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THE U. S. NAVAL SHIP MODEL MAGNETIC FACILITY

By
Milton H. Lackey

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# THE U. S. NAVAL SHIP MODEL MAGNETIC FACILITY

Prepared by:
Milton H. Lackey

ABSTRACT: This paper contains a brief, illustrated description of the Magnetic Model Facility at the U. S. Naval Ordnance Laboratory. The primary emphasis is on the use of the Facility in conducting magnetic ship model studies. First, a synopsis is given of techniques for designing magnetic ship models and of problems associated with scaling magnetic characteristics of ferrous items. Next, a description is given of the Facility including: the coil system, the model range, the digital recording system, and other major items of equipment. Finally, a discussion is included on techniques of automated data acquisition and data analysis.

U.S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

2 December 1970

The U. S. Naval Ship Model Magnetic Facility

An earlier version of this paper was presented before the Fifth NATO Degaussing Symposium in London, England, on 22 September 1970. This version is scheduled to be included in Volume II of the Proceedings of the Fourteenth Technical Conference on the Naval Minefield. Much of the research and development work related to the Navy's degaussing program is supported by magnetic model studies conducted in the coil facility described in this paper. Target signatures are also obtained for use in weapons development and evaluation. Recently, several major improvements have been incorporated into the facility instrumentation to automate the model testing and to increase the accuracy of the measurements. The test data is now recorded in a form which allows computer processing techniques to be used for the data analysis.

The programs for the numerical extrapolation were developed by Mr. R. H. Ryswick. Also, Mr. W. H. Wertman devised programs to plot the data as three-dimensional projections.

GEORGE G. BALL
Captain, USN
Commander

James M. Martin

JAMES M. MARTIN
By direction

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# THE U. S. NAVAL SHIP MODEL MAGNETIC FACILITY

## INTRODUCTION

The Magnetic Model Facility at the U. S. Naval Ordnance Laboratory is an automated degaussing range which supports the Navy's degaussing program. Magnetic ship models are designed, constructed and tested in the Facility. Tests are also conducted on ordnance devices to determine certain magnetic characteristics. The capabilities of the Facility are closely related to those of a field degaussing range with several special features including:

a. Control of the background magnetic field

b. An automatic deperming system

c. Variable range depth and sensor spacing

d. An automatic digital recording system

e. Variable transit time

f. Capability of measuring longitudinal, athwartship, or vertical magnetization independent of each other

g. Capability of measuring any component of the magnetic signature of a model.

Model studies are used in the design and evaluation of degaussing coil systems and in the development and evaluation of range instrumentation and procedures for degaussing and deperming the Navy's fleet of ships. Ship models are also used in tests to define target signatures for use in the development and evaluation of weapon systems. These studies support a variety of tasks ranging from test and evaluation projects to long-range research and development projects.

Ship model tests are conducted inside a 30 x 30 x 37-foot coil system which controls the background magnetic field. The coil system consists of three orthogonal sets of coils capable of generating magnetic fields to simulate the geomagnetic conditions for any location and ship heading. The amount of permanent magnetization in the model can also be varied for any simulated location and heading. The magnetic measurements for each model test are recorded automatically in analog and digital form. The digital recordings are made on punched cards which are processed and analyzed by computer.

MAGNETIC MODELLING

INTRODUCTION. Procedures for constructing magnetic models vary widely depending on the required complexity of the model. The complexity is determined by the type of tests to be conducted, the accuracy required for the tests, and the amount of details available on the full-scale ship specifications. Preliminary factors to be resolved prior to constructing the model are the scale factor, the type of ferrous material to be used, and the total number of ferrous items to be reproduced. The latter determines the model detail and is related to the scale factor.

SCALE FACTOR. The range of realistic scale factors can be bracketed by considering the shallowest depths of the proposed measurements and the size of the full-scale vessel. A model must be sufficiently large to permit measurements at "shallow" depths, and small enough for easy handling in the model range. The models are generally made as large as practical. Models have been made with scale factors ranging from 1:24 to about 1:144. These models range from 3 to 12 feet long.

MODEL MATERIAL. One of the biggest problems in the construction of magnetic models is that of duplicating the magnetic characteristics of the ships. It is generally not practical to obtain sheet steel for model construction which has the proper permeability and thickness. Therefore, a characteristic called the "permeability thickness product" is used to model items which are constructed of steel plates. It is possible to use sheets of steel to represent the scaled "permeability thickness" of the particular ship steel. The magnetic characteristics of the full-scale item and the modelled item are then similar if the "permeability thickness" is scaled. For the few items requiring short bars or rods of steel, the correct permeability must be used and the dimensions are directly scaled.

MODEL DETAIL. The detail of the structural framing and of the items to be included on a model are largely determined by the scale factor. If the model is too small to allow the reproduction of each frame, then they are "smeared" together so that although fewer frames are constructed, the total amount of material in all the frames is constant. This technique is also used with items such as electronic equipment, storage lockers, washers, dryers, etc., which contain small ferrous parts distributed about the interior of steel plate boxes. In these cases the amount of material inside the item is approximated by making steel plate boxes of the proper size but with an exaggerated thickness to account for the internal ferrous parts. There are also cases where items are too small to be significant after scaling. These include small fan motors, small appliances, etc. These items are generally not included in the model, although as much detail as practical is included.

Even with the greatest of care and precision, it is still very difficult to construct models which exactly duplicate the magnetic characteristics of a particular ship. Problems generally are associated with incomplete ship specifications and permeability dissimilarities. It is also difficult to exactly duplicate degaussing coils. Model degaussing coils generally have larger diameters then the scaled diameters of the ship coils. The large diameters make the model coils harder to position accurately.

The problem of being unable to exactly duplicate the magnetic characteristics of ships is not restricted to models. There are dissimilarities between the ships of a particular class even with the same specifications. A study was made when models were first being constructed which compared model versus ship signatures. The conclusion of the study was that the model for any class of ships represents that ship class as closely as any particular ship represents the class.

## FACILITY DESCRIPTION

INTRODUCTION. The three major components of the Facility are the coil system, the model range, and the digital recording system. Figure 1 contains a cutaway sketch of the Facility showing the layout of these systems. The wooden forms containing the building coils are shown along the walls. The center of the system is in the plane of the horizontal coil shown just above the top of the doors. The model range is at the bottom of the vertical beams. The model carriage travels along the horizontal beams over the array of magnetic sensors (on a beam at the left center of the figure). The instrumentation and control equipment is housed in the circular console on the right side of the figure. The magnetizing and demagnetizing coils are also shown in the center of this figure along the horizontal beams.

### PRIMARY EQUIPMENT.

Coil System. The coil system contains three mutually perpendicular sets of coils as shown in Figure 2. The coils are labeled x, y, and z, respectively, for coils with magnetic axes aligned along north-south, east-west, and vertical lines. The coil dimensions are approximately 37, 30, and 30 feet, respectively, for the x, y, and z directions. The system has the capability of generating uniform magnetic fields to simulate the geomagnetic conditions for any cruising location. As the figure shows, each set of coils contains a number of equally spaced segments. These segments are connected in series for each set of coils. Notice that the number of turns in each segment varies. These values were selected to give a condition of maximum uniformity for the generated magnetic field. The region of uniformity is defined as an area about 12 x 3 x 3 feet in which the field magnitude varies less than ±0.07 percent. The coil system is capable of generating fields with magnitudes from 0 to 0.6 oersteds in any direction. Special equipment has been added which stabilizes the magnetic field inside the coil system. Fields can be held constant to about $10^{-5}$ oersteds.

Model Range. The model range consists of the model carriage, the track for the carriage, and an athwartship array of magnetic sensors. Cruising conditions are simulated by moving the model down the range in a background magnetic field representing the cruising latitude and heading for the tests. Figure 3 shows a top view of the relationship between the model and the array of sensors. Notice how each sensor is shifted longitudinally relative to the adjacent sensors. This slight shift compensates for the motion of the model while the sensor array is being scanned. Also notice the slotted bar. This bar and the sensor array remain fixed while the model is moving down the range. A photo diode is attached to the model carriage to sense the model position relative to the slotted bar (and therefore, relative to the sensor array). At each slot the photo diode triggers the digital recording system which takes a reading of one of the sensors. This process is repeated as the model and carriage move continuously down the range. The effect is a repeated scanning of the sensor array. The scan sequence is from port to starboard. Generally, about 61 scans are made for each model transit or "run." Figure 4 shows the recording positions for a 9 x 17 point data matrix. The scan spacing is fixed so that one scan is made for every four inches of model travel. This amounts to about 15 or 20 scans per model length since the models generally average around six or seven feet in length.

Digital Recording System. The digital recording system consists primarily of a scanner, a digital voltmeter, and a card punch as shown in Figure 5. The system is triggered through the scanner by the photo diode on the model carriage. Each pulse from the photo diode advances the scanner to the next magnetometer, and causes the digital voltmeter to take an average reading of the magnetometer output over a tenth of a second time period. This reading is then fed to the card punch which records the digital value. The system now operates at about one reading per second, or one scan in about ten seconds. Current plans include the addition of a high-speed, paper-tape punch to the present system to increase both versatility and recording speed.

AUXILLARY EQUIPMENT

Power System for the Coil System. The coil system is powered by transistorized power supplies as shown in Figure 6. The power supplies are programmed to maintain constant output currents to the coils. The output currents are fed through standard resistors which are connected in series with the supplies and with the field coils. The resistors are maintained at a constant temperature in an oil bath. The stability of the currents is provided by the programming unit which causes the power supplies to maintain a constant voltage across the standard resistors. The programming unit is designed to read directly in oersteds with increments of $10^{-5}$ oersteds. Associated with each circuit is an on-off relay and a reversing relay which controls the polarity of the field.

Magnetizing and Demagnetizing System. The magnetizing and demagnetizing system provides a means of either removing the permanent magnetism from a model or of magnetizing the model to simulate prolonged cruises at specific locations and headings. Figure 7 shows a block diagram of the system and the shape of the idealizing field applied to the model. The system can generate either an ac sine wave field or a dc pulse field. The ac field has a frequency of 60 Hz and an amplitude which cycles from zero to 50 oersteds and back to zero over a period of about one minute. The pulsed field has a period of about five seconds. The amplitude of the pulses slowly decreases from a maximum value (up to 50 oersted) to zero in about 15 or 20 minutes. The magnetizing and demagnetizing coil has a magnetic axis along the longitudinal axis of the model as shown in the sketch of the Facility, Figure 1.

Degaussing Current Distribution System. The degaussing current distribution system provides up to 40 degaussing currents to the model coils even while the model is in motion. Figure 8 shows a block diagram of this system. Current controls are available to provide individual adjustments of the coil currents. The currents are read directly in milliamperes on the digital voltmeter. The system contains a matrix plug board which allows a variety of interconnections between degaussing coils and current controls.

Feedback Stabilization System. The feedback stabilization system is one of the latest additions to the Facility. In recent years model studies have required more accuracy in the data to allow more sophisticated analysis techniques to be applied. This has given rise to the problem of obtaining a better signal-to-noise ratio for the measurements. The problem is not only one of designing more sensitive magnetometers but also one of reducing the background noise level. The latter is turning out to be the most difficult to accomplish. Although a steady battle has been fought to keep the immediate area of the Facility free from magnetic noise sources, the background noise level has continued to increase. This probably results from the general increase in activity in the one-square-mile area centered on the Facility. Background recordings are now being made to try to correlate the noise with known events, and therefore to identify noise sources.

A feedback stabilization system was designed to reduce as much of the background noise as possible by feeding back equal and opposite "noise" into the coil system. This works very well for fluctuations below about 2Hz, including drift in the earth's magnetic field and slight variations in the currents in the coil system. The system can reduce the drift of the field to below $10^{-5}$ oersteds for two or three hours. The principle of operation is illustrated in Figure 9. Any changes in the background field or in the coil current are measured by the feedback sensor. These changes are then fed through the feedback magnetometer and amplifier into a separate field coil. Notice that the sensor is positioned off to the side of the coil system and inside a small coil. This position is remote enough from the model range so that the sensor will not receive any appreciable fluctuations from the model. The small coil around the sensor provides a slight opposing field (or aiding field if required) so that the overall coil constant (magnetic field per unit of current) at the sensor location is the same as the coil constant in the center of the model range. Figure 10 illustrates the remote monitor unit which contains both the feedback sensor and the small coils. The coil positions relative to the sensor are adjusted to obtain the desired coil constant. Figure 11 shows typical response curves of the system for the north-south direction to pulses of 10 mOe, 1 mOe, and 0.1 mOe. Figure 12 shows the stability of the system over a five-hour period compared with the ambient field external to the coil system. The variation in the stabilized field is not noticeable when plotted on the scale.

## DATA ACQUISITION

Figure 13 shows a side view of the model range and includes an identification of parameters associated with the range. The main ones are the extent of model travel, the depth of the sensor array, and the spacing of the individual sensors. The longitudinal position of the sensor array can also be adjusted to vary the relationship between the model travel and the sensor array, but the sensor array is usually centered for most tests. Each of the parameters is adjusted prior to beginning the magnetic testing. The next step is to set the proper background magnetic field and magnetically idealize the model with the magnetizing and demagnetizing system. The instrumentation is then calibrated, and recordings are made on the digital recording system. The magnetometers associated with the sensor array are the flux-gate type with an accuracy of $\pm 1$ percent or $\pm 10^{-5}$ oersted, whichever is greater. They are calibrated prior to each series of measurements by generating a known change in the background field and adjusting each magnetometer output to directly read this change. This field change is generated by the feedback stabilization system and therefore causes no problem with automatic compensation.

