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HUMAN FACTOR PROBLEMS IN ANTI-SUBMARINE WARFARE

Technical Report 206-23

**STUDIES OF DOPPLER RECOGNITION
USING THE SQS-23 SONAR (U)**

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HUMAN FACTOR PROBLEMS IN ANTI-SUBMARINE WARFARE

Technical Report 206-23

STUDIES OF DOPPLER RECOGNITION USING THE SQS-23 SONAR (U)

- I. DOPPLER RECOGNITION THRESHOLDS**
- II. RECOGNITION OF THE ABSENCE OF DOPPLER**
- III. DOPPLER DISCRIMINATION AS A FUNCTION
OF THE AUDITORY DISPLAY FREQUENCY**

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and
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Prepared for

**Personnel and Training Branch
Psychological Sciences Division
Office of Naval Research
Department of the Navy**

by

**Human Factors Research, Incorporated
Los Angeles, California**

**June 1963
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SUMMARY AND CONCLUSIONS

Introduction

Auditory discrimination of doppler continues to play a major role in the detection and classification of underwater targets. All classification techniques in current use depend heavily on the ability of the sonar operator to correctly identify the presence or absence of doppler. The capabilities and limitations of operators to perform this critical task, therefore, merit continuing investigation. A redetermination of their ability is necessary whenever fundamental changes in transmission frequency, pulse length or signal processing techniques are introduced. The lower operating frequency and increased power output of the SQS-23 necessitated the present study of doppler discriminability using signals processed through that equipment.

Three studies of doppler discrimination were conducted using a test composed of 62 sea-recorded sequences of echoes from submarine targets. The echoes were recorded at the standard display frequency of approximately 800 cps, and, for the purposes of one of the three studies, were heterodyned to six experimental display frequencies ranging from 400 to 1000 cps.

The submarine target operated at depths of 50 - 300 feet and at speeds of 3 and 6 knots. The amount of doppler (in cps) for each of the 62 sequences was computed from the target angle, the speed of the submarine, and the transmission frequency of the sonar. All sequences were obtained using an SQS-23 aboard the USS EDSON off the coast of California.

Purpose

These studies were performed primarily to answer the following questions:

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1. How many cycles of doppler are required to obtain its reliable recognition by sonar operators using the SQS-23?
2. How large are individual differences in doppler recognition ability among sonar operators?
3. Do sonar operators accurately report the absence of doppler when, in fact, either no doppler, or an indiscriminable amount of doppler is presented? What confidence can be placed in their report of "no doppler"?
4. Is the traditional 800-cps presentation frequency optimum for doppler discrimination?

In addition, these studies permitted an exploration of several subsidiary questions:

5. Is there a relationship between ability to recognize the presence of doppler and the correct use of the response of "no doppler"?
6. Are there factors other than pitch discrimination involved in the recognition of doppler?
7. To what extent does "practice" increase the accuracy of doppler discrimination?

Findings and Conclusions

1. Typical sonar operators can reliably* determine the presence and direction of doppler when about 12 cycles of doppler are presented by the SQS-23. Thus, discrimination of doppler with the SQS-23 is superior to that achieved with the older SQS-10 and -11

*84% accuracy.

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(24 cps), the SQS-4 Mod. 3 (22 cps), and the SQS-31 and -32 (22 cps) sonars. Since this is contrary to expectations, it is suggested that the improved discriminability may be due to increased pitch stability of the reverberations and consequent increased tonality of the entire audio pattern.

In spite of improved discriminability, the correct perception of doppler is contingent on greater target speeds because of the lower transmission frequency of the SQS-23. Approximately 3.6 knots of submarine speed (radial component in the sound beam) are required for a reliable discrimination using the SQS-23 (a 5-kc sonar); 2.7 knots are required using the SQS-31 (12 kc), and the SQS-32 (14 kc); and only 1.5 knots were required using the SQS-10 (20.5 kc) and the SQS-11 (25.5 kc). Stated another way, the probability of discriminable doppler being displayed has been reduced.

Thus the likelihood of obtaining valid target movement information by means of doppler has been reduced with the SQS-23 in spite of its superior audio presentation. This will be an increasing problem as transmission frequencies are lowered still further.

2. There are marked differences among operators in ability to discriminate doppler. The most sensitive 25% of the operators correctly discriminate as little as 8 cycles of doppler. In contrast, the poorest 25% require over twice as much doppler for correct recognition. Obviously, advantage should be taken of such differential ability in assigning responsibilities among the various members of the ASW team.
3. Sonar operators do not accurately use the response of "no doppler." When items having no doppler were presented, the probability of their actually reporting "no doppler" was only about .33; this is a chance level of performance in a situation that permits only three alternative judgments.

It must be concluded that inferences about lack of target movement on the basis of doppler are made with considerable risk using present day sonars. Classification procedure must depend even more heavily than in the past upon a correlation of displayed clues in arriving at a conclusion about target motion.

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A possibility remains that it may be easier to discern absence of doppler from nonsubmarine targets that are, in fact, undopplered. This hypothesis could not be tested within the framework of the present study.

4. There is an inverse relationship between doppler discrimination accuracy and audio presentation frequency; i.e., within the range of 500 to 1000 cps, the lower the frequency, the greater the accuracy. This result is consistent with those of laboratory studies in which pure, rather than complex, tones were the stimuli. On the basis of this study, 500 cps, rather than the presently used 800 cps, is the optimal display frequency for doppler discrimination.
5. There is a positive relationship between ability to discriminate the presence of doppler and the accurate use of the response of "no doppler." However, even those operators who were most proficient at discriminating the direction of doppler did not adequately identify the absence of doppler, their performance being 40% correct or only slightly better than chance. Evidently, the selection of sonar operators on the basis of their ability to discriminate pitch differences does not guarantee that those selected will adequately identify the absence of doppler.
6. There appear to be factors in addition to pitch sensitivity leading to small but important differences among sonar operators in accuracy of doppler recognition. Where submarine targets are concerned, a qualitative difference between the portion of the echo returning from the target and that returning from its wake is frequently recognized. This may aid the experienced operator in reaching a correct doppler impression; it frequently confuses the inexperienced operator, resulting in a reverse perception.
7. The results of the present study indicate that once the initial concept is learned, additional training in doppler recognition produces only limited improvement (2 or 3 cps). Probably this improvement is related to the recognition of more subtle characteristics of the echo such as that mentioned above. In any event the contribution of additional training can be expected to be relatively small compared to that made by basic individual differences in sensitivity to pitch differences.

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STUDIES OF DOPPLER RECOGNITION USING THE SQS-23 SONAR (U)

INTRODUCTION

The auditory discrimination of doppler continues to be the most important single discrimination for the valid classification of underwater targets. The accuracy of this discrimination depends, of course, upon the amount of doppler present which, in turn, is directly related to the sonar transmission frequency.

A recent and continuing trend in sonar design has been toward lower transmission frequencies, the purpose being to increase sonar detection ranges. An extrapolation of this trend suggests that, in the future, the doppler available from a slowly moving submarine will not be detectable by the human operator.¹ Because of the importance of doppler discrimination for classification and the reduced evidence of doppler with newer sonars, it appears essential to establish the doppler recognition threshold (DL) for typical fleet operators. Such data provide important benchmarks for those concerned either with the development of electronic doppler discriminators or with target classification aids.

The doppler threshold (DL) is herein defined as the amount of doppler in cps for which the probability of correct response equals 0.84. It may be interpreted as the amount of doppler that produces correct judgments 84% of the time.

DLs have been reported for a variety of past sonars. Kimmel, Parker, and Mackie (1958) reported a DL of 50 cps for SQS-4 (12 kc) sea-recorded returns. In a later study, Harabedian and Parker (1961)

¹Detection of doppler from a slowly moving submarine (less than 3 or 4 knots) is considered crucial for correct classification in that such targets generate few other cues of movement, if any. Detection of doppler from a fast-moving submarine is not as critical because other cues of movement displayed by the PPI and graphic recorder are enhanced.

