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COMPARISON OF PERFORMANCE OF AN CRD-2
DAU AND FH & RADIO DIRECTION FINDERS

BY

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WASHINGTON, D.C.

RADIO DIVISION DIVISION II
RADIO COUNTERMEASURES SECTION

31 December 1946

COMPARISON OF PERFORMANCE OF AN CRD-2
DAU AND PH 4 RADIO DIRECTION FINDERS

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Report #2949
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ABSTRACT

Comparison is made of the performance of the AN/CRD-2 an Army Signal Corp Type of radio direction finder employing an electronic goniometer with a Navy Model DAU using a mechanically rotating goniometer and a British FH4 instantaneous direction finder of the Watson-Watt type. Tests indicate that the Model DAU possessed the greatest bearing sensitivity, the FH4, the lowest instrumental error as well as the greatest effectiveness against pulsed signals with the DAU ranking second in this particular.

The chief advantage of the AN/CRD-2 appears to lie in the absence of any mechanically rotating parts such as used in the DAU and of difficult maintenance alignment (such as is required with the FH 4) but this apparent advantage is questionable in view of the use of balanced modulator input circuits which lack stability and requires the matching of tubes.

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INTRODUCTION

1. This report covers the evaluation of an electronic goniometer provided for in Reference 1 by NRL Problem No. S1178T-C. The object of the evaluation was to determine the general over-all performance in taking bearings on various types of signals, pulse signals included; and any advantages or disadvantages of the electronic goniometer over the present mechanical goniometers in equipments such as the DAQ, DAU and DAJ. This problem was later extended to include a comparison test of the FH4. (Reference 2.)

EQUIPMENTS EVALUATED AND COMPARISONS MADE

2. The equipments evaluated and reported herein are: (a) The Army Signal Corps AN/CRD-2 electronic goniometer type radio direction finder, prototype model, (b) the Navy DAU mechanically rotated goniometer type, Serial No. 33, (c) the British FH4 Watson-Watt type radio direction finder, Serial P-95.

3. The AN/CRD-2 is a radio direction finder designed to take bearings on the vertically-polarized components of ground waves or sky waves in the frequency range of from 1.5 to 30 megacycles. The equipment is designed and packaged to be transportable by mobile conveyances such as trucks, planes, etc. It utilizes four omnidirectional antennas of 24 ft. height placed at the corners of a square having a 16 foot diagonal. Each of these monopoles has a circular polar directivity characteristic and the signal derived from each is modulated by a voltage of 150 cycles per second. This gives an effect equivalent to a mechanical goniometer operating at 9000 revolutions per minute.

4. The modulation is accomplished by using balanced modulators units at the base of each antenna. The output of these balanced modulators is a carrier suppressed modulated signal. The four signals are combined in a common combining impedance which is placed at the physical center of the array. The output of this impedance is identical to the output of a mechanically rotated goniometer (See Appendix 1.) and is fed into the input of a receiver. The output of the receiver detector is used to control the amplitude of a 200 kc oscillator. The output of this oscillator is inversely proportional to the detector signal, i.e. the output is maximum on the receiver null, and is fed in parallel to two additional balanced modulators. The grids of one balanced modulator are differentially fed by a sine wave of voltage of the same frequency as the antenna modulating voltage, and the grids of the other balanced modulator are additionally differentially fed with a like cosine voltage wave. These outputs of the balanced modulators are fed to the proper plates of the oscilloscope to give a circle. However, with no receiver output, the balanced modulators receive a 200 kc voltage which presents a rotating line on the oscilloscope. Because the radial velocity of the 200 kc sweep is zero at the two ends of the line, two circles are effectively presented during one cycle of the modulating voltage. Since the amplitude of the 200 kc voltage fed into the balanced modulators is controlled by the receiver output, it is apparent that a filled-in propeller shaped

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pattern will appear on the oscilloscope on interception of a signal. This propeller shaped pattern will be generated twice, once by each end of the line, which gives two propeller shaped patterns, one 180 degrees out of phase with the other one but which under perfect conditions would be coincidental and appear as a single pattern.

5. Sense patterns are obtained by:

- (a) Unbalancing each set of antenna balanced modulators.
- (b) The 90 degree phase shifting of the input to the oscilloscope.
- (c) Blanking out one side of the line generating the pattern.

Under sense operating conditions the voltage feeding the receiver is identical to that obtainable by adding the output of another antenna shifted 90° in phase.

6. A split bearing, causing the two patterns to swing apart and present a bearing at the intersections of the patterns, is obtainable by performing only the first of the above three operations. Plate No. 27, Figure No. 3 is a typical split pattern.

7. The FH4 is a direct reading cathode ray direction finder designed for use on board surface vessels. It covers the frequency range of 1-25 Mc. in five bands. The antenna system used consists of two crossed screened loops. The outputs of these loops are amplified separately in two channels which are aligned as to phase and amplification. The i-f. output of the two channels are placed on the horizontal and vertical deflection plates of the cathode ray tube. This makes a trace which indicates the direction of arrival of the intercepted wave. The total time necessary to present a bearing is one cycle of the i-f. frequency which is 450 kc.

8. The XDL, an NRL developmental radio direction finder, is identical in operating principles to the FH4 but has a wider i-f. bandwidth and a higher i-f frequency.

9. The DAU is a mechanically rotated goniometer radio direction finder designed to take bearings on the frequency range of 1.5-30 Mc. in four bands. Its antenna system consists of crossed loops, the outputs of which are fed to separate coils of the goniometer. The null as picked out by the rotor of the goniometer presents the direction of arrival of the signal. The goniometer is rotated at 1140 rpm.

10. These equipments were tested in regard to sensitivity, accuracy and bearing presentation under different pulsed conditions. In addition, the AN/CRD-2 was tested with respect to stability of the bearing presentation of the system.

INDICATOR TEST

11. To properly test the indicator system of the AN/CRD-2 in regard to sense determination and bearing splitting properties, it was necessary to feed the antenna boxes with a signal of the proper phase as determined from a square antenna array having a 16 foot diagonal and the desired angle of arrival of the incoming wave. This is due to the fact that a part of each antenna input is taken and run through an integrating circuit to obtain the sense and bearing splitting voltages.
12. It may be seen from Plate No. 1, that the phase difference between the North antenna and the East antenna is the amount of phase shift that takes place in the distance F to East. Similarly between the North and South antennas, D to South, and between the North and South antennas as A to West. These distances may be determined by geometry and the amount of phase shift differences calculated on the basis of the distances and the frequency involved. Another way to obtain the same amount of phase shift is to replace these space distances with lines having equivalent electrical distances plus a uniform buffer section to allow connections to be made to a signal generator. This would give an all-frequency system which would indicate a desired angle plus the octantal error of the array for which it was designed.
13. A system of this type was made for the AN/CRD-2 using RG-9/U cable which had a measured velocity of propagation of 65.97% and a characteristic impedance of 52 ohms. The angle decided upon was $22\frac{1}{2}$ degrees.
14. The indication of the AN/CRD-2 was set-up on this set of lines and a cw signal used to determine the bearing splitting properties and the sense determination properties over the frequency range from 1.5 to 30 mcs. The results of this test appear in Table No.1.
15. Interesting to Note about this test is: (a) the bearing may be changed by tuning the receiver. This change in bearing was observed to be on the order of 4 degrees at some points. (b) The split bearing and the bearing do not always coincide. (c) The split pattern is the same as the sense pattern without a 90 degree rotation or a blanking of one of the propellers used in the indication. (d) The split pattern and the sense pattern became weak at 22 mcs and became unusable at 25 mcs. At 30 mcs. the sense was reversed.
16. To determine the reaction of the system to pulses, a pulse generator (Colonial Radio Corp.) was used to modulate a signal generator (Measurements Corporation Model 80). The bearing set up was 45 degrees with a pulse width which was continuously variable from 0.5 to 120 microseconds and a repetition rate variable from 20 to 20,000 cps. The output of the signal generator was fed to the antenna boxes through a goniometer which provided the 45 degree indication. The results of this test may be seen in Table 2. The bearing errors in this table are the result of observational difficulties and actual bearing shift due to mistuning.

17. The system was capable of taking a bearing on a $\frac{1}{2}$ microsecond pulse down to a repetition frequency of 10,000 cps. However, at 10,000 cps, a pulse width of 3 microseconds was necessary to give a smooth pattern. At 5,000 cps repetition rate, the pulses began to appear outside of the pattern. At repetition frequencies of 1000 cps the screen was completely filled in and the bearings became very hard to read. At 500 cps, a pulse width of 120 microseconds was necessary to take a bearing.

18. There were many points at which a bearing was impossible due to the synchronization of some frequencies of the pulse with the frequencies being used to present the bearing. At these points the screen became filled in and the bearing lost in the blur. It was impossible to determine the cause of synchronization due to the extreme multiplicity of the pulse and modulation frequencies involved.

19. The presentation of the FH4 was very good for pulses with a bearing being readable at any of the available widths and above an approximate 50 cps repetition rate. The XDL using the same type of presentation showed a very readable bearing over the same range. The limit of bearing readability of these equipments is the result of the loss of intensity of the indication due to the low repetition rates and short pulse durations.

20. Plate Nos. 25 and 26 show a comparison of the bearings presented by the AN/CRD-2, FH4, XDL and DAU with more emphasis on the DAU presentation as it is similar in appearance to that of the AN/CRD-2 presentation. Plate No. 25 shows the presentations of all four of the above mentioned instruments at a repetition rate of 600 cps and a pulse width of 100 microseconds. The bearing may be seen to be readable on the DAU, FH4 and XDL while the AN/CRD-2 gives no bearing at all. Plate No. 26 shows the presentations of the DAU and AN/CRD-2 at 60 and 6000 cps with a 100 microsecond pulse width. The 6000 cps repetition rate may be seen to give a readable bearing for both although the AN/CRD-2 presentation has pulses occurring outside of the pattern. At 60 cps, neither presents a bearing. A good presentation on the AN/CRD-2 may be seen in Plate 27, figure no. 2. This is a cw presentation which was photographed during the stability test.

BEARING STABILITY OF AN/CRD-2

21. A stability test was run to determine what the accuracy of the bearing presentation of the AN/CRD-2 was over a period of time and the approximate time that the balanced modulator system would maintain its adjustment.

22. The test was run for a continuous period of 524 hours, covering 22 days. The last 89 hours of the test, an angle $22\frac{1}{2}$ degrees and a frequency of 15.0055 megacycles was set up by lines as described in the indicator test using a navy model LR-2 Heterodyne Frequency Meter for the signal source. The data for the test were recorded by means of synchronized motion picture cameras which were connected into a timing circuit that exposed one frame every ten minutes. Pictures from the test film may be seen in Plate No. 27. The timing circuit consisted of a micro-switch and

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a 1 rpm motor geared down to 1 revolution per 10 minutes. One camera was used to record the indicator pattern while the other recorded the frequency, time, date, temperature and humidity. The test was run in a shielded constant-temperature room.

23. The test was run for a continuous period of 524 hours, covering 22 days. The last 89 hours of the test were run after the equipment had been readjusted. Tubes used in the balanced modulators were matched with regard to λ before the test was started.

24. The data taken were read from the films and plotted on a chart, excerpts from which are shown in Plates Nos. 21 and 22. The humidity ranged from 40-83% of relative, the temperature varied around 21 degrees centigrade and the frequency varied from the norm over the range of from 5.4 to 7.4 kilocycles, the norm being 5.5. Voltage regulators were placed in the line feeding the AM/CRD-2 which insured that its supply voltage remained constant within $\pm \frac{1}{2}\%$. None of the variations with the exception of the humidity should be enough to throw the system out of balance. On the chart which was plotted, the humidity showed no trend towards unbalancing the system and so far as could be determined these factors had little or no effect on the test.

25. The indicator indicated the correct bearing for the first 156 hours of the test. It changed abruptly at the end of that time to indicating a 2 degree error. The 2 degree error persisted for 8 hours and a three degree error bearing was presented. The 3 degree error bearing changed to a 4 degree error bearing at the end of approximately 60 hours. This 4 degree error bearing was then held constant until the time at which the instrument was realigned. This was a period of 203 hours. After realignment the instrument presented the correct bearing and held it constant for 89 hours or until the end of the test.

26. During the test, it was noticed that the bearing became split and readjusted itself to a single indication. This may be seen in Plate No. 27, Figure No. 3. This split occurred in both the balanced (both lobes equal) and unbalanced (lobes unequal) condition. The film indication could show only the occurrence of the split as covering a 10 minute interval and it was plotted that way on the graph. However, direct visual observation of bearing indications during the test showed that the split would occur at different time intervals. The bearing would split and return to normal in the period of a second or less depending upon the amplitude of the split. This occurred over periods of as high as 7 hours as recorded from the graph. The occurrence was very erratic occurring at the 35, 85, 121, 164 and 193 hour points and at other times during the test. At the 236 hour point the split became permanent with no apparent return to the normal unsplit condition. This balanced 2 degree split increased to a balanced 4 degree split and then became unbalanced at the 275 hour point. Plate No. 21, an excerpt from the graph, shows a typical section of the split occurrence. Plate No. 22 shows another section of the graph in which the split period was followed by an increase in bearing error. After realigning the instrument, no further evidence of the split occurring was noticed for the

duration of the test.

27. To further determine the cause of this erratic splitting, a test was run independently on a balanced modulator using approximately the same circuit as the balanced modulators in the AN/CRD-2. Sections of this graph are shown in Plates No. 23 and 24. For this test, the circuit was set up and continuous readings taken on Esterline-Angus automatic recording equipment, of plate supply voltage, modulator output and filament voltage. A total continuous run of 320 hours covering a period of 14 days was made. This test showed an unbalance of the modulator occurring at irregular times. This unbalance probably coincides with the split bearing appearing on the stability test. This test showed the modulator to unbalance and then rebalance with the effect getting successively worse until the modulator operated in a state of unbalance.

28. The unbalancing action of the modulator showed no correlation with plate or filament supply voltage variations. Accordingly, the unbalance would appear to be a function of a variation in the characteristics of the vacuum tubes.

BEARING ACCURACY TESTS

29. Bearing accuracy tests were run on the equipment by means of an accuracy test rig, developed at the Naval Research Laboratory and reported in the NRL Report No. R-2707. The rig is a voltage divider network which has been calibrated for the injection of voltages into the antenna terminals. Its accuracy has been established to be within one degree. For a further theoretical and constructional description of the test rig reference is made to the above mentioned report. (Reference 8).

30. The E.S.L. instruction books which arrived with the AN/CRD-2 equipment gave the alignment and adjustment frequency of the set as being 6 mcs. However, the books disagreed on the modulating voltage level, Book No. 3 gave 35 microamperes for the operating modulating voltage level while book No. IV-E gave 10 microamperes. This modulating voltage level was indicated by a meter on the equipment which read in microamperes. Therefore, the true modulating voltage level is not known and reference is made on the curves and graphs to the indicated modulating voltage level being in microamperes as read from this meter. For each of the accuracy tests, the equipment was aligned at 6 mcs. In order to determine the effect of the modulating voltage level on the accuracy, tests were made at levels of 5, 35, and 45, microamperes. Accuracy tests for all modulating voltage levels were run at frequencies of 2, 2.5, 3.5, 5, 7, 10, 14, 22, and 30 megacycles.

31. Careful inspection of Plates No. 4 through 13 will show that at none of the frequencies tested did the errors plotted over 180 degrees for any one frequency lie totally within the experimental accuracy of the test rig. At all frequencies, a modulating voltage level of 5 microamperes proved to

be the most accurate operating point.

