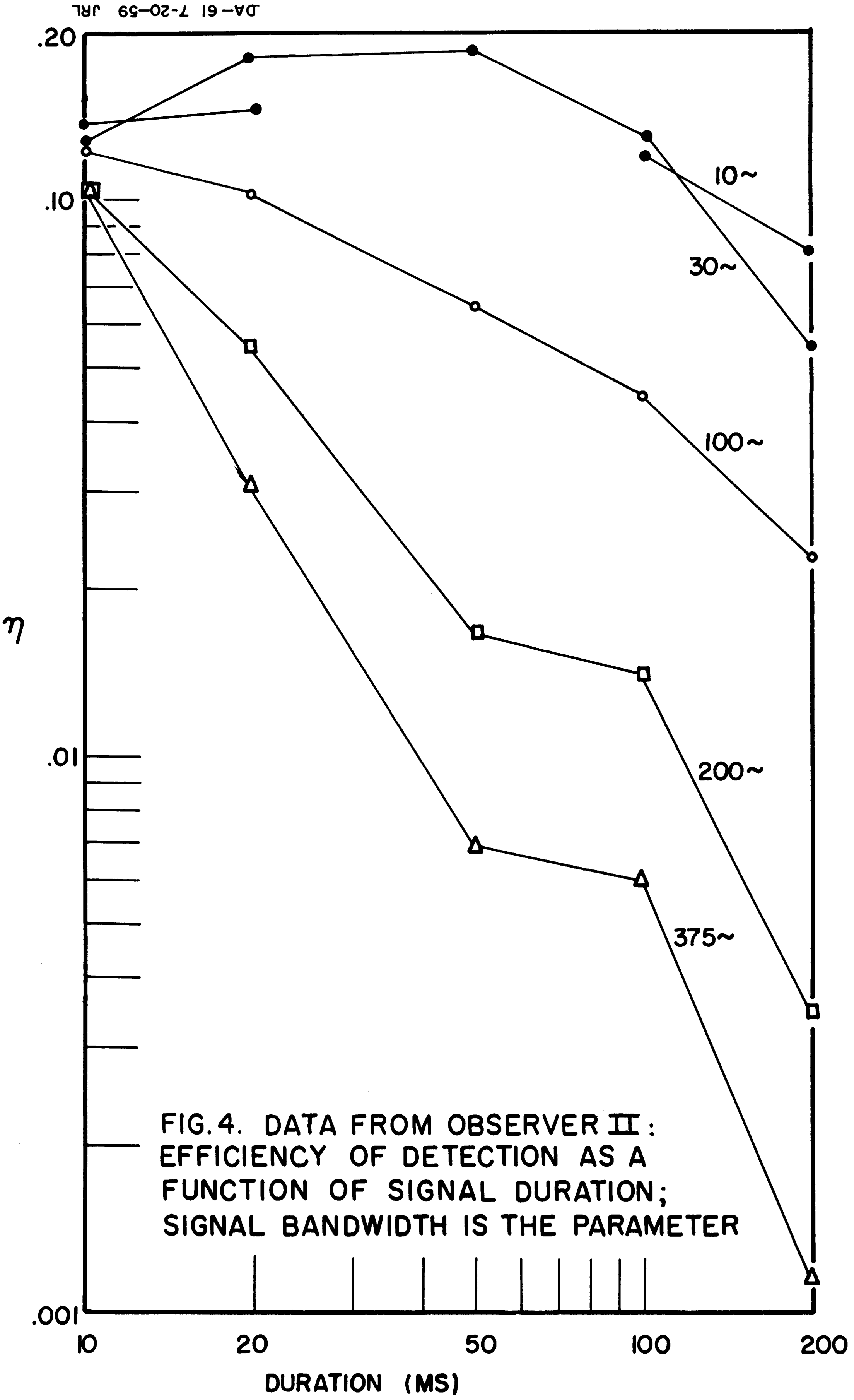

FIG. 4. DATA FROM OBSERVER II: EFFICIENCY OF DETECTION AS A FUNCTION OF SIGNAL DURATION; SIGNAL BANDWIDTH IS THE PARAMETER