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reported DLs of approximately 22 cps for SQS-4 (12 kc), SQS-31 (12 kc), and SQS-32 (14 kc) sea-recorded returns. The large DL in the first study was attributed to an echo recognition problem associated with a low signal to noise (reverberation) ratio. Harabedian and Parker concluded that 22 cps is a more accurate estimate of the DL for the SQS-4 or SQS-29 series when the echo from the target is relatively discriminable from the total pattern of displayed auditory information.

Harsh and Eady (1955) reported a DL of 24 cps for the SQS-10 (20.5 kc) and SQS-11 (25.5 kc), again using sea-recorded returns.²

On the basis of these results, it can be concluded correctly that the accuracy of doppler discrimination was not impaired as a consequence of the lower transmission frequency of the SQS-4. However, the probability of discriminable doppler being displayed by that equipment was substantially lower than with the SQS-10 and -11. While only about 1.5 knots (radial component of submarine speed) were required to produce discriminable doppler (84% accuracy) with the SQS-10/11, 2.7 knots were required with the SQS-4.

²A DL of 24 cps is based on a re-analysis of the data reported by Harsh and Eady. The DL reported by Harabedian and Parker was based on a two-category (up or down doppler) response, but in the Harsh and Eady study a three-category response was permitted, viz., up, down, and no doppler. To make the DLs from the two studies comparable, the number of "no doppler" responses to each item was divided equally between the "up" and "down" categories. The DL was then determined from the number of cycles required for 84% accuracy.

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STUDY I: DOPPLER RECOGNITION THRESHOLDS FOR THE SQS-23

The most recently developed active sonar in general fleet use is the SQS-23 with a 5-kc transmission frequency. Using this sonar the amount of doppler displayed by a given target is less than half that available with the SQS-4. If one were to assume that the doppler DLs for these two sonars were equal, nearly 6 knots of target speed in the sound beam would be required to discriminate the direction of doppler reliably using the SQS-23.

Extrapolation of the SQS-4 or SQS-29 doppler DL to the SQS-23 was not felt to be warranted because of the subjective impression that the SQS-23 reverberation pattern was more stable and the echo and reverberations more tonal than those of the earlier equipments. If this apparent increase in pitch stability and in tonality were real, there would be predicted a reduction in the size of the doppler DL in SQS-23 returns.

The primary purpose of the present study was to estimate the doppler DL for SQS-23 sonar returns and consequently to determine whether the lower transmission frequency of the SQS-23 had increased the target speed required for displaying a recognizable amount of doppler. A secondary purpose was to estimate the magnitude of differences among typical sonar operators in doppler discrimination ability.

METHOD

Collection of Recorded Returns at Sea

The audio recordings which provided the basis for the development of a doppler discrimination test were gathered during the first two weeks of May, 1962, off the coast of California between San

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Francisco and Los Angeles.³ DRT overlays were designed prior to the cruise to insure that returns were obtained from targets making known speeds and headings. During each run the submarine operated on a predesignated course at depths ranging from 50 to 300 feet. The audio was recorded on a Concertone Mark VII magnetic tape recorder directly from the output of the receiver. Information from the DRT plots was used to estimate target angles, and data from the submarine's log, photographs of the PPI scope, and TRR traces were used to verify these estimations.

Test Construction

Only the returns from medium pulse (30 ms) operation were used in constructing the doppler test.⁴ All recordings for which target angles could not be verified were eliminated and the remaining materials were cataloged into 5-ping sequences. The average amount of doppler in each sequence was calculated from target angle and submarine speed using the following formula (Horton, 1957).

$$f = (0.69) (fp) (v) (\cos \theta)$$

in which

- f = approximate amount of doppler shift in cps
- fp = frequency of transmitting source (kc/sec)
- v = submarine speed in knots
- 0.69 = the doppler constant for echo transmission (cps/kt. x kc)
- θ = target angle (relative bearing of the recording ship from the submarine)

All items (5-ping sequences) having any of the following

³The exercise at sea was conducted as part of a larger investigation of the classification potential of the SQS-23.

⁴This test has been made available to the Fleet ASW School, San Diego, for use in operator training

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characteristics were eliminated:

1. A multiple echo on one or more pings.
2. A change of 3 degrees or more of cursor bearing during the item.
3. Target turning during the item.
4. Target not detectable in one or more pings.

After this initial screening, 62 acceptable items remained. The means and standard deviations of amount of doppler for these 62 items are shown in Table 1.

Table 1
Means and Standard Deviations of Amount of Doppler (cps)
In Recognition Test Items

	Up Doppler	No Doppler	Down Doppler
M	7.0	0	7.8
σ	4.4	-	4.6
# Items	35	5	22

The means and standard deviations of target range are shown in Table II.

Table II
Means and Standard Deviations of Target Ranges (yards)

	Up Doppler	No Doppler	Down Doppler
M	1900	2700	2000
σ	900	560	1200
# Items	35	5	22

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The items were spliced together with a 5-second blank interval between each item to provide time for the operator's response. The position of each item within the test was determined randomly. Four practice items, two having up and two having down doppler, were also included to acquaint the operators with the nature of the test and to provide a warm-up exercise.

Test Administration

The doppler test was administered to 155 operators, 141 Class "A" students, who had completed their doppler recognition training, and 14 Class "B" students, at the Fleet Anti-Submarine Warfare School, San Diego. Fifty-three of the subjects had been previously tested on the same test heterodyned to a different presentation frequency (see Study II).

Prior to test administration, the general nature of the test was explained to the operators. They were told that their scores would not affect their school grades, but would be used only to provide information regarding the discriminability of doppler.

The subjects were instructed to listen to each item and then respond by marking the answer sheet either "U" (up doppler) or "D" (down doppler) before or during the 5-second interval following the presentation of each item. The instructions emphasized that if the doppler were not perceptible on an item, they were to guess.

The practice items (with immediate feedback) and test were presented by means of an Ampex Model 354 or a Concertone Model Mark VII tape recorder over a loudspeaker to the 155 subjects in 14 groups ranging in size from 7 to 26 operators.

The test was administered in two equal parts with a 5-minute rest between parts. Test administration took approximately 45

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minutes, 15 minutes for instructions and warm-up, and 30 minutes for testing.

RESULTS AND CONCLUSIONS

Reliability of the Doppler Test

The reliability of the doppler discrimination test was estimated by use of split-half correlation. For this purpose only the responses to 48 of the 62 items were scored as correct or incorrect. The remaining 14 items were not scored because they could not be keyed confidently as up or down doppler, i.e., the doppler computed for these items was zero or less than 2 cps (less than the recognition threshold even for pure tones). The correlation between scores on the odd and even numbered scorable items was computed, corrected for doubled length with the Spearman-Brown prophecy formula, and was found to be .77. Reliability of this magnitude was considered adequate for the purposes of the study.

Accuracy of Doppler Discrimination

There were no significant differences in average level of performance (mean number of items correct) between the Class "A" and the Class "B" students. Consequently, the responses of the two classes of operators were combined for the analyses that follow.

The responses of all the operators next were combined for each of the 62 items to obtain a point of subjective equality (PSE) and a difference limen (DL).⁵

⁵ In the present context, the PSE is the amount of doppler in cps at which the probability of a response of up (or down) doppler equals .50. Stated in another way, it is the amount of doppler that can exist and still have the pitch of the echo judged as equal to the pitch of the reverberations. Any deviation of the PSE from zero cps may be interpreted as a judgment (or response) bias.

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A psychometric plot of the data was made by determining the proportion of up-doppler responses to each item and plotting these proportions on normal probability paper against the computed amount of doppler in cps. Inspection of the plot showed the trend to be linear.

A linear function was calculated to fit the data points by the method of least squares. The standard deviation of the function (i.e., the reciprocal of the slope) was used as the DL (Guilford, 1954).

The DL and PSE for the SQS-23 were found to be 12.5 and 0.0 cps, respectively. It is concluded that the average sonar operator can discriminate approximately 12.5 cps of up or down doppler 84% of the time with the type of materials and target ranges used in this study.

