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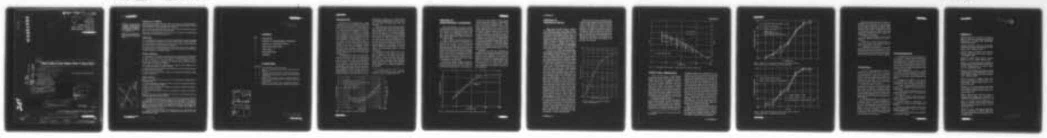

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Recent Studies of Some Auditory Factors in Sonar Search

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statement of problem

BuShips problem NE 121301 (NEL 1B1): "Study and conduct tests and measurements on the psychophysical problems arising from the human detection, recognition, and evaluation of information from sonar equipment and systems . . ."

BuAer T. E. D. Project NEL-EL-800 (NEL 1B2): "Study human factors involved in operation of airborne anti-submarine warfare equipment . . ."

This report is concerned with an analysis of the ear's performance in detecting weak signals similar to those encountered in sonar.

conclusions

1. Aural detection of pure tones of at least one-second duration, masked by random noise, is significantly improved by the use of filters narrower than the aural critical band.

2. Aural detection of sounds having continuous spectra similar in shape to the background-noise spectrum is impaired by narrow filtering.

3. Laboratory tests indicate the possibility that the search rate of a sonar system involving one operator can be doubled by the operator's simultaneous use of both ears for search, each ear on a different bearing.

recommendations

1. Consider the use of multiple narrow filters centered in separate aural critical bands for sonar equipment designed for passive detection of single-frequency components.

2. Utilize a wide band — not less than 2000 cps, and wider if possible — for sonar systems used to detect screw cavitation. The frequency band presented to the ear should contain the region around 800 cps.

3. Investigate the feasibility of heterodyning sonic frequencies above 3000 cps down to the region around 800 cps to improve detection.

4. Make field tests comparing duplex aural presentation and conventional aural presentation for echo-ranging search.

5. Continue research on utilization of duplex aural presentation, emphasizing possible extension to passive sonar.

work summary

Laboratory psychophysical tests were made on aural recognition of masked signals of the following types:

1. Pure tones masked by noise bands of widths varying from 5 to 3000 cps with center frequencies at 200, 800, and 3200 cps.

2. Bands of noise of widths from 5 to 7000 cps, centered at 200, 800, and 3200 cps, masked by similar noise bands.

3. Dopplered echoes masked by noise and reverberation for duplex aural presentation tests.

Signal and noise were carefully controlled, and from five to twenty listeners were used to provide measurements of high reliability.

The experimental work was performed by members of the Psychophysics Branch; C. A. Shewmaker and P. O. Thompson conducted the psychophysical tests under the general supervision of T. H. Schafer. H. R. Beitscher was responsible for providing the recorded sounds. The assistance of the Recording Laboratory and the Instrumentation Section in providing test material and equipment is gratefully acknowledged. The wholehearted cooperation of the many observers from San Diego State College was essential to the success of the study.

The work covered by this report was completed prior to 31 October 1950, and was presented at the Navy Symposium on Underwater Acoustics, New London, Connecticut, November 1950.

CONTENTS

ILLUSTRATIONS

INTRODUCTION

The human ear has developed into a highly specialized instrument for detecting and identifying sounds. Inasmuch as detection and identification are two of the essential purposes of sonar equipment, it is important to study the operation of the ear in order to utilize fully its capabilities in aural reception of information, and to adapt such knowledge to the presentation of sonar information by means of visual displays. This paper presents the results of three experiments on the performance of the ear as a detector of weak signals similar to those encountered in sonar. The first study deals with the audibility of pure tones in a background of random noise. The second concerns the audibility of noise-like spectra, such as propeller cavitation noise, in a background of random noise. The third study deals with the independent use of the two ears for echo-ranging search.