32. At 2 megacycles, a modulating voltage level of 5 microamperes gave a maximum error of 5 degrees while one of 45 microamperes gave a maximum error of 9.5 degrees. This error decreased as the frequencies increased to 6 Mc. and then increased as the frequencies went through the range of 6 to 30 Mc. At 30 Mcs, a modulating voltage level of 5 microamperes gave a maximum error of 9 degrees while one of 45 microamperes gave a maximum error of 14.5 degrees. The improvement in accuracy at the 5Mc. and 7 Mc. frequencies may be attributed to the proximity of each to the alignment frequency which was 6 Mc.
33. The accuracy tests made on the DAU mechanically rotated goniometer equipment were made at the same frequencies and with the same test rig, setting the zero at the lower end of each frequency band. The DAU accuracy tests were plotted on Plates 4 through 13 along with the AN/CRD-2 accuracy tests. Comparison of the accuracy curves shows that the DAU gives a more accurate bearing at all frequencies than the most accurate modulating level of the AN/CRD-2. The maximum error for the DAU at 2.5 megacycles is within the accuracy limit of the test equipment while at 30 Mc. the maximum error may be seen to be less than 8 degrees.
34. The FH4 equipment was tested at three frequencies, 1.5, 14, and 25 Mc. At none of the frequencies was the error greater than two degrees and only at the 1.5 Mc. frequency was the error greater than the accuracy of the test rig. The FH4 accuracy curves are plotted on Plate No. 14. These curves show the FH4 to be more accurate than the DAU.

SENSITIVITY TEST

35. The sensitivity tests were run on the standard 20 db signal plus noise to noise ratio. Due to the difference in characteristics in the input circuits of the equipments to be tested, it was decided to test each under R-Z matched conditions, where the term R-Z match is used in this report to mean: matching the absolute magnitude in ohms of the impedance of the input by an equal magnitude in ohms of resistance of the test rig output, this condition giving a basis of comparison between the systems. The test rig diagrammed in Plate No. 2 was developed for this purpose. It uses a 120 ohm line to run from the signal generator to an unbalanced-to-balanced transformer and another line to run from the transformer to the input of the equipment to be tested. This line was terminated in carbon resistors equal in ohms to the characteristic impedance of the line. A five ohm section at the midpoint of this termination was tapped to give a balanced driving voltage to the output. This output was designed to allow different sizes of resistors to be placed in the line thus matching, in ohms, the impedance of the set under test without causing a mismatch to the line. Calibration curves of the test rig were then run to determine the loss through the rig at different frequencies. The input to the match could then be determined by reading the calibrated attenuation pad in the signal generator and dividing by the proper factor as determined from the

calibration curve.

36. The input impedances of the various equipments tested were measured by use of the test rig and when possible by means of a General Radio 916-A bridge. The impedances could be determined by the test rig by setting a standard output such as 10 volts from the second detector and keeping this ten volts constant while varying the resistance in the match and the input voltage. Measurements were made at 5, 135, 285, 985, and to 9,985 ohms. Assuming that the input current must be the same for all conditions of a constant ten volts output, and knowing the input to each of the combinations the impedance of the set may be determined by a simple calculation. These impedances are shown on Plate No. 3. The correspondence between the impedance as obtained by R.F. Bridge and test rig methods is shown by the curve for the input impedance to the AN/CRD-2. The tests of all systems were made by using two antenna inputs in the case of a four antenna array or one input in the case of a loop antenna array. The output for all systems was taken as the output from the second detector.

37. Sensitivity tests on the AN/CRD-2 were made holding the frequency constant and varying the indicated modulating voltage and holding the indicated modulating voltage constant and varying the frequency. As the indicated modulating voltage is increased, the sensitivity improves. However, the increase in sensitivity approaches an asymptote at approximately an indicated modulating voltage corresponding to 45 microamperes. On the basis of Plate No. 15, the trend would show that any further increase in indicated modulating voltage would result in no appreciable increase in sensitivity with the present circuits. The sensitivity as seen on Plate No. 16 is approximately constant over the range of 2 to 14 megacycles and becomes worse over the range of 14 to 30 megacycles.

38. Plate No. 17 shows a comparison of the AN/CRD-2 best sensitivity (at an indicated modulating voltage corresponding to 45 microamperes), FH4 sensitivity, and DAU sensitivity under the test conditions plotted against frequency. The DAU has the best sensitivity on the 2-3.5 megacycle range, the FH4 has the best sensitivity on the 4-14 megacycle range. The AN/CRD-2 sensitivity is appreciably worse with the exception of one reading at the 30 mc. point. However, up to date design and the use of modern precision components might raise the sensitivity of the FH4 to better than that of the DAU on all ranges due to absence of goniometer loss.

39.. The noise factors were calculated on the basis of 1.41 signal to noise plus noise voltage ratio. This ratio was divided by the calculated root mean square microvolts of thermal agitation noise generated in the resistors used to match the input. The perfect receiver implied by zero DB noise factor is one which has no internal noise generator so that all the noise it sees is a function of the antenna resistance. Plate No. 18 shows the AN/CRD-2 noise factor variation with the variation in indicated

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modulating voltage. This follows the corresponding sensitivity very closely as would be expected. Plate No.19 shows the AN/CRD-2 noise factors plotted against frequency for constant values of modulating voltage. This curve also exhibits the same characteristics as the corresponding sensitivity curve. Plate No.20 shows a comparison of the best AN/CRD-2 noise factor with the DAU and FH4 noise factors under the test conditions. This Plate shows the DAU to have the best noise factor with the FH4 and AN/CRD-2 approximately equal, the AN/CRD-2 being better on the low frequency range (2-5 megacycles) and the FH4 better on the high frequency (5-30 megacycles).

SUMMARY

40. The bearing indication system used on the AN/CRD-2 is capable of presenting bearings on pulsed signals with a repetition rate more than 500 cps and at a frequency which does not synchronize with any of the frequencies used in the presentation. At points at which synchronization occurred the screen was completely filled-in and the bearing lost in the haze. This is inferior to the presentation of the DAU which is capable of taking a bearing on pulsed signals with a repetition rate of more than 450 cps regardless of synchronization with the frequencies used in the presentation. The DAU is also capable of taking a bearing on pulsed signals below a 450 cps repetition rate as long as synchronization does not occur and the tube used is of sufficiently long persistence to allow the pattern to be filled in. The FH4 is capable of presenting a bearing on any pulsed signal of long enough duration or fast enough repetition rate to allow the line indication to become visible on the screen.

41. The bearing presented on the AN/CRD-2 varies with the tuning of the receiver within the limits of aligning both lobes of the indicator to equal strength and within the limits of the audio tuning indication available. This variation is of the order of 4 degrees at most frequencies. The split bearing presentation and the direct bearing presentation do not give the same bearing in all cases. The sense presentation as noted in the report does not function at 25 Mcs. and above.

42. The AN/CRD-2 stability of bearing presentation was completely satisfactory with the exception of the automatic splitting feature. This feature would be all right except in those cases in which the direct presentation does not coincide with the split presentation. In this case, the operator would have difficulty in taking a bearing due to the short periods of time that the split occurs. Regular operation of the AN/CRD-2 requires alignment nearly as often as the FH4. This is in contrast to the DAU which requires alignment approximately every three months. The alignment procedure on the AN/CRD-2 is not as complicated as the alignment procedure used on the FH4. During the time that the work proceeded on the AN/CRD-2 the equipment was operating for approximately 1100 hours. The maintenance work required during this period of time consisted of replacing one high voltage rectifier tube and three low voltage rectifier tubes.

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In addition to these replacements, three of the lights used to illuminate the indicator burned out during the stability test. Six of the lights were replaced at this time with no further failures resulting after the change.

43. The accuracy of the AN/CRD-2 at its most accurate indicated modulation voltage operating condition is still not as great as the DAU. The most accurate indicated modulating voltage condition coincides with the least sensitive condition. This makes the operation of the system unfeasible at that point. The DAU is not as accurate as the FH4 which indicated to be within the experimental accuracy of the equipment used to test it.

44. The sensitivity of the AN/CRD-2 at the most favorable operating conditions, which correspond to the most inaccurate conditions, has been shown to be unsatisfactory when compared to the mark set by the direction finding systems now in use by the Navy. The DAU showed the greatest sensitivity of the three systems tested, on the 2-4 and 14-30 megacycle range with the FH4 best on the 4-14 megacycle range; however, improvements in the design of the FH4 might improve its sensitivity over that of the DAU on the remaining ranges.

45. With a redesign of the indicator and goniometer system, the AN/CRD-2 would be extendable to higher frequencies than the DAU. The resulting sensitivity and accuracy at these higher frequencies do not lend themselves to conjecture and consequently nothing may be suggested as to their probable magnitudes.

CONCLUSIONS

46. It is concluded:

- a) That direction finder equipments employing electronic goniometers such as exemplified by the AN/CRD-2 possess no immediate advantages over other types of automatic indicating equipments other than the absence of mechanically rotating parts with their maintenance problems, noise of operation and shorter life.
- b) That the probability exists that it might be possible in the future to extend the frequency range of such equipments more readily to higher frequencies than other types of equipments.
- c) That the instrumental errors of the AN/CRD-2 equipment are higher than either the Model DAU (representing rotating goniometer types of equipment) or the FH 4 (representing the instantaneous type).
- d) That both the maximum response sensitivity and the bearing sensitivity of the AN/CRD-2 are much poorer than those of the FH4.
- e) That the number of operating adjustments necessary to maintain the AN/CRD-2 in proper operating condition over a period of time are greatly in excess of those of the DAU but less than the

FH4.

f) That the AN/CRD-2 is much less effective against pulsed signals than the DIU and very much less than the FH 4.

g) That the accuracy of the bearing indication is dependent on the tuning of the receiver because of the high equivalent rotational speed of the goniometer, and the necessarily limited bandwidth.

h) That the design of the AN/CRD-2 equipment is such that the settings for maximum sensitivity and for best accuracy are incongruous.

i) That the stability of the bearing indication of the AN/CRD-2 is poorer than the DIU but better than the FH 4.

j) That the maximum "rotational" speed of any goniometer system, whether electronic or mechanical, is limited (for a given instrumental error) by the pass band width of the receiver; therefore, the use of electronic goniometers for the sole purpose of obtaining high rotational speed is of questionable value, particularly in light of the complications and deleterious features indigenous to such devices.

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1. BuShips ltr. Serial No. 2027 (925Dk) to NRL of 14 July 1946.
2. NRL ltr. Ser. c-701-2893/45, C-S67/69 (701) of 18 July 1945 to Chief of Bureau of Ships.
3. Bureau of Ships ltr. Ser. 4-3308(925DK) of 11 Feb. 1946 to **NRL**
4. Eatontown Signal Laboratory, Instruction Manual, Radio Set AN/CRD-2, Direction Finding, Copy IV-E, 3 June 1944.
5. Eatontown Signal Laboratory, Instruction Manual, Radio Set AN/CRD-2, Direction Finding, Copy 3, 3 June 1944.
6. Eatontown Signal Laboratory Engineering Report No. ST-5, Radio Set AN/CRD-2, 10 May 1944.
7. Patent petition of Paul Hansel, signed at Eatontown, 8 June 1944 .
8. NRL Report R-2707, "Sensitivity and Accuracy Comparisons of DAU vs DAJ Goniometers for DAJ-a Installations".

Original data and designs recorded in NRL Log Book 5861.

APPENDIX 1

ANALYTICAL COMPARISON OF THE MECHANICALLY ROTATED GONIOMETER
OUTPUT WITH THE OUTPUT OF THE ELECTRONIC GONIOMETER

1. For this analysis, the antenna voltages used are those which would be present for four omni-directional antennas placed at the four corners of a square having a diagonal equal to two d and with a vertically-polarized incoming wave of the form $E = E_m \sin \omega_c t$ at the center of the array.

MECHANICALLY ROTATING GONIOMETER ANALYSIS:

2. The antenna voltages from the above described array may be calculated to be:

$$e_N = E_m h_e \sin(\omega_c t + \frac{2\pi d}{\lambda} \cos \theta) - - - - - (1)$$

$$e_S = E_m h_e \sin(\omega_c t - \frac{2\pi d}{\lambda} \cos \theta) - - - - - (2)$$

$$e_E = E_m h_e \sin(\omega_c t + \frac{2\pi d}{\lambda} \sin \theta) - - - - - (3)$$

$$e_W = E_m h_e \sin(\omega_c t - \frac{2\pi d}{\lambda} \sin \theta) - - - - - (4)$$

Where:

e_N, e_S, e_E and e_W are the antenna voltages corresponding to the placement of the array with respect to the compass points.

E_m is a constant depending on the incoming signal strength.

h_e is the effective antenna height.

$\omega_c = 2\pi$ times the carrier frequency.

t = time

d = distance from the antenna to the center of the array.

λ = wave length of the incoming signal.

θ = angle of arrival of the signal measured positive towards the east antenna from a line drawn through the center of the array and the north antenna.

3. For the antenna pairs connected opposing as in an Adcock Array:

$$e_{N-S} = e_N - e_S \quad e_{E-W} = e_E - e_W$$

The following assumptions must be made:

$$(a) \cos \frac{2\pi d \cos \theta}{\lambda} \approx 1 \quad \text{--- (5)}$$

$$(b) \sin \frac{2\pi d \cos \theta}{\lambda} \approx \frac{2\pi d \cos \theta}{\lambda} \quad \text{--- (6)}$$

(c) The stator impedances of the goniometer are equal,

(d) The maximum coefficient of coupling is identical between each stator and the rotor.

(e) A pure sine law coupling relation exists between each stator and the rotor, i.e., no goniometer error.

These assumptions may be made as the analysis progresses, but are made here to facilitate the analyzing procedure.

4. Expanding the antenna voltages and substituting relations 5 and 6:

$$e_N = E_m h_e \sin \omega t + E_m h_e \frac{2\pi d \cos \theta}{\lambda} \cos \omega t \quad \text{--- (7)}$$

$$e_S = E_m h_e \sin \omega t - E_m h_e \frac{2\pi d \cos \theta}{\lambda} \cos \omega t \quad \text{--- (8)}$$

Subtracting 7 from 8 to get the N-S Adcock array voltage yields:

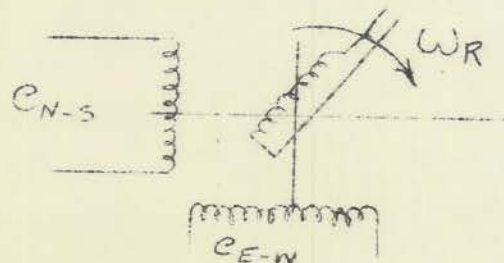
$$e_{N-S} = e_N - e_S = 2 E_m h_e \frac{2\pi d \cos \theta}{\lambda} \cos \omega t \quad \text{--- (9)}$$

$$e_E = E_m h_e \sin \omega t + E_m h_e \frac{2\pi d \sin \theta}{\lambda} \cos \omega t \quad \text{--- (10)}$$

$$e_W = E_m h_e \sin \omega t - E_m h_e \frac{2\pi d \sin \theta}{\lambda} \cos \omega t \quad \text{--- (11)}$$

Subtracting 10 from 11 to get the E-W Adcock Antenna voltage yields:

$$e_{E-W} = e_E - e_W = 2 E_m h_e \frac{2\pi d \sin \theta}{\lambda} \cos \omega t \quad \text{--- (12)}$$



5. These voltages (9 and 12) are the ones which are fed to the two stator coils of the goniometer.

6. All terms containing the subscript R will now be defined to represent rotor terms, for instance, $\omega_R = 2\pi f_R$ where f_R is the speed of rotation of the goniometer.

7. In addition to the other assumptions made, assume K to be the constant relating Φ_m , the flux, to E_m , maximum primary voltage, in the rotation $\Phi_m = K E_m$. This merely facilitates the analysis and has no bearing on the actual outcome.

8. There will be two voltages induced in the rotor by the application of equations 9 and 12 to the stators. One voltage arises from the $e_R = -N \frac{d\Phi}{dt}$ transformer action and the other from the $e_R = b \frac{dV}{dt}$ motor action of the rotating coil.