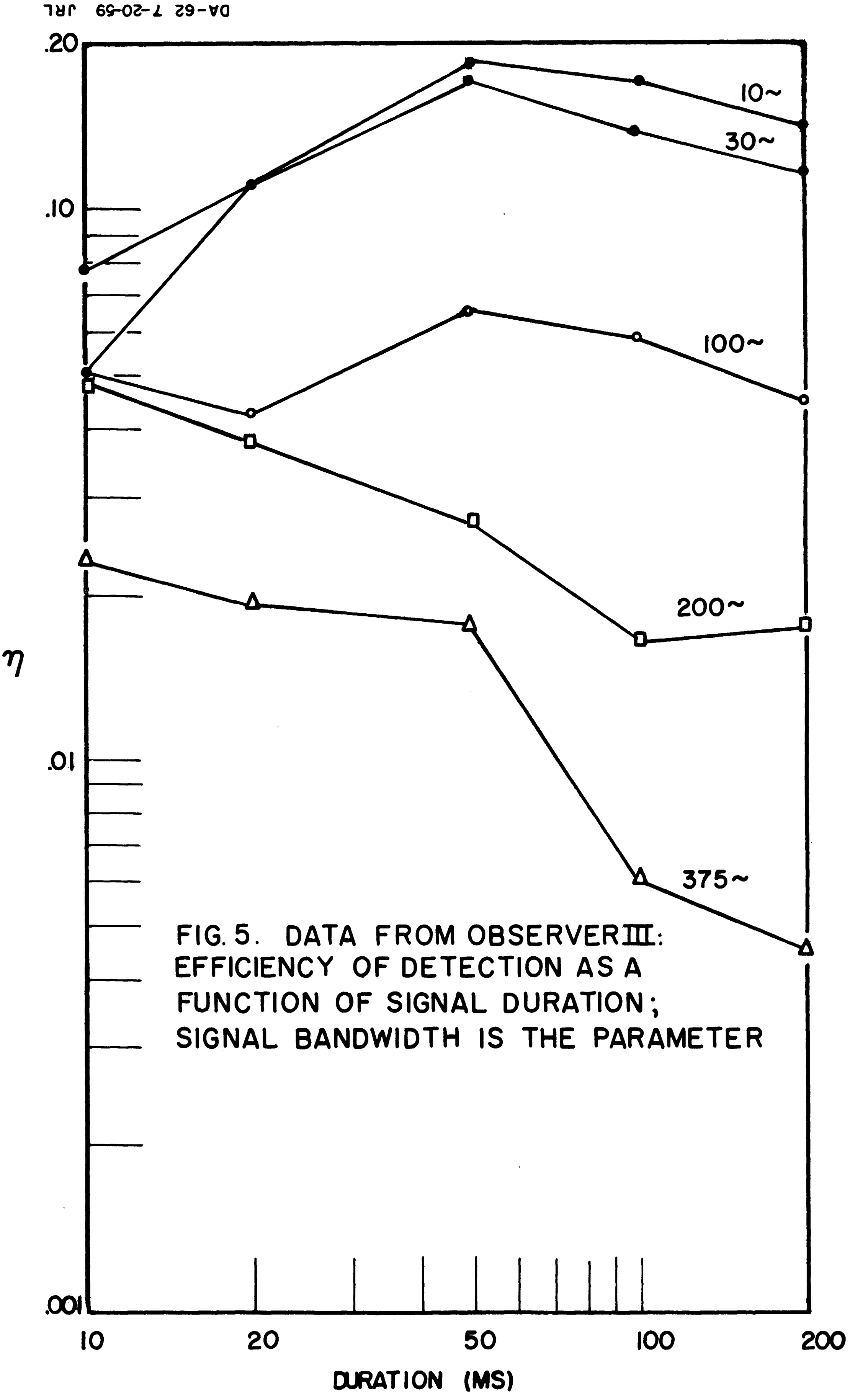

FIG. 5. DATA FROM OBSERVER III: EFFICIENCY OF DETECTION AS A FUNCTION OF SIGNAL DURATION; SIGNAL BANDWIDTH IS THE PARAMETER

of the number of pulses if signal energy is held constant. Some simplifying assumptions (number of pulses large, $2E/N_0$ small) lead to the prediction of a slope on a log-log plot of -1. This seems to agree fairly well with the obtained data, and seems reasonable. A rapidly decaying pulse has very little amplitude at the end to serve as a "cue" to the phase at the start of the following pulse.