## DATA ANALYSIS

DATA PROCESSING AND PLOTTING. Recording the data from the measurements in digital form allows a variety of computer analysis techniques to be used. The techniques range from simple conversion of the data units to complicated numerical analysis procedures. Computer programs have been developed to take care of the majority of the data processing problems including the generation of analog plots. Figure 14 shows an example of the type of graph which is generated directly by computer. These graphs are normally inserted directly into informal technical reports. The original data for this example was supplied to the computer as a 9 x 61 point data matrix along with other information such as the units conversion ratio, the ship length, the grid spacing for the data matrix, etc. The computer program converted the data units, centered the curves vertically and horizontally, filled in the curves between the data points, and plotted the data. Other formats can be used to display the data. One of the most spectacular forms is the three-dimensional projection shown in Figure 15. This method allows a qualitative inspection of the ships field to determine areas of significant magnetization. The viewing angle for three-dimensional projections can be varied as desired.

DATA SMOOTHING. Other methods of data processing and analysis are used. The next three figures show a technique of data smoothing which can be used to filter noise from the data. Figure 16 shows an example of noisy data prior to smoothing. This particular noise was associated with the two magnetometers at 30 and 40 feet starboard. Figure 17 shows the result of smoothing the data by converting it to a truncated Fourier series containing only low-order terms. Notice that the general shape of the curves is maintained after smoothing.

INTERPOLATION. Another numerical technique used in data analysis is that of interpolation. The technique is used to fill in the missing data points between those from the measurements, or to vary the grid size and location of the data matrix. Figure 18 shows an example of interpolation. The measured data points are marked and connected with straight line segments. Notice how the interpolation process connects the points with a fairly smooth curve and fills in the peaks.

DEGAUSSING. Computer techniques are also used to determine the degaussing currents and the degaussed signature for minesweepers. The techniques are based on measurements of the undegaussed magnetic state of the model and the individual coil effects. A least square technique is used with the assumption that the magnitude of the coil-effect data varies linearly with the coil current. Computer degaussing has proven to be faster and more accurate than manual degaussing. Figure 19 shows a comparison of a manually degaussed signature and a computer degaussed signature. In this particular example the maximum peak of the degaussed signature was reduced 50 percent when the computer was used to determine the degaussing coil currents. Figure 20 shows that the assumption of the linearity of the coil effects with respect to current generally holds for wooden hull ships. The figure shows the results of measurements of coil effects for two different currents, one of which was linearly scaled to the other current. Techniques are now being developed to estimate coil effects by computer. The coordinates and ampere turns of the coils, and the depth of the calculations are used in the computations. Figure 21 shows a comparison of the calculated coil effects with measured coil effects, and includes measurements with and without a large ferrous item inside the coil. The calculated effects coincide exactly with the measured effects without the core. These are therefore plotted as a single set of curves.

EXTRAPOLATION. The final analysis technique considered is that of numerical extrapolation. The Laboratory originally had a large analog computer which was used to extrapolate ship signatures from shallow to deeper depths. The computer actually had a grid of solenoids which was used to produce a scaled equivalent of the magnetic field of a ship. The extrapolation was then performed by measuring the resultant magnetic field at the scaled equivalent of the desired depth. This procedure was both expensive and time consuming. A numerical technique was developed to perform the extrapolation using a high-speed digital computer. The last two figures demonstrate this technique. Figure 22 shows an undegaussed signature of a longitudinally magnetized model at a shallow depth. This data was extrapolated to a deeper depth and compared with measurements at that depth. This is shown in Figure 23. In theory the accuracy of the numerical extrapolation process decreases with increasing horizontal distance from the center of the data, but this figure shows that the extrapolated data is still relatively accurate even at 40 feet port and 40 feet starboard.

## CONCLUDING REMARKS

The general comments included in this paper are really only a brief introduction to the equipment and techniques used by the Laboratory in conducting magnetic studies of ship models. Reports containing more details on specific areas are listed in the bibliography. There are many other aspects of magnetic model testing which have been left out because of the excessive details involved. The discussion on data analysis has probably suffered the most from the lack of details. It could easily take several reports to cover it adequately.

Methods to improve both data acquisition and data analysis are continuously being developed and evaluated. The instrumentation in the Facility is frequently modified and improved as electronic hardware become available. Much of the electronic design work is handled by Facility personnel since the equipment is so specialized.

Numerical analysis techniques are also being developed and applied by Facility personnel. Most of the data analysis is now performed with the use of high-speed computers. Computer services available to Facility personnel include time-sharing systems operated through teletype consoles and batch processing devices which use punched cards and magnetic tapes.

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19. NOLTN 8776 - Calibration Instructions for the Feedback Stabilization System of Building 206
20. NOLTR 68-48 - A CALCOMP Package for 3D Plotting

