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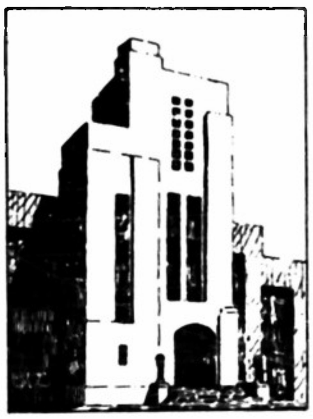
ANALYSIS OF THE RADIATED NOISE TRIALS CONDUCTED WITH THE EPC618 IN 1951

by

K. W. Perkins



January 1953 Report C-529

NS 715-102

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ABSTRACT

A series of full-scale noise trials was performed during the spring and summer of 1951 near Key West, Florida with the EPC618 serving as the test vessel. Self-noise and radiated-noise measurements were taken both when the EPC618 was self-propelled and when it had its propellers removed and was towed by another vessel. The radiated noise was measured through two hydrophones suspended from a stationary listening vessel while the EPC618 passed close by on a fixed course.

These trials were carried out:

1. To determine the reasons for the variability of the data obtained during the 1950 trials conducted with the same vessel;

2. To discover the sources of radiated noise and sonar self noise on the EPC618;

3. To develop improved techniques of instrumentation and measurement; and

4. To determine the precise paths by which the self noise of the EPC618 traveled to the sonar dome, with the hope of discovering means of locating and constructing the dome so that the noise background in the sonar gear would be as low as possible.

The self noise was treated in a previous report. This report discusses the radiated noise phase of the trials. The results of these tests clearly show the following:

1. The propellers were the principal source of noise radiated by the EPC618 when the vessel was self-propelled; it was not possible to determine the exact sources responsible for the noise radiated when the ship was under tow.

2. The noise radiated by the EPC618 had a much more rapid rate of increase with speed when the ship was towed than when it was self-propelled.

3. Ship machinery noise was not a major factor in radiated noise.

4. Radiated-noise levels measured at distances of 32 yards or less did not conform to the inverse square law of propagation.

The acoustic techniques and instrumentation used were found to be

fundamentally sound as far as they went, but the methods of measuring distances and the procedure used in indexing the sound recordings of the EPC618 as that vessel passed by the stationary listening ship were found to be unsatisfactory, and proposed new methods for application to future trials are described.

In this report the acoustical instrumentation, test and measurement procedure, sources of error, and data obtained are discussed, after which a summary of the results is presented.

INTRODUCTION

During a period of time extending from May through August of 1951, an extensive series of full-scale self- and radiated-noise measurements was conducted with the EPC618 in the operating areas near Key West, Florida by personnel of the David Taylor Model Basin. The radiated-noise trials were undertaken:

1. To determine the reasons for the variability of the data obtained during the 1950 trials conducted with the same vessel;
2. To discover the sources of radiated noise on the EPC618; and
3. To develop improved techniques of instrumentation and measurement.

The trials were carried out in accordance with the request of Reference 1* as a part of Project Bu/S166/S68. All tests were under the cognizance of the Taylor Model Basin.

Personnel of the Model Basin were at sea for a total of 35 operating days from 14 May 1951 through 24 August 1951. The major portion of the operating time was devoted to measurement of the self noise and radiated noise of the EPC618 self-propelled and under tow. The ship was self-propelled for 15 days and under tow for 20 days. When the EPC618 was towed, its propellers were replaced by dummy hubs, and a 1000-foot towing cable was used. The radiated noise was measured through two hydrophones suspended from a stationary listening vessel while the EPC618 passed close by on a fixed course. The frequencies measured ranged from 0.1- to 30-kc.

The present report deals with all phases of the radiated-noise trials conducted on the EPC618 with the exception of the MASKER trials, which were conducted during the period 23 July to 8 August. The effectiveness of MASKER, a bubble-screen generating system, was discussed fully in Reference 2. However, it was found that data obtained during the MASKER trials in those intervals when the MASKER equipment was not operating are comparable to data obtained during the other operating days, and hence they have been included in the accompanying graphs and tabulations. Included in the text of the present report are

*References are listed on page 37.

descriptions of the acoustical instrumentation and the test and measurement procedure, a presentation of the data with notes on possible sources of error, and a discussion of the results. A report dealing with the self noise of the EPC618 was recently published.[3]

All ships used during the trials were under the operational control of the Surface Anti-Submarine Development Detachment, Key West, Florida. The ships utilized, in addition to the EPC618, were the USS SARSFIELD (DD837), the USS WILKE (DE800), the USS SAUFLEY (DDE465), and the USS TUSCARORA (YTB341) as towing vessels; and the USS ALBATROSS (AMS1), the PCS1431, the C33 and the TUSCARORA as listening vessels.

The ocean depth in the operating areas ranged from 24 to 350 fathoms, with most runs taken at depths greater than 36 fathoms. The sea state varied from 0 to 4, with a majority of sea states between 0 and 1. The sea water temperature remained quite constant (84 - 85 deg F) throughout the trials.

The procedures used during the 1951 trials were similar to those used during the tests conducted in 1950,[4] with a number of refinements which are described in the appropriate sections.

ACOUSTICAL INSTRUMENTATION

Two hydrophones were used to take sound measurements on the listening ship. They were the CQA 51074 No. 231 (commonly known as the "JT") and the AX-120 No. 011. The JT, a 5-foot line-type magnetostrictive unit which is directional,* was suspended over the side of the listening vessel in a manner which permitted it to remain in a comparatively fixed horizontal and vertical position despite rolling of the ship. The AX-120, a transducer whose sensitive element is composed of ammonium dihydrogen phosphate (ADP) crystals, was attached to a buoy which was payed out from the listening vessel on a 45-yard cable. The AX-120 is nondirectional at frequencies up to 10 kc. Both the AX-120 and the JT were placed about 10 feet below the ocean surface.

The frequency response of the JT No. 231 is shown in Figure 1, and that of the AX-120 No. 011 is presented in Figure 2. Directivity patterns of the JT No. 231 at frequencies of 5, 10, and 25 kc are shown in Figures 3, 4, and 5, respectively. Both the JT and the AX-120 hydrophones were calibrated at the Naval Ordnance Laboratory facility, Barcroft, Virginia.

A block diagram of the acoustical instrumentation is presented in Figure 6. The output of the JT was connected to a preamplifier having a maximum gain of 40 db, the output of which was connected to four amplifier-filters in parallel which provided channels of 1 - 30 kc, 4.5 - 5.5 kc, 9 - 11 kc and 22.5 - 27.5 kc. Sound Apparatus Company type RX twin

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*A directional hydrophone was selected for use at the listening vessel in order to ensure that interference from the towing ship would be minimized during the towed runs.

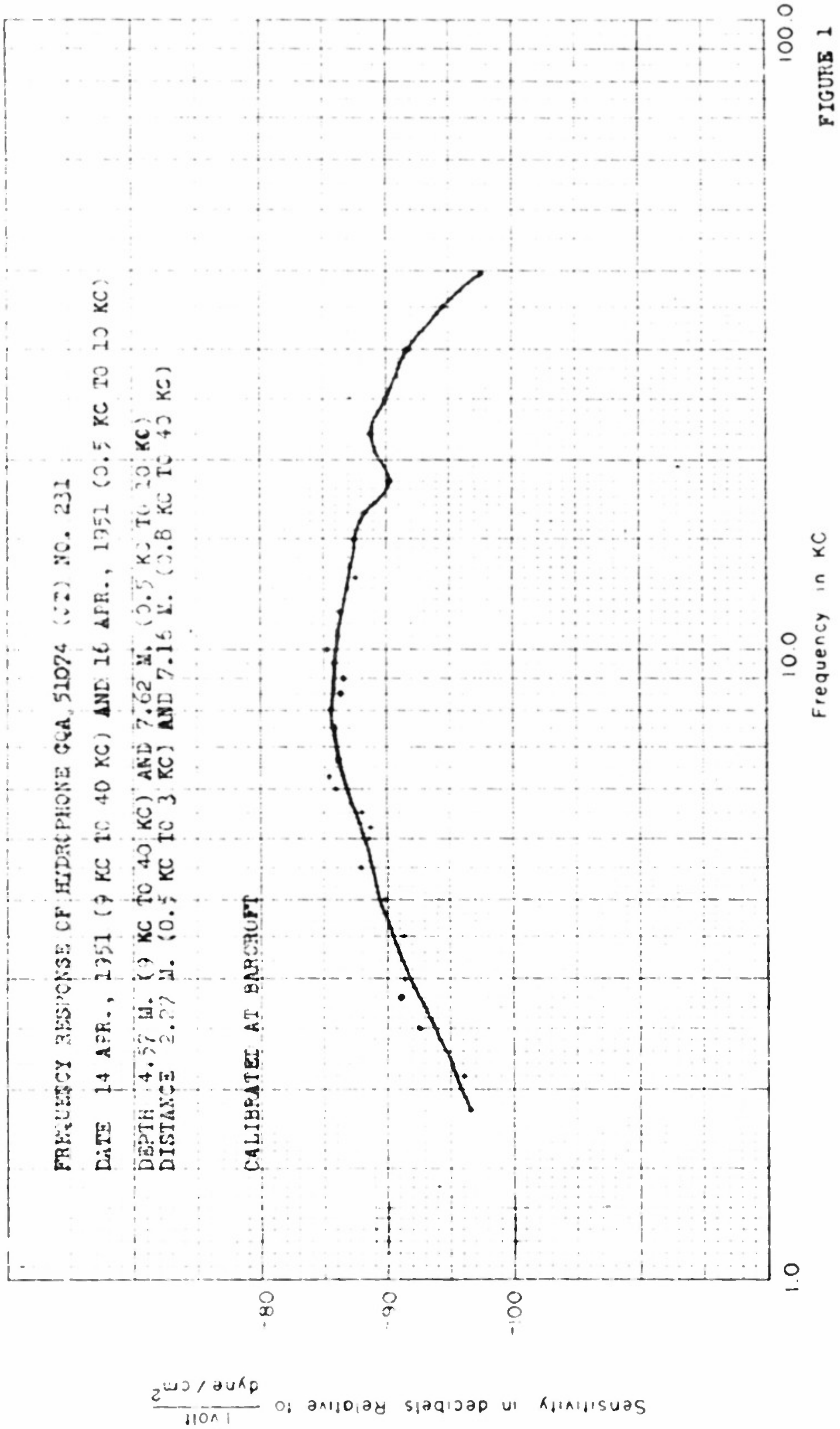

FREQUENCY RESPONSE OF HYDROPHONE GGA 51074 NO. 231
DATE 14 APR., 1951 (9 KC TO 40 KC) AND 16 APR., 1951 (0.5 KC TO 10 KC)
DEPTH 4.57 M. (9 KC TO 40 KC) AND 7.62 M. (0.5 KC TO 10 KC)
DISTANCE M. (0.5 KC TO 3 KC) AND 7.16 M. (0.8 KC TO 40 KC)
CALIBRATED AT BARCROFT
-80
-90
-100
1.0
10.0
100.0
Frequency in KC
Sensitivity in decibels Relative to 1 volt / dyne/cm²

FIGURE 1

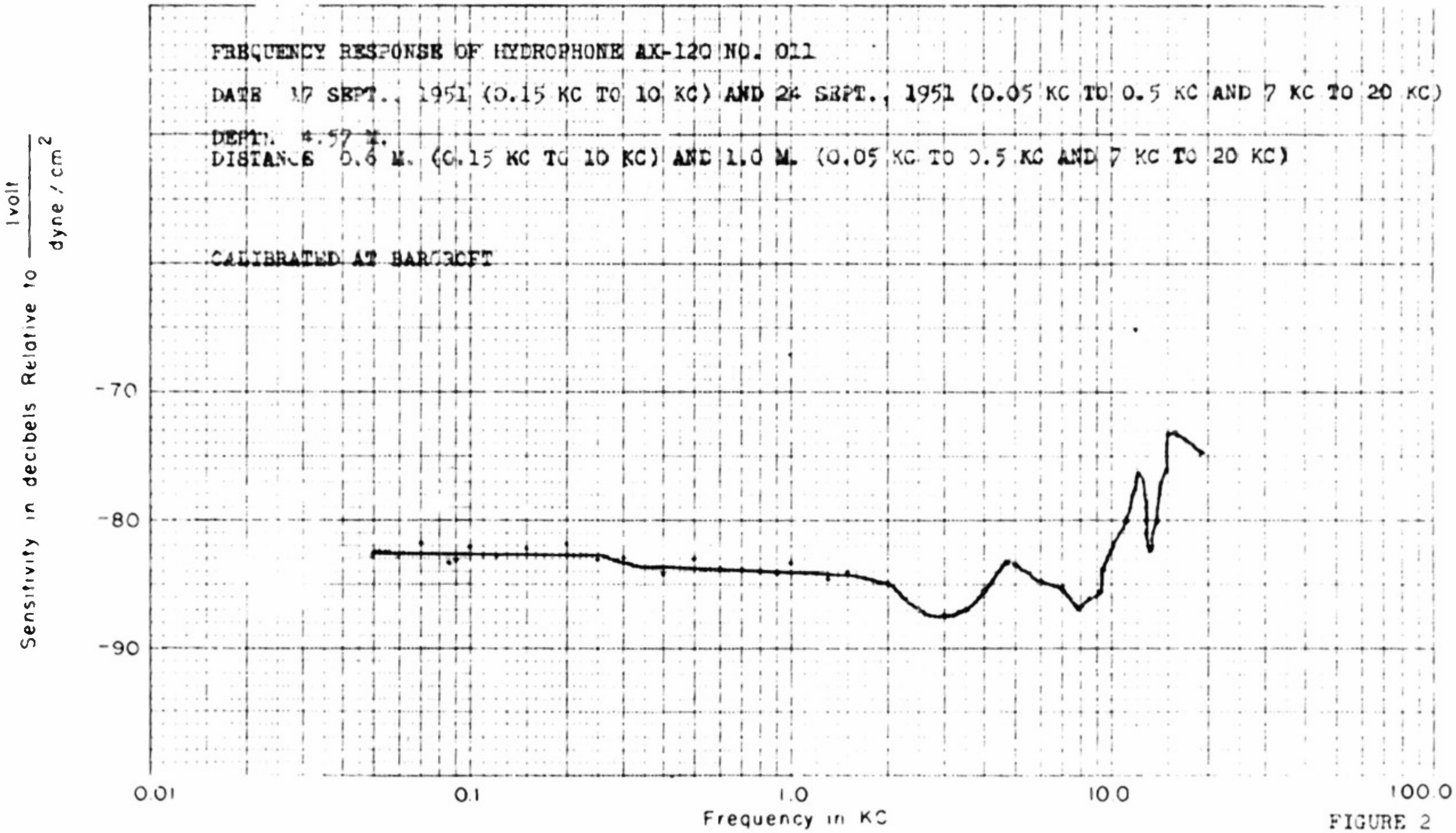


FIGURE 2

CONFIDENTIAL

strip recorders* recorded the output of each of the four frequency channels.

