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NRL Report No. R-2332
BuShips Problem S411

21 July 1944

NAVY DEPARTMENT

Report on

RADAR CROSS SECTION
OF SHIP TARGETS, IV

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ABSTRACT

The radar cross sections of DD-695, and of AGC-9 have been measured for frequencies ranging from 200 to 3060 Mc/s. The destroyer results are compared with those previously obtained on DD-496. The destroyer radar cross section was also measured at 700 Mc/s by a radar at a lower elevation and at shorter ranges than heretofore obtainable. The radar cross section as a function of ship aspect was determined for one range by having the target destroyer turn in a very slow tight circle during the measurements.

An analysis of the near-zone radar cross sections of different ships as a function of frequency is made on the basis of the few data available from previous reports in this series.

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1. INTRODUCTION

1-1. The work reported here has been conducted under the authorization of NRL Problem No. S411R-S. This report is the fourth in a series under the title "Radar Cross Section of Ship Targets", the preceding ones being NRL Reports RA-3A-213A, R-232, and R-2295. In the following, these earlier reports will be referred to as Reports I, II, and III, respectively.

1-2. The radar cross section of a destroyer is especially important because of the importance of this type of ship in tactical operations. It was felt that the early measurements that were made on DD-496 should be repeated, taking advantage of improvements in technique and equipment now available. In connection with some other work, two destroyers, DD-403 and DD-695, were made available for radar cross section measurements. This afforded a 700 Mc/s Mark 4 radar on DD-403, with antenna height of 50 feet, from which measurements could be made, supplementing the measurements from the land-based Mark 4 at the Chesapeake Bay Annex, the latter radar having an antenna height of 116 feet. DD-695 was used as the target ship. In addition, by suitable disposition of DD-403 in Chesapeake Bay in front of the Annex, the measurements from its radar could be made at much closer ranges than was possible from the land-based sets.

1-3. The measurements of the destroyer reflections were made on 30 and 31 May, 1944. The weather during the runs on 30 May was calm, fair, and hazy, while on 31 May the weather remained fair but moderately breezy. The change in weather on 31 May, it will be seen, affected the results obtained.

1-4. Radar cross section measurements were also made of AGC-9 (U.S.S. Wasatch) on 10 June 1944, after it had completed other tests at Chesapeake Bay Annex. The weather on this day was similar to that on 31 May.

1-5. In report III, the accumulated data on far-zone radar cross sections (σ_f) were examined to determine their trend with frequency. In this report, the few data available on near-zone radar cross sections (σ_n) are analyzed in a similar manner.

2. METHODS OF MEASUREMENT

2-1. The method of measurement has been described in Reports II and III. The shore-based radars and the corresponding standard targets were those listed in Table I of Report II, with the change of height of the one-foot square corner reflector mentioned in Report III. This reflector is used as the standard target for the SF and Mark 12 radars. The values of σ_0' (equivalent free-space radar cross section; see equation (6) of Report II) of this target for these two sets are 550

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and 54 square meters, respectively. Measurements on 400 Mc/s were not obtained, since the Mark 5 radar broke down early in the program.

2-2. During the radar cross section measurements, DD-403 was anchored about 2000 yards from shore, between the target ship (DD-695) and the shore-based radars at the Annex. A 4x4-foot flat screen, at a mean height of 27 feet above the water, was aimed at the anchorage of DD-403, and was intended to be used as a standard target for its Mark 4 radar. Land echoes received on the side lobes of the antenna, however, obscured the standard target from that particular anchorage. The measurements of radar cross section made from DD-403, therefore, were calibrated on a following day (2 June), when it was operating to the northward of the standard target. In this area, the shore line cuts back to the westward. A run was made on a course broadside to the target, while measurements were made of received echo at various ranges. No difficulty due to landscape echoes was experienced during this run. Unfortunately, there is no assurance that the output of the radar transmitter remained constant from the time the runs on DD-695 were made until the calibration measurements were taken.

2-3. Since the values of radar cross section for the broadside aspect are of greatest interest, a full quota of "circle" runs, as described in Report II, was made. During the evening of 30 May, a down-bay circle run was made, with the return leg a bow-on run. These runs covered ranges between 8000 and 33,000 yards. On the morning of 31 May, two across-bay circle runs were made to cover the shorter ranges, between 2500 and 12,000 yards. Limitations of time did not permit making any stern runs, or shorter-range bow runs.

2-4. In addition to the above-mentioned measurements, a very slow tight circle run at a range of about 8000 yards from the shore radars (6000 yards from DD-403) was made, in order to obtain a rather detailed measurement of the aspect pattern of radar reflection. During this slow circle, which covered about two complete rotations of the ship, measurements were made, usually at intervals of $\frac{1}{2}$ - 1 minute, of the maximum echo received during the preceding time interval. The ship recorded its true heading versus time, so that the measurements of radar echoes could be correlated with ship's aspect. The slow circle measurements covered an interval of about one and one-half hours. The ship turned clockwise, starting from approximately bow on. Due to the finite diameter of the circle and the finite time interval covered by each measurement, indicated aspects are probably accurate to only within about ± 5 degrees.

2-5. The measurements made on 10 June 1944 of radar echoes from AGC-9 consisted of a circle run down bay, followed by a bow run on the return leg. Time did not permit making a complete set of runs. Measurements were made on 200,560,700, and 3060 Mc/s.

3. DATA OBTAINED

3-1. Measurements of Radar Cross Section of DD-695.

3-1-1. The results of the measurements of the echoes from DD-695 are shown in Figs. 1-18. The values of radar cross section deduced from these graphs are tabulated in Table I.

3-1-2. Table I also gives the transition ranges for the various frequencies. The transition range is the range at which the eighth power line fitted to the data in the far zone intersects the fourth power line fitted to the data in the near zone. It thus represents the minimum range at which the far zone radar cross section, σ_f , may be employed. As pointed out in Report I, this transition range depends on the height of the radar antenna.

3-1-3. As was mentioned in the Introduction, a change in weather occurred between the two days of the runs on DD-695. This resulted in a difference in the measured values of σ_f on these two days. Table II lists the two sets of values obtained. All these values are for the broadside aspect, since only one bow run was taken.

3-2. Measurements of Radar Cross Section of AGC-9.

3-2-1. Data on the AGC-9 were obtained for bow and broadside aspects only. The results are shown in Figs. 20-24. The values of radar cross section obtained are tabulated in Table III.

4. DISCUSSION OF DD-695 MEASUREMENTS

4-1. Far-Zone Radar Cross Section (σ_f)

4-1-1. The measurements made on the evening of 30 May yielded greater values of σ_f than those on the morning of 31 May. In comparing Tables I and II, it will be noted that the smaller of the two sets of values of σ_f has been put forth as the more probable "normal" values. The ratio of the two values was 5 decibels for 200 and 700 Mc/s, but 10 decibels for the 970 Mc/s measurements.

4-1-2. The only bow run was taken on 30 May, which suggests that the values deduced from those measurements also may be larger than would have been obtained under normal conditions. The type of curve presented in the bow run of Fig. 16 (runs on 30/5/44 for 3060 Mc/s) has been obtained at the Annex rather frequently in calm weather such as prevailed on that date. The echoes increased regularly from extreme range into about 18,000 yards, where they suddenly dropped in amplitude. At about 15,000 yards, the operator making the measurements gave up waiting for strong echoes to reappear and resumed the

measurement of the prevailing levels. From this range inward, the echoes increased in power rather regularly to minimum range; but in this part of the run the echo powers were about one-tenth those expected from inward extrapolation of the values beyond 18,000 yards. This condition of strong echoes from long ranges followed by a "drop-out" is believed due to anomalous refraction by the atmosphere. The amount of this refraction probably varies during the run. On one calm day of this type, the echo from Sharps Island Lighthouse at 14,700 yards range was observed on 3060 Mc/s (antenna height 137 feet) to vary more than 15 decibels during five minutes. For DD-695, the drop-out occurred only on 3060 Mc/s. In earlier measurements on CV-13, made on a day of this type, a drop-out during a bow run was found on all frequencies used, (which included 200 Mc/s), with at least two drop-outs on 3060 Mc/s. The depth and frequency of occurrence of the drop-outs seems to increase with frequency.

4-1-3. The variation of σ_f with frequency is of interest. A plot of the values for DD-695 is shown in Fig. 19. A fourth power law seems to fit best to the results of the present measurements; i.e., σ_f is more nearly proportional to the fourth power of the frequency than to any other integral power. The value of σ_f for the broadside aspect on 3060 Mc/s is inexplicably low. Table IV lists the values of σ and K in the equation $\sigma_f = K \cdot f^4$, obtained from the lines drawn in Fig. 19.

4-2. Effect of Antenna Height on Radar Cross Section.

4-2-1. The use of the two 700 Mc/s radars with different antenna heights presented the first opportunity of checking directly the effect of antenna height on radar cross section. Theoretically, the radar cross section should be the same for both heights, while the transition range should be proportional to antenna height. However, the values of σ_f and σ_n obtained by DD-403 were respectively 5 and 10 decibels less than those obtained by the Annex set. Unfortunately, the comparison is rendered unreliable by the delay in obtaining the standard target measurements. If it is assumed that a 5-decibel error in σ_f is due to the delayed calibration on DD-403, then there is still an additional 5 decibels to be accounted for between the values of σ_n . As a result of this discrepancy in values of σ_n , the values of transition range also do not agree.

4-2-2. Some of the discrepancy might be attributed to insufficient allowance for TR recovery. It happened that the DD-403 set had to be used on other tests before a TR recovery check could be made; an estimate of recovery-time corrections, therefore, was made by using a previous calibration of the recovery characteristics of the Annex set. The results of this correction have been included in Fig. 10.

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4-3. Aspect Patterns.

4-3-1. The received echo is by no means a regular function of aspect, as is shown by Figs. 5, 8, 12, 15, and 18 (no results were obtained on the slow circle for 200 Mc/s). This is especially apparent at the higher frequencies, where the maximum signal during an interval appeared as a sudden flash of from 4 to 10 decibels above the corresponding signal from neighboring aspects. The disposition of the SC-3 radar antenna on DD-695 may have affected the pattern somewhat, and should be considered as a possible variable factor in dealing with the ship's patterns. The range of the ship from the radars at the Annex, 8000 yards, was such that part of the ship was at the maximum of the vertical lobe pattern for frequencies of 700 Mc/s and higher. Thus, the patterns obtained for those frequencies do not necessarily hold for greater ranges, where the influence of topside portions of the ship would be greater. At greater ranges, orientation of the search radar antenna on the target ship becomes of increasing importance, as pointed out in Report III.

4-3-2. For 560 Mc/s (see Fig. 5), the broadside echo was two decibels stronger than the strongest echo from the starboard. Likewise, the stern aspect averaged stronger than the bow by two decibels. Echoes from aspects within 20° of the bow were at least 15 decibels weaker than from the port broadside. The fact that values for corresponding aspects do not coincide on successive circles is presumably due to the fact that the roll of the ship is unrelated to the ship's heading.

4-3-3-. On 700 Mc/s, measured from the Mark IV radar at the Annex, (see Fig. 8), the port broadside aspect again gave the strongest echo, exceeding the starboard broadside echo by one decibel on each circle. Stern and bow echoes appeared to be about equal. The broadsides were somewhat sharper than on 560 Mc/s. At aspects 10° from the broadside the signals were at least five decibels down. Within $\pm 25^\circ$ of bow and stern, echoes were at least 15 decibels weaker than from the port broadside.

4-3-4. The measurements from the Mark IV radar on DD-403 (see Fig. 12), were interrupted several times during the slow circles, which may have caused a sharp maximum off the starboard beam to be missed. Aspects within 25° of the bow gave echoes at least 13 decibels weaker than the maximum echo off the port beam.

4-3-5. At 970 Mc/s, (see Fig. 15), the average starboard broadside echo equalled the single port measurement. In addition to a peak 1.5 decibels below the broadside, 30° forward of the starboard beam, a peak of equal height 30° forward of the port beam appeared on both circles. The broadside echoes averaged at least 9 decibels higher

than any other echo measured, except for the secondary peaks mentioned above.

4-3-6. At 3060 Mc/s, (see Fig. 18) the port and bow peak echoes averaged the same, and were about 15 decibels stronger than those within $\pm 35^\circ$ of the bow. The signal underwent exceedingly rapid fluctuations, and the echoes recorded were the highest among those from nearby aspects. In Fig. 15, where many degrees of ship's heading occur between successive recorded echoes, the peak values of the pip at intermediate headings were weaker than at either end of the interval.

4-3-7. The secondary peak at about 30° forward of starboard on each frequency except 3060 Mc/s may possibly be attributed to reflections from the SC-3 radar antenna on DD-695. If this explanation is accepted, the lack of corresponding peaks at 3060 Mc/s can easily have been due to the extreme sharpness of the reflected beam from the SC-3 antenna at this frequency ($\approx \frac{1}{2}$ degree). However, corresponding peaks 30° aft of port are not indicated.

4-3-8. In general, the ratio of peak signals varied over a range of 15 decibels or more with aspect. The strongest signals invariably were received from the broadside aspect. It should be kept in mind that these figures refer to the maximum value of the echo received in a specified time interval, in the order of 1 minute. The ratio between the maximum signal and the minimum signal received during a circle is very much greater, probably exceeding 60 decibels.

5. DISCUSSION OF AGC-9 MEASUREMENTS

5-1. The points obtained for the broadside measurements on AGC-9 fall off fairly regularly with increasing range, but the results for the bow run show a certain degree of scatter which is somewhat similar on all the frequencies used. Examination of the radar plot of AGC-9 during this run shows that the ship traversed a zig-zag course, so that the aspect did not remain constant.

5-2. The plot of the 3060 Mc/s measurements on AGC-9 (Fig. 24) does not indicate any region where the received echo decreases as the eighth power of range. Hence, no value of σ_f for this frequency can be deduced. However, a lower limit for the value of σ_f can be obtained by fitting on an inverse eighth power line at the extreme range of the measurements. This yields a value of $1.3 \cdot 10^{17}$ square meters.

5-3. In Fig. 25, the values of σ_f obtained for AGC-9 are plotted against frequency. The best fit to the points is provided by a line of fourth-power slope, both for bow and broadside aspects. It is interesting to note that the lower limit to the value of σ_f for 3060 Mc/s lies to the left of the fourth-power line by an order of magnitude. Table IV gives the values of s and K for the lines of Fig. 25.