The basic problem in sonar search is the detection of the presence of a signal in a background of noise. The term noise is here used in the general sense and includes sea reverberation. Noise will always be present in a properly engineered system, for the absence of noise indicates that insufficient amplification is being used. The ear has proved to be an exceptionally efficient detector under noise-limited conditions, for the ear, without the aid of external filtering, can hear some signals as far as 20 or 30 db below the over-all level of many noise backgrounds. An alternate way of stating this is that aural recognition differentials* of —20 to —30 db have been observed (UCDWR M399, 1946). (See References.)

It has been shown by NEL and others that the ear has this high degree of signal discrimination because its performance is similar to that of an equipment provided with a set of contiguous bandpass filters such that detection occurs in that filter having the most favorable signal-to-noise ratio (UCDWR, 1944; Schafer, *et al.*, 1950, pp. 490-496). The effective widths of these filters are essentially those of the aural critical bands introduced by Fletcher, and vary from about thirty to several hundred cycles per second, depending on the frequency of the signal (Fletcher, 1940; French, 1947). Figure 1 shows the values of critical bandwidths reported by various experimenters.

Since the ear acts as though it has its own filter, the addition of a filter wider than the critical band is usually not of much help in aural recognition, except in cases where it allows the operator to raise his gain to the point where background noise in the vicinity of the signal frequency becomes audible (NDRC, 1946, p. 124), or where distractive sounds extraneous to the detection problem may be eliminated.

* The recognition differential is the value of the signal-to-noise ratio, expressed in decibels, at which a signal is perceived 50 per cent of the time (NDRC, 1946, p. 61).

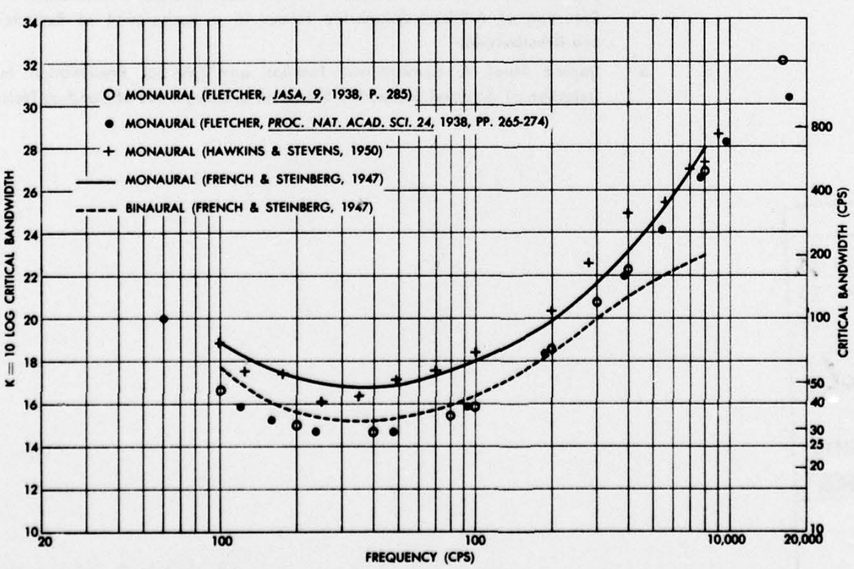

Figure 1. Aural critical bands as a function of frequency.

DETECTION OF SINGLE-FREQUENCY COMPONENTS

Ships and submarines are known to radiate spectra with discrete frequency components, even at low speeds. The ear is an excellent detector of this type of signal in a background of random noise, yet it can be aided considerably by the use of filters narrower than the ear's critical bands (Schafer, *et al.*, 1950, p. 492).

Figure 2 shows the improvement measured in recent tests of 20 listeners at this Laboratory for filter bands as narrow as 5 cps with a pure-tone signal of 1.5-sec duration. Curves are shown for signal frequencies at 200, 800, and 3200 cps. The improvement possible with narrow filters is, of course, subject to the theoretical limit that the bandwidth must be at least equal to the reciprocal of the signal length in order to pass the principal spectrum component. In practice, variations in frequency with time encountered for most radiated ship sounds impose a practical limit on the pass band.