The output of the AX-120 hydrophone was connected to amplifier-filters which provided 0.1- to 15-kc and 9- to 11-kc channels, whose output levels were inscribed onto Sound Apparatus Company type FR strip recorders.

A Magnecorder, a type of magnetic tape recorder which possesses a substantially uniform frequency response throughout the range 0.1 - 15 kc, was also connected to the output of the hydrophone. It was anticipated that frequency analyses of the magnetic tape recordings obtained would subsequently be made by using a Gertsch half-octave filter set.

All of the strip recorders were provided with indexers in order that the times of closest approach of the bow and stern of both the EPC618 and the towing vessel to the hydrophones might be marked.

Preceding each day's trials, the measuring systems on the listening vessel were calibrated electrically by applying signals of known voltages to the inputs of the preamplifiers and adjusting the gain on each of the amplifier-filters so that the attenuation plus tape level read the correct value in decibels on each strip recorder. This value was easily calculated since the sensitivity of the hydrophones was known. This calibration process had two distinct advantages:

1. It gave the absolute sound levels for every run by direct reading from the recorder charts (except for the corrections of bandwidth and distance).

2. It permitted the data to be examined day by day, so that any doubtful data could be quickly detected and investigated.

The Magnecorder was calibrated each day by inserting signals of constant known voltage and various specified frequencies from an oscillator into the battery box and recording them on the magnetic tape. Although the levels of these recorded signals revealed a slight day-to-day variation when they were later played back onto a strip recorder, the correct absolute sound levels of the runs recorded on any specified day could be computed by using the levels of the calibrations recorded on that day.

TEST AND MEASUREMENT PROCEDURE

Radios supplied by the Taylor Model Basin were installed on the EPC618, the listening vessel, and the towing vessel for the purpose of communicating test information. For each run the EPC618 proceeded past the listening vessel on a relatively fixed course and at a predesignated speed. Self-propelled runs were made at ship speeds of 7.5, 10, 12.5, 15 and 17.5 knots. Mechanical difficulties prevented obtaining a sufficient number of self-propelled runs at lesser or greater speeds to provide dependable average values. Towed runs were made at speeds of 10, 12.5, 15, 17.5 and (approximately) 19.6 knots. All ship speeds

*In this report the term "strip recorder" will be used to denote a graphic level recorder which gives a record of sound level versus time, as shown in Figure 8. Such usage is necessary to distinguish this type of recorder from a "polinear recorder," a frequently used type of graphic level recorder[3] which gives a record of sound level versus angle of train.

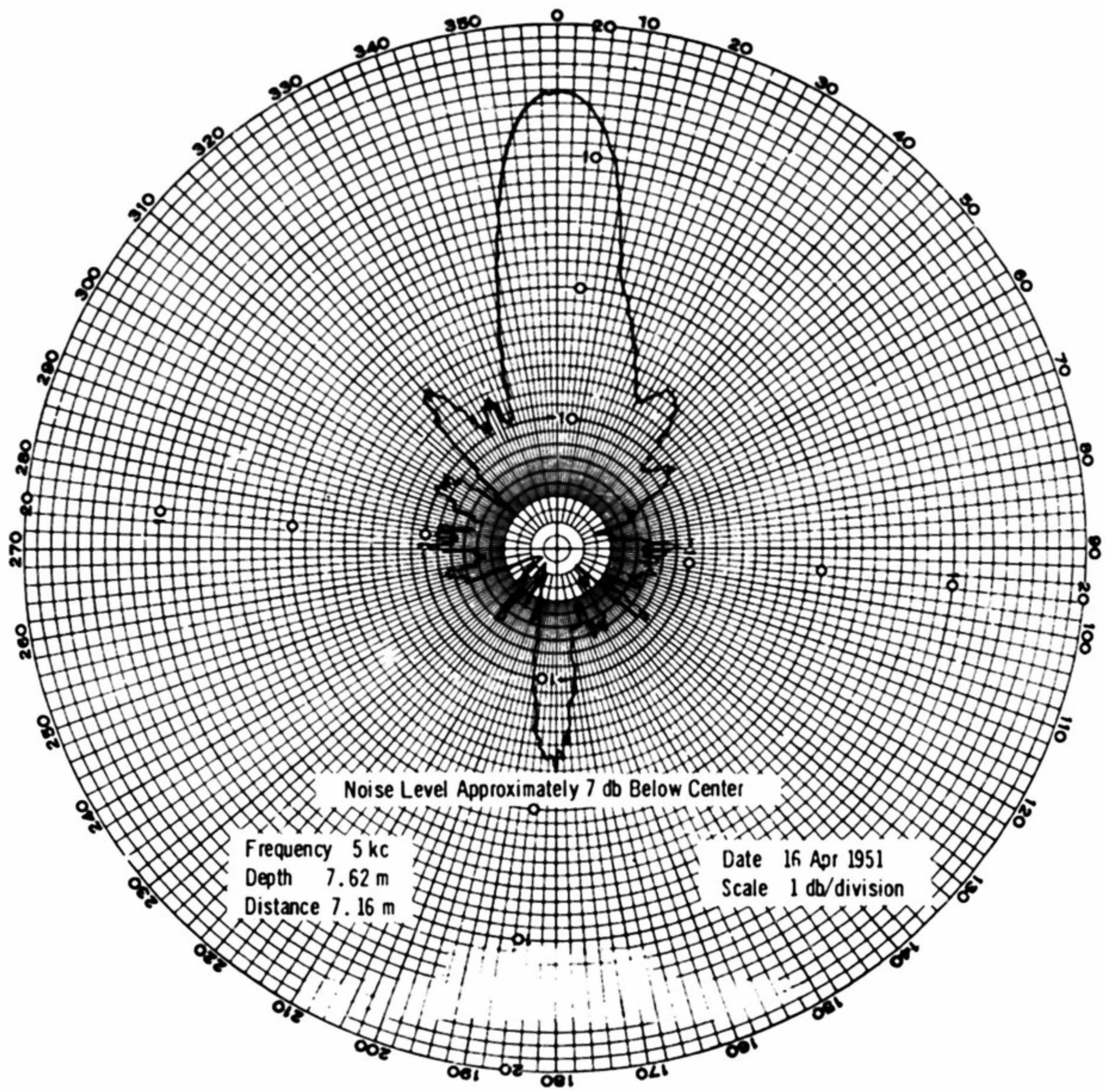


Figure 3 - Directivity Pattern of JT No. 231 Hydrophone, Frequency 5 kc

were measured by pitometer logs. A specially constructed broad-band TMB mechanical noisemaker attached to the propeller shaft strut (Reference 3, Figure 1) was operating during many of these runs. When the EPC618 was self-propelled at 7.5 knots, only one of the ship's main engines was utilized - that on the side of the ship closest to the listening vessel during a run. In some instances the actual ship speed was not quite equal to one of the specified nominal speeds. This was particularly true of the high-speed towed runs, in which the speed

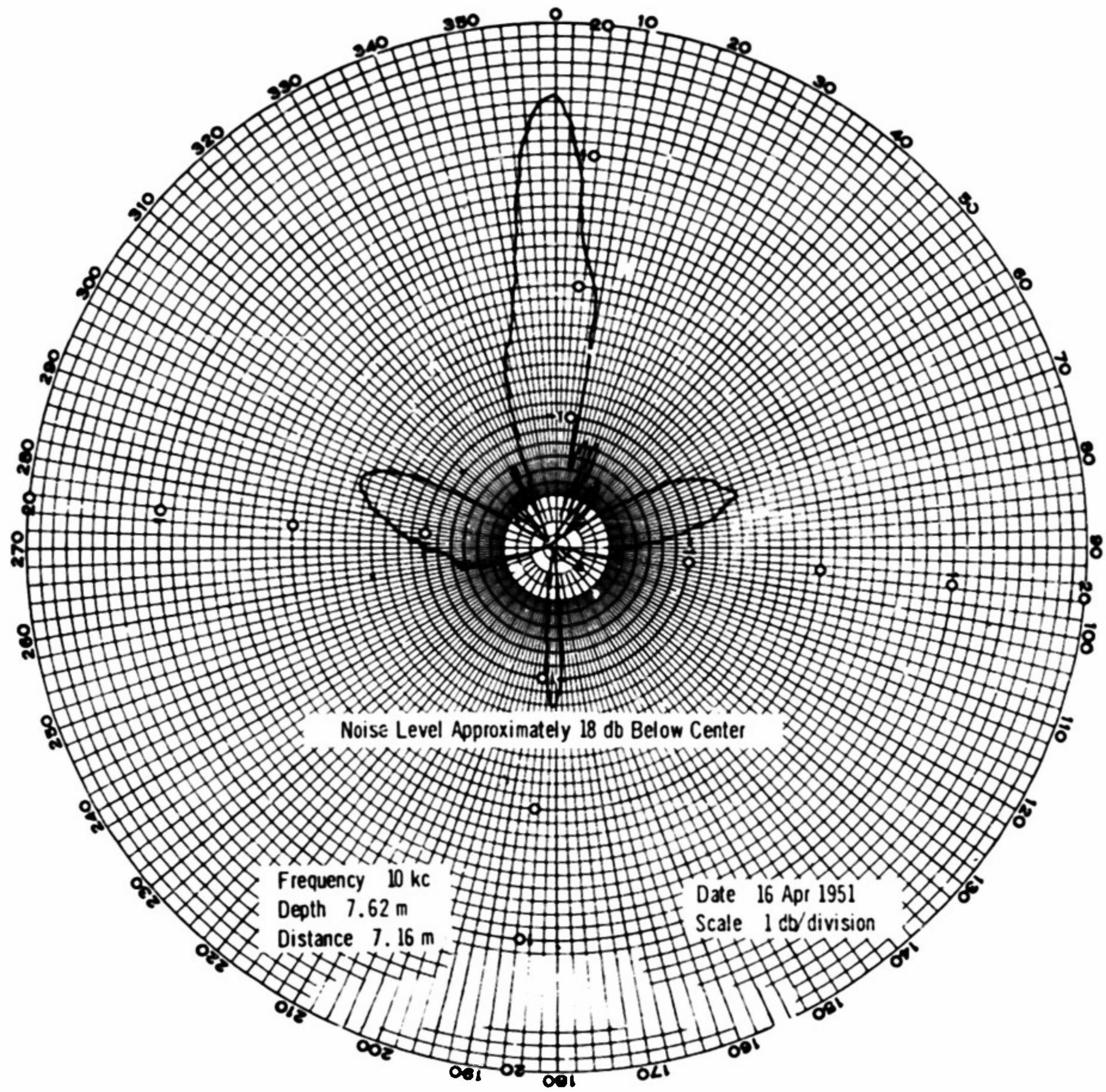


Figure 4 - Directivity Pattern of JT No. 231 Hydrophone, Frequency 10 kc

for individual runs ranged from 19.0 to 20.5 knots. In these cases the speeds were averaged arithmetically, and the averaged noise levels were plotted at that averaged speed on Figures 9 - 14.

It is generally known (e.g., Reference 3, Table 1) that the bubbles in a ship's wake serve to attenuate noise. When the EPC618 was under tow, it was therefore necessary to keep it clear of the wake of the towing vessel and on the side nearest to the listening ship.

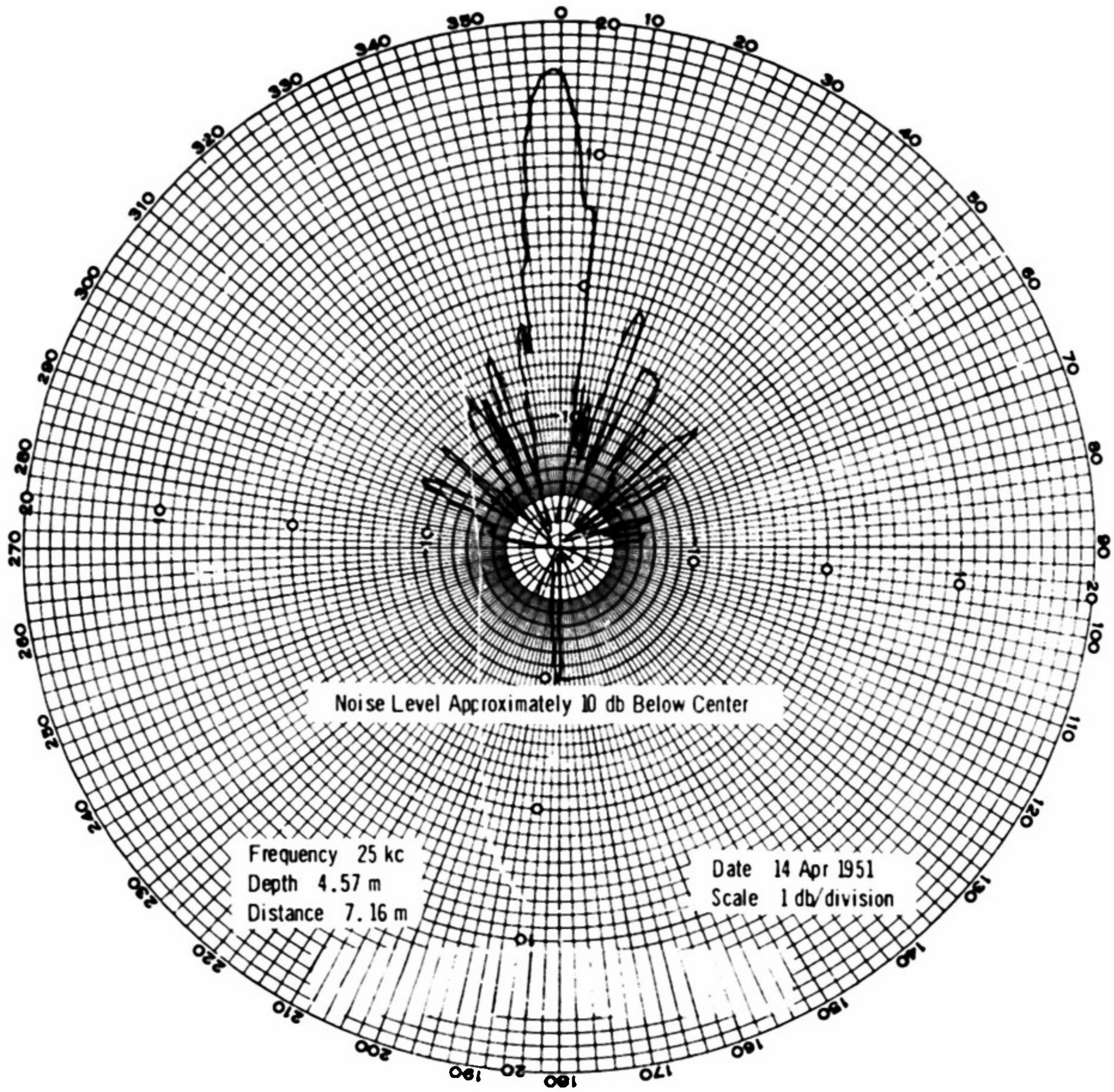


Figure 5 - Directivity of JT No. 231 Hydrophone, Frequency 25 kc

During each run, the EPC618 passed as close as practicable to the buoy containing the AX-120 hydrophone. The strip recorders and the Magnecorder were turned on a short time before the bow of the EPC618 was at a minimum distance from the hydrophones and were kept operating until the stern of the EPC618 was approximately a ship length past both hydrophones. The noise radiated by the towing vessel was also recorded on those days when the EPC618 was under tow.