6. NEAR-ZONE RADAR CROSS SECTION AS A FUNCTION OF FREQUENCY

6-1. In Report III, an examination was made of the way in which the values of far-zone radar cross section, σ_f , varied with frequency. The corresponding data for near-zone radar cross section, σ_n , are much less complete, making it more difficult to draw conclusions regarding variation with frequency. On the assumption that the radar echo from a ship is built up from completely random scattering from the various portions of the ship, the near-zone radar cross section turns out to be independent of the frequency. On the other hand, coherent scattering should give values of σ_n which increase with frequency, the increase being at least proportional to the frequency.

6-2. Examination of the values of σ_n listed in Table II of Report III shows quite definitely that the trend is to increase with frequency. Due to variations that occurred as a result of propagation conditions and set difficulties, not all the data are considered of equal reliability. If the more reliable data are selected, the set of values listed in Table V results. These values have been plotted in Fig. 26.

6-3. The trends with frequency revealed by Fig. 26 are as follows: CL-89 (broadside), first power; AM-246 (broadside), about second power; AM-246 (stern), first power; DD-695 (broadside), inconclusive. The value of σ_n at 3060 Mc/s for DD-695 is only slightly larger than the value for 700 Mc/s. As mentioned in paragraph 4-1-3, the value of σ_f for this frequency was also correspondingly low relative to the values for the other frequencies.

7. CONCLUSIONS AND RECOMMENDATIONS

7-1 Conclusions.

7-1-1 From the experience gained in the measurements made from DD-403, it is concluded that it is feasible to make quantitative radar cross section measurements aboard ship, but that due care must be exercised in choosing ship's location to avoid obscuring standard target echoes by landscape clutter.

7-1-2. Abnormal propagation conditions can increase values of radar cross section by 10 decibels in the far zone.

7-1-3. The strongest echoes from a destroyer are from the broadside aspects. The ratio of echo peaks varies over a range of 15 decibels or more with aspect. Minimum values are encountered around bow and stern aspects. Usually in a region about 25 degrees either side of bow the echo peaks are about 15 decibels below the broadside peaks.

7-1-4. The trend of the values of near-zone radar cross section is to increase with frequency, roughly as the first power.

7-2. Recommendations.

It is recommended that, whenever possible, ships made available for radar cross section measurements be accompanied by a destroyer, in order that measurements at very close ranges may be made by using the radars on board the destroyer.

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TABLE 1.

Values of σ_f and σ_n in Square Meters for DD-695

Frequency, Mc/s	200	560	700	700	970	3060
Antenna Ht., Ft.	110	113	116	50	126	137
σ_f , bow *	$4.6 \cdot 10^{10}$	$1.7 \cdot 10^{13}$	$1.6 \cdot 10^{13}$		$1.1 \cdot 10^{14}$	$4.2 \cdot 10^{15}$
σ_f , broadside	$1.0 \cdot 10^{12}$	$2.6 \cdot 10^{14}$	$4.1 \cdot 10^{14}$	$1.2 \cdot 10^{14}$	$1.0 \cdot 10^{15}$	$7.4 \cdot 10^{15*}$
σ_n , broadside		$2.5 \cdot 10^5$	$1.1 \cdot 10^6$	$1.0 \cdot 10^5$	$4.6 \cdot 10^6$	$1.6 \cdot 10^6$
Transition Range in yards	<4000	6500	5300	3100	4600	>10000
Equivalent Height in feet	< 105	59.2	37.6	51	21.7	>14.0

* Abnormal propagation conditions.

TABLE II

Frequency, Mc/s	200	560	700	700	970	3060
Antenna Ht., ft.	110	113	116	50	126	137
σ_f , 30 May 1944	$3.4 \cdot 10^{12}$	$7.6 \cdot 10^{14}$	$1.4 \cdot 10^{15}$		$1.0 \cdot 10^{16}$	$7.4 \cdot 10^{15}$
σ_f , 31 May 1944	$1.3 \cdot 10^{12}$	$2.6 \cdot 10^{14}$	$4.1 \cdot 10^{14}$	$1.2 \cdot 10^{14}$	$1.0 \cdot 10^{15}$	

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TABLE IIIValues of σ_f and σ_n in Square Meters for AGC-9

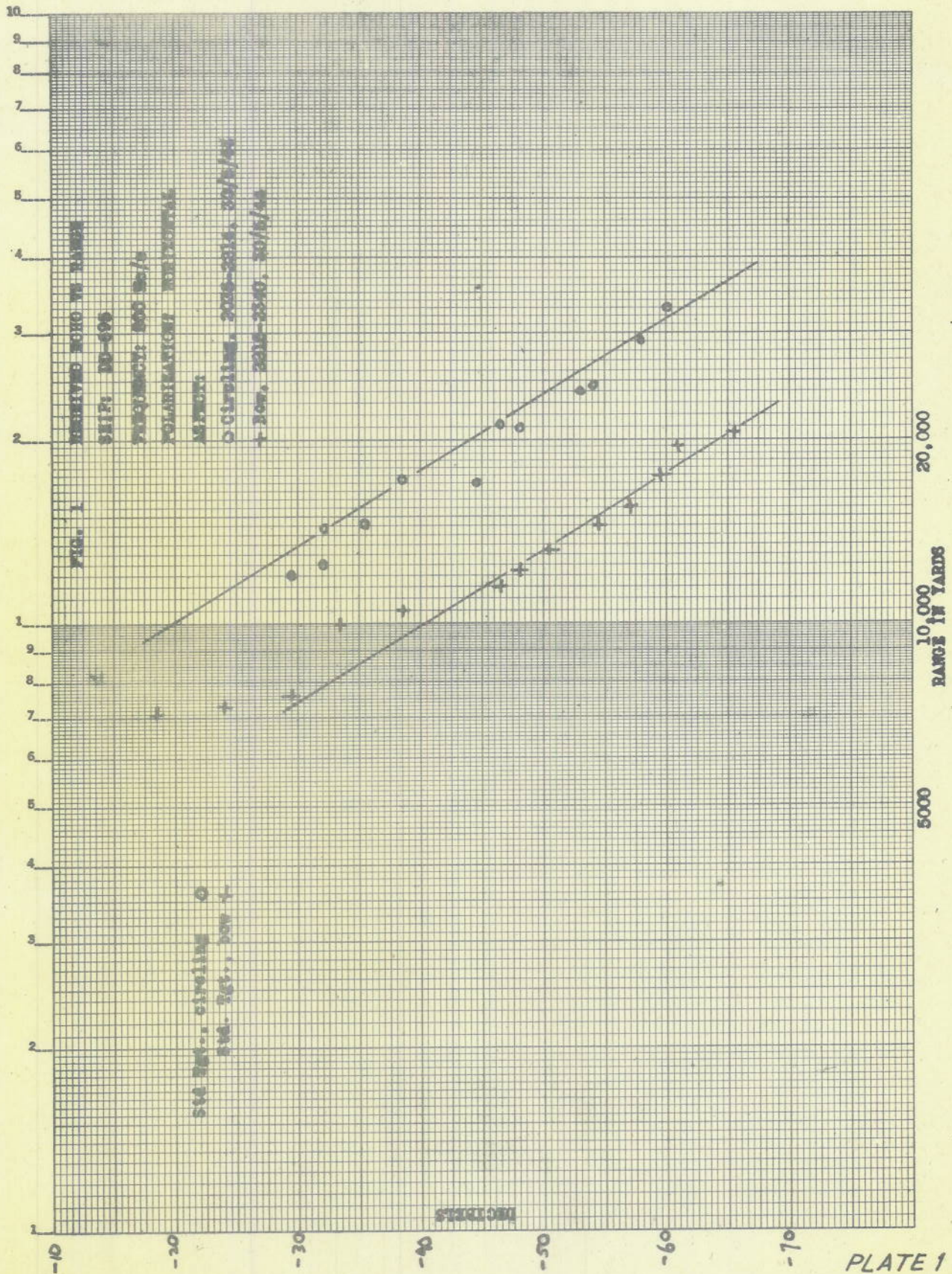
Frequency, Mc/s	200	560	700	3060
Antenna Ht., Ft.	110	113	116	137
σ_f , bow	$1.1 \cdot 10^{12}$	$1.3 \cdot 10^{14}$	$3.4 \cdot 10^{15}$	$3.3 \cdot 10^{16}$
σ_f , broadside	$1.2 \cdot 10^{13}$	$9.7 \cdot 10^{14}$	$1.5 \cdot 10^{16}$	
σ_n , bow				$4.3 \cdot 10^5$
σ_n , broadside				$1.7 \cdot 10^7$
Transition Range in yards	(bow (broadside			15,000 >20,000

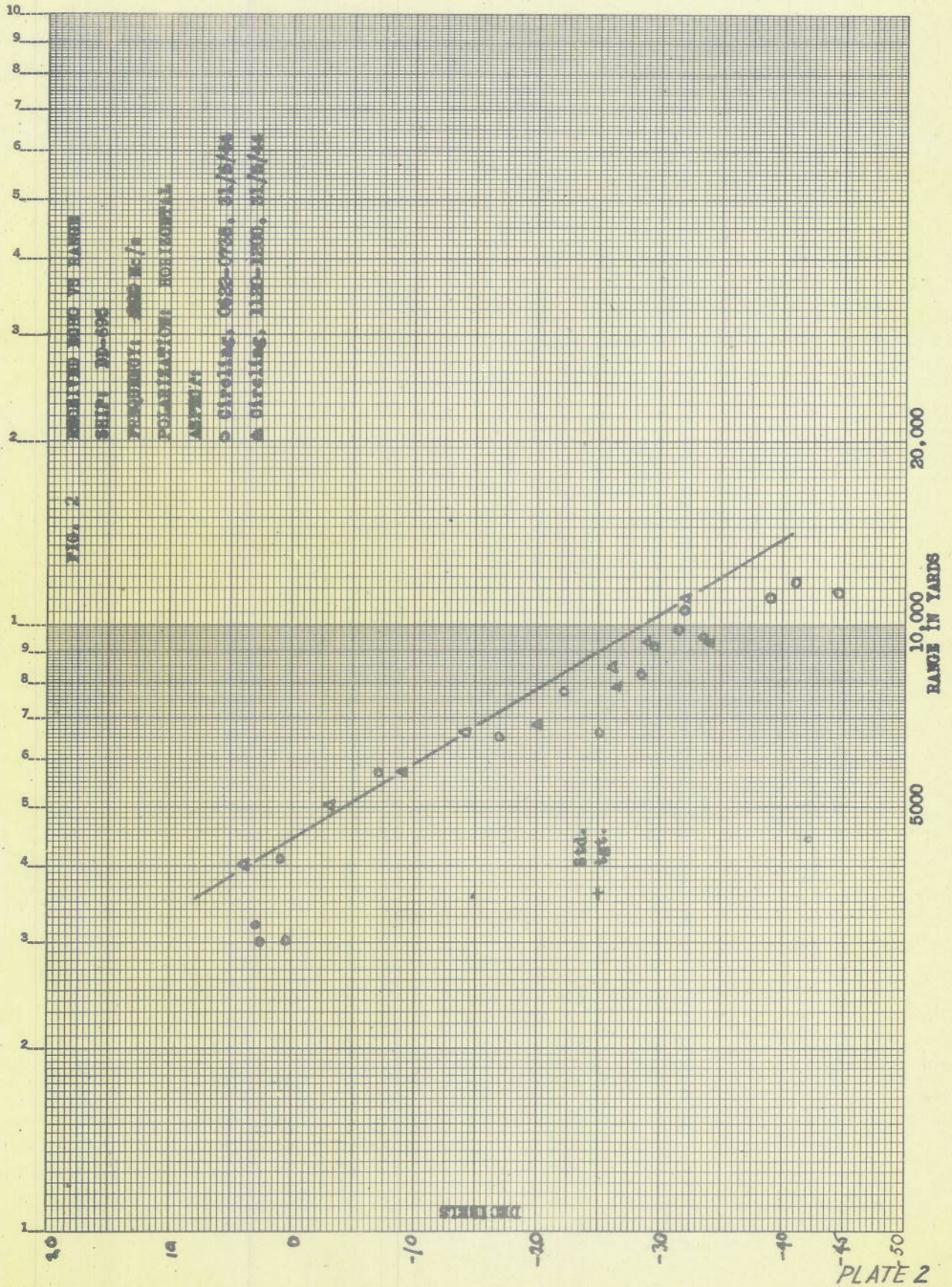
TABLE IVValues of s and K in formula: $\sigma_f = K \cdot f^s$

