A mining research contract report
31 DECEMBER 1982

EVALUATION OF PROXIMITY WARNING DEVICES

(PHASE III, VOLUME 1)

Contract No. J0188082
Southwest Research Institute

BUREAU OF MINES
UNITED STATES DEPARTMENT OF THE INTERIOR

REPORT DOCUMENTATION PAGE	1. REPORT NO. BuMines OFR 100(1)-83	2.	3. Recipient's Accession No. P883 210260
4. Title and Subtitle Evaluation of Proximity Warning Devices. (Phase III, Volume 1)			5. Report Date December 31, 1982
			6.
7. Author(s) J. H. Nixon, J. E. Hipp, T. C. Green, G. H. Munsch, and J. P. Cater			8. Performing Organization Rept. No.
9. Performing Organization Name and Address Southwest Research Institute 6220 Culebra Rd. San Antonio, TX 78284			10. Project/Task/Work Unit No.
			11. Contract(C) or Grant(G) No. (C) J0188082 (G)
12. Sponsoring Organization Name and Address Office of Assistant Director--Mining Research Bureau of Mines U.S. Department of the Interior Washington, DC 20241			13. Type of Report & Period Covered Contract research 9/29/78--12/31/82
			14.

15. Supplementary Notes

Approved for release May 11, 1983.

16. Abstract (Limit: 200 words)

A three-phase program evaluated commercial proximity warning devices, developed and designed a microprocessor-based electrostatic field measurement instrument, and utilized the instrument to investigate the electrostatic fields about powerlines. Phase I consisted of test evaluations of these commercially available proximity devices. Phase II resulted in the design and development of a microprocessor-based distributed sensor ac electrometer that measures the electrostatic field at 17 discrete locations along a crane boom. Under the phase III program, electrostatic fields around a crane boom were measured by the instrument at 17 high voltage powerlines of various voltages and geometries. The data were processed and plotted versus boom distance from the powerlines. Analysis of the data indicate that the distances at which a single sensor alarm will activate vary by a factor of 3 to 1, due primarily to variations in boom orientation. The results also indicate that in the case of multiple powerlines, a single electrostatic field sensor cannot reliably be used to determine the distance from a powerline.

17. Document Analysis a. Descriptors

Mining
    Proximity warning devices
    Electrostatic field measurement instrument

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group   08I

18. Availability Statement Release unlimited by NTIS.	19. Security Class (This Report) Unclassified	21. No. of Pages 91
	20. Security Class (This Page) Unclassified	22. Price

FOREWORD

This report was prepared by Southwest Research Institute, Electromagnetics Division, 6220 Culebra Road, San Antonio, TX 78284, under USBM Contract No. J0188082. The contract was administered under the technical direction of Pittsburgh Mining and Safety Research Center with Dean Ambrose and George Conroy acting as Technical Project Officers. Doyne W. Teets was the contract administrator for the Bureau of Mines. This Final Report is a summary of the work over the period 29 September 1978 to 31 December 1982. No concepts or technology set forth in this report is considered a subject invention as defined in the contract under which the work was performed. The draft of this report was submitted by the authors on 25 August 1982. The completed report was submitted on 31 December 1982.

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I. INTRODUCTION

The final report provided herein describes the work performed under U. S. Bureau of Mines Contract J0188082, "Evaluation of Proximity Warning Devices," conducted by Southwest Research Institute over the period 29 September 1978 through 28 May 1982. The program was conducted in three phases with Phase I consisting of testing and evaluation of commercially available proximity warning devices. Phase II consisted of the design and development of a microprocessor based electrostatic field strength measurement instrument group for crane boom applications. Phase III was used to test the AC Electrometer and extensively map and analyze the electric field patterns around power lines.

The objectives of Phase I of this contract were to perform a comprehensive search for procurement of all commercially available power line proximity warning devices. Each device was then subjected to extensive comparative testing. During the contract, three proximity warning devices manufactured in the U. S. were identified and purchased. Each of these devices operated on the same principle of detecting the electrostatic field intensity for determining the proximity to power lines. The performance of these devices was evaluated with full scale cranes and high voltage power line systems, a scaled model facility, environmental testing facilities and theoretical/numerical analysis. Besides providing a qualitative comparison between the three units, the tests evaluated performance variation resulting from such parameters as power line configuration, crane configuration, sensor placement, conducting structures, and environmental changes.

A complete description of the work accomplished under Phase I, including the test and evaluation of the proximity warning devices, and conclusions and recommendations for device improvement are found in the Phase I interim report dated 22 February 1980.* Specific references to the data and resultant conclusions from these tests should be acquired from the subject interim report.

One of the conclusions gained from the Phase I program stated that in addition to design deficiencies, which varied from device to device, the reliability of all proximity warning devices was severely limited by the physical principle (electrostatic field sensing) on which these devices operate. Physical phenomena associated generically with electrostatic field sensing devices and observed to produce undesirable performance in the commercially available proximity warning devices included field distortion from multi-line power circuits, polarization effects, boom shielding of the sensors, and sensitivity variations with boom orientation and extension.

* J. E. Hipp, F. D. Henson, P. E. Martin, G. N. Phillips, Evaluation of Proximity Warning Devices, Phase I Report for U. S. Bureau of Mines, Contract J0188082.

The objective of the subsequent Phase II program was to develop a microprocessor based data acquisition system to measure and collect field strength at distributed points around the crane boom. The developed equipment group (referred to as the Distributed Sensor AC Electrometer) is designed to accurately measure the distributed field strength around a crane boom with minimum error. Specific sources of measurement anomalies determined in the Phase I program which this system is designed to quantify include:

(1) Polarization effects

(2) Sensor shielding by the crane boom

(3) Sensitivity variation with boom orientation

(4) Sensitivity variation with boom extensions

(5) Sensitivity variation with sensor position on boom

The complete description of the Distributed Sensor AC Electrometer may be found in the Phase II interim report dated 13 February 1981.* Although the system description is presented thoroughly in this final report, the Phase II interim report describes in detail the development and construction of the Distributed Sensor AC Electrometer (hereinafter referred to as the Electrometer).

The objective of the Phase III program was to conduct electric field strength measurements in the vicinity of a variety of power line configurations in order to map the fields, employing the Electrometer developed in Phase II of the contract. The sets of measurements were to be taken at ten sites in the San Antonio area, and would include three different line voltages (13.2 KV, 34.5 KV and 69 KV) and three different geometrical configurations. Because of the difficulty in finding some of the particular line geometries with associated voltage ranges, some of the tests made during the Phase III tasks contained slightly different line voltages or varying configurations.

The data acquired from the field site testing utilizing the Electrometer is presented in detail in this final report. A detailed computer analysis of the electrostatic field distribution data was performed and the results are presented in section III. Plots of all measured data (949 plots total) are provided in Appendix D and E. Interpretation of the analysis results and the usefulness of this data in the design and operation of proximity warning devices are discussed in the conclusions section. Recommendations for future research associated with proximity warning devices are also included herein.

* T. C. Green, J. P. Cater, J. H. Nixon, Evaluation of Proximity Warning Devices, Phase II Completion Report for U. S. Bureau of Mines, Contract J0188082.

Acknowledgement

The assistance of City Public Service, San Antonio, Texas (the San Antonio power utility) in locating and providing access to the various power line configurations used in the electric field measurements is appreciated.

II. EXECUTIVE SUMMARY

A. Background

The results of the Phase I program revealed that the electrostatic field distribution around overhead power lines varies significantly with power line circuit configuration. In addition, the field distribution is distorted by the presence of the crane boom to the extent that theoretical prediction of the electrostatic field distribution are no longer quantitatively valid. The results of the Phase II program produced a microprocessor based electrostatic field strength instrument measurement group which could accurately and efficiently measure the field distribution in the vicinity of overhead power lines and record the data on magnetic tape for post processing analysis. In addition, the developed equipment group (referred to as the Electrometer) was designed to measure the distorted electrostatic fields at discrete points along the complete line of a typical crane boom, to quantitatively describe the factors that limit the performance of commercially available proximity warning devices.

B. Measurement Equipment Group Description

The Distributed Sensor AC Electrometer equipment group developed under the Phase II program consists of the master processor, four remote processors, and seventeen electric field probes. The complete equipment group is shown in Figure 1. During normal operation the master processor, shown in Figure 2, queries each of the four remote processors. These in turn sample data from up to 5 electric field probes each (17 supplied). This data is transmitted via a serial data line to the master processor where it is analyzed, printed and recorded. Unique features of the display and recording system include an internal real time clock and custom user defined header capabilities. Each data set which was taken during the Phase III tasks includes the time (minute, hour, day, month, year) that the test was made, and a 14-digit header entered by the operator as he performed each data acquisition task. The time and header information printed on the internal printer is also recorded on the self contained tape recorder for data archiving. This feature allows automatic post analysis of the field strength data with associated test location identification.

The Electrometer utilized in the Phase III tests is designed to accurately measure the distributed field strength about a crane boom with minimum error. Sources of the field anomalies which this distributed sensor system quantifies include: 1) polarization effects, 2) sensor shielding by the crane boom, 3) effects of sensitivity variation with boom orientation, 4) effects of sensitivity variation with boom extension, 5) measurements over full boom length.
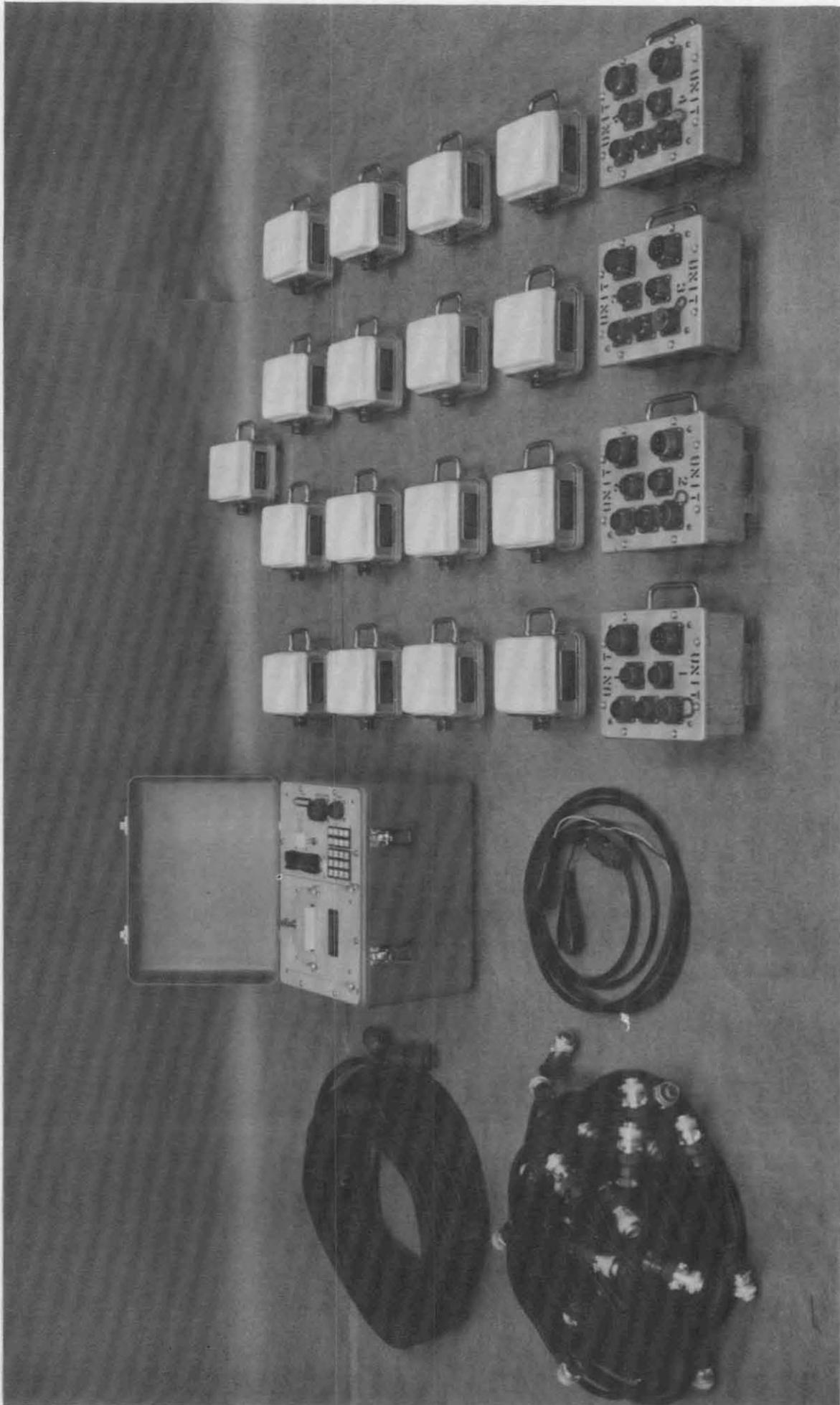
FIGURE 1. DISTRIBUTED SENSOR AC ELECTROMETER EQUIPMENT GROUP
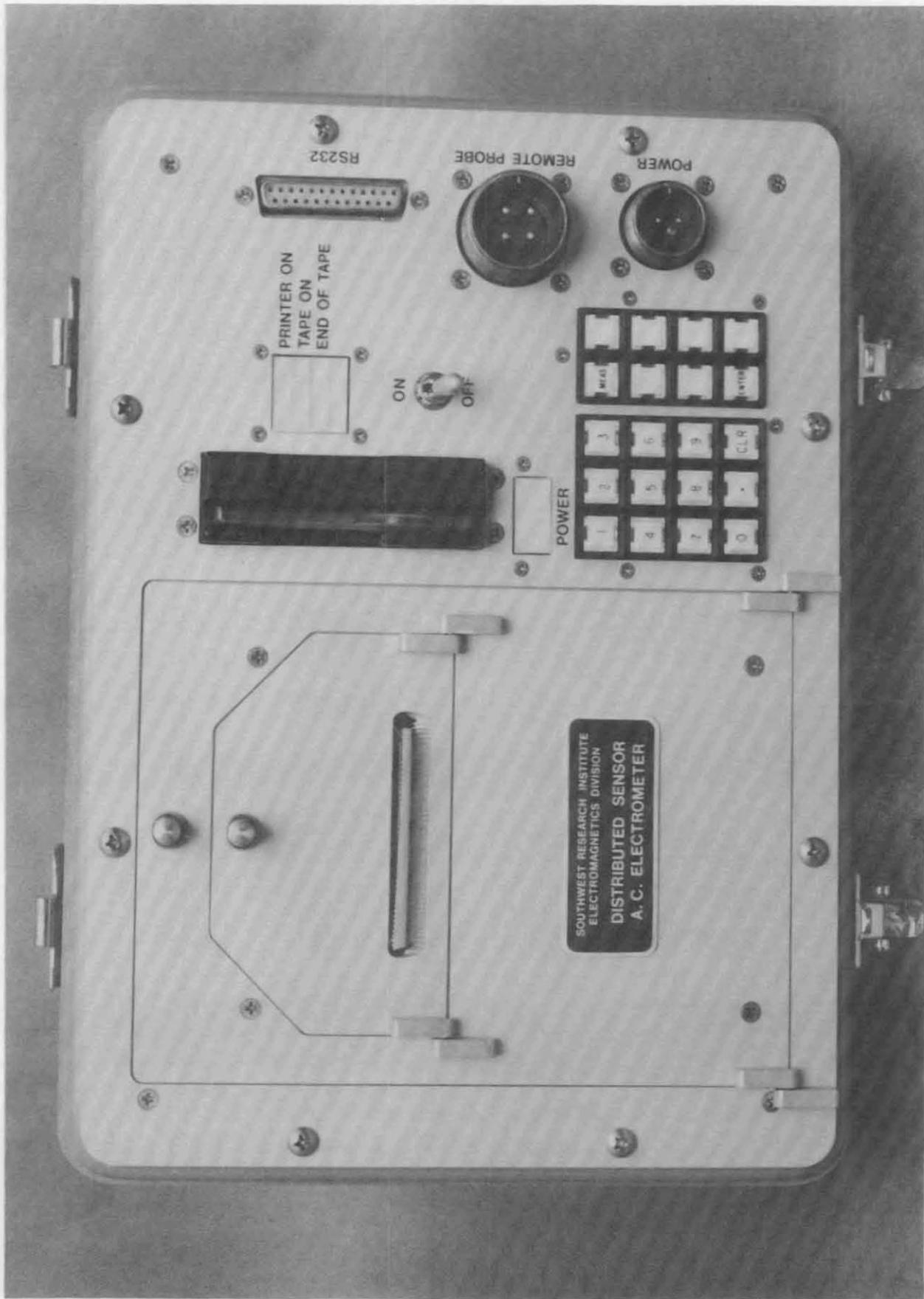
FIGURE 2. MASTER PROCESSOR

All of the above sources of error can generally be overcome by the placement of multiple point sensors distributed around the boom and along the length of the boom. Figure 3 illustrates the concept of the multiple sensor placement along the crane boom. The output of each sensor is separately monitored and recorded to totally map the field distribution along the interfering structure.

A significant feature in the design of the Electrometer is the use of a distributed processor system which allows rapid and accurate measurement of the field strength from multiple sensors. Under the distributed processing philosophy, multiple microprocessors are used in the master control unit and at discrete locations along the crane boom to monitor and record field strength voltages from the multiple sensors. The microprocessor in the master control unit provides a powerful capability for processing the measured field strength data and includes such features as self-calibration, averaging, storage, display, printing of data, and operator inputs to the measurement process. This concept also provides high reliability operation since each sensor performs internal self tests and monitors the data line for transmission or reception errors.

C.   Electric Field Measurements

Phase III of the subject contract under the Phase III part of the program, extensive measurements of the electrostatic field distribution about various power line configurations were obtained. The SwRI designed Electrometer used for the measurements was mounted on the boom of an extendable boom crane as shown in Figure 3. The various sites which were chosen for field strength measurement and analysis were all located in the near San Antonio vicinity. The sites had voltage readings from 13.8 KV through 69 KV and consisted of various line configurations (i.e. vertical or horizontal, various number of conductors, various ground configurations, etc.). Data from each site was obtained with the crane boom manuevered through varying elevations and azimuth positions. This combination of boom manuevers and varied crane position provides for a wide range of boom proximity.

Sensor Group 4 {

Sensor Group 3 {

Sensor Group 2 {

Sensor Group 1 {
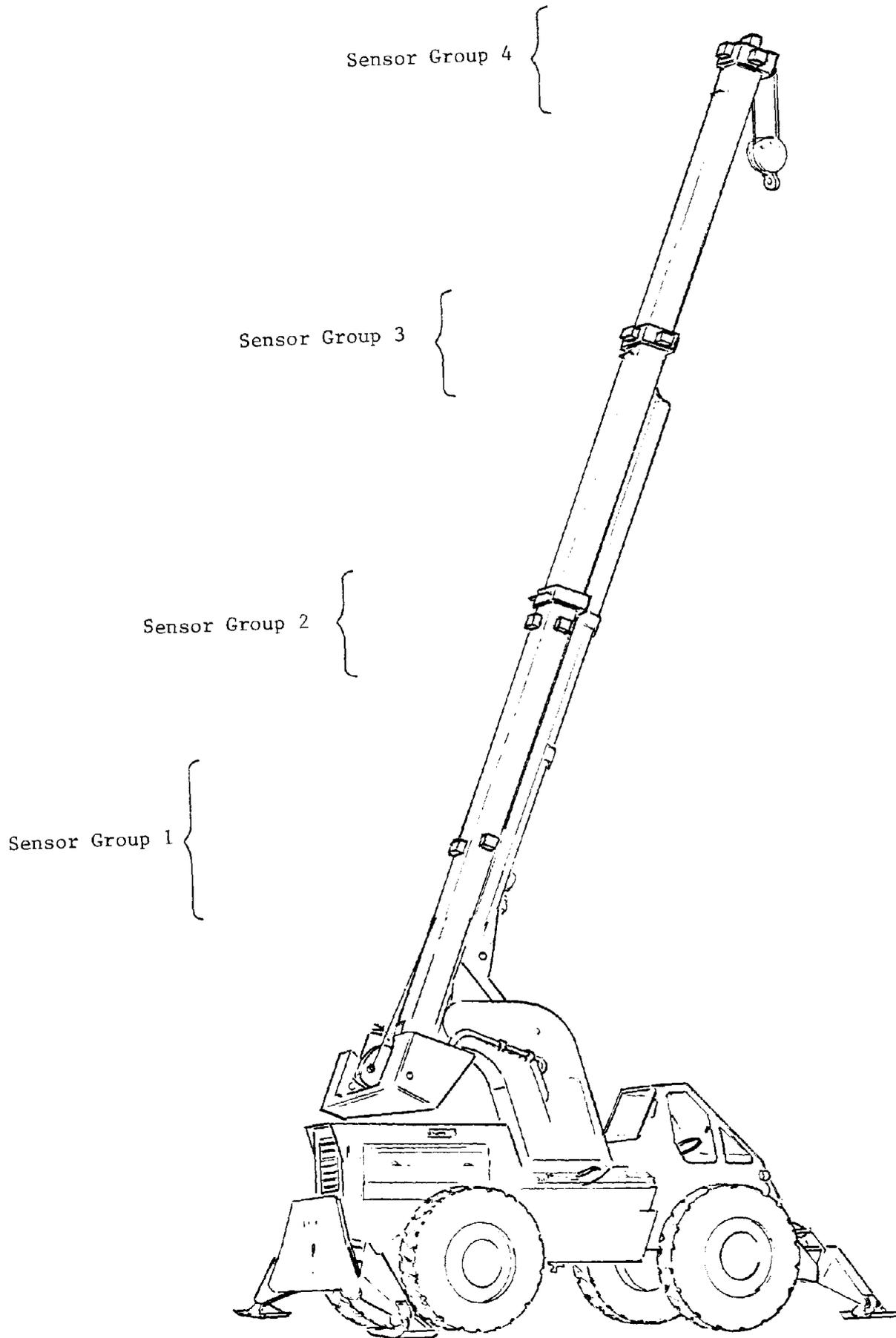
FIGURE 3. CRANE BOOM CONFIGURATION

80B044-0

III. TECHNICAL DISCUSSION

A. Distributed Sensor AC Electrometer Description

1. Specific Approach to AC Field Measurements

The basic measurement approach used in the Electrometer is high impedance AC field metrology. In fact, the method of AC pickup is similar to that used in commercially available crane-mounted power line proximity alarm systems. Several differences exist, however, which make the SwRI system quite unique. The primary differences are the capability of absolute field measurements (rather than a threshold alarm capability) and the configuration and number of sensors.

The development of a system with a capability for multiple field measurements around the boom of a crane presents numerous problems, if the field is to be measured accurately. Since the field will vary somewhat inversely to the distance from a power line, the problem arises as to where to actually measure the existing field during the power line approach. A measurement at any specific point on the boom of the crane will give the value of the exact AC field at that point; however, the field strength at other places on the boom may be greater or less than the measured value, thus causing some uncertainty in the measurement for an alarm field value, depending on the approach configuration. The uncertainty is due both to the varying distance to the source and to the shadowing effect of the boom.

The solution to the point measurement problem was solved in the SwRI distributed sensor system by providing the capability for up to 17 simultaneous AC field measurements around the crane boom, thus providing a field contour description of the ambient 60 Hz field during power line approach. Use of multiple sensors deployed on all sides and over the length of the crane boom also provides accurate measurements on fields of arbitrary polarization.

The logistics of taking such a large group of measurements would normally be rather complex and tedious for the instrumentation operator. The SwRI system, however, is provided with a multi-processor control architecture to establish the concurrence of measurements in time, and the sequential distribution of the measured data to a master control center, all under computer control. In effect, the operator is working with a total of up to 17 individual field sensor systems, but the system appears (to the operator) as a single control panel, AC field strength instrument.

Another significant feature of this system is the use of a capacitive electric field sensor for each of the remote field probes. Since the reception of 60 Hz electrostatic fields is very inefficient

with dipole or monopole-type antennas (the antenna length being much shorter than a small fraction of the wave length), a capacitive plate sensor shown in Figure 4 was utilized at each remote probe to provide a reliable and efficient voltage transfer device and to produce a low profile sensor at each point on the crane boom. The use of a high impedance input amplifier at each remote probe location also allows the use of a rather small (3 inch square) capacitive plate field sensor. This ensures that the sensor effective size will not interfere with the AC fields being measured.

A design consideration which arises when making quantitative field measurements around crane booms is the need for a wide dynamic range system. This is due to the large range of field strength values anticipated for the various power line configurations under test (e.g., 13.8 KV to 69 KV) and the range of distances between the probes and power lines (e.g., 15 ft. to 130 ft.). The wide dynamic range is provided in each remote probe by a compression amplifier having a transfer response curve approximating the function $V_{out} = K \left(V_n \right)^{1/2}$ where K is the gain of the compression amplifier.

2. Electronic System Design Concepts

All of the electronic assemblies developed under the Phase II program utilized state-of-the-art circuit design and components to provide tremendous system flexibility and simple operation. The instrumentation is, in effect, a five-computer network configured as shown in Figure 5. The master computer, which also contains the operator control panel, normally resides in the cab of the crane on which the measurements are to be taken. Each of the remote task computers in turn has the capability for connection of up to five remote field probes, and is programmed to acquire data from these probes upon command from the master computer. A complete set of schematic diagrams for the Electrometer can be found in Appendix A.

One of the significant design features of the Electrometer is the distribution system of commands and remote data along the boom of the crane. In order to provide the minimum in wiring harnesses and system cabling, the data transfer technique along the boom is serial multiplexed with each computer talking over a single one-way party line. This design feature allows a boom cable having only four wires to be used to connect the entire system together. The signals on each of these wires are: (1) ground, (2) +12 Volts, (3) serial "up boom" data, and (4) serial "down boom" data. In addition to providing a simplified cabling arrangement, the serial data transfer system provides for later expansion to more than four remote computers.

The capability also exists to delete remote processors when necessary. This will allow instrumentation of very small cranes where the full array of remote field probes is not needed. The deletion of remotes requires no operator interaction other than the simple disconnection of the unnecessary probes and remote processors.