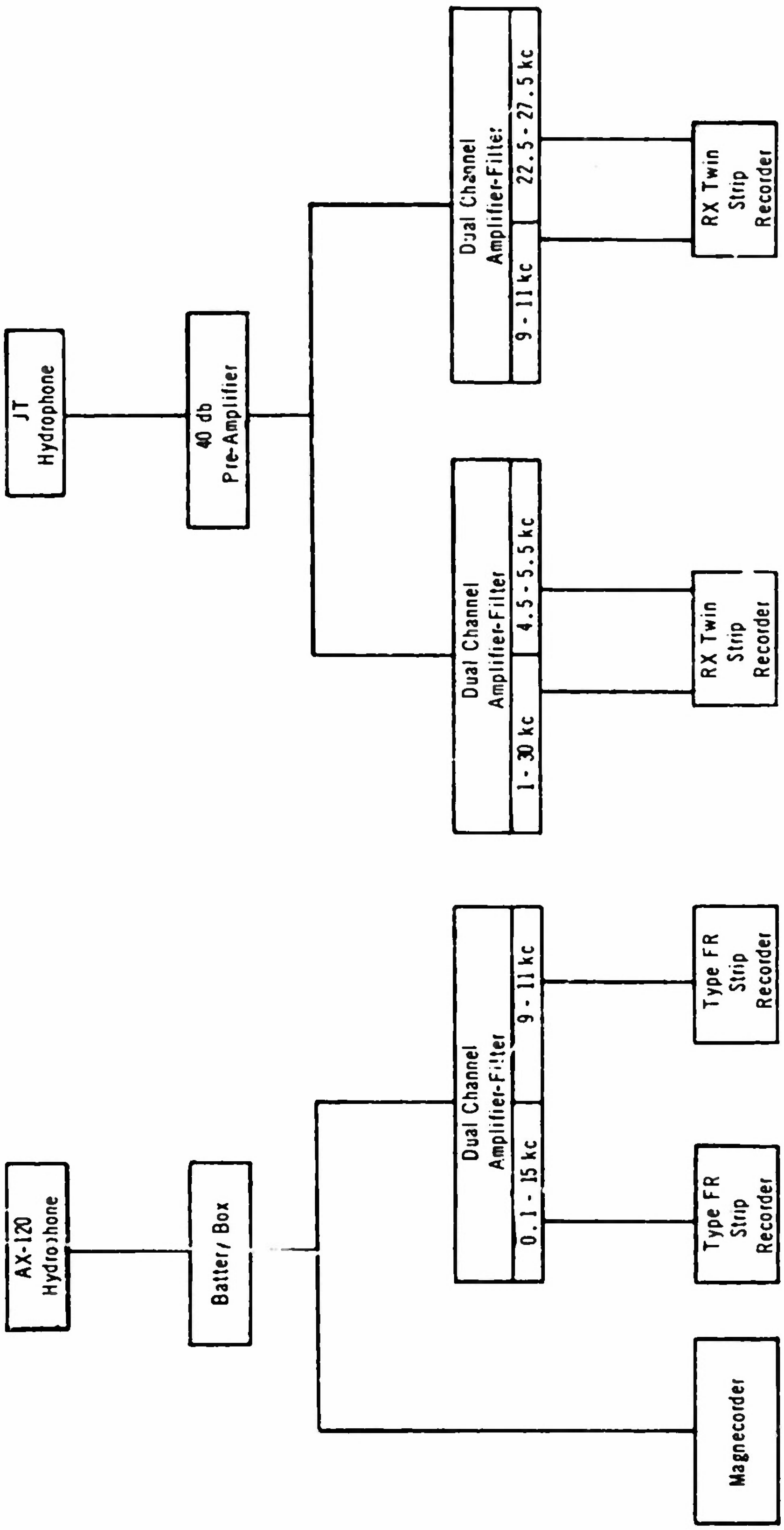


Figure 6 - Block Diagram of Instrumentation on Listening Ship

TABLE 1

Exponents in the Power Law, Sound Intensity $\propto$ (Ship Speed)^n

EPC618	JT				AX-120	
	1 - 30 kc	5 kc	10 kc	25 kc	0.1 - 15 kc	10 kc
Towed	14.8	15.0	11.1	13.7	7.1	12.8
Self-propelled	5.5	5.2	7.2	6.2	4.0	7.0

The JT was trained on the buoy by hand as the towing vessel and the EPC618 passed by the listening ship. The person training the JT was provided with a master marker which he depressed at the two instants when the bow and stern of the EPC618 were in line with both the JT and the buoy (Figure 7). For approximately 17 percent of the runs taken during the trials, it was felt advisable to train the JT perpendicular to the anticipated course of the EPC618, rather than on the buoy, because for those runs the angle of approach of the EPC618 was such that the distance between the EPC618 and the JT at the time when measurements were taken was considerably closer when this procedure was used (Figure 7).

Two methods were used to index the closest approach points of the bow and stern of the EPC618 to the buoy. In the first method, observers aboard the EPC618 stood at the bow and stern and waved flags when the buoy seemed closest to them. In the second method, the person training the JT made visual estimates of the closest approach points of the EPC618 to the buoy and gave vocal signals to the persons operating the AX-120 recording equipment; the latter then marked the strip recorder charts. The Magnecorder tapes were indexed by momentarily shorting the input signal at a fixed arbitrary time (7 seconds) after the vocal signal for the stern passage was given. This was accomplished with the help of a stop watch. Without this delay period, the record would have been distorted at the point of closest approach. When the Magnecorder tapes were later played back onto a strip recorder for analysis, the points where the input signal had been shorted were plainly shown on the recorder charts. Since the speed of rotation of a strip recorder drum is known, it was a simple matter to calculate back to a point 7 seconds earlier on the chart. In nearly all runs, both towed and self-propelled, it was found that the maximum noise produced by the EPC618 came from points quite close to its stern, according to the markings on all the strip recorder charts.

An observer on the listening ship measured the range to the towing vessel, the EPC618, and the buoy during each run with a half-meter optical rangefinder at the (apparent) time of closest approach of the foremast of each vessel.

As the EPC618 passed by the listening vessel, the angular bearing of the buoy was taken from the EPC618 at the instant when the stern of the listening vessel and the buoy were in line, as viewed from the bridge of the EPC618. A visual estimate of the closest distance

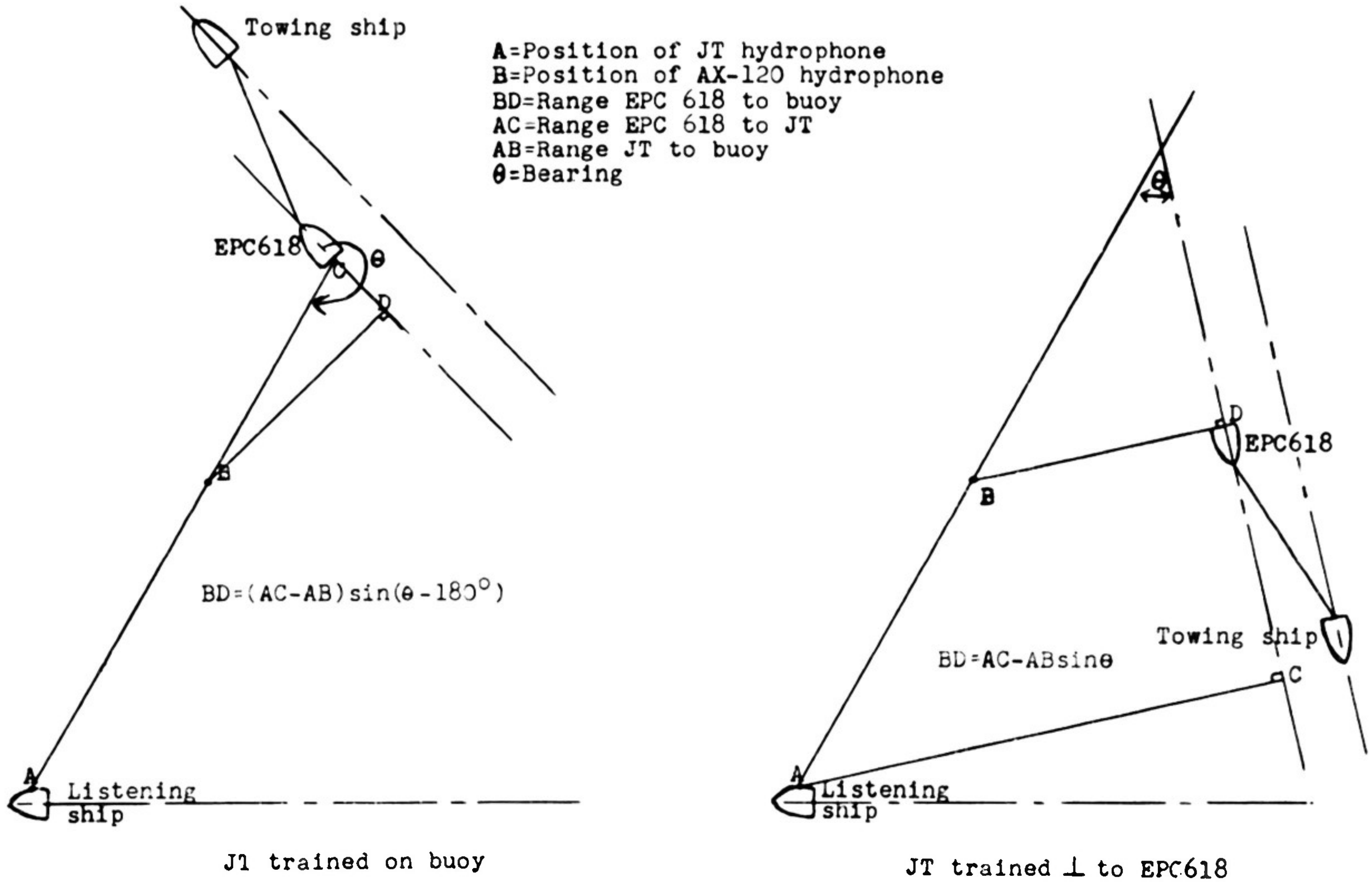


Figure 7 - Alternative Methods of Calculating Distance Between EPC618 and Buoy

of the EPC618 to the buoy was made by the deck officer of that vessel. The bearing and estimated range were communicated to the listening vessel upon the completion of each run. The bearing was essential in the calculation of the true ranges (Figure 7), and the estimated range furnished an approximate check on the calculated range.

For the machinery noise test, the EPC618, its propellers replaced by dummy hubs, was set adrift approximately 50 yards from the stationary listening vessel, and the radiated noise was measured as various machinery items of the EPC618 were secured in turn. During the first measurement, the main engines (making turns for 10 knots) and all the normal auxiliaries were in operation, then the main engines were shut off, and so on. The machinery items in operation during each individual measurement are listed in Table 2. The noise was measured through both the JT and the AX-120 hydrophones. The JT was hand-trained successively on the bow, stack, and stern of the EPC618 during each measurement, but no change in noise level was detected when this was done, perhaps because the ships were not always parallel to each other. The distance between the EPC618 and the listening ship was obtained by rangefinder from the latter vessel during each measurement.

SOURCES OF ERROR

The precision of measurement of radiated noise was about ± 2 db. This includes errors due to calibration of the hydrophones and errors in the electronic equipment but not the fluctuations due to variations in the intensity of the sound being measured or variations in the attenuation experienced by that sound on its way to the hydrophones. The resultant of these fluctuations was at least ± 5 db in the majority of cases, with variations as great as ± 10 db observed occasionally.

Another important factor affecting the noise measured was that the short samples obtained during the individual measurements may not have been completely representative of the time average of the sound intensity. Each separate measurement (among a group of like measurements used to compute an average level) itself represented an average noise level taken over a very short interval of time. The statistical variations alone were as much as ± 10 db during the trials, meaning that there was a statistical spread of 20 db. There seemed to be a tendency for readings to cluster about some high value for a while and then about some lower value for a while; the timing of these slow variations was highly irregular and completely unpredictable. There is, therefore, some doubt as to whether the samples taken were representative, repeatable and reliable.

In any discussion of possible sources of error, the problem of range must be considered. All of the points plotted in Figures 9 to 14 (graphs of sound level versus ship speed) are based on an average of a number of measured values. Sound intensity always decreases as the distance from the sound source increases, provided that focusing effects are absent and that local variations due to interference are disregarded. Hence it was necessary to devise some means of correcting the range of each run to a fixed arbitrary range in order that the radiated-noise levels could be properly compared.

There were two other reasons for reducing all ranges to a standard range; first, it permitted comparison of the 9- to 11-kc sound levels of the JT and the AX-120 hydrophones, and, second, it expedited the tabulation and graphing of the data. A standard range of 200 yards was chosen because the data taken during the full-scale trials conducted with the EPC618 the previous summer, as well as those taken during other full-scale trials, had been corrected to 200 yards and the use of a common reference range facilitated comparisons.

The errors in the actual measurements of the ranges and those resulting from the use of empirically discovered range correction laws could both affect the final accuracy of the radiated-noise data. Since the points plotted in Figures 9 to 14 are, for the most part, based on a great many measured values, the accuracy would be improved if the range errors were equally divided between over- and under-estimations. There is, of course, no way of telling whether this was the case. The measured minimum distances between the stern of the EPC618 and the AX-120 hydrophone varied from 2 to 52 yards during the trials, with the majority between 6 and 32 yards. The measured minimum distances between the stern of the EPC618 and the JT varied from 27 to 143 yards, with the majority between 48 and 88 yards.

The sound levels of radiated noise were computed for each frequency band by using the peaks near the stern markings on the recorder charts as the (uncorrected) noise levels for the individual runs. The peaks were due to the fact that the point of closest approach of the stern represented the minimum distance to the listening vessel hydrophones of the portion of the EPC618 that radiated the most noise.* The peaks on the strip recordings taken through the JT were in part due to the directivity of that hydrophone. Radiated noise information was obtained solely from the small portion of the record corresponding to the vicinity of closest approach in order to minimize computations.

When these sound levels were plotted against range, it was found that there were large random variations in level and that the correlation between sound level and range was not at all close. It was realized that variations in the transmission anomaly and/or the output of the noise sources could cause this sort of trouble and that there was an extremely high probability that both the output and the transmission anomaly *were* highly variable. It was felt desirable, therefore, to obtain at least an approximate average noise level for each run. As time was not available for point-by-point computation and there was no high-speed computer readily adaptable to the problem, a short-cut computation method suggested by Mr. Murray Strassberg, then of Code 371, Bureau of Ships, was used.