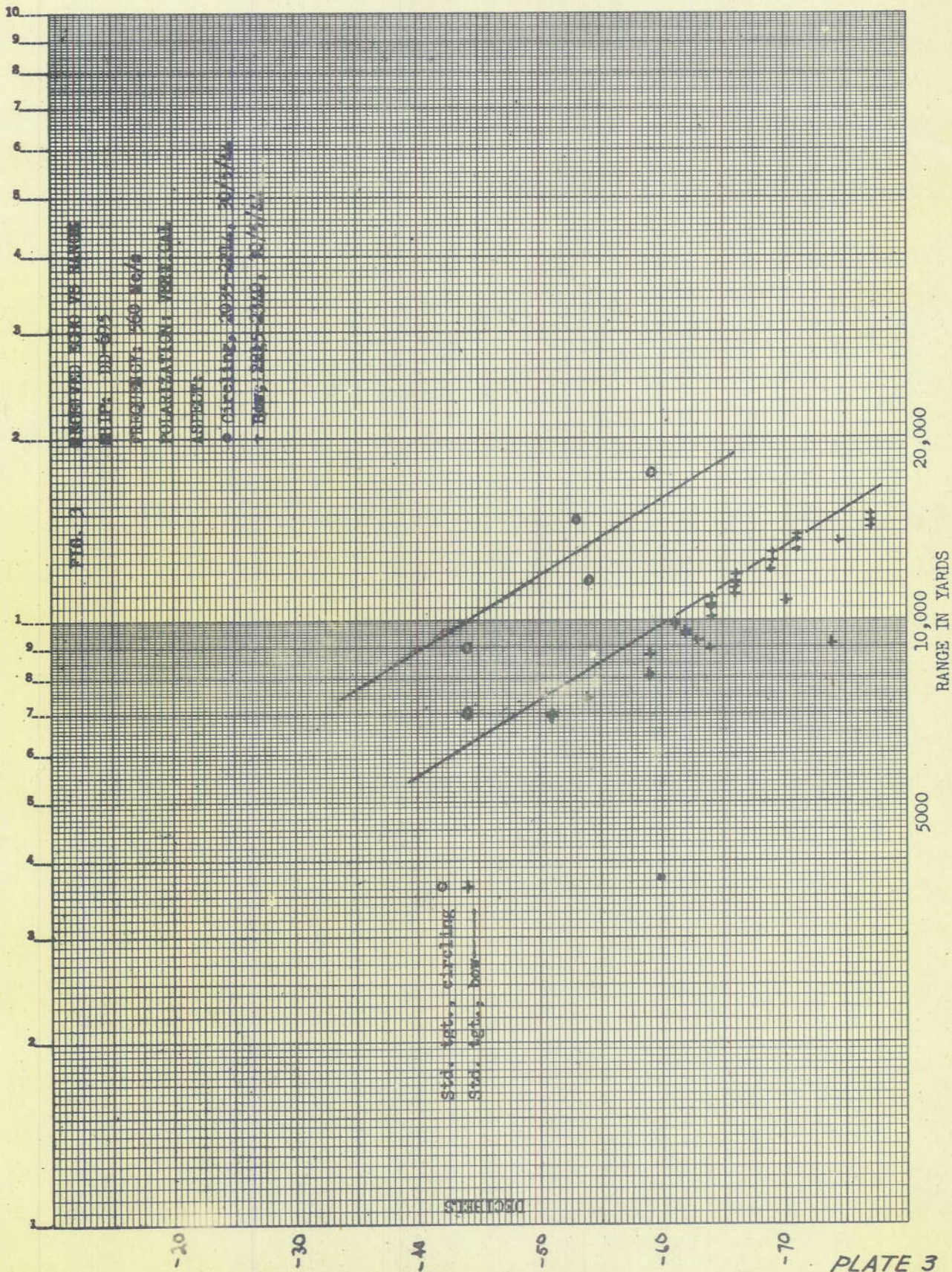
Ship	<u>Bow</u>		<u>Broadside</u>	
	s	K	s	K
DD-695	4	80	4	$7.5 \cdot 10^2$
AGC-9	4	$1.6 \cdot 10^3$	4	$1.9 \cdot 10^4$

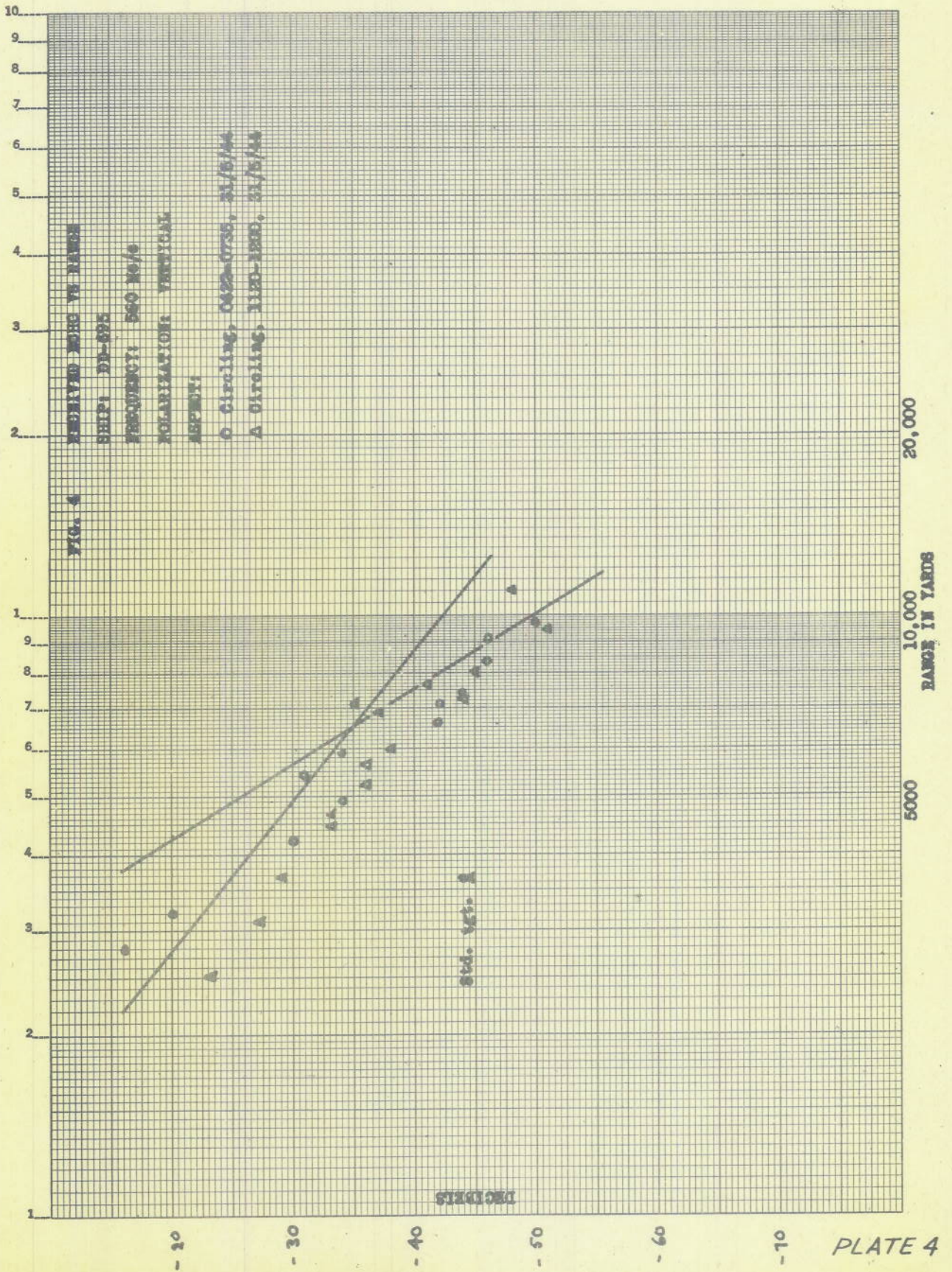
TABLE VValues of σ_n in Square Meters

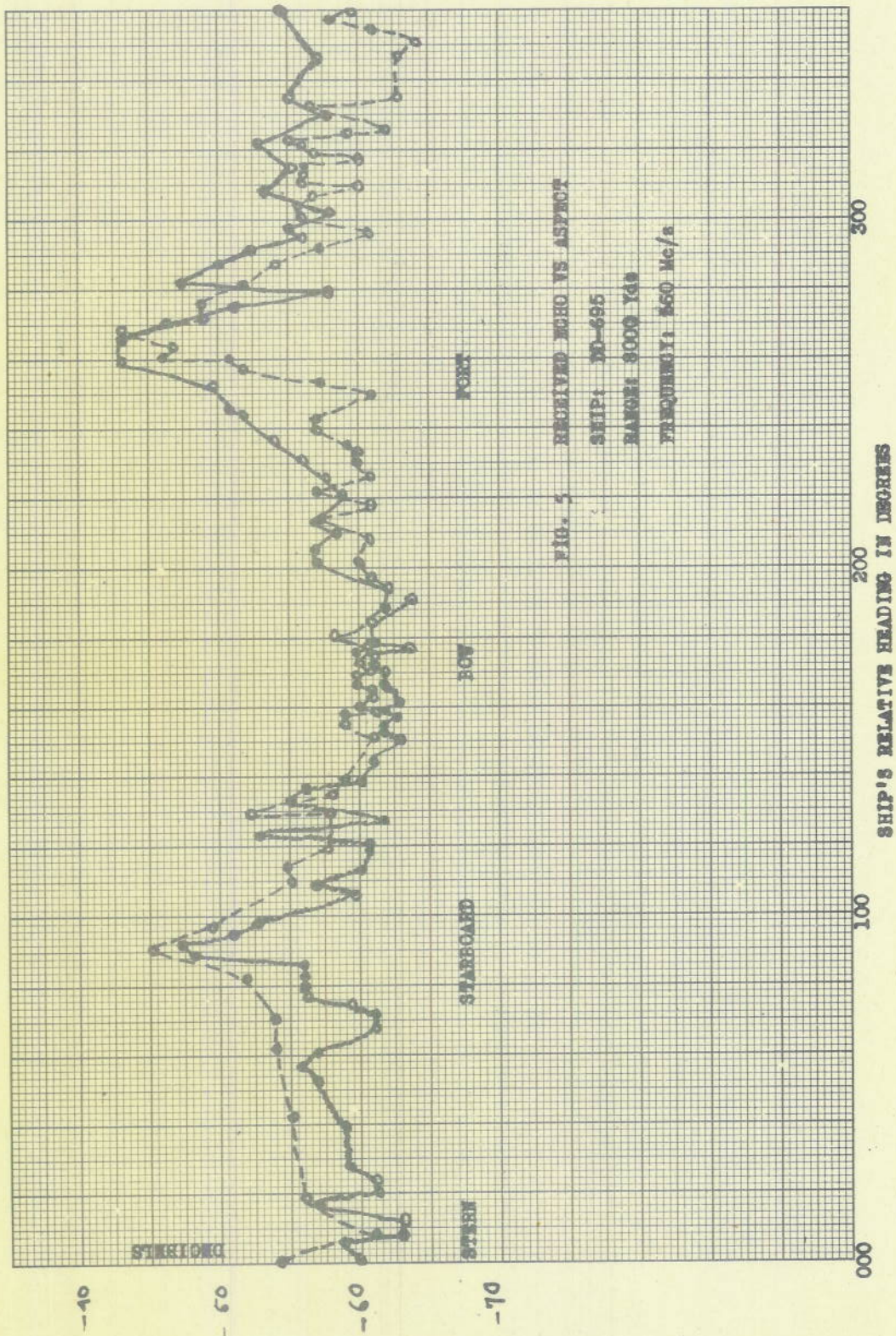
Ship	Frequency in Mc/s		
	700	970	3060
CL-89 (broadside)	$2.4 \cdot 10^6$	$3.3 \cdot 10^6$	$1.3 \cdot 10^7$
AM-246 (broadside)	$8.3 \cdot 10^4$	$5.4 \cdot 10^5$	$9.4 \cdot 10^5$
AM-246 (stern)	$1.6 \cdot 10^4$	$1.6 \cdot 10^4$	$4.8 \cdot 10^4$
DD-695 (broadside)	$1.1 \cdot 10^6$	$4.6 \cdot 10^6$	$1.6 \cdot 10^6$