Individual Differences in the Accuracy of Doppler Discrimination

An impression of the magnitude of individual differences in the accuracy of doppler discrimination can be gained from inspection of Figure 1. The data points in this figure were obtained by assigning each of the 155 subjects to one of six proficiency groups on the basis of his doppler test score (number of items correct). Twenty-six subjects were assigned to each of five groups, and 25 to the sixth, or least proficient, group. Essentially, each group contained about 17% of the sample. A DL was computed for each group using the procedure described in the previous section.

The DL is the amount of doppler in cps at which the probability of correct response equals 0.84 (Woodworth, 1938). It may be interpreted as the amount of doppler that produces correct judgments 84% of the time. The only circumstance under which the DL can be interpreted to mean that a given number of cycles of up or down doppler was detectable 84% of the time is when the PSE equals zero. The DL, then, is the average discriminable amount of up and down doppler.

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The percentage of operators who had DLs greater or less than a given number of cycles can be determined from Figure 1 by selecting the desired number of cycles on the abscissa and reading the corresponding percentage of operators on the ordinate; e.g., 40% of the operators had DLs less than 10 cps while 60% had DLs in excess of 10 cps.

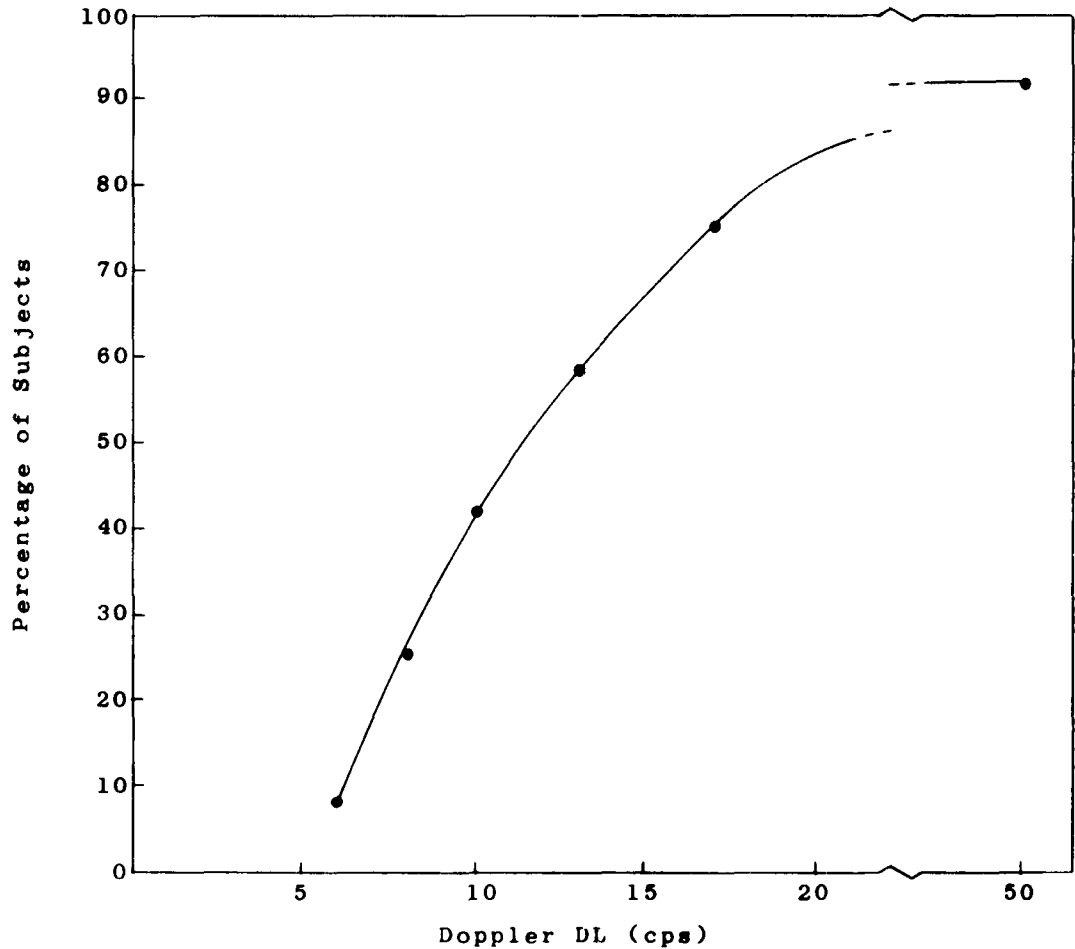


Figure 1. Cumulative percentage of subjects that reliably discriminated a given number of cycles of doppler (N = 155). The 50 cps is based on extrapolation from the data. Note that the median DL for the total group is 11.5, a value slightly less than the mean DL of 12.5 cps. The reason for this is that the distribution of DLs was slightly positively skewed.

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It should be noted that the DL of 50 cps for the poorest performance group is an extrapolated value in that 20 cps was the maximum amount of doppler in the test. While the exact nature of the function beyond 17 cps cannot be stated, there is no doubt that roughly 25% of the subjects had DLs in excess of 17 cps. Further, it seems safe to conclude that 8% of the operators had DLs far in excess of 17 cps, and that the assignment of such men to the doppler judgment task should be studiously avoided. Conversely, advantage certainly should be taken of those having superior doppler recognition ability in assigning responsibilities to the target classification team.

The Effects of "Practice" on the Accuracy of Doppler Discrimination

One hundred and five of the subjects in the present study also participated in that phase of the investigation concerned with presentation frequencies (Study III). Because of the overall experimental design, approximately half (N = 53) of these subjects had had practice in doppler recognition prior to taking the test developed for Study I; the other half (N = 52) had not had such practice. This practice occurred just before testing and was not accompanied by feedback. Thus it constituted exposure rather more than it did training.

A doppler DL was calculated for each of the two groups using the procedure previously described. The DLs for the "practice" and "no-practice" groups were 10.0 and 12.5 cps, respectively.

Because of the absence of an acceptable statistical procedure to test the significance of a difference between DLs, the significance of the difference was estimated by testing the difference between the mean number of items correct for each group. The number of items correct for each subject was obtained by keying the 48 items as either up or down doppler. These 48 items could be

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confidently keyed because they involved targets generating ± 4.4 cps, or more, of doppler.

The mean number of items correct for the "practice" and "no-practice" groups was 38.8 and 36.2, respectively. A t-test of the difference between means was significant beyond the .01 level ($t = 3.2$); consequently it was inferred that the difference of 2.5 cps between the DLs was very likely a real difference.

DISCUSSION AND OPERATIONAL IMPLICATIONS

The results of this study indicate that doppler discrimination with the SQS-23 is superior to that observed with the older SQS-10/11, SQS-4, SQS-31, and SQS-32 sonars. We are of the opinion that this improved discriminability is a result of increased pitch stability in the reverberations probably due mainly to the narrow transmission sector employed.

While this improved discriminability of doppler using the SQS-23 is advantageous and encouraging, it does not necessarily mean that there will be a corresponding improvement in determining target movement or target nature. For this to occur the improvement must be sufficient to offset the reduction of the doppler effect consequent to the use of lower transmission frequencies. This has not proved to be the case. Despite the improved presentation of doppler with the SQS-23, more target speed is required to produce enough doppler for reliable discrimination than with the older, higher frequency, sonars.

Table III compares the amount of doppler and corresponding submarine speeds required to discriminate doppler reliably on three sonars that differ markedly in transmission frequency.

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Table III

Amount of Doppler and Submarine Speed Required for a Reliable Report (84% Accuracy) of Direction of Doppler

	SQS-10/11	SQS-4 (Mod. 3) SQS-31/32	SQS-23
Transmission Frequency	20.5 - 25.5 kc	12 - 14 kc	5 kc
Doppler Threshold (DL) (cps)	24.0 ~	22.0 ~	12.5 ~
Target Speed Required (Radial Component in the sound beam) (knots)	1.5 kts	2.7 kts	3.6 kts

The adverse effect of lowering the sonar transmission frequency is readily apparent. The amount of target speed required for sonar operators to recognize doppler has more than doubled since the SQS-10 in spite of the improved presentation of the more recent equipment.