A series of curves of sound level versus time, computed from the inverse square law, were plotted on strip recorder paper. Ten curves were drawn, each based on a different ratio of ship velocity to range at closest approach. Ratios were chosen so that the curves would be equispaced and so that the entire spread of ratios actually obtained during the trials would

*This is strictly true only if constant output of the noise sources as well as constant transmission anomaly are assumed.

be encompassed. These theoretical curves were then superposed on the strip recorder charts containing the runs recorded through the AX-120, and the closest "fit" was determined for each run. The velocity-to-range ratio on which the closest-fitting theoretical curve was based was assumed to represent the correct ratio for a given run and, since the ship velocity was known, the theoretical AX-120 range for that run could be readily calculated. This calculated range usually agreed fairly well with the range obtained by the optical rangefinder, as closely as could be determined with the set of curves used. For example, the record representing the EPC618 on Figure 8 has superposed on it a theoretical curve based on a ratio of ship velocity to range amounting to 0.935. Since the speed for that run was 17.5 knots, the "theoretical" range is $\frac{(17.5)(6080)}{(0.935)(3600)(3)} \cong 11$ yards whereas the measured range was 14 yards. However, the theoretical curves nearly always showed peaks which were considerably broader than those obtained on the strip recorder charts, immediately suggesting departures from the inverse square law at short range. The peak noise level, as given by the theoretical curve when it had been fitted as well as possible to the recorded run, was taken as the noise level for that run, and this level was then corrected to 200 yards by the inverse square law, using the theoretical range.

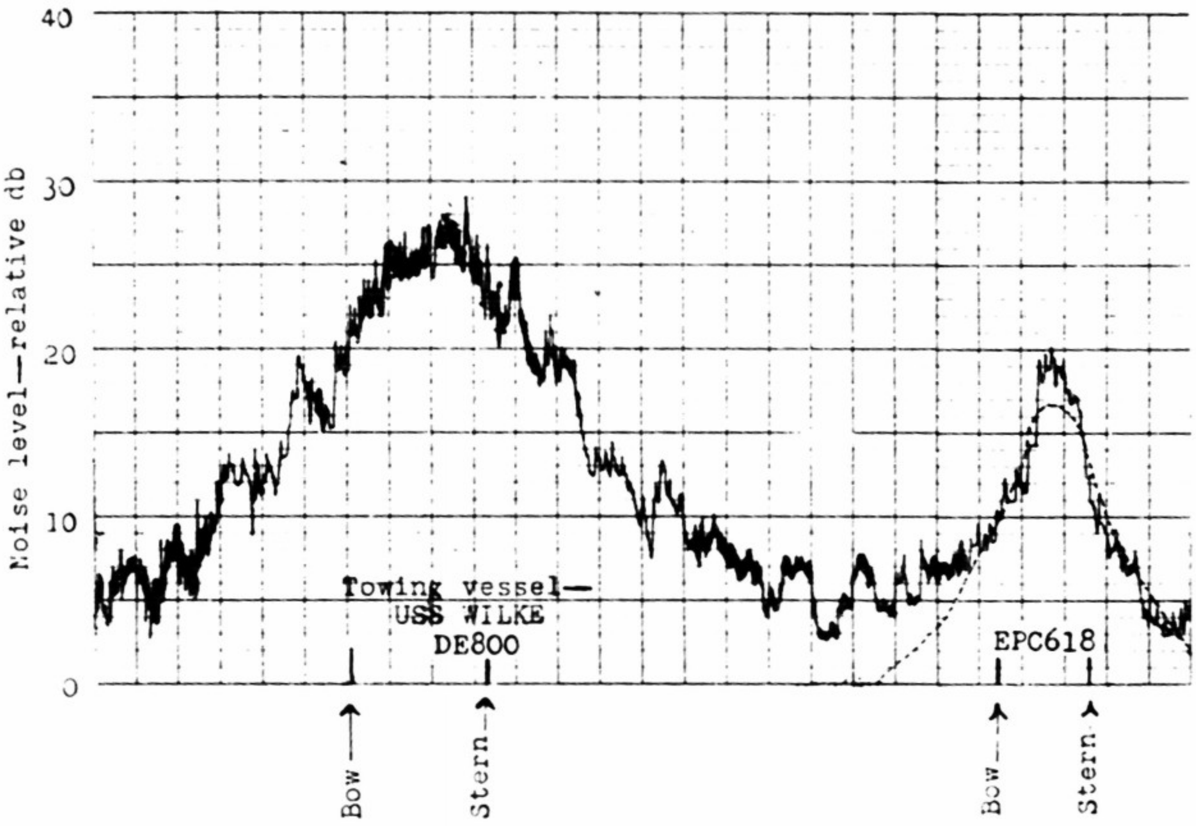
It was hoped that this method would show less variation in sound level for like runs and better correlation between sound level and distance, as well as better agreement between the AX-120 data and the data obtained with the JT hydrophone. None of these hopes was fulfilled. It was concluded that the results obtained by using only the maximum recorded noise levels were more reliable than the results obtained by the method just outlined. Consequently, the data presented in this report are those computed from the peak sound intensities recorded during each run.

There are two possible reasons why the use of this method for averaging the noise output did not improve the over-all consistency of the data:

1. The intensity of the sound radiated by the EPC618 may have been dependent on aspect angle as well as range. (Pages 134 to 141 of Reference 5 indicate that this is true in certain frequency bands for certain ships; there is no reason not to believe that it is true in general.)

2. The variation of sound intensity with range may not have followed the inverse square law. (As will be shown in succeeding paragraphs, the measurements taken did *not* agree with the inverse square law. In considering this point, it must be remembered that the inverse square law of radiation holds true only in the case of a point source of sound in a perfectly homogeneous medium, with reflectors and scatterers absent and attenuation and refraction effects negligible. The EPC618 can scarcely be considered a point source at the ranges used; furthermore multiple paths, reflectors, scatterers, and a variable transmission anomaly are present in sea water. The observed departures from the law are therefore not altogether surprising.)

In Reference 2 it is explained how an empirical formula for distance correction was derived for the AX-120 data in order to correct that data to 200 yards. This formula was applied



Port side of EPC618 closest to buoy

SHIP NOISE			
Date	4 June	Sea State	1
Hydro	AX-120	Hydro Depth	10 ft
Run #	4	Noise Source	Off
Freq. Range	10 kc	Distance	14 yd
Att'n	70	Ship Speed	17.5 k

Figure 8 - Strip Recording of Radiated Noise

to all AX-120 MASKER data,* except that taken when the noisemaker was operating. The latter data showed no correlation with range, so a fixed range of 20 yards was assumed for all runs in which the noisemaker was operating (20 yards was the average of the ranges calculated for those runs), and the levels were then corrected to 200 yards by the inverse square law. Similarly, all JT MASKER data were assumed to have been taken at a distance of 70 yards, and the inverse square law was used to reduce the data to 200 yards.

When all of the radiated noise data taken during the 1951 trials had been assembled and tabulated, a further attempt was made to derive more satisfactory range formulas. It was found that the following formula, when applied to *all* measurements, gave excellent agreement between the JT and the AX-120 data: Intensity (in db) at 200 yards = Intensity (in db) at any range − 8.46 log (200/range).** However, since the optical rangefinders used in taking the distance measurements were believed to be somewhat untrustworthy, it was decided to apply the same types of range corrections that had been applied to the MASKER data and to work out a more accurate method of obtaining ranges for subsequent full-scale trials.

The average range of the EPC618 to the JT for all runs taken was found to be 67.0 yards and the average range to the AX-120 was found to be 16.8 yards. These ranges were used as averages instead of 70 and 20 yards, respectively, which were used in conjunction with the MASKER data. The noise levels of the WILKE were corrected to 200 yards by the inverse square law, assuming all JT measurements to have been taken at the average JT range to the WILKE, which was found to be 88.7 yards, and assuming all AX-120 measurements to have been taken at 40 yards, which was the average range of the AX-120 hydrophone to the WILKE. Actually, the JT ranges to the WILKE varied between 55 and 120 yards with most ranges between 70 and 110 yards.

DATA AND DISCUSSION OF RESULTS

REDUCTION OF DATA

Since both the JT and the AX-120 had been calibrated, it was possible to calculate the absolute sound levels from the data to conform to any standard set of reference levels. It was decided that all sound levels would be expressed as the sound field in the direction of maximum receiver sensitivity which would produce the observed hydrophone output; this equivalent sound field was expressed in decibels relative to 0.0002 dyne/cm^2. All the data were corrected to a standard distance of 200 yards by the methods outlined in the preceding section. In addition, all the data of the 5-, 10-, and 25-kc channels were reduced to a 1-cps

*In order to satisfy priorities, it was necessary to reduce all the MASKER data first before commencing work on the non-MASKER data.

**This formula indicates a diminution of sound intensity of 2.5 db per distance doubled, whereas the inverse square law shows a diminution of intensity amounting to 6 db per distance doubled.

bandwidth by subtracting the decibel equivalent of the effective bandwidth of each filter used. In all instances where there was more than one measurement taken for the same test condition, the levels were averaged together. Arithmetical averages of the decibels were used,for reasons presented in Reference 3.

SOUND LEVEL VS SHIP SPEED

Graphs of sound level versus ship speed for the six frequency bands used for measurement of radiated noise are presented in Figures 9 to 14. Figures 9 to 11 show the noise levels for the WILKE; the EPC618 self-propelled, port side closest to buoy; the EPC618 self-propelled, starboard side closest to buoy; and the EPC618 towed. Figures 12 to 14 show the noise levels for the EPC618 towed and self-propelled, noisemaker on;* and for the EPC618 self-propelled, noisemaker off, port side closest to buoy.

When all the data were assembled, it was found that the port side of the self-propelled EPC618 radiated considerably more noise than the starboard side at all speeds and in all frequency bands tested. Therefore these groups of noise levels were averaged separately. No such difference was found for the towed EPC618 or for the WILKE.

In evaluating Figures 9 through 14, it should be borne in mind that the points plotted are based on averages of a varying number of runs, ranging from 2 to 63. In nearly all of the graphs drawn, the greatest number of runs from which the average values were computed was usually at 10 knots. There were also a fairly large number of levels to average at 12.5, 15, and 17.5 knots for most graphs. For the graph of Figure 9, representing the EPC618 self-propelled, starboard side closest to buoy, for example, there were 19 measured values available with which to compute the average sound level at 10 knots, 11 values at 12.5 knots, 9 values at 15 knots, 9 values at 17.5 knots, but only 2 values at 7.5 knots.

It is readily apparent from Figures 9 to 11 that the sound radiated by the self-propelled EPC618 was of a considerably higher level than that radiated by the towed EPC618. Since the presence or absence of the propellers represented the only physical difference between the EPC618 self-propelled and the EPC618 towed,** it must be concluded that the propellers dominated the noise radiated by the self-propelled EPC618. Visual observations made in 1950[6] revealed that the propellers of the EPC618 cavitated at all the speeds tested.

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*Since the noise output of the noisemaker was considerably greater than that of the EPC618 for either the self-propelled condition or the towed condition at all speeds and in all frequency bands tested, it was decided to combine the levels of the self-propelled and towed runs in which the noisemaker was operating. This decision proved to be valid upon examination of the data.

**Save for the fact that the main propulsion machinery usually was not operating when the EPC618 was towed. The main engines *were* turned on, however, several times during the towed runs and no resulting increase in noise level was detected. The results of the machinery noise test (page 27) also show that ship machinery noise did not dominate the towed radiated noise.

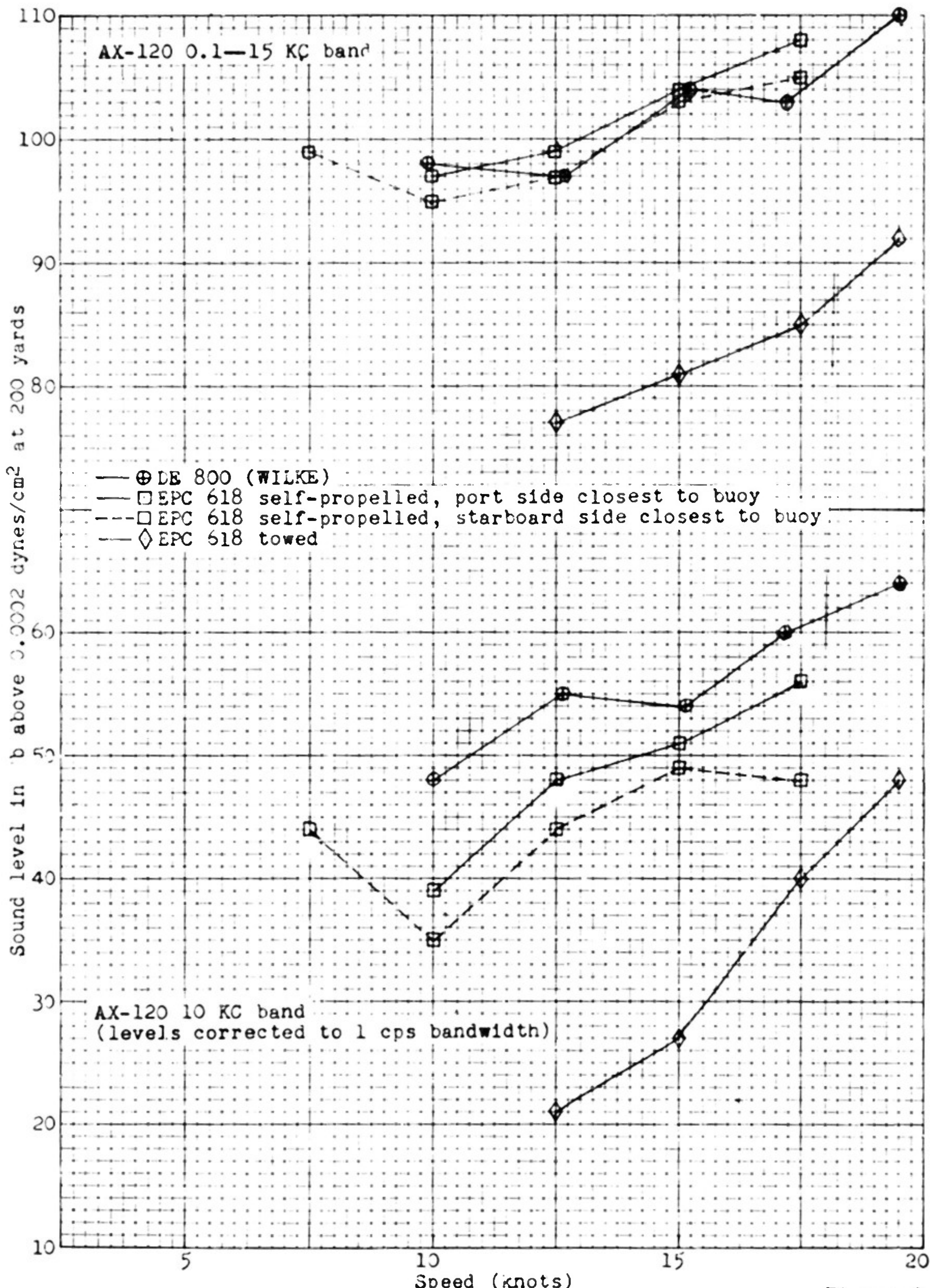
AX-120 0.1—15 KC band
—⊕ DE 800 (WILKE)
—□ EPC 618 self-propelled, port side closest to buoy
---□ EPC 618 self-propelled, starboard side closest to buoy
—◇ EPC 618 towed
AX-120 10 KC band
(levels corrected to 1 cps bandwidth)
Sound level in db above 0.0002 dynes/cm² at 200 yards
Speed (knots)
110
100
90
80
60
50
40
30
20
10
5
10
15
20