FIGURE 4. CAPACITIVE PLATE SENSOR

Remote
Processor

Remote
Processor

Bi-directional
Data Link

Electric
Field
Probes

Remote
Processor

Remote
Processor

Digital
Recorder

Clock

Master
Computer

RS-232 port

Math
Processor

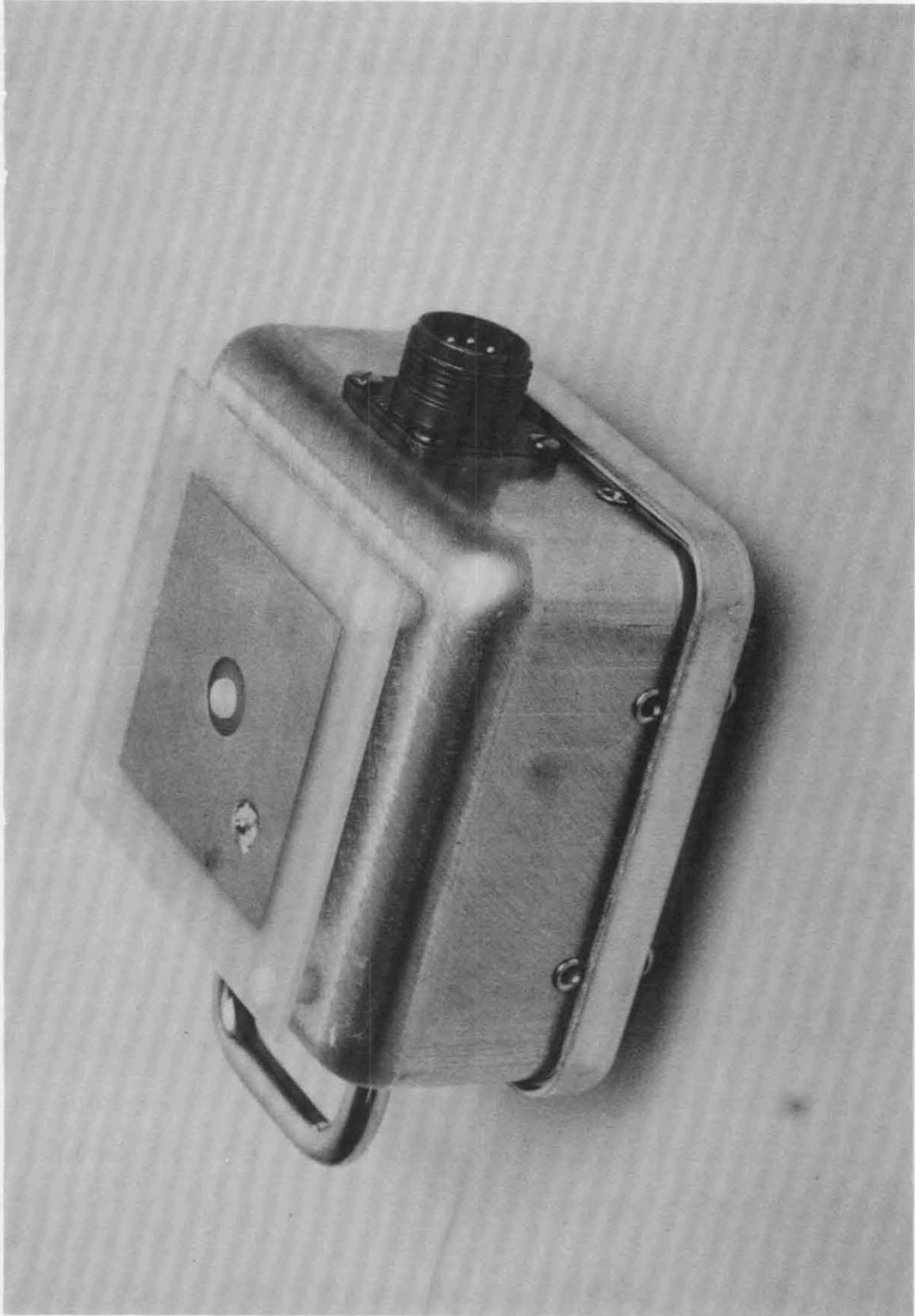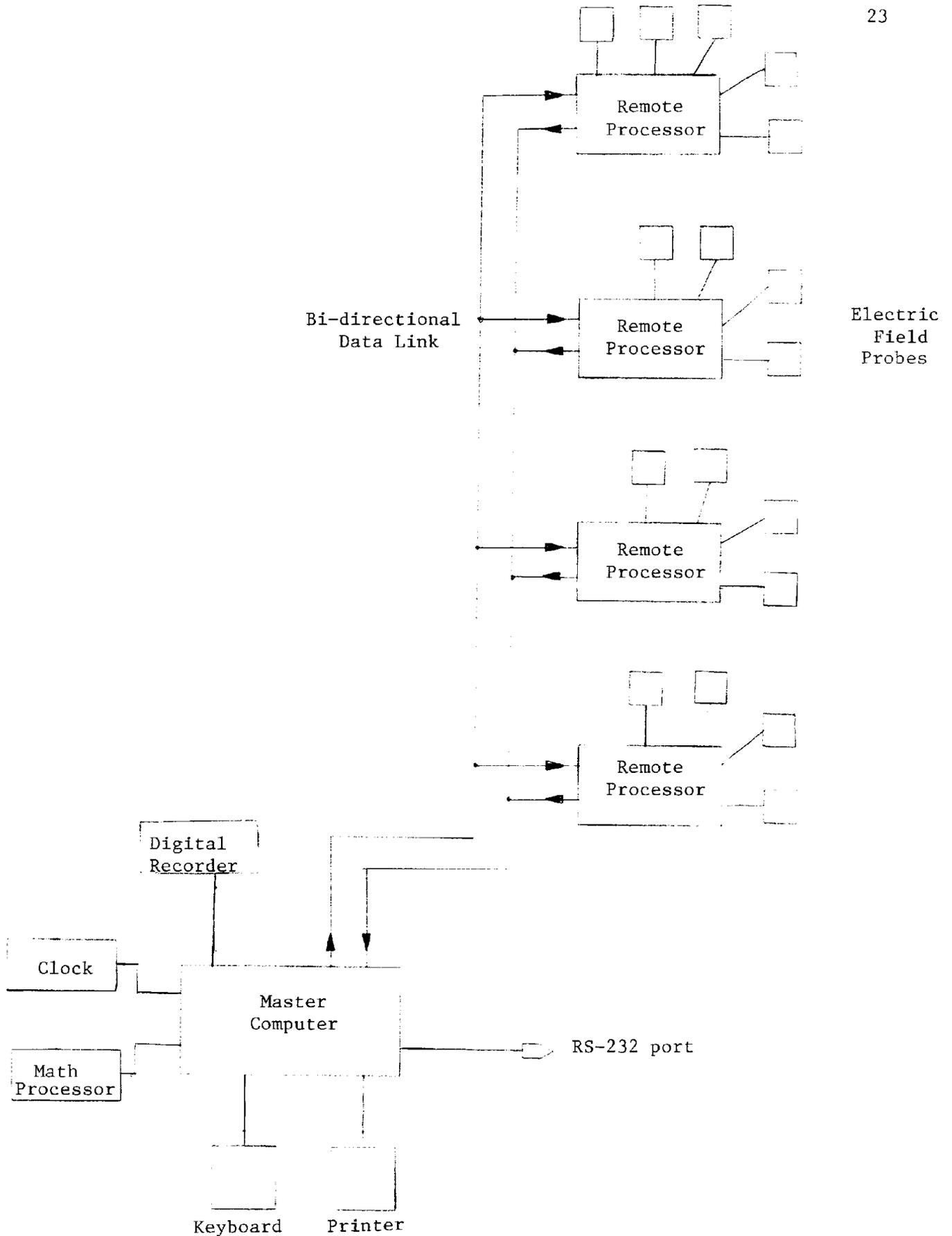Keyboard   Printer

FIGURE 5.   SYSTEM BLOCK DIAGRAM

It should be pointed out that while the computer network in Figure 5 looks rather complex for operator control, the software in the master computer is written so that the operator need only control the single master computer through the operator control panel. All testing of the remote computers and associated data collection from each of the remote probes is controlled automatically by serial data commands transferred along the boom of the crane under measurement.

During normal operation, when the operator desires to initiate data acquisition, the master computer queries each of the four remote task computers which in turn samples data from each of its four or five electric field probes. After the simultaneous data acquisition has occurred, the master computer begins to sequentially query each task computer for the resultant measured field data. This data is transmitted down the crane boom in a processor sequential manner via the serial data line to the master control unit (master computer) where it is processed and scaled according to calibration data, then printed, and finally recorded on the internal magnetic tape system. A feature added to the printer and recording system for increased data file management capabilities is the master computer internal real time clock and operator defined numeric header. With each data set taken, i.e., each time data acquisition is commanded, the time (hours, minutes, seconds, days, month, and year) and a 14-digit header, defining the site and crane orientation, is printed by the internal printer mechanism for a paper record and recorded on the magnetic tape system for later file identification. The combined file identification system is the equivalent of named and dated data files for later processing, analysis, and archiving of data. A complete measurement set for 17 probes, including automatic internal self checks requires nominally 5 seconds.

3. Electronic System Implementation

a. Remote AC Field Probe

The electric field probe shown in Figure 6a and 6b consists of five separate electronic selections as shown in the block diagram in Figure 7. The signal received by the capacitive sensor probe is buffered by the high impedance input, source follower amplifier, with positive AC feedback to increase the effective AC input impedance to 30 megaohms. The buffered signal is then filtered by a three-pole passive 60 Hz filter to remove extraneous high frequency signals and input noise. The buffered filtered signal is amplified and compressed by the compression amplifier. The characteristic transfer function of this amplifier is $V_{out} = (V_n/A)^{1/B}$ where B is nominally 2. The effect of the exponent on the transfer function is to increase the dynamic range of the probe, thus allowing measurements of widely varying fields from less than 10 volts/meter to more than 3000 volts/meter. The output of the AC compression amplifier is converted to an AC proportional direct current level by the RMS converter. The AC proportional rectified signal is then
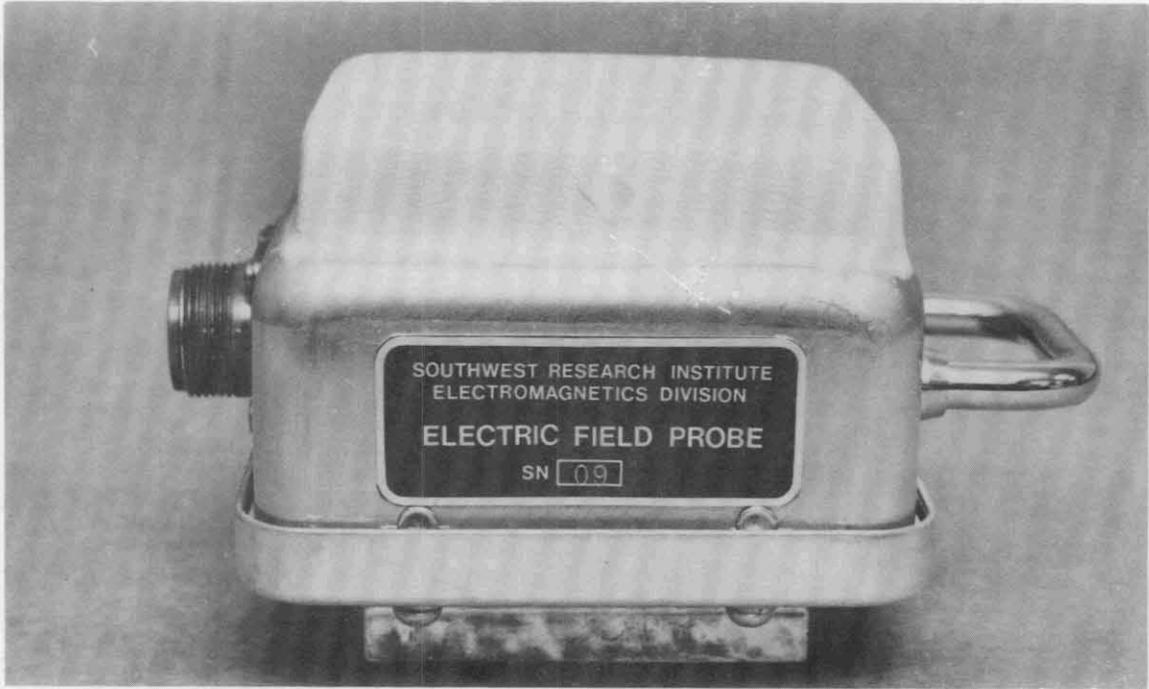
a. Field Probe

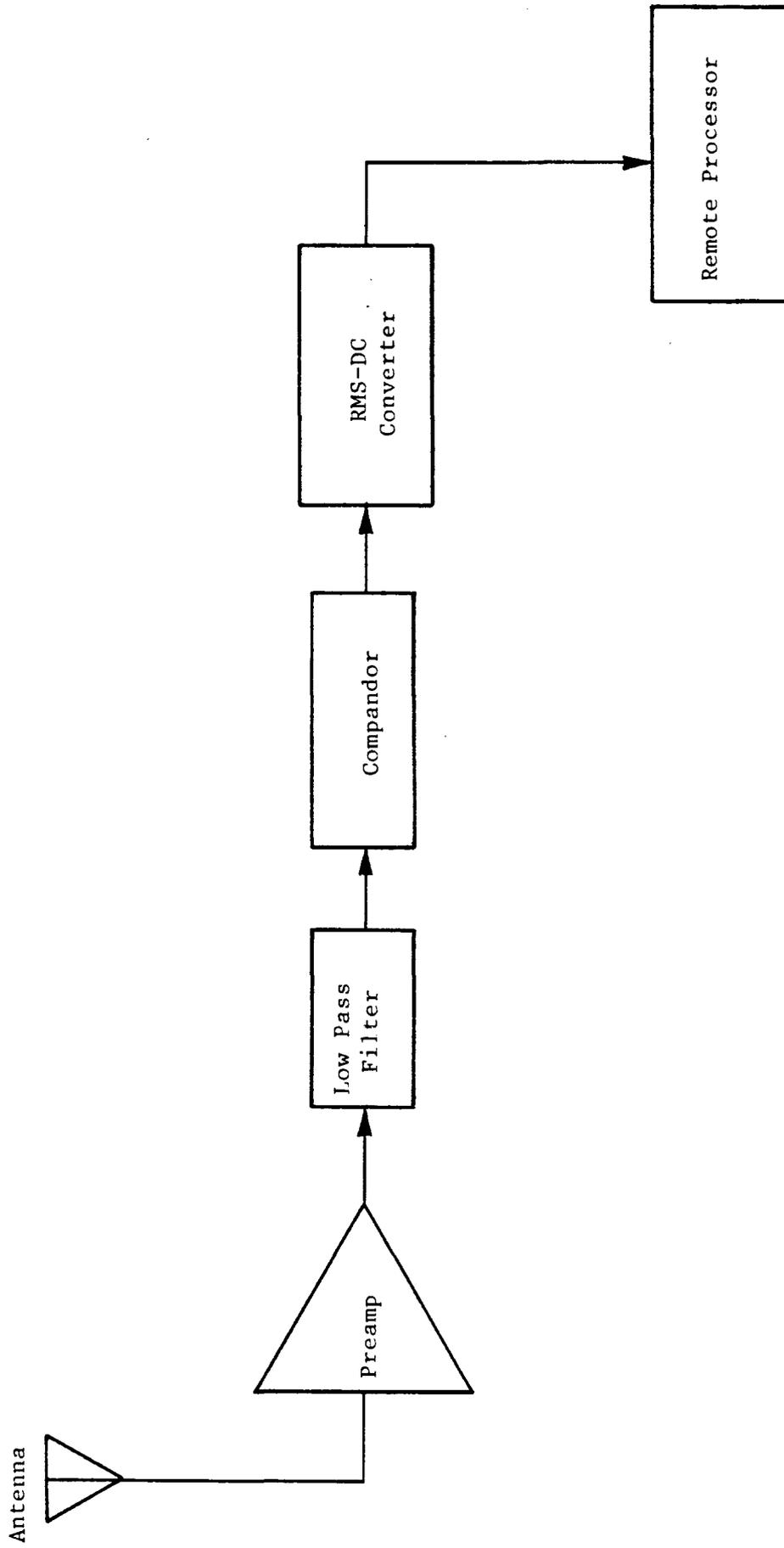b. Magnetic Attachment Bracket

FIGURE 6. ELECTRIC FIELD PROBE

FIGURE 7. BLOCK DIAGRAM--ELECTRIC FIELD PROBE

transferred through a short length of cable to the remote processor (task computer) for digitization and subsequent transferral of the measured field data to the master computer.

The typical transfer characteristic of a remote analog probe is plotted in Figure 8. The characteristics of all the 17 remote probes supplied with the Distributed AC Sensor Electrometer are nominally within 15% of the measured curve.

b.   Remote Processor

The remote processor shown in Figure 9a and 9b, functions as a data management and interface unit between the individual remote electric field probes and the master computer. The task of each remote processor (given by the master computer) is to digitize the electric field potential values from up to five electric field probes and transmit the corresponding digital data, along with the operational status of each probe, to the master computer. This function is accomplished in each of the remote task computers by a 6500/1 single chip microcomputer. The software, which is identical in each remote processor computer, checks the serial "up boom" data line between it and the master computer for the receipt of its particular task address. When it determines that its specific address has been transmitted along the "up boom" data line, it sequences through the five electric remote field probe connectors, checking for the presence of probes, testing connected probes for proper operation by injecting a calibrated amplitude 60 Hz test signal into each probe, and comparing the resultant output of each probe with a preset threshold tolerance. If a probe is not connected or the probe malfunctions due to a component failure, the probe output signal which is proportional to the AC calibration signal will fall outside these threshold boundaries. In this instance, a fault condition will be serially transmitted to the master computer on the "down boom" data line at the request of the master computer.

If the integrity checks are positive (the probes are connected and the calibration output falls within the required threshold band), the remote processor then digitizes the electric field value measured at each probe and, upon command from the master computer, transfers the data in binary form along the "down boom" line. A complete description of the operational software is provided in Section D.

c.   Master Processor

The master computer processor functions as the system controller and instrument input/output device to the operator. It is responsible for (1) sequentially accessing the four remote processors in data collection, (2) commanding simultaneous data acquisition and integrity test, (3) determining calibration constants and scaling factors for the measured electric fields, (4) printing the resultant data on the internal impact printer, and (5) storing the measured data
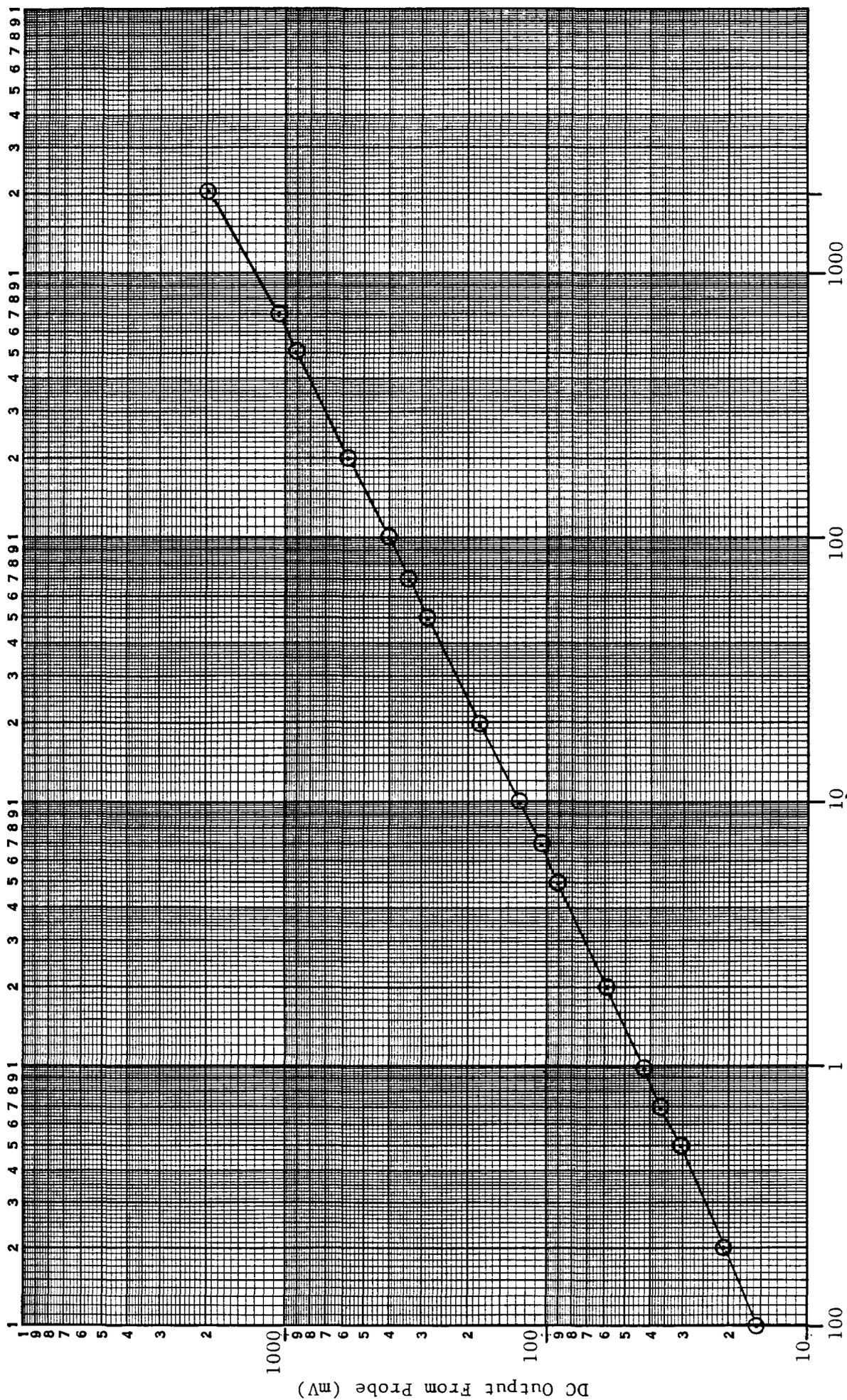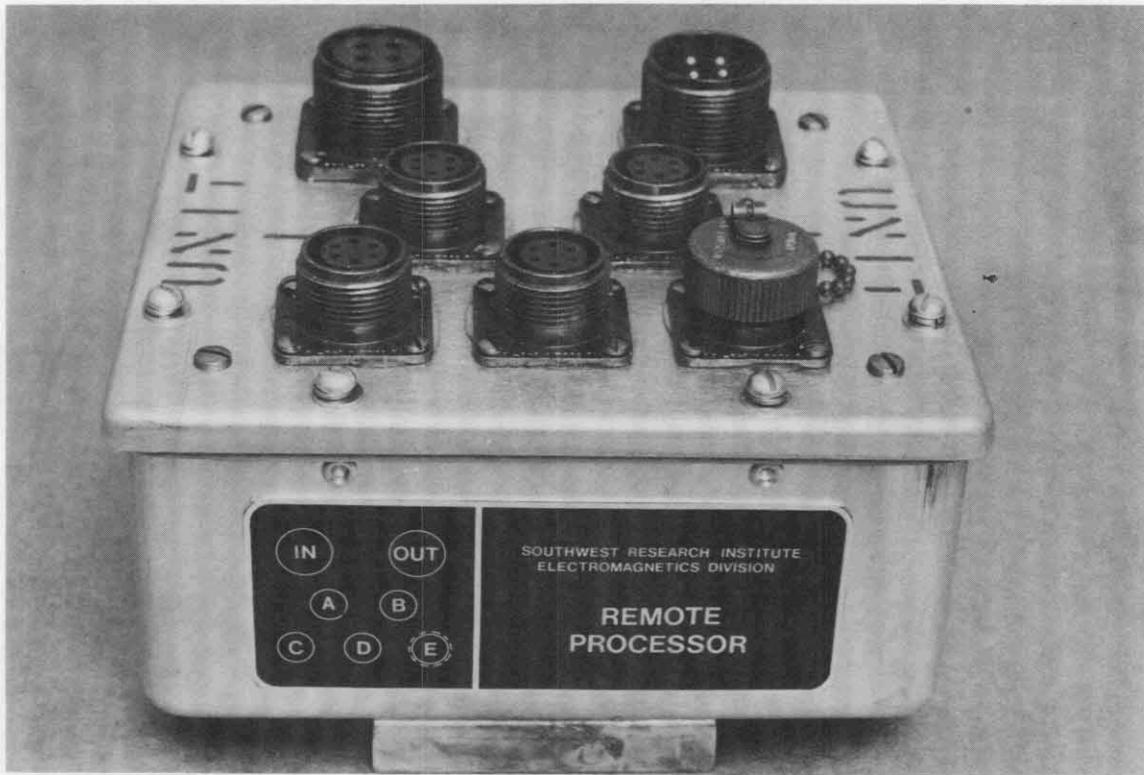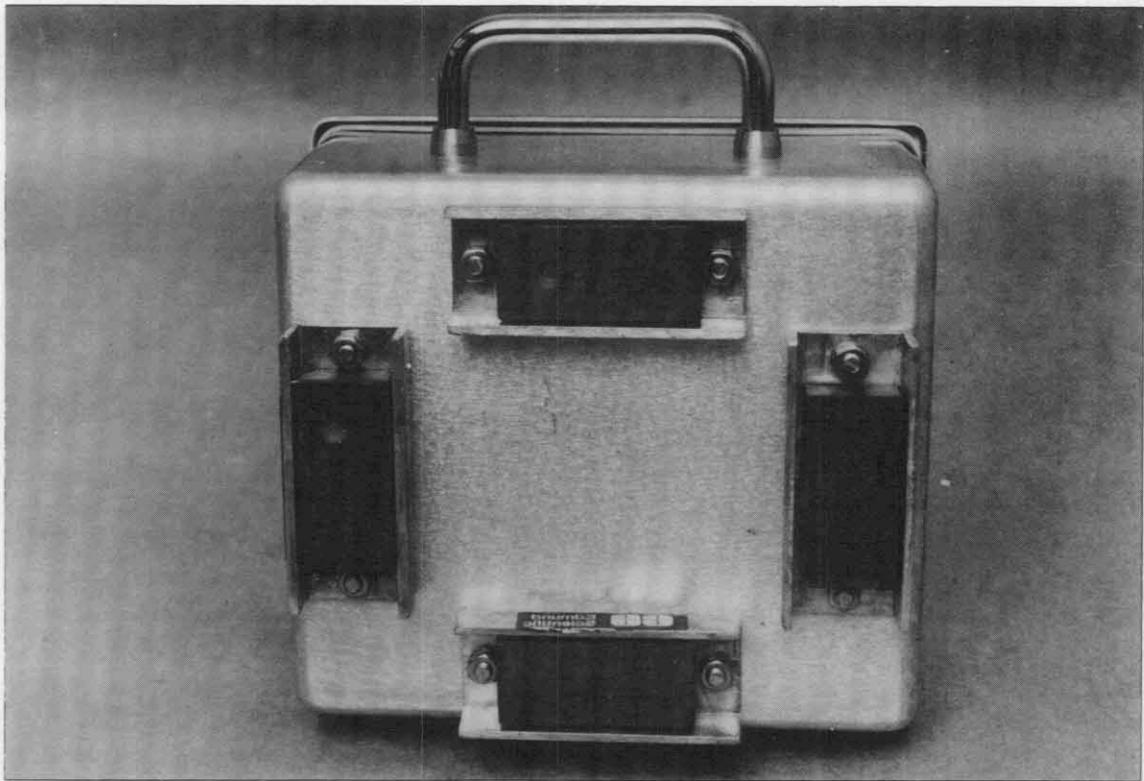
FIGURE 8. FIELD PROBE TRANSFER CHARACTERISTICS

a. Processor Package and Connectors

b. Magnetic Attachment Bracket

FIGURE 9. REMOTE PROCESSOR

on the internal magnetic tape recording system. The master computer for the Electrometer is shown in Figure 10. The operator controls, printer, and magnetic tape recorder can be seen on the front panel along with annunciator lamps to signal system operation. Figure 11a and 11b show the master processor chassis removed from its portable container. All circuitry and electromechanical components are readily accessible for maintenance and component removal and replacement.

System calibration was accomplished by measuring the transfer characteristic of each probe at 8 known electric field intensities varying from 1 to 3000 volts/meter. These calibration points were programmed into the master computer memory and are used by the master computer in calculating measured electric fields. The master computer converts the raw digitized electric field data to volts/meter by finding the two calibration points closest to the raw data and solves for the variables in the probe transfer function $E_{field} = B \ (V_{raw})^A$ using these calibration points.

A sample graph showing the typical transfer function of all probes was shown in Figure 8. The straightline response on log-log paper demonstrates the power response characterization capabilities. Typical variability from unit to unit is $\pm 15\%$.

The application of the known calibration field to each probe can be accomplished in the field by the use of the capacitive plate test fixture developed at SwRI for the remote probe system. The capacitive plate field generator shown in Figure 12 consists of two aluminum plates each measuring 24 inches by 24 inches spaced .1 meter apart. The grounded plate is cut out so that each remote probe may be placed within the capacitive plate system with a known distance configuration. Although this field calibration method may be somewhat awkward on larger cranes, it does allow the operator to verify all operating parameters and confirm calibration factors for critical field measurements.