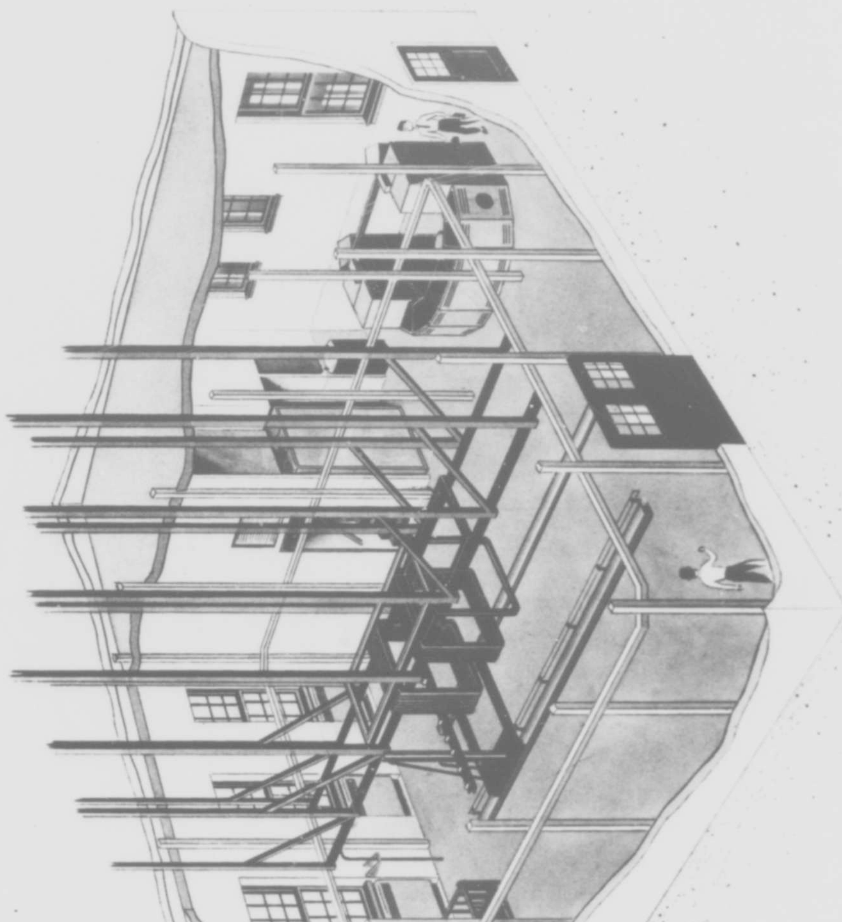

FIG. 1 SKETCH OF FACILITY

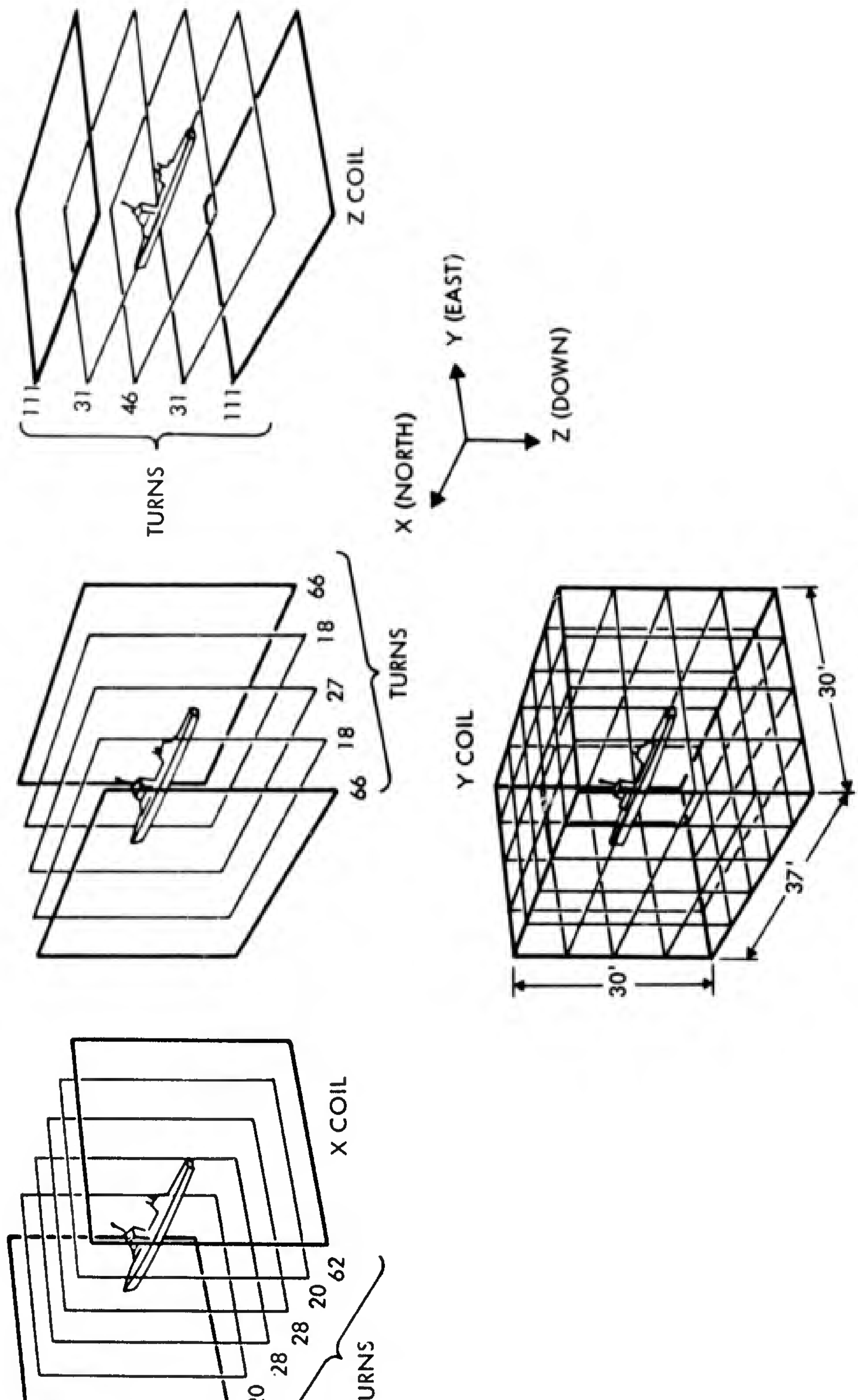


FIG. 2 DIAGRAM OF COIL SYSTEM

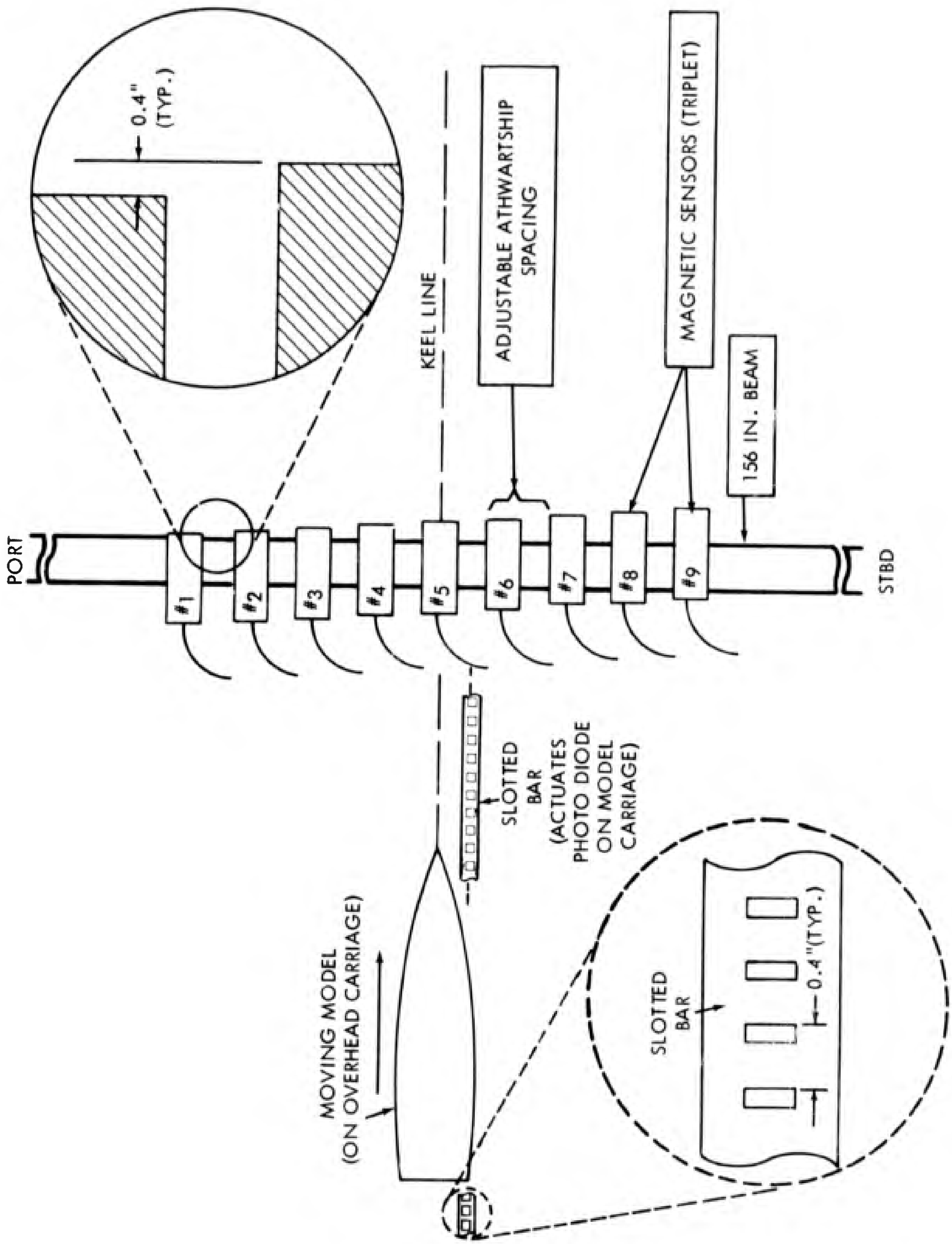


FIG. 3 TOP VIEW OF MODEL RANGE

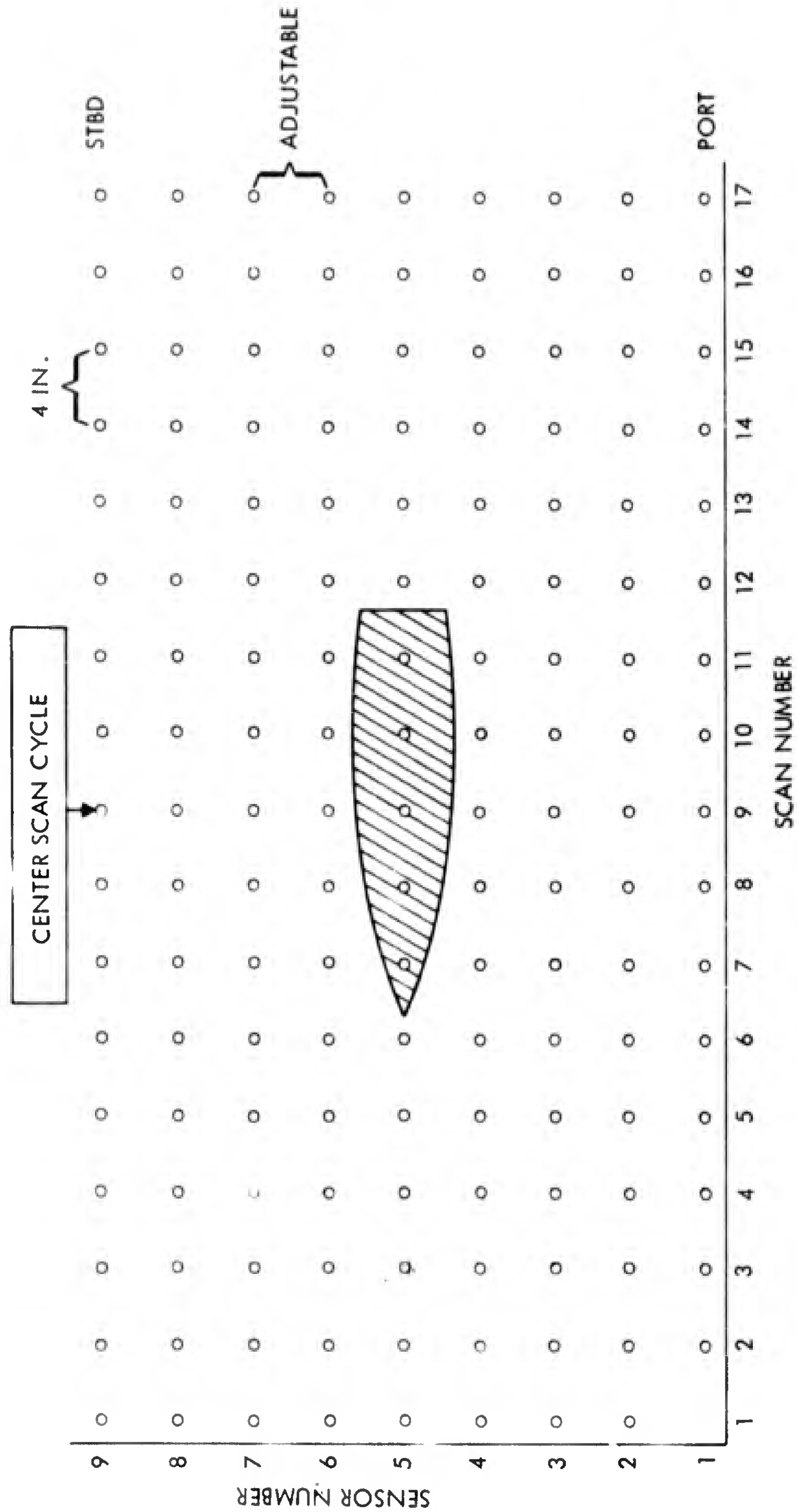


FIG. 4 TOP VIEW OF 9 x 17 POINT DATA MATRIX

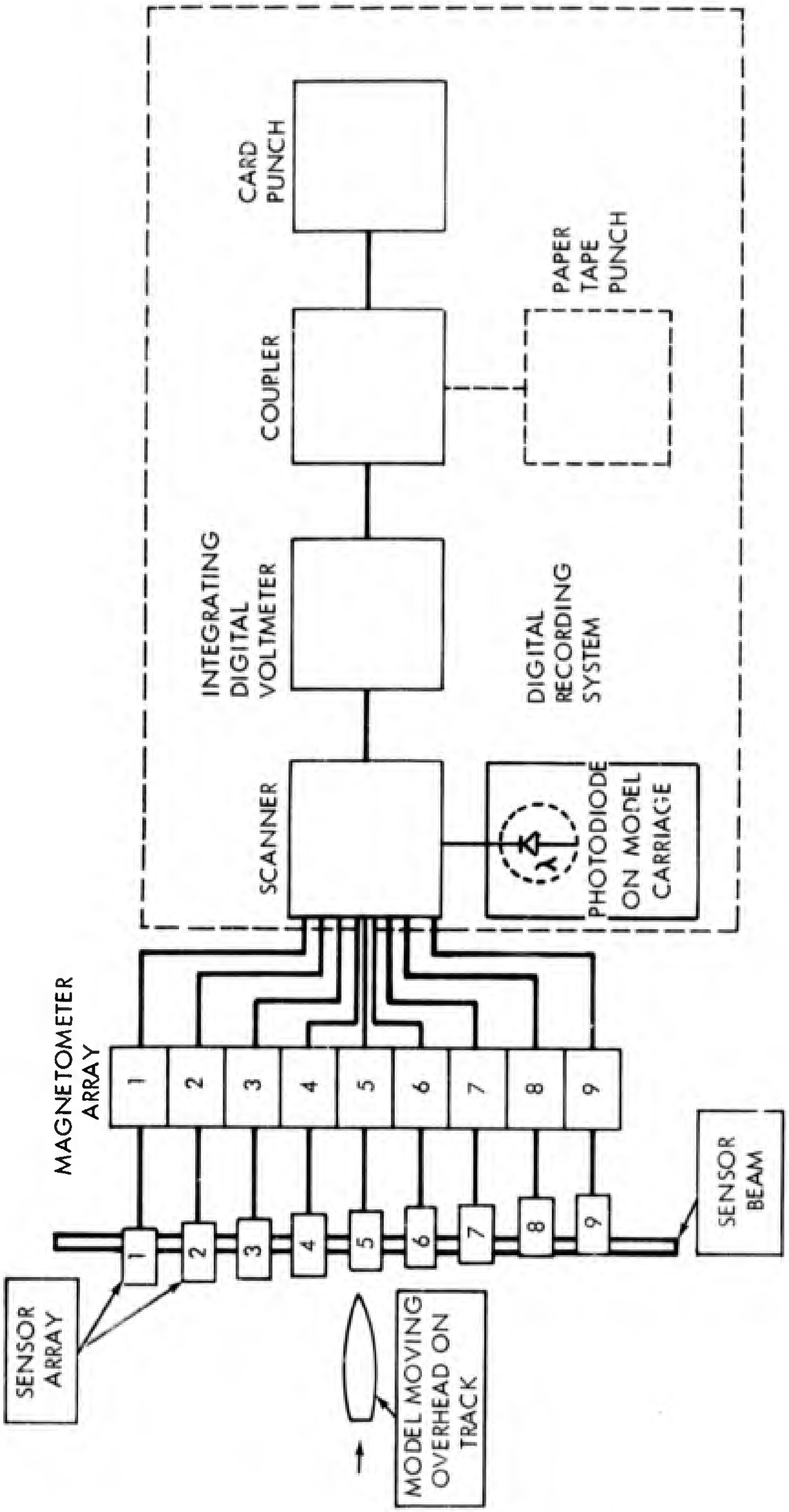


FIG. 5 BLOCK DIAGRAM OF DIGITAL RECORDING SYSTEM

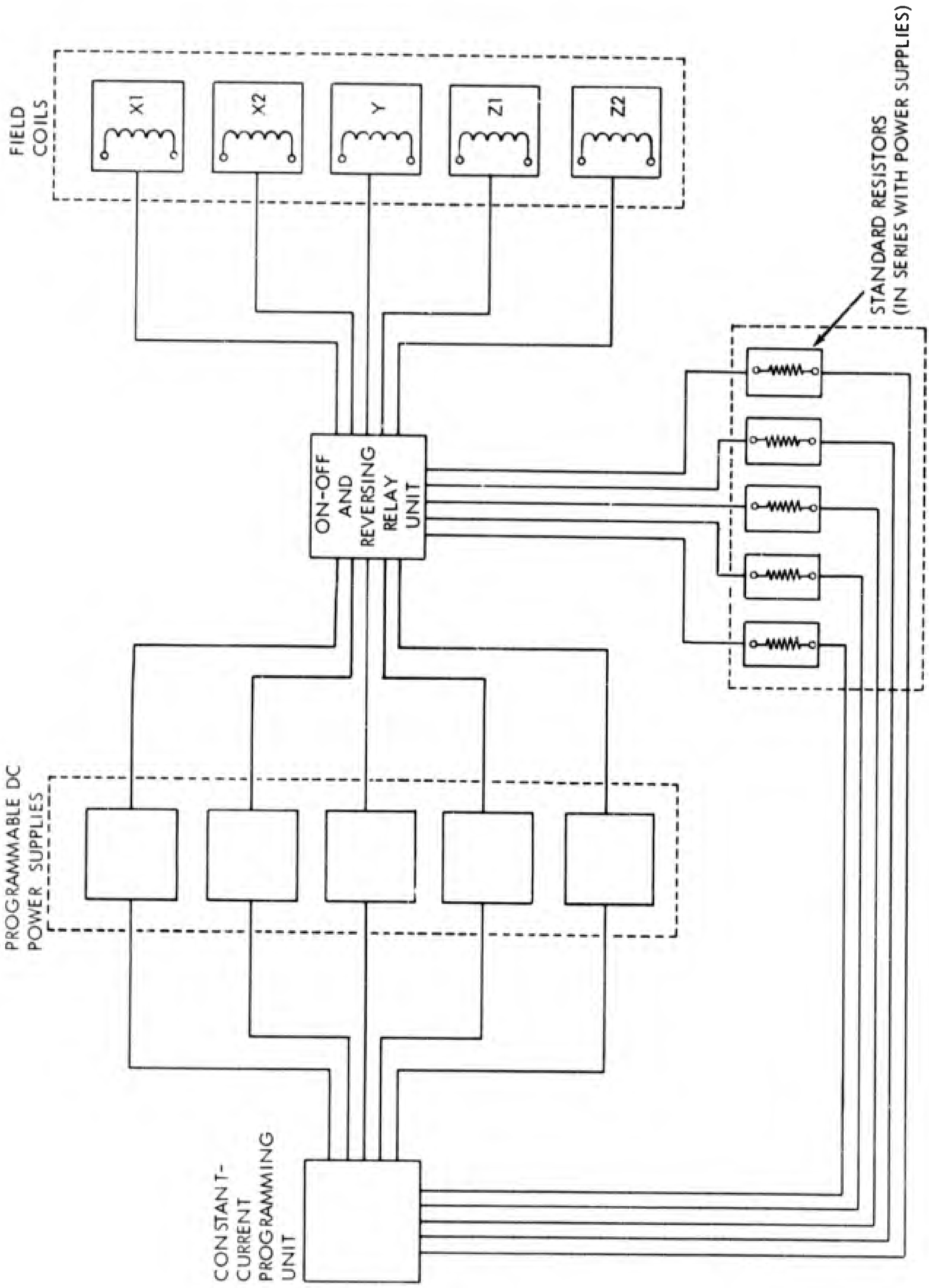


FIG. 6 BLOCK DIAGRAM OF POWER SYSTEM FOR FIELD COILS

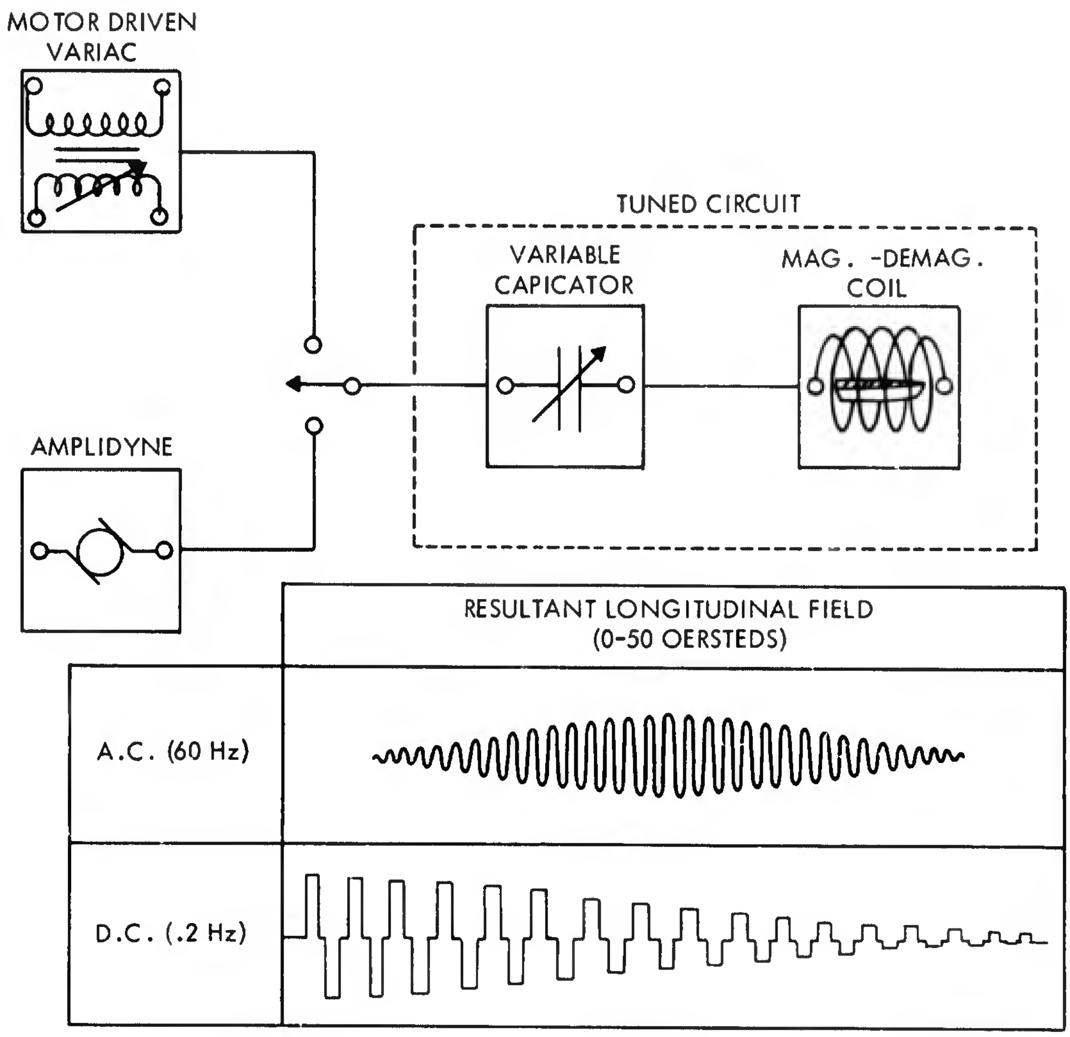