Figure 9

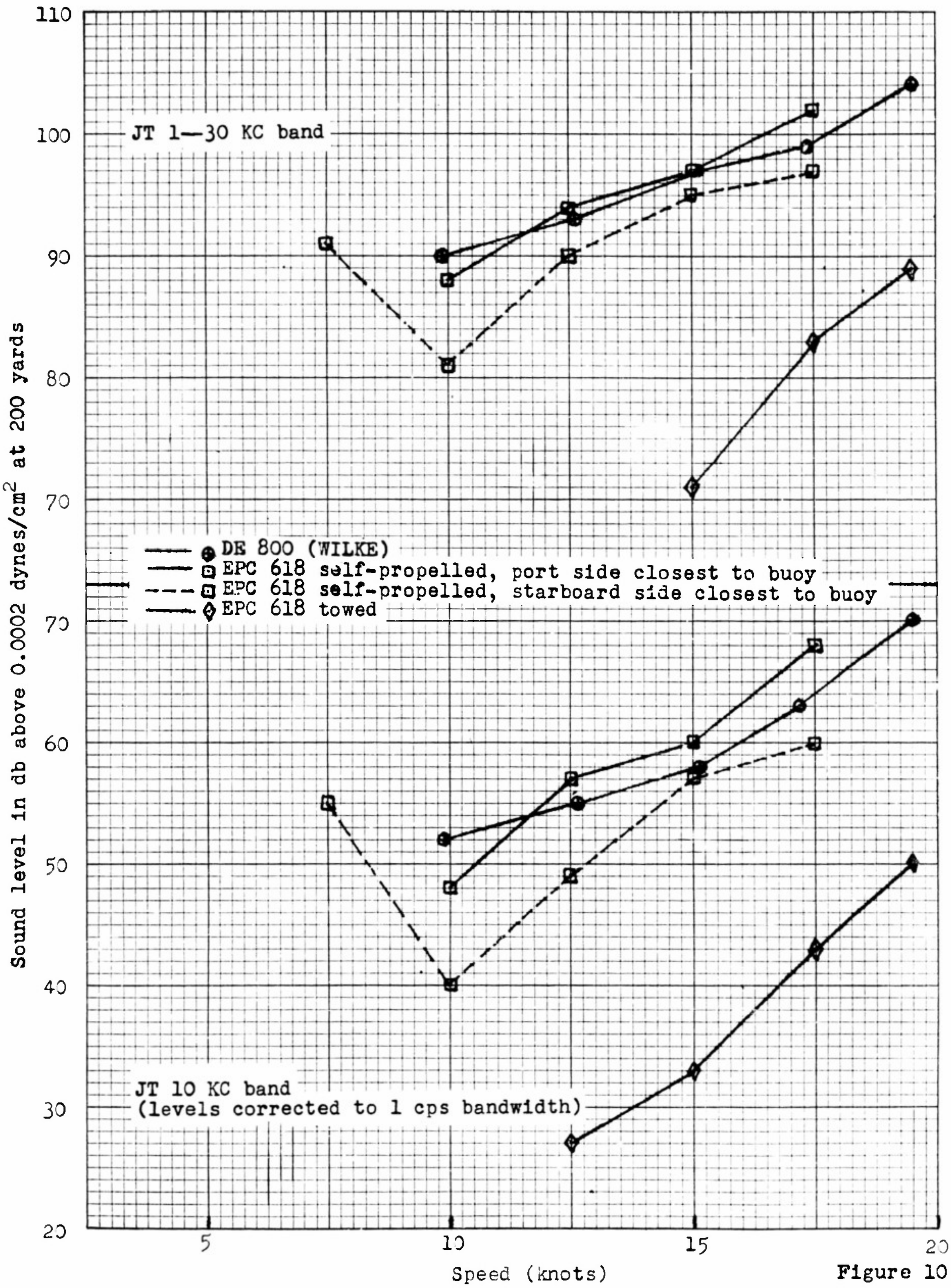
110
100
90
80
70
70
60
50
40
30
20
JT 1—30 KC band
DE 800 (WILKE)
EPC 618 self-propelled, port side closest to buoy
EPC 618 self-propelled, starboard side closest to buoy
EPC 618 towed
JT 10 KC band
(levels corrected to 1 cps bandwidth)
Sound level in db above 0.0002 dynes/cm2 at 200 yards
5
10
15
20
Speed (knots)

Figure 10

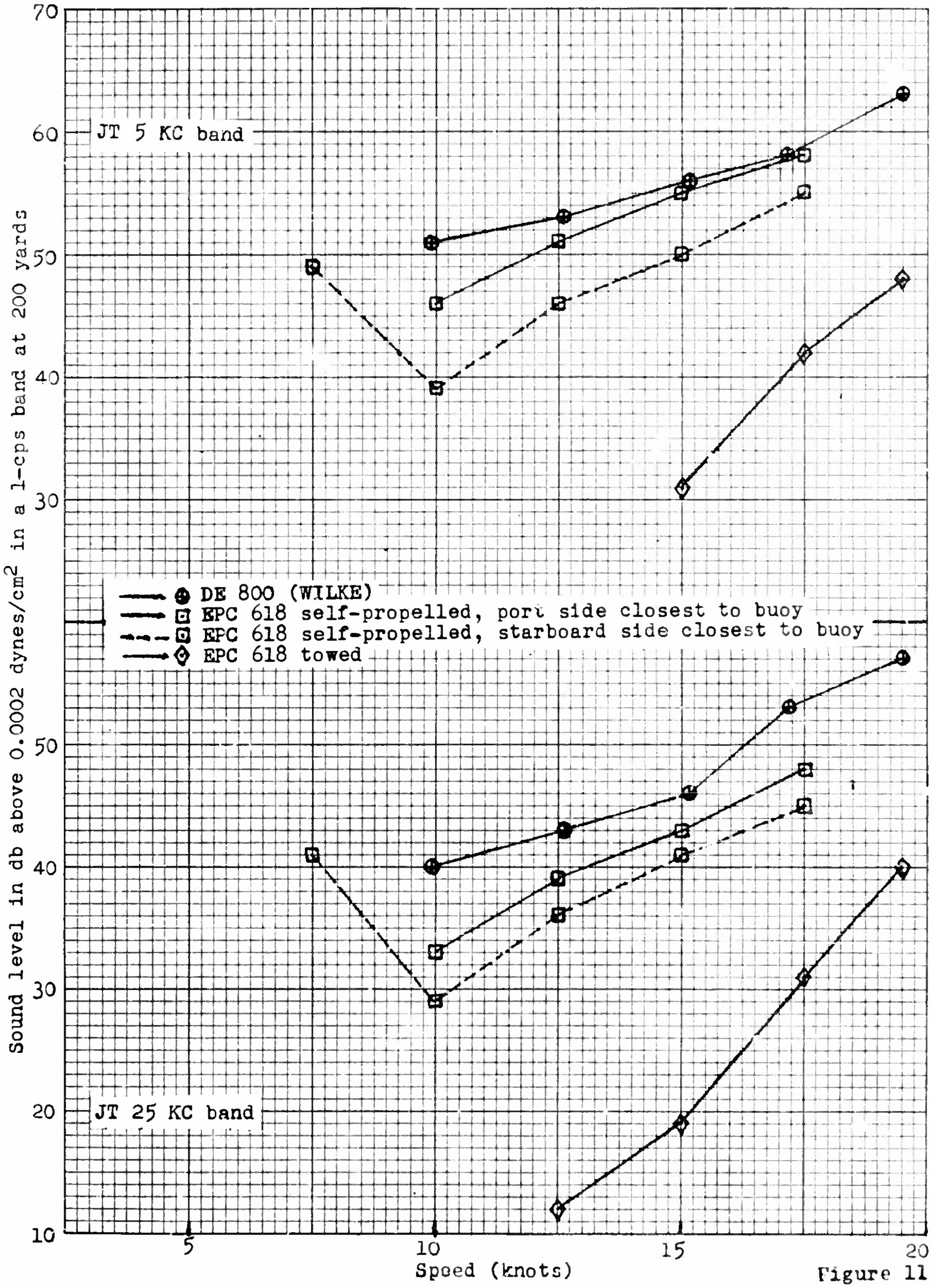
70
60
50
40
30
50
40
30
20
10
JT 5 KC band
JT 25 KC band
DE 800 (WILKE)
EPC 618 self-propelled, port side closest to buoy
EPC 618 self-propelled, starboard side closest to buoy
EPC 618 towed
Sound level in db above 0.0002 dynes/cm2 in a 1-cps band at 200 yards
5
10
15
20
Speed (knots)

Figure 11

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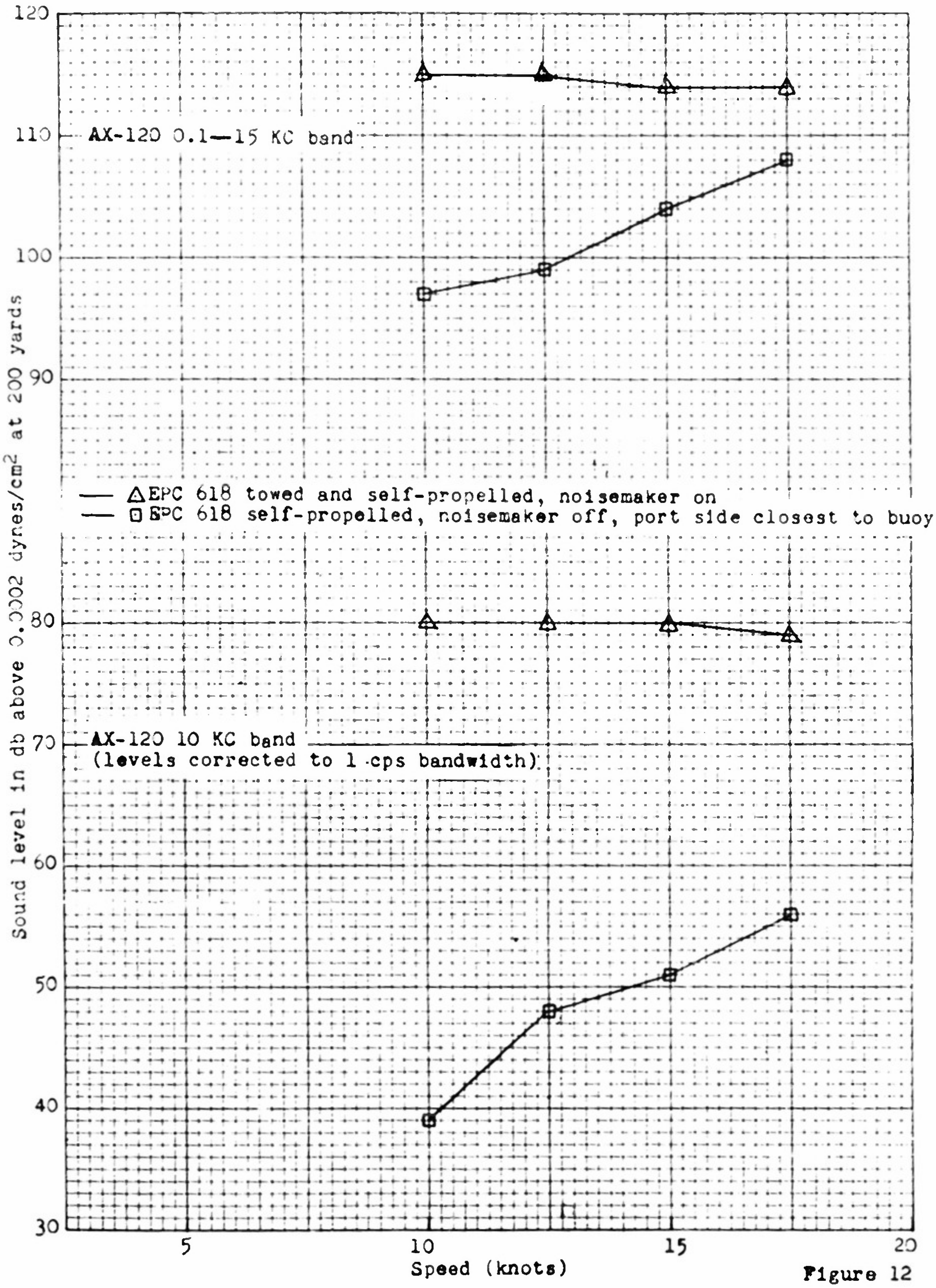

Figure 12

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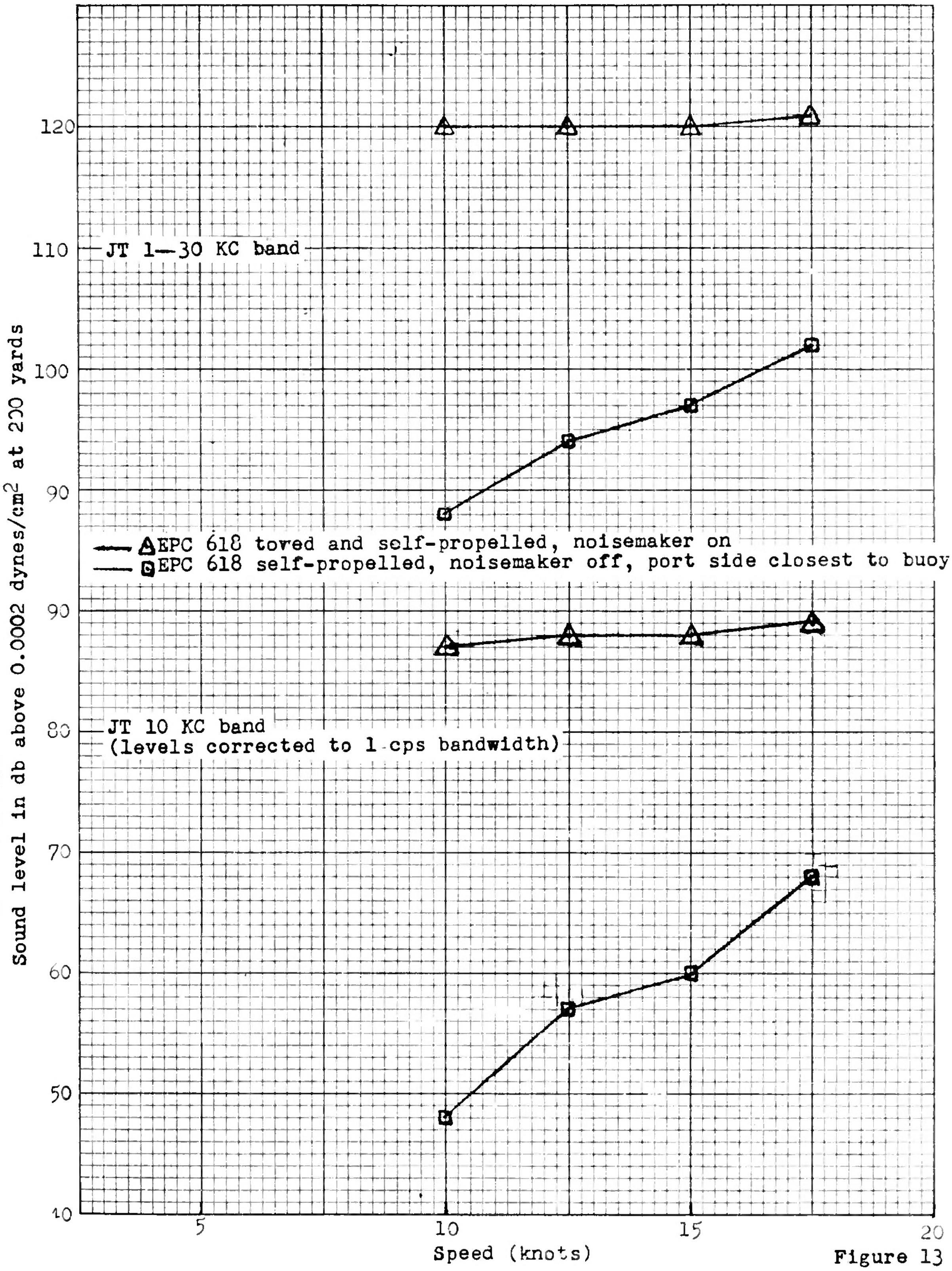
120
110
100
90
90
80
70
60
50
40
JT 1—30 KC band
EPC 618 towed and self-propelled, noisemaker on
EPC 618 self-propelled, noisemaker off, port side closest to buoy
JT 10 KC band
(levels corrected to 1 cps bandwidth)
Sound level in db above 0.0002 dynes/cm² at 200 yards
5
10
15
20
Speed (knots)