Accuracy of the individual electric field probes were measured after calibration using the capacitive plate field generator shown in Figure 12 and a Precision AC Meter Calibrator. The accuracy measurements were made at fields between the calibration points which should give the worst case error. Graphs of the accuracy curves are given in Appendix B.

d. System Cabling Techniques

The cabling for the entire system (shown in the lower left corner of Figure 1) is relatively simple, considering the complexity of the system configuration. Each remote field probe is connected to a remote processor (task computer) by a six-foot length of five-conductor cable. One added conductor is supplied in this cable group to allow the remote computer to query for probe presence
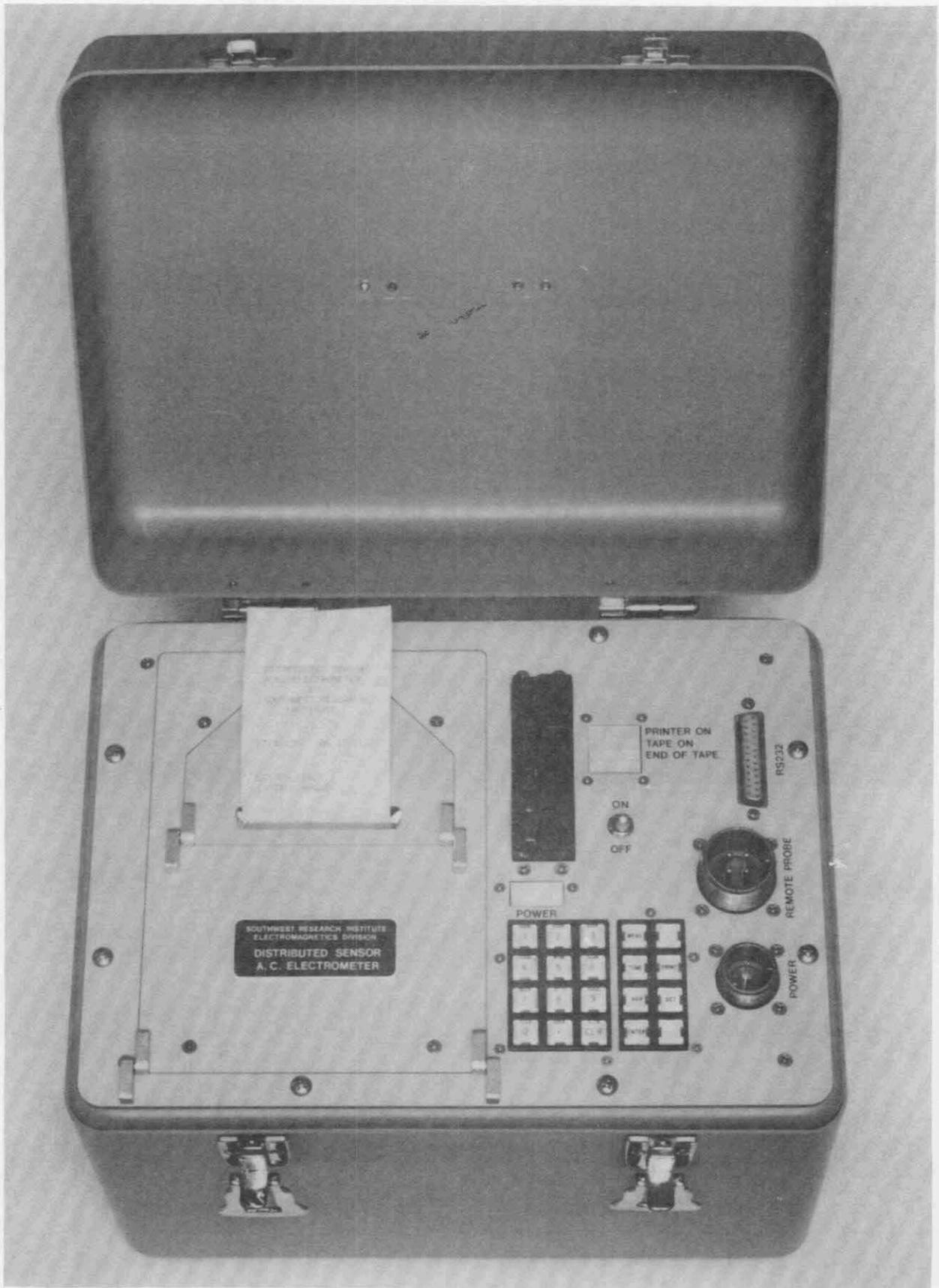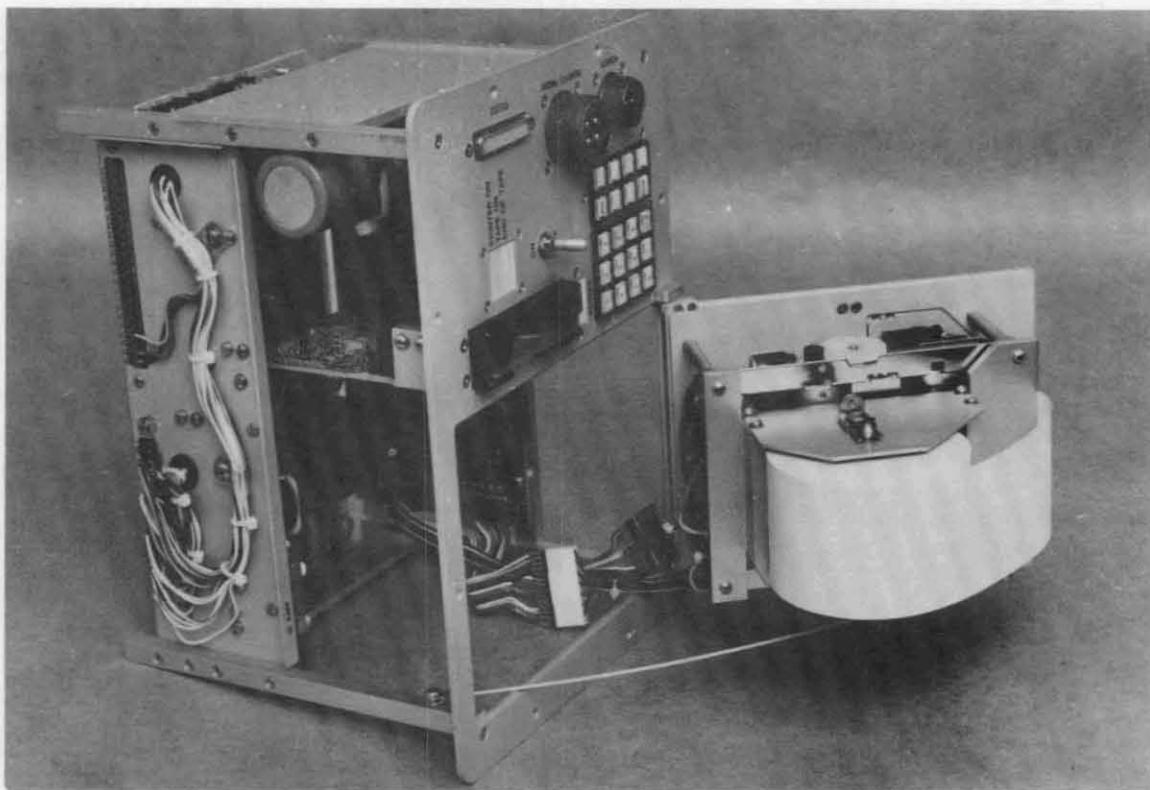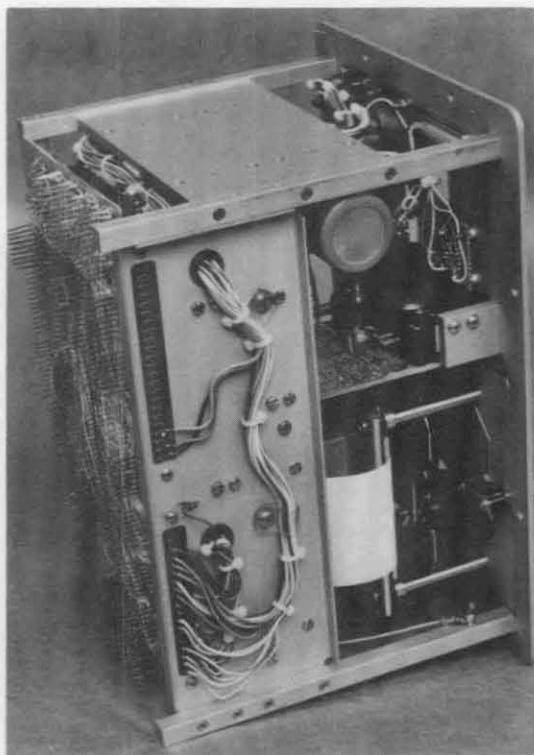
FIGURE 10.   MASTER PROCESSOR AND CARRYING CASE

a. Front and Side View

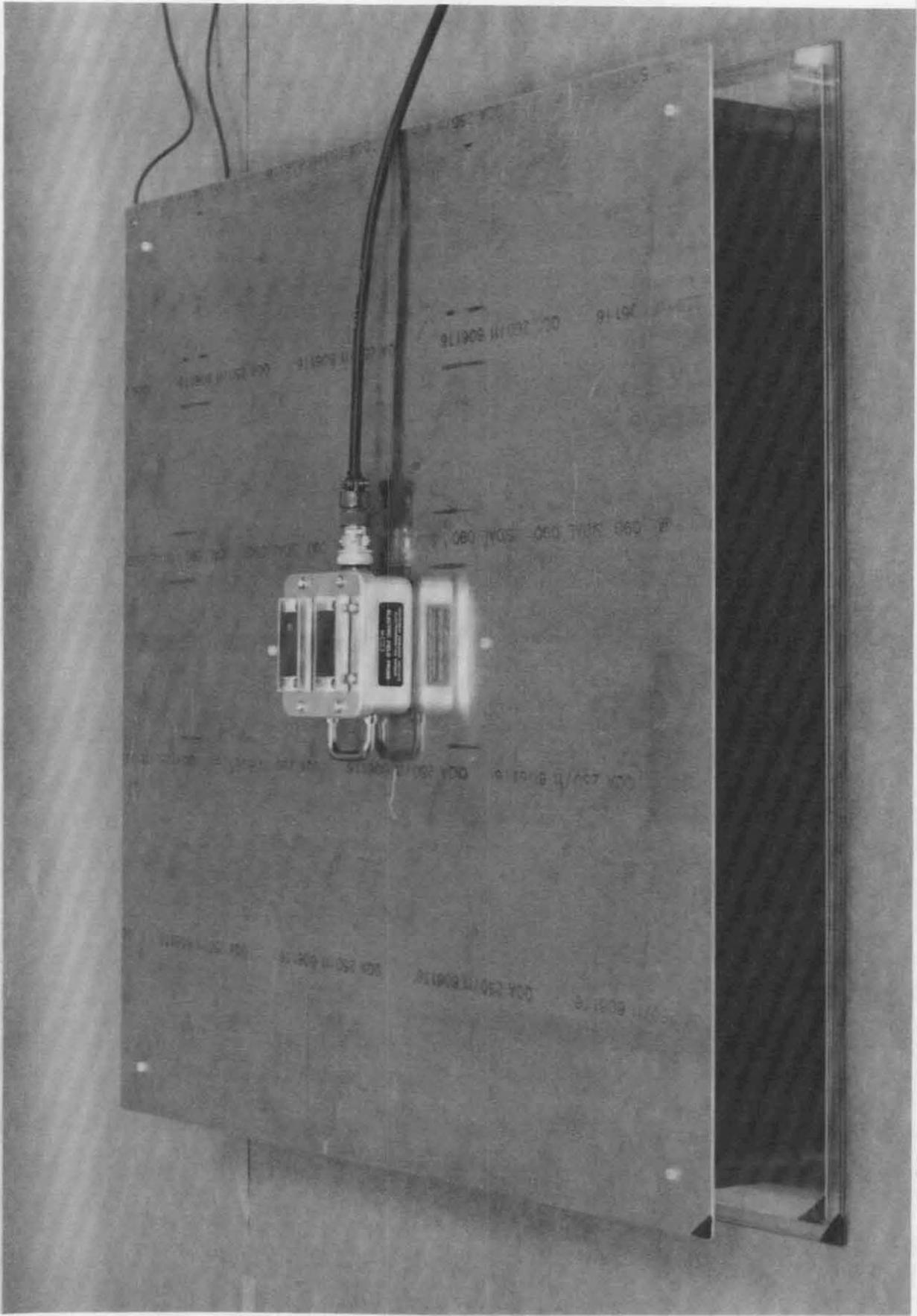b. Bottom and Rear Panel View

FIGURE 11. MASTER PROCESSOR

FIGURE 12. FIELD PROBE CALIBRATION FIXTURE

during the measurement process. In this manner, the remote computer can determine if a probe is connected and malfunctioning or simply not connected to the connector. This feature allows the system to be used with a variable number of probes connected, providing a versatile data acquisition capability.

The longer cable consists of four segments, three at 25 feet in length and the fourth at 35 feet in length, is used to interconnect the remote processors and the master computer control unit. This durable four-conductor cable extends from the cab of the crane under measurement to the tip of the boom being measured. Connection is by weatherproof, military standard screw-on type connectors.

4. Software Design and Implementation

a. Software Design Concepts

The software utilized in the Electrometer is written in 6502 assembly language code. The main function of this software is data collection, data conversion, data recording, and output.

There are basically two software packages which run independently of each other. The first of these is utilized in the remote processors and is primarily responsible for data collection/ conversion and testing the remote field probes status and integrity. The second software package is utilized in the master processor. It is responsible for communication and command of the remote processors, data reduction and conversion, and hard copy and recording of data on cassette tape. To aid in the data reduction and conversion process, an AMD 9511 arithmetic processor has been incorporated. This hardware device performs fixed and floating point arithmetic and a variety of floating point transcendental operations.

The software in both processing units is written following a modular software design concept. The modular concept is the development of functional subroutines, each assigned a particular task. These subroutines are linked together in a main line program which accomplishes the desired function. This type of design leads to easy modification of existing software operation and allows future addition of new features.

b. Flow Chart of Operation

During data acquisition, two independent, but interactive, software programs are running in the distributed sensor system. The master computer contains a system controller-type software which tasks and queries each remote computer for measured field data, then sequentially prints and records the reported data from each remote processor. The flow chart of the master computer operation is given in Figure 13.
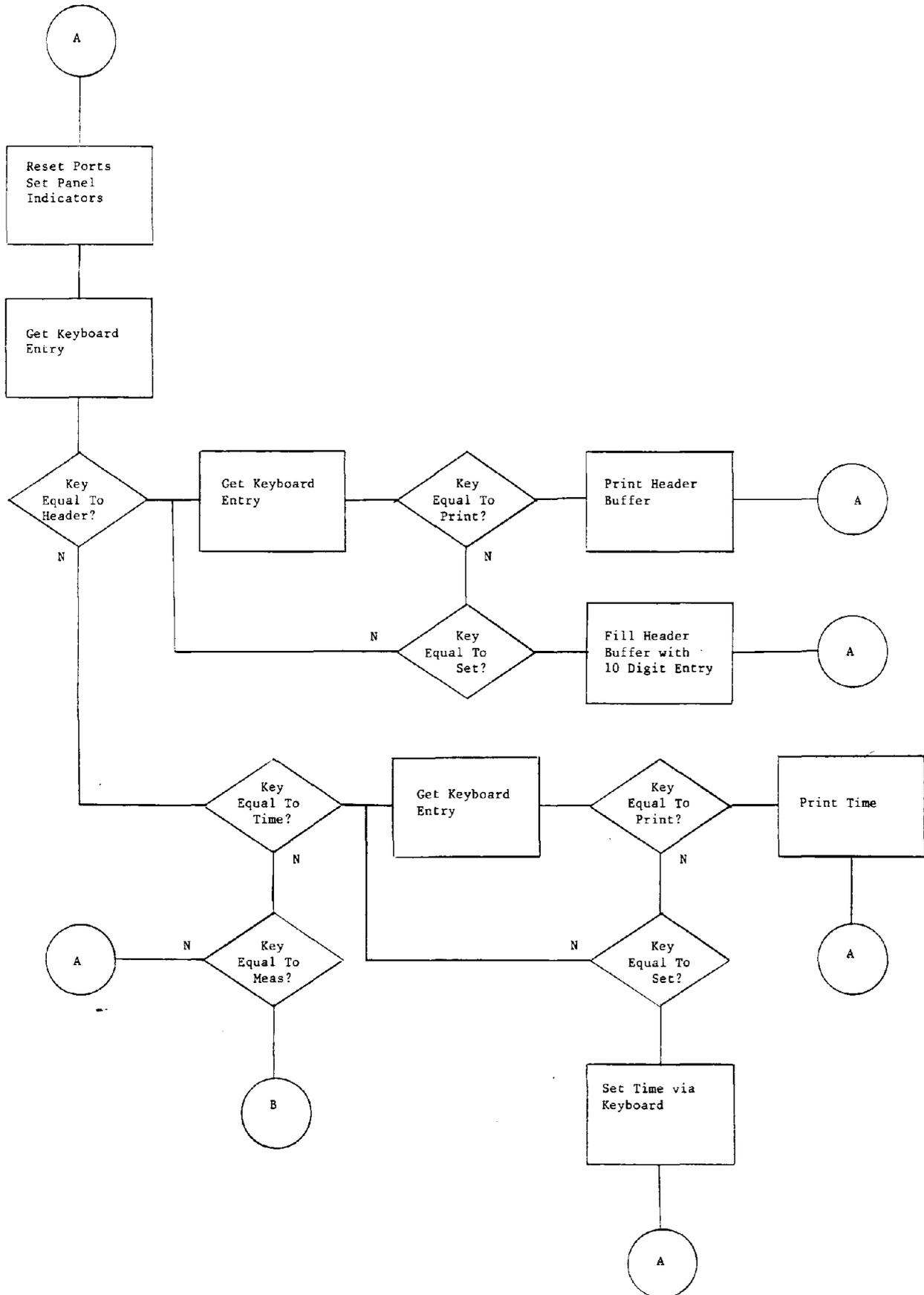
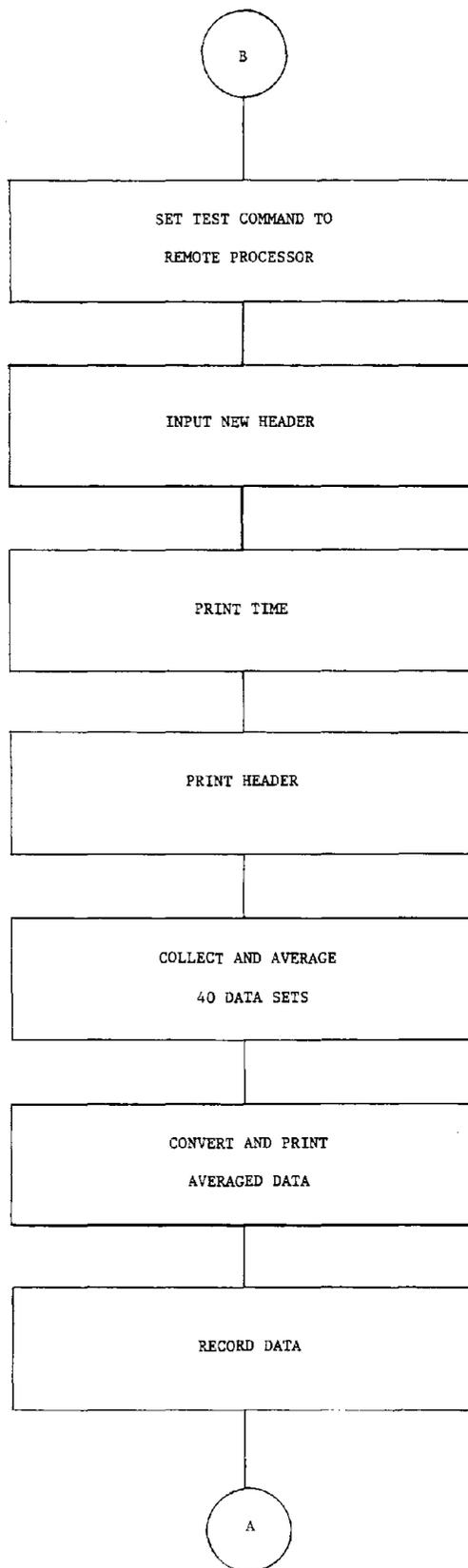FIGURE 13.   MASTER COMPUTER SOFTWARE FLOW DIAGRAM

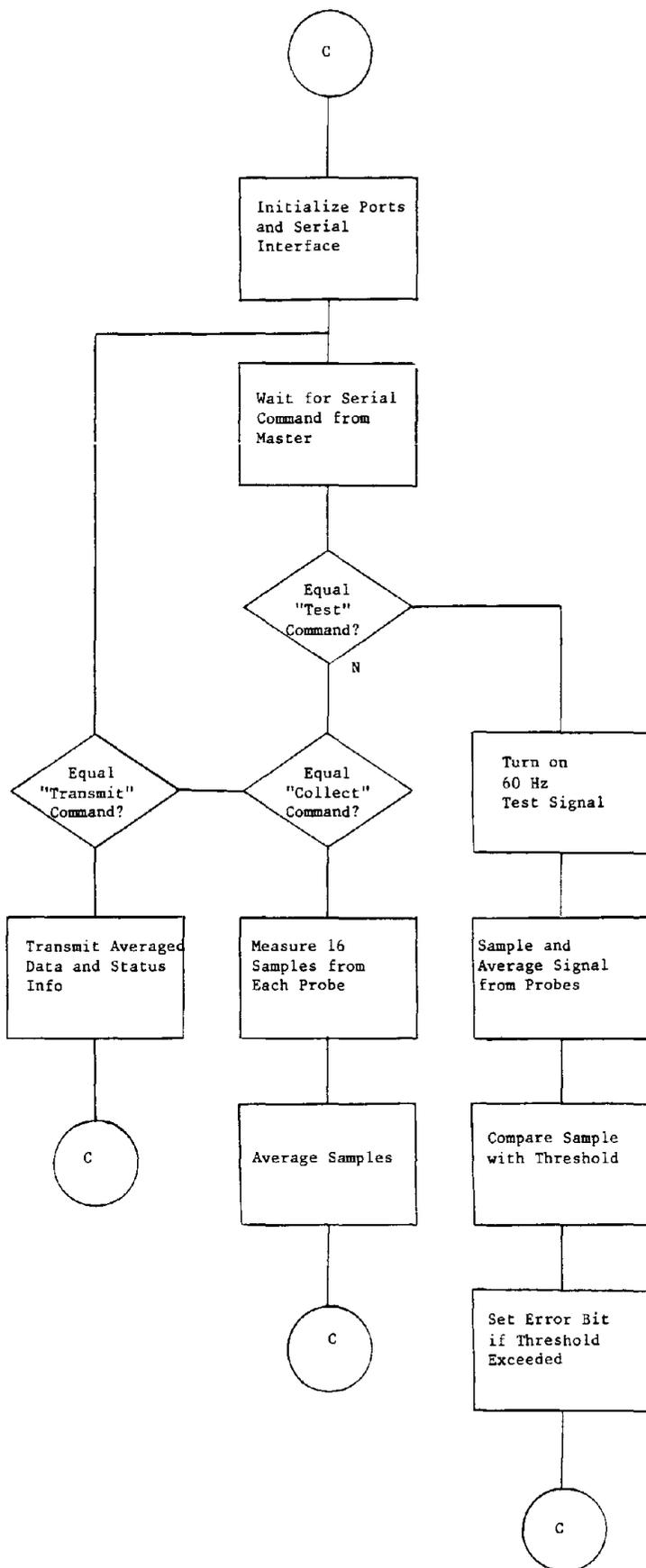FIGURE 13. MASTER COMPUTER SOFTWARE FLOW DIAGRAM (CONT)

FIGURE 14.   REMOTE PROCESSOR SOFTWARE FLOW

The primary operating mode of the master processor is in the keyboard query loop where the master computer awaits operator commands. From this point in the program, the operator can command data acquisition, header or time print out, or header or time information entry. If data acquisition is commanded, the master computer signals over the "up boom" data line for all remote processors to perform self-test and acquire field data. After a delay of nominally 5 seconds, for awaiting the acquisition of self-test data from all probes, the master computer begins to sequentially query the remote processors for individual field strength data from each remote probe. As the data is acquired, the master computer stores the information for operator print out and serial data storage on the internal magnetic tape. Following the completion of data collection, the master processor returns to the keyboard query loop awaiting other operator instructions.

If the operator depresses the HEADER and SET keys, then the master computer requests a 14-digit header ID number from the operator for use in field data identification. The header identifies the azimuth and elevation of the crane boom, the distance of the crane from the power line and the site number. The header is stored temporarily for use on subsequent data sets collected along with the updated time and calendar information.

If the operator depresses the HEADER and PRINT keys, the master computer simply prints the most recent header entry. The TIME and PRINT keys do the same for the time of day and calendar information supplied from the internal time-of-day clock.

The second software system in operation during data acquisition is resident at each remote processor (task computer). The primary operation loop for the remote processors is the "serial wait loop" for "up boom" data. The remote processor continuously polls the "up boom" data line awaiting a command for either data acquisition or acquired field data transmission. The flow chart in Figure 14 illustrates the particular wait loop along with the remainder of the tasking software. Three sequential commands to the remote software processor are generated by the master computer when the operator depresses the MEAS key.

Any of three commands generated by the master computer can be expected to activate any individual remote processor unit. The "test" command forces all remote processors into a self-test mode with the calibration signal applied to the input of each remote probe amplifier. The data is taken in turn from each remote probe, then averaged and compared with a threshold value to determine correct operation and calibration for each probe. If any probe is found to be out of tolerance in amplification, a malfunction bit is set for later transmission to the master computer.

A second master computer command recognized by all remote processors is the "data acquisition" command. This command forces each processor to begin sequencing through the connected remote probes and digitizing the field values for 16 individual successive measurements. The 16 measurements are then averaged for each remote probe and stored in temporary buffer awaiting the processor "transmit data" command from the master computer.

The third master computer command encountered by the remote processors on the "up boom" line is the "transmit data" command for each individual remote processor. This command has an associated address corresponding to the individual remote processor, so that the "down boom" line is not simultaneously acquired by more than one remote processor. If a valid address is found for the data transmit command, then after a short delay, the addressed remote processor begins serially transmitting the digitized data to the master computer. Each data set transmitted to the master computer contains not only binary field strength data but status data concerning the connection and calibration of each of the connected remote field probes.

5. System Operating Procedures

    a. System Installation

         Installation of the Distributed Sensor AC Electrometer has been simplified by the incorporation of magnetic bases on each of the remote processor units and remote field probe units. Depending on the length of the boom to be measured and the particular orientation of field measurements desired, the processors and probes may be placed in an orderly equidistant fashion along the crane boom as shown in Figure 1. The system should be cabled with the 25-foot sections between each of the remote processors and the 35-foot section from the lowest remote processor to the crane cab which contains the master computer control unit. Since the probes have been individually calibrated, it is necessary to connect each probe to its appropriate remote processor and connector as described in Table 1.

         A power cable supplied with the master control unit should be connected to the power receptacle on the control panel at one end and clamped to a 12 volt or equivalent dc battery source at the opposite end of the cable.

                    WARNING: CONNECTION OF THE MASTER CONTROL
                    UNIT TO ANY BATTERY OR SUPPLY VOLTAGE WHICH
                    MAY EXCEED 14 VOLTS COULD LEAD TO POSSIBLE
                    DAMAGE OF THE MASTER CONTROL UNIT AND
                    ASSOCIATED REMOTE PROCESSORS AND FIELD
                    PROBES.

         As with standard wiring practices for a power connection, the red clamp should be connected to the positive battery

TABLE 1.   PROBE INTERCONNECTION TABLE

	REMOTE PROCESSOR CONNECTOR				
UNIT NUMBER OF REMOTE PROCESSOR	A	B	C	D	E
	PROBE SERIAL NUMBER				
1	01	02	03	04	None
2	05	06	07	08	None
3	09	10	11	12	None
4	13	14	15	16	27

terminal and the black power clamp should be connected to ground or the negative 12 volt battery terminal.

  b. Data Acquisition Techniques

        After all installation connections are properly made and the power cable is attached to a 12 volt source, the system will, on POWER ON initiation, begin its reset sequence by printing out the heading identification label, followed by the date and time of day from the clock as shown in Figure 15a. Before the actual beginning of the first data set, the operator should verify that a blank data cassette is inserted in the tape unit on the front panel of the master computer.