Applying these relations:

$$e_R = -K \omega_c N^2 E_m h_e \frac{2\pi d \cos \theta}{\lambda} \cos \omega_c t \cos \omega_R t \\ - K \omega_c N^2 E_m h_e \frac{2\pi d \sin \theta}{\lambda} \cos \omega_c t \sin \omega_R t \\ - K \omega_R \sin \omega_c t \cos \omega_R t - K \omega_R \sin \omega_c t \sin \omega_R t \quad (13)$$

due to the fact that $\omega_c \gg \omega_R$ the last two terms of equation 13 may be neglected and equation 13 becomes:

$$-e_R = K N^2 \omega_c E_m h_e \left[\frac{2\pi d \cos \theta}{\lambda} \cos \omega_c t \cos \omega_R t \right. \\ \left. + \frac{2\pi d \sin \theta}{\lambda} \cos \omega_c t \sin \omega_R t \right] \quad (14)$$

9. The minus sign in equation 14 has no significance other than to show the phase inversion through the goniometer. It could be compensated for by placing another transformer at the input to the receiver. It may be compensated for by merely transposing the leads and may be neglected for the sake of this analysis.

10. The output of the mechanically rotated goniometer may then be written as:

$$e_R = K N^2 \omega_c E_m h_e \frac{4\pi d}{\lambda} [\cos(\theta - \omega_R t) \cos \omega_c t] \quad (15)$$

ELECTRONIC GONIOMETER ANALYSIS:

11. Repeating the antenna voltages in the preceding analysis:

$$e_N = E_m h_e \sin(\omega_c t + \frac{2\pi d}{\lambda} \cos \theta) \quad (1)$$

$$e_S = E_m h_e \sin(\omega_c t - \frac{2\pi d}{\lambda} \cos \theta) \quad (2)$$

$$e_E = E_m h_e \sin(\omega_c t + \frac{2\pi d}{\lambda} \sin \theta) \quad (3)$$

$$e_W = E_m h_e \sin(\omega_c t - \frac{2\pi d}{\lambda} \sin \theta) \quad (4)$$

12. The output of one antenna is fed in parallel to the grids of the two tubes in the antenna modulator unit. These tubes have their plates in push-pull across the combining impedance. The output of the balanced modulator tubes then will flow in opposite direction through the combining impedance.

This may be formulated as :

$$i_{p1} = \frac{ue_g}{R_p} = e_g G_{m1} \quad \text{--- (16)}$$

$$i_{p2} = -\frac{ue_g}{R_p} = -e_g G_{m2} \quad \text{--- (17)}$$

13. However e_{N1} and e_{N2} will be obtained at the receiver input in place of e_g therefore substituting e_N in the above equations:

$$e_{N1} = E_m h_e G_{m1} Z_t \sin(\omega_c t + \frac{2\pi d}{\lambda} \cos \Theta) \quad \text{--- (18)}$$

$$e_{N2} = -E_m h_e G_{m2} Z_t \sin(\omega_c t + \frac{2\pi d}{\lambda} \cos \Theta) \quad \text{--- (19)}$$

Where Z_t = transfer impedance of the load on the modulator. Other factors are as previously designated.

14. To obtain the modulating voltage, G_m is varied sinusoidally so that:

$$\begin{aligned} G_{m1} &= G_{m10} (1 + A_m \cos \omega_R t) \quad \text{---} \\ G_{m2} &= G_{m10} (1 - A_m \cos \omega_R t) \quad \text{---} \end{aligned} \quad \text{--- (20)}$$

G_{m10} average transconductance

A_m modulation factor

$\omega_R = 2\pi f_R$ Where f_R is the frequency of modulation

15. Substituting these expressions in 18 and 19:

$$e'_{N1} = E_m h_e G_{m10} (1 + A_m \cos \omega_R t) Z_t \sin(\omega_c t + \frac{2\pi d}{\lambda} \cos \Theta) \quad \text{--- (21)}$$

$$e'_{N2} = -E_m h_e G_{m10} (1 - A_m \cos \omega_R t) Z_t \sin(\omega_c t + \frac{2\pi d}{\lambda} \cos \Theta) \quad \text{--- (22)}$$

16. The voltage appearing across the combining impedance due to the north antenna is the sum of 21 and 22:

$$e_N' = 2E_m h_e Z + A_m G_{m0} \cos \omega_R t \sin(\omega_c t + \frac{2\pi d}{\lambda} \cos \theta) \dots (23)$$

17. It should be noted that: if the average transconductances of the two tubes used in the balanced modulator circuit are not identical, a voltage of the carrier frequency will effectively be placed in the input to the combining impedance. This is due to the fact that the terms in 21 and 22 which contain the carrier voltage will not be cancelled out when the two equations are added. This of course will carry into the output as an unbalance in the modulator itself.

18. By similar analysis the following expressions may be found:

$$e_s' = -2E_m h_e Z + A_m G_{m0} \cos \omega_R t \sin(\omega_c t - \frac{2\pi d}{\lambda} \cos \theta) \dots (24)$$

$$e_e' = 2E_m h_e Z + A_m G_{m0} \sin \omega_R t \sin(\omega_c t + \frac{2\pi d}{\lambda} \sin \theta) \dots (25)$$

$$e_w' = -2E_m h_e Z + A_m G_{m0} \sin \omega_R t \sin(\omega_c t - \frac{2\pi d}{\lambda} \sin \theta) \dots (26)$$

19. It should be noted in the above equations that the addition of these voltages at this point corresponds to connecting the East-West and North-South Antennas in an adcock array opposing. This makes possible the use of the accuracy test rig described in R-2707.

20. The total voltage in the combining impedance is :

$$e_R = e_N' + e_s' + e_e' + e_w' \dots (27)$$

So that:

$$e_R = 2E_m h_e Z + A_m G_{m0} \left[\sin(\frac{2\pi d}{\lambda} \cos \theta) \cos \omega_R t + \sin(\frac{2\pi d}{\lambda} \sin \theta) \sin \omega_R t \right] \cos \omega_c t \dots (28)$$

Assuming

$$\sin \frac{2\pi d}{\lambda} \cos \theta = \frac{2\pi d}{\lambda} \cos \theta$$

$$\sin \frac{2\pi d}{\lambda} \sin \theta = \frac{2\pi d}{\lambda} \sin \theta$$

Then:

$$e_R = E_m \frac{4\pi d}{\lambda} h_e Z + A_m G_{m0} [\cos(\theta - \omega_R t) \cos \omega_c t] \dots (29)$$

21. However, the combining impedance is essentially a transformer. Applying the $e = -N \frac{d\phi}{dt}$ transformer action formula, the output of the combining impedance is seen to be:

$$-e_R = N\omega_c Z_t A_m G_m c 2K, E_m h e \frac{2\pi d}{\lambda} [\cos(\theta - \omega_R t) \cos \omega_c t] - - (30)$$

where the minus sign bears the same significance as before discussed and may be omitted, and K, has the relation discussed in Appendix paragraph 7. The equation becomes:

$$e_R = Z_t A_m G_m c \omega_c N K, E_m h e \frac{4\pi d}{\lambda} [\cos(\theta - \omega_R t) \cos \omega_c t] - - (31)$$

This is compared to equation 15; (the output of the mechanically rotated goniometer).

$$e_R = K \omega_c N E_m h e \frac{4\pi d}{\lambda} [\cos(\theta - \omega_R t) \cos \omega_c t] - - - - (15)$$

22. It may be seen that the total information determining the bearing of the incoming signal is contained within the brackets of equations 15 and 31 and is identical in both equations. The terms preceding the brackets in equations 15 and 31 are constants depending on the signal and also on the gain or loss through the type of goniometer used.

23. Therefore, insofar as the receiver input is concerned, the electronic and mechanical goniometers produce identical effects.

TABLE NO. 1

SIMULATED ANTENNA SYSTEM TESTS ON THE AN/CRD-2

Results of tests run on the AN/CRD-2 Radio Direction Finder using a simulated antenna system indicating a bearing of 22.5 degrees exclusive of the octantal error of the array.

Frequency Mc.	Bearing	Sense	Split	Remarks
1.5	21.0	yes	21.0	Distorted pattern one lobe approx. 3 times other lobe.
3.0	21.0	yes	21.0	Slightly distorted pattern one lobe sharp, one pointed.
4.5	22.5	yes	22.5	Same as above
6.5	22.0	yes	22.0	Same.
10	24	yes	24	Tuned to lobes of equal strength
10	22.5	yes	22.5	Reduced signal strength
14	25	better	25	Sharpening of lobes
20	25	yes	29	
25	27	no	--	Split doesn't read.
30	20	reversed	13	

Results of test run on the AN/CRD-2 Radio Direction Finder using a simulated antenna system indicating a bearing of 337.5 degrees exclusive of the octantal error of the array.

1.5	343	yes	345	Pattern lopsided
3.0	343	yes	345	Pattern slightly improved; one lobe fat, other thin.
4.5	343.5	yes	343.5	One lobe larger than the other.
6.5	342	yes	342	Slightly distorted but improved
10.0	340	yes	341	
14.0	339.0	yes	340	
20.0	339.0	yes	340	Sense very poor; lobes on sense drawn almost into the center of the screen.
25.0	339.0	none	none	
30.0	345.0	reversed	345	

TABLE NO. 2

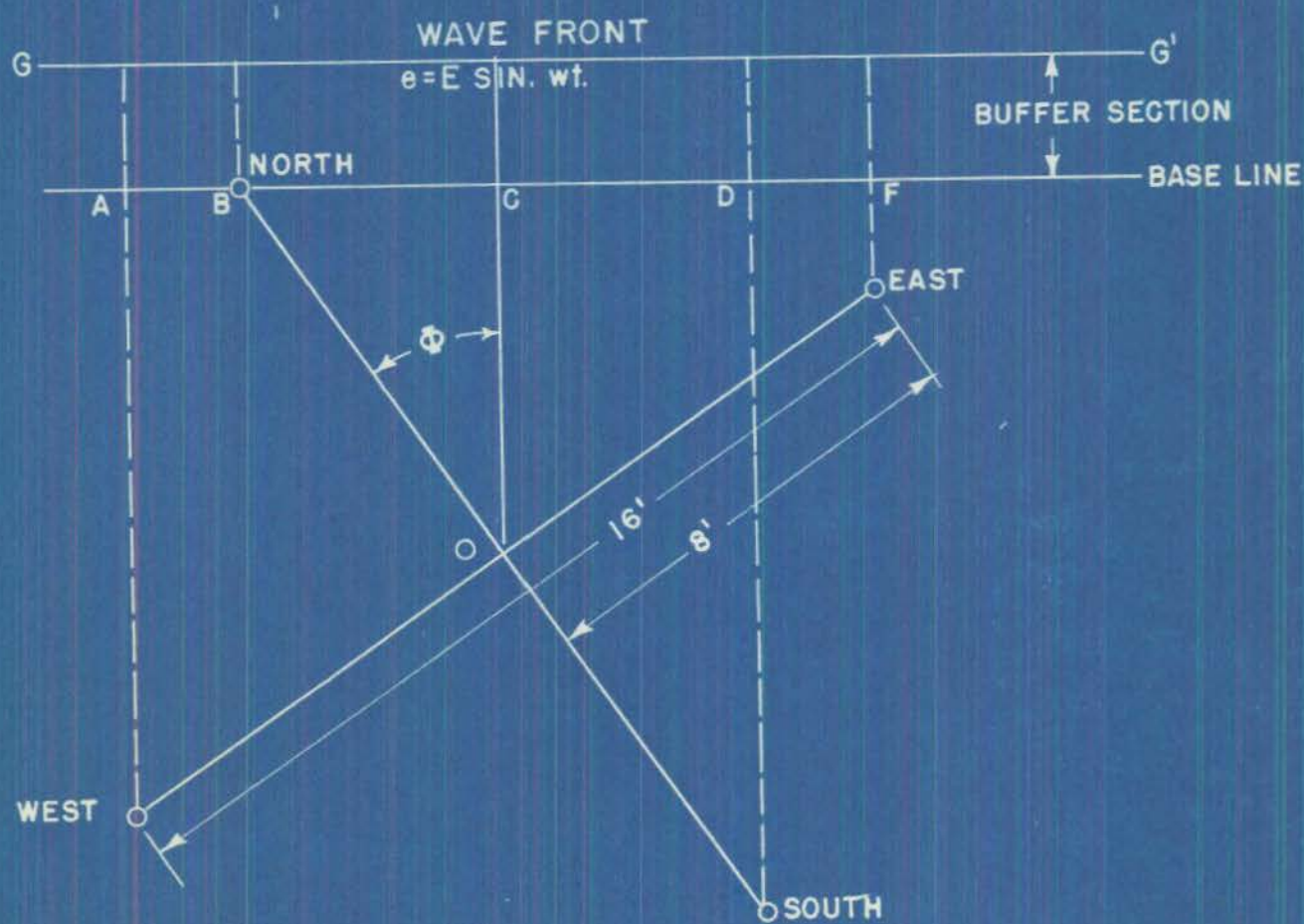
RESULTS OF PULSE INDICATION TEST ON THE AN/CRD-2

Pulse Repetition (Cycles per sec.)	Pulse Width (Micro Secs)	Bearing (Degrees)	Remarks
20,000	120	41	
20,000	0.5	39.9	
15,000	120	40.5	
15,000	0.5	40.5	
10,000	120	40.5	
10,000	0.5		Bearing may be readable to an experienced opera- tor, range of readings 39-44.
10,000	3	41.5	
5,000	120	42.5	Pulses began appearing outside of the pattern
5,000	3	39.5	
1,000	120	42.	Screen completely filled in, bearing read through haze
	3	43	
750	120	41	
500	120	39.5	
490			Synchronization

Listed below are a few of the pulse repetition rates at which bearings are unobtainable due to the synchronization of the equipment with one or more of the frequencies generated by the pulse.

1,920
470
440
410
390
377
367
352
342
330
322
314
292
262

It should be noted that this is not all of the frequencies at which synchronization may occur, even within this range. It is merely a representation of a cross-section of the synchronous frequencies.