Figure 13

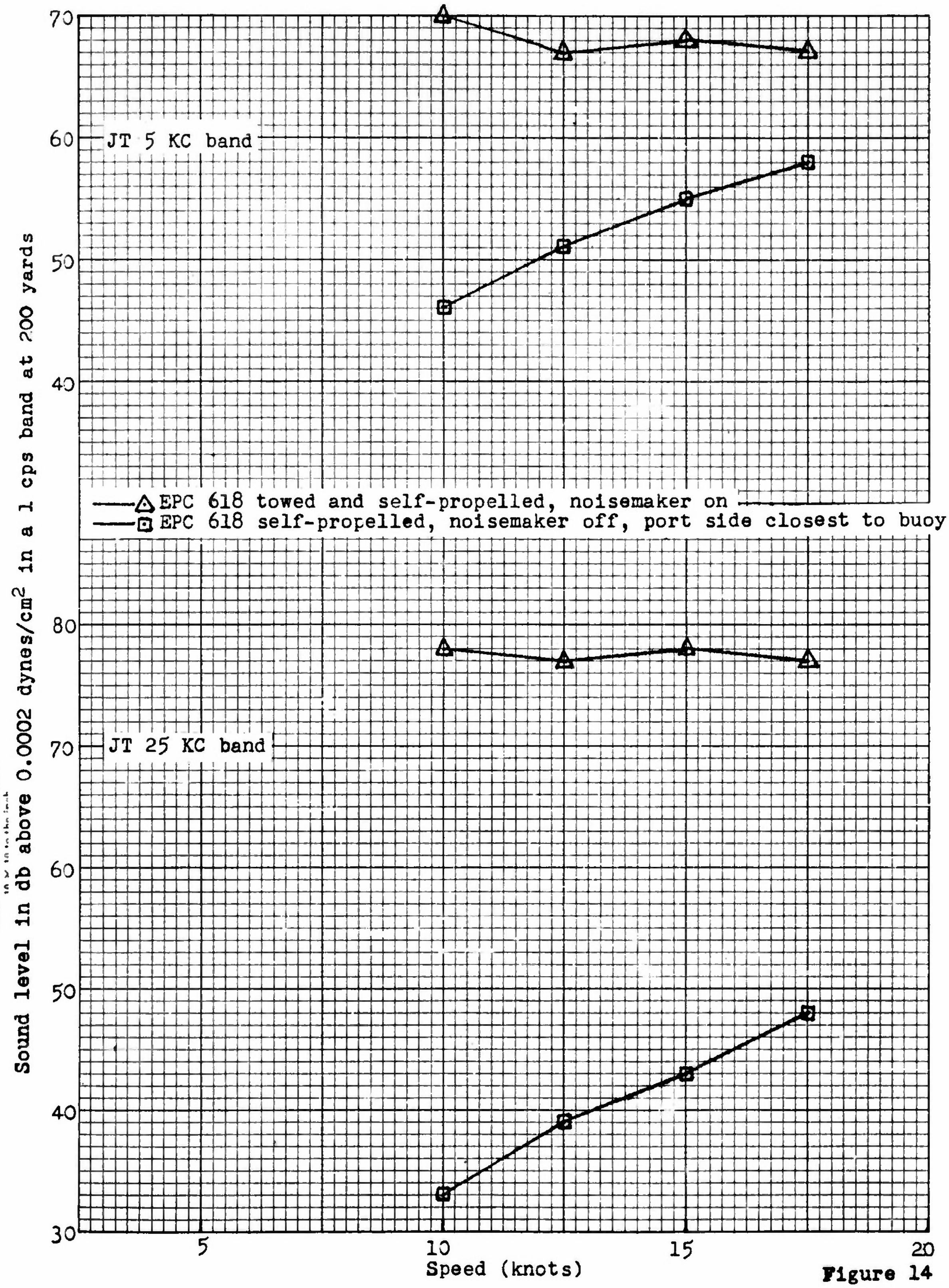
JT 5 KC band
JT 25 KC band
EPC 618 towed and self-propelled, noisemaker on
EPC 618 self-propelled, noisemaker off, port side closest to buoy
Sound level in db above 0.0002 dynes/cm² in a 1 cps band at 200 yards
Speed (knots)
70
60
50
40
80
70
60
50
40
30
5
10
15
20

Figure 14

With the solitary exception of the noise level of the starboard side at 17.5 knots measured through the 10-kc band of the AX-120 hydrophone (Figure 9) all of the graphs representing the EPC618 self-propelled in Figures 9 to 11 show an increase of noise level with speed for ship speeds in excess of 10 knots. This particular level is based on an average of 9 values and thus should be reasonably reliable. It is probable that the noise levels measured during these runs were near the extreme low end of the normal statistical spread. The values averaged ranged from 43 to 53 db. A possible explanation for this abnormally low noise level is the fact that it has been established[3] that the propeller noise of the EPC618 varied greatly with rudder movement.

When the EPC618 was self-propelled at 7.5 knots, only one engine was utilized, and, as a result, the single propeller in operation was cavitating badly and was consequently radiating an abnormally large amount of noise. Therefore all noise levels at 7.5 knots should be disregarded in any analysis of propeller noise output as a function of ship speed.

All the graphs in Figures 9 to 11 representing the EPC618 towed show an increase of sound level with speed. It was difficult to obtain reliable noise measurements of the EPC618 towed at speeds of less than 12.5 knots because prominent noise peaks were not obtained on the strip recorder charts, except at extremely close ranges. The reason for this was that the background noise was oftentimes of the same order of magnitude as the noise radiated by the towed EPC618 at 10 knots and, occasionally, at 12.5 knots. Background noise measurements were taken on each operating day. The background noise was caused mainly by the towing ship and was also due in part to the ambient sea noise, the few essential auxiliaries remaining in operation on the listening vessel, and submarines and surface vessels* outside the operating areas. Although this noise varied by as much as 28 db from day to day, all of the towed noise levels plotted in Figures 9 to 11 are based on averages of levels that were safely above the background noise on whatever day those particular levels were obtained.

When the EPC618 was under tow, noise peaks were consistently obtained on the strip recorder charts at points near the stern markings. This proves that the principal sources of radiated noise were near the stern when the ship was towed. It is impossible to state with certainty just what sources produced this "stern noise", but the most likely possibilities were cavitating appendages and/or noise originating in the portion of the EPC618's wake just aft of the stern. The abrupt decrease in slope of the "stern noise" graphs of self noise as the speed is decreased from 12.5 knots[3] suggests that appendages near the stern began to cavitate at a speed of approximately 12.5 knots and dominated the noise radiated by the towed EPC618 from then on.

*On one occasion the AX-120 hydrophone picked up sound radiated by the WILKE when that vessel was doing 12.5 knots three miles away. The WILKE then reduced its speed to 0 knots, whereupon the noise level of the 0.1- to 15-kc band dropped by 12 db.

Figures 9 to 11 indicate that the noise radiated by the WILKE was approximately equal to, or slightly greater than, the noise radiated from the port side of the self-propelled EPC618. The WILKE noise levels were undoubtedly somewhat higher than they would have been if that vessel had been running free. Towing the EPC618 reduced the WILKE's speed by approximately 2 knots at the same propeller rpm.

It is known that the propellers of the EPC618 were extremely noisy for a vessel of this size.* Hence it is not unreasonable that a self-propelled destroyer escort was not significantly noisier than the self-propelled EPC618. The poor agreement shown between the 10-kc levels measured through the JT and AX-120 hydrophones suggests that the range correction formulas applied to the WILKE data are not as accurate as they might have been. The 10-kc levels measured through the JT are consistently higher than those measured through the AX-120. The WILKE levels are based on averages of a very large number of values. For example, 58 AX-120 10-kc levels and 62 JT 10-kc levels were used to compute the average sound level at 10 knots, yet the JT 10-kc band shows a corrected sound level for the WILKE which is 4 db higher than the corresponding sound level computed from the AX-120 data. Even so, the differences between the WILKE data obtained with the two hydrophones are considerably less than the differences between the EPC618 data obtained with the same two hydrophones.

All the graphs depicting the sound levels obtained when the noisemaker was operating (Figures 12 to 14) show essentially a constant sound level at all ship speeds in a given frequency band. This is precisely what one would expect since the noisemaker noise was considerably greater than the screw noise of the EPC618 at all speeds and frequencies tested. It should be noted, however, that the effect of the noisemaker on the ship's own sonar varied markedly with speed[3], presumably because of attenuation by bubbles between the noisemaker and the sonar dome. The fact that the radiated noise levels of the noisemaker showed no variation with speed suggests that these bubbles did not attenuate the radiated noisemaker noise, i.e., they must have passed above the noisemaker.

The rate at which the noise radiated by the EPC618 increased with ship speed** can

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*Reference 7 contains the results of radiated noise measurements of another patrol craft, the EPC818, and on page 116 of Reference 5 there is a series of semi-theoretical graphs of sound level vs. ship speed which applies to surface ships of over 400 tons displacement. Since the full-load displacement of the EPC618 is 490 tons, and that of the WILKE is 2170 tons, the following levels are obtained:

Ship Speed knots	Spectrum Level at 5 kc and 200 yds				
	EPC618 (Fig. 11)	EPC818 (Ref. 7)	490-ton ship (Ref. 5)	WILKE (Fig. 11)	2170-ton ship (Ref. 5)
10	46	30	32	51	39
12	50	30	37	53	44
14	53	35	41	55	48
15	55	40	43	56	49

**Or shaft rpm. A graph of shaft rpm vs. water speed of the EPC618 revealed essentially a straight line relationship.

be shown very conveniently by fitting an empirical curve of the type "Sound Intensity $\propto$ (Ship Speed)^n" to the data. Values of the exponent n for the different frequency bands used are given in Table 1 (page 11). These exponents were derived by replotting the graphs of the radiated noise of the EPC618 self-propelled and towed from Figures 9 to 11 onto semi-logarithmic paper and obtaining the average slopes of the resultant graphs.

The bottom row of Table 1 shows that the noise radiated from the port side of the self-propelled EPC618 increased with speed in each frequency channel. If the exponents derived for the 6 channels are averaged together, it is seen that this noise is proportional to about the fifth power of the speed.

The top portion of the table indicates at what power of the ship speed the "stern noise" increased. If the 6 exponents are averaged together, the stern noise is found to be proportional to about the twelfth power of the speed. The use of decibels to express sound levels tends to obscure these high rates of increase.

MACHINERY NOISE TEST

Table 2 gives the results of the machinery noise test conducted on the EPC618. During this test both the EPC618 and the listening vessel were adrift, and the distance between the ships, as measured by rangefinder, varied from 39 to 83 yards, hence range corrections had to be applied to the measured noise levels.

TABLE 2

Machinery Noise Test on EPC618

Items Operating	Sound level in db above 0.0002 dynes/cm^2 in a 1-cps band at 200 yards					
	JT				AX-120	
	1 - 30 kc	5 kc	10 kc	25 kc	0.1 - 15 kc	10 kc
Main Engines Plus Normal Auxiliaries	77	30	20	24**	79	21
Normal Auxiliaries Only	77	20	16	24	68	15
Fire and Flushing Pump and Generator	79	16	15	24	69	14
Generator Only	79	15	16	24	66	13
Nothing Operating*	77	13	15	24	68	11
Generator of Listening Ship Secured*	79	11	15	24	68	11

*Gyroscope operating, but ice machine secured. Both ice machine and gyroscope operating in all other conditions.

**In electrical background.

NOTE: The levels 0.1 - 15 kc and 1 - 30 kc not reduced to 1-cps bandwidth

A comparison of Table 2 with Figures 9 to 11 shows that ship machinery noise did not contribute significantly to the noise radiated by the self-propelled EPC618 in any of the frequency bands through which measurements were taken. With the notable exception of the JT 1- to 30-kc band, the comparison shows that machinery noise did not dominate the noise radiated by the towed EPC618, except perhaps at 10 knots.

The levels of the JT 1- to 30-kc band given in Table 2 (page 27) are so much out of line with the rest of the data tabulated that little reliance should be placed on them. At one time during the machinery noise test, the JT was trained *off* the EPC618, and the tape levels on the strip recorder charts which were recording the outputs of the JT 5- and 10-kc bands dropped several decibels. However, the tape level of the 1- to 30-kc band did *not* drop. This suggests that there was an intense noise source (or sources) in the area during the machinery noise test which was radiating sound mostly at frequencies less than 4.5 kc. On this particular day several merchant vessels passed through the operating area and caused unusually high background noise.

Figure 15 shows the results of a Gertsch pass-band filter analysis of Magnecorder recordings taken during the machinery noise test. The sound levels are plotted for the main engines plus normal auxiliaries and for the normal auxiliaries only. These recordings were taken through the AX-120 hydrophone.

According to Figure 15, the machinery noise decreased at a rate of nearly 8 db per octave at frequencies greater than 0.7 kc. The graphs of Figure 15 do not represent continuous spectra; the separate points plotted have been connected merely for convenience. A narrow-band spectral analysis of the magnetic tape recordings from which the sound levels of Figure 15 were obtained showed that there were several instances of line spectra. Spectra which consist chiefly of discrete lines are not adequately represented by a broad-band analysis. However the frequency stability of the ship machinery items was sufficiently uncertain as to render the narrow-band analysis somewhat untrustworthy.