        After the POWER ON sequence, the operator should position the boom of the crane into the desired position with respect to the power line and depress the MEAS pushbutton on the right two-column keyboard of the operator control panel.

        The system will then print the header ID previously entered. At this time, the operator enters the current header information as discussed in Section 5.c and presses the ENTER key. This initiates the measurement process which requests a self test of the electric field probes by the remote processor, acquires and averages 40 samples of electric field data (each sample being an average of 16 sequential measurements), converts the raw averaged data to volts/meter, displays the converted data on the printer, and archives the data on magnetic tape. An example of the data display format for electric field measurements is given in Figure 15b.

        If a probe is not connected to an associated remote processor, the appropriate identification number will not be printed on the data listing. If that probe is connected and malfunctioning, however, by erratic gain or out-of-tolerance operation, then the system will print malfunction beside the probe ID number and will not supply measured field value for that probe.

  c. Printout Instructions and Interpretation

        In addition to the capability of field strength measurements, the system has several other command keys which allow the operator to set predetermined variables within the measurement system. The TIME PRINT mode prints the time of day and calendar upon operator command, while the decimal point key (.) provides a single line feed each time it is depressed. The HEADER PRINT command provides for visual confirmation of the internal header.

        If the operator depresses TIME and SET in that sequence, the system will respond with:

                  ENTER TIME THIS ORDER
                  HR,MIN,DAY,MO,YR

a.

b.

FIGURE 15.   POWER ON AND FIELD MEASUREMENT PRINT OUT.

At this point the operator should enter the requested data with leading zeros included. For example, the entry sequence:

1604   25   1281

will preset the internal calendar clock to a time of 4:04 P.M. and a date of 25 December 1981. As the final digit is entered for the year, the system will respond to the operator by typing PRESS ENTER TO SET. As the ENTER key is pressed, the system will record and display this time and begin operation from that point. Note that the clock is a 24-hour clock and should be set accordingly. Internal battery backup of the calendar ensures infrequent time setting.

The header can be entered by pressing the HEADER and SET command keys or upon entry of the MEAS command. This first step in the header entry sequence is the display of the previous header. The format for the display is shown below.

ELV.AZM.DIST.SITE
060.030.0020.0003

The first row displayed is abbreviations identifying the parameter displayed on the second row. The four parameters are elevation, azimuth, distance and site number. To change the elevation value, the new value is typed on the numeric keyboard. After the elevation is entered, a decimal point (.) is typed to allow alteration of the next parameter.

If no modification is required of a particular parameter, a decimal point (.) is typed without entering any numeric values. If no further modifications are required, the ENTER key is pressed and the master computer exists the header set mode.

d.   Data Transfer from Magnetic Tape

After the electric field data has been logged on magnetic tape, it is necessary to transfer the recorded data to a general purpose computer for analysis. This is done by the master computer via an RS-232 port on the front panel. Data is read from the magnetic tape and transmitted serially over the RS-232 interface upon commands received over the serial port. Other commands which the master computer will respond to include finding the end of tape and exiting the computer command mode.

Entry into the tape access programs is made by pressing the DUMP key found on the front panel of the master computer. When the DUMP key is pressed, the master computer will respond by printing a menu describing the options available. An example of the menu is given in Figure 16a. The options available to the operator are 1) exit tape dump, 2) find the end of tape, 3) read and print one record from tape, 4) go into computer control and 5) set external RS-232 port baud rate.

a. Tape Dump Commands

b. Baud Rate Select Commands

c. Computer Control Commands

Figure 16. TAPE DUMP, BAUD RATE SELECT, AND
COMPUTER CONTROL COMMANDS

If the Exit Tape Dump command is entered, the system will return to normal operation. The Find End of Tape command searches the magnetic tape until the end of tape marker is found. The end of tape light is illuminated when this is accomplished. The Set Baud Rate command allows selection of the baud rate or speed at which serial data is transmitted over the RS-232 port. When this command is entered, the display in Figure 16b is printed. Selection of a baud rate from 300 baud to 9600 baud can be made giving compatibility with a variety of data rates. The entered rate is printed for verification of entry.

The Print One Record command allows access to data on the magnetic tape without an external computer or terminal. The data is read from tape and printed on the internal printer. Occasionally errors occur in the data reading process due to a faulty tape or factors during the recording process. In this case, the characters in question are replaced with asterisks (*).

The Computer Control command transfers control of the master computer to a host computer. The host computer controls the data transfer and tape transport function using the RS-232 serial port. The commands available to the computer are printed upon execution of this mode as shown in Figure 16c. Data is transferred in ASCII code and the same information displayed during the measurement process is read from tape. When no probe is present, a NOPRB is given in place of the electric field measurement and when a probe malfunctions the MLFCT code is given.

B.   Power Line Field Measurements

1.   Power Line Configurations.

The line configurations tested were all three phase and included the following combinations of voltage and geometry:

69KV   Vertical and delta.
34.5KV   Vertical and horizontal.
13.8KV   Vertical, horizontal and delta.

The lines were selected with assistance from the local utility, San Antonio City Public Service (CPS). They supplied maps of many potential locations, which were then visually inspected by project personnel. The main selection criteria were voltage, configuration, access, and absence of other primary conductors within 500 feet. However, the site 15 location was selected to include multiple power lines of various voltages. Measurements taken at this site documented the effects of interferring fields caused by multiple line configurations. There are few locations with vertical construction of 13.8 kV and 34.5 kV in the CPS system, and the sites selected were marginal in meeting the specified construction geometries.

The line heights configurations and voltages for the 17 sites surveyed are shown in Table 2. Figures 17 through 27 provide a brief narrative description and photographs (where available) of each site. In the table, the physical location of the primary conductors with respect to each other is given in the "Configuration" column (H for horizontal, V for vertical, and D for delta configurations). Exact details about the specific power line geometry and measurements are found in the site figures. The "Other Conductors" column describes the other grounded conductors present. These included guy wires, telephone and cable TV messengers and the vertical static drains attached to the poles. No sites contained secondary conductors.

2.   Measurement Procedures

The measurements were performed using an extendable boom crane, with the boom extended to a length of 50'from the pivot. The sensors were located in the following manner: Set #1 was on the main boom, 10' from the elevation axis. Set #2 was at the end of the outer section of the main boom, 20' from the pivot. Set #3 was at the end of the intermediate section, 35' from the pivot, and set 4 was located on the end of the boom. The sensors identified as A were located on the left side of the boom (as viewed by the operator), B was on top of the boom, C was to the operator's right, and D was below the boom. Set #4 was unique in that it also contained a sensor E which was located as near the tip of the boom as was possible, adjacent to the sheave for the main working cable. Figure 28a shows an example of the crane with sensors in place.

The other crane boom dimensions were:

Section:	Height:	Width:
Main	16"	12"
Second	14"	10"
Tip	12"	8"

The following measurement sequence was developed at site 1 and used throughout the tests. The crane boom was extended to a working length of 50' from the center of rotation to the tip of the boom where sensor 4E was located. The distance from the line was measured as the distance from the vertical plane containing the nearest primary conductor to the center of rotation of the crane boom.* The center of horizontal rotation and the elevation axis intersected on the pivot crane. This intersection was therefore used as the distance measurement point. Figure 28b illustrates the azimuth and elevation geometry nomenclature.

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*The distance measured here is not the one used for data analysis. The closest distance between the power line and the crane boom was calculated and used in presenting the measurement results.

TABLE 2. TEST CONFIGURATIONS 47

| Site #	Line Voltage (KV)	Config.	Line Height	Other Conductors
1A	13.8	H	28'	Neutral at 19'6".
1B	13.8	H	25'	Neutral at 22'6", Vertical static drain.
2	34.5	H	30'	Neutral at 21'6".
3	34.5	H	35'	Neutral at 26'6", Vertical static drain.
4	69	V	31'	Ground at 64'.
5	69	V	31'6"	Ground at 65', Tower 20' right.
6	69	D	40'6"	Ground at 20', 60'.
7	69	D	47'	Ground at 27', 65'.
8	13.8	V	27'	Neutral at 23', 36'.
9	13.8	D	25'6"	Neutral at 35'5".
10	13.8	D	27'	Neutral at 34', Vertical static drain.
11	13.8	H	29'	Neutral at 20'5", Vertical static drain on pole, 6' chain link fence.
12	34.5	H	30'	6' chain link fence, Neutral at 21'6".
13	34.5	H	31'	Fence, Vertical static drain on pole, Neutral at 22'.
14	69	D	45'6	Ground at 65', Perpendicular to the Meas. Line, 138 KV line across street.
15	34.5	H	37'8"	Street light cirucit at 29'.
	13.8	H	34'	3 grounds (Tel, TV, Neutral) from 20' – 28'; 138 KV parallel across street.
16	34.5	H	32'	Neutral at 23'6", Tel at 17'6", guy wire at 19'.
17	34.5	V	26'6"	Neutral at 23'.

Site 1
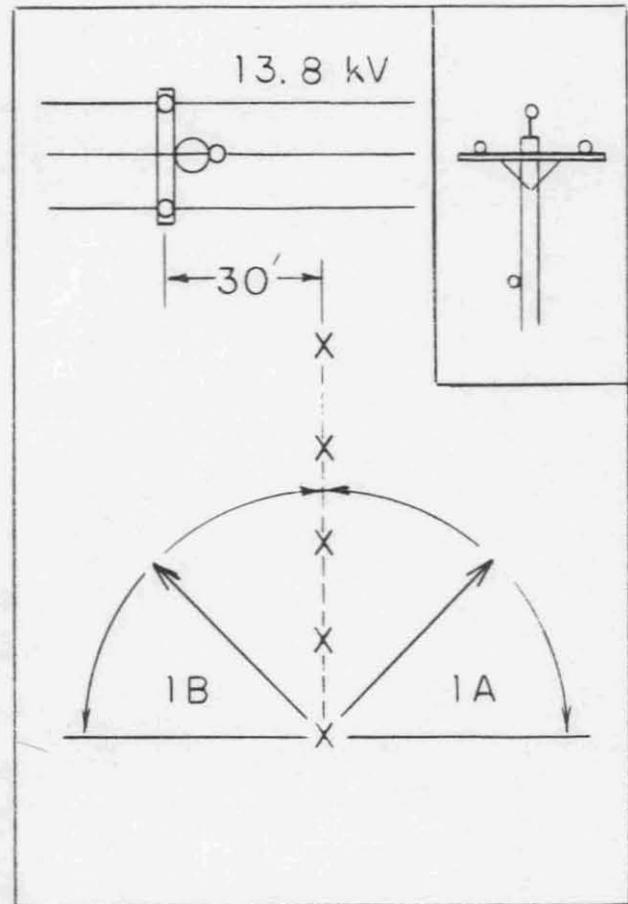
Power Line Configuration
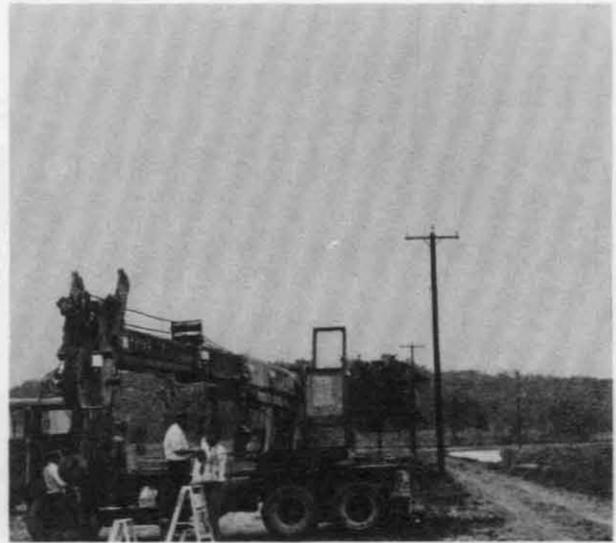
Site Description

Site 1 was located on the SwRI grounds and served as a convenient location to confirm the measurement procedures and to develop the most efficient measurement sequence. The effect of the static drain (vertical ground wire) attached to the pole was observed and the test procedure was modified to include additional measurements near grounded structures.

This power line configuration is a standard three-phase 13.8 kV installation. Two phases are located at the outer pin locations in an 8-foot crossarm on a wooden pole, while the center phase is mounted on the pole top. A low voltage neutral is pole-mounted 8 feet below the crossarm and a three-strand barbed wire fence 4 feet high runs directly underneath the line. Some brush also exists around the site, extending to 12 feet high. All measurement locations were in the clear except for 30' 30° which placed the second set of sensors in immediate proximity of a small Mesquite tree. Site 1A consisted of two crane booms being moved from the center of the conductor span clockwise. Site 1A consisted of the crane boom being moved from the center of the conductor span counterclockwise toward the vertical (grounded) support pole.
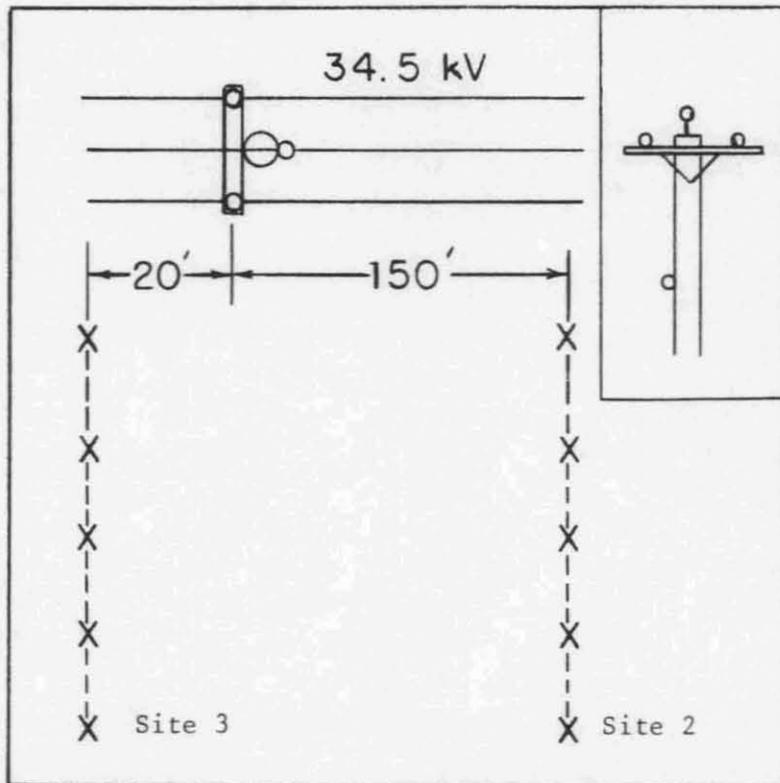
FIGURE 17. SITE 1 PHYSICAL CHARACTERISTICS
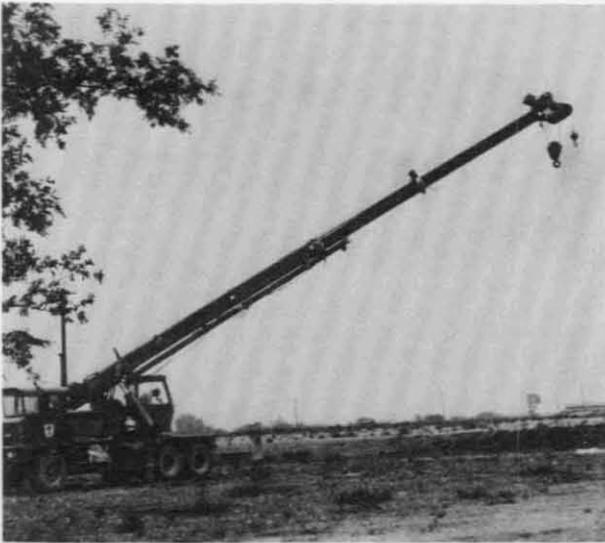
Site 2

Site 3

Power Line Configuration

Site Description

Sites 2 and 3 were located in a freshly cleared area which is to be developed into an industrial park. There were no trees, fences, or other structures within several hundred feet of the measurement location. The line structure was the same as Site 1 except the large insulators required higher voltage.
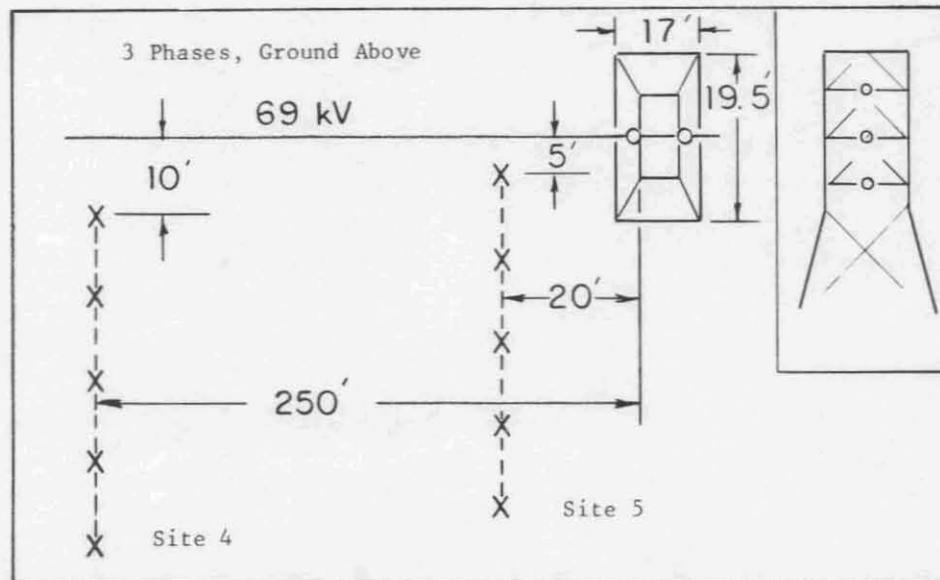
FIGURE 18. SITES 2 AND 3 PHYSICAL CHARACTERISTICS

Site 4

Site 5

3 Phases, Ground Above

69 kV

10'

250'

17'

19.5'

5'

20'

Site 5

Site 4
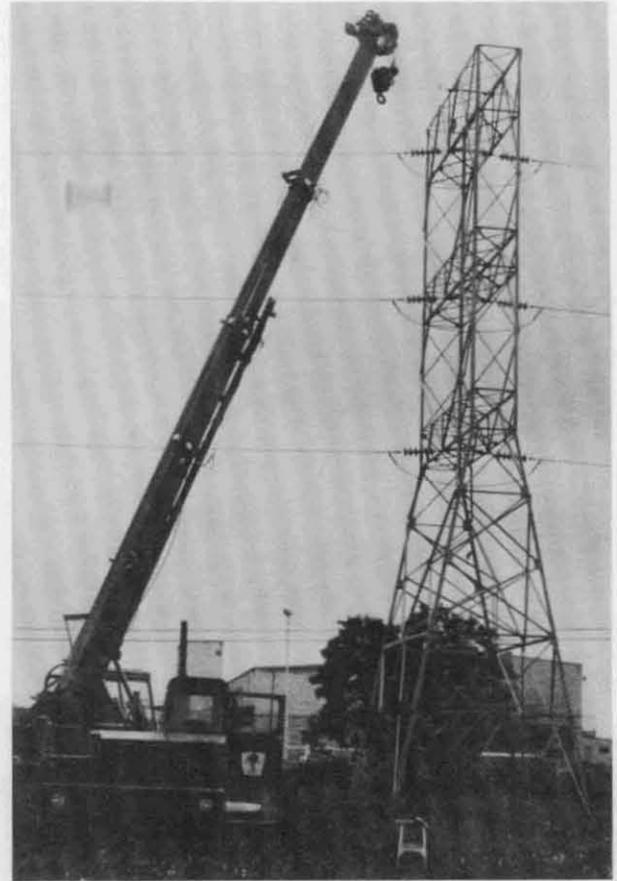
Power Line Configuration

Site Description

Sites 4 and 5 were located along an exit feeder from a small power generating station. The measurement location was nearly 2000 feet from the station and 1000 feet from other transmission lines. The line studied was carried vertically for 2500 feet from the power station to a corner tower where it made a 90° turn and became a delta configuration. The measurements were made near mid-span between the corner tower and the adjacent vertical configuration support tower (Site 4) and also in the vicinity of this tower (Site 5).
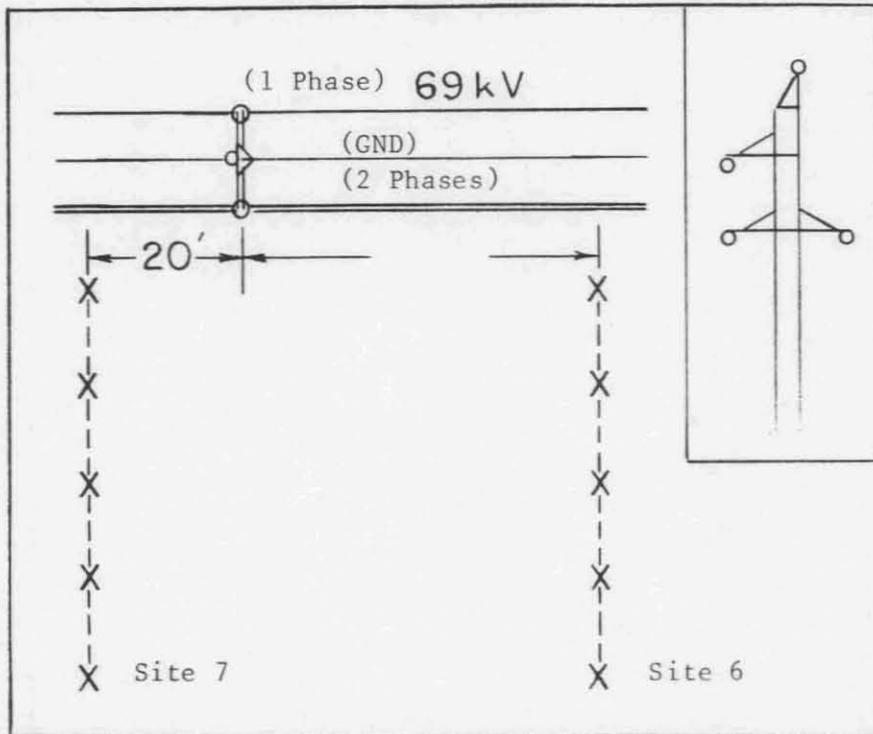
FIGURE 19. SITES 4 AND 5 PHYSICAL CHARACTERISTICS

Site 6   Site 7

(1 Phase) **69 kV**
(GND)
(2 Phases)

20'

Site 7   Site 6
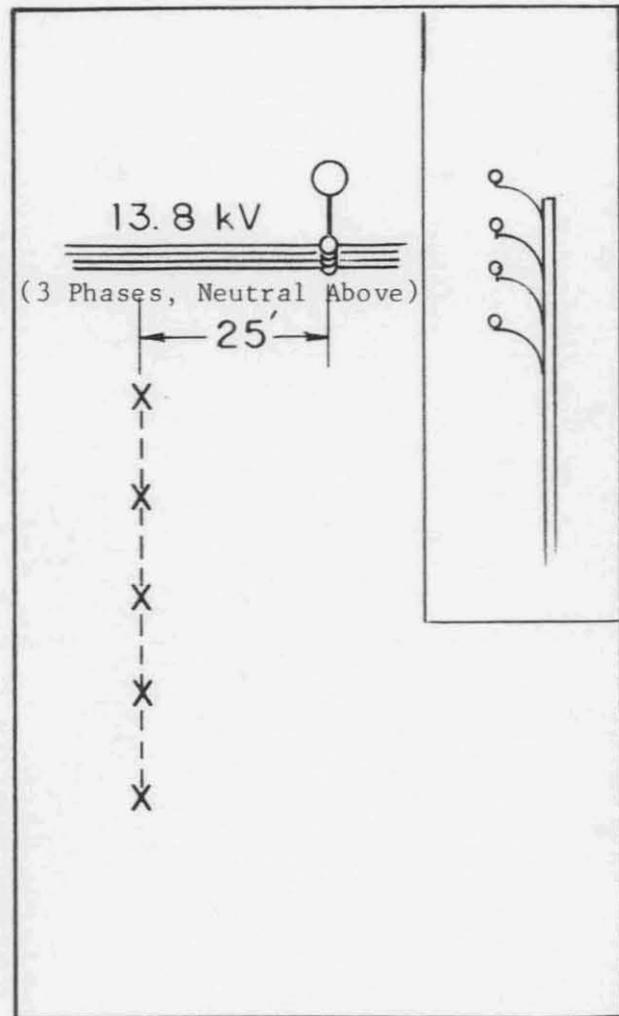
Power Line Configuration

Site Configuration

Sites 6 and 7 were located 1000 feet further along the same line as Sites 4 and 5 where the conductors were arranged in a delta configuration. The support towers were 12 inches square open steel lattice construction and two phases were supported in the same horizontal plane from an upper steel crossarm with the third phase supported directly below the near side phase of the upper pair. Measurements were made at mid-span (Site 6) and adjacent to a support tower (Site 7). A lightning wire ran along the tower tops above the primary phases and a telephone cable messenger was attached to the towers and ran some 20 feet below the primary phases.