There is little doubt that the comparatively low transmission frequency of the SQS-23 has reduced its classification potential. This should not necessarily be interpreted to mean that overall target classification capability using the SQS-23 is less than that of the older sonars (though this, too, may be true), but only that the lowered transmission frequency has decreased the likelihood of obtaining valid target movement information.

The trend toward lower frequency sonars continues with the advent of the SQS-26, a 2.5- and 3.5-kc sonar, that is currently under evaluation. This sonar will produce approximately 2 cycles of doppler per knot of target speed in the sound beam. Obviously, unless some improved method of display can be found, operators will

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be unable to detect doppler reliably from targets that elect to move slowly. (In fact, in some operating modes the SQS-26 will not have a doppler display at all.)

To date, doppler discrimination machines have met with very limited success, probably because they have been designed as a replacement for the operator rather than as a device for aiding his judgment. A successful device would seem to have to take advantage of the best capabilities of both the man and the machine.

Despite the fact that all potential sonar operators are screened with respect to their ability to discriminate pitch differences, the results of the present study show that marked differences remain among operators in ability to discriminate doppler. While the average SQS-23 operator can be expected to discriminate about 12 cycles, some operators will be distinctly better, others very inferior, at the task. About one operator in 10 should never be used for the task at all and every effort should be made to insure that the best available man makes the judgment whenever possible. It is doubtful, however, that most ASW teams know who their best doppler discriminators are, although, with the numbers of sonarmen on board, each ship is likely to have at least one superior one. It is likely that more stringent selection procedures would increase the number of superior doppler discriminators substantially but the limited pool of personnel probably precludes this approach.

Another possible solution is suggested by the fact that "practice" results in a slight, but statistically significant, improvement in doppler discrimination accuracy. These results are somewhat surprising in that "practice" in the present study was limited to the taking of a 62-item doppler test, with no knowledge of results, at some frequency other than 800 cps. However, the effects of "practice" were quite small compared to the individual differences noted earlier.

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Although these results may not be considered definitive with respect to the effects of training, they are consistent with those reported by Meister (1953) which showed that improvement in the accuracy of doppler discrimination, if it occurs at all, appears very early (within three hours) during training. In the present study, an improvement was demonstrated after 30 minutes of "practice," but, as in Meister's study and in other studies cited by Pickering (1959), the improvement was quite small, being about 2.5 cps on the average.

In 1946 the UCDWR staff summarized the effects of training on the accuracy of doppler discrimination as follows: "The inherent ability to detect pitch change is a remarkably stable one, not subject to much improvement once the student has grasped the problem, but experience with complex pitch changes undergone by underwater sounds is of distinct value." This conclusion still appears appropriate today.

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STUDY II: RECOGNITION OF THE ABSENCE OF DOPPLER

INTRODUCTION

Although it is not always emphasized, the valid classification of underwater targets is often heavily dependent upon the sonar operator's ability to correctly recognize "no doppler," when in fact there is none. Although this might be assumed to be an easy task compared to recognizing the presence and direction of doppler, it is not by any means always the case.

Two identifiable target classification systems are in current existence: the NEL (HHIP) system which can be considered operational, and the HFR system as described in NAVPERS which is used as the basis for instruction in the ASW schools. While the two systems are somewhat similar, they require the operator to report judgments of doppler in different ways. The NEL system requires that the operator indicate whether or not doppler is present and, if so, its direction; the HFR system requires that he indicate simply whether doppler is present or absent. Reliable recognition of the absence of doppler thus is important in both systems, while the discrimination of direction is important only in the NEL system.

The results of a study conducted by Harsh and Eady (1954) showed that the response of "no doppler" was reasonably correctly used; in the absence of doppler their subjects reported correctly 64% of the time. However, their study was conducted using the higher frequency SQS-10/11 sonars and subjects who were more highly trained and motivated than the typical fleet operator. An investigation of the ability of a representative sample of operators to make this judgment, using the SQS-23, was therefore considered desirable. This was the primary purpose of the present study.

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It also had two secondary purposes: (1) to determine whether there is a relationship between ability to discriminate the direction of doppler, when it is present, and the ability to recognize "no doppler" when, in fact it is absent; and (2) to explore the hypothesis that some operators make errors in doppler recognition because they improperly distinguish between that part of the echo returning from the submarine and that part returning from the submarine and that part returning from its wake.

METHOD

Test and Subjects

The doppler discrimination test used in Study I was administered using the same tape recorders, to 50 operators: 36 Class "A" and 14 Class "B" students, at the Fleet Anti-Submarine Warfare School, San Diego.

Test Administration and Instruction

The test was administered twice to groups of 12, 14, and 24 subjects with 10 minutes' rest between the two administrations.

During the first administration, the subjects were told to respond by marking their answer sheets with a "U" for up doppler and a "D" for down doppler during the 5-second interval following each item. The instructions emphasized that if the doppler were not perceptible, they were to guess.

During the second administration, they were told to respond with "U" or "D" or "N" (for no doppler) as if they were making a doppler judgment for classification purposes.

The test was in two halves with a 5-minute rest between halves. The order in which the two halves were presented was reversed for

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the second administration. None of the subjects was aware that he had taken the same test twice.

The four practice items which were used for Study I were added to two additional practice items having no doppler and these were presented, with feedback, prior to the second administration of the test.

RESULTS AND CONCLUSIONS

The Use of the Response of "No Doppler"

The responses of all subjects were combined for each item and the proportions of U and D responses were plotted separately on normal probability graph paper. Inspection of the plots showed the trends to be linear and linear functions were calculated to fit the data points using the method of least squares.

Figure 2 shows these functions as well as the curve of "no doppler" according to the amount of doppler presented. The latter curve was obtained by subtracting the proportion of U and D responses at a given point on the abscissa from 1.00.

Figure 2 may be interpreted as follows. For example, for 15 cps of up doppler, 68% of the responses were "up," 21% were "no," and 11% were "down." The distribution of responses for any amount of doppler shown on the abscissa can be read from the three curves in the same manner.

The important result to note is that all three curves intersect 0.0 cps at approximately the same ordinal point, representing a proportion of 0.33. This means that all three responses, U, D, and N, were equally likely to occur when no doppler was presented. Stated differently, no reliable use of the response "no doppler" was made to undopplered items, the proportion of correct responses,