During the measurement in which the main engines were operating, they were making turns for 10 knots (i.e., 166 rpm); however, the load on them was negligible. The noise produced by the main engines of a ship is slightly greater under a load in actual operation.[8]

SOUND LEVEL VS FREQUENCY

Figures 16 to 19 show the results of a Gertsch pass-band filter analysis of selected magnetic tape sound recordings of the EPC618 towed and self-propelled and of the WILKE self-propelled, taken through the AX-120 hydrophone. Each separate graph involving the EPC618 is based on averages of at least 5 and as many as 9 runs. The sound levels of 2 runs were averaged together to obtain each of the graphs involving the WILKE. The total number of runs analyzed was 69. The runs for which the ranges calculated from the rangefinder readings agreed most closely with the ranges given by visual estimate were the ones chosen for analysis. Each of the runs selected was played back through 9 Gertsch pass bands onto

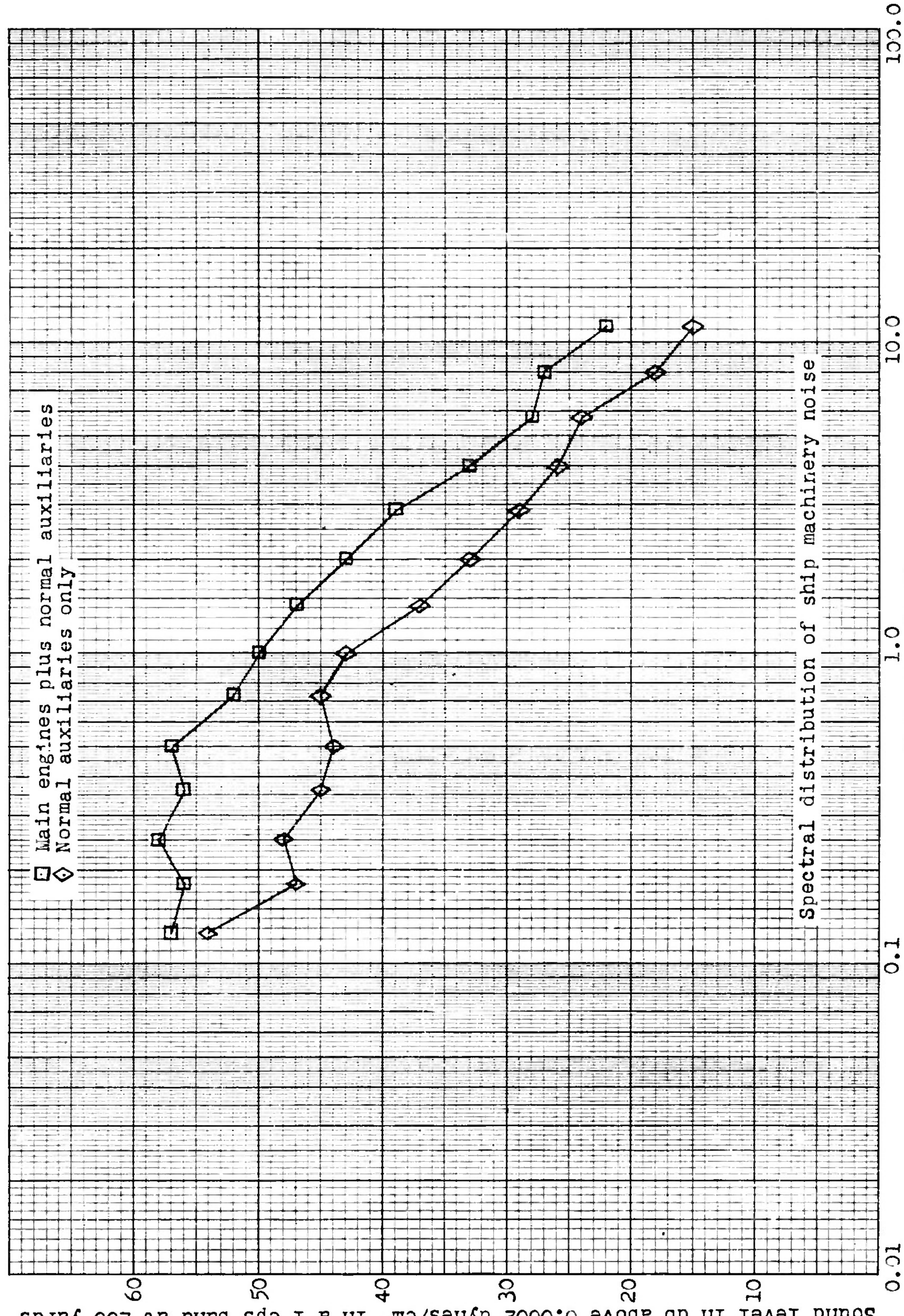
Main engines plus normal auxiliaries
Normal auxiliaries only
Spectral distribution of ship machinery noise
Frequency in KC
0.01
0.1
1.0
10.0
100.0
Sound level in db above 0.0002 dynes/cm² in a 1 cps band at 200 yards
10
20
30
40
50
60

Figure 15

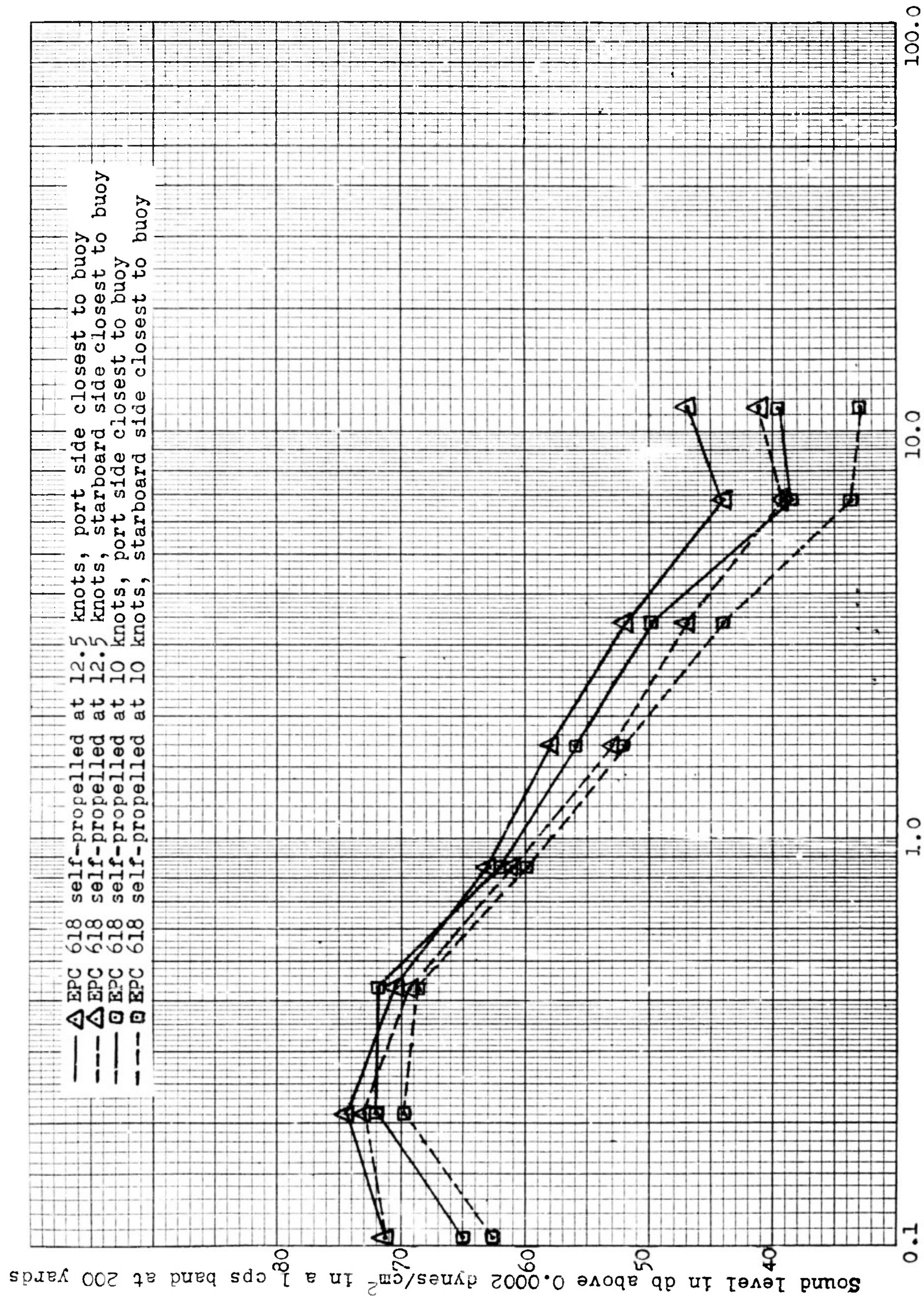
EPC 618 self-propelled at 12.5 knots, port side closest to buoy
EPC 618 self-propelled at 12.5 knots, starboard side closest to buoy
EPC 618 self-propelled at 10 knots, port side closest to buoy
EPC 618 self-propelled at 10 knots, starboard side closest to buoy
0.1
1.0
10.0
100.0
Frequency in KC
80
70
60
50
40
Sound level in db above 0.0002 dynes/cm² in a 1 cps band at 200 yards

Figure 16

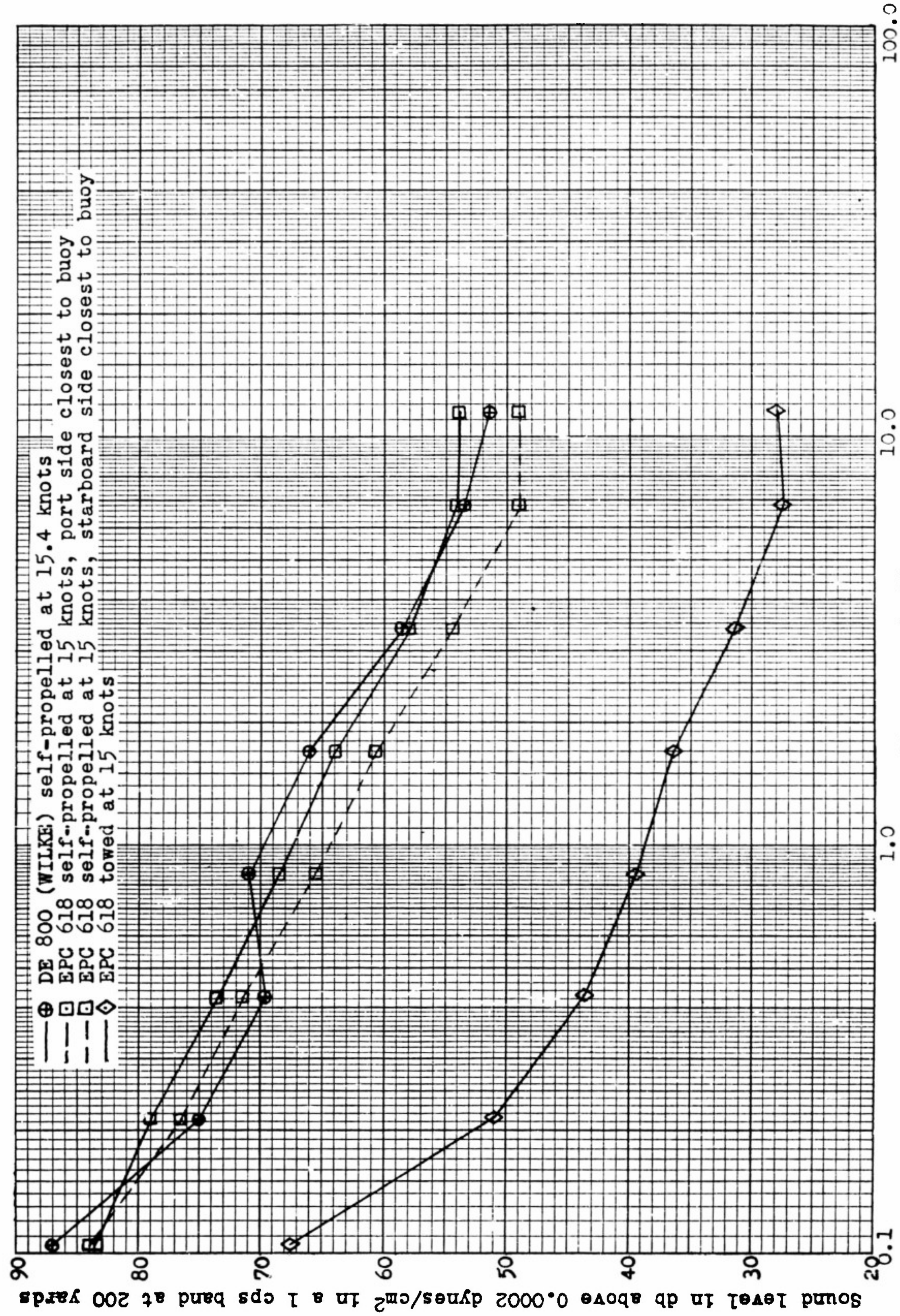
DE 800 (WILKE) self-propelled at 15.4 knots
EPC 618 self-propelled at 15 knots, port side closest to buoy
EPC 618 self-propelled at 15 knots, starboard side closest to buoy
EPC 618 towed at 15 knots
Sound level in db above 0.0002 dynes/cm² in a 1 cps band at 200 yards
90
80
70
60
50
40
30
20
0.1
1.0
10.0
100.0
Frequency in KC