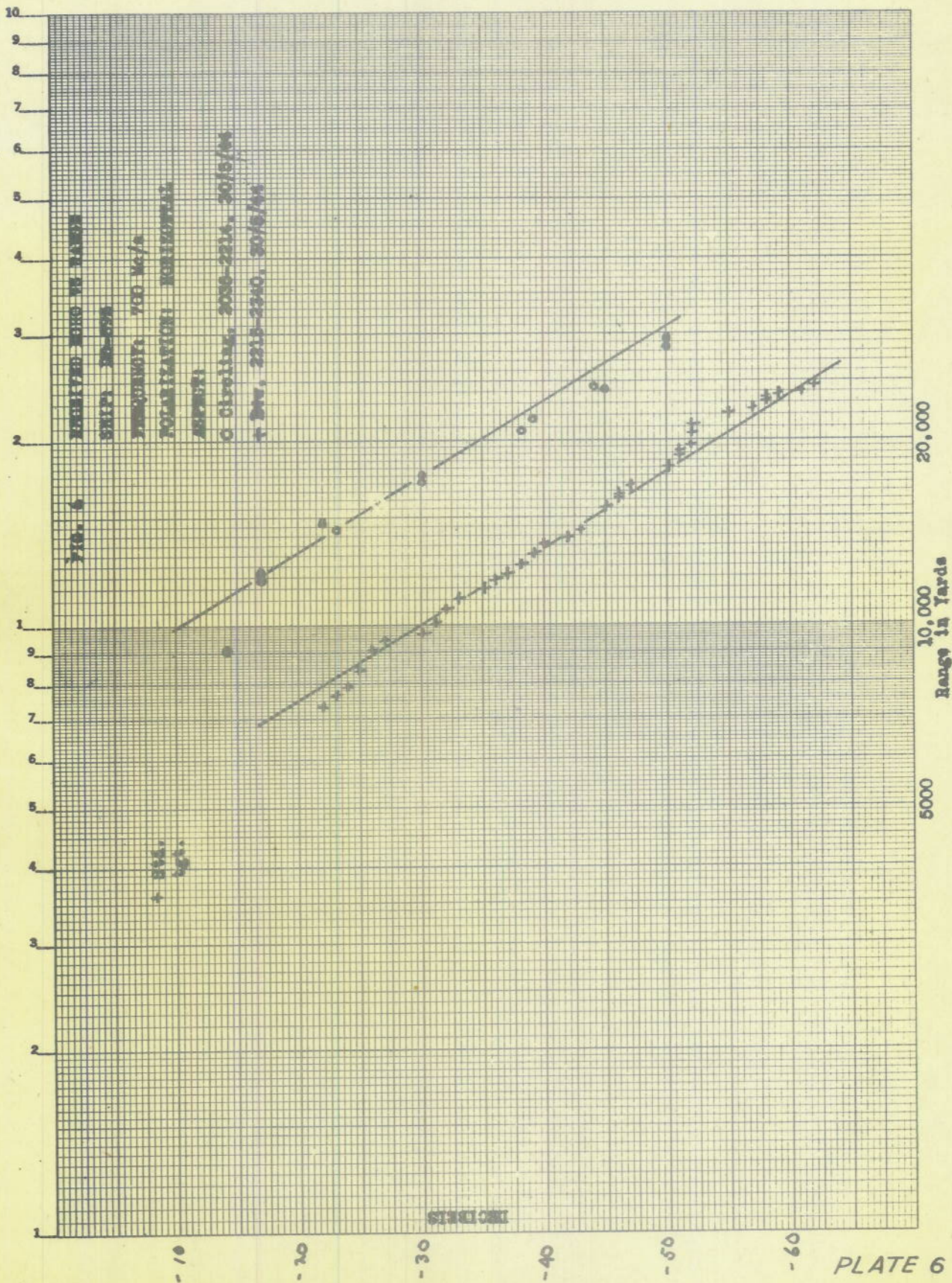


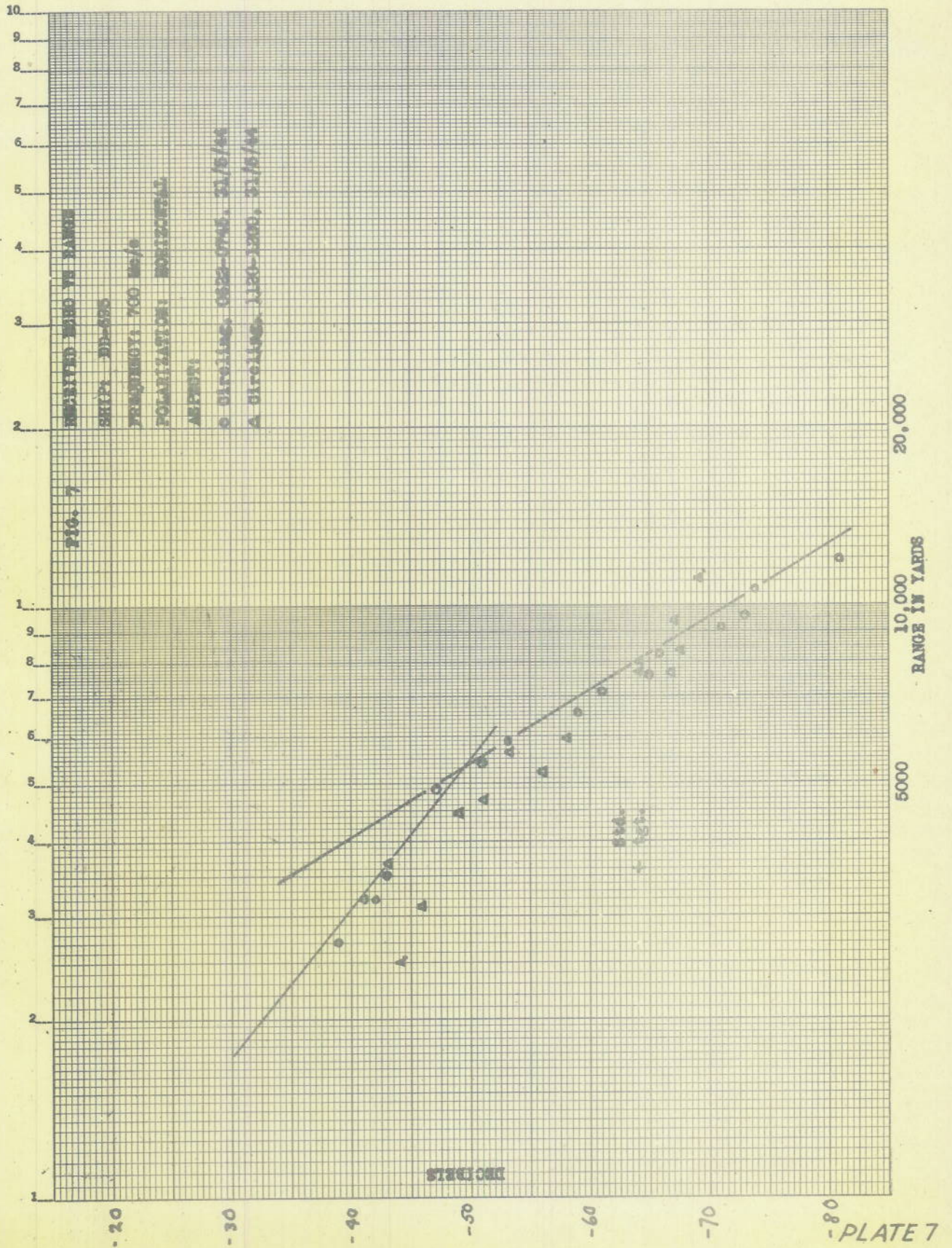












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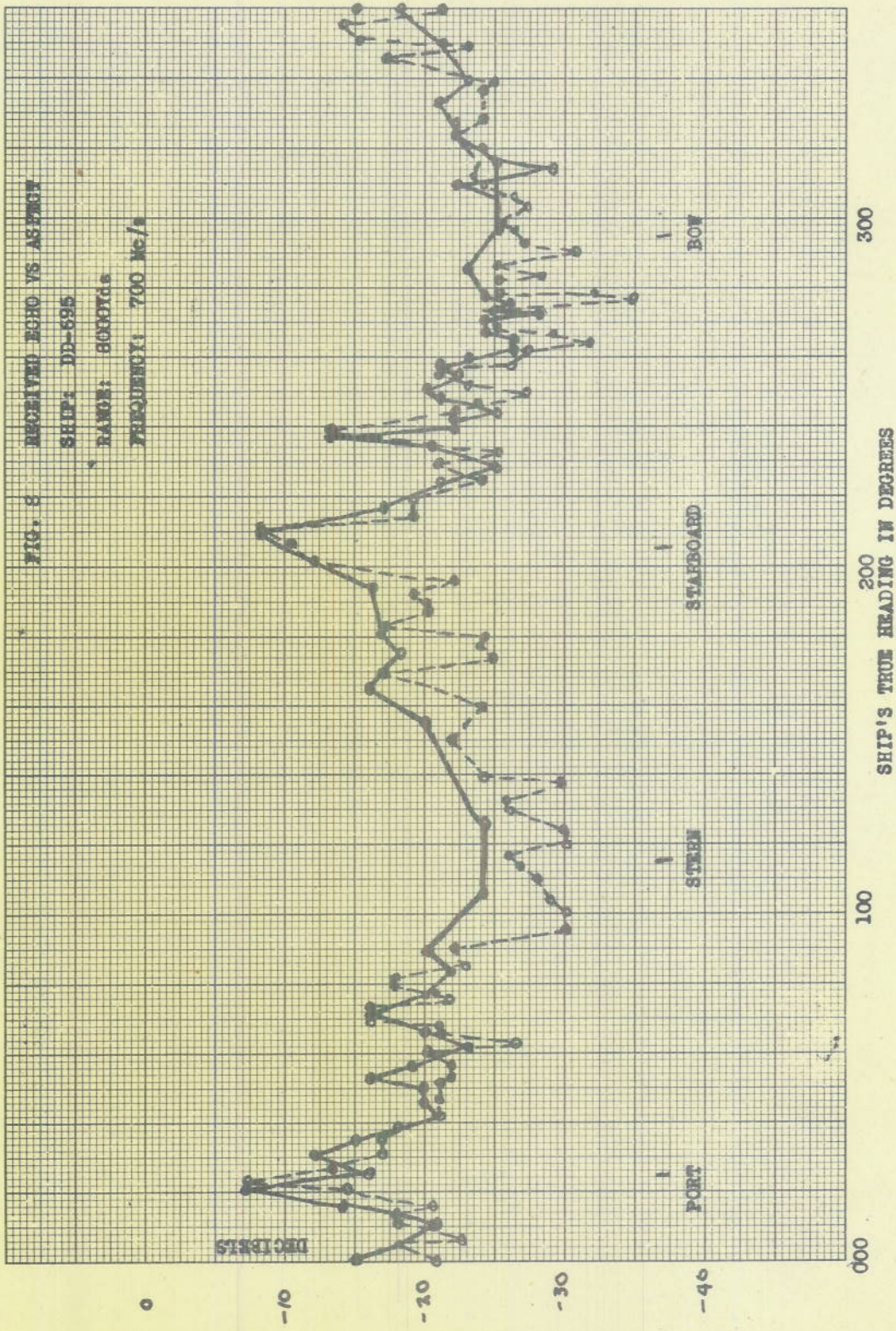
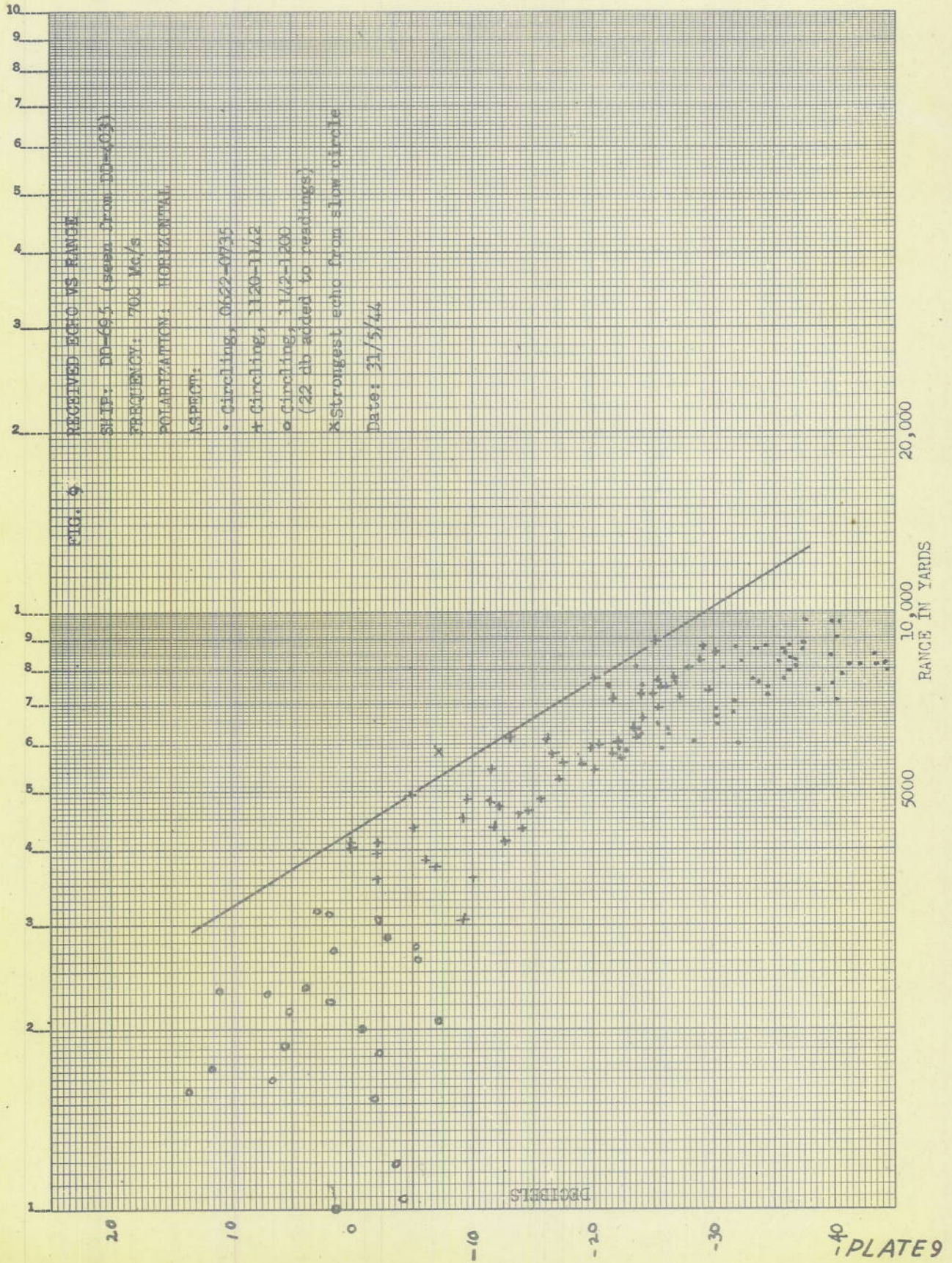
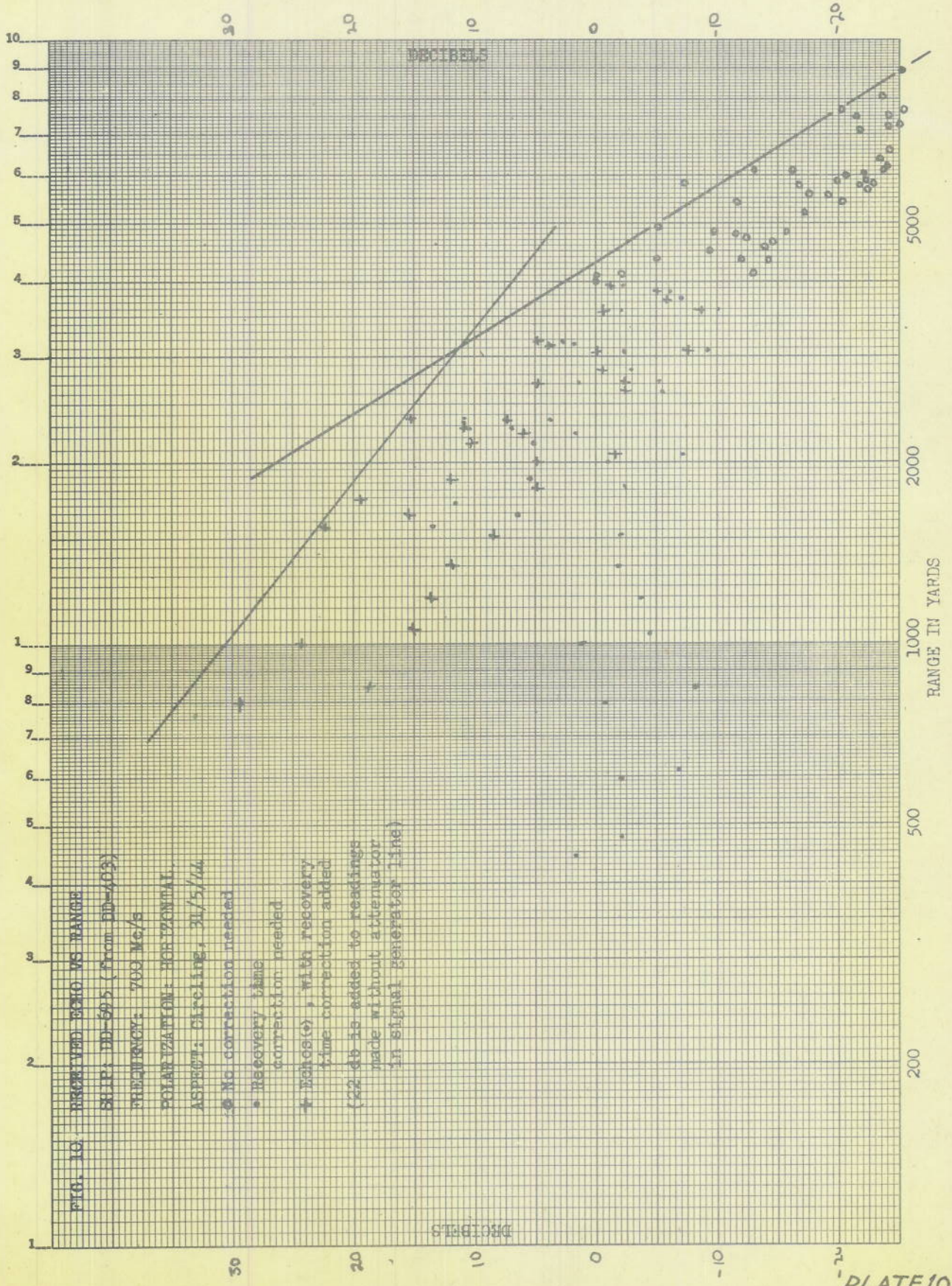
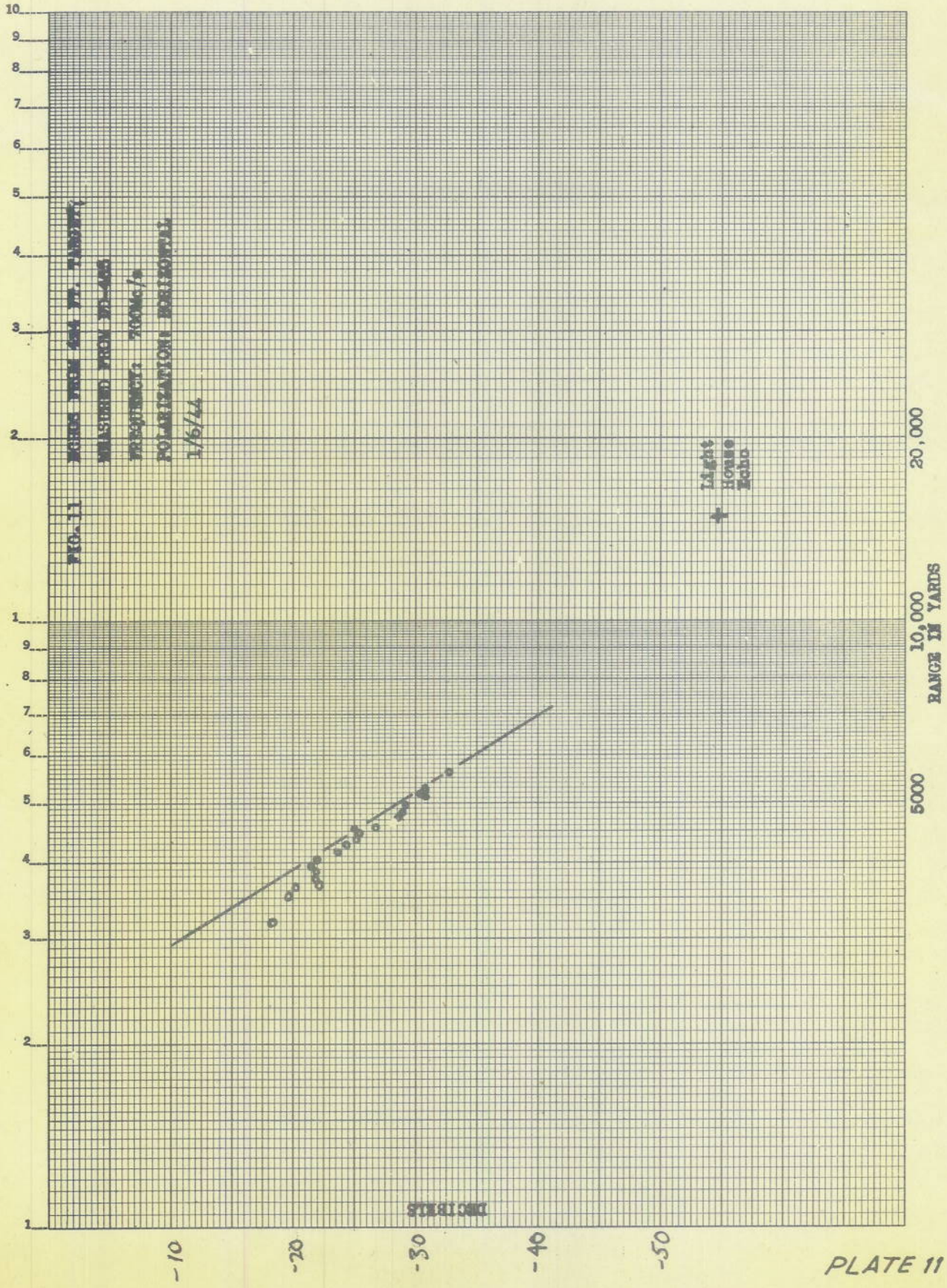