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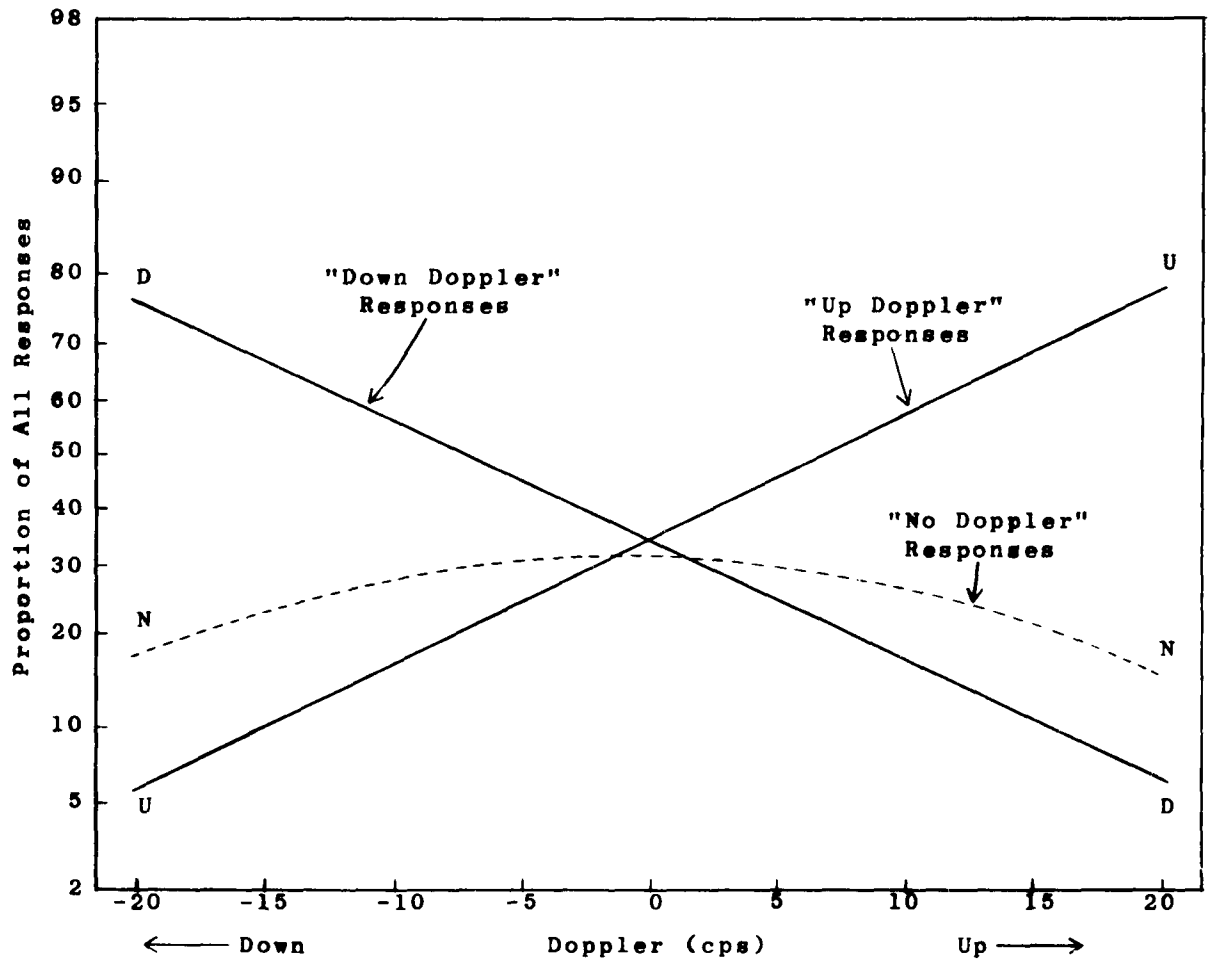


Figure 2. Proportion of up, no, and down doppler responses as a function of amount of doppler.

in fact, being no greater than that expected by chance.

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The Relationship Between Ability to Discriminate the Direction of Doppler and the Correct Use of the Response of "No Doppler"

To establish groups that differed in ability to discriminate the direction of doppler, each of the 50 subjects was assigned to one of four groups on the basis of his score (number of items correct) on the two-choice (U-D) doppler test. The two groups most proficient at doppler discrimination each contained 12 operators; the remaining two groups each contained 13 operators.

To determine how much the four groups differed in ability to discriminate doppler, a psychometric plot was made for each group; i. e., the proportion of responses of "up doppler" for each item was transformed to a z-score (normal deviate score) and plotted against the amount of doppler in cps.⁶ Inspection of the plots showed the trends to be linear, and, linear functions were calculated to fit the data points. The slopes of the functions (in z-units) were used as measures of ability to discriminate.

To properly obtain the percentage of correct "no-doppler" responses, it was necessary to correct for any group differences (biases) in willingness to use, or not to use, the response of "no doppler." To do this the percentage of "no doppler" responses to items not having doppler was divided by the sum of the percentages of "no doppler" responses to all items.

Figure 3 shows the resulting percentages of correct "no doppler" responses for each group.

⁶ Transformations of proportion to z scores usually results in a linear regression of z on stimulus values (cps of doppler).

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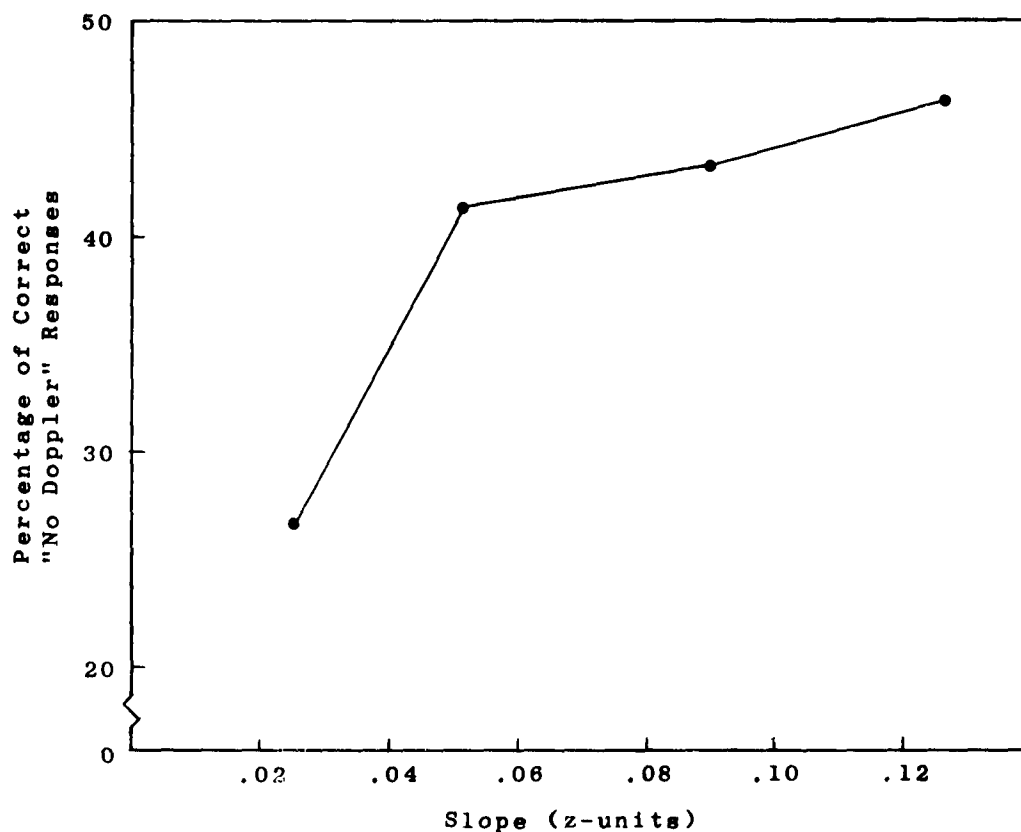


Figure 3. The percentage of correct "no doppler" responses as a function of ability to discriminate the direction of doppler. (The slope is a measure of ability to discriminate doppler, the larger values meaning better discrimination.)

The results show a positive relationship between ability to discriminate the direction of doppler and the percentage of correct responses of "no doppler." While the differences among the three groups of great ability were small, the group performing poorest in making the up-down discriminations was also markedly inferior in identifying the absence of doppler.

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Recognition of the Components of the Echo as a Possible Source of Individual Differences in Doppler Discrimination

Incidental observations of SQS-23 audio returns had suggested that doppler generated by submarines at bow aspect was more difficult to recognize correctly than the same amount of doppler generated by submarines at stern aspect. With direct aspect targets, echoes are commonly produced from both the submarine and its wake. It was hypothesized that, because the up-doppler echo from a bow submarine is frequently quite weak, the operator might not clearly distinguish it from the reverberations. If he did not, he might interpret the downward shift in pitch between the target echo and the essentially undopplered wake echo as a case of "down doppler."

The substantial differences among operators in accuracy of doppler discrimination, then, might not be entirely the result of differences in recognizing pitch shifts but, in part, a result of failure to distinguish between that portion of the echo from the submarine and that portion from its wake.⁷ If this were so, the following predictions should hold. The poorer performers in judging the direction of doppler (on a two-choice test), when given the opportunity to make three alternative responses—"up" - "down" - "no"—will show a greater number of reversal responses (reports of doppler in the wrong direction) to items with up doppler (bow targets) than to items with down doppler (stern or quarter targets). In addition, the poorer performers, although making a greater absolute number of errors on all types of items will make a proportionally larger number to up-doppler items than to undopplered items.