Figure 17

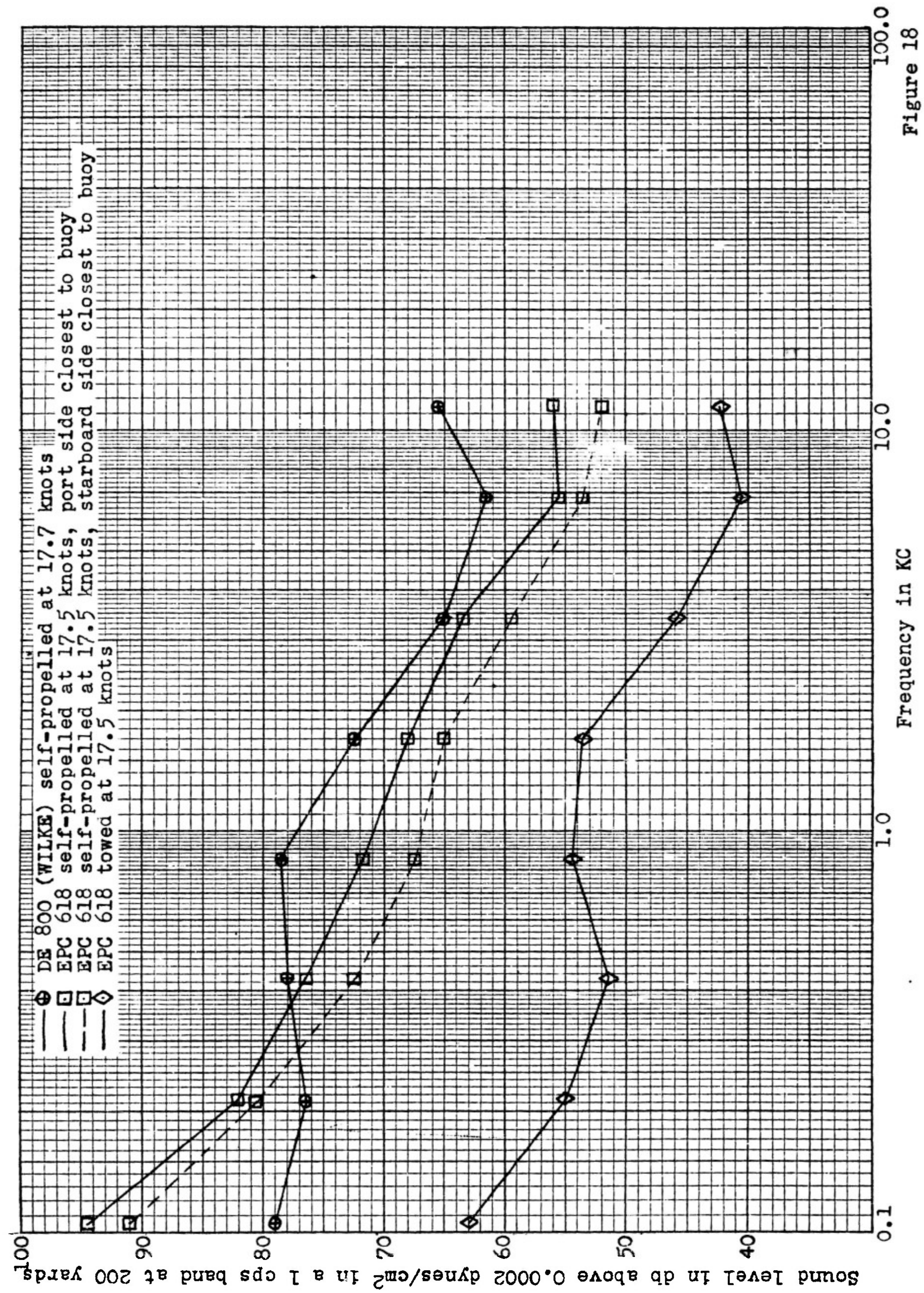
DE 800 (WILKE) self-propelled at 17.7 knots
EPC 618 self-propelled at 17.5 knots, port side closest to buoy
EPC 618 self-propelled at 17.5 knots, starboard side closest to buoy
EPC 618 towed at 17.5 knots
Frequency in KC
0.1
1.0
10.0
100.0
Sound level in db above 0.0002 dynes/cm² in a 1 cps band at 200 yards
100
90
80
70
60
50
40

Figure 18

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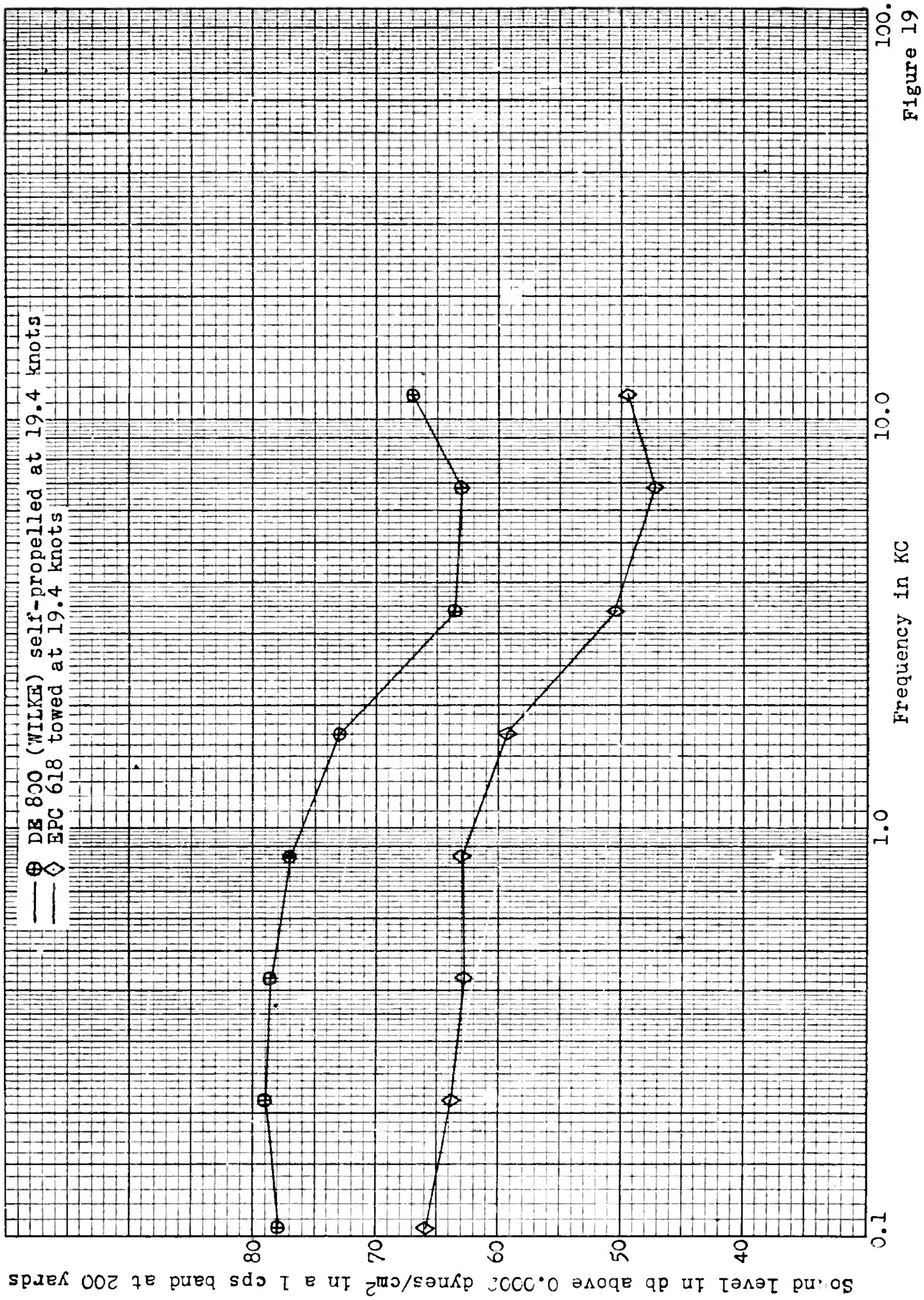

Figure 19

CONFIDENTIAL

a strip recorder. The pass bands selected were the 0.075- to 13.6-kc band, the 9.6- to 13.6-kc band, and the 7 octave bands extending from 0.075 to 9.6 kc. The peak near the stern marking on the recorder chart was used as the basis for computing the sound level for each pass band of each run. The points plotted in Figures 16 to 19 represent the average sound levels per cycle at the mid-band frequencies of these pass bands. It was found (page 18) that the port side of the self-propelled EPC618 radiated more noise than the starboard side, hence it was necessary to separate the data accordingly in Figures 16 to 19.

It has been concluded (page 18) that propeller noise represented the dominant component of the noise radiated by the self-propelled EPC618; hence the graphs representing the self-propelled EPC618 in Figures 16 to 18 actually show propeller noise spectra at the indicated speeds. These graphs reveal that the frequency at which the maximum propeller noise was radiated decreased with increasing speed. At 10 knots, the peak noise occurs between 200 and 300 cycles on the graphs, at 12.5 knots it occurs at approximately 200 cycles, and at speeds of 15 and 17.5 knots it occurs at 100 cycles or, more probably, at some lower frequency. (Measurements were not taken at frequencies below 100 cycles). All of the graphs representing the EPC618 self-propelled show a rapid decrease of sound level with frequency for frequencies up to 9.6 kc.* The relatively high level of the pass band centered at 11.4 kc is present on all the graphs in Figures 16 to 19.

It may be seen from the figures that the difference in sound level between the port and starboard propellers gradually increased with increasing frequency.

The graphs representing the self-propelled WILKE are more similar in shape to those representing the towed EPC618 than to those representing the self-propelled EPC618, at least in Figures 18 and 19. Sound measurements of the WILKE under tow have never been made. The WILKE is a turbo-electric-powered ship, whereas the EPC618 is diesel-powered. Furthermore, it should be kept in mind that towing the EPC618 reduced the WILKE's speed by approximately 2 knots at the same propeller rpm and also changed the slip. A radically different sound spectrum might have been found for the WILKE were she free from a load.

The striking similarity between the graphs representing the WILKE and those representing the towed EPC618 on Figures 18 and 19 suggests that what has been assumed to be EPC618 noise might actually have been WILKE noise reflected from the latter's wake and received by the listening vessel hydrophones. However, although such a situation is theoretically possible, it is quite certain that it did not occur. The evidence against its occurrence is as follows:

1. In order for noise radiated by the WILKE to be reflected from the WILKE's wake and produce a secondary noise peak well astern of the WILKE (Figure 8), reflection from the wake would have to be critically dependent on the angles of incidence and reflection. Such a possibility seems unlikely in view of the fact that wake echoes are caused by bubbles.

---

*6.8 kc is the mid-band frequency of the octave band extending from 4.8 to 9.6 kc.

Individual bubbles do not reflect sound at definite angles; they generally scatter it in all directions. Prominent noise peaks were consistently obtained on the strip recorder charts at points which coincided approximately with marks indicating the closest approach distances of the stern of the EPC618 to the listening vessel hydrophones. If these peaks were due to some "quasi-specular" type of reflection, the probability that they always occurred at a time when the EPC618 was at its minimum distance to the listening vessel is very small indeed, since the geometrical relationships existing during a given run would have to be exactly right.

2. When the magnetic tape recordings of the noise radiated by the towing vessel and the towed EPC618 were played back, screw beats of the towing vessel were clearly audible during the approach of the towing vessel, the passage of the towing vessel, and the approach of the EPC618. However, as the EPC618 came closer to the listening vessel and the noise level began to rise for the second time, the propeller noise of the towing ship was completely masked by another type of noise which possessed a sound similar to that of a roaring waterfall. This new sound was dominant until the EPC618 had proceeded past the listening vessel, after which the screw beats of the towing vessel once again became audible.

3. The graphs of Figure 17 representing the towed EPC618 and the WILKE are not nearly so similar in shape as are the corresponding graphs of Figures 18 and 19. The individual graphs which were averaged to give the graphs shown on the figures were all quite similar to one another in shape.

4. The noise radiated by the towed EPC618 showed a much faster rise with speed than did the noise radiated by the WILKE (Figures 9 to 11). If the towed EPC618 noise was actually reflected WILKE noise, one would expect identical rates of increase with speed.

5. The general character of the strip recorder records of the WILKE noise and the towed EPC618 noise is different. The noise peaks caused by the passage of the EPC618 were usually sharper than those caused by the passage of the WILKE (Figure 8); furthermore, a greater amount of short-term variation was recorded near the WILKE noise peaks. If the proposed reflection process caused a loss of detail with regard to these short-term variations, it should also have caused a broader secondary noise peak. The difference in the character of the records obtained is, therefore, inconsistent with the reflection theory.

SUMMARY OF RESULTS

1. The maximum component of the noise radiated by the self-propelled EPC618 was due to the propellers, the propeller on the port side being several decibels noisier than the one on the starboard side. Propeller noise increased with increasing speed for speeds of 10 knots and greater. The increase was approximately exponential with speed, the exponent being at least 4.0 and perhaps as high as 7.2. The self-propelled EPC618 was always noisier than

the towed EPC618.

2. The noise produced by the towed EPC618 was due primarily to noise sources near the stern. This stern noise increased approximately exponentially with speed at a much higher rate of increase than did the propeller noise.

3. The spectral distribution of the noise radiated by the self-propelled EPC618, the towed EPC618 and the self-propelled WILKE at various speeds was as shown in Figures 16 to 19.

4. Ship machinery noise dominated neither the towed nor the self-propelled radiated noise at frequencies between 1 and 30 kc when the ship speed was between 10 and 20 knots.

5. The inverse square law of radiation was not applicable to radiated noise levels measured at distances of 32 yards or less.

6. The sound levels produced by a typical self-propelled destroyer escort were as shown in Figures 9 to 11. Despite its much greater size, the WILKE (DE800) produced only slightly more noise than the self-propelled EPC618, due to the fact that the propellers of the EPC618 were extremely noisy.

PROPOSED IMPROVEMENTS IN TECHNIQUES AND INSTRUMENTATION

A more accurate method of obtaining ranges should be used in any future full-scale trials wherein radiated noise is to be measured. Two methods have been suggested. The first calls for the hydrophones to be suspended a safe distance under water at the center of a cable; one end of the cable would be attached to a stationary buoy and the other end to a self-propelled buoy. The test vessel would run between the two buoys.

The second method proposed calls for the hydrophones to be attached to a self-propelled buoy. The buoy would be controlled from the listening ship and would be positioned so that the axis of that ship would be perpendicular to the hydrophone cable leading to the buoy, with the distance to the buoy determined by the length of the cable. The test vessel would proceed past the buoy at as close a distance as feasible each run. Two transit-like devices would be installed on the test vessel, one amidships and one at the stern. These would be trained on the buoy as the test vessel approached, and at the instant the amidships transit indicated that the axis of the test vessel was perpendicular to an imaginary line connecting the transit to the buoy, a radio signal would be automatically transmitted to the listening vessel which would serve to index the strip recorder charts. As the test vessel proceeded, a radio signal would be automatically transmitted to the listening vessel at each change of 30 deg in the angle between the axis of the test vessel and the line connecting the buoy to the amidships transit until the stern transit showed that the axis of the test vessel was perpendicular to an imaginary line connecting that transit to the buoy; at that time a final radio signal would be transmitted which would determine the stern marking on the listening vessel recorders. The distance from the test vessel to the buoy would be the altitude of the right triangle whose vertices would be the two transits and the buoy; this could be readily calculated since the distance between the two transits and the angle between the hypotenuse and the axis of the test vessel would be known. The series of indices obtained would give a number of check points to the data. The error due to the obvious existence of small solid angles in the trigonometric relationship discussed would be negligible, even at extremely close distances.

Better methods of indexing the strip recorder charts should be worked out so that the precise location of the major noise source(s) on the test vessel can be determined. The proposed procedure for obtaining ranges outlined in the preceding paragraph gives a satisfactory solution to this problem. The magnetic tape recordings should be indexed electronically at a fixed arbitrary time subsequent to the closest approach of the test vessel. The magnetic tape recorder circuits could be modified so that an automatic time delay could be provided for indexing.

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19 Commander, Operational Development Force, U.S. Atlantic Fleet. U.S. Naval B[illegible]se, Norfolk 11, Va.

20 Commanding Officer, USS EPC618, FPO, New York, N.Y.

21 Director, Ordnance Research Laboratory, State College, Pa., via Development Contract Administrator

22 Hudson Laboratories, Columbia University, 145 Palisades St., Dobbs Ferry, N.[illegible], via ONR, New York

23 - 31 British Joint Services Mission (Navy Staff), P.O. Box 165, Benjamin Franklin Station, Washington, D.C.

32 - 34 Canadian Joint Staff, Washington, D.C.