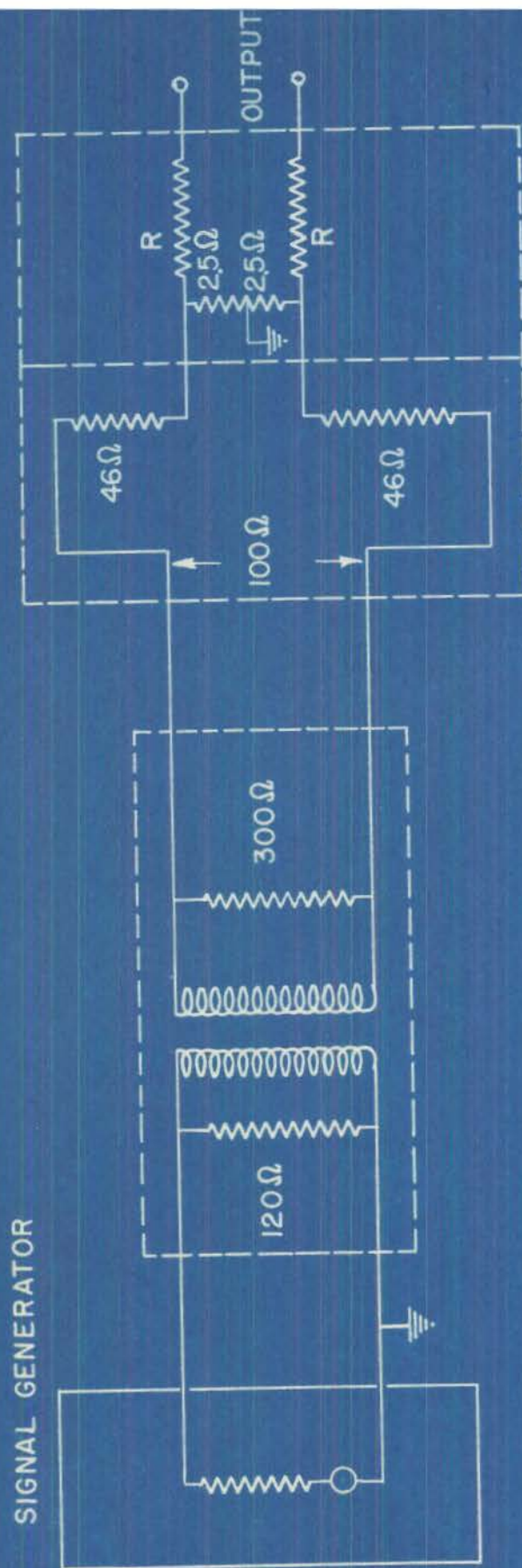


SIMULATED ANTENNA ARRAY

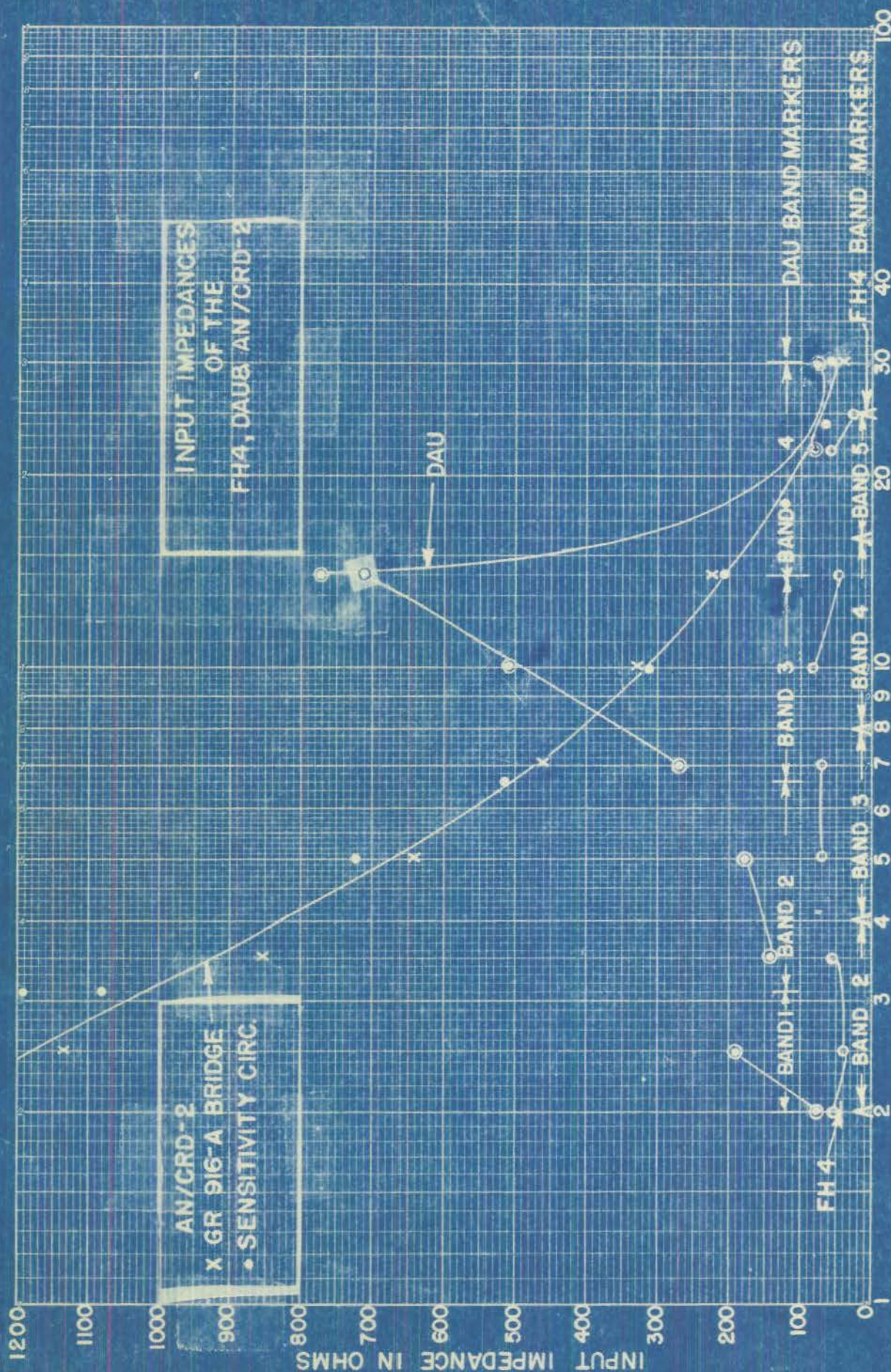
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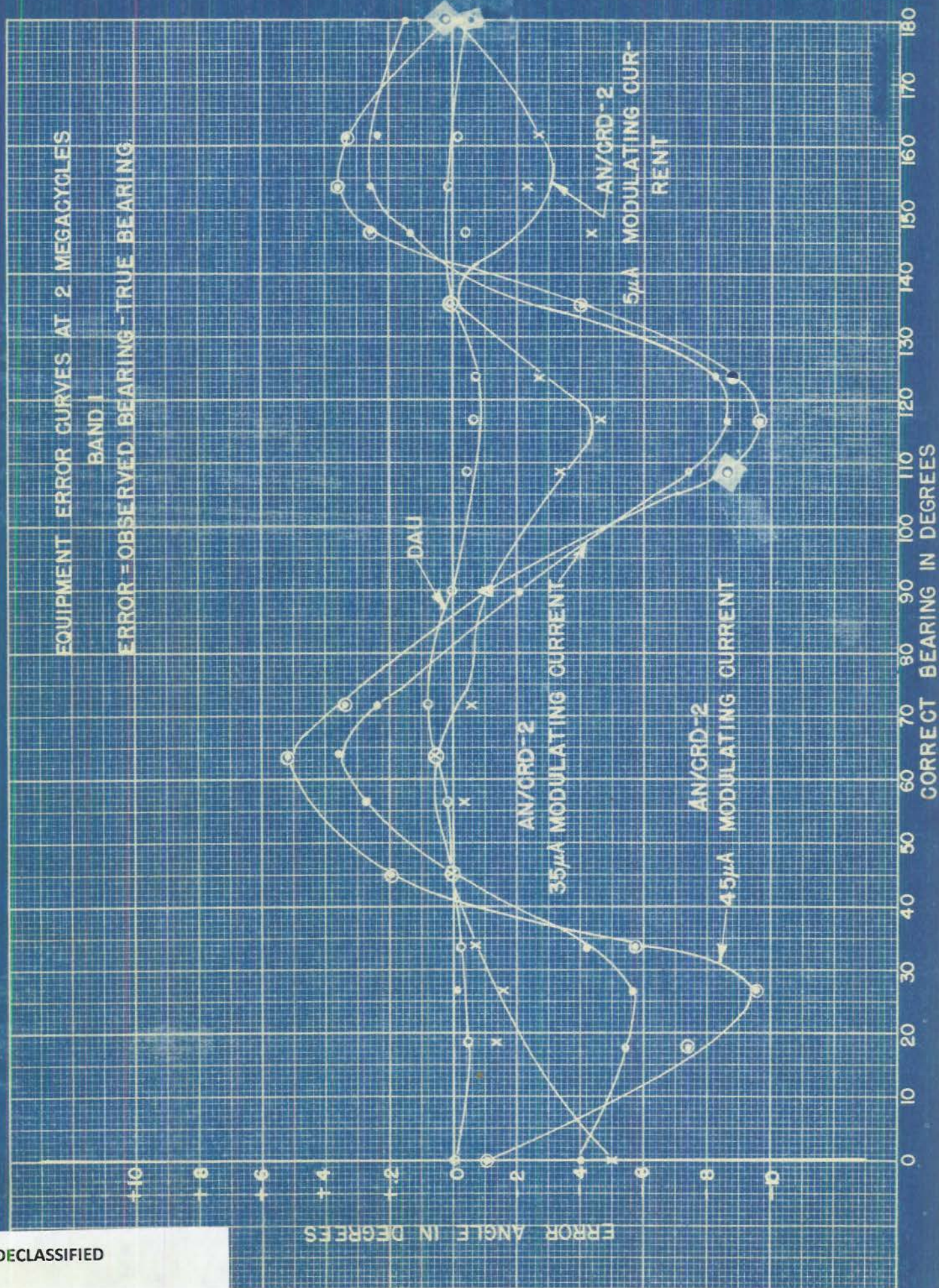
PLATE 2

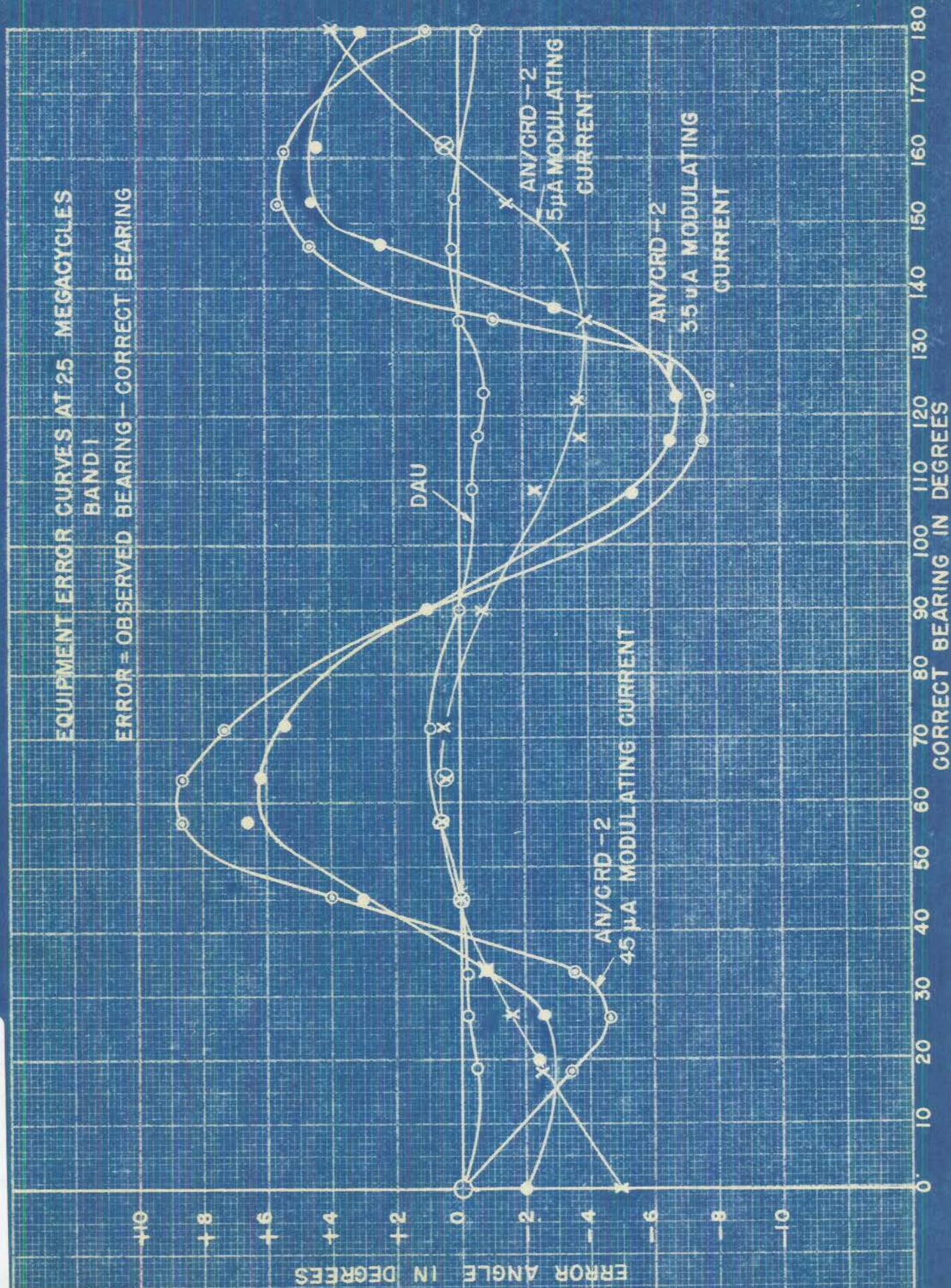


SENSITIVITY TEST RIG



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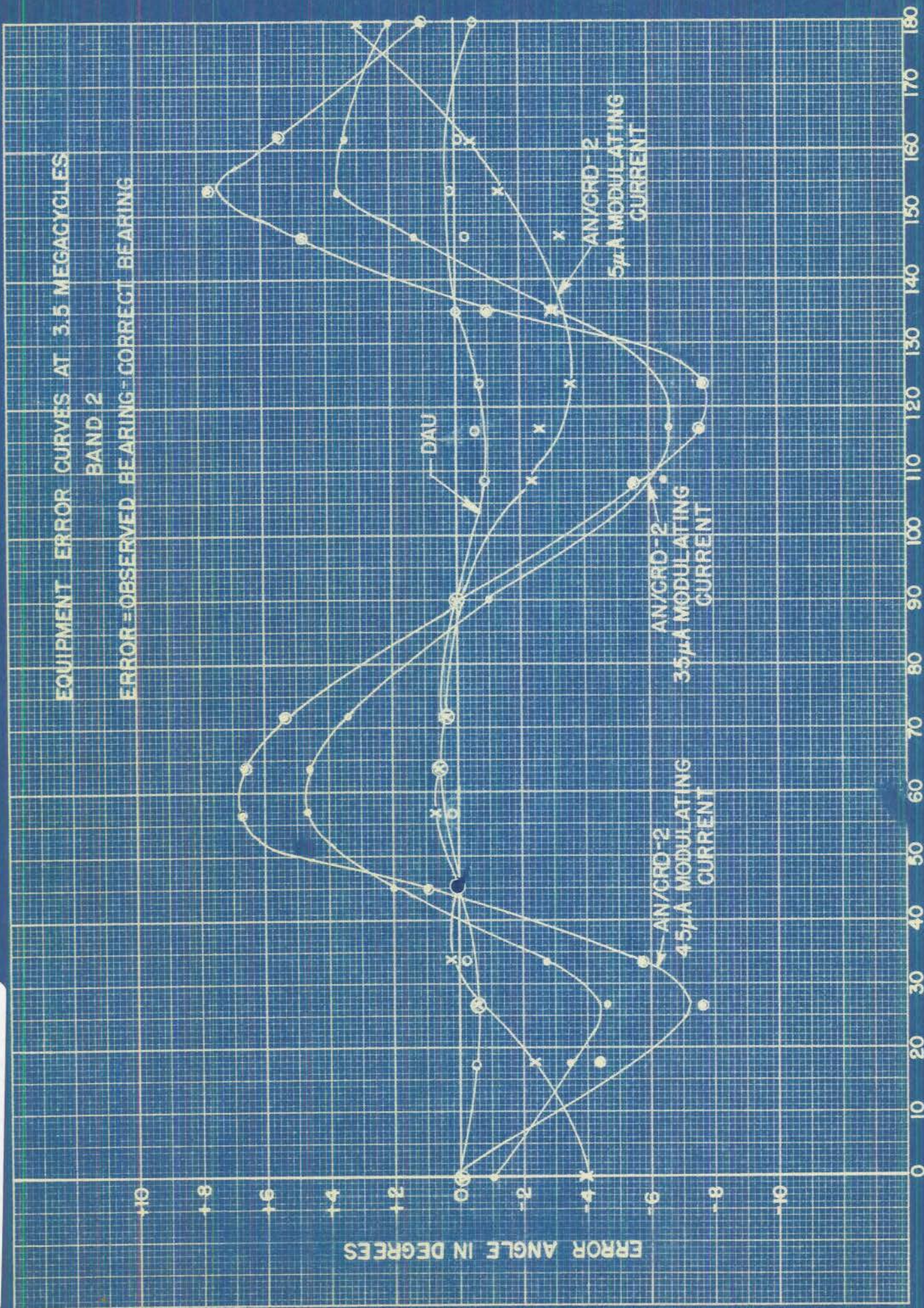