Another way of characterizing these data might be to consider the observers unable, for one reason or another, to match their receptive mechanisms to the complex spectrum of a wide-band signal. A longer sample of the signal would, under this interpretation, lead to more opportunity for such a mismatch. If this were the case a further experiment investigating amplitude discrimination in a forced-choice situation would be expected to lead to even greater discrepancy between narrow- and wide-band detection at long durations. If phase incoherence between pulses (repeat cycles, in this case) is a reasonable explanation for the present data, the discrepancy might be expected to be less in an amplitude discrimination task where more phase information would be carried by the signals themselves. This assumption is based on a recent mathematical study by Birdsall[14], who considered the effect of a limited, noisy memory capacity in an observer on detection. It was shown that such a noisy memory has a greater depressing effect on efficiency at low than at high values of $2E/N_0$. In intuitive terms this seems reasonable, in that a signal which is "loud and clear" carries with it much information which could be utilized by the observer, making the imperfect memory less of a handicap.

Individual differences of a qualitative sort appear quite often in psychophysical experiments. The data from Observer III exemplify the sort of problem this raises. Where the first two observers could be characterized as being able to match their receptive systems to the incoming signal, this observer may be seen as having a fixed upper limit on bandwidth of roughly 100 cycles. Such an interpretation qualitatively predicts the form of the data, but is hardly sufficient to account quantitatively for them. Further experiments testing the adequacy of implications of this interpretation would be needed.

This experiment was run and is being reported with the aim of question-raising rather than question-answering. The results point toward some answers to problems in the perception of complex signals. Explanations were offered only as rough-hewn hypotheses for further test and eventual shaping and polishing. The question of individual differences in the ways observers listen for stimuli has hardly been touched in psychophysics and requires extensive consideration. The adequacy and explanatory power of postulating an adjustment mechanism in human observers which is matched to the stimulus needs to be further explored and the parameters of this mechanism understood for individual observers.

The stimuli used in this experiment were chosen for their similarity to speech signals. The results point toward the feasibility of studying speech detection from the view point of signal detectability theory. They also suggest the unavoidable complexities to be met in extending the theory in this direction. The available power and precision of the model make such an extension seem well worth the effort involved.

REFERENCES

1. W. P. Tanner, Jr., J. A. Swets, and D. M. Green, "Some General Properties of the Hearing Mechanism," Electronic Defense Group Technical Report No. 30, The University of Michigan Research Institute, Ann Arbor, (1956).

2. J. C. R. Licklider, "Three Auditory Theories," in S. Koch, Ed., Psychology: A Study of a Science, McGraw-Hill, New York, 1959.

3. W. W. Peterson and T. G. Birdsall, "The Theory of Signal Detectability," Electronic Defense Group Technical Report No. 13, The University of Michigan Research Institute, Ann Arbor, (1954).

4. D. M. Green, T. G. Birdsall, and W. P. Tanner, Jr., "Signal Detection as a Function of Signal Intensity and Duration," J. Acoust. Soc. Am., 29, 523-531 (1957).

5. O. P. Gandhi and G. E. Peterson, "Recurrently Impulsed Resonators," (in preparation) Speech Research Laboratory, The University of Michigan Research Institute.

6. D. M. Green, "Detection of Multiple Component Signals in Noise," J. Acoust. Soc. Am., 30, 904-911 (1958).

7. T. Marill, "Detection Theory and Psychophysics," Technical Report No. 319, Research Laboratory of Electronics, M. I. T., 1956.

8. H. Fletcher, "Auditory Patterns," Revs. Modern Phys., 12, 47-55 (1940).

9. D. M. Green, "Detection of Signals in Noise and the Critical Band Concept," Electronic Defense Group Technical Report No. 82, The University of Michigan Research Institute, Ann Arbor (1958).

10. J. C. R. Licklider, "Basic Correlates of the Auditory Stimulus," in S. S. Stevens, Ed., Handbook of Experimental Psychology, John Wiley and Sons, New York, 1951.

11. G. A. Roberts, "The Operational Features of N. P. Psytar," (in preparation) Electronic Defense Group, The University of Michigan Research Institute, Ann Arbor (See also Green, Birdsall, and Tanner, op. cit.).

12. W. P. Tanner, Jr. and T. G. Birdsall, "Definitions of d' and η as Psychophysical Measures," J. Acoust. Soc. Am., 30, 922-928 (1958).

13. P. B. Elliott, "Tables of d'," Electronic Defense Group Technical Report No. 97, The University of Michigan Research Institute, Ann Arbor, 1959.

14. T. G. Birdsall, "Detection of a Signal Specified Exactly with a Noisy Stored Reference Signal," Electronic Defense Group Technical Report No. 93, The University of Michigan Research Institute, Ann Arbor, 1959.