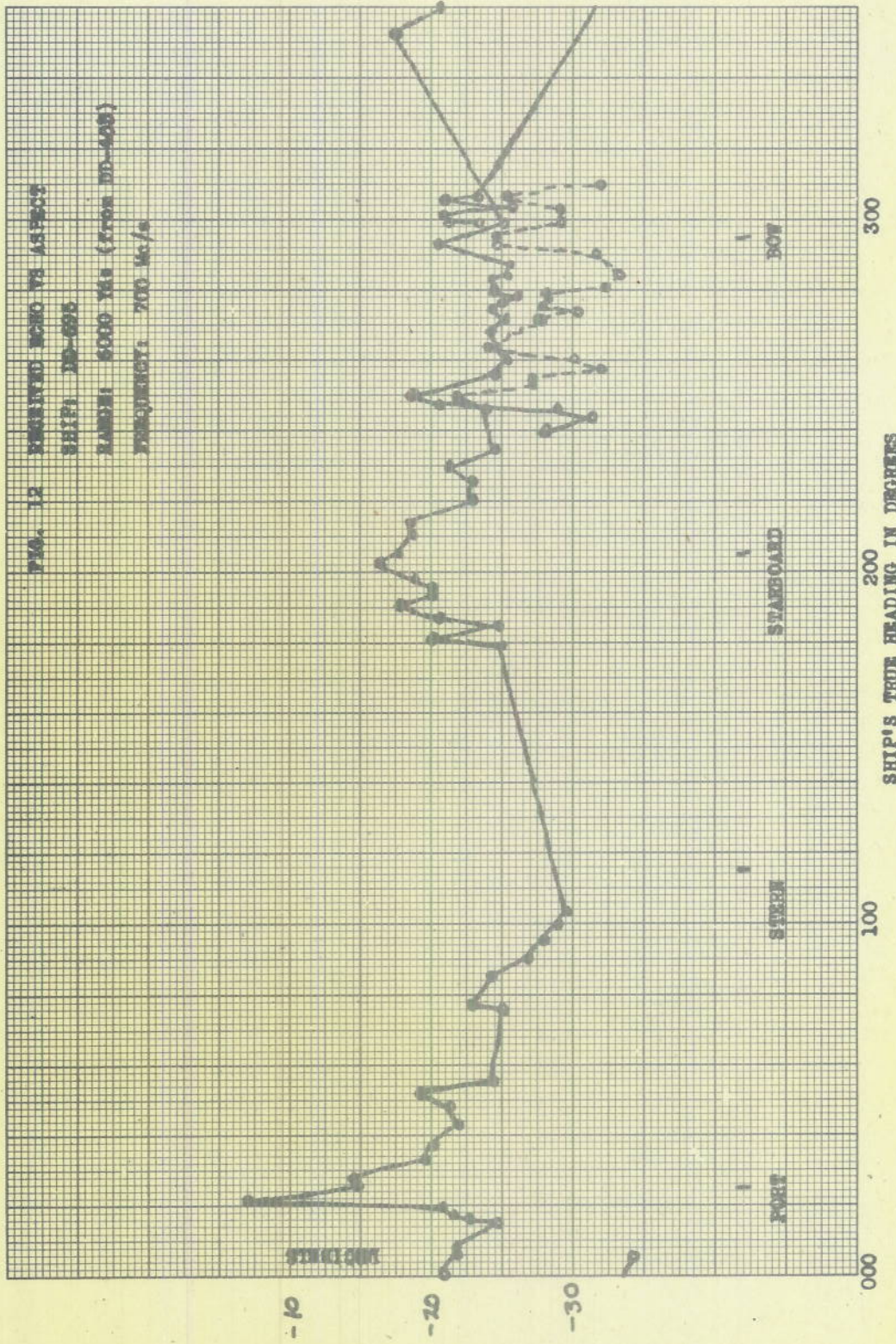
PLATE 8

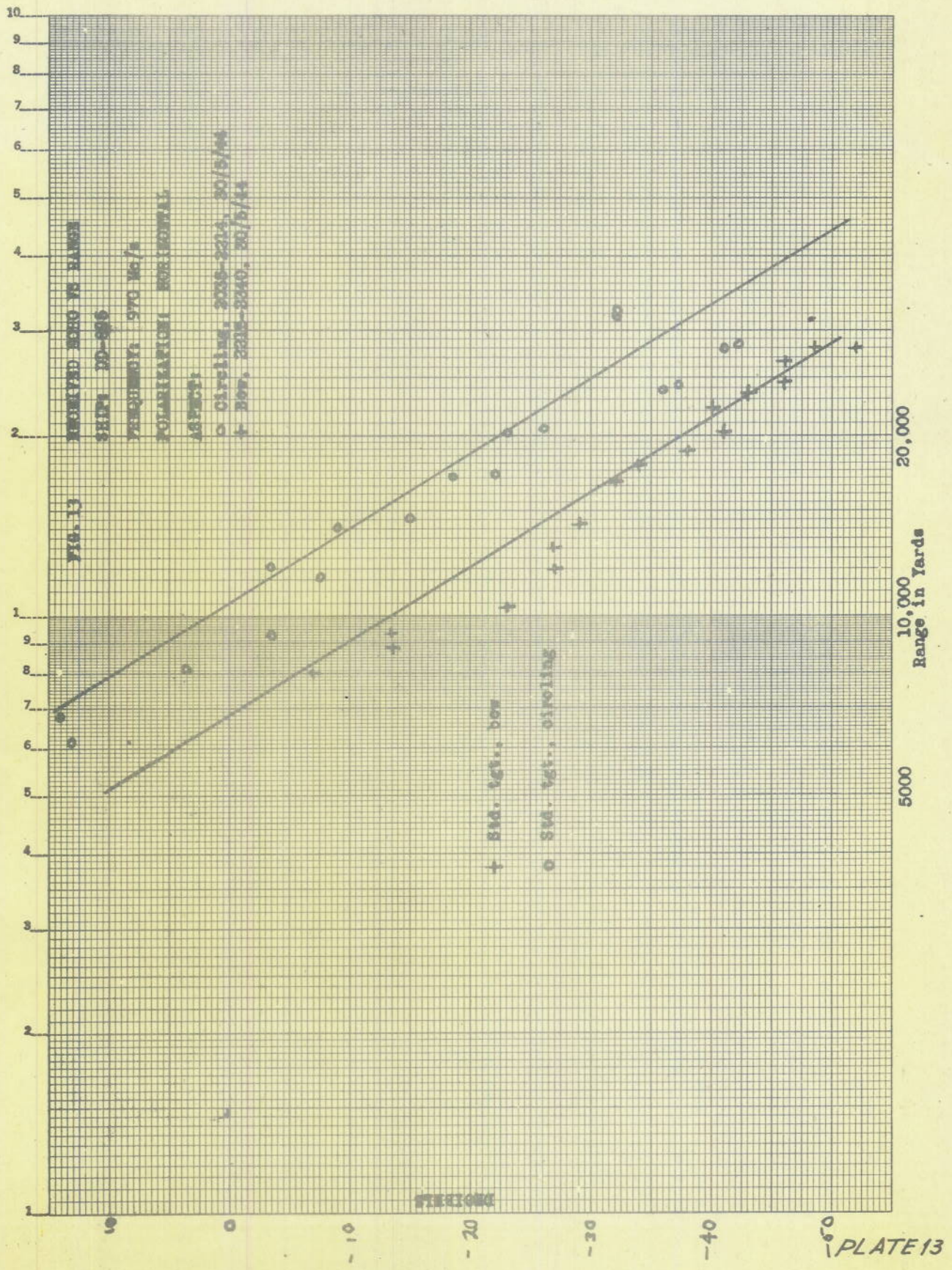
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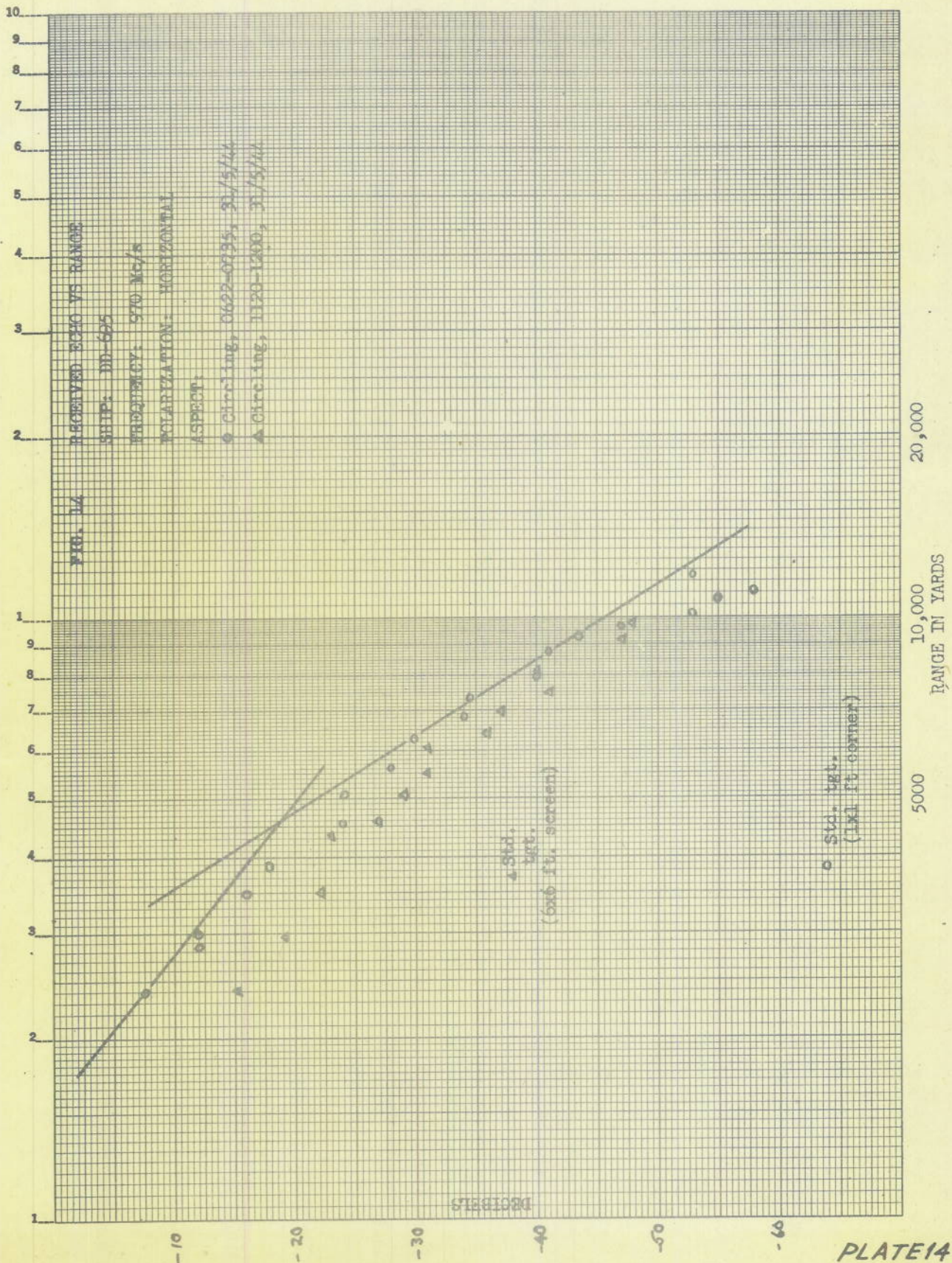