It should be noted that detection of sounds of unknown frequency requires a method of frequency scanning with these narrow filters. With filters narrower than the critical band it is not necessary to use the ear as a final indicator in order to achieve the performance shown in figure 2. A visual indicator such as a cathode-ray oscilloscope, meter, or chemical recorder would do essentially as well for monitoring a single channel. The ear, however, has a marked advantage where many channels are to be monitored; for instead of requiring a large number of separate indicators to be manned, or to be scanned consecutively, the feeding of each filter into a separate aural critical band allows simultaneous monitoring of many channels by a single operator. The number of independent channels which can be monitored effectively with no appreciable adjacent-channel-noise interference has not yet been determined, but theoretically may be as many as 90 per ear, which is essentially the total number of critical bands available.

Experiments are under way to determine the feasibility of this multi-channel presentation for eight channels. Numerous applications of this principle to extend the search capabilities of sonar systems in frequency and directional coverage suggest themselves. One example is a multiple-frequency search device having many very narrow response bands; this device, known as a "comb filter," is currently under development by the Federal Telecommunication Laboratories.

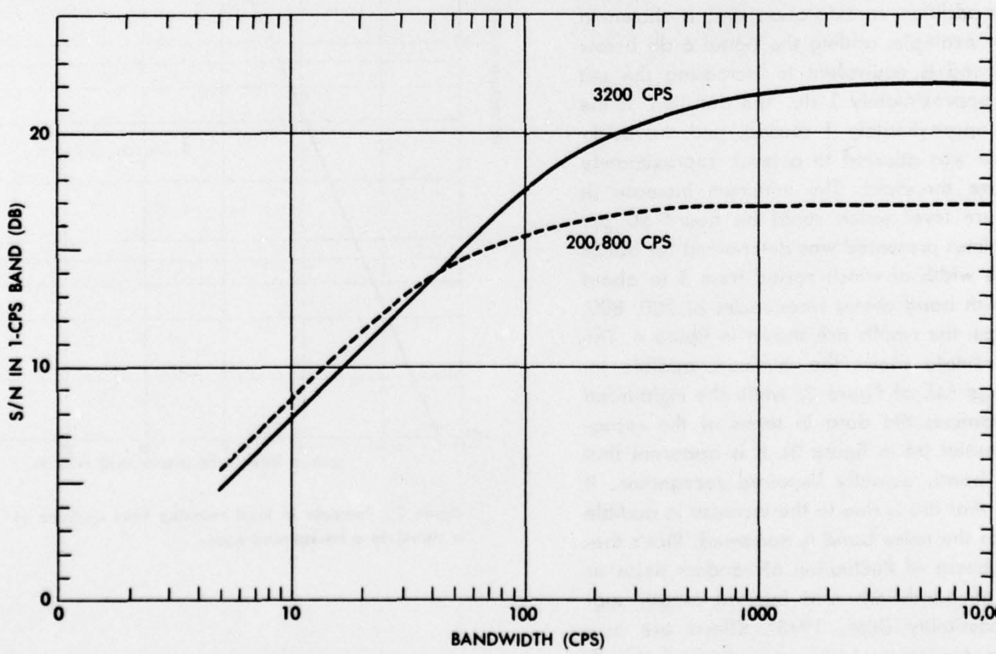

Figure 2. Level of pure tones relative to spectrum level of noise for 50 per cent recognition.

DETECTION OF CONTINUOUS SPECTRA

Sonar systems are often required to detect a very different type of signal, for example, one which has a continuous spectrum identical with that of the background noise. Propeller cavitation noise is of this type and is often described as being audible as merely an increase in the background noise on a certain bearing. Where signal and noise spectra are identical in shape, it is apparent that no gain in signal-to-noise ratio is obtainable through filtering of any sort. Filtering does affect aural detectability of this type of signal, however, as shown by the results of studies just completed at this Laboratory.