EQUIPMENT ERROR CURVES AT 3.5 MEGACYCLES BAND 2

ERROR = OBSERVED BEARING - CORRECT BEARING

ERROR ANGLE IN DEGREES

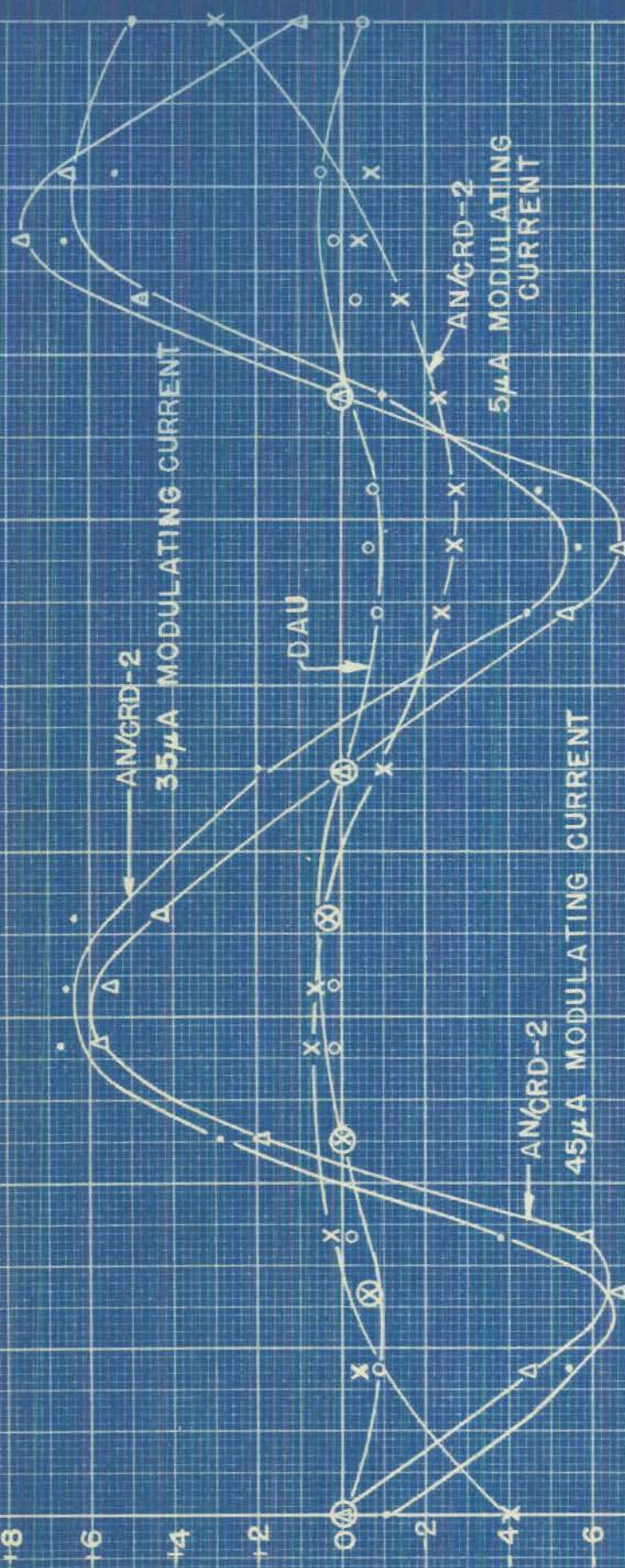
CORRECT BEARING IN DEGREES



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ERROR ANGLE IN DEGREES

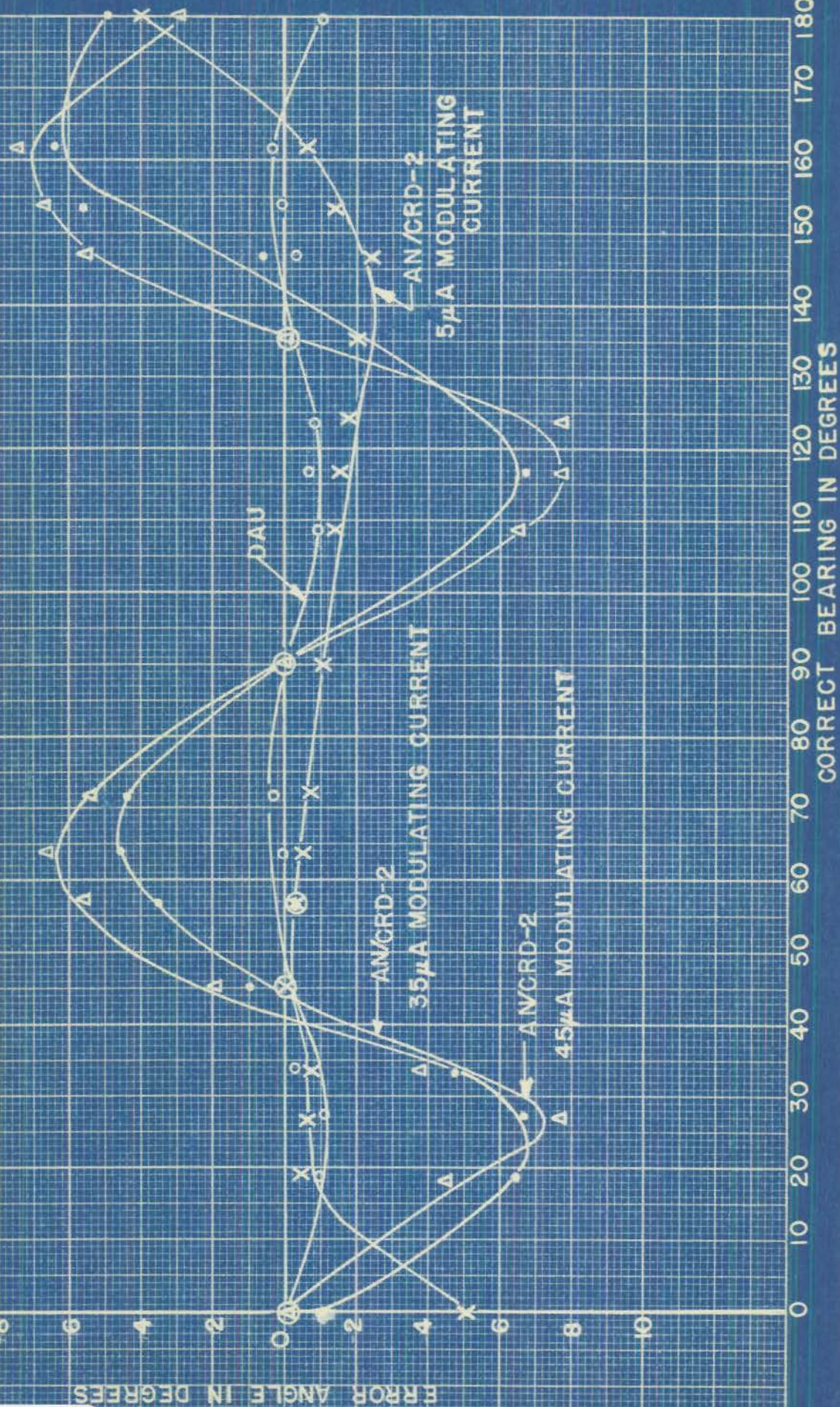
EQUIPMENT ERROR CURVES AT 5 MEGACYCLES
BAND 2
ERROR = OBSERVED BEARING - CORRECT BEARING



DECLASSIFIED

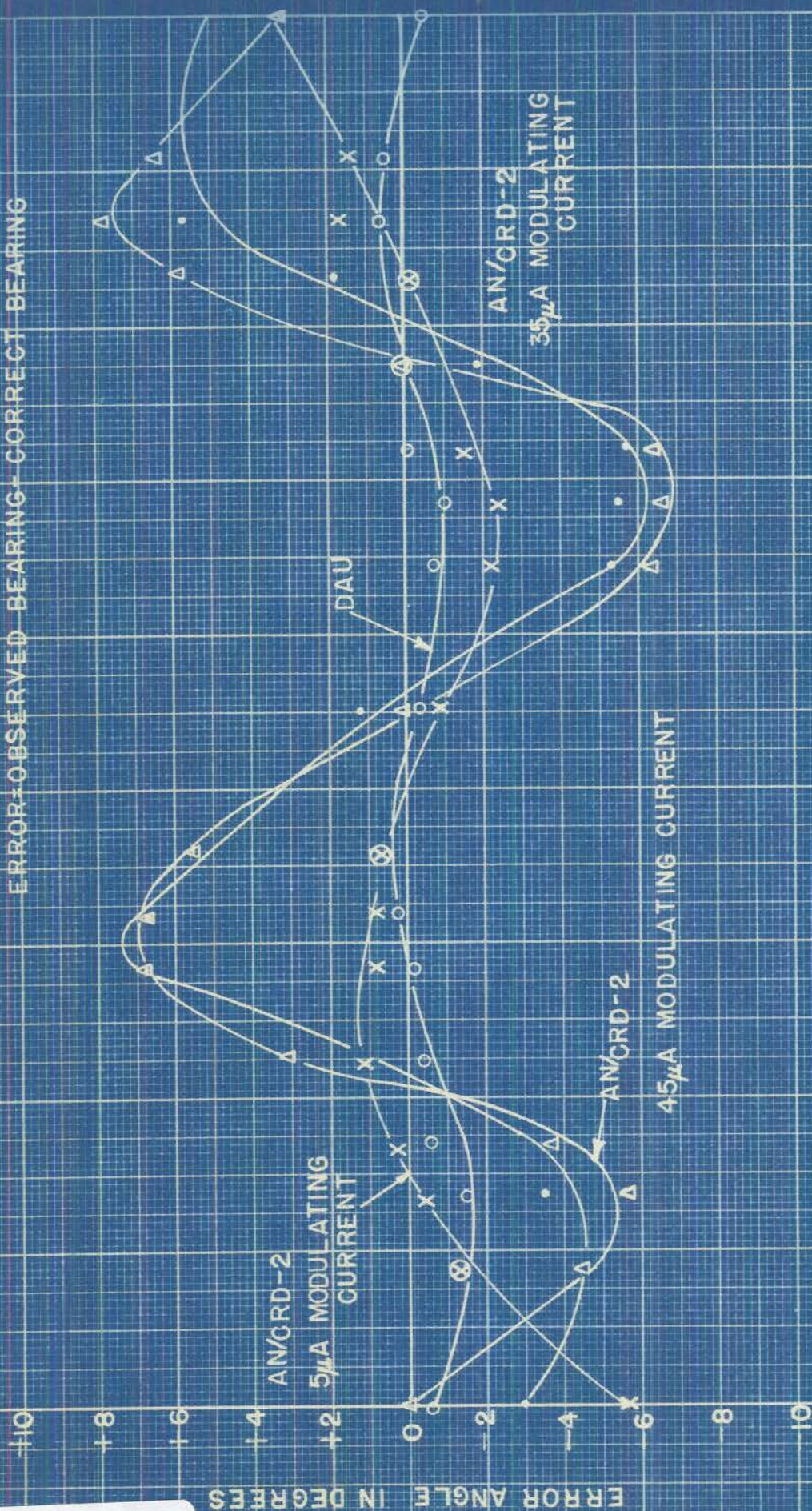
EQUIPMENT ERROR CURVES AT 7 MEGACYCLES
BAND 3