**FIGURE 20. SITES 6 AND 7 PHYSICAL CHARACTERISTICS**
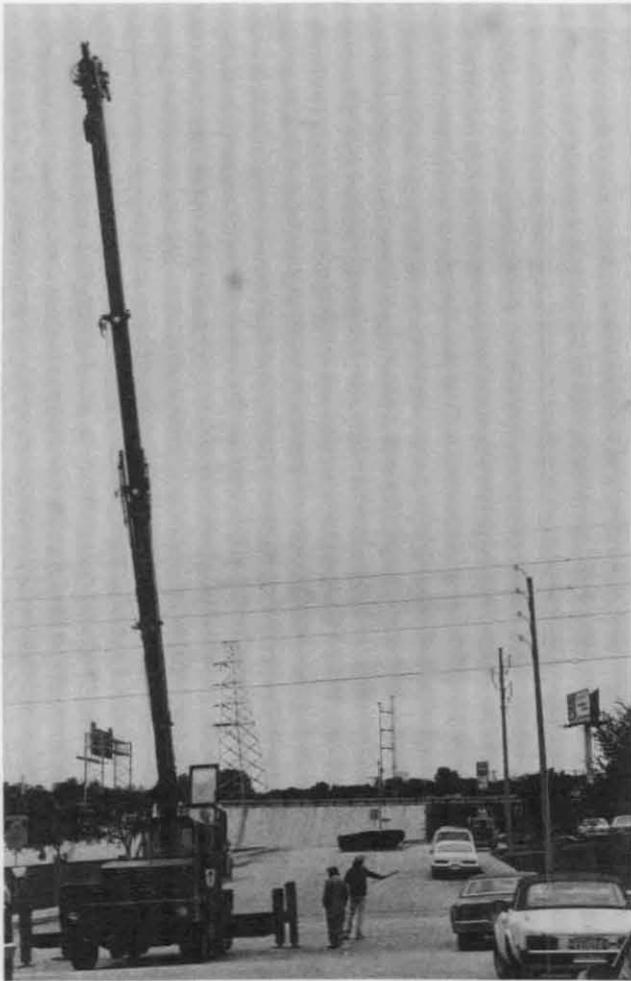
Site 8

Power Line Configuration

Site Description

Site 8 is in a developed office park and is in the vicinity of several buildings, trees, and other structures. The measurements were made in the center of a street perpendicular to the lines. The support structures were tapered hexagonal prestressed cement poles, approximately 12 inches in width at the ground and 8 inches in width at the top. A ground conductor was cast into the pole and exited at the neutral and pole top. There was a static drain above the conductors and a neutral below, all in the same vertical plane. Another circuit intersected the main line 30 feet right of the measurement location. The conductors are supported from the poles with projecting insulator brackets which space the lines about 14 inches from the face of the pole.
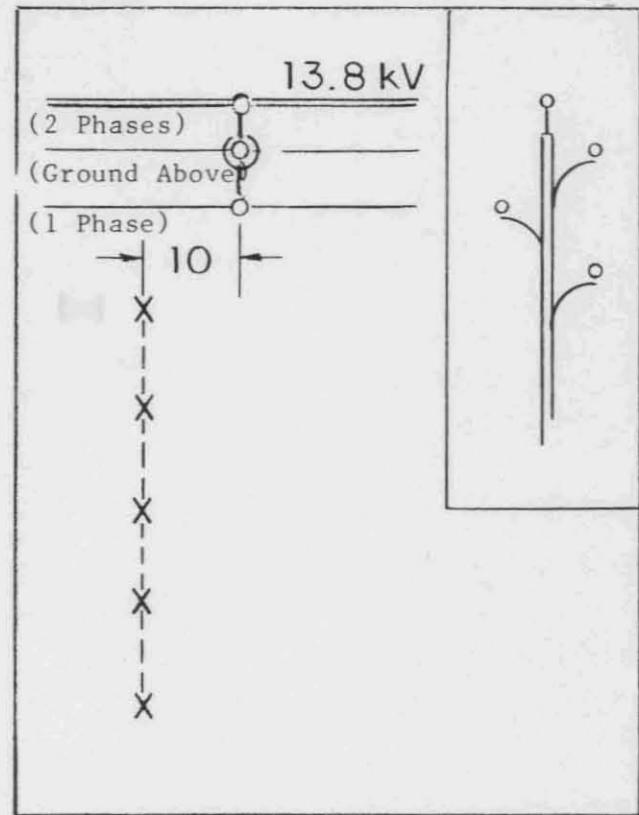
FIGURE 21. SITE 8 PHYSICAL CHARACTERISTICS
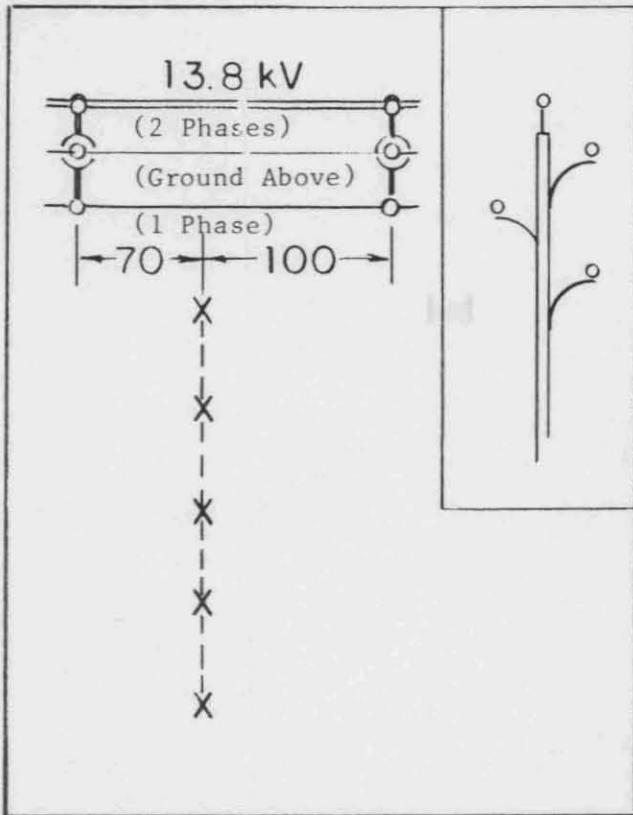
Site 9 Power Line Configuration

Site 10 Power Line Configuration

Site Description

Site 9 was in the same office park as Site 8 and was a location further along the same line where the construction was delta configuration. Two phases were supported from insulator brackets on the near sides of the poles and the third phase on the far side with elevation half-way between the near phases. A static drain was supported above the phases at the tops of the poles. The site was at mid-span, about 100 feet from either pole.

Site Description

Site 10 was in the same area as Sites 8 and 9 and was chosen adjacent to a support pole. In addition to the static drain cast into the pole, there was also a vertical 2-inch conduit containing underground primary feed attached to the pole. There was a static drain on top of the pole and the phase configuration was delta as at Site 9.

FIGURE 22. SITES 9 AND 10 PHYSICAL CHARACTERISTICS

Site 11

Power Line Configuration
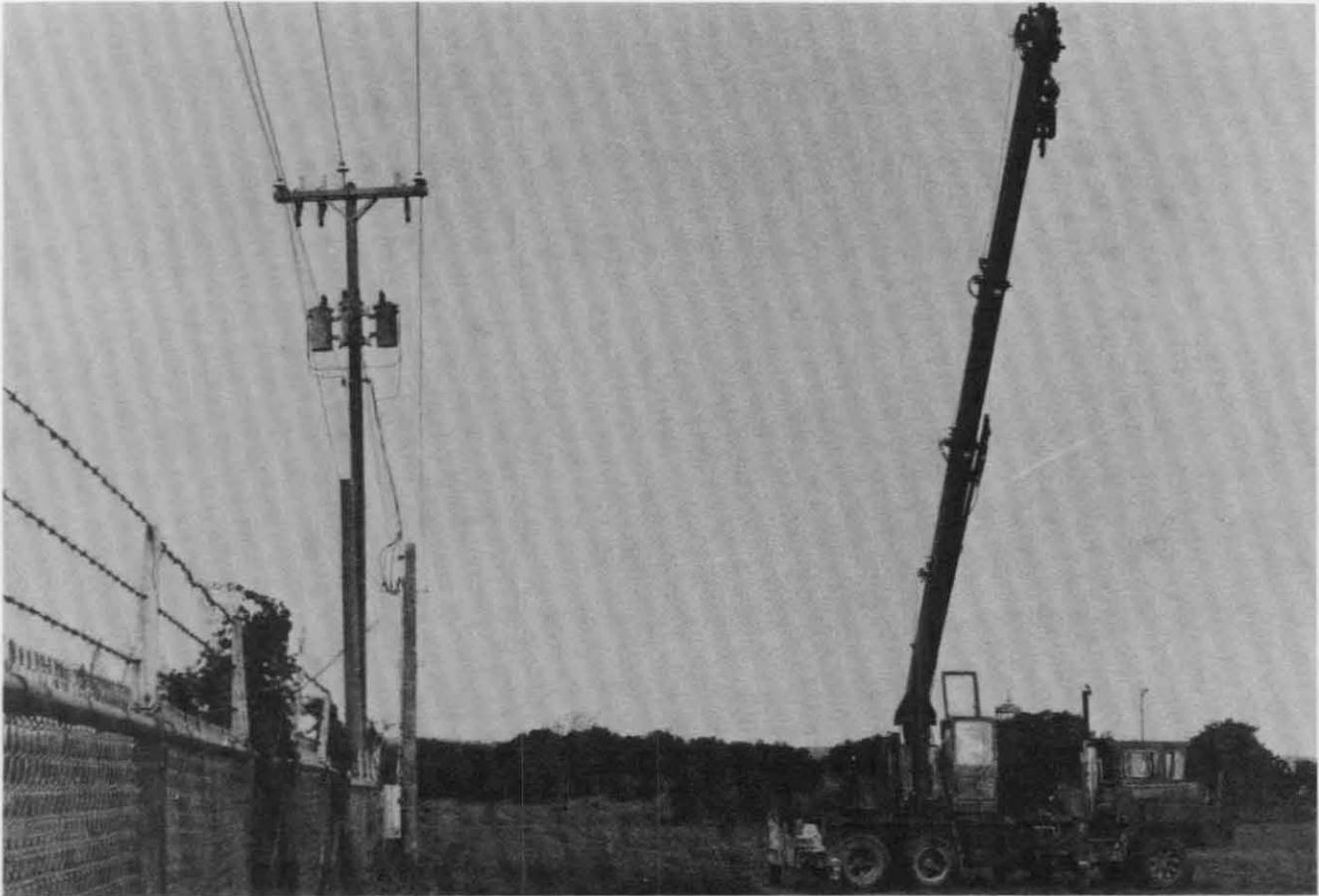
Site Description

Site 11 was chosen on the same line as Site 1, about 2500 feet away, where there was no vegetation. A 6-foot chain link fence runs under the line and the support pole contains a power transformer feeding an underground secondary through a vertical metallic conduit attached to the pole. The primary phase and secondary neutral configuration are the same as Site 1.
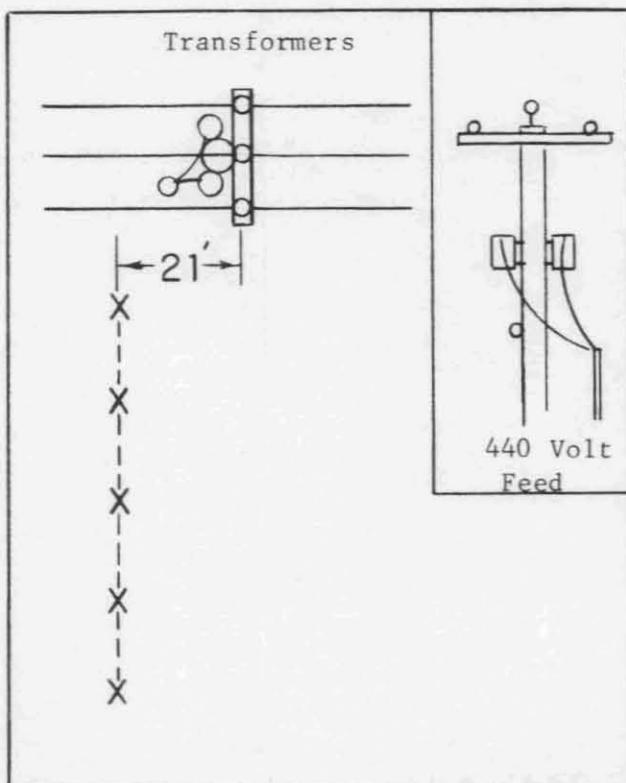
FIGURE 23. SITE 11 PHYSICAL CHARACTERISTICS

Sites 12 and 13

Power Line Configuration
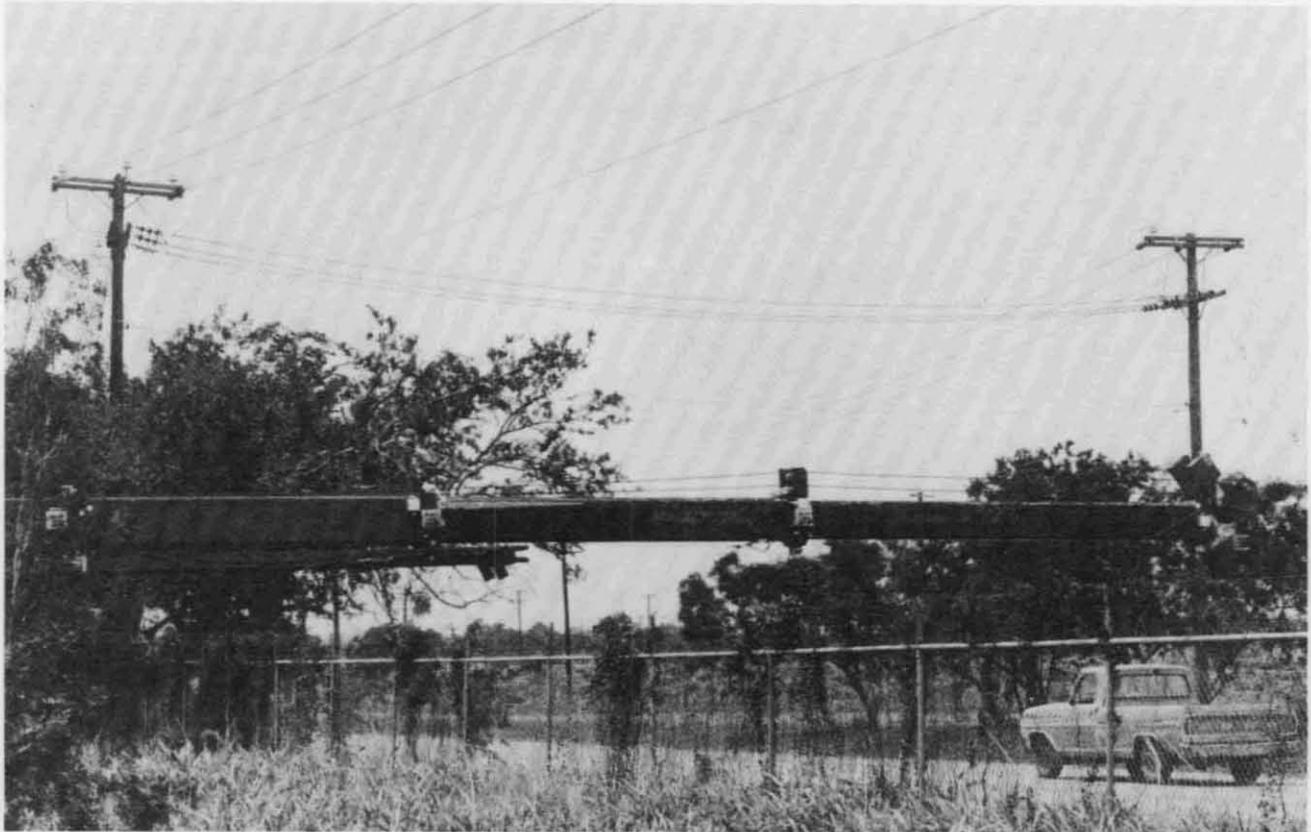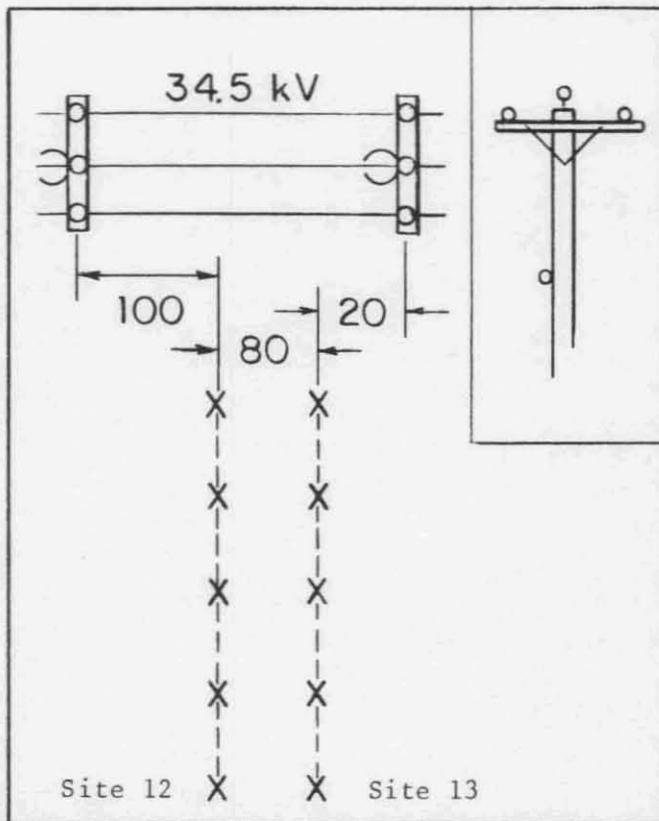
Site Description

Sites 12 and 13 were a standard con-
figuration 34.5 kV line with 8-foot
crossarms identical to the arrangement
described for Sites 2 and 3.   This
location had a 6-foot chain link fence
below the line. Measurements were made
at mid-span (Site 12) and adjacent to a
pole (Site 13) with a full-length static
drain wire.

FIGURE 24.   SITES 12 AND 13 PHYSICAL CHARACTERISTICS

Site 14
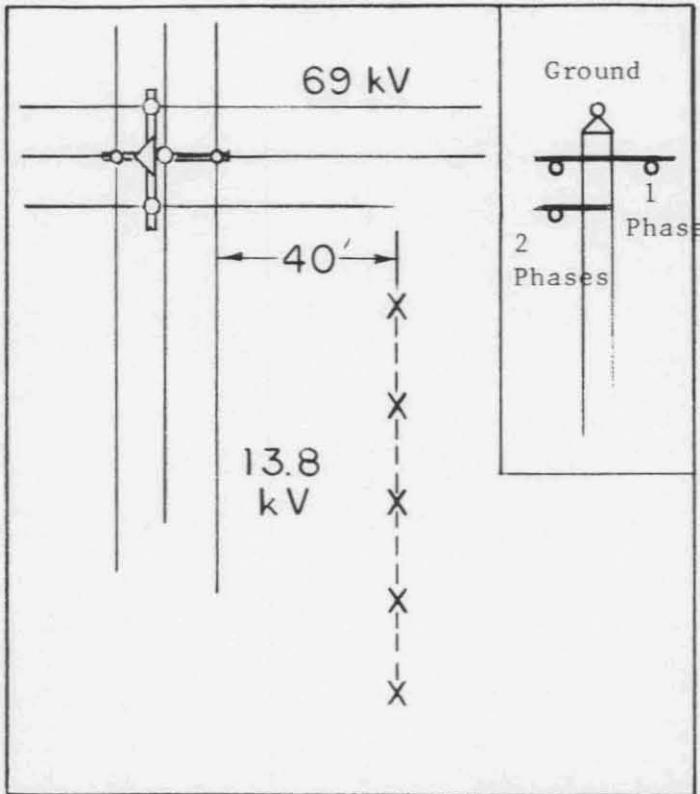
Power Line Configuration

Site Description

Site 14 was a more built up area along the 69 kV line described for Sites 6 and 7 and there was a perpendicular 13.8 kV line across the street from the line which was measured. All other configuration parameters were the same as Site 6.

FIGURE 25. SITE 14 PHYSICAL CHARACTERISTICS

Site 15
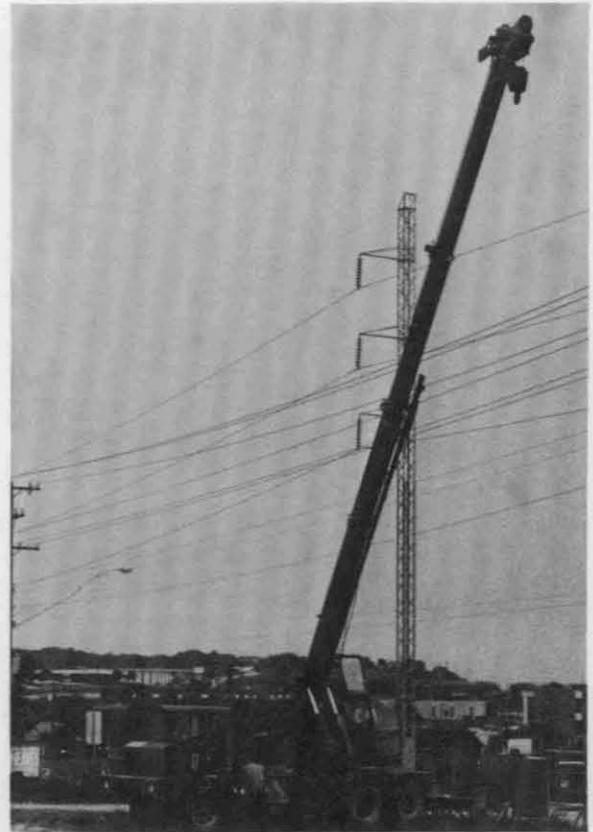
Site 15 (Alternate View)
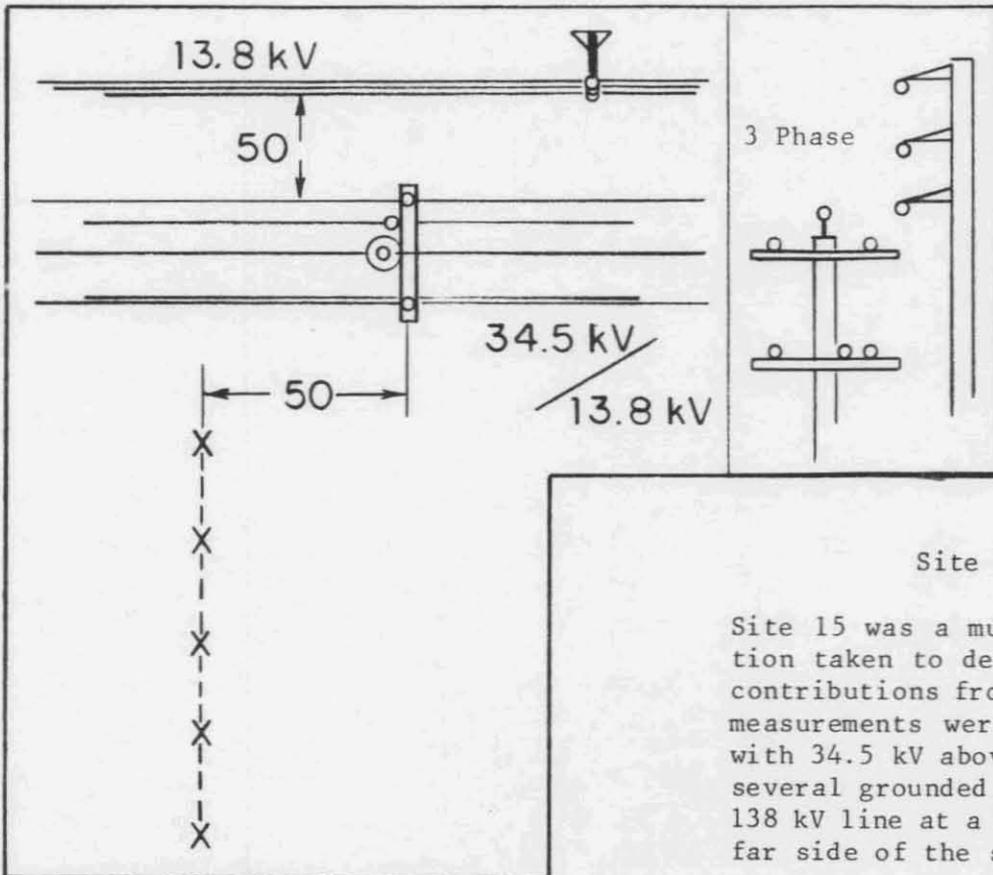
Power Line Configuration

Site Description

Site 15 was a multiple line configuration taken to determine the results of contributions from several sources. The measurements were made on a dual line with 34.5 kV above 13.8 kV. There were several grounded conductors below and a 138 kV line at a higher elevation on the far side of the street.

FIGURE 26. SITE 15 PHYSICAL CHARACTERISTICS
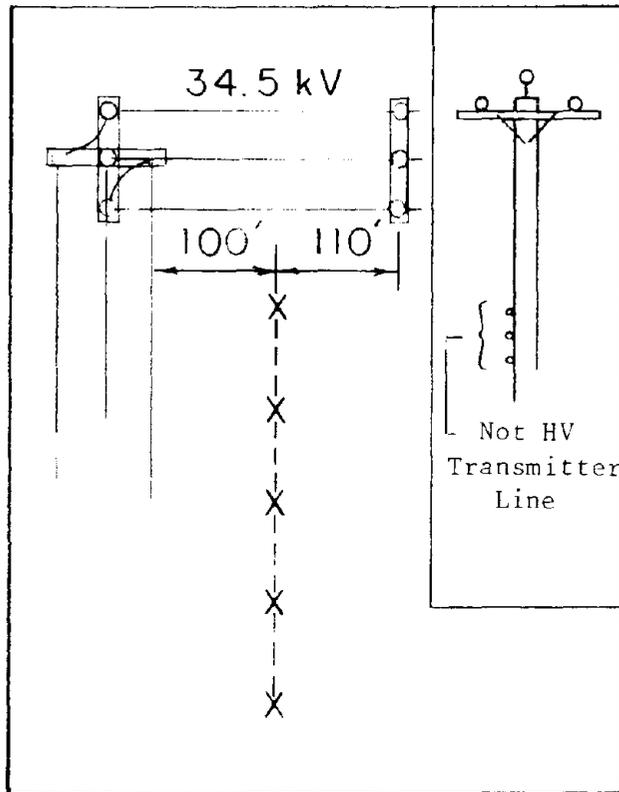
Site 16 Power Line Configuration

Site 17 Power Line Configuration

Site Description

Site Description

Site 16 was a single 34.5 KV line of standard configuration with grounded lines below the primary circuits. The site was a vacant lot with no trees near the lines.

Site 17 was the other side of the vacant lot of Site 16 where the line had been reoriented to a vertical configuration. The primary was one span of pure vertical structure with the secondary neutral below the three primary conductors. No static wires were present and the configuration precluded making any measurement in the vicinity of the support poles.

FIGURE 27. SITES 16 AND 17 PHYSICAL CHARACTERISTICS
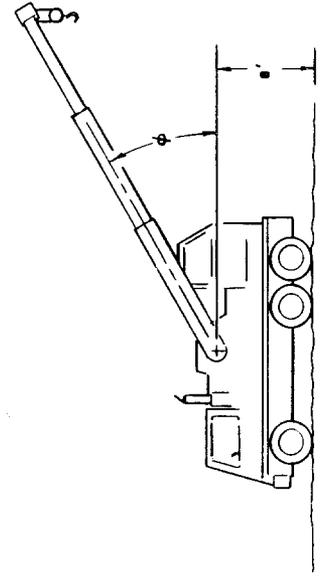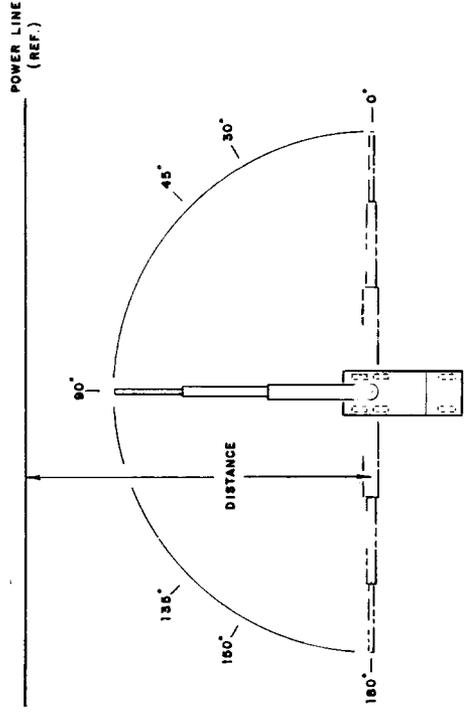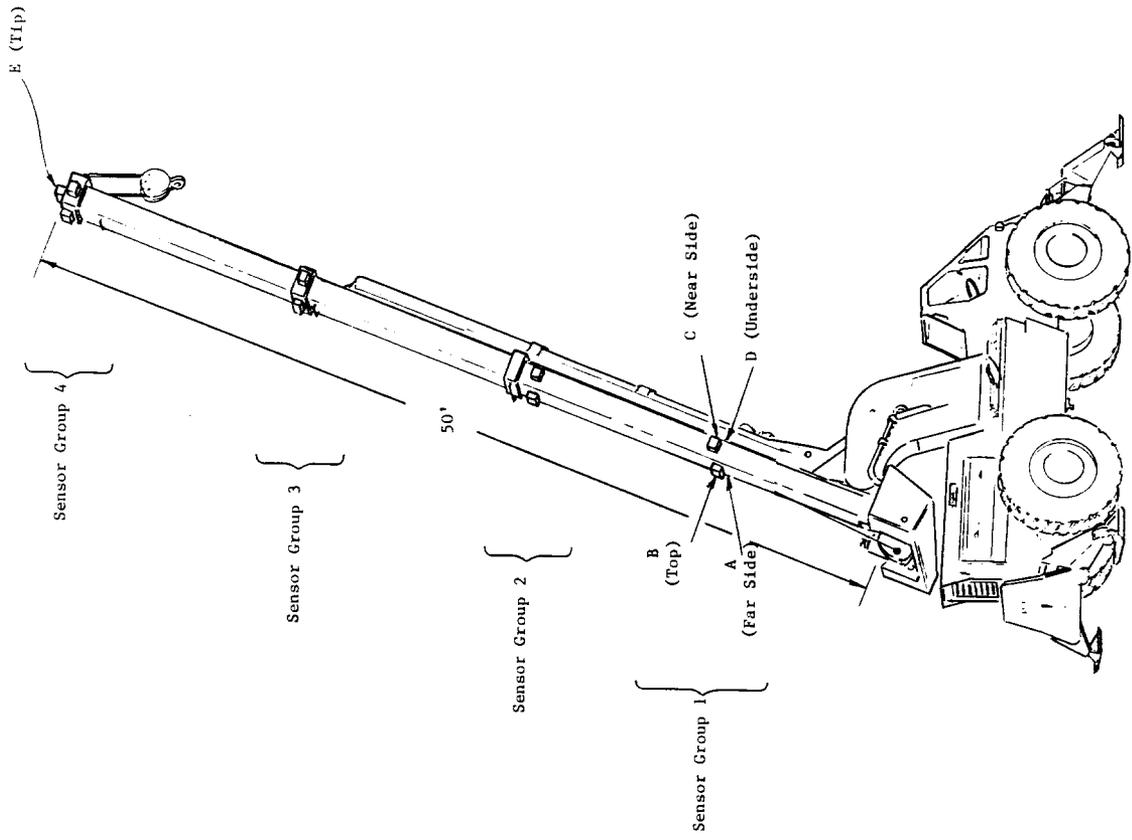
b. Azimuth and Elevation Geometry

a. Probe Placement

FIGURE 28. MEASUREMENT CONFIGURATION FOR CRANE BOOM

The operating sequence of the master computer has been described previously. In the field, the measurement procedure followed the same general pattern with minor variations due to site peculiarities. The first step was to select a line location which was as clear of obstacles (trees, buildings, etc.) as possible and where no other power carrying conductors were present. The preferred spot was also at mid span on the line (between support poles). The ideal site provided a clear, 100' wide by 150' long working area perpendicular to the power line. A point on the ground directly under the nearest primary phase was determined by simple survey techniques, and marked. From this point, distances of 10', 30', 50', 70', 90', and 110' were measured perpendicular to the line and marked with a paint spot. The vertical axis of the crane was located directly over each of these marks in sequence for the tests. Where accessible, a second set of marks and measurements were made adjacent to a support pole or tower.