Tests were run on five normal-hearing college students listening with headphones on two ears. Each test consisted of listening continuously to a background of filtered random noise into which random noise from another generator, identically filtered, was added at intervals and at various levels relative to the background noise. This second noise was called a "signal" and was audible only as a brief increase in level of the original background noise. The increase in level, ΔL, occasioned by adding the signal M db below the original noise is easily computed from power-addition consideration and is shown in figure 3; for example, adding the signal 6 db below the background is equivalent to increasing the net noise level approximately 1 db. The duration of the signal was approximately 1 second, and the background noise was adusted to a level approximately 30 db above threshold. The minimum increase in sound-pressure level which could be heard 50 per cent of the times presented was determined for bands of noise, the width of which varied from 5 to about 7000 cps, with band center frequencies at 200, 800, and 3200 cps; the results are shown in figure 4. The left-hand ordinate shows the minimum audible intensity change (ΔL of figure 3) while the right-hand ordinate expresses the data in terms of the recognition differential (M in figure 3). It is apparent that the narrow bands actually impaired recognition. It is suspected that this is due to the increase in audible fluctuation as the noise band is narrowed. Rice's theoretical treatment of fluctuation of random noise as a function of bandwidth and interval length suggests this possibility (Rice, 1943). Efforts are now being made to interpret the experimental results quantitatively in terms of fluctuation theory.

Figure 4 also shows that, for comparable bandwidths, the band centered at 800 cps was superior to bands at 200 or 3200 cps. This supports the current practice of heterodyning screw noise, in supersonic listening, to the frequencies near 800 cps for aural presentation. It suggests further that sonic listening in the frequency range above 3000 cps would be improved by heterodyning to the frequency region near 800 cps. Some evidence of the effectiveness of this technique has been supplied by a heterodyne device developed by David Taylor Model Basin for improving JT sonic listening.

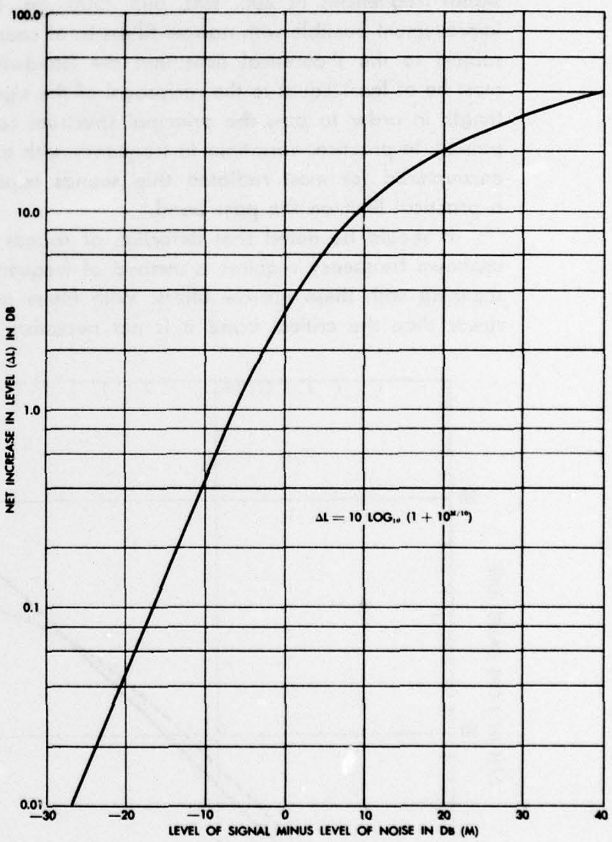

Figure 3. Increase in level resulting from addition of a signal to a background noise.