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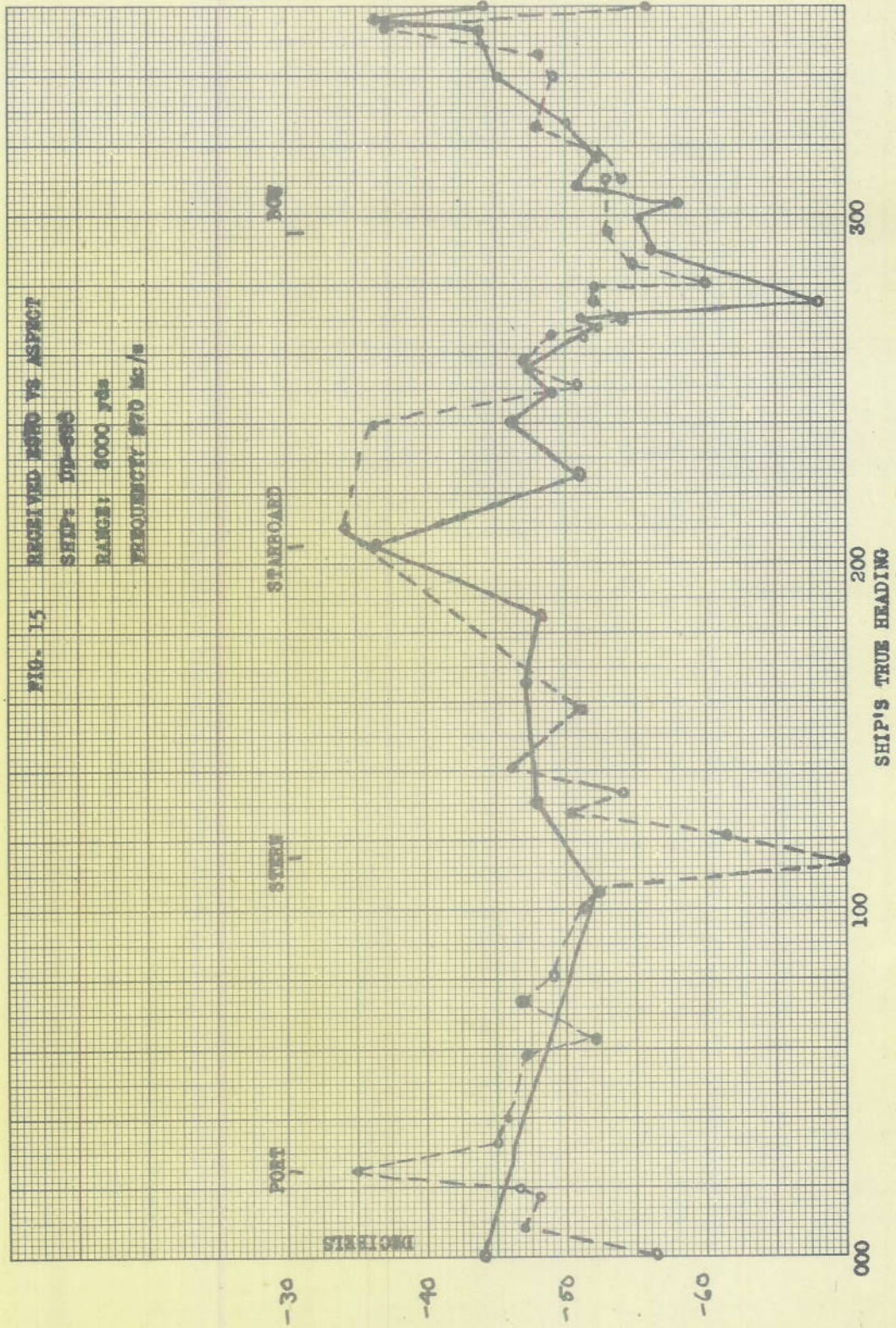
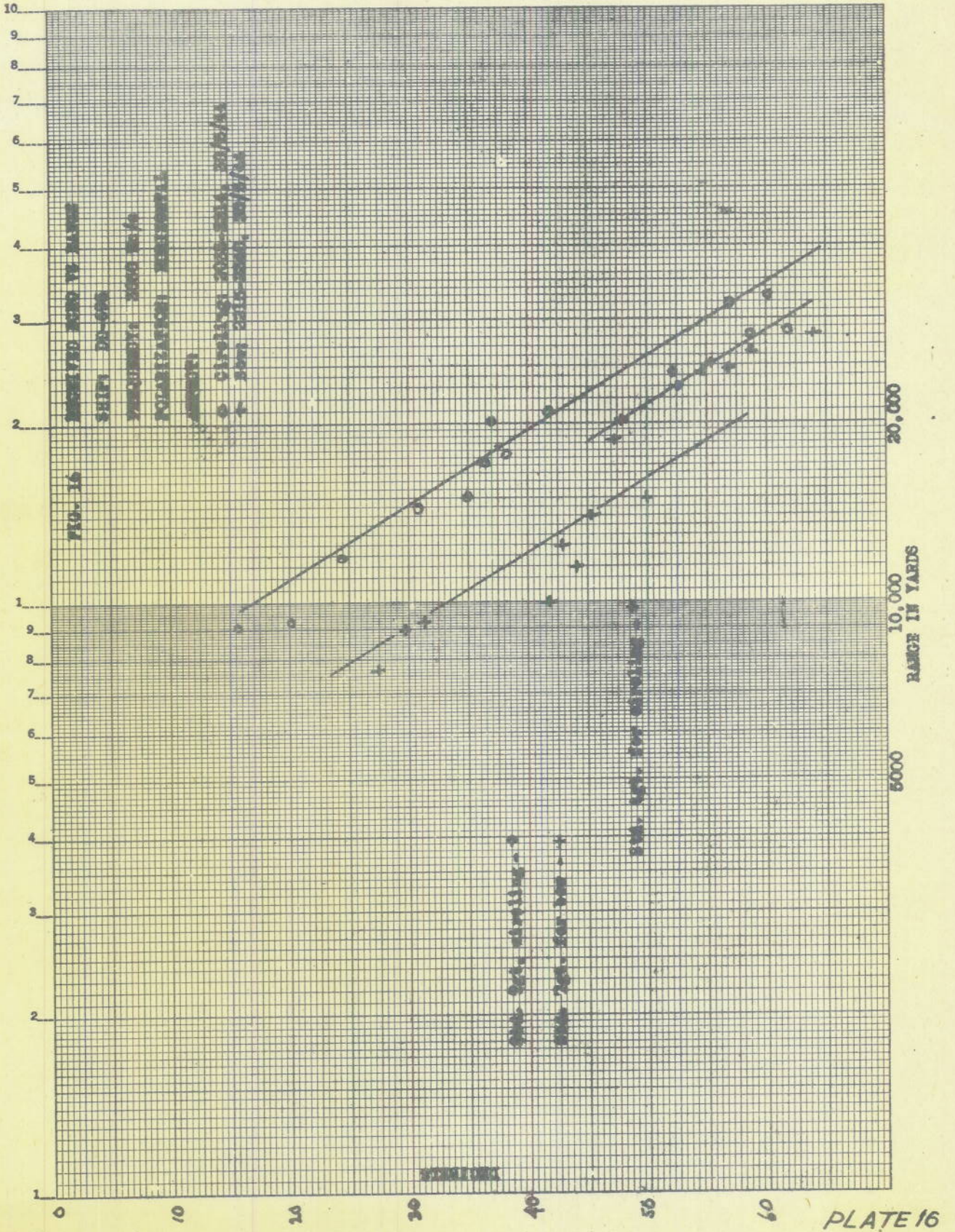
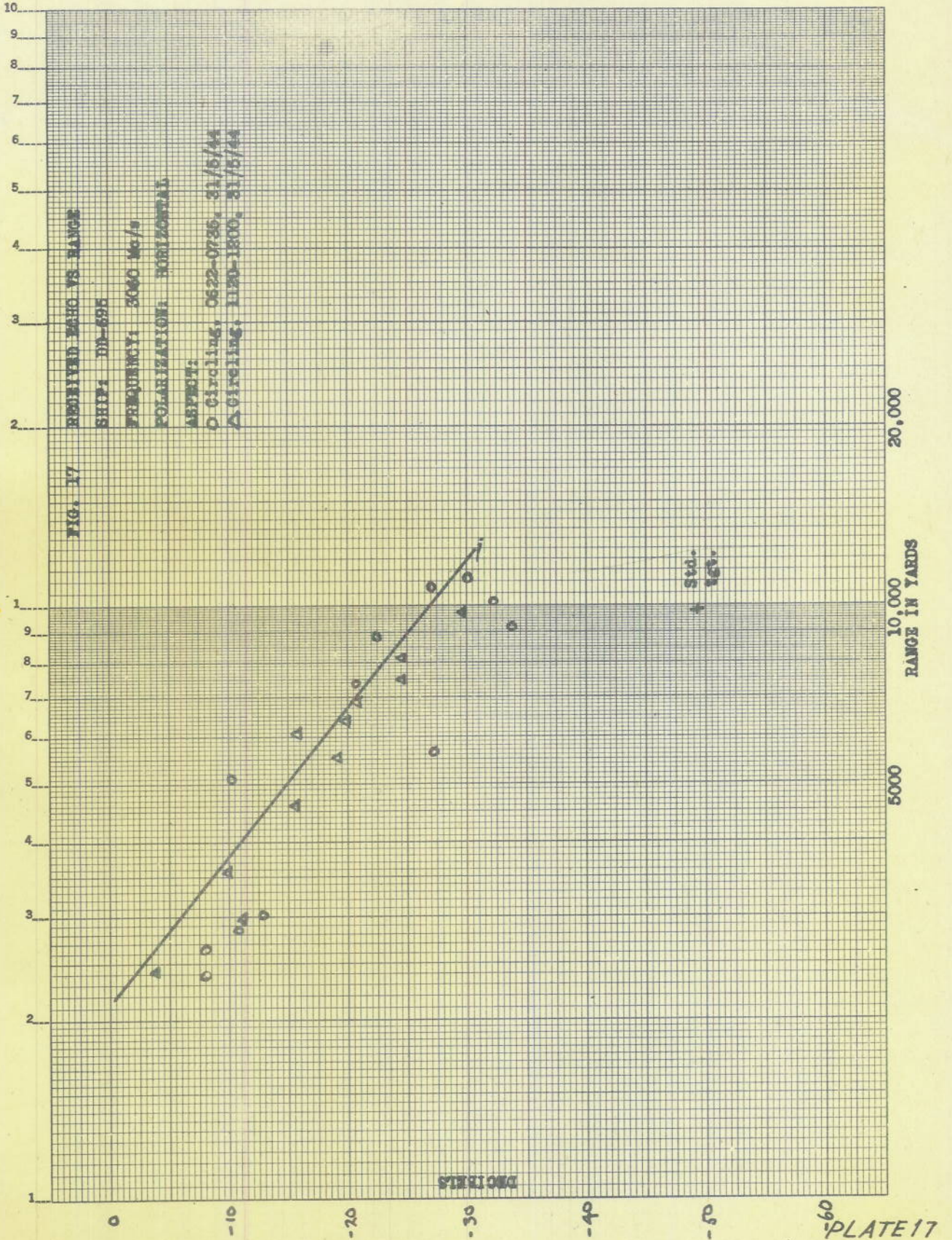
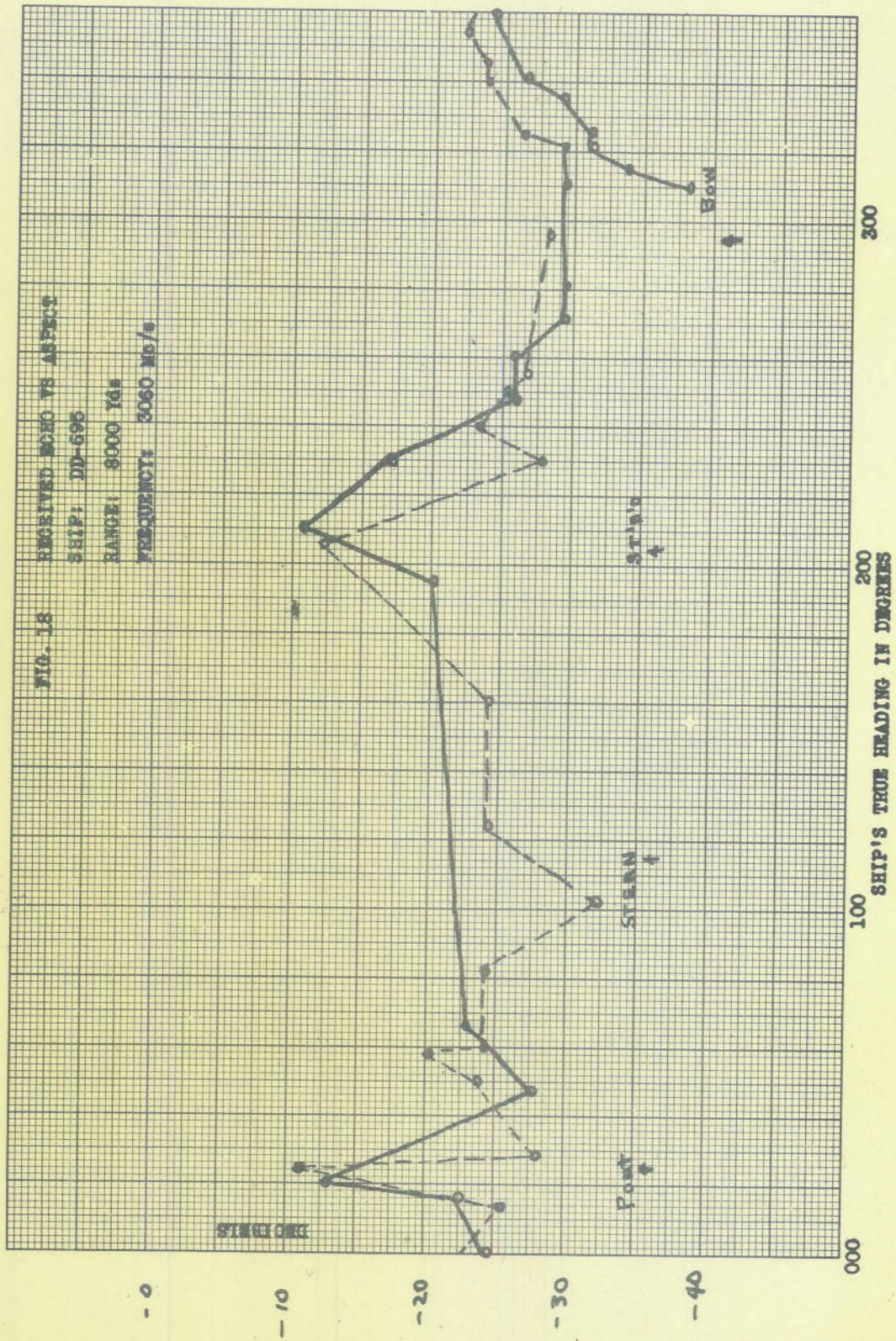