On the other hand, if sensitivity to pitch changes were the only factor responsible for accurate doppler discrimination, one

⁷ A similar prediction would not be made for targets at stern aspect. In this case, since the first portion of the echo comes from the target's wake, there should be a recognizable intervening pitch shift between the reverberations and the initial echo.

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would expect that the subject confronted with three alternative responses would be more likely to report "no doppler" when slight doppler were present than he would be to make a reversal response. If pitch alone were involved, the less sensitive the subjects the more likely the pitch of reverberation and echo should appear to be equal and the greater should be the tendency to respond "no doppler."

To test these hypotheses, the data from the three-choice test were reanalyzed. The percentage of reversal responses to items with up and down doppler for each proficiency group (described on page 23) was obtained by totaling the frequency of "down" responses to up-doppler items and "up" responses to down-doppler items and dividing each sum by the total number of responses made to all items in each group. The results are shown in Figure 4.

It will be noted that there was a substantial negative relationship between general proficiency and number of reversal responses. More important, as predicted, the least proficient operators made a disproportionate number of reversal responses to items having up doppler. Groups 1 and 2 showed a slight opposite effect, in fact, which may have been due to the fact that the mean amount of doppler for down-doppler items (-8.5 cps) was slightly less than that for the up-doppler items (9.6 cps).

It should be noted also that the percentage of reversal responses to up-doppler items increased at a much greater rate than did the responses of "no doppler." In fact, Group 4, the least proficient group, responded "down doppler" more often than "no doppler" to items actually having up doppler. In contrast, the percentage of reversal and "no-doppler" responses to items having down doppler increased at about the same rate. Group 4 did not show a disproportionate increase in reversal responses to down-dopplered items.

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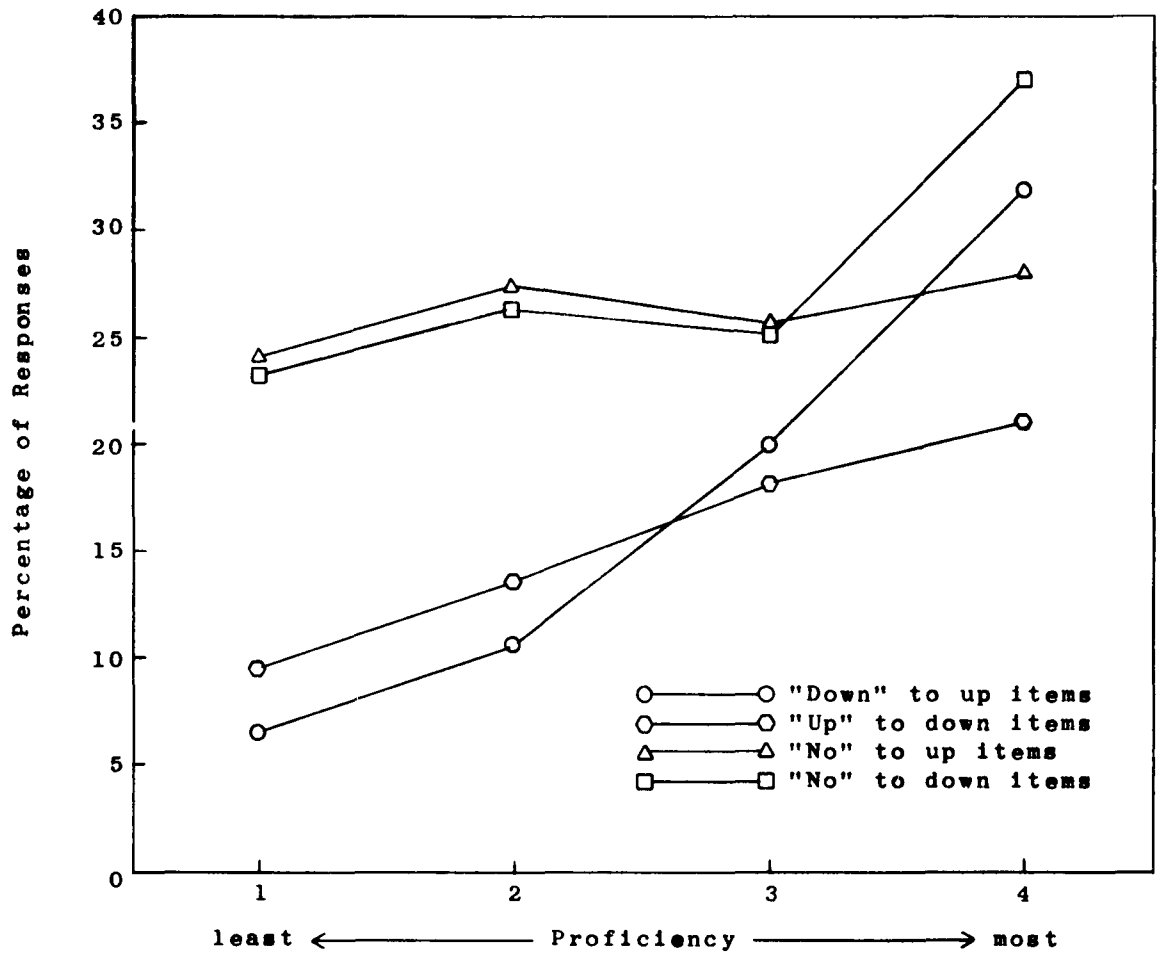


Figure 4. Percentage of reversal and "no doppler" responses for four proficiency groups.

These results support the hypothesis that the magnitude of operator differences in the accuracy of doppler discrimination are not only a result of differences in sensitivity to pitch changes but are, in part, related to the ability of the operators to properly distinguish various portions of the echo that may be associated with the target proper or with its wake.

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DISCUSSION AND OPERATIONAL IMPLICATIONS

As was pointed out in the introduction, present active sonar classification systems depend rather substantially upon the ability of the sonar operator to accurately report the presence or absence of doppler. The results of the present study showed that sonar operators, as a group, were unable to reliably recognize the absence of doppler. The average operator reported "no doppler" only about 33% of the time (chance performance) when in fact the item was undopplered.

This result is not consistent with those of Harsh and Eady (1954) who reported 64% accuracy for undopplered targets. However, their results were obtained using SQS-10 sonar and a small group of highly trained and strongly motivated subjects.

Assuming that the results of the present study can be generalized to the sonar operator population, it is clear that the efficiency of active sonar classification systems will be reduced by the inability to depend on the "no doppler" judgment.

Since the effects of training appear to be limited, some improvement might be realized by having the operator express the confidence with which he reports the presence or absence of doppler. A measure of confidence may more validly reflect the presence (or absence) of doppler than the direct report by itself.

There is evidence that supports the feasibility of such an approach. Johnson (1939) reported that confidence in the judgment of a difference is positively related to the magnitude of the difference between the stimuli being judged. Whether or not such a relationship would hold in judging doppler is a question that requires further experimentation.

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The results have shown a positive relationship between ability to discriminate doppler and valid use of the response "no doppler." However, the relationship was marked only for the least proficient performers. Evidently those operators who are the least proficient at discriminating the direction of doppler are also the least accurate in recognizing the absence of doppler.

However, the selection of potential sonar operators on the basis of their ability to discriminate pitch differences does not guarantee that those selected will adequately recognize the absence of doppler. Even those operators who were the most proficient at discriminating the direction of doppler did not adequately identify the absence of doppler, their performance being only slightly better than chance.

A reanalysis of the data from the present study indicated that the substantial differences among operators in the accuracy of doppler discrimination (see Study I) are probably not completely attributable to differences among operators in pitch sensitivity. The results supported the hypothesis that differences in accuracy among operators may be partly a result of a tendency to confuse the submarine echo with its wake echo particularly for targets at bow aspect. In the present study this adversely affected the performance of the poorer operators. Presumably, training procedures could capitalize on the ability of men to recognize different portions of an echo and improved performance would be the result. Incidental observation suggests that sophisticated observers may well do this, although frequent refresher training is required.