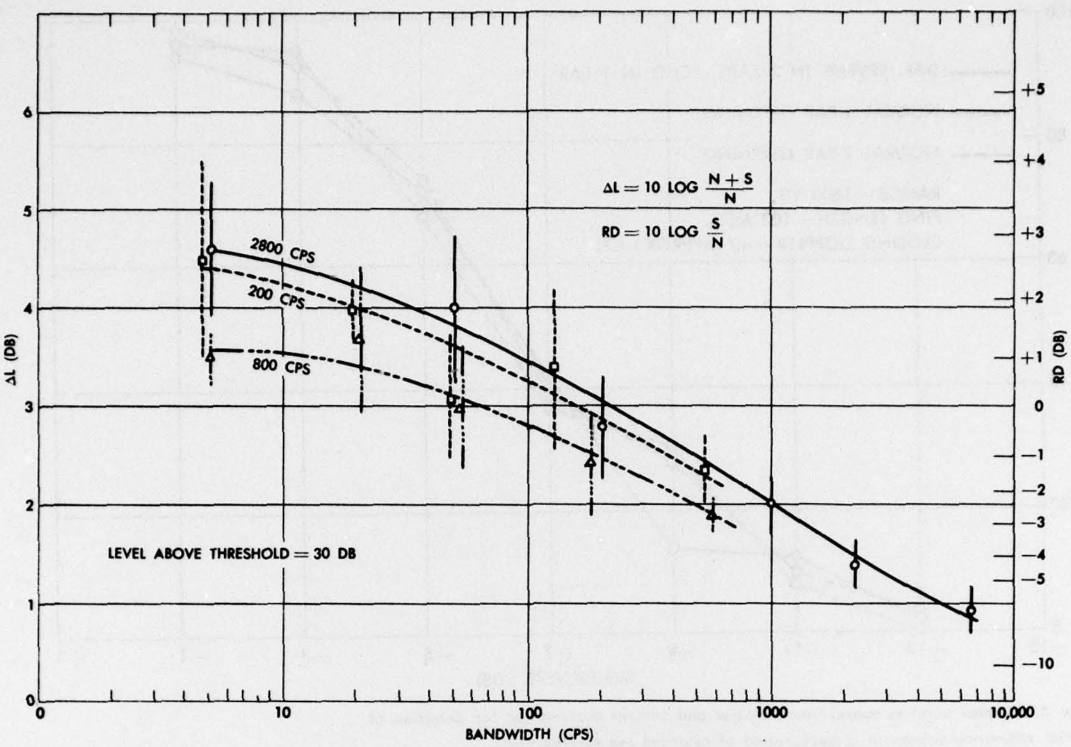

Figure 4. Aural recognition of small increases in the sound pressure level of bands of random noise.

DUPLEX AURAL PRESENTATION

The use of both ears as a single direction-determining system has already proved its utility in binaural sonar systems. The application herein described, however, makes independent use of each ear as far as masking is concerned. It is based on the fact that a sound in one ear does not appreciably mask a sound in the opposite ear unless it exceeds the level of the sound in the opposite ear by at least 40 db. This fact suggests* that the two back-to-back echo-ranging transducers on the AQS-1 dipping sonar could be monitored by the two ears of a single operator, rather than using two operators in an already overloaded helicopter.

To determine whether this rather unusual aural display would confuse the operator and whether a reduction in detectability would occur, simulations were arranged in the Laboratory for both reverberation-limited and noise-limited detection. Since the outputs of the two transducers are uncorrelated, film recordings of different sea reverberations from msec pings were fed into the two ears, but synchronized such that the pings occurred at the same time. An artificial echo of 100-msec duration and 40-cps low-doppler was injected into a single ear at various intensities above and below threshold for five observers. The results of these tests were compared with those of similar tests where the echo and reverberation were fed into one ear only and the normal case where both the echo and reverberation were fed into both ears. The results are shown in figure 5, in terms of the per cent of echoes heard vs the level of the echo relative to the reverberation. No significant difference is observable between the three types of presentation. The value of the 50 per cent recognition differential (—6.5 db) is essentially that observed in other studies (UCDWR M431, 1946) for a 100-msec echo with 40-cps low-doppler.

Similar tests were made with a noise background, two separate noise generators being used to produce uncorrelated random background noise in the two ears. The results of these tests are shown in figure 6 and likewise show no significant difference in detection between the methods of aural presentation.