FIG. 7 BLOCK DIAGRAM OF MAGNETIZING AND DEMAGNETIZING SYSTEM

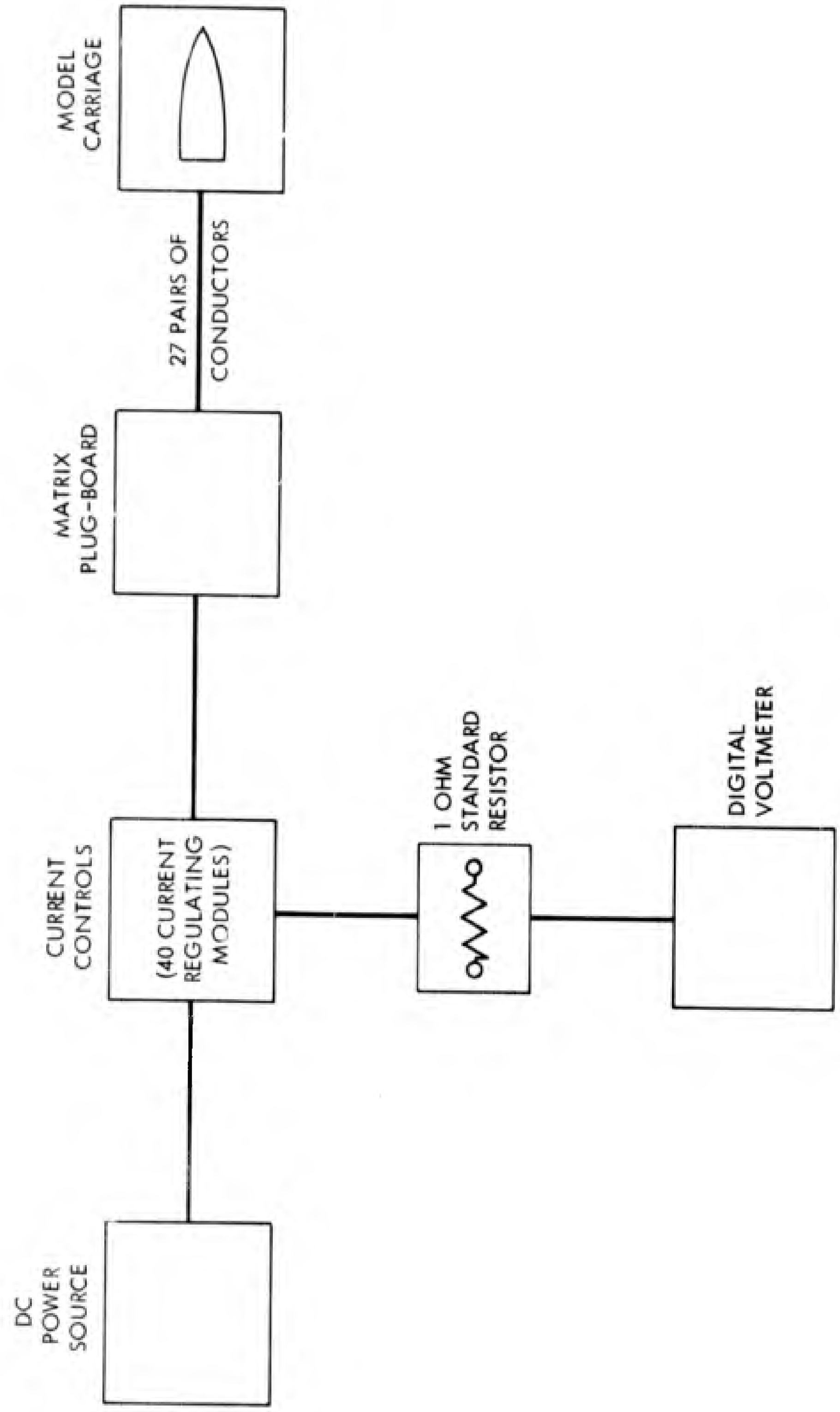


FIG. 8 BLOCK DIAGRAM OF DEGAUSSING CURRENT DISTRIBUTION SYSTEM

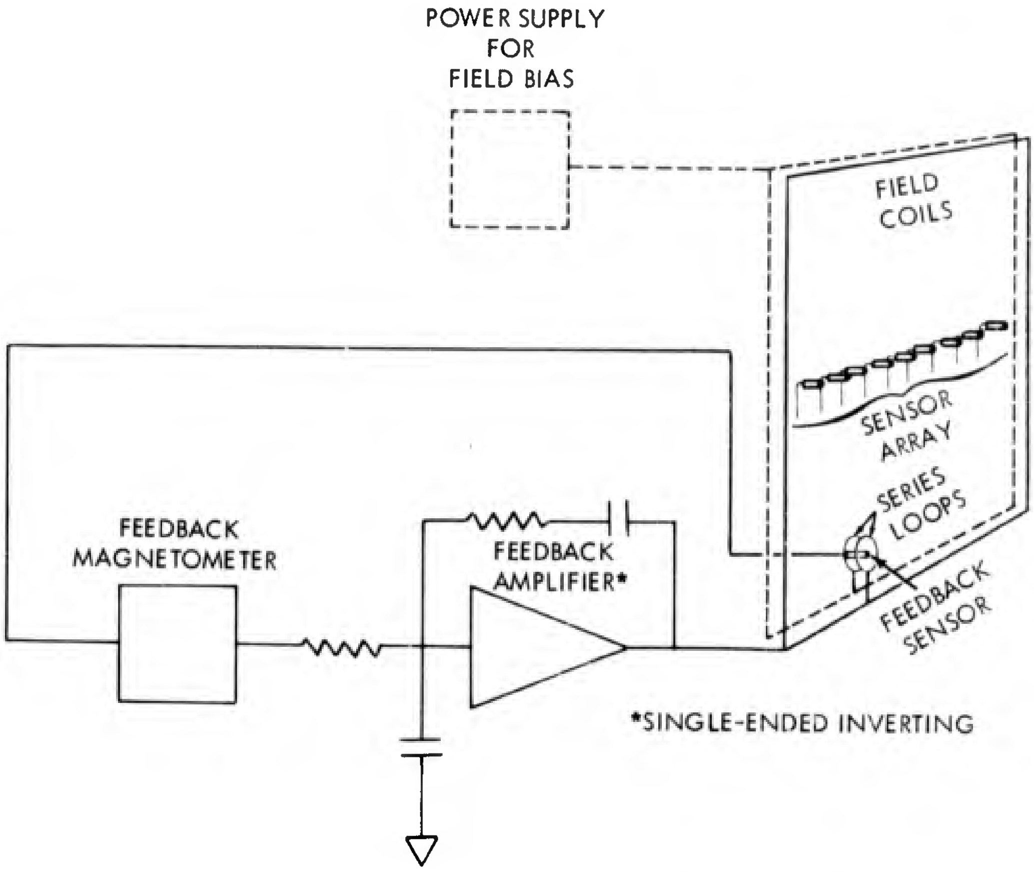


FIG. 9 BLOCK DIAGRAM OF SINGLE CHANNEL OF THE FEEDBACK STABILIZATION SYSTEM

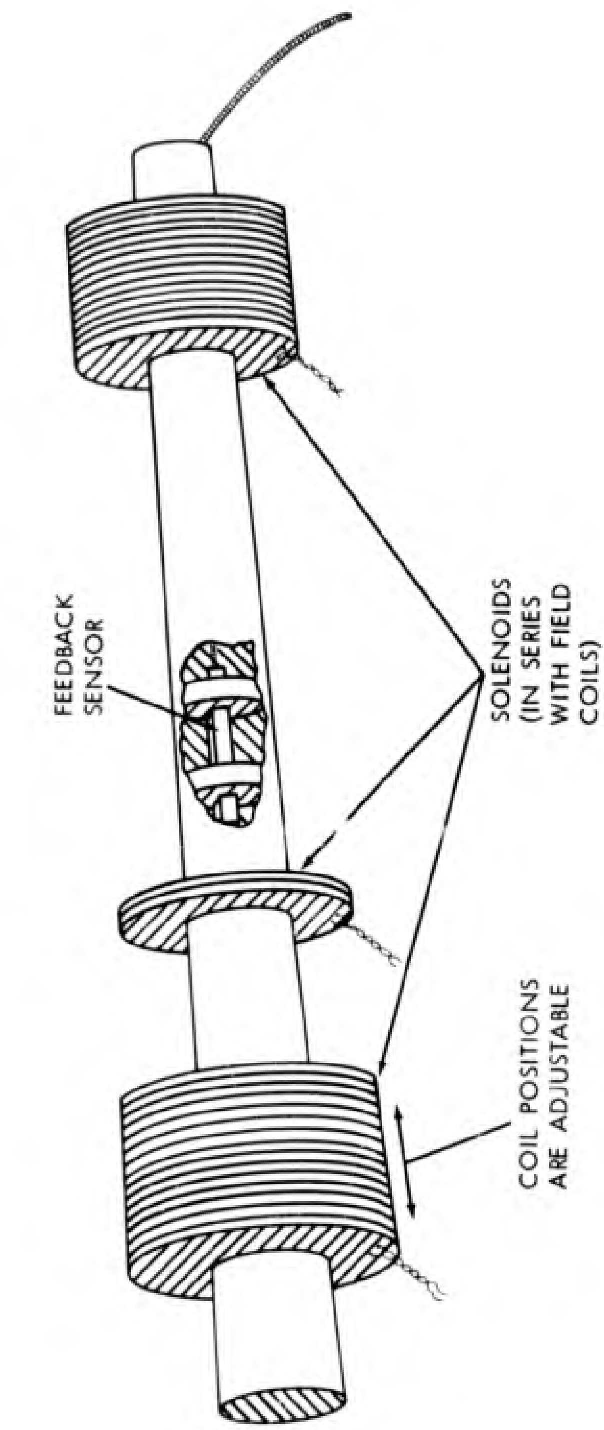


FIG. 10 REMOTE MONITORING UNIT FOR THE FEEDBACK STABILIZATION SYSTEM

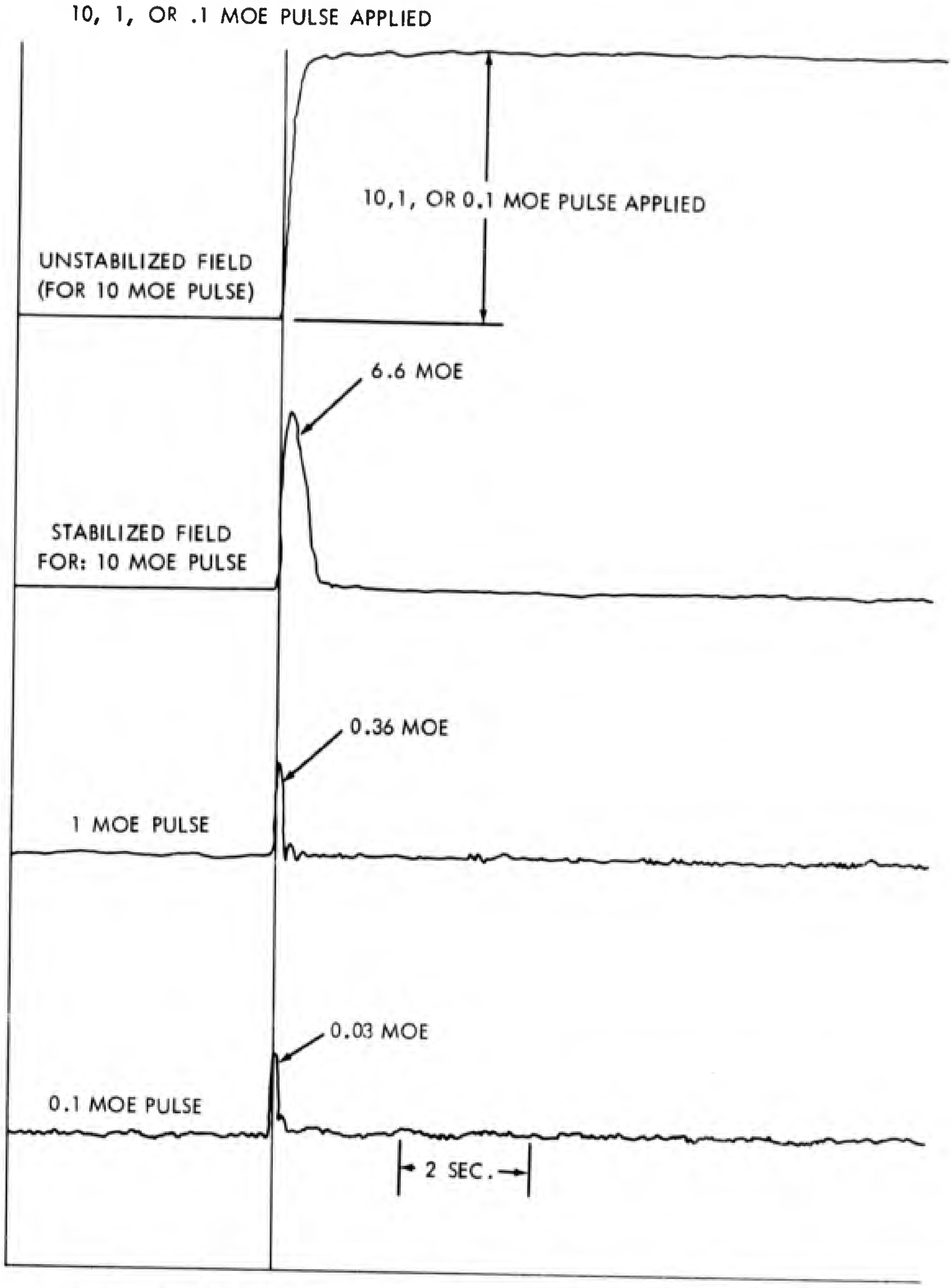


FIG. 11 RESPONSE CURVES FOR Z-CHANNEL OF FEEDBACK STABLIZATION SYSTEM

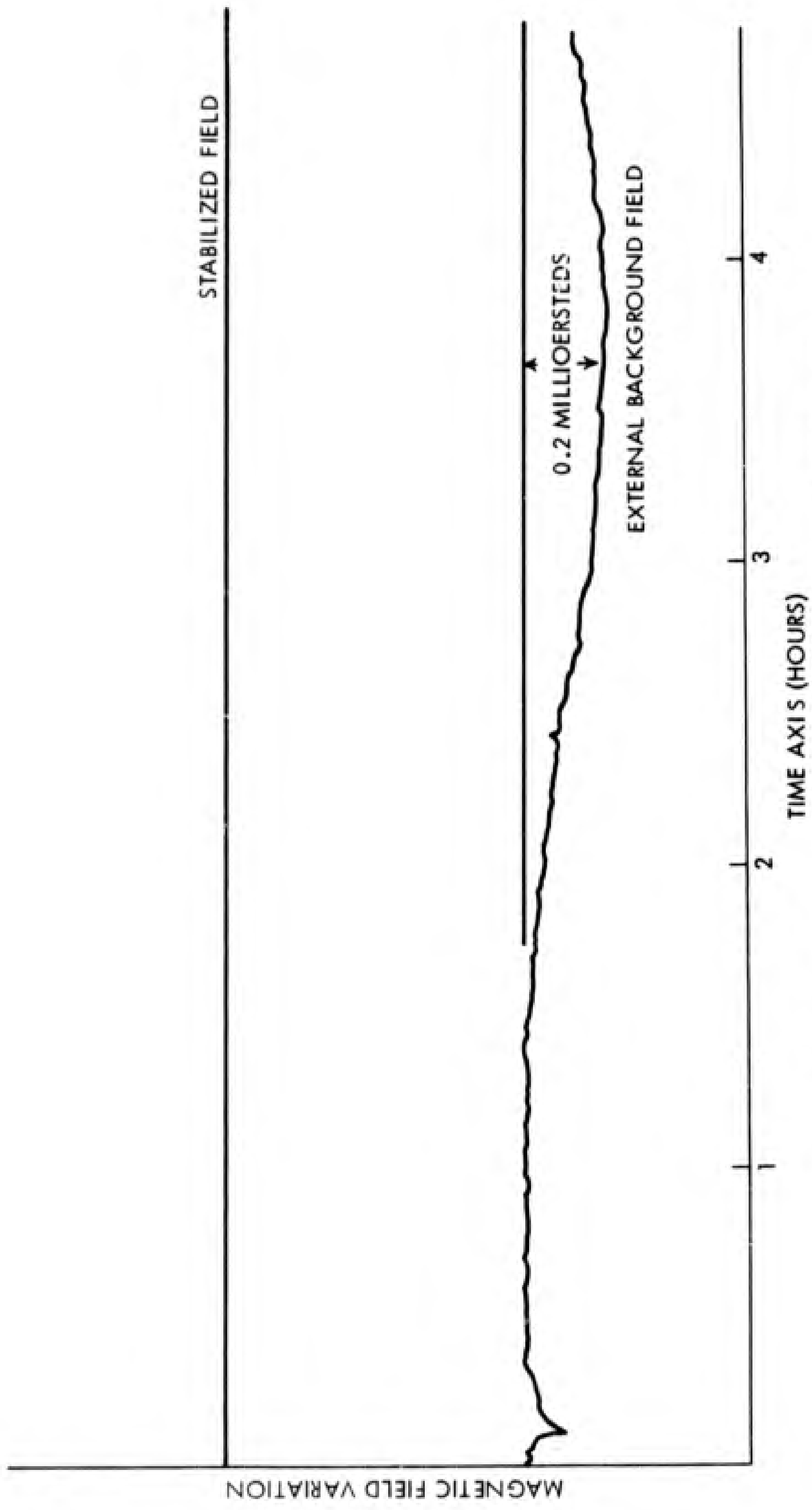


FIG. 12 LONG TERM STABILITY OF FEEDBACK MAGNETOMETER