ERROR = OBSERVED BEARING - CORRECT BEARING

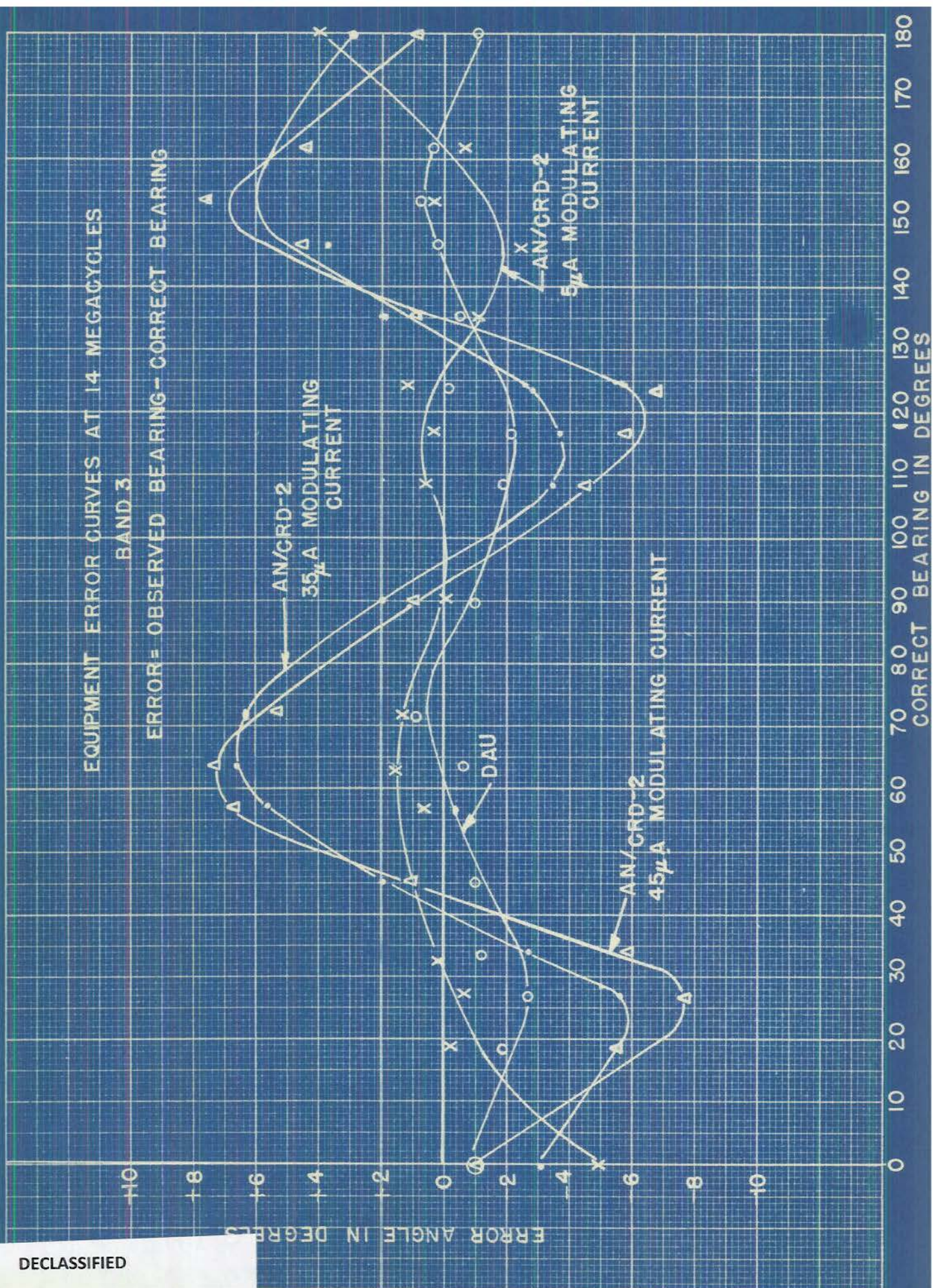


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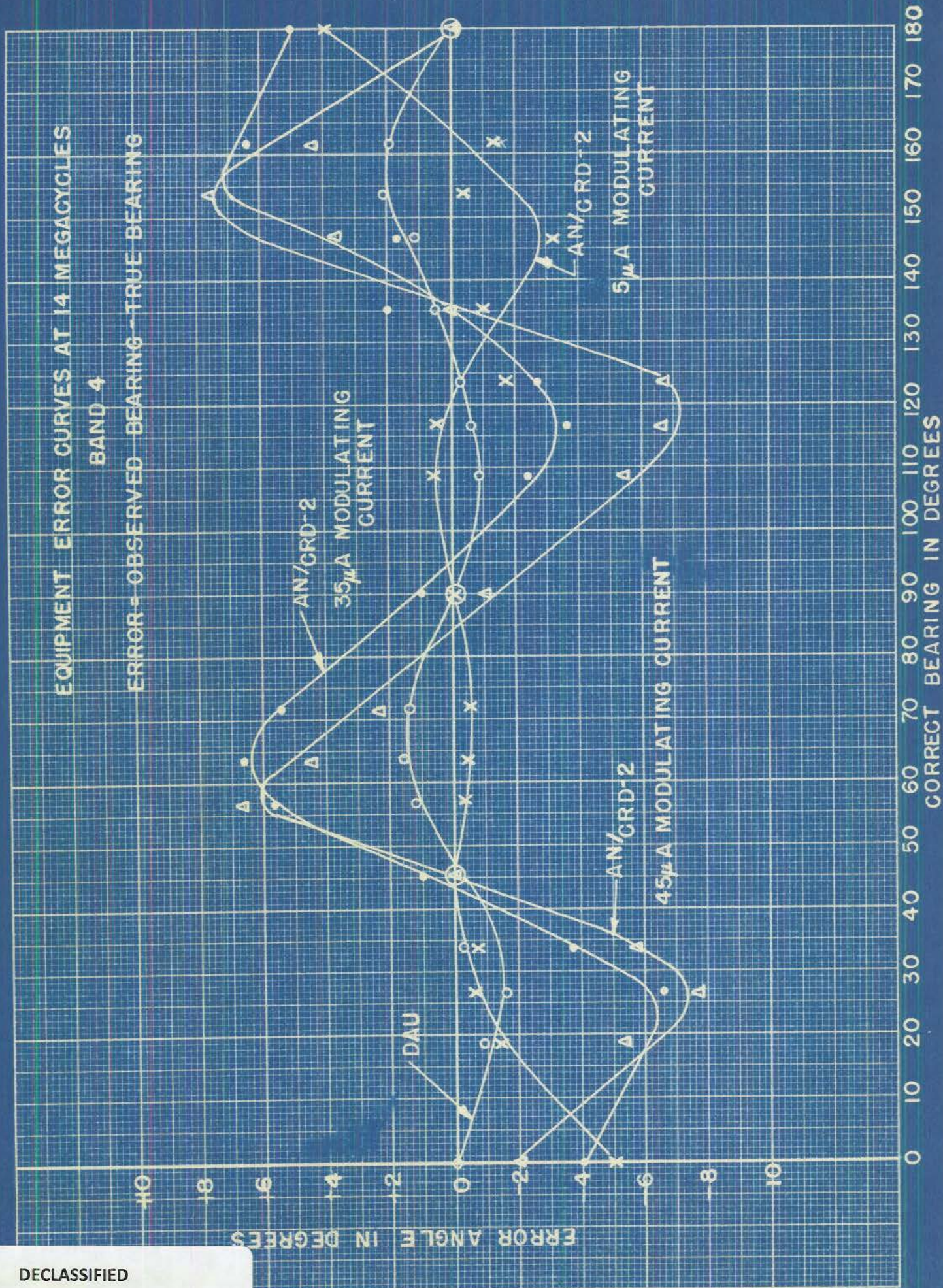
EQUIPMENT ERROR CURVES AT 10 MEGACYCLES
BAND 3
ERROR-OBSERVED BEARING-CORRECT BEARING



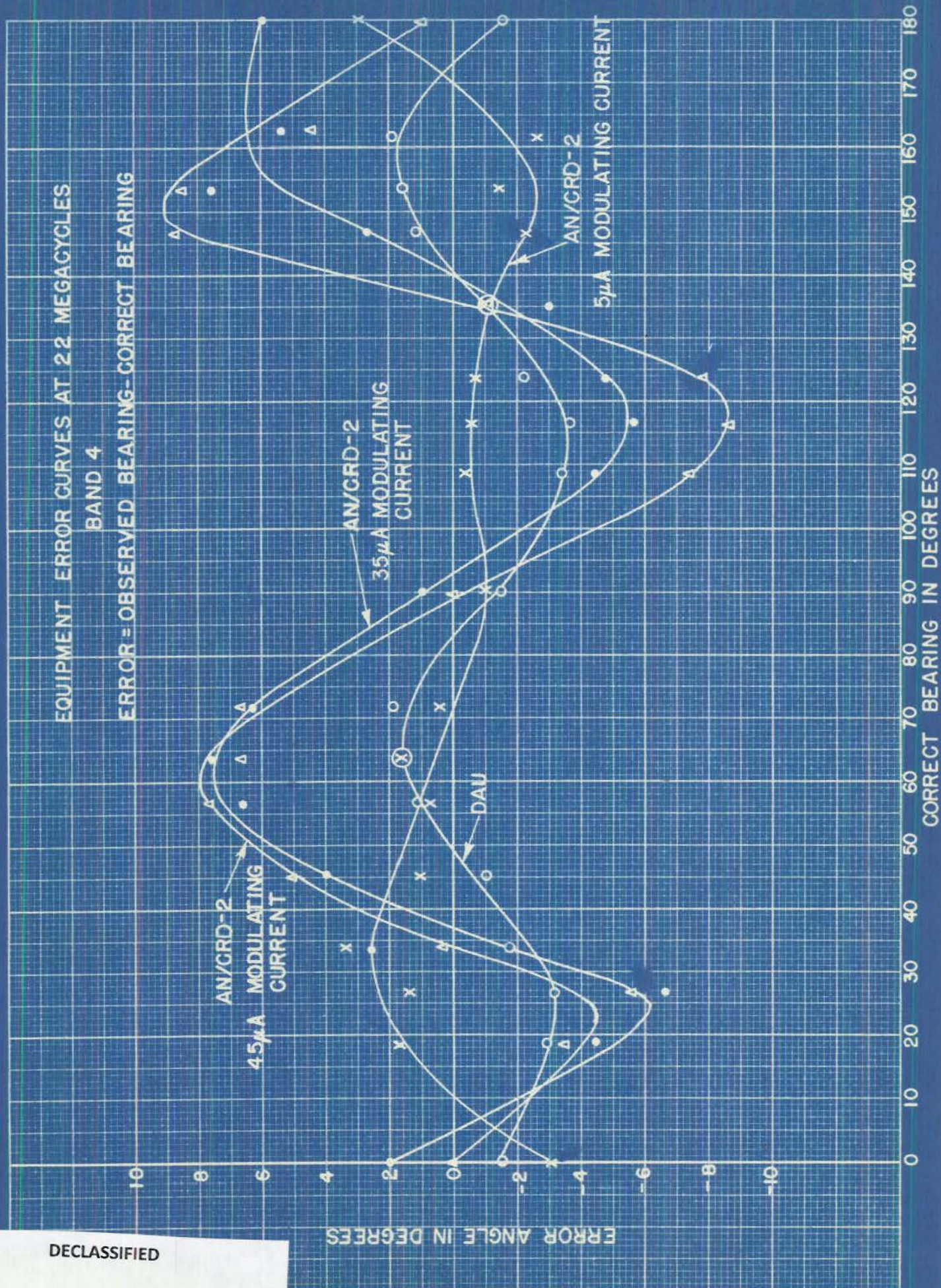
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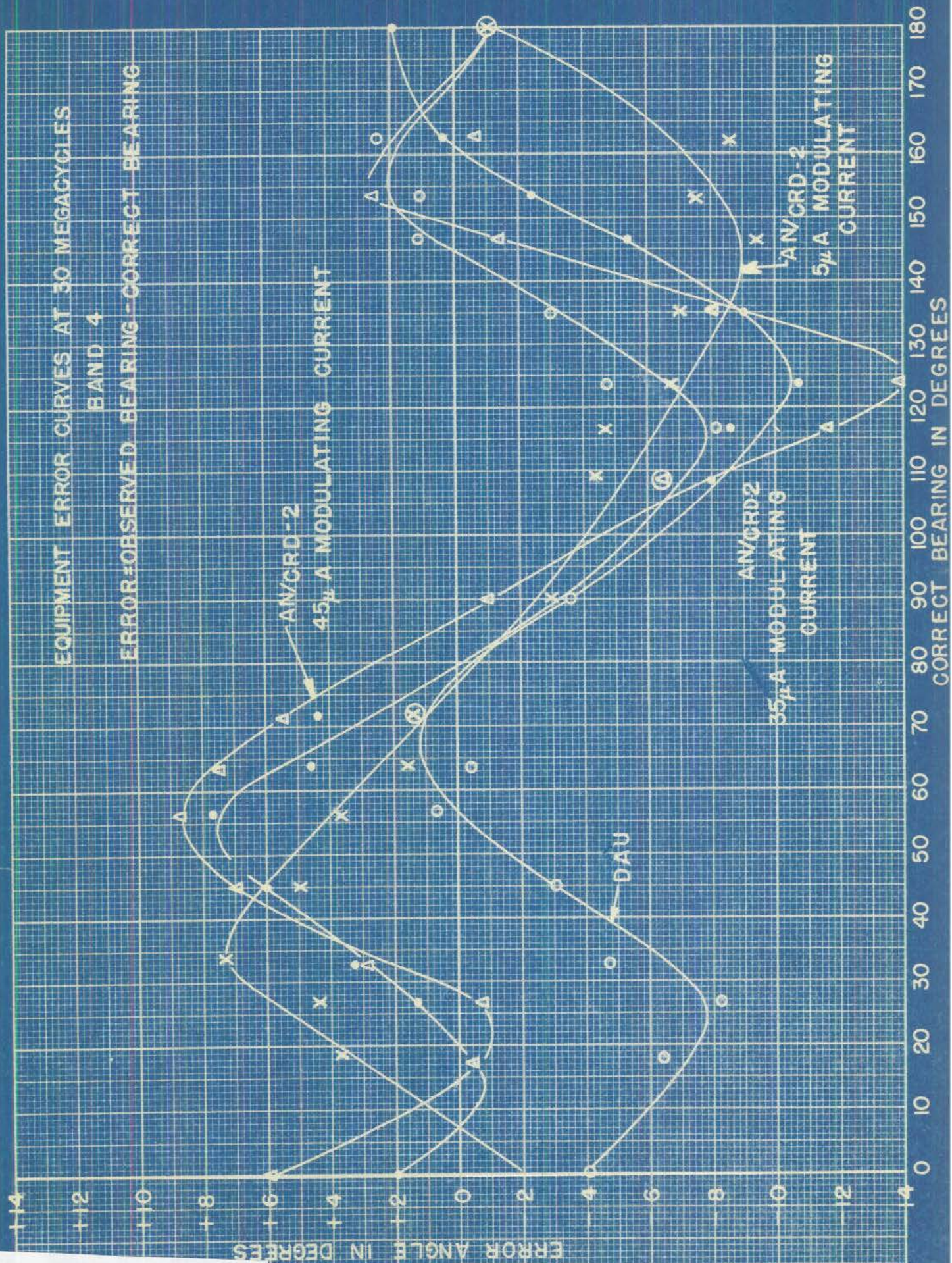
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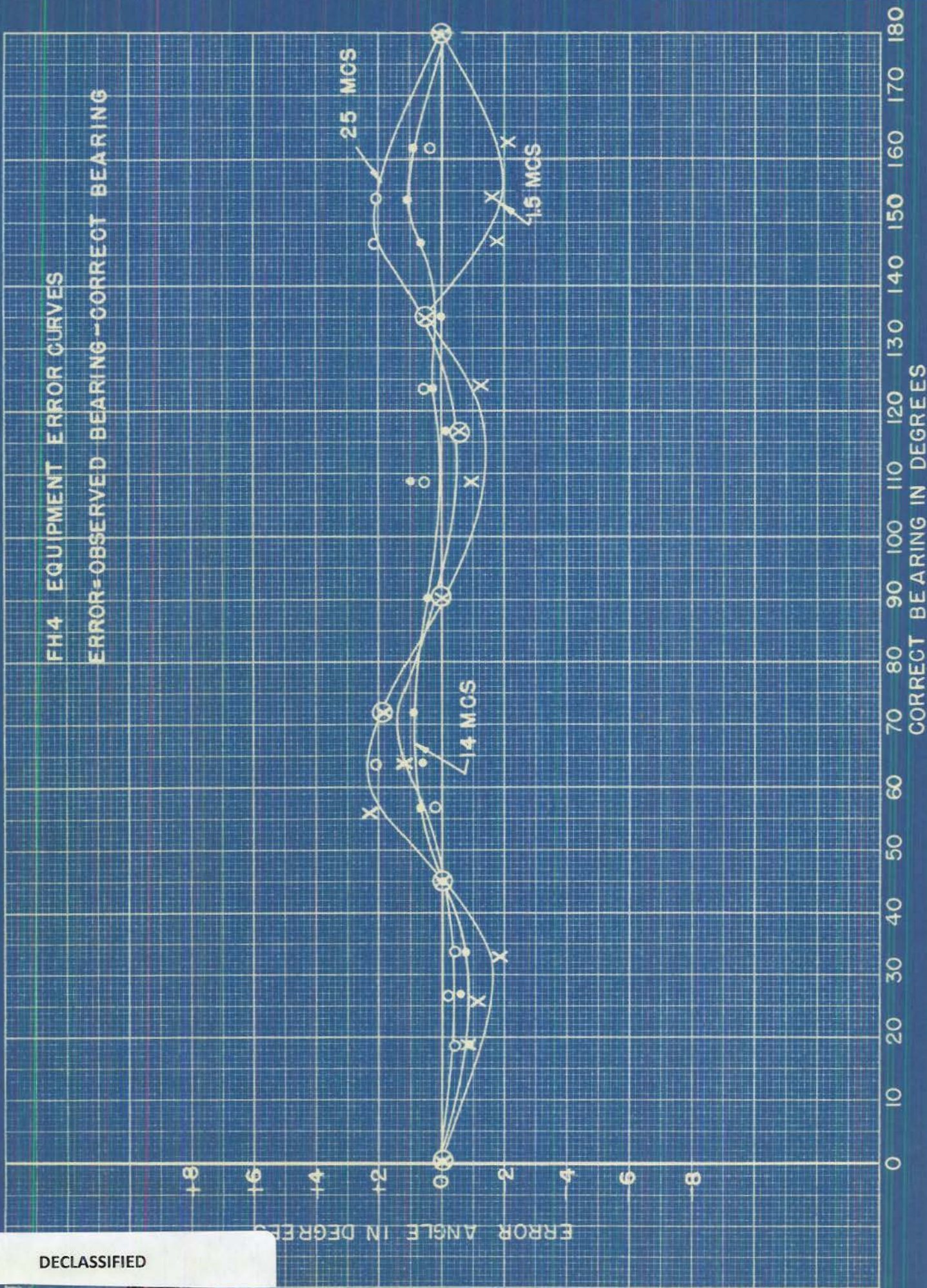