PLATE 15

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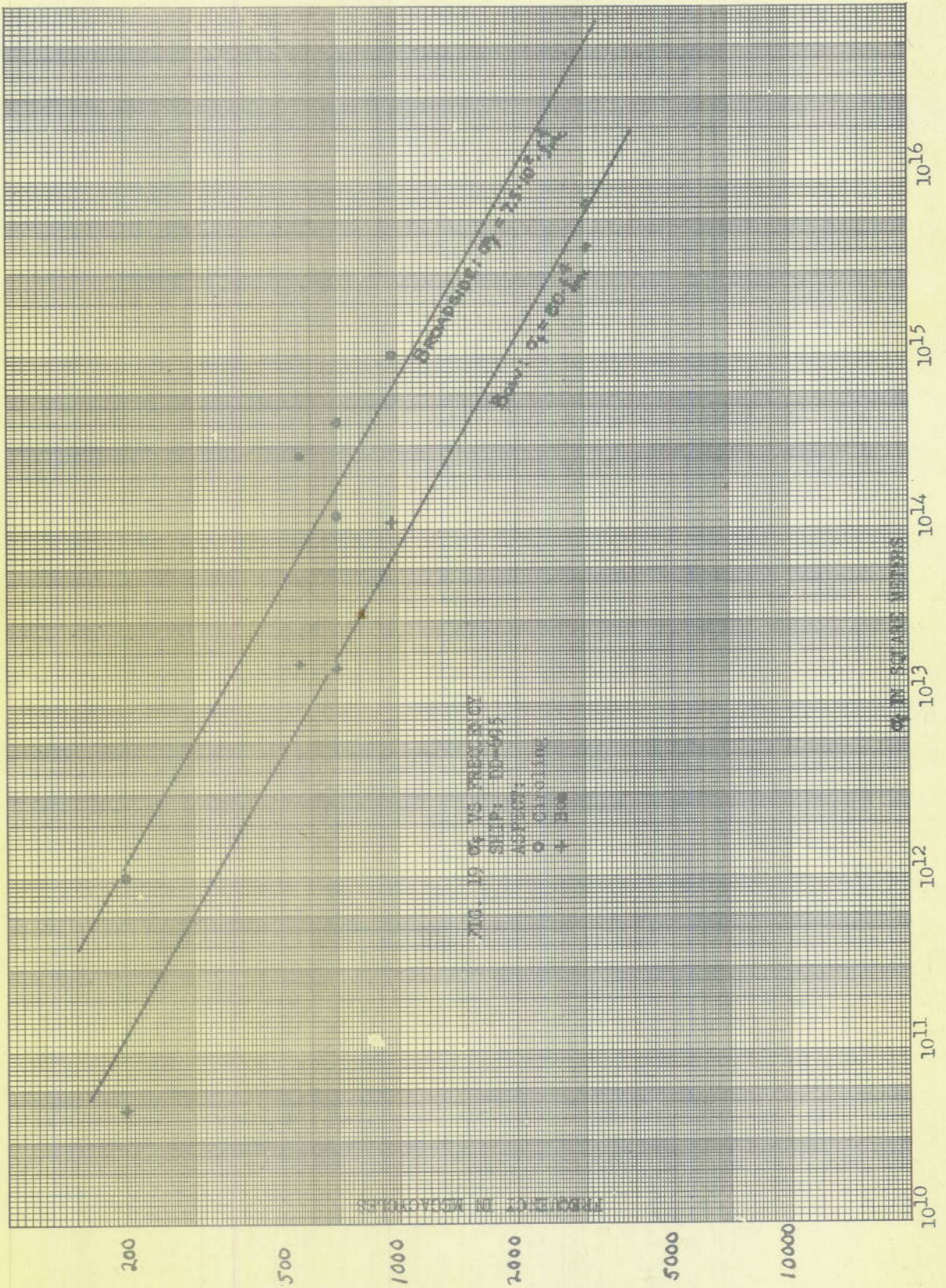
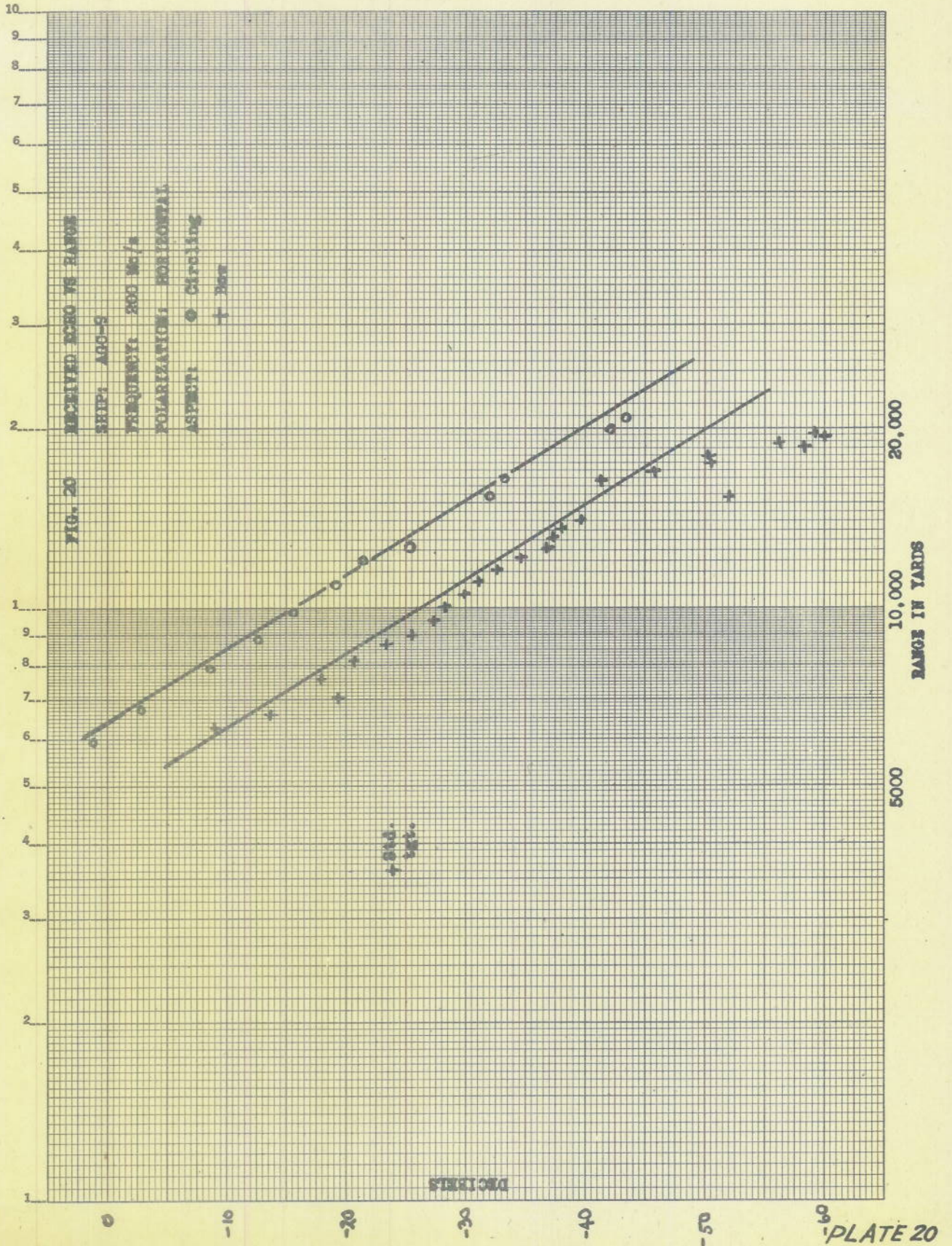
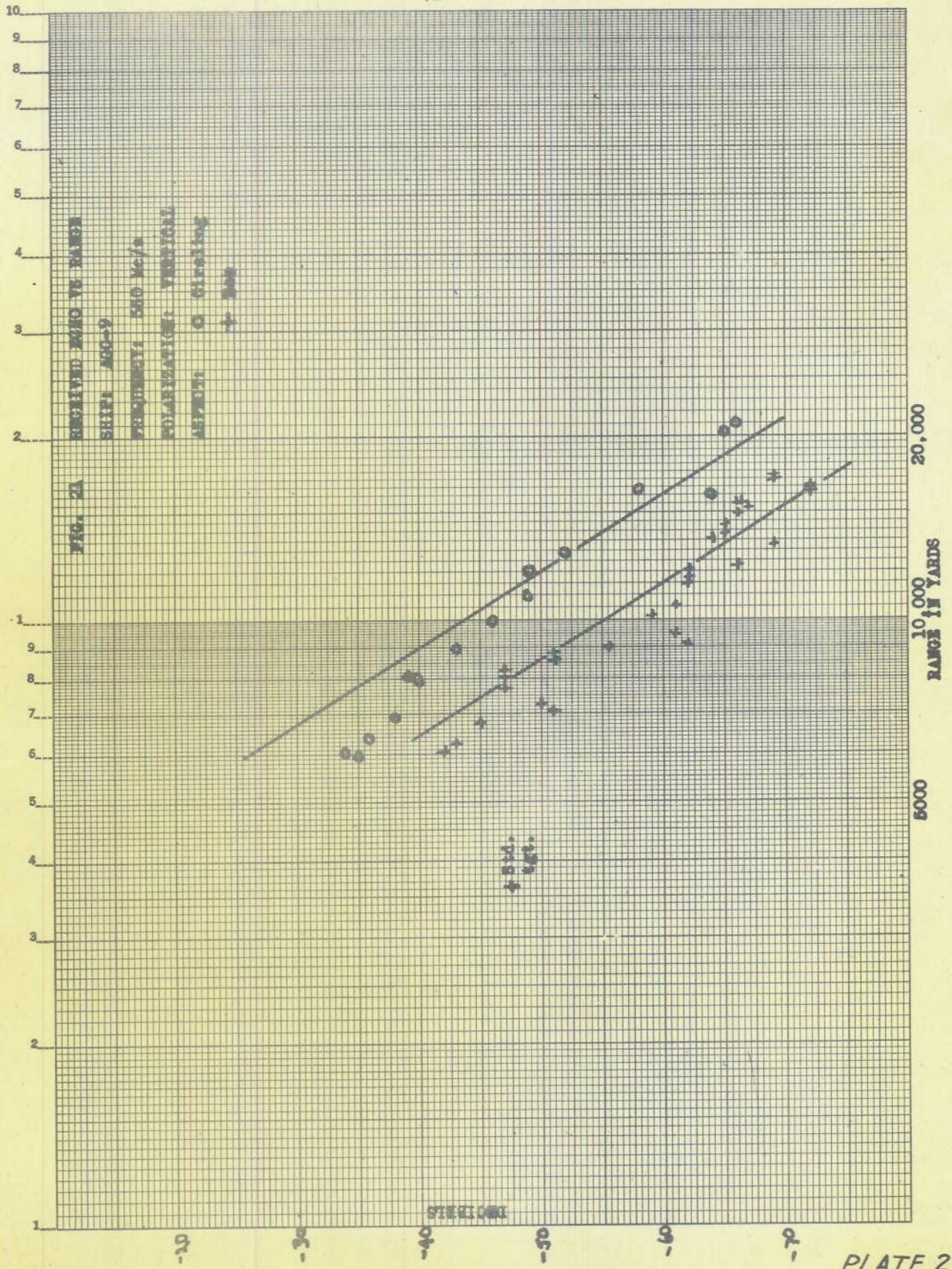
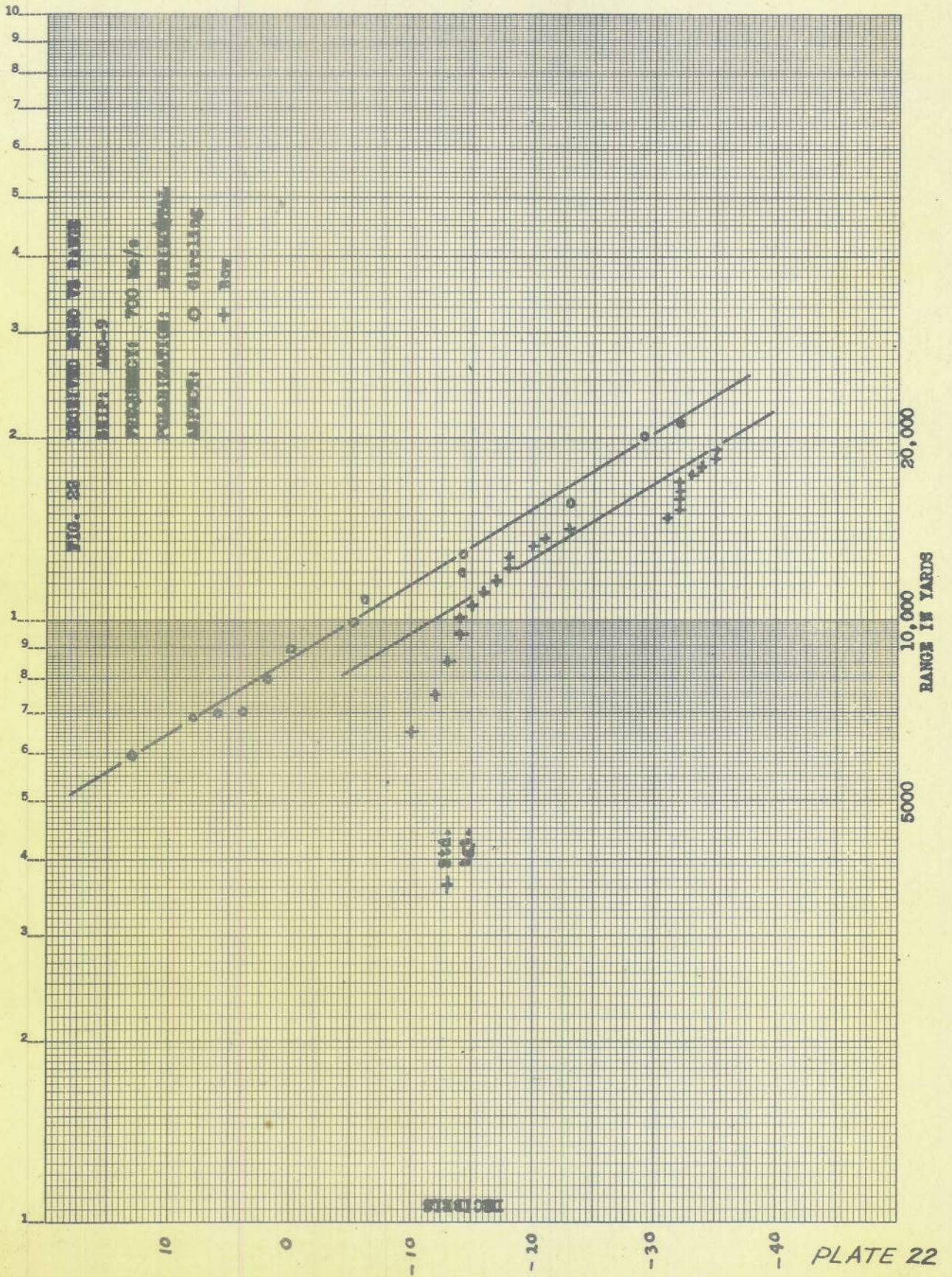
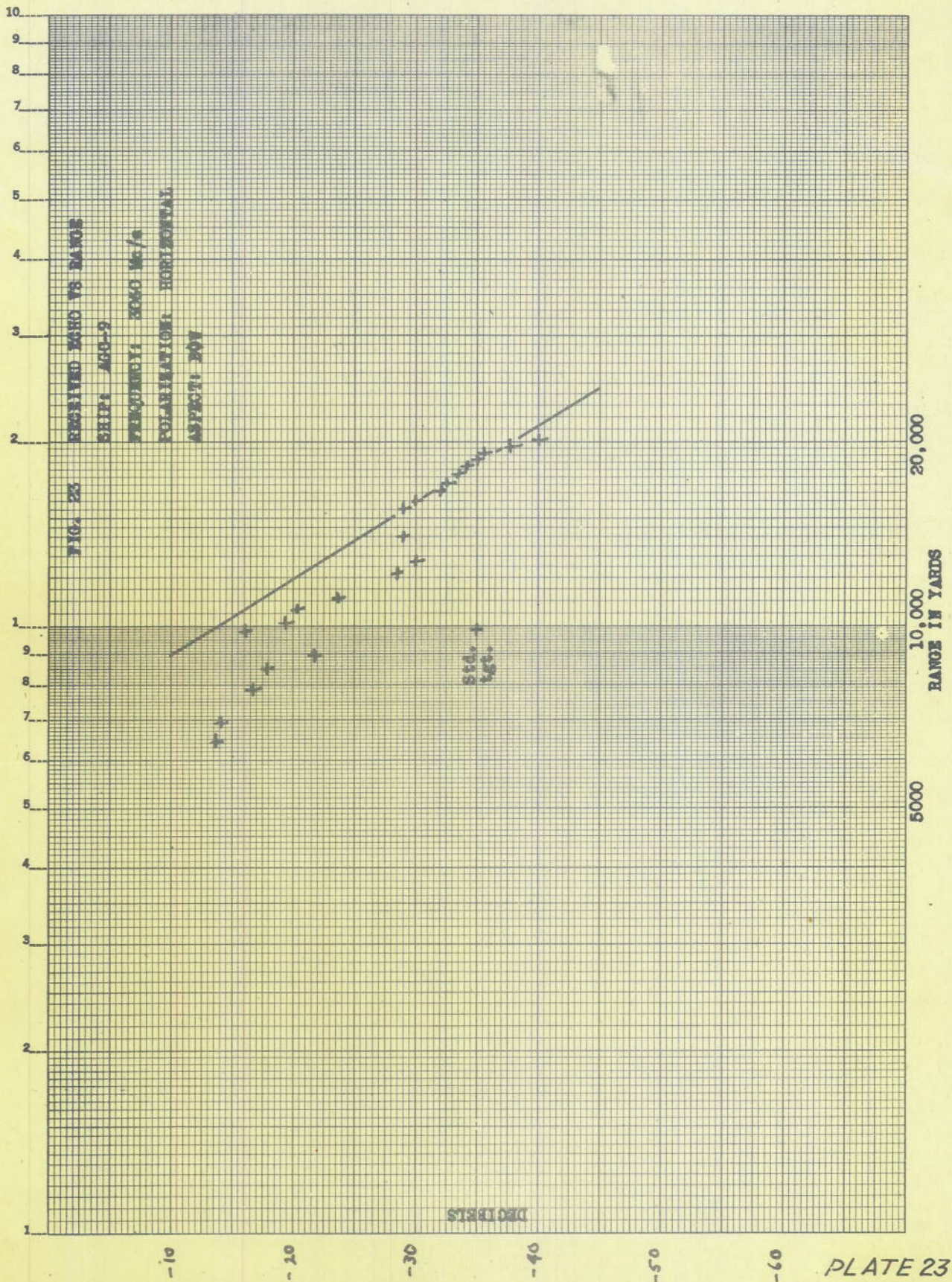