* Suggested verbally by Dr. J. J. Coop of Naval Air Development Center.

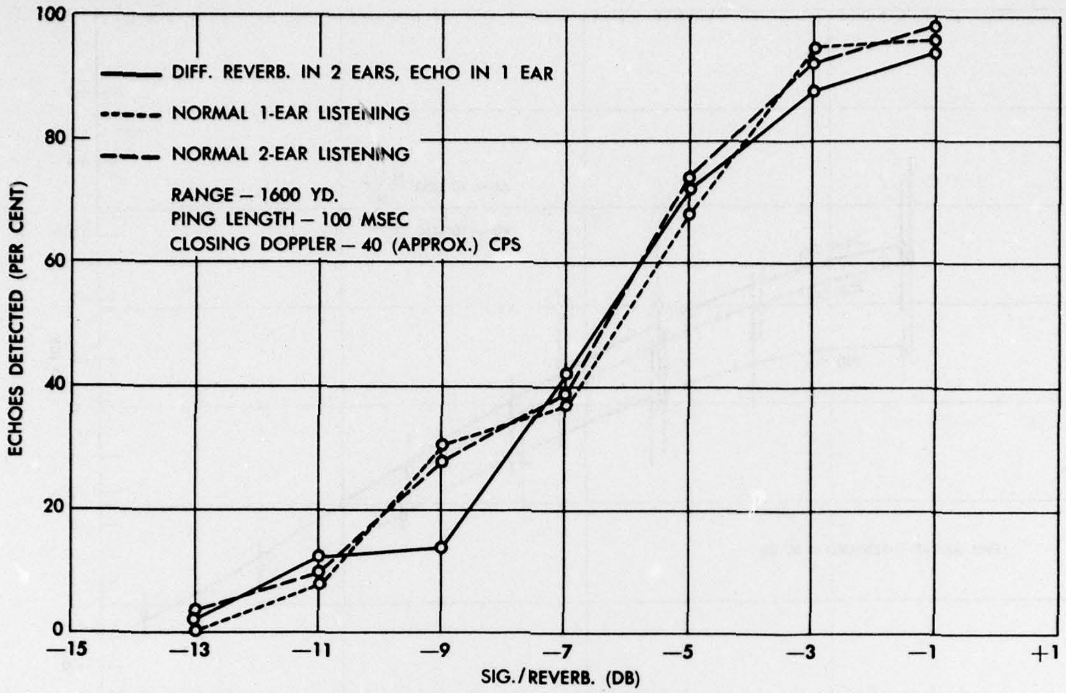

Figure 5. Duplex aural vs conventional two-ear and one-ear presentation for detection of artificial submarine echoes in a background of recorded sea reverberation.