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FH4 EQUIPMENT ERROR CURVES

ERROR-OBSERVED BEARING-CORRECT BEARING

ERROR ANGLE IN DEGREES



SENSITIVITY IN MICROVOLTS

AN/CRD-2
SENSITIVITY VARIATION WITH MODULATION
VOLTAGE

80

70

60

50

40

30

20

10

0

14 MCS (BAND 4)

3.5 MCS (BAND 2)

7 MCS (BAND 3)

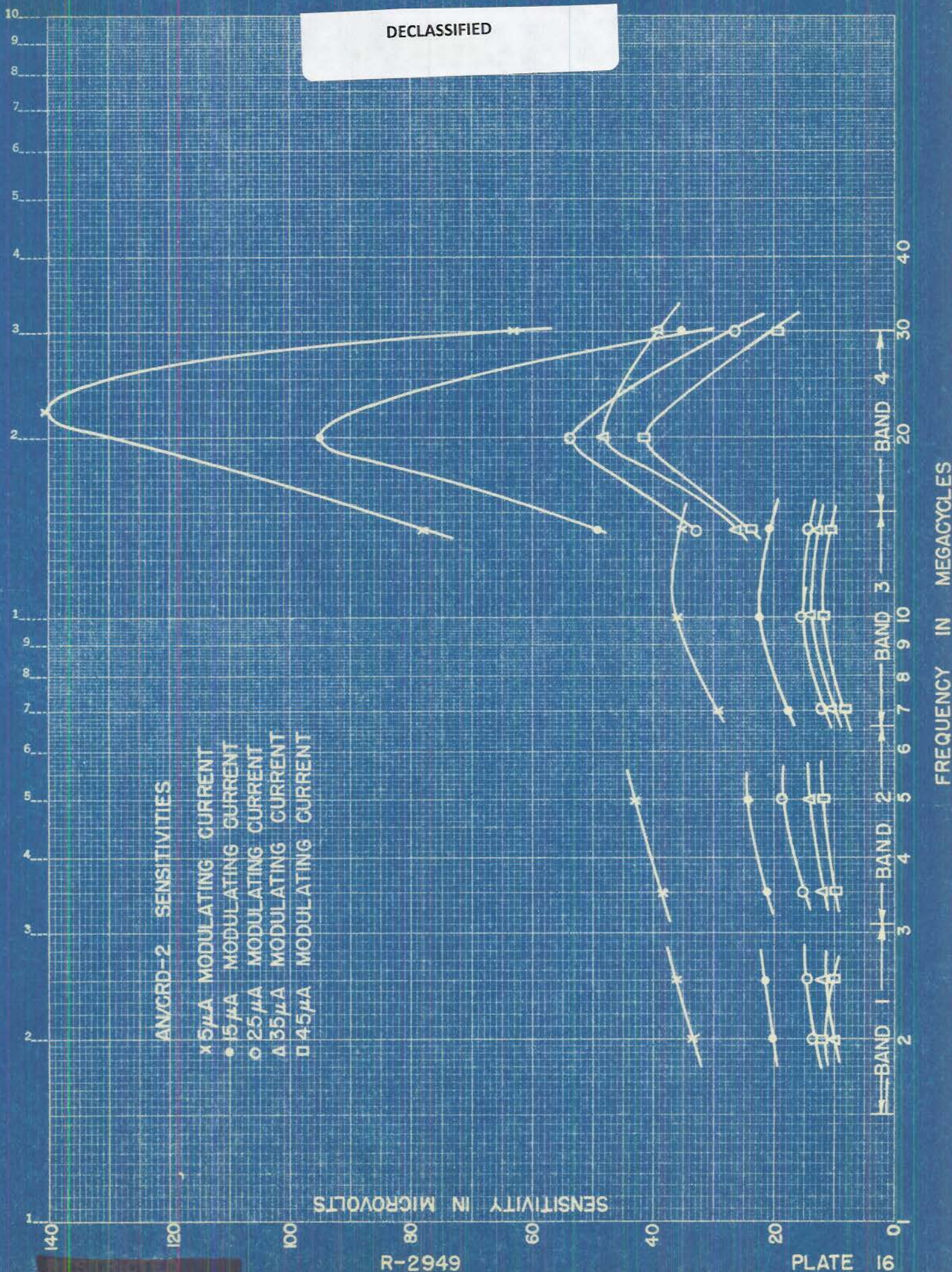
2 MCS (BAND 1)

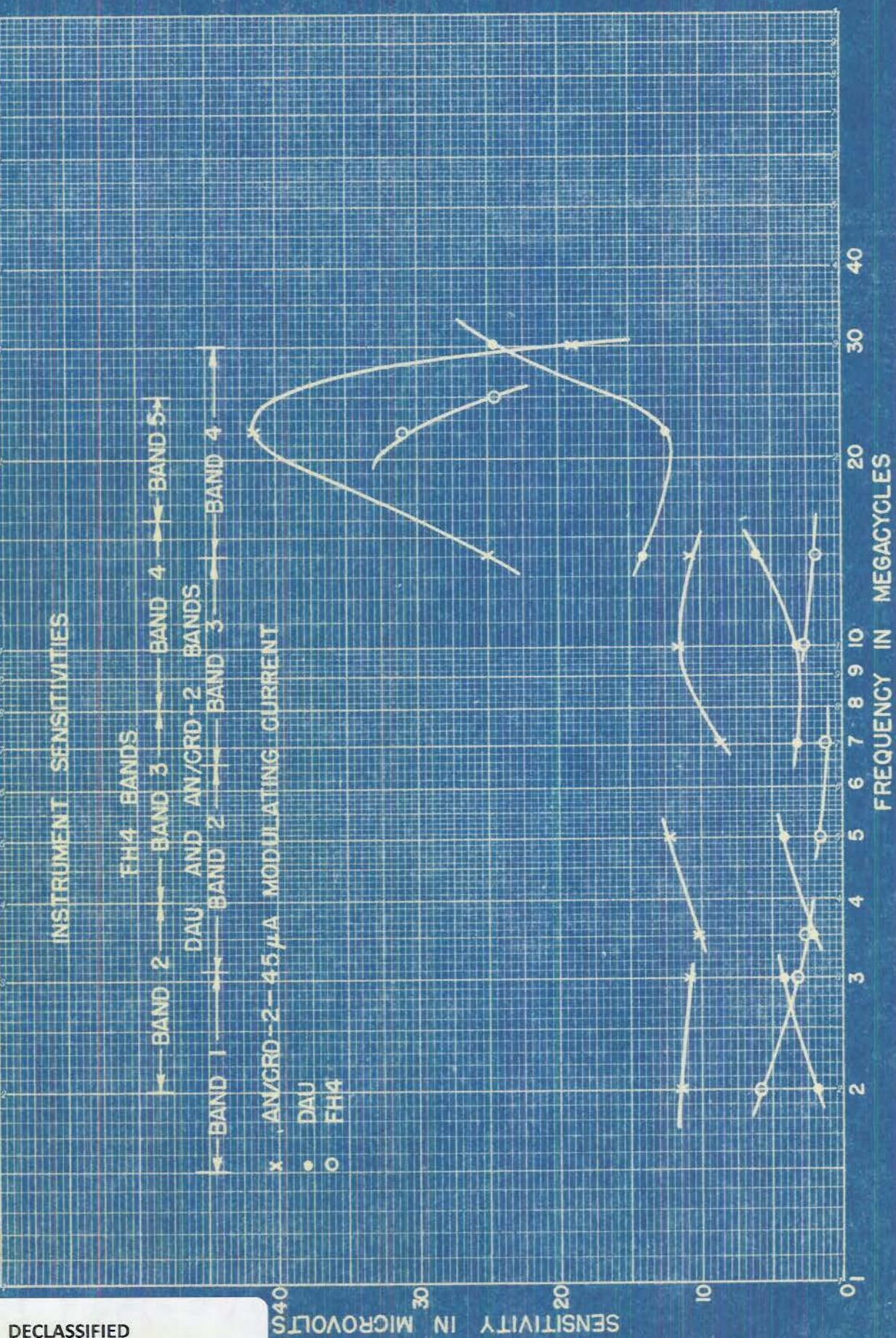
INDICATED MODULATING VOLTAGE IN MICROAMPERES

DECLASSIFIED

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KUPFER & KESSEL CO., N. Y. NO. 355-95
Sens. 1.0 per inch, 2 Cycles, X 1/2 to the inch,
MADE IN U. S. A.

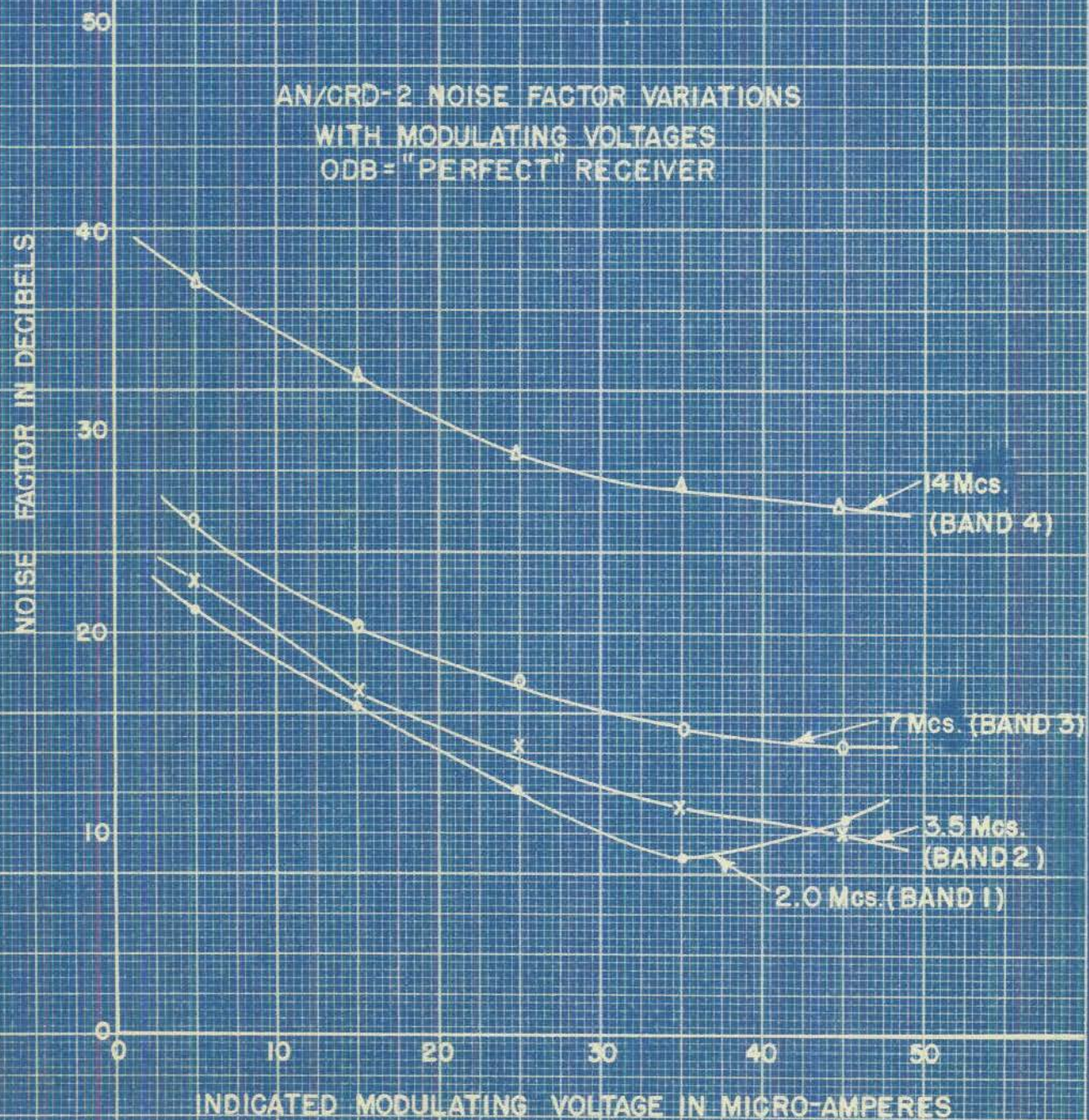




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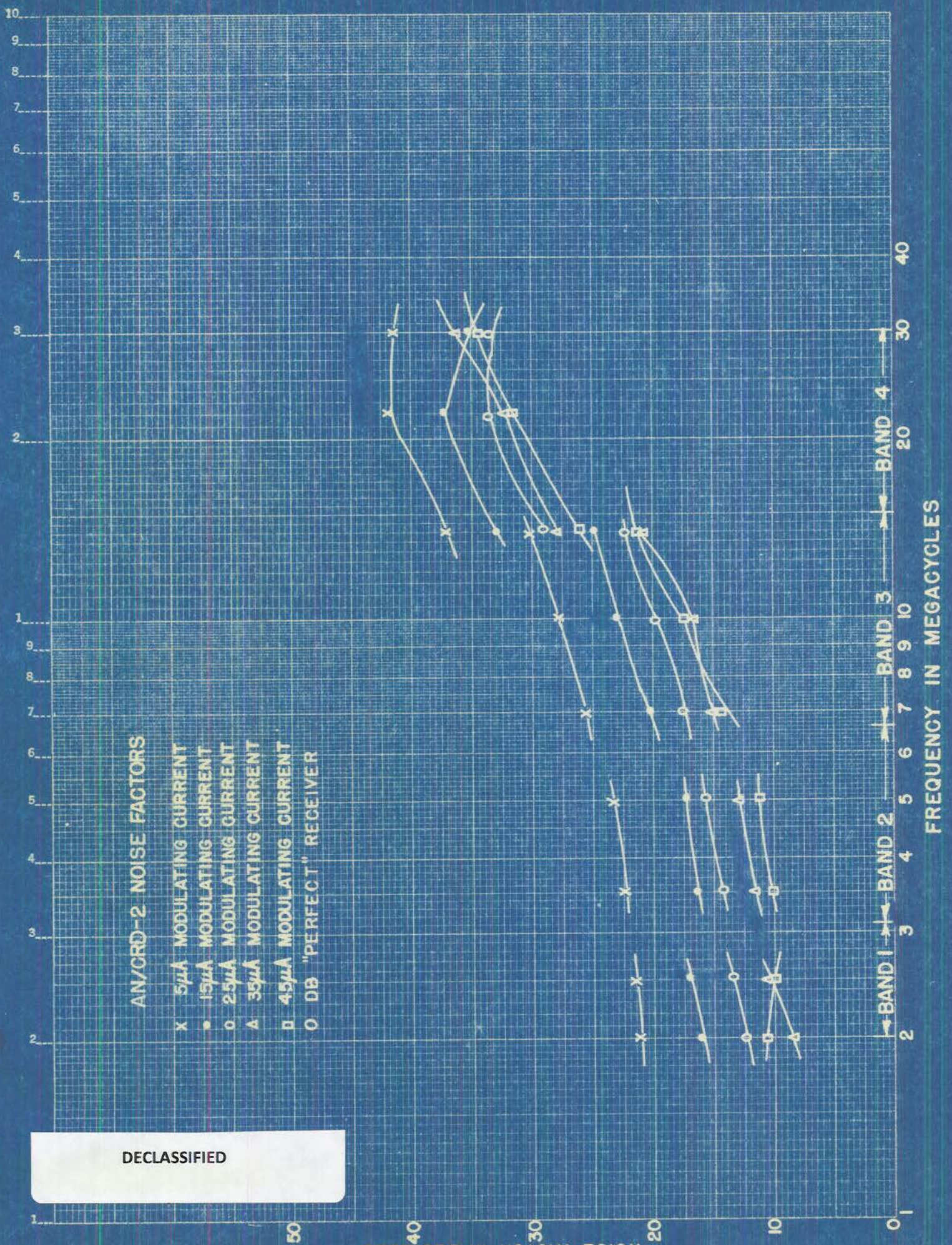
R-2949