The measurements were made at the following positions:

Dist:	Azimuth[(1)]	Elevation[(2)]			Notes
10'	0°(180°)	0°	30°	60°	(1) 135°, 150°, 180° measurements made only at Sites 1 & 11.
30'	0°(180°)	0°		60°	(2) Measurements made as permitted
	30°(150°)		30°		by minimum 10' clearance to
	45°(135°)	0°		60°	energized line permitted.
	90°	0°		60°	
50'	0°	0°	30°	60°	(3) To 130° on 69KV lines.
to 110'(3)	45°	0°	30°	60°	
	90'	0°	30°	60°	
etc.					

The crane was initially moved into the measurement location at 10', the sensors installed, the control unit sequence was initiated, the new parameters entered, and the measurement taken. The printed readout was reviewed at the time of testing to ensure that all channels contained data and that the values were within expected ranges. All possible boom elevations and azimuth angles were recorded at a given distance before moving to the next distance. Measurements of elevations and angles which would have brought any point on the boom closer than 10' to a primary phase were not attempted for safety reasons.

Data was not taken at 110' on 13.8KV lines, as the rate of change of field strength had dropped to a very low value (below threshold) past 90'. Two data runs were taken at each location, if possible. One was near mid-span and the second was adjacent to a grounded structure, either a pole with a static drain wire or a grounded metal tower. In some cases (e.g. sites 1 and 11), equivalent

data was taken by swinging the boom to both sides of center which brought it adjacent to the pole on one side. These azimuths were recorded as 135°, 150° and 180°. The three elevations, 0°, 30° and 60° were taken as line clearance permitted. The tests were performed in the sequence shown in Table 2, over a period of about three weeks. The height shown is to the nearest conductor. The 69KV delta configuration consisted of two phases in a horizontal plane at the lower level, with the third phase directly above the near side lower phase. The 13.8KV delta consisted of two phases in a vertical plane on the far side, with the third phase mid-way in elevation on the near side.

C.   Data Reduction and Analysis

1.   Background

SwRI had originally planned on comparing the measured data with theoretical field strength contour. However due to limited contract funds and the questionable usefulness and difficulty in performing such a comparison, emphasis was placed on reduction and analysis of the measured data.

2.   Validity of Electric Field Measurements

a.   Sources of Measurement Error

There are various factors which affect the validity of the electric field measurements made using the Electrometer. These factors include:

1) Validity of initial probe calibration

2) Temperature sensitivity of probe electronics

3) Electronic noise

4) Data digitization errors

5) Recorded data integrity

6) Critical temperature sensitivity of master computer

The validity of the calibration was initially checked by measuring fields generated by the capacitive plate field generator and an AC meter calibrator. It was found that a majority of the probes were within +5% accuracy for fields between 10 and 2000 Volts/Meter. There were 5 probes (SN-2,3,7,15 and 16) which had measurement errors between +10% and two probes (SN-4 and 8) whose accuracies were slightly poorer. Accuracy measurements were made on all 17 probes at fields between the calibration points to verify both the calibration data and the software interpolation algorithm which approximates the

probes transfer function. The calibration points used by the master computer are at 1, 3, 10, 30, 100, 300, 1000 and 3000 Volts/Meter. The fields used to verify the calibration are at 1, 2, 6, 10, 20, 60, 100, 200, 600, 1000, 2000 and 5000 Volts/Meter. A typical plot of the accuracy measurements is given for SN-01 in Figure 29. The entire set of accuracy plots is found in Appendix B.

Temperature sensitivity of the electric field probes was investigated by comparing the measurement error at room temperature (75°F) with the measurement error at approximately 120°F. The probes accuracy were degraded by a nominal 20% at the elevated temperatures. A graph of the measurement error for the two temperatures is given in Figure 30. A major factor in the temperature sensitivity of the probe are the temperature coefficients of the electronic components used in the probes construction. Although a majority of components have low temperature coefficients, some are inherently temperature sensitive.

Electronic noise generated in the probes circuitry also contributes to probe measurement errors. The effect of noise, particularly when measuring low level 60 Hz fields, is compounded by the nonlineraties of the compression amplifier. Sources of noise are the FET buffer amplifier, passive components, and the integrated circuits used in the compression amplifier and RMS to DC converter.

Errors are also introduced in the signal digitization process. However, a large amount of data averaging is done for each measurement, therefore, reducing the normally distributed digitization errors. The data averaging also reduces the effect of gaussian noise introduced by other sources.

A limited test was conducted to determine the drift in the probes accuracy. Data collected during the initial calibration check of SN-1, and additional accuracy data taken a year later is compared in Figure 31. It is observed that a drift occurs in field measurements between 1 volt/meter and 100 volts/meter. The long term drift (over a period of a year) is not apparent due to the wide short term variation of accuracy as observed in the measurements taken on two consecutive days.

The variation and drift of the probes accuracy has little effect on measurements between 100 volts/meter and 2000 volts/meter. The measured drift for fields in this range is within a +5% tolerance. Since a majority of the measurements taken are in this range, the effect of the drift is negligible.

The electric field data can be corrupted between the measurements in the field and the final processing and presentation of the data by computer analysis. The major factors in this type of data corruption are in the method used to record data and the media on which it was stored. The Electrometer uses two methods to archive the
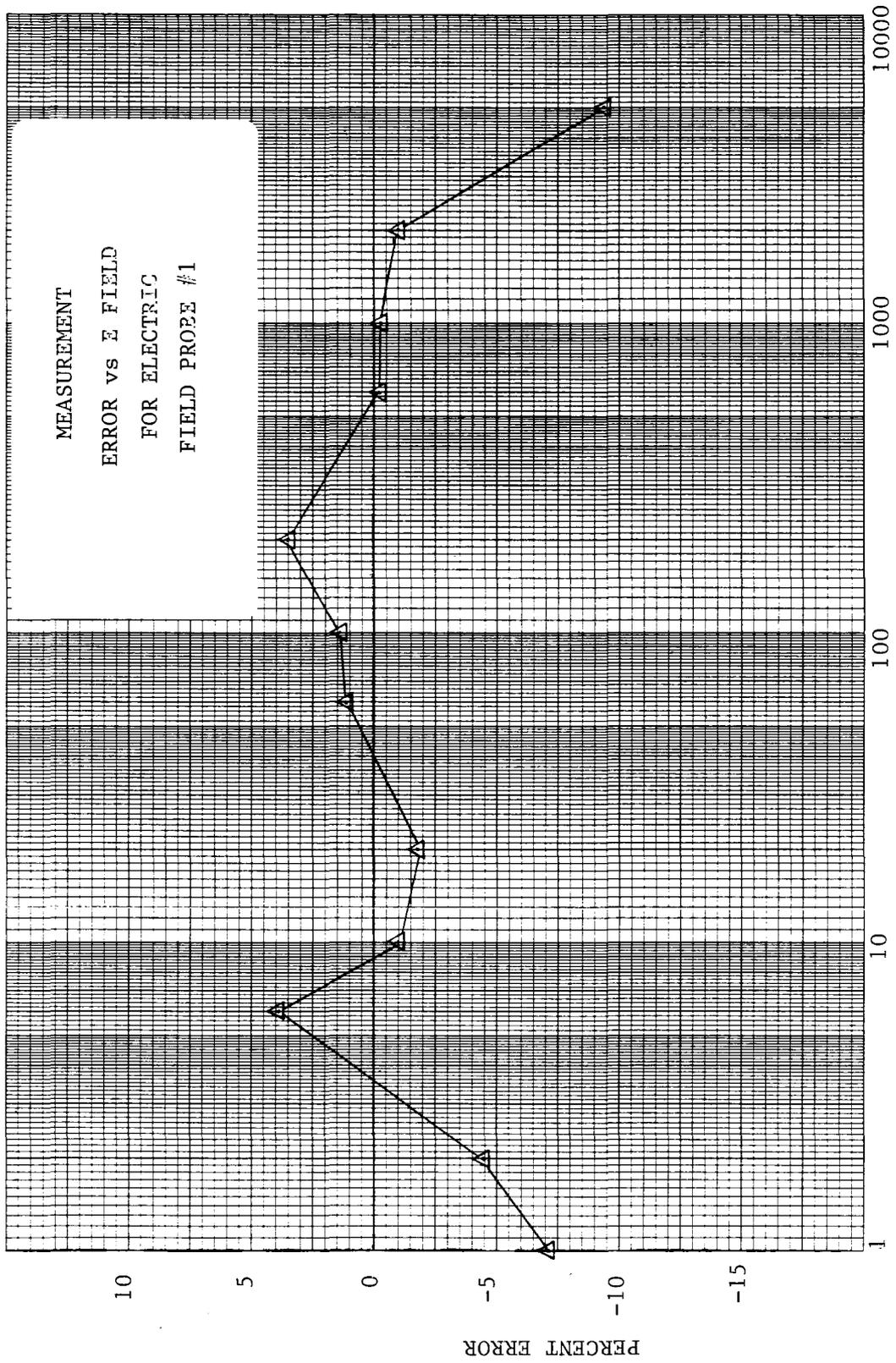
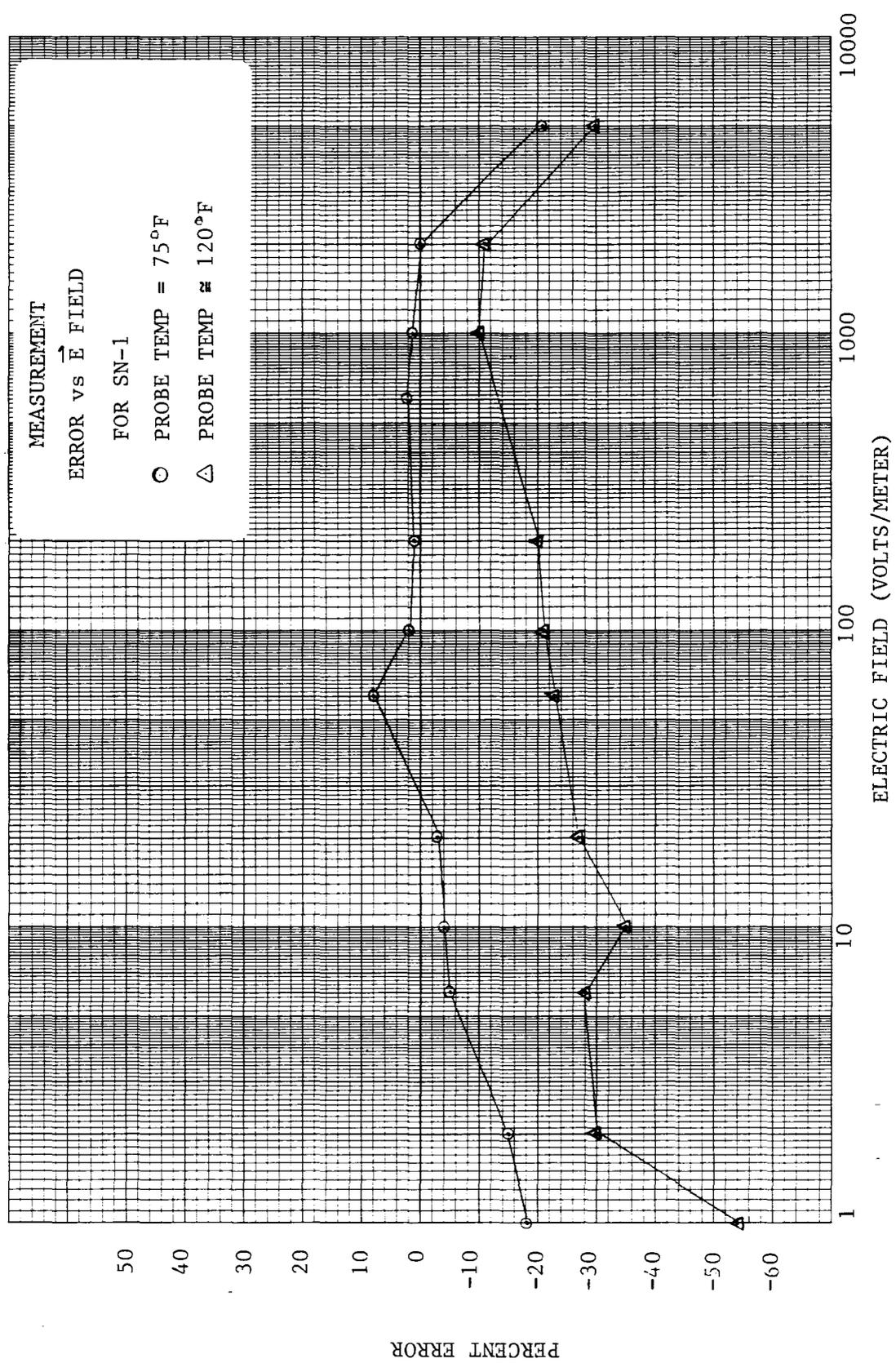FIGURE 29. MEASUREMENT ERROR OF PROBE #1
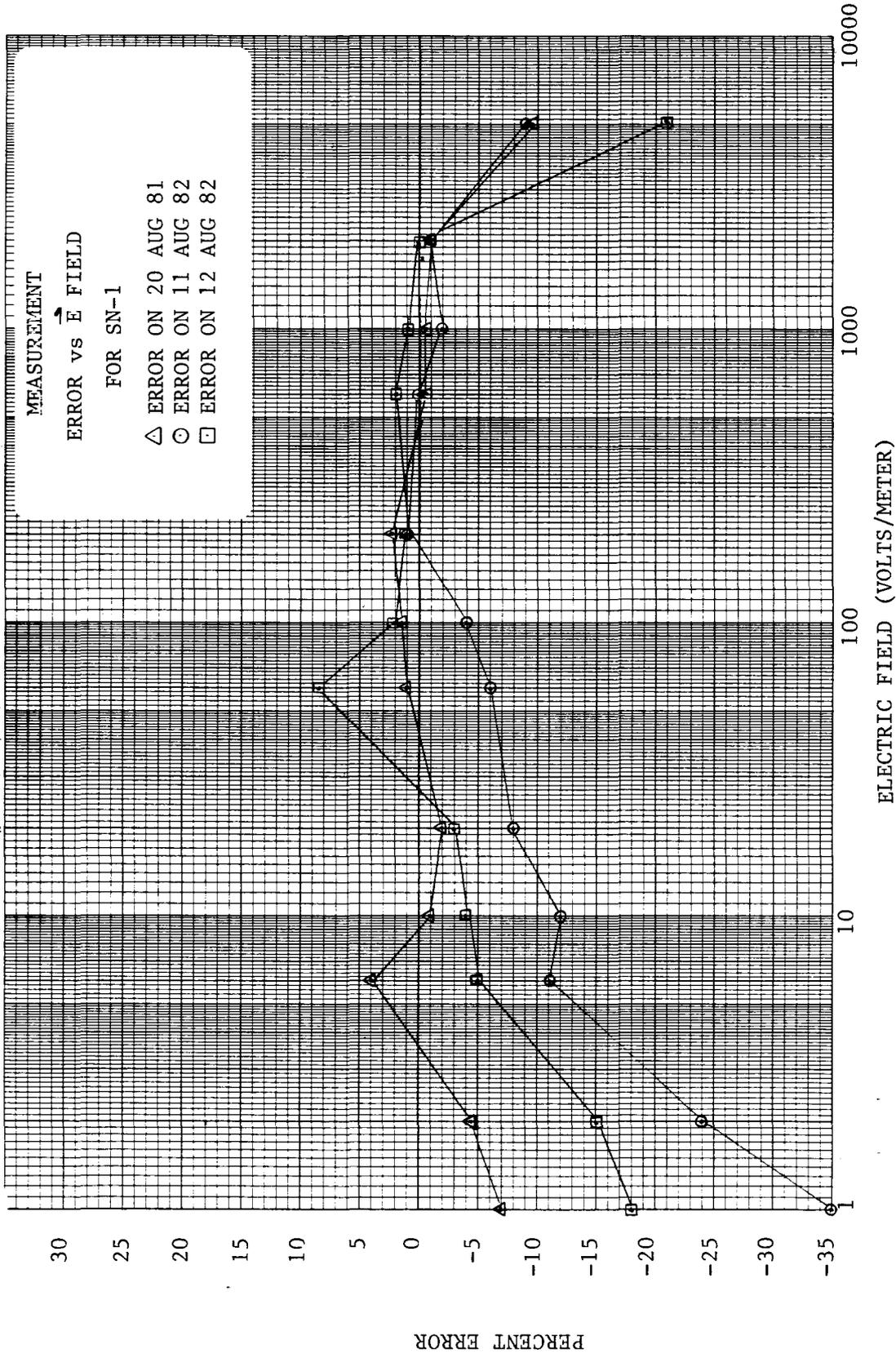
FIGURE 30. TEMPERATURE SENSITIVITY OF FIELD PROBE

FIGURE 31. DRIFT OF FIELD PROBE ACCURACY

measured electric field data. The one most evident to the operator is the printing of the data on standard calculator paper. This process is very reliable and is easily interpreted. The second method used is the storage of data on magnetic tape. This method is not easily verified in the field and the stored data is much more vunerable to corruption. To overcome this problem, the master computer encodes error detection information on the magnetic tape during data recording and upon playback is able to detect falsely read data. When false data is encounted, it is replaced by an asterisk and can be identified by the host data processing computer. The printed data can be used as a backup to correct the incorrectly read data.

During the data logging phase of the project, a temperature sensitivity in the master computer was discovered. Direct sunlight upon the front panel of the master computer results in ambient temperatures in excess of 95°, which in turn caused overheating and malfunction of the master computers electronics. Components used in the master computer which made it susceptible to high temperatures are: 1) a high power 5 volt regulator requiring a large amount of heatsinking, 2) the arithmetic processing unit which dissipates a large amount of energy, 3) the use of many commercial temperature range components which are not guaranteed to operate over a wide temperature range and 4) a cartridge data recorder which becomes unreliable at elevated temperatures. Since the Electrometer is a precision measurement instrument and designed for research purposes, the overheating problem was remedied by operator awareness of the problem and protection of the master computer from direct sunlight. Future designs, however, should be directed at eliminating the problem.

b.   Effect of Errors

The effect of the measurement errors, particularly on reduced accuracy, are negligible when considering the manner in which the data is presented. An error of 15% does not affect the analysis performed given the dynamic range of measured fields (1 volt/meter to 10000 volts/meter) and the logarithmic scale used to graphically present the data. However, in applications other than electric field data logging instrumentation, it would be advised to refine the probes design and reduce the effect of the factors mentioned in the above paragraphs.

3.   Methods of Data Reduction

The data logged from the 17 field sites was processed and plotted using facilities at Southwest Research Institute. The electric field data was processed using a 16 bit minicomputer and the processed data was plotted using an X-Y four-color plotter. The data was transferred from the master computer to the minicomputer using the RS-232 interface incorporated on the master computer. The programs for automatic data transfer from the master computer to the minicomputer were also developed at SwRI. The data transfer program was written in Fortran along with the curve fit and plot programs. The electric field data base management was handled using PL/1

programming language. Listings of these programs can be found in Appendix C.

Once data transfer was accomplished, the data was grouped into files according to site number, boom elevation and azimuth, and probe groupings. To interpret the electric field strength data in terms of proximity warning device performance, the entire set of data was analyzed to produce plots of electric field strength vs the miss distance to the power line. The miss distance is the shortest path between the power line and the crane boom as calculated for each combination of crane location and crane boom orientation. The data was analyzed in three different formats to provide varying degrees of emphasis on detail and/or generalization.

a. Electric field strength vs miss distance, probe position, boom orientation, and power line site.

A least squares curve fit was performed on the data to generate a smooth curve representing the contour of electric field as the boom moved away from the power line. A cubic spline curve fit was considered but analysis of the data using this method produced a multiple-jointed curve, whereas the least squares curve fit performed some filtering and generated a smooth curve. The X axis of the plot is the miss distance and was generated by calculating the shortest distance from the power line to the crane boom for each crane position. The Y axis of the plot represents the electric field intensity and was plotted on a logarithmic scale to accommodate the wide range of electric field variation. An example of four plots generated by the color plotter is given in Figure 32. This gives an example of the four-color plotting capability, yielding a highly readable graph. Unfortunately reproduction costs were such that black and white copies of the plots were required for the 17 sites.

In this form of analysis, each page of plots summarizes the electric field strength variation with miss distance at all seventeen probes for a single combination of boom azimuth, boom elevation and power line site. The plots are presented in the four quadrants of the page, with a separate quadrant for each of the four probe groups. This form of analysis allows detailed and specific analysis of electric field strength variation with crane boom azimuth, crane boom elevation, probe location, and power line configuration. Detailed specific analysis for any of these four parameters is achievable by comparing data for selected sequences of the parameter to be varied. However, in this form, a large number of plots must be compared to determine the electric field variation vs any single parameter under general conditions of other parameters. For this reason, the other two forms of analysis were performed to allow an easier interpretation of probe performance for (1) an aggregate of all boom orientations, and (2) an aggregate of all combinations of boom orientations and power line sites.
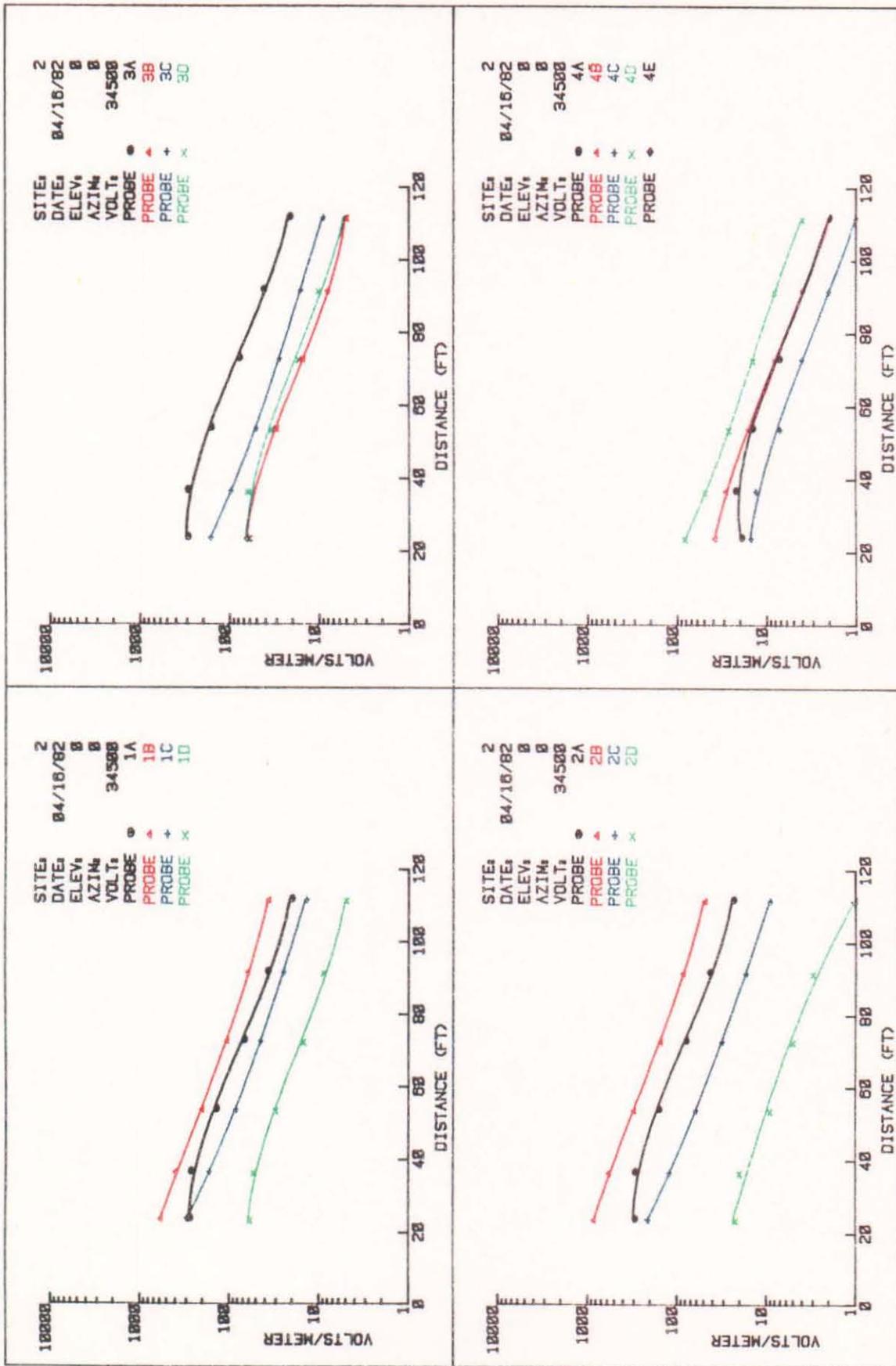
FIGURE 32. EXAMPLE OF ELECTRIC FIELD PLOT

b. <u>Electric field strength vs miss distance, probe position, and power line site</u>

This analysis was performed to present the electric field strength distribution at each probe location and at each site for all combinations of crane boom azimuth and crane boom elevation. As illustrated for site 1, probe group 1 in Figure 33, the resulting format is a separate scatter plot for each of the seventeen probes showing the distribution of measured field strength vs miss distance to the power line. This format includes four scatter plots per page with one page per probe group. This presentation of data facilitates analysis at a single power line site for individual probe performance as a basis for a proximity warning device. It also facilitates comparative probe performance, i.e., the comparison of probe sensitivity, the consistency of measured field strength vs miss distance under a wide variety of boom orientations, and the overall spread of miss distances for fixed probe signal response.

c. <u>Electric field strength vs miss distance and probe position</u>

The aggregate performance of each probe was analyzed as a single scatter plot for that probe showing the distribution of measured electric field strength vs miss distance for all combinations of boom elevation, boom azimuth and power line sites. These scatter plots are presented four per page, with one quadrant per probe, and one page per probe group as illustrated for probe group 2 in Figure 34. This form of presentation facilitates analysis of overall performance of individual probes for the aggregate condition of all parameters combined, to help in evaluation of (1) the practicality of a fixed (i.e. not adjustable) sensitivity alarming device, (2) the overall dynamic range required of a proximity alarm device, (3) the influence of position along and around the crane boom on the overall sensitivities of a proximity warning device probe, (4) the overall spread of electric field strength for fixed miss distances, and (5) the overall spread of miss distances for fixed electric field strengths.