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STUDY III: DOPPLER DISCRIMINATION AS A FUNCTION OF THE AUDITORY DISPLAY FREQUENCY

INTRODUCTION

The obvious purpose of a sonar and its associated displays is to maximize the detectability of a signal and its information-carrying properties. Because the observer's senses form a part of any sonar system, efficient sonar design should capitalize upon the fact that human sensitivity is far more discriminating in some stimulus ranges than in others.

The auditory display serves a classification, and to some extent, a detection function, and like all sonar displays, it should provide processed information in a manner which maximizes the probability that the operator's decisions will be correct. The audio presentation frequency of most active sonars (past and present) is 800 cps. However, experimental evidence from laboratory studies of hearing suggests that 800 cps may not be the optimal display frequency for doppler recognition.

It is known, with pure tones at least, that ΔF (minimum number of cycles of difference that can be discriminated reliably) is a function of the frequency at which the tones to be compared are presented. Stevens and Davis (1947) reported pure tone ΔF 's for 250, 500, 800, 1000, and 2000 cps to be approximately 2.4, 1.7, 2.6, 3.4, and 7.2 cps, respectively (ref. a 60-db sensation level). The fact that ΔF for pure tones is minimal near 500 cps suggests that fewer cycles of doppler may be discriminated at 500 cps than at any other presentation frequency, including 800 cps.

With respect to the problem of detection, the audio is an important secondary or back-up display for the video and consequently detection requirements should also be considered in choosing a presentation frequency. The results of pure tone studies (Stevens

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and Davis, 1947, Ch. 4) have shown that at intensities above 40 db (which is far below the gain level used by operators) equal intensive changes between 300 and 2000 cps are essentially equally discriminable. Based on work done by NEL with synthetic "echoes" in wideband noise, however, Urich and Pryce (1953) reported contrary results which showed that for "echo" durations of 50 ms or longer, detectability was better at 400 cps than at 800 cps.

Based on the results of these two studies, it appears that echo detection (based on intensive changes) is either equivalent over a wide range of frequencies, or that it is best at some frequency close to 400 cps. In either case, the suspected optimal frequencies for target detection and doppler recognition (approximately 500 cps) do not seem to be incompatible.

The purpose of this study was to explore, with SQS-23 sea-recorded auditory materials, the possibility that some frequency other than 800 cps may be superior as a presentation frequency for doppler recognition. Six presentation frequencies, ranging from approximately 400 to 1000 cps were studied.

METHOD

The Experimental Doppler Discrimination Tests

Doppler discrimination tests were developed at 6 experimental frequencies by heterodyning the 800-cps test used in Study I. It was assumed, for the purposes of the present study, that 800 cps was the original presentation frequency for all items in that test.⁸

⁸ This assumption may not have been completely valid. It is well known that because of calibration problems and ODN limitations, the display frequency varies somewhat among sonars, and within a sonar on different occasions. However, based on subjective estimates, the reverberation frequency of all test items was within ± 25 cps of 800 cps.

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To obtain the 6 experimental frequencies, the 800-cps test was played on an Ampex Model 354 tape recorder (see Figure 5) and the output of the recorder was mixed with a 4200-cps pure tone from an oscillator. The principle of frequency mixing holds that whenever two frequencies are combined in a non-linear system, the result is the sum, the difference, and the two original frequencies. In the present case, the result would be a 5000-, a 3400-, and an 800-cps sonar signal and a 4200-cps pure tone.

The 5000-cps signal was then extracted by running these 4 resultant frequencies through a 5000-cps narrow band-pass filter. This signal was then mixed with each of the pure tones shown in Stage 2 of Figure 5 and the resulting mixture was applied to the 400 - 2500 cps band-pass filter to eliminate the unwanted summation frequency (5000-cps sonar plus the pure tone), the pure tone produced by the audio oscillator, and the original 5000-cps sonar signal. The resulting 6 experimental frequencies are shown on the right side of Figure 5.

The 5000-cps narrow band-pass filter passed a highly attenuated 4200-cps pure tone as well as the 5000-cps sonar signal. The mixture of this 4200-cps tone with the band from 3990 to 4515 cps produced difference frequencies ranging from 105 to 310 cps. These frequencies were low enough to be effectively filtered out by the 400 - 2500 cps filter. However, the mixture of the 4615 and the attenuated 4200 cps produced a difference frequency of 415 cps. This unwanted difference frequency was so close to the desired experimental frequency of 385 cps that attempts to filter it were somewhat unsuccessful. The 385-cps test was administered despite this possible inadequacy. However, during the administration, it was apparent that the presence of the unwanted frequency made the test qualitatively poorer than the others. It was decided that an unfair test of the 385-cps presentation frequency would have resulted and consequently the data from this portion of the study were discarded.

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Stage 1
Translation of
800 ~ Sonar to 5000 ~ Sonar

Stage 2
Translation of 5000 ~ Sonar
to 6 Experimental Frequencies

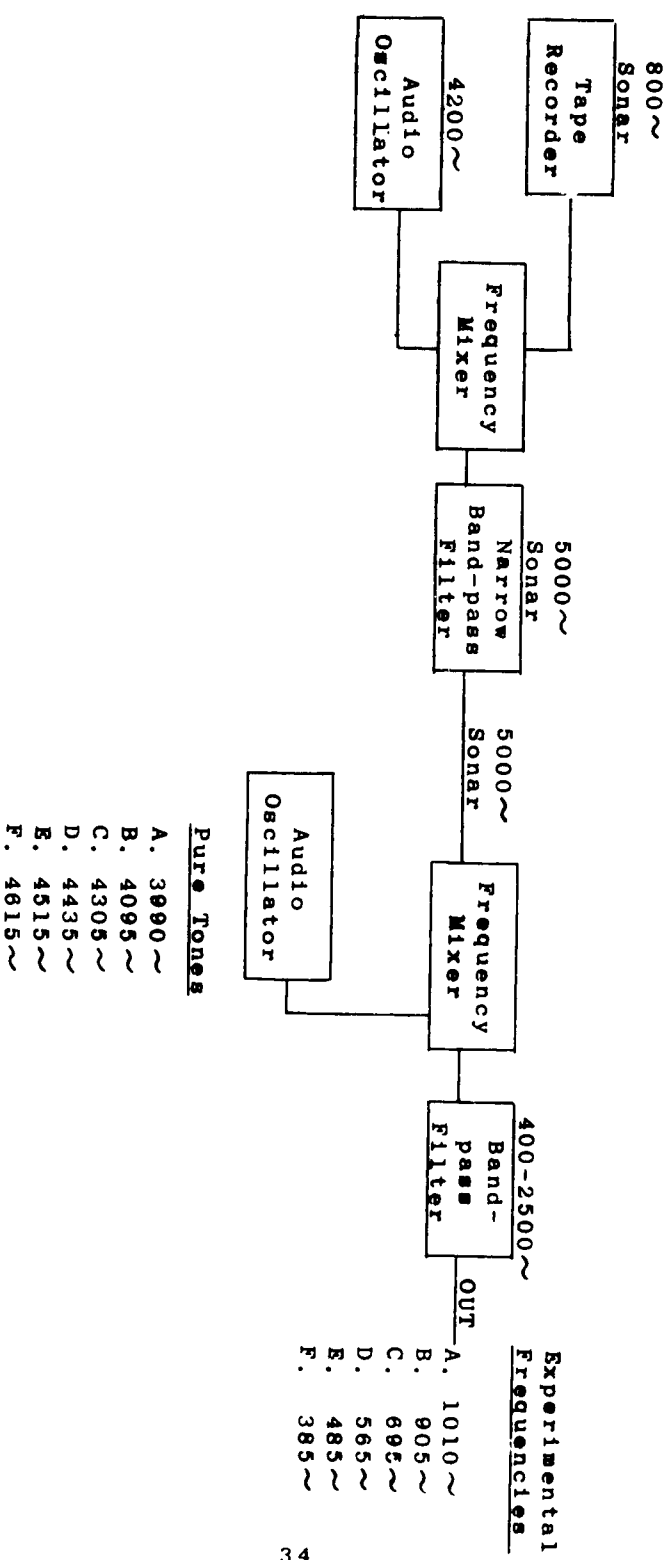


Figure 5. Block diagram of the apparatus used to develop doppler discrimination tests at 6 experimental frequencies.