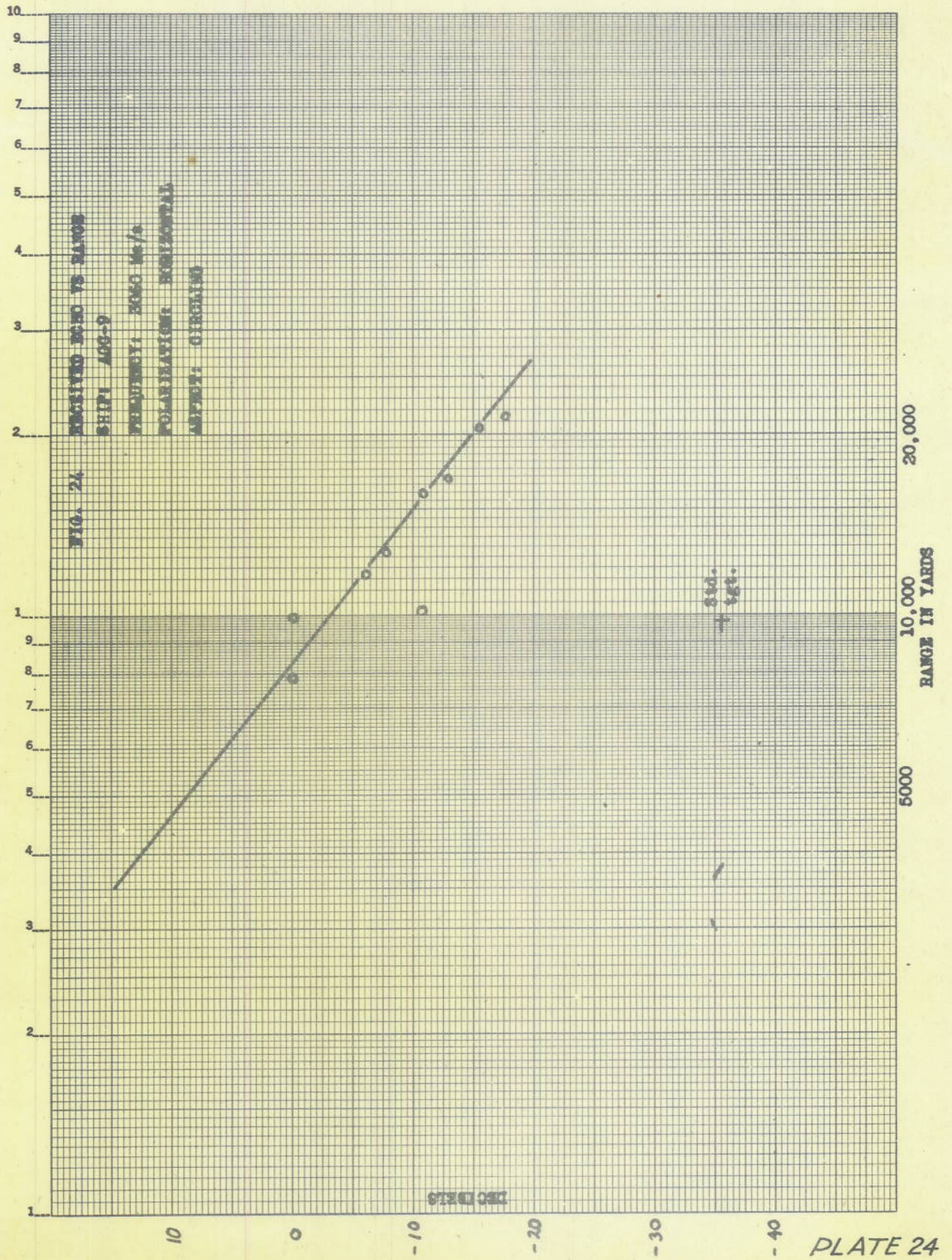
PLATE 19

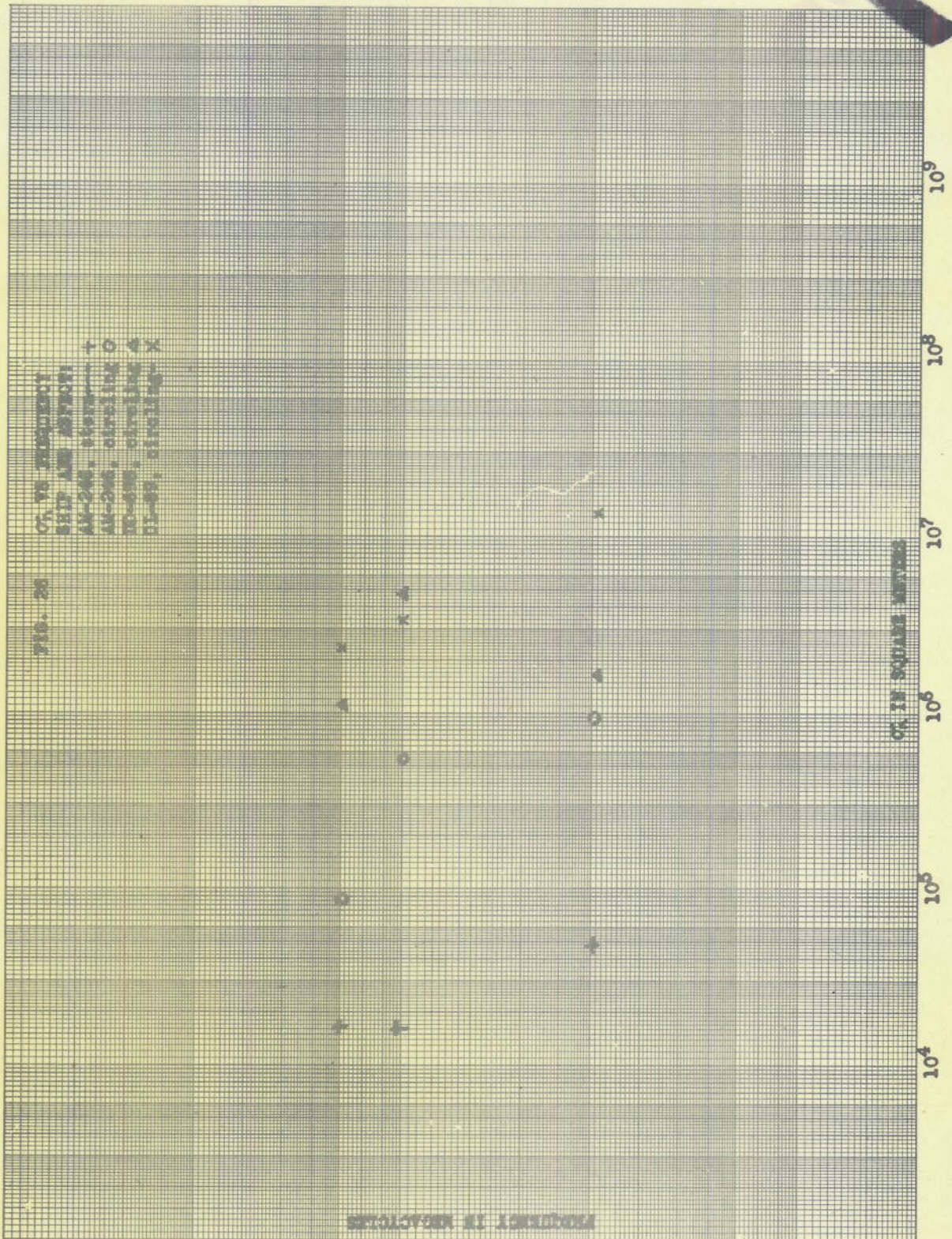












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