4. <u>Data Analysis Results</u>

To be effective as an ideal proximity warning device, a system must provide a signal that reliably indicates crane distance to the power line. For this to be accomplished, the output signal characteristics of the ideal system must provide a monotonically varying curve of output signal vs miss distance between the crane and the power line. This means that regardless of crane boom orientation, each value of ideal proximity warning device system output signal must correspond uniquely to a single value of miss distance, and correspondingly, each miss distance must result in a single value of output signal. When this criteria is satisfied, the alarm threshold can be adjusted to produce alarms at a fixed distance regardless of crane boom orientation. To the extent that the miss distance spreads (e.g. because of boom orientation changes) for a fixed output signal level, the miss distance corresponding to alarm activation will spread.
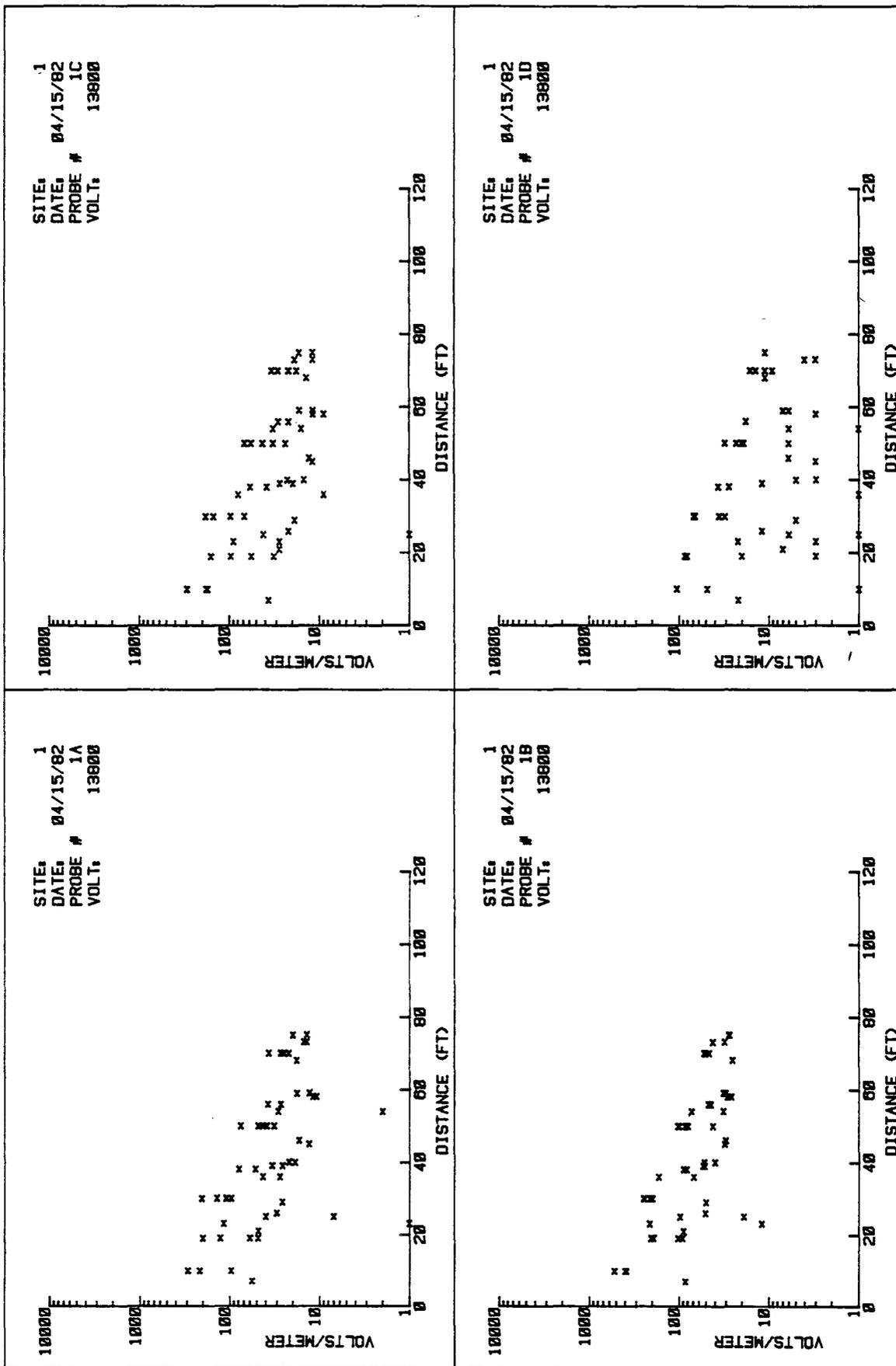
FIGURE 33. SCATTER PLOT OF MEASURED ELECTRIC FIELD STRENGTH vs MISS DISTANCE FOR PROBE GROUP 1, SITE 1, ALL BOOM ORIENTATIONS
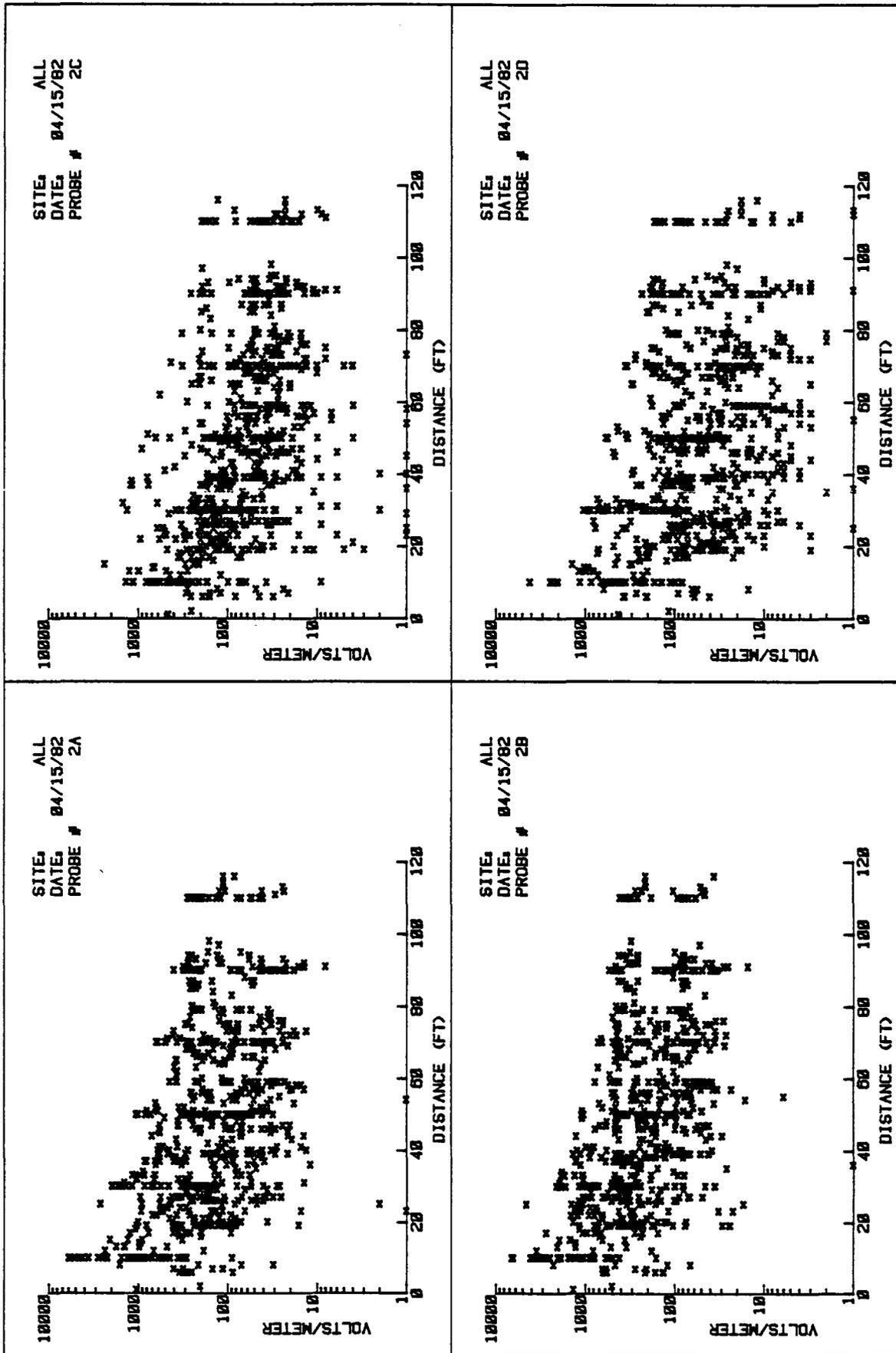
FIGURE 34. SCATTER PLOT OF MEASURED ELECTRIC FIELD STRENGTH vs MISS DISTANCE FOR PROBE GROUP 2, ALL COMBINATIONS OF SITES AND BOOM ORIENTATION

a.   Effect of Boom Orientation

The scatter plots of electric field strength at individual sites show that the field strength at any probe location is a significant departure from a single valued curve of field strength vs miss distance. For example, Figure 35 shows that the electric field strength at the position of probe 4B varies from 9 v/m (volts per meter) to 50 v/m for a miss distance of about 20 feet at site 1. This spread in measured field strength is due entirely to the variation of boom orientation. If the measured electric field strength intensity at the position of probe 4B were used to activate a proximity warning device and insure that the crane never comes closer than 20 feet to the power line, a threshold value of about 9 v/m would be required for the set of data presented in Figure 35. However, Figure 35 also demonstrates that if a value of 9 v/m is selected as the threshold value for such a proximity warning device, the electric field strength can exceed that threshold value for distances out to about 60 feet. Stated differently, Figure 35 demonstrates that a proximity warning device with a probe at the position of probe 4B and a threshold adjusted to 9 v/m would produce alarm activation at distances ranging from 20-60 feet, depending on the combination of crane boom azimuth and elevation. This example represents the best proximity warning device performance for any of the probe locations in the site 1 data.

The set of data for each site showed that the measured electric field strength was influenced by both crane boom azimuth and crane boom elevation. The azimuthal dependence results from two sources, (1) the azimuthal dependence of individual probe distance to the power line for fixed miss distances, and (2) the azimuthally dependent shading of probes mounted on either side of the boom. The azimuthal dependence of probe distance to the power line for fixed miss distances can be illustrated by considering the case where the crane boom is parallel to the power line vs the case in which the crane boom is perpendicular to the power line. When the crane boom is parallel to the power line, all probes are equidistant to the power line, at a distance equal to the miss distance between the power line and the crane. In contrast, when the crane boom is oriented perpendicular to the power line, the miss distance typically corresponds to the power line distance to the nearest probe, (e.g. the probe on the boom tip), whereas the power line distance to the farthest probe is signficantly more than the miss distance. Figures 36 and 37 illustrate this form of azimuthal dependence. In Figure 36, the crane boom is parallel to the power line, all probe groups (1-4) are at approximately the same distance to the power line, and the signal levels of each probe group are consequently the same from one group to the next. In Figure 37, the crane boom is perpendicular to the power line, and probe groups 3, 2, and 1 are progressively further than probe group 4. Consequently, the signal levels from probe groups 3, 2, and 1 are progressively lower than the signals from probe group 4, and are also progressively lower than the corresponding levels in Figure 36. The crane boom azimuth also influences the degree of shading by the crane boom, especially for the probe positions mounted on either side of the crane boom (i.e. probes 1A, 2A, 3A, 4A and
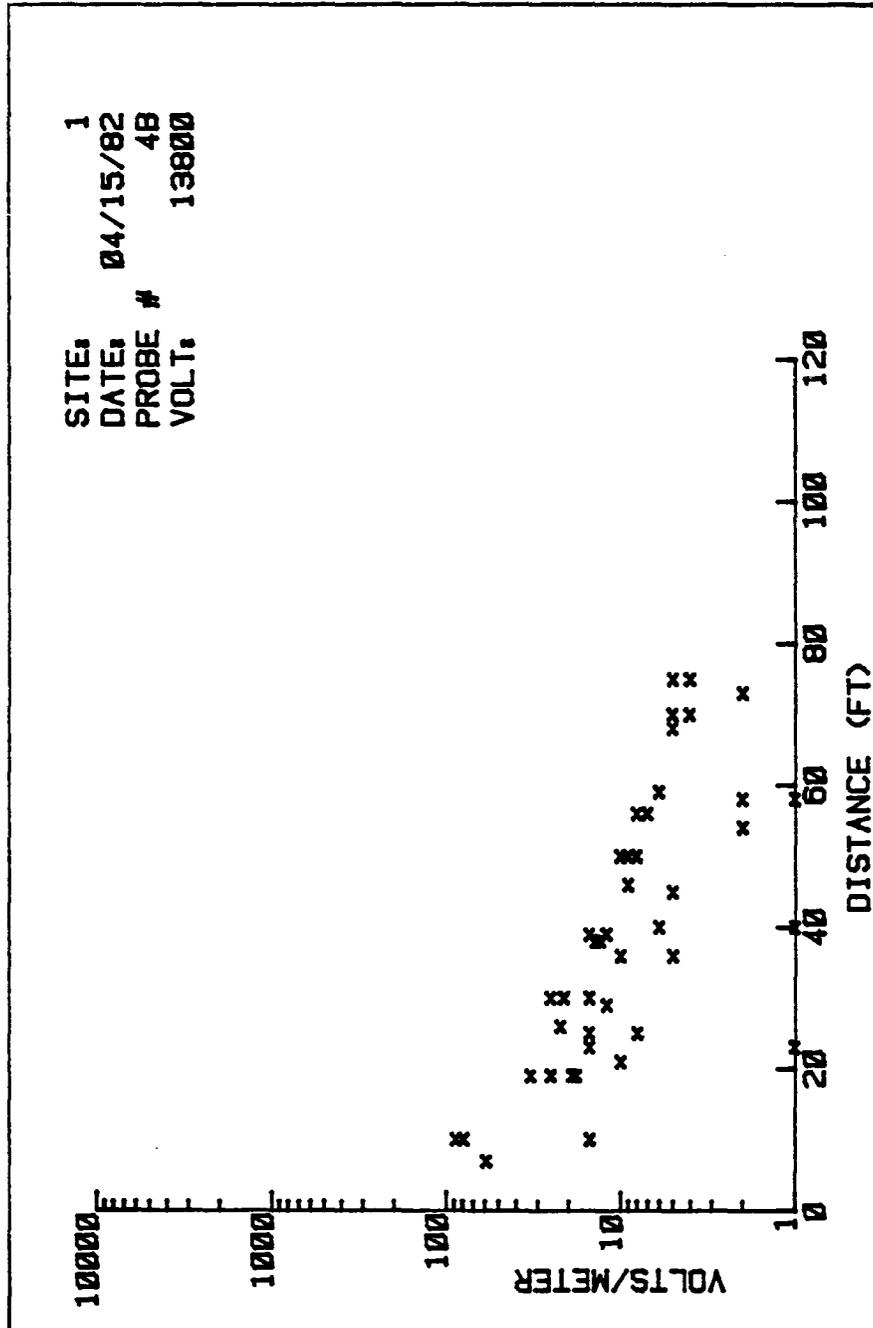
73

FIGURE 35. DISTRIBUTION OF MEASURED ELECTRIC FIELD STRENGTH
vs MISS DISTANCE FOR PROBE 4B, SITE 1

probes 1C, 2C, 3C and 4C). Only a very small portion (i.e. for azimuths 135° and 180°) of data taken was for crane boom orientations with the crane boom between the power line and the A group of probes. In contrast, approximately 2/3 of the data (i.e. for azimuths 0° and 45°) was taken when the crane boom was between the C group of probes and the power line. As illustrated in Figure 38, the scatter plots for the combination of all sites show an average of about 6dB lower field strength for the C probes than for the A probes.

The crane boom elevation also tended to show a significant effect on measured electric fields. This was especially true for probe group 4. As illustrated in Figures 39, 40, and 41, the change of electric field strength with boom elevation for probe group 4 was typically much more pronounced between 0° and 30° elevation than it was between 30° and 60° elevation. The larger spread in the scatter plots for probe group 4 is attributed primarily to the dependence on crane boom elevation.

b. The Effect of Probe Position

As summarized in the various scatter plots of electric field strength vs crane miss distance, the measured field strength varies both in absolute amplitude and in the distance variation characteristics from one probe position to another. The variation in absolute field strength from one probe position to another is important for a proximity warning device only when it becomes so drastic as to exceed the dynamic range of the instrumentation. However, the characteristic variation of the signal strength vs miss distance is crucial and is the primary factor that determines the reliability of a proximity warning device.

In general, the measured electric field strength was most intense at the position of probe 4E, regardless of site or boom orientation. Electric field intensities are typically greater near sharp outside corners and less near inside corners. Probe 4E is near the tip of the crane boom, which is by far the most protruding structure and consequently the most prominent sharp outside corner. In contrast to probe 4E, probe 1D followed by probe 4D and probe 3B are located at points where electric field strength is least. Probe 1B is located on the underside of the crane boom and almost surrounded by the crane boom jib in its storage position. As a consequence, probe 1D is near an inside corner and is effectively shielded by the crane boom jib. Probe 4D is also located on an inside corner near the "throat" of the crane boom "head". Probe 3B is located on the crane boom top, but is near the roller support for the work cable, and is partially shielded by that roller support.

For the set of data collected during this series of experiments, the measured electric field strength was in general about 6dB less at the C group of probes than at the A group of probes. This difference in average field strength, as described in the preceding section, is a result of shading by the crane boom for the 0° and 45°
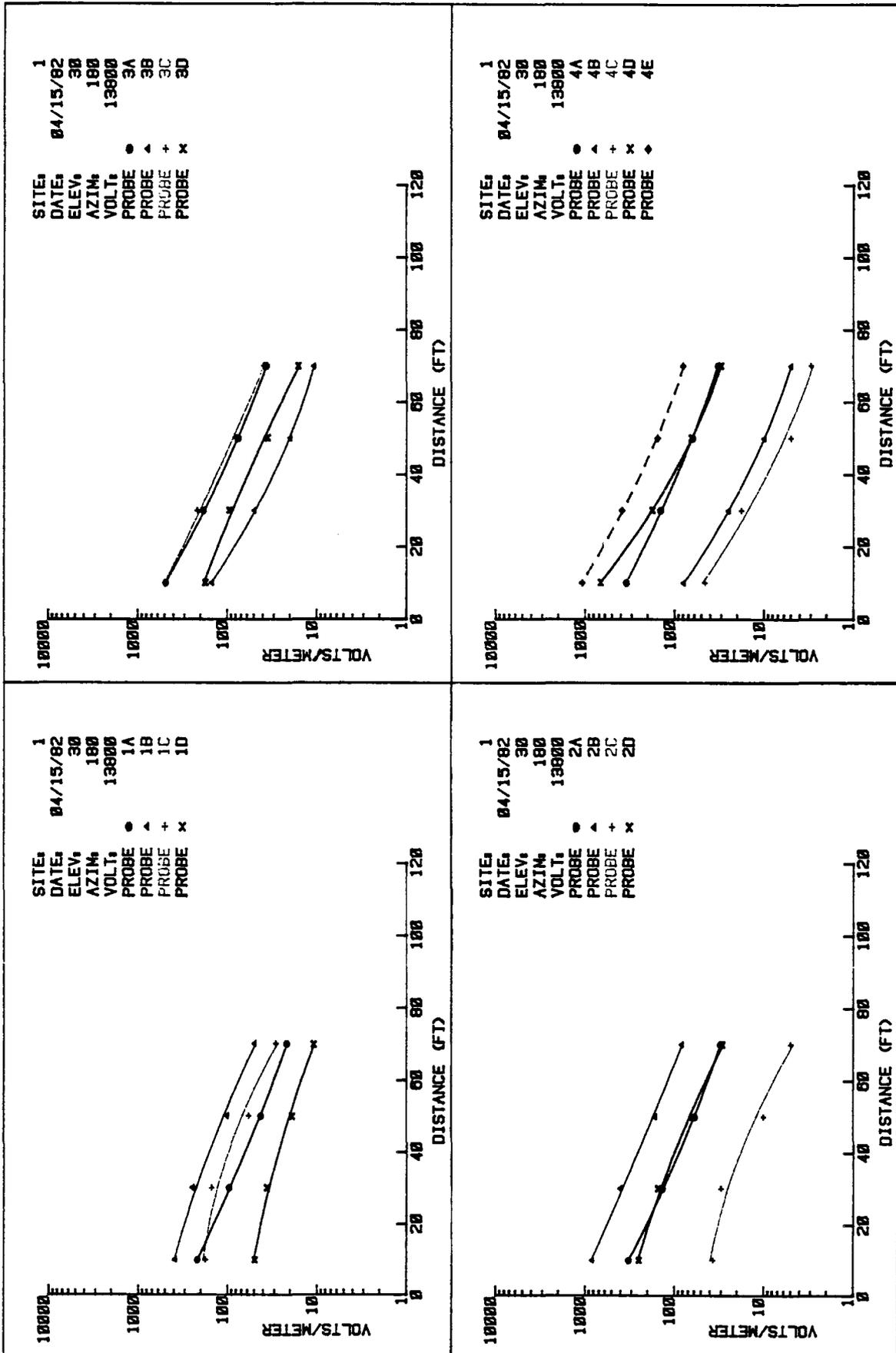
FIGURE 36. MEASURED ELECTRIC FIELD STRENGTH AT SITE 1 FOR CRANE BOOM PARALLEL TO POWER LINE

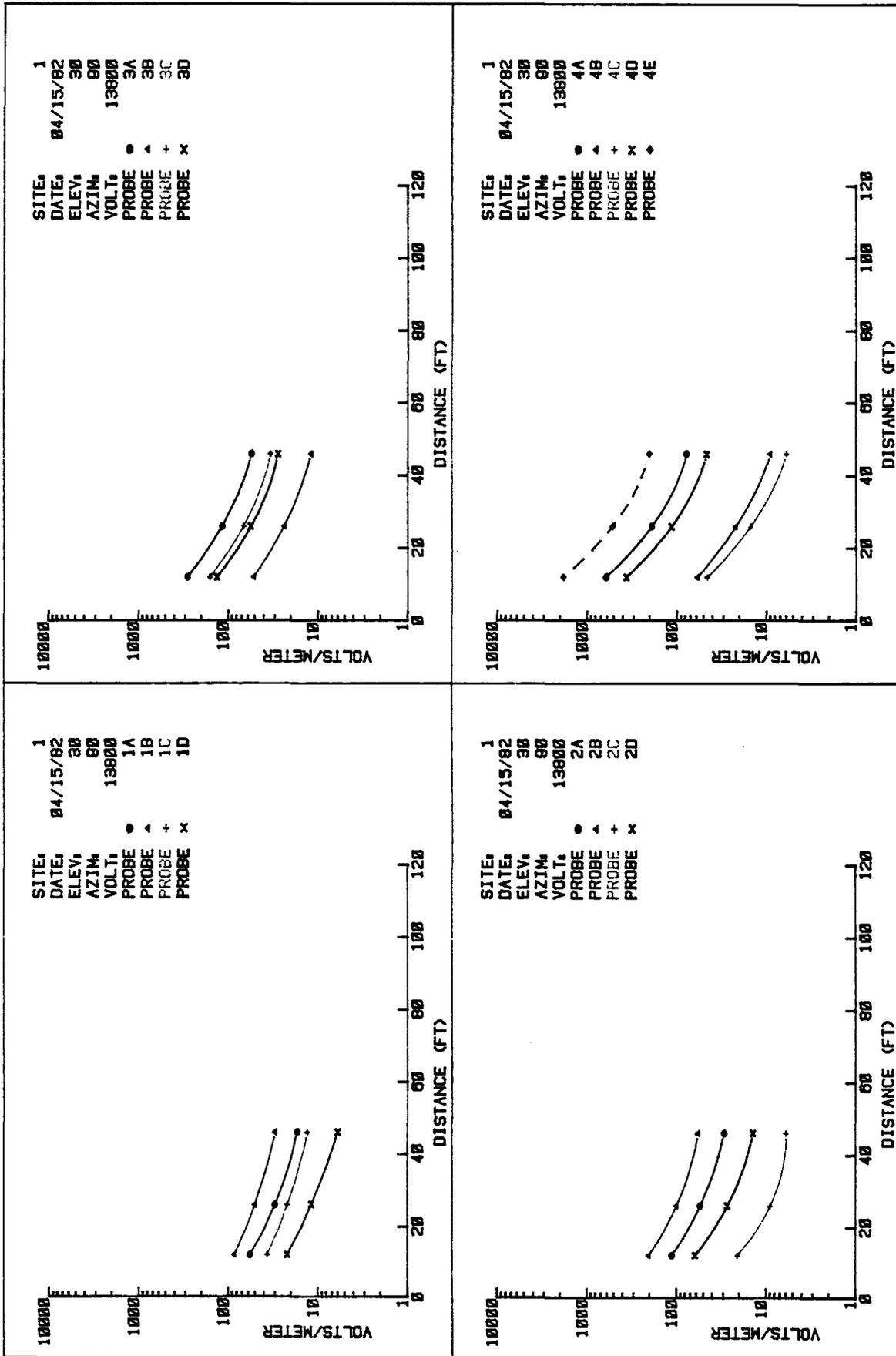FIGURE 37. MEASURED ELECTRIC FIELD STRENGTH AT SITE 1 FOR CRANE BOOM PERPENDICULAR TO POWER LINE
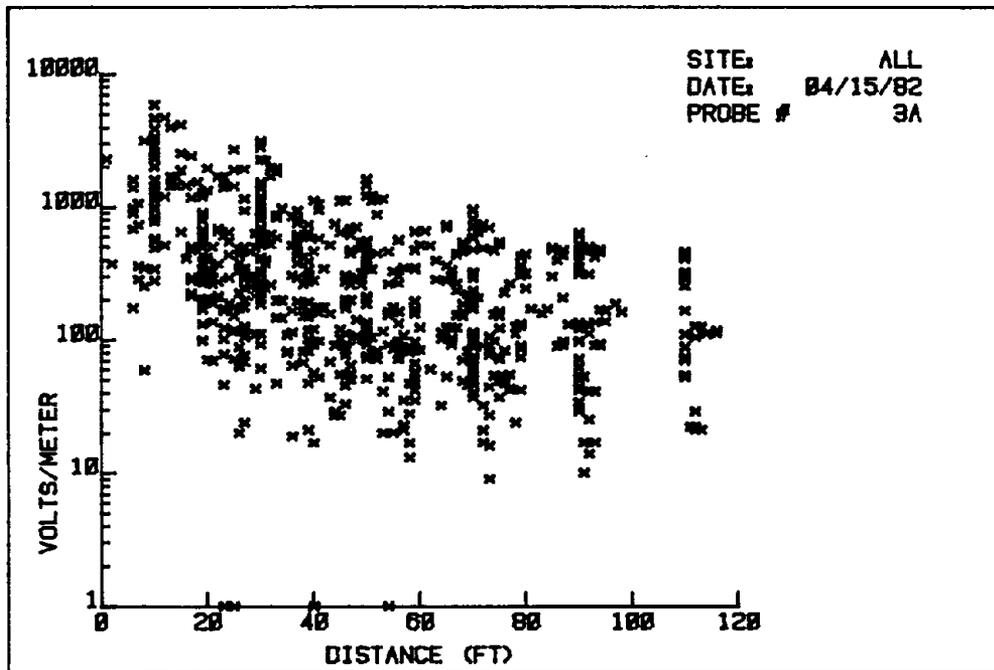
a.   Probe 3A
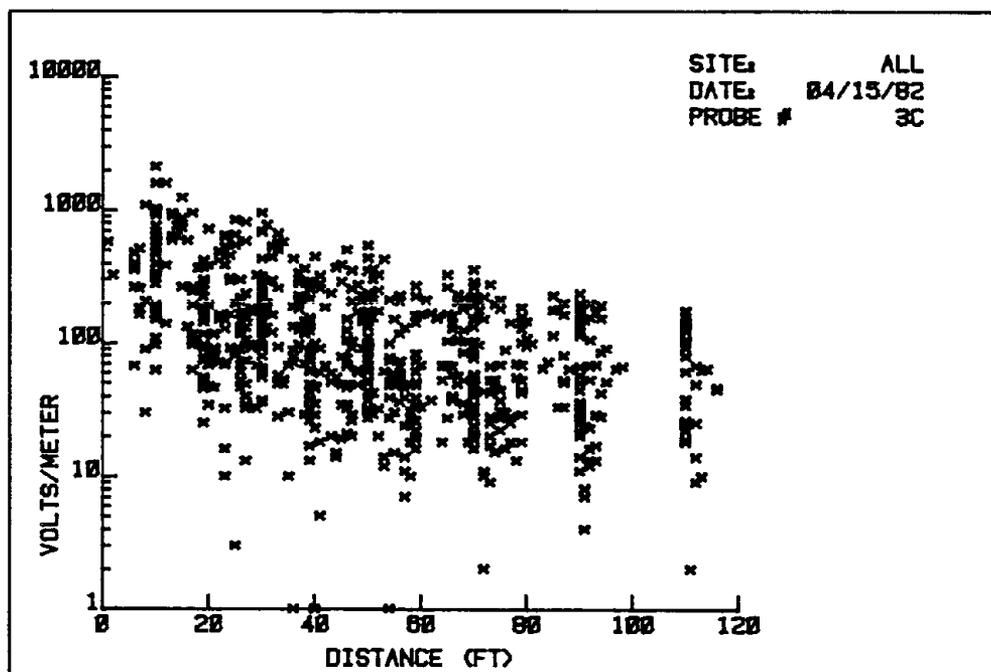
b.   Probe 3C