PLATE 17

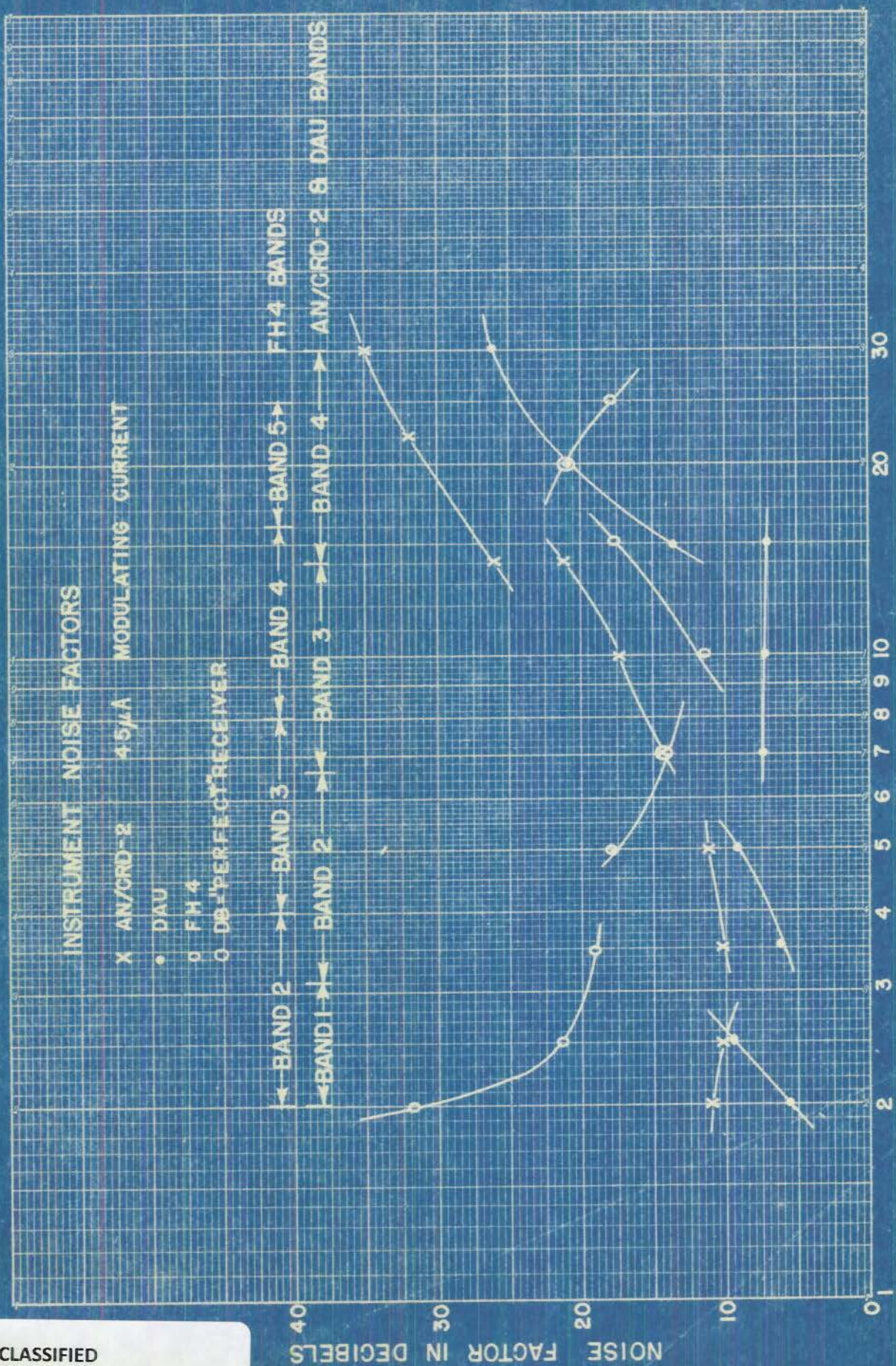


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SECTION OF BLANK TEST GRAPH

BEARING ERROR

DEGREES OF
BEARING SPLIT
SYMMETRICAL
ASYMMETRICAL

FREQUENCY
DEVIATION FROM 15 MCS
IN KILOCYCLES
REFERENCE 5.5

TEMPERATURE
DEGREES CENTIGRADE

HUMIDITY
PERCENT OF RELATIVE

UPPER RIGHT INDICATOR
LIGHT OUT

FRAME NUMBER - 1 FRAME EXPOSED EVERY 10 MINUTES

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H-2949

PLATE No. 21

SECTION OF BALANCE TEST GRAPH No. 2



R-2949

PLATE No. 22

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IND. U.S.A.

ES

PLATE VOLTAGE

450
400
350
300
250
200
150
100
50

100

90

80

70

60

50

40

30

20

10

0

SECTION OF MODULATOR TEST GRAPH

N

1

Noon

11

IND. U.S.A.

WCH

MODULATOR OUTPUT
DEGREE OF UNBALANCE IN MILLIAMPERES

100
90
80
70
60
50
40
30
20
10
0

100

90

80

70

60

50

40

30

20

10

0

N

1

Noon

11

IND. U.S.A.

WCH

FILAMENT VOLTAGE

10
9
8
7
6
5
4

100

90

80

70

60

50

40

30

20

10

0

99

DURATION OF TEST IN HOURS

98

97

N

1

Noon

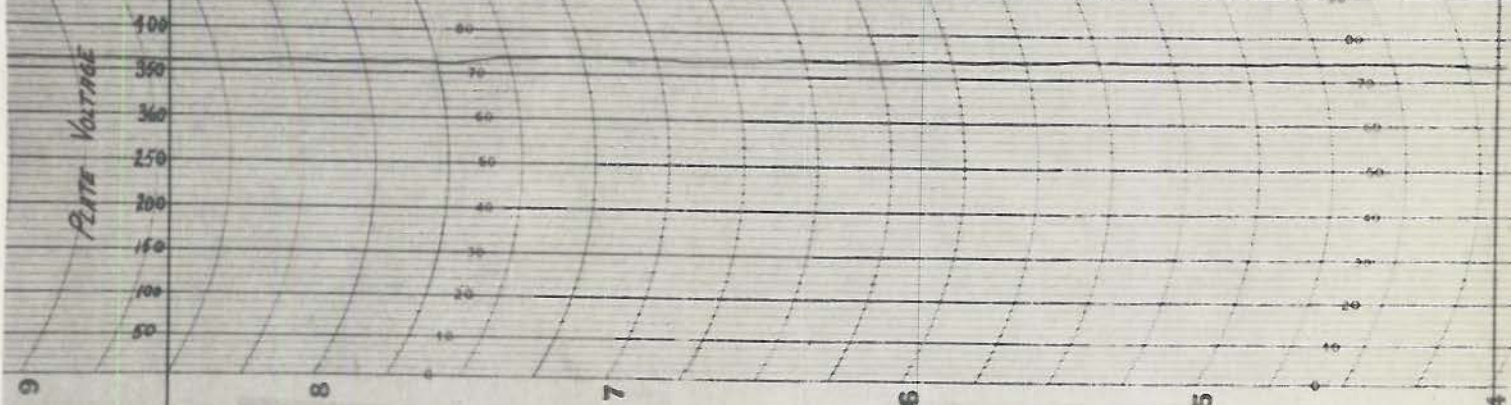
PLATE No. 23

R-2949

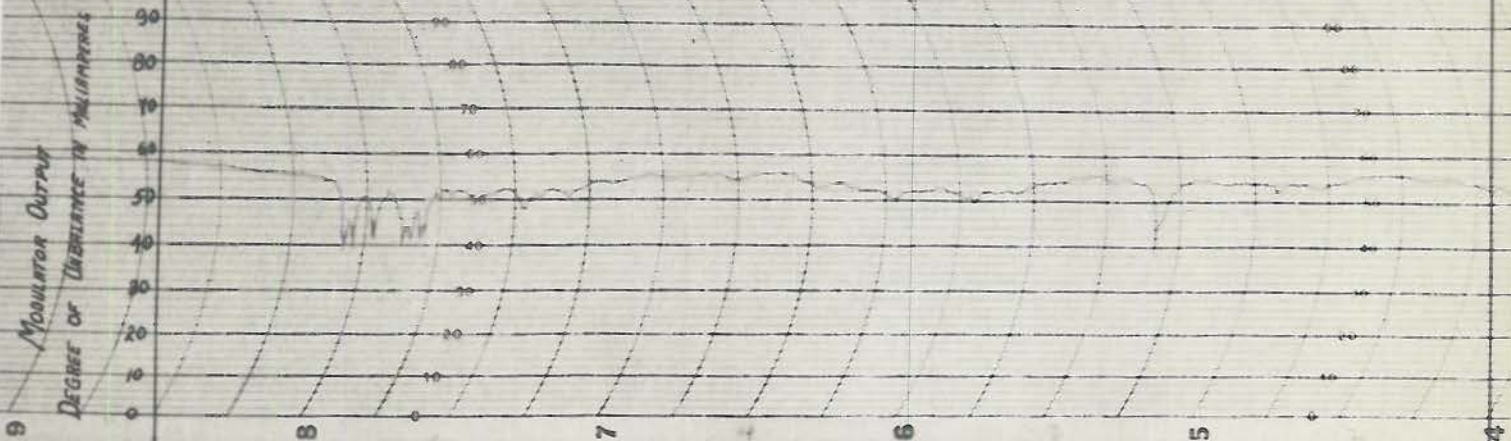
DECLASSIFIED

MAPOLIS, IND., U.S.A. CHART NO. 4313-C

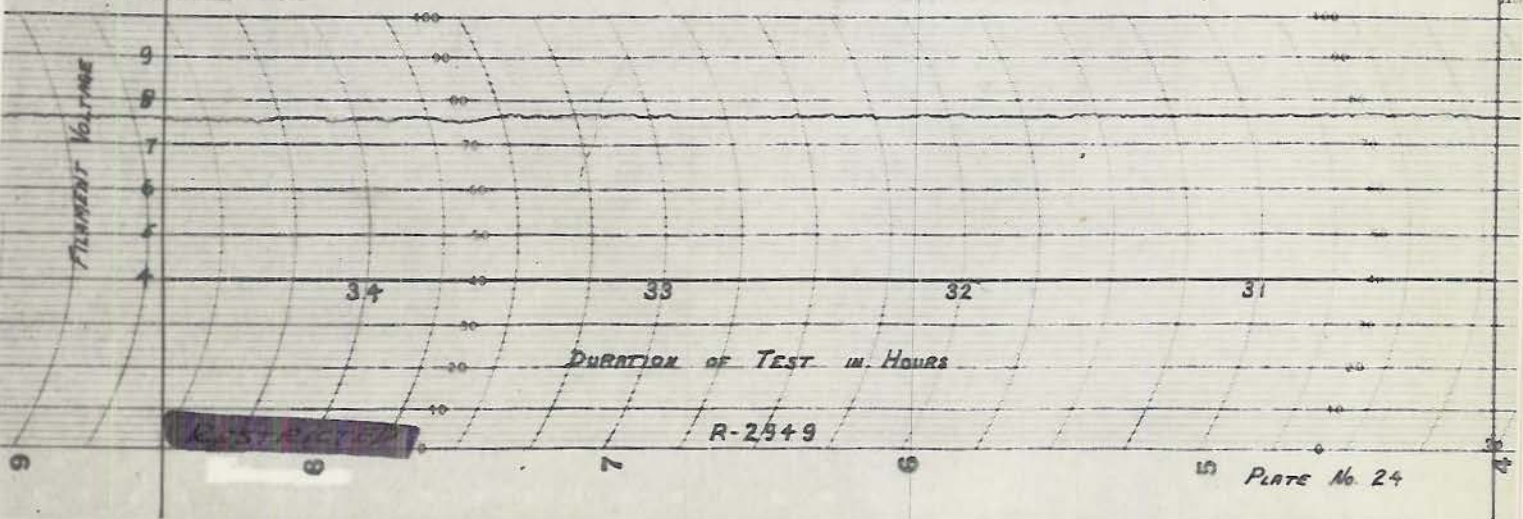
SECTION OF MODULATOR TEST GRAPH No. 2



MAPOLIS, IND., U.S.A. CHART NO. 4313-C



MAPOLIS, IND., U.S.A. CHART NO. 4313-C



DECLASSIFIED

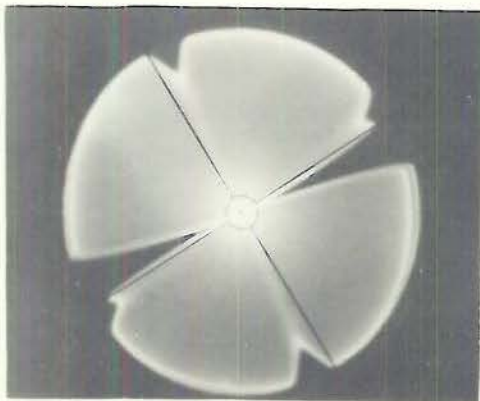


FIG. NO. 1 AN/CRD-2

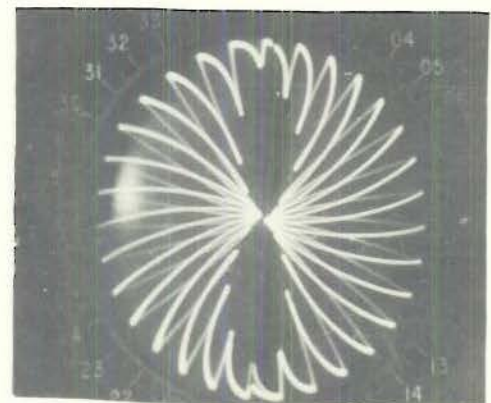


FIG. NO. 2 DAU



FIG. NO. 3 FH4

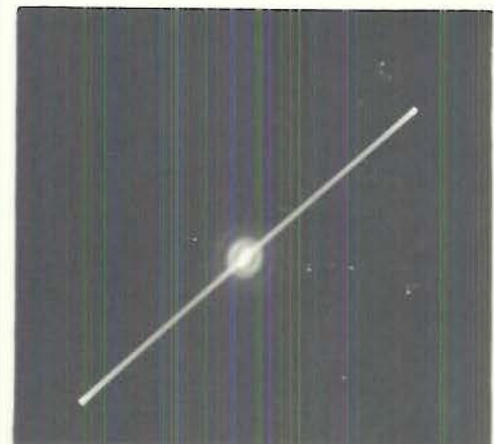


FIG. 4 XDL

BEARING PRESENTATION AT A PULSE RATE OF 600 CPS

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RESTRICTED

R-2949

PLATE 25

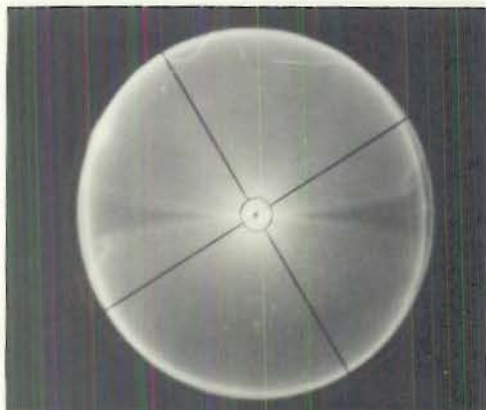


FIG. NO. 1 AN/CRD-2
PRESENTATION AT 60CPS



FIG. NO. 2 DAU
PRESENTATION AT 60CPS



FIG. NO. 3 AN/CRD-2
PRESENTATION AT 6000CPS

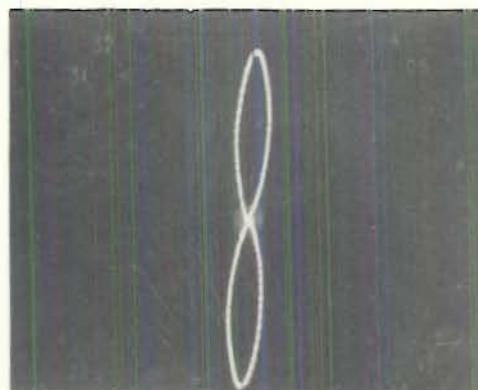


FIG. NO. 4 DAU
PRESENTATION AT 6000CPS

BEARING PRESENTATION AT PULSE RATES
OF 60 AND 6000 CPS

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PLATE 26

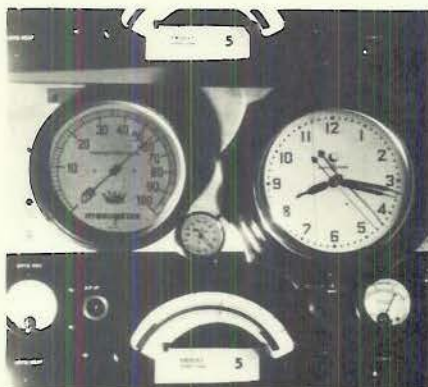


FIG. NO. 1 BALANCE TEST
METERS



FIG. NO. 2 CW BEARING
PRESENTATION

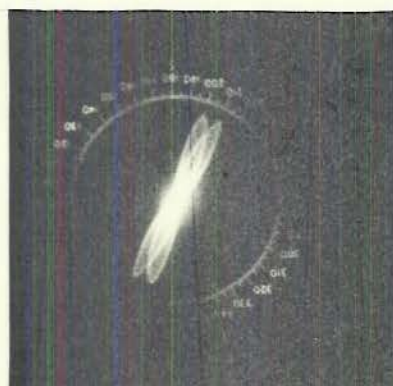


FIG. NO. 3 SPLIT BEARING
PRESENTATION



FIG. NO. 4 BEARING PRESENTATION
WITH BEARING ERROR

PICTURES FROM STABILITY TEST FILM

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PLATE 27



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