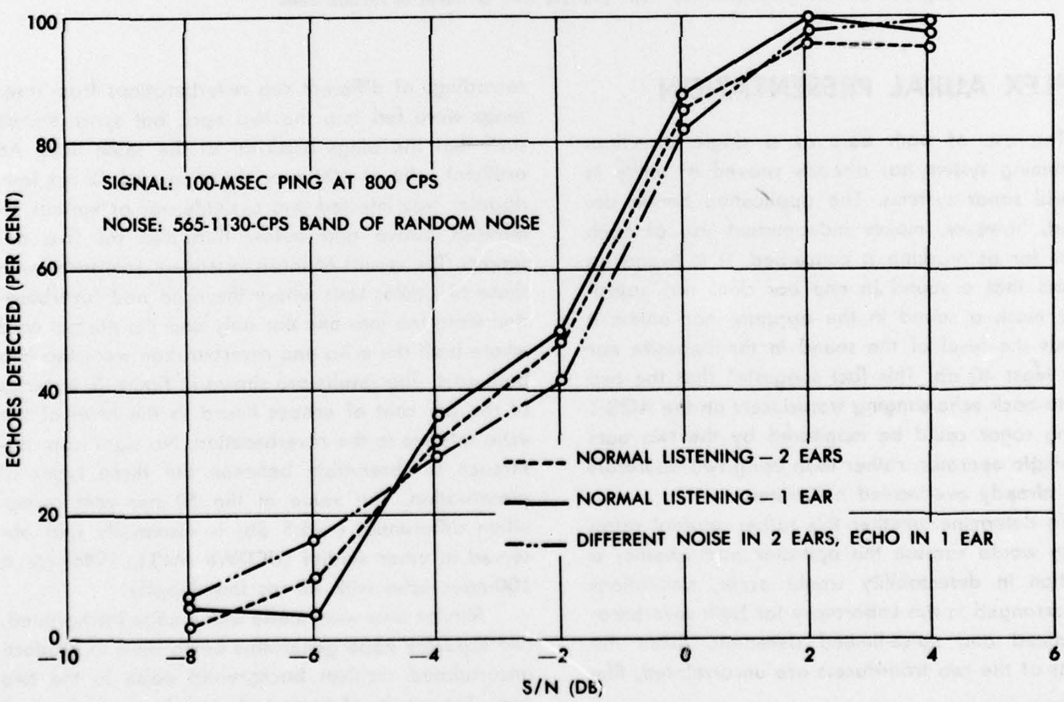

Figure 6. Duplex aural vs conventional two-ear and one-ear presentation for detection of artificial submarine echoes in a background of random noise.

Since the observers also had no difficulty in discerning which ear received the echo, it appears that this system of duplex aural presentation might be quite effectively employed in sonar search systems. Of course, when contact is established, the output of the particular transducer having contact would ordinarily be switched to both ears to continue the tracking phase of the operation.

To improve the performance of sonar systems further, two additional possibilities are being investigated:

1. Application of duplex aural presentation to passive sonar systems is being studied by means of tests on the detection of ship's sounds.

2. Multifrequency presentation of information from several sonar channels simultaneously is under study. This method involves signals (either on active or passive sonar) presented at different frequencies separated sufficiently that mutual masking is negligible.

CONCLUSIONS

1. The use of band-pass filters of widths less than those of the critical bands of the ear improves the aural detectability of pure tones of more than 1-second duration in a background of masking random noise. This improvement appears to be due to removal, by the narrow filter, of noise energy from the frequency region within the same critical band that is excited by the pure-tone signal.

2. The narrow filters, however, impair aural detectability of signals, such as propeller cavitation noise, which are composed of distributed components and have spectra nearly identical with those of the background noise, apparently because of the increased audible fluctuation in narrow bands. Such signals are more easily detected at 800 cps than at 200 or 3200 cps.

3. The aural detectability of an artificial echo of 100-msec duration in a masking background is, for practical purposes, as good when presented to one ear as when presented to both ears. This was found to be true whether the same background was present in one ear or both ears, or whether two incoherent but similar backgrounds were presented to both ears; it was also true for backgrounds of sea reverberation or random noise.

RECOMMENDATIONS

1. Consider the use of many narrow filters, each of which falls in a separate aural critical band, in the development of sonar systems for passive detection of single-frequency components such as are radiated from ship and submarine machinery. When the exact frequency to be detected is unknown, the frequencies of these filter peaks should be slowly varied to provide frequency search.

2. Utilize wide-band *sonar* systems — not less than 2000 cps, and wider if possible — for detection of screw cavitation noise. The frequency band presented to the ear should contain the region around 800 cps.

3. Investigate the feasibility of heterodyning sonic frequencies above 3000 cps so that they are presented to the ear in the region around 800 cps.

4. Indicate, in operating doctrine, the use of as wide a band as possible for supersonic search for propeller noise.

5. Compare duplex aural presentation with conventional aural presentation for echo ranging search in actual field tests.

6. Continue research on duplex aural presentation to determine additional uses, particularly in passive sonar systems.

7. Continue research on simultaneous aural presentation of information at many frequencies to determine:

a. how many separate channels can be aurally monitored simultaneously for search with no appreciable interference; and

b. how well any one channel can be identified when it receives a signal.

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