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Subjects and Experimental Design

One hundred and five subjects, Class "A" students at the Fleet Anti-Submarine Warfare School, San Diego, participated in the study.

The subjects were divided into 6 groups, five groups of 18 subjects and one of 15. The doppler test was administered to each group at one experimental frequency, with the 905-cps test being administered to the group of 15 subjects. An 800-cps control test was also administered to each group. This test was administered first to half of the subjects in each group. The remaining half took the tests in reverse order.

Test Administration and Instructions

The test administration procedure and instructions were identical to those in Study I. In addition, the subjects were told that the purpose of the study was to evaluate the effects of display frequency on the accuracy of doppler discrimination.

RESULTS AND CONCLUSIONS

To test the hypothesis that doppler discrimination is superior at some frequency other than 800 cps, the number of items correct on the experimental frequency test and the control (800 cps) test was obtained for each subject in each group.

A t-test of the difference between correlated means was made for each group. Initially, only two of the five differences were found to be statistically significant: for one group, performance on the 800-cps test (35.7 items correct) was significantly superior ($P < .05$) to that on the 1010-cps test (32.6 items correct); for another, performance on the 485-cps test (41.7 items correct) was significantly superior ($P < .01$) to that on the 800-cps test (39.4 items correct).

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A direct comparison among performances on the experimental tests was desirable but not warranted because such a comparison would require that the subjects in each group be closely matched in sensitivity to pitch and other relevant variables. This was not possible in the present study since subjects had to be obtained by sonar class rather than on a random or matching basis. Thus the possibility remained that differences between groups would obscure differences in performance using the experimental frequencies.

To test whether or not the differences among groups were random, the mean number of items correct for each group on the 800-cps test was compared. A one-way analysis of variance showed that the differences among means were significantly different beyond the .05 point ($F = 2.87$; $df = 4$ and 82). It was concluded that there were differences in doppler discrimination ability among groups, and therefore, that a direct comparison of the differences in performance on the experimental frequency tests was not warranted.

To obtain a more adequate description of the relationship between accuracy of doppler recognition and presentation frequency, it was necessary to eliminate the differences among the mean scores on the experimental frequency tests due to group differences in doppler discrimination ability. Therefore, the mean number of items correct for each experimental frequency was statistically adjusted by a covariance technique (Lindquist, 1956, Ch. 14) in which the 800-cps test scores served as the control measures.

Figure 6 shows the adjusted means for each experimental frequency.

An analysis of covariance indicated that the differences among the adjusted means were significant beyond the .001 point ($F = 9.87$; $df = 4$ and 81). In addition, t-tests of the difference between the means of the 1010- and 905-cps tests and the 565- and 485-cps tests indicated that these differences were significant beyond the .001

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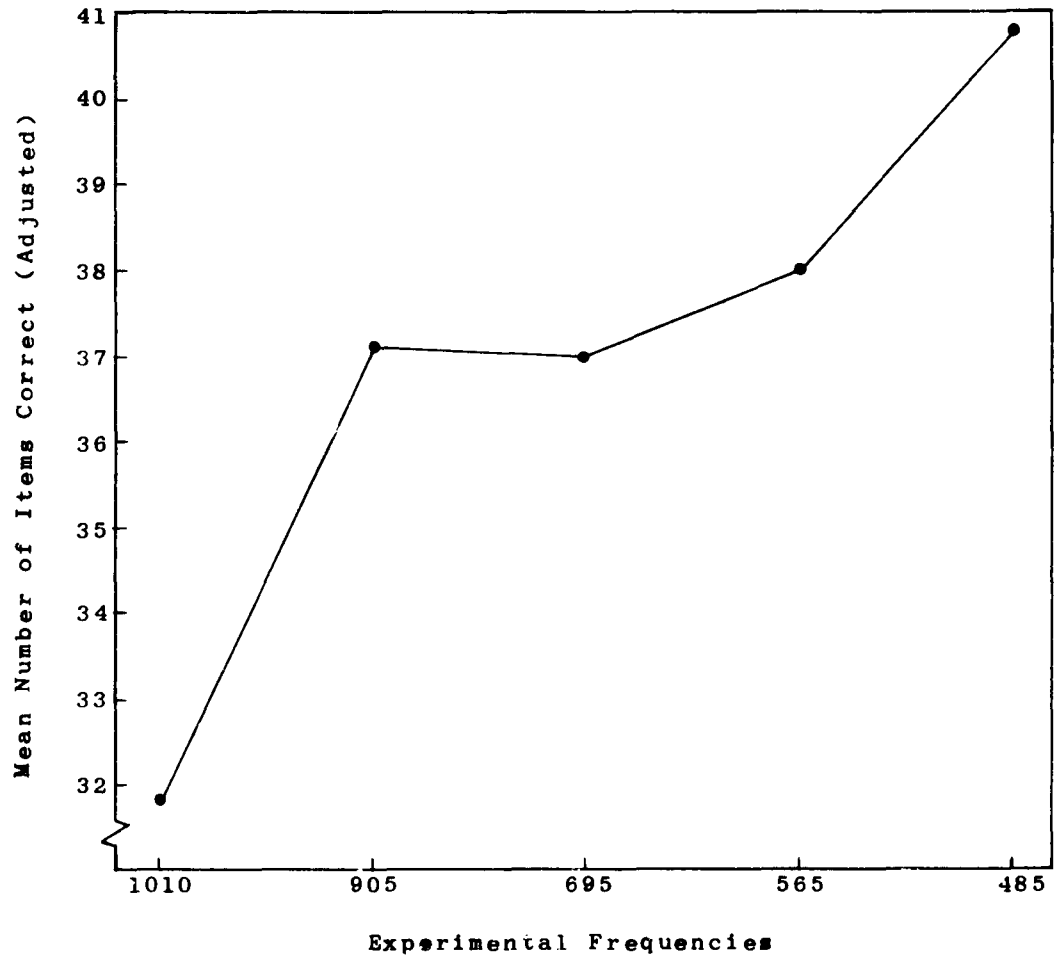


Figure 6. Adjusted mean number of items correct for each of the experimental frequency tests.

level ($t = 3.97$) and .05 level ($t = 2.12$), respectively. The differences among the means of the 905-, 695-, and 565-cps tests were not significant.

On the basis of these results, it is concluded that doppler discrimination accuracy, within the range of 1010 to 485 cps, is

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inversely related to frequency, and is best at some frequency very close to 500 cps.

DISCUSSION AND OPERATIONAL IMPLICATIONS

The results of the present study showed that there was an inverse relation between doppler discrimination accuracy and presentation frequency; i.e., within the range of approximately 500 - 1000 cps, the lower the frequency, the greater the accuracy. This result is consistent with the results of laboratory studies in which pure tones were used.

Whether or not the use of a frequency lower than 500 cps would have resulted in even better doppler discrimination could not be ascertained. Unfortunately, results from the 385-cps test could not be used because of limitations in the heterodyning apparatus. The results of pure tone studies (Stevens and Davis, 1947, p. 89) do indicate, however, that discrimination of a frequency change becomes progressively poorer below 500 cps. Presumably, 500 cps, or some frequency very close to 500 cps, is the optimal display frequency for doppler discrimination.

A change in the audio presentation frequency from 800 cps to 500 cps would entail very little cost for most sonars. Recalibration of the beat frequency oscillator and minor changes in the filter circuitry would be required. This latter would be necessary because the center response characteristic of the filter is 800 cps.

The results presented here also emphasize the possible adverse effects of improper sonar calibration on the discriminability of doppler. The results of a recent study conducted by HFR (Parker, in prep.) showed that, in 25% of the SQS-23 sonars inspected, the auditory display frequency was more than 75 cps above the intended display frequency. In such cases, the improper calibration of the beat frequency oscillator obviously may result in some additional loss in the discriminability of doppler.

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