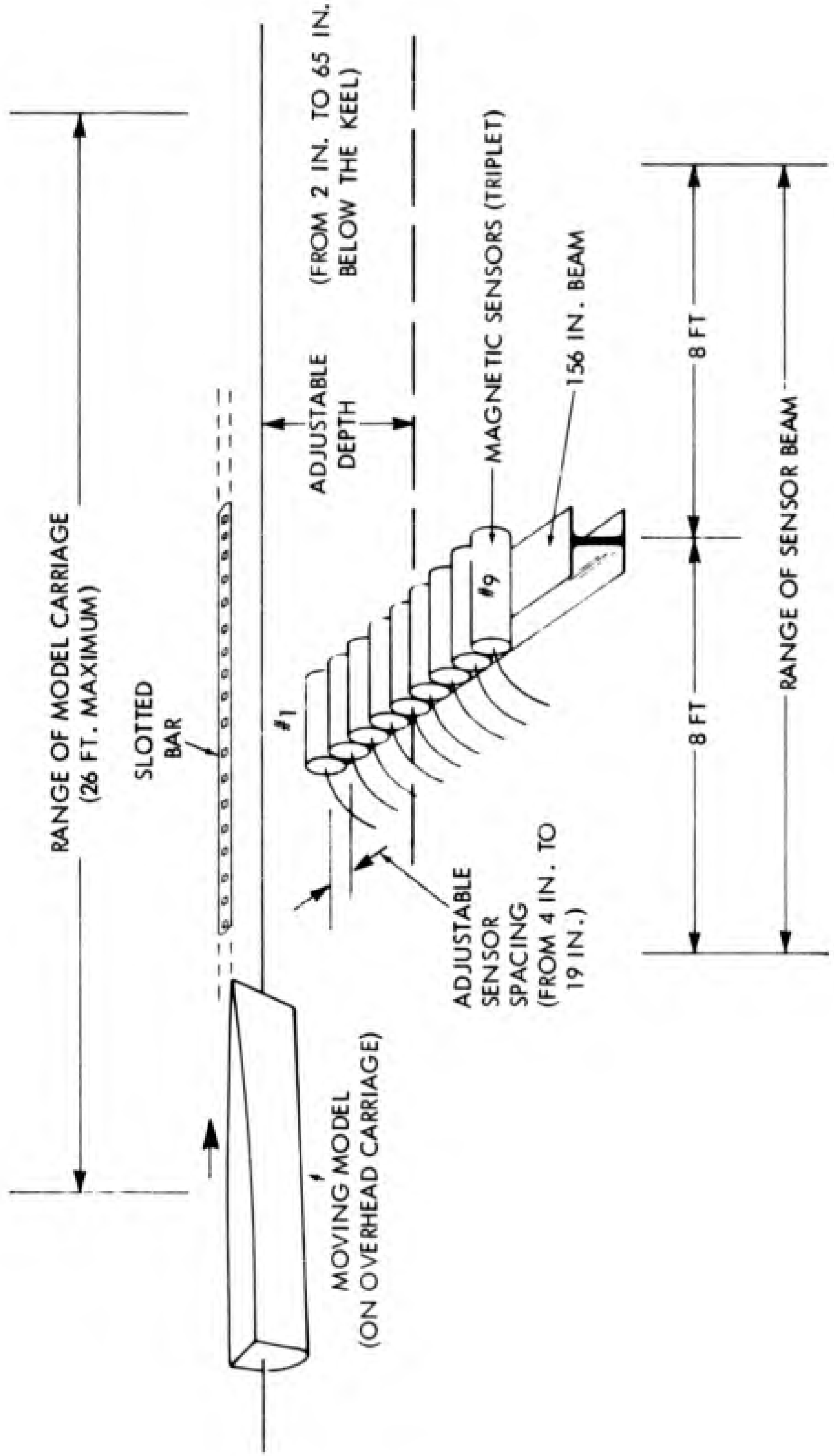


FIG. 13 SIDE VIEW OF MODEL RANGE

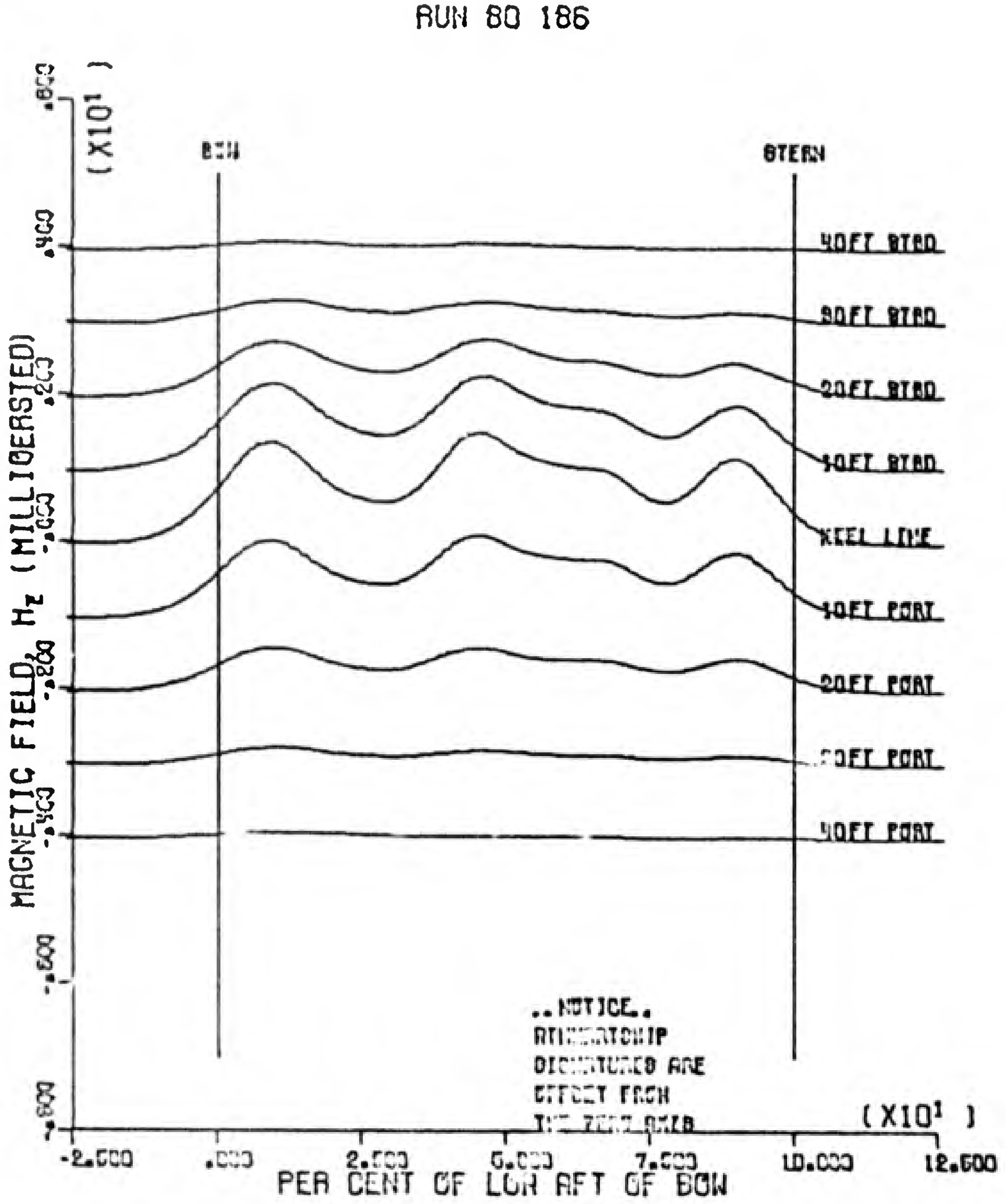


FIG. 14 EXAMPLE OF A DATA MATRIX PLOTTED AS LONGITUDINAL CURVES

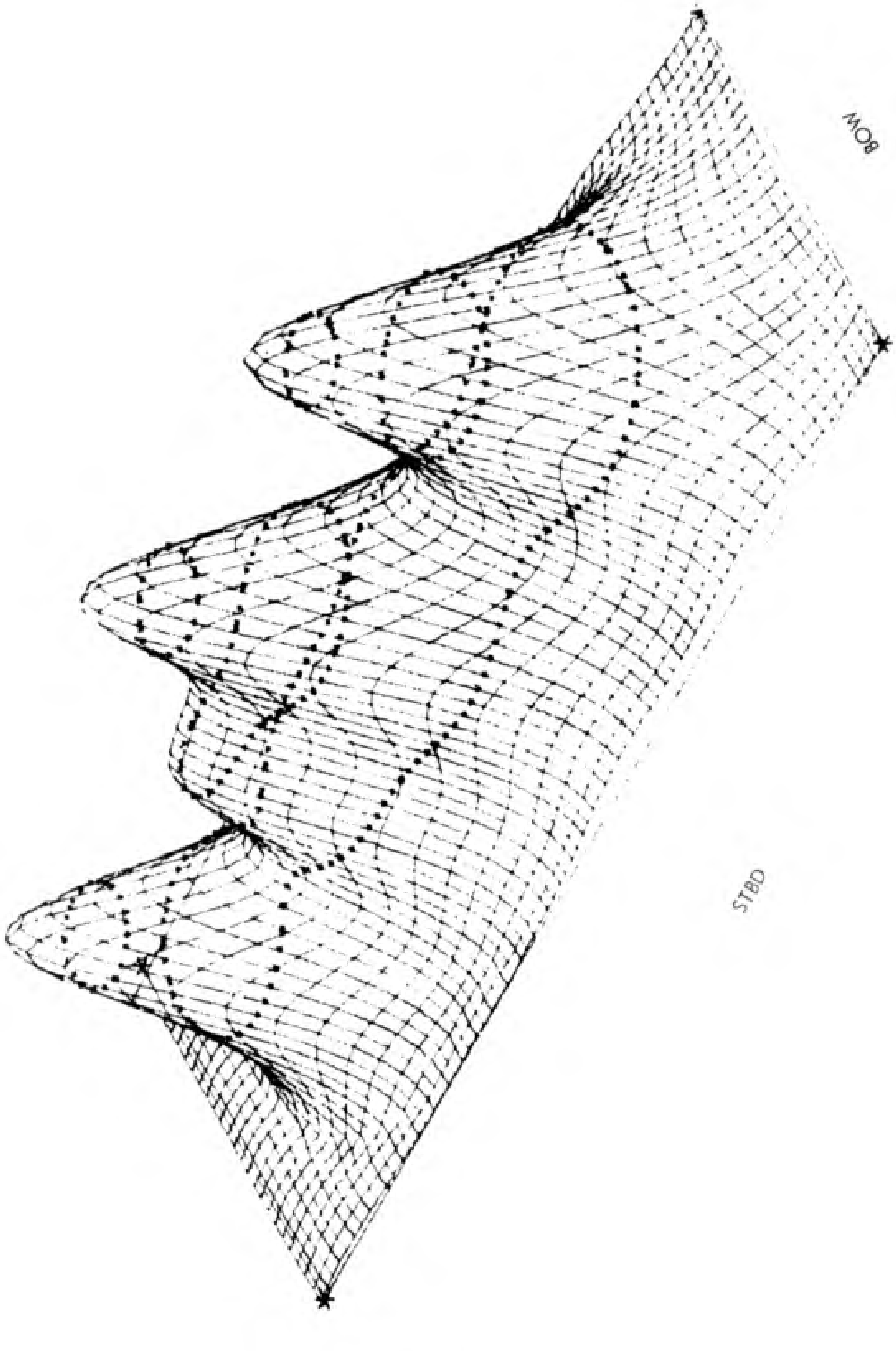


FIG. 15 EXAMPLE OF A DATA MATRIX PLOTTED AS A 3-DIMENSIONAL PROJECTION

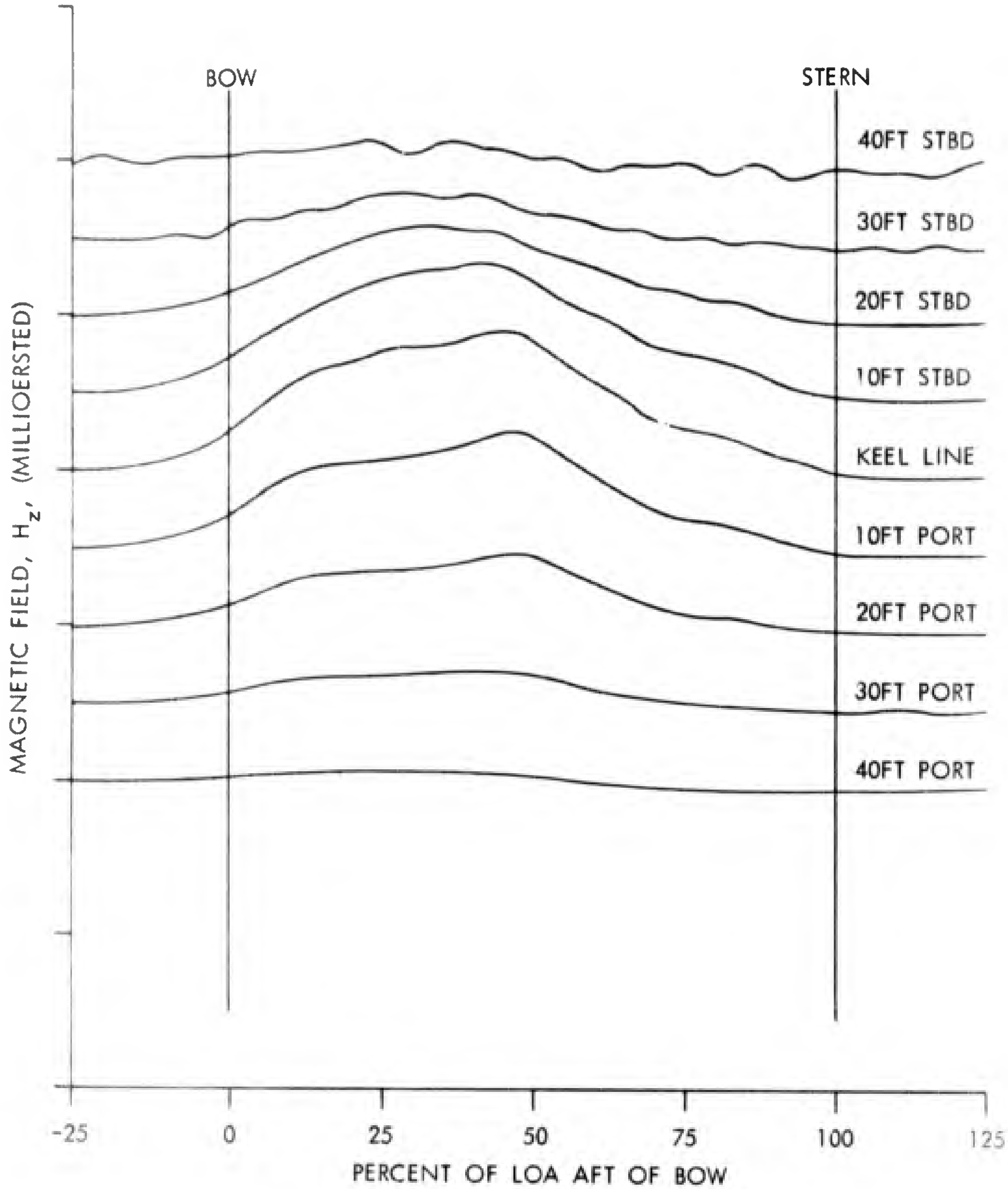


FIG. 16 ORIGINAL DATA PRIOR TO SMOOTHING

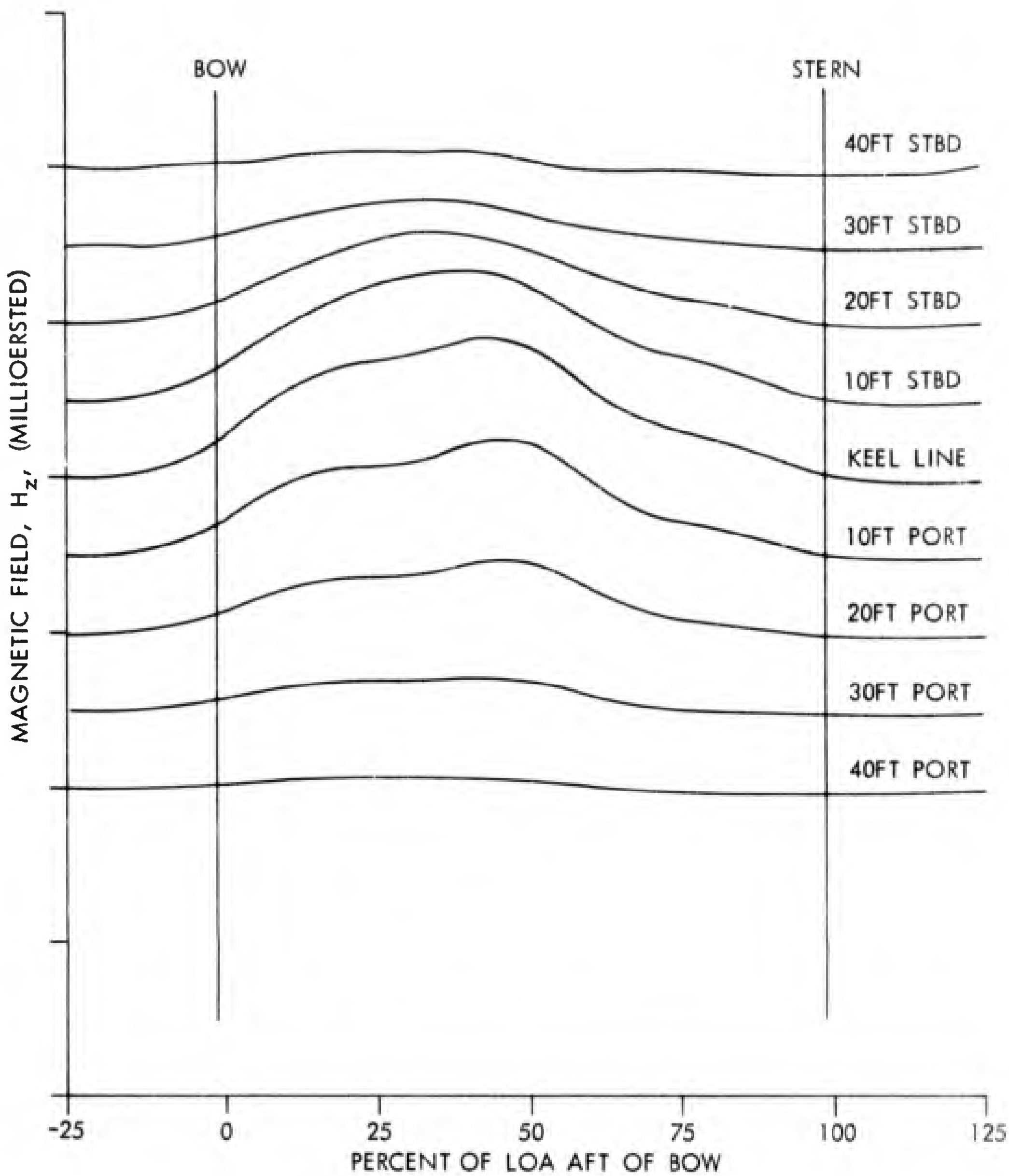


FIG. 17 DATA AFTER SMOOTHING

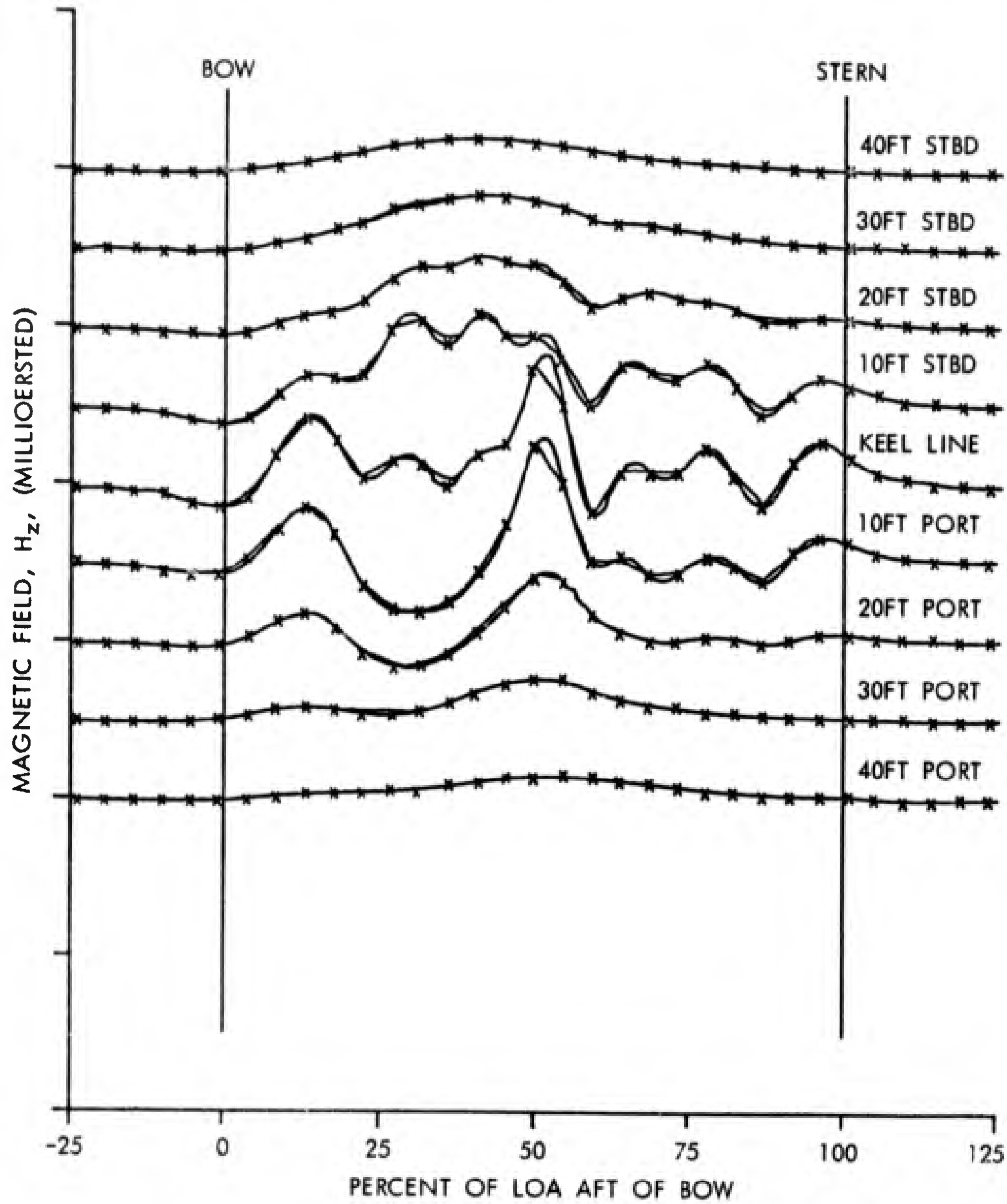


FIG. 18 EXAMPLE OF NUMERICAL INTERPOLATION

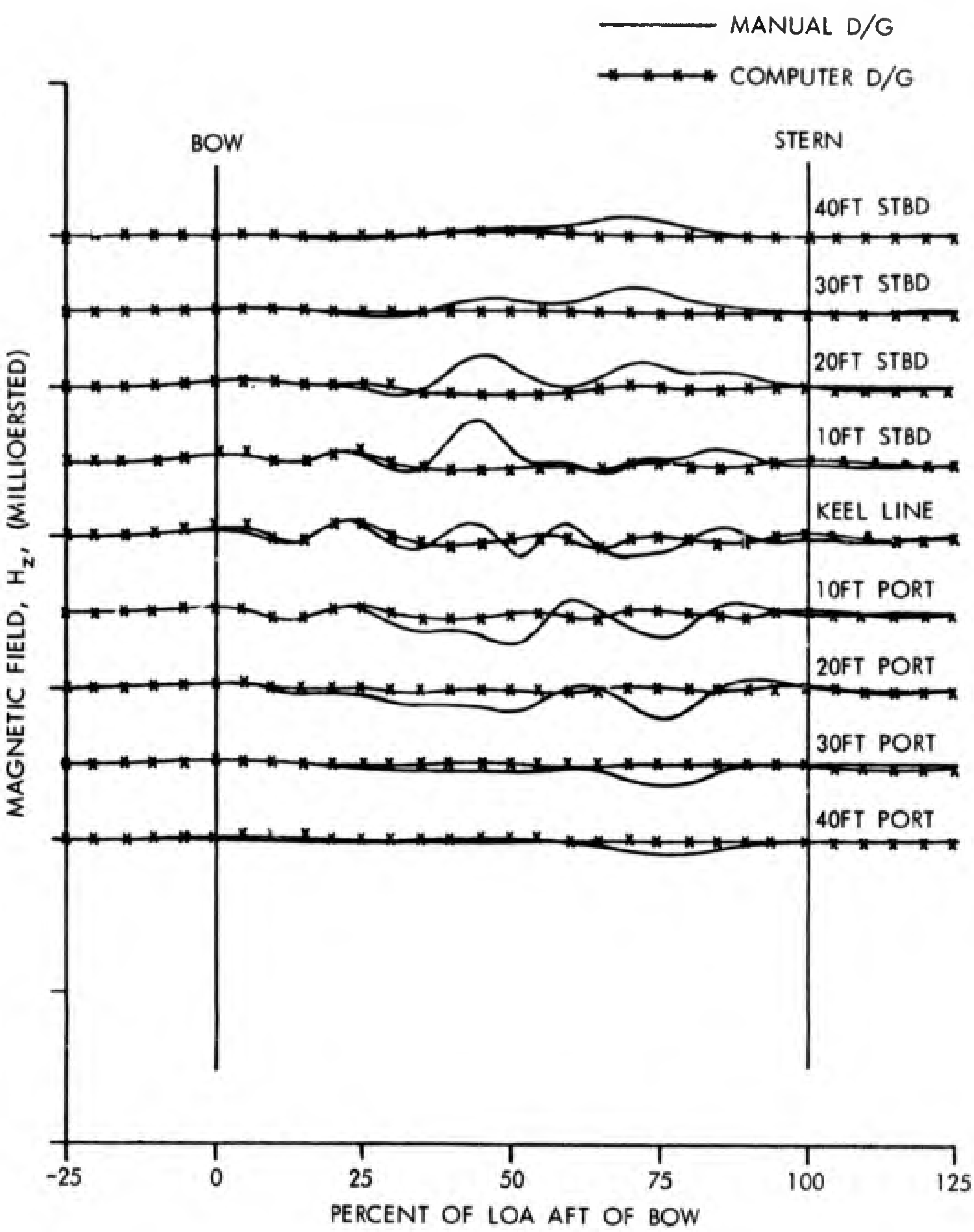


FIG. 19 COMPARISON OF MANUAL AND COMPUTER DEGAUSSING

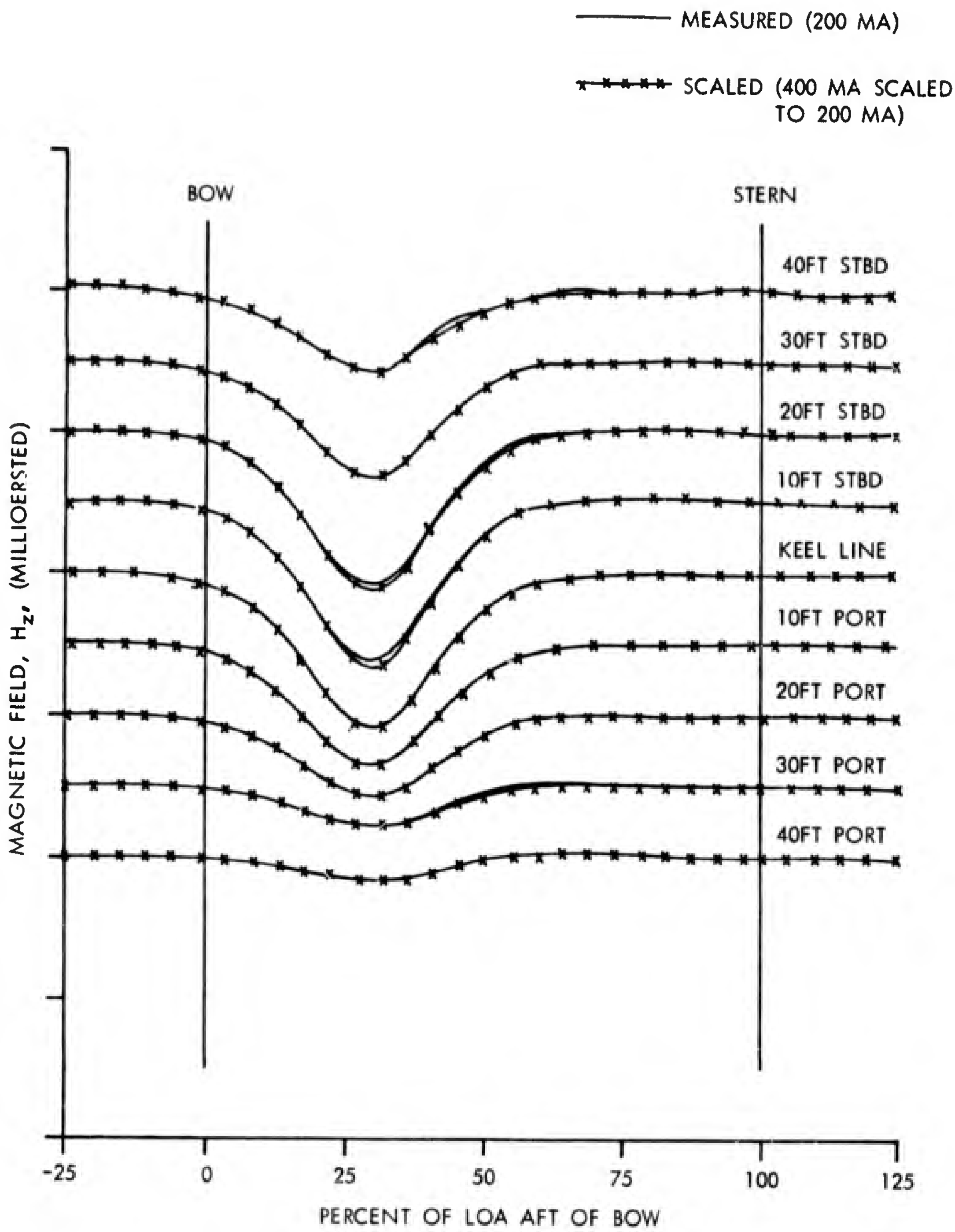


FIG. 20 SCALED COIL EFFECTS

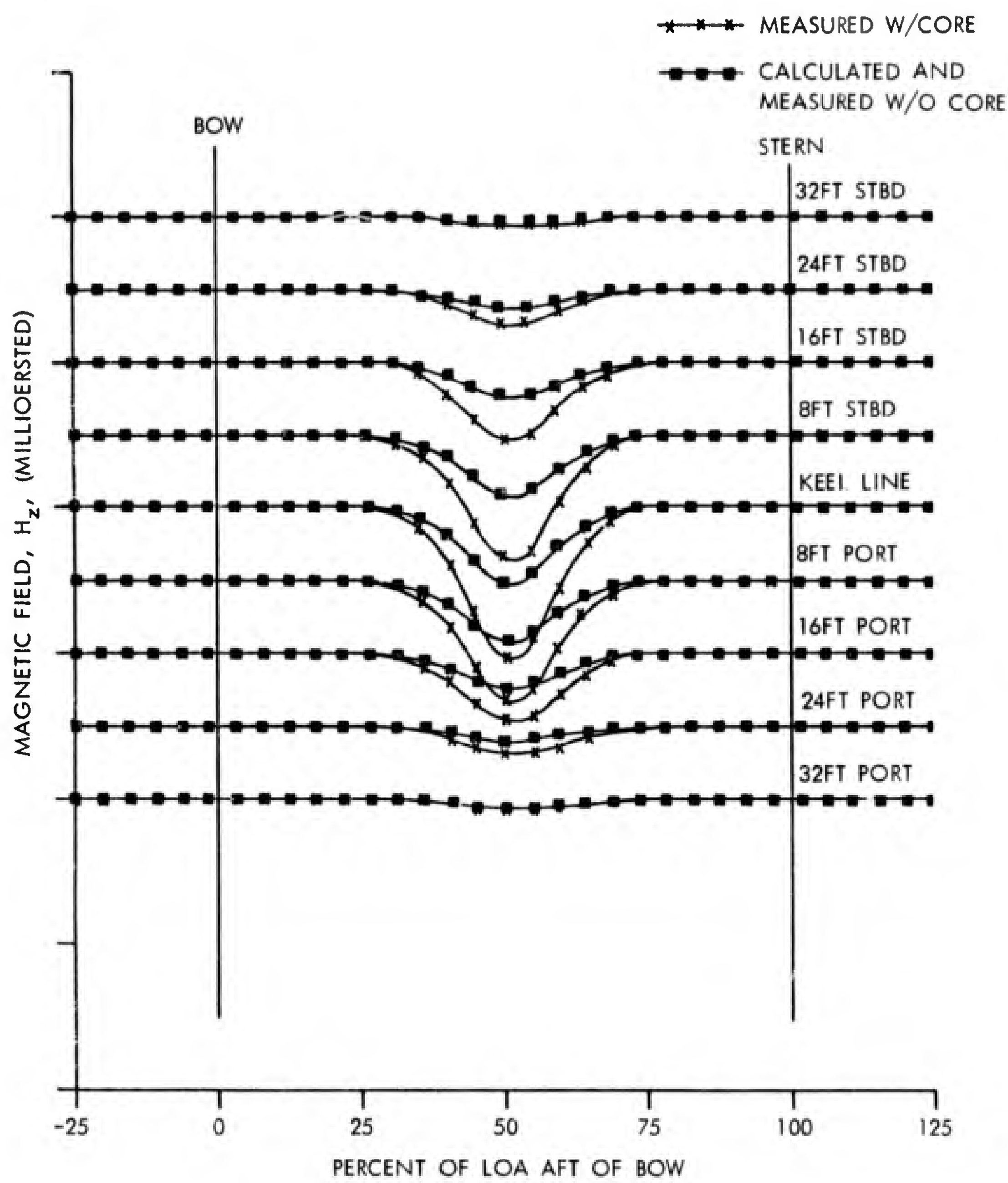


FIG. 21 CALCULATED COIL EFFECTS

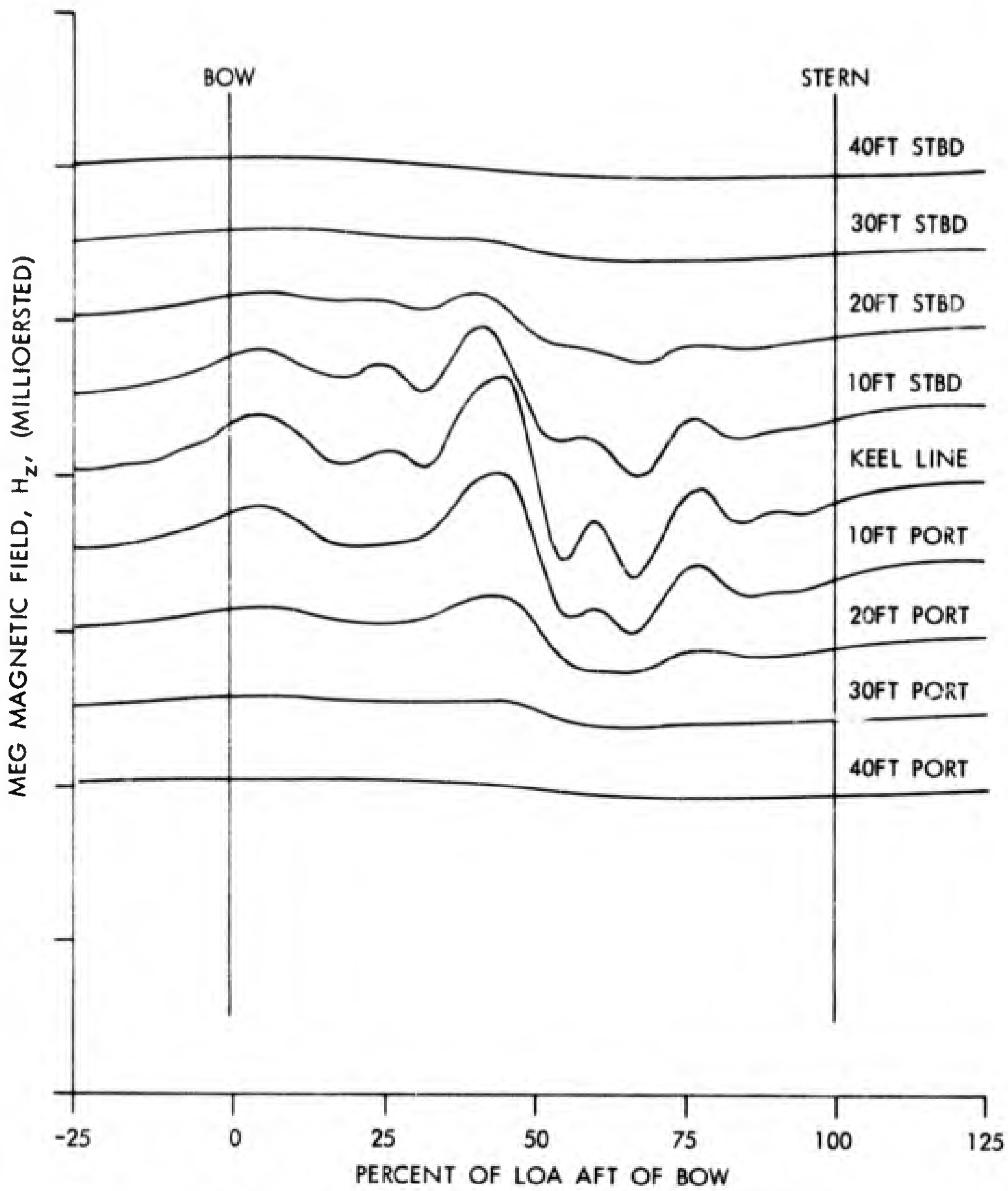


FIG. 22 ORIGINAL DATA PRIOR TO EXTRAPOLATION

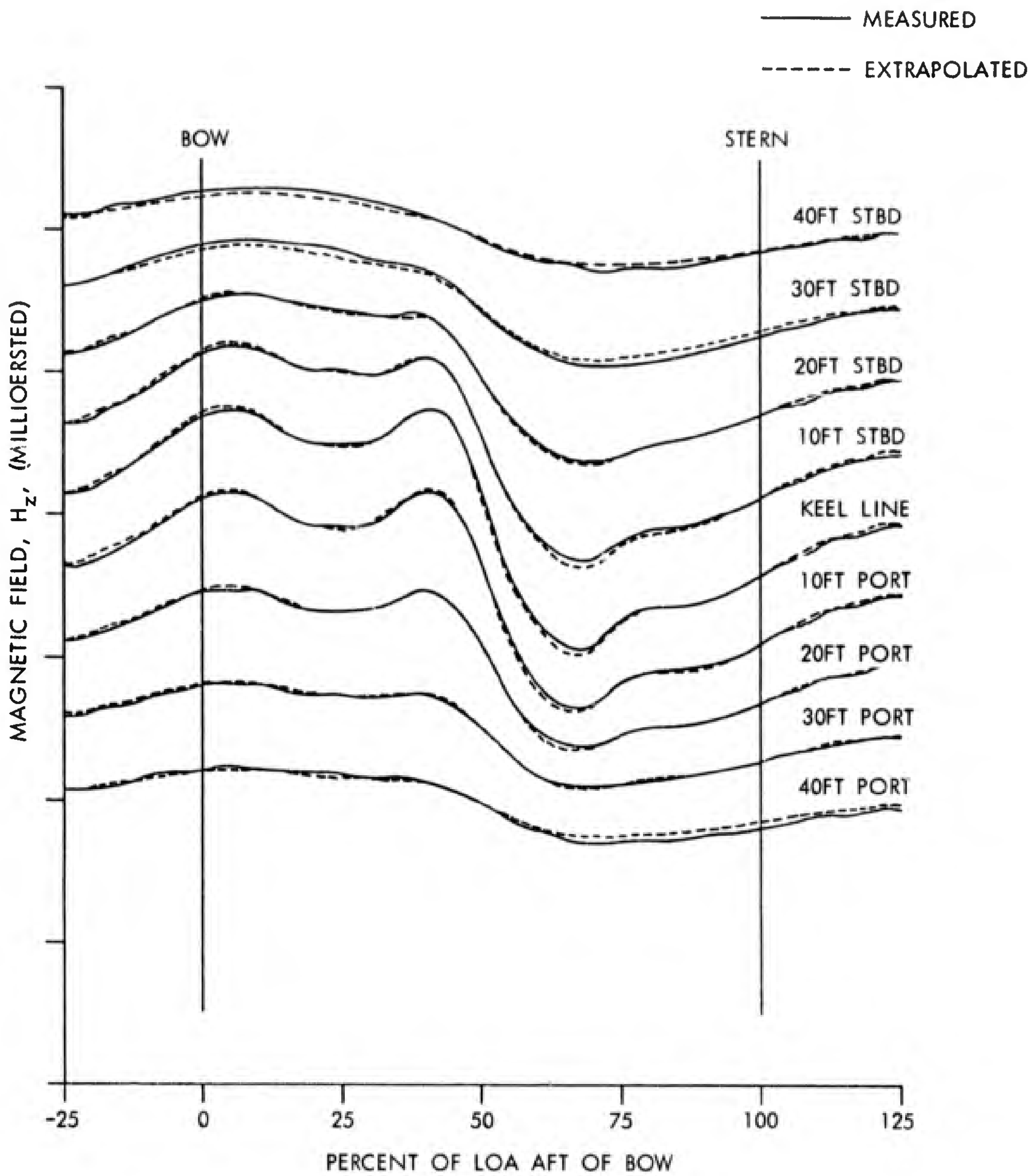


FIG. 23 COMPARISON OF MEASURED DATA WITH EXTRAPOLATED DATA

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13. ABSTRACT

This paper contains a brief, illustrated description of the Magnetic Model Facility at the U. S. Naval Ordnance Laboratory. The primary emphasis is on the use of the Facility in conducting magnetic ship model studies. First, a synopsis is given of techniques for designing magnetic ship models and of problems associated with scaling magnetic characteristics of ferrous items. Next, a description is given of the Facility including: the coil system, the model range, the digital recording system, and other major items of equipment. Finally, a discussion is included on techniques of automated data acquisition and data analysis.

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| 14 KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| Coil Facility | | | | | | |
| Computer Analysis | | | | | | |
| Date Acquisition | | | | | | |
| Date Analysis | | | | | | |
| Data Processing | | | | | | |
| Degaussing | | | | | | |
| Magnetic Field | | | | | | |
| Magnetic Measurements | | | | | | |
| Magnetic Scaling | | | | | | |
| Magnetic Ship Models | | | | | | |
| Magnetism | | | | | | |
| Magnetometer | | | | | | |

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