FIGURE 38.   DISTRIBUTION OF MEASURED FIELD STRENGTH vs MISS
DISTANCE FOR ALL BOOM ORIENTATIONS AND ALL SITES
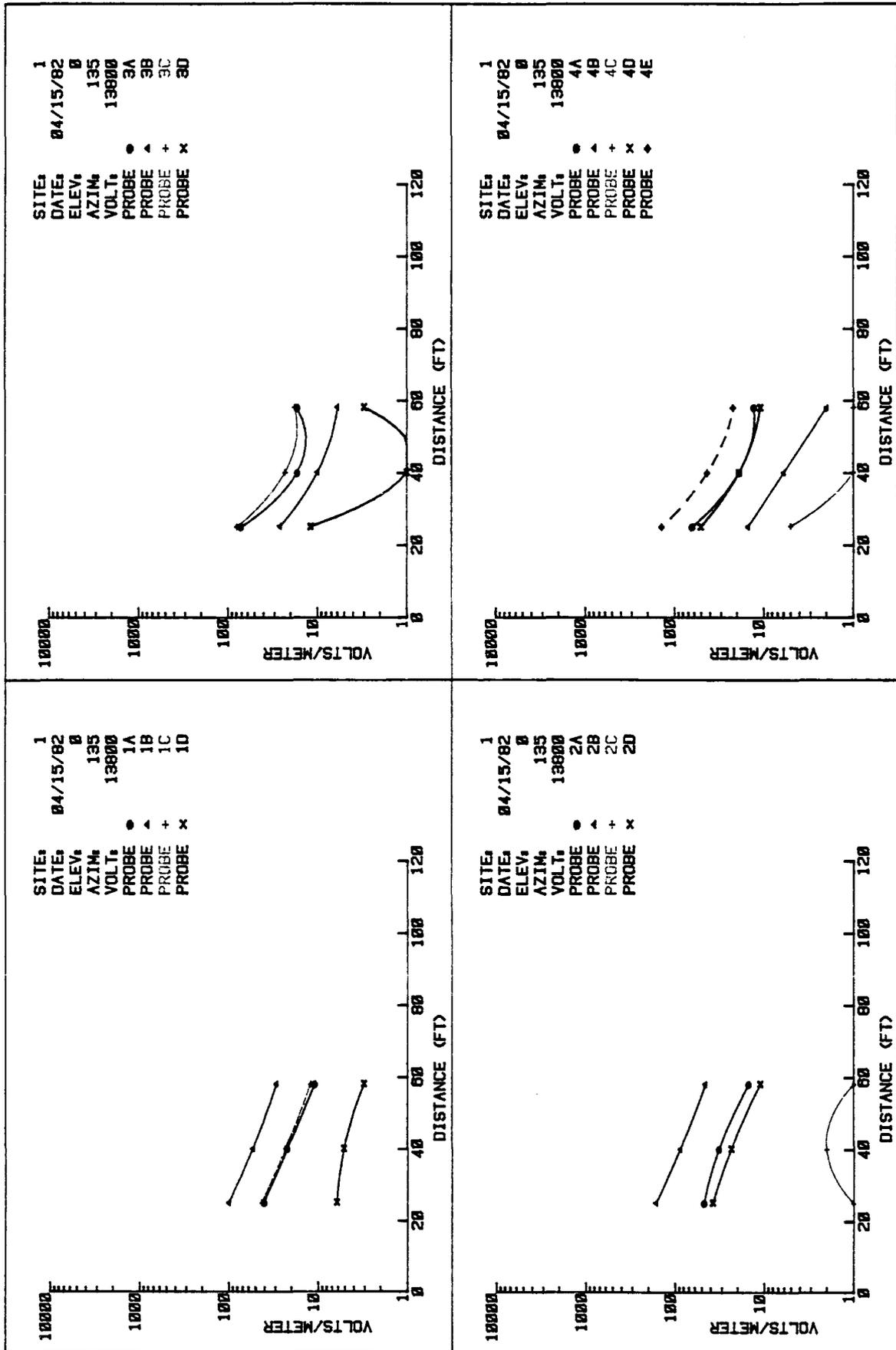
FIGURE 39. MEASURED ELECTRIC FIELD STRENGTH vs MISS DISTANCE
AT SITE 1 FOR 0 DEGREES ELEVATION
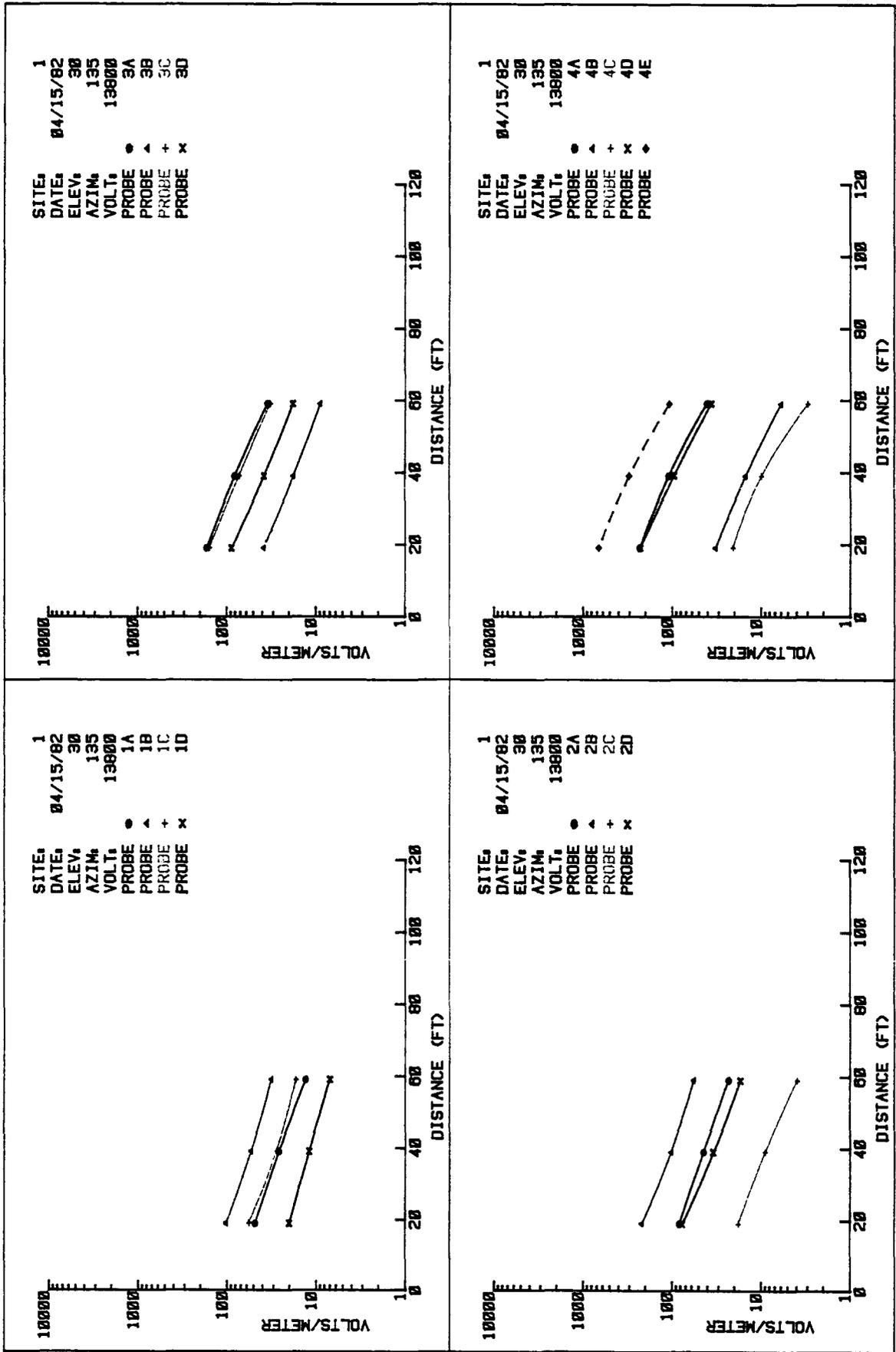
FIGURE 40. MEASURED ELECTRIC FIELD STRENGTH vs MISS DISTANCE AT SITE 1 FOR 30 DEGREES ELEVATION

FIGURE 41. MEASURED ELECTRIC FIELD STRENGTH vs MISS DISTANCE
AT SITE 1 FOR 60 DEGREES ELEVATION

azimuth data sets. The C group probes are mounted in positions corresponding to the A group probes (but on opposite sides of the crane boom) and in general should have overall similar sensitivity. In fact, Figures 42 and 43 describe a case in which the relative field strength at probes 1A and 1C are interchanged as the crane boom changes from 180° azimuth to 0° azimuth.

The scatter plots for the probes show that probes 1B and 2B experience the least spread of all the probes. The decreased spread in the scatter plot of field strength vs miss distance is desirable and indicates that positions 1B and 2B should be given high consideration when choosing the optimal location for a single sensor proximity warning device. As a group, the group 1 probes show the least spread in the scatter plots, while the group 4 probes show the most spread, indicating that near the pivot point is a better place to locate the probe of a small sensor proximity warning device.

c. The Effects of Multiple Circuits

Site 15 was chosen as a site with known multiple circuits. Scatter plots for site 15, as illustrated in Figure 44, illustrate the futility of using electric field strength measurements to indicate the distance to a power line in the presence of multiple circuits. Figure 44 shows that in general, the measured electric field strength is independent of distance to the power line at site 15. The distance independence probably results from a primary response to some more distant power line than the one to which the distance is being measured. This characteristic was observed not only on site 15, but also at sites 4, 5, and 14 and to a lesser extent at site 8. Although none of the latter sites were chosen with the intention of including multiple power lines, other circuits were in the vicinity and probably influenced the measurements significantly. The problem caused by multiple circuits is very severe in its consequence on proximity warning device performance (for systems based on the principle of sensing electric field strength), and the problem is significant in its frequency of occurence, as illustrated here.

d. Effect of Power Line Voltage

The effect of power line voltage should only influence the absolute signal levels and should have no direct influence on the dependence of relative field strength vs distance. Figures 45 and 46 illustrate the change of absolute levels for two different line voltages and also demonstrate the obvious need for sensitivity adjustment at each site. Except for the change in absolute field strength levels, the characteristics of the field strength variation are identical.

FIGURE 42. MEASURED ELECTRIC FIELD STRENGTH AT PROBE GROUP 1,
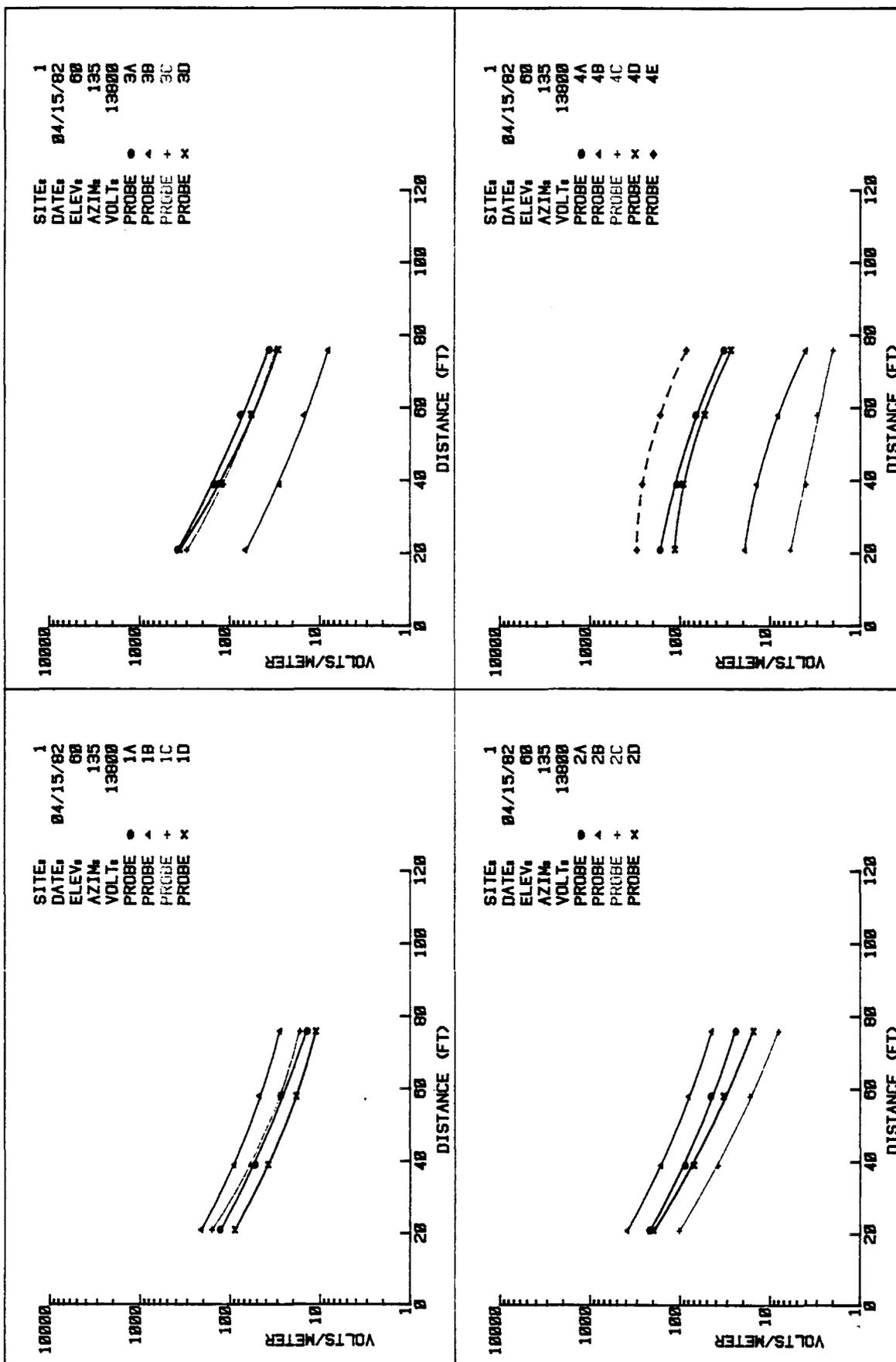SITE 1 FOR CRANE BOOM AT 0 DEGREES AZIMUTH

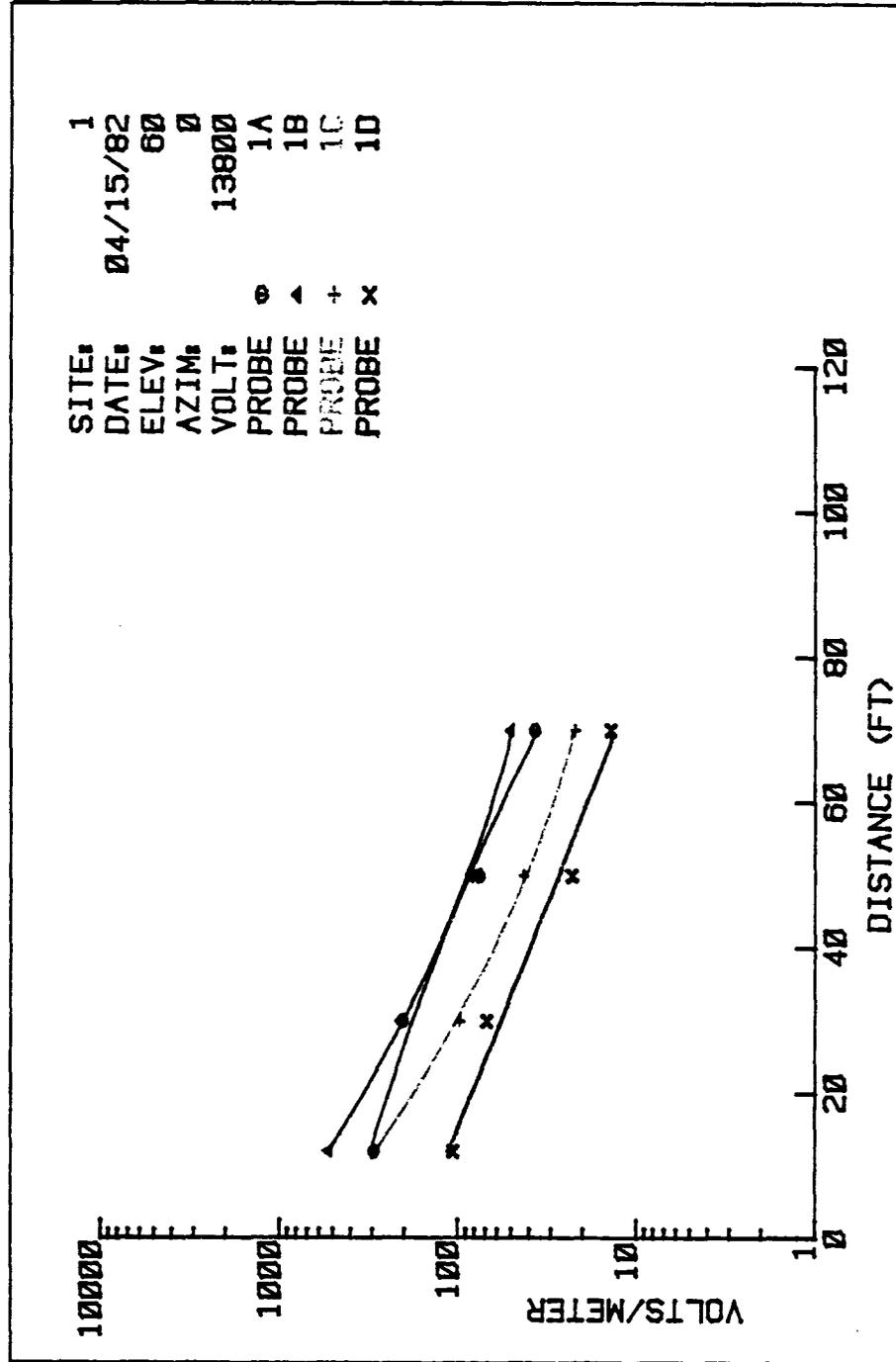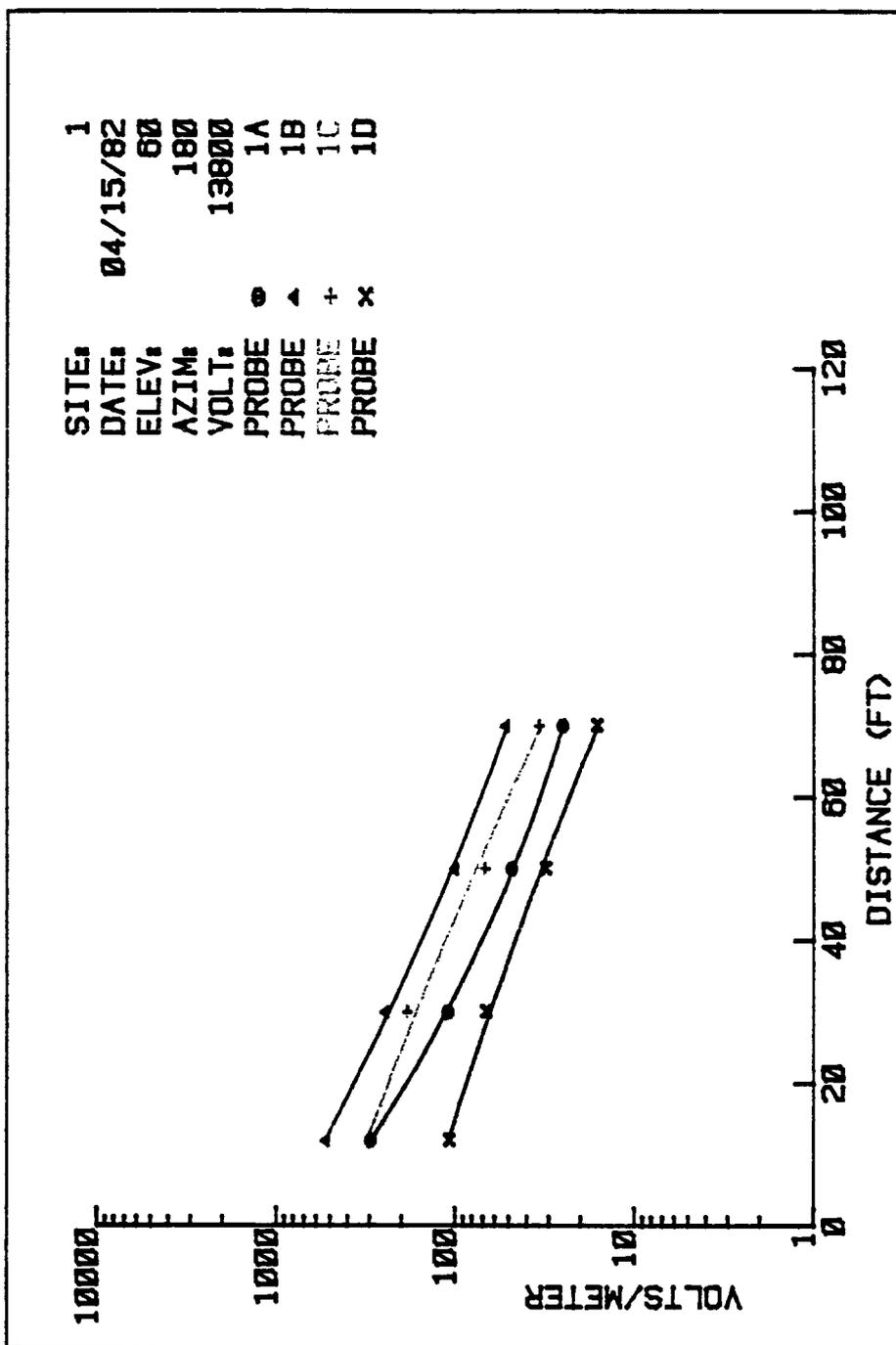FIGURE 43. MEASURED ELECTRIC FIELD STRENGTH AT PROBE GROUP 1,
SITE 1 FOR CRANE BOOM AT 180 DEGREES AZIMUTH

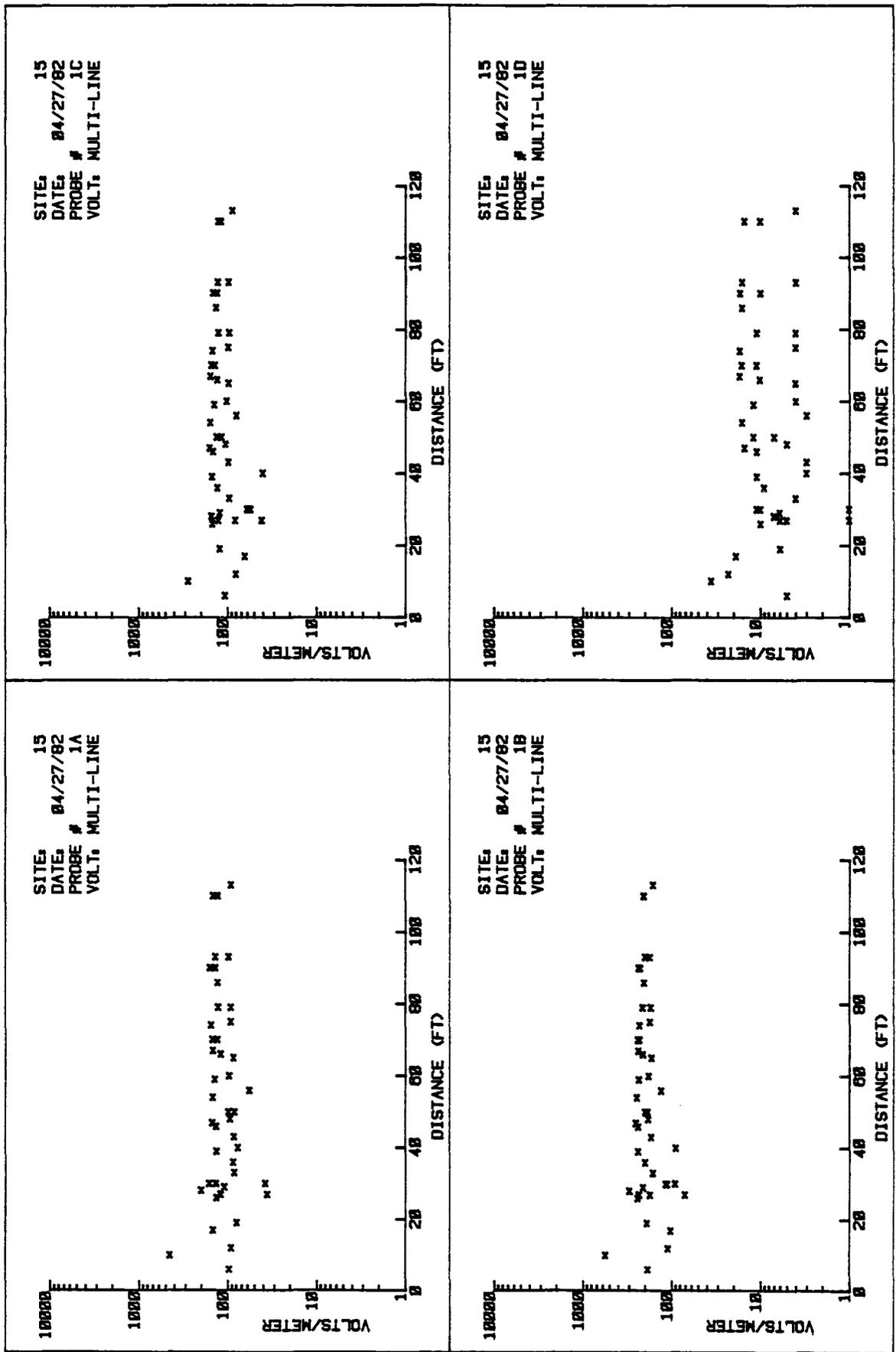FIGURE 44. DISTRIBUTION OF MEASURED ELECTRIC FIELD STRENGHS vs MISS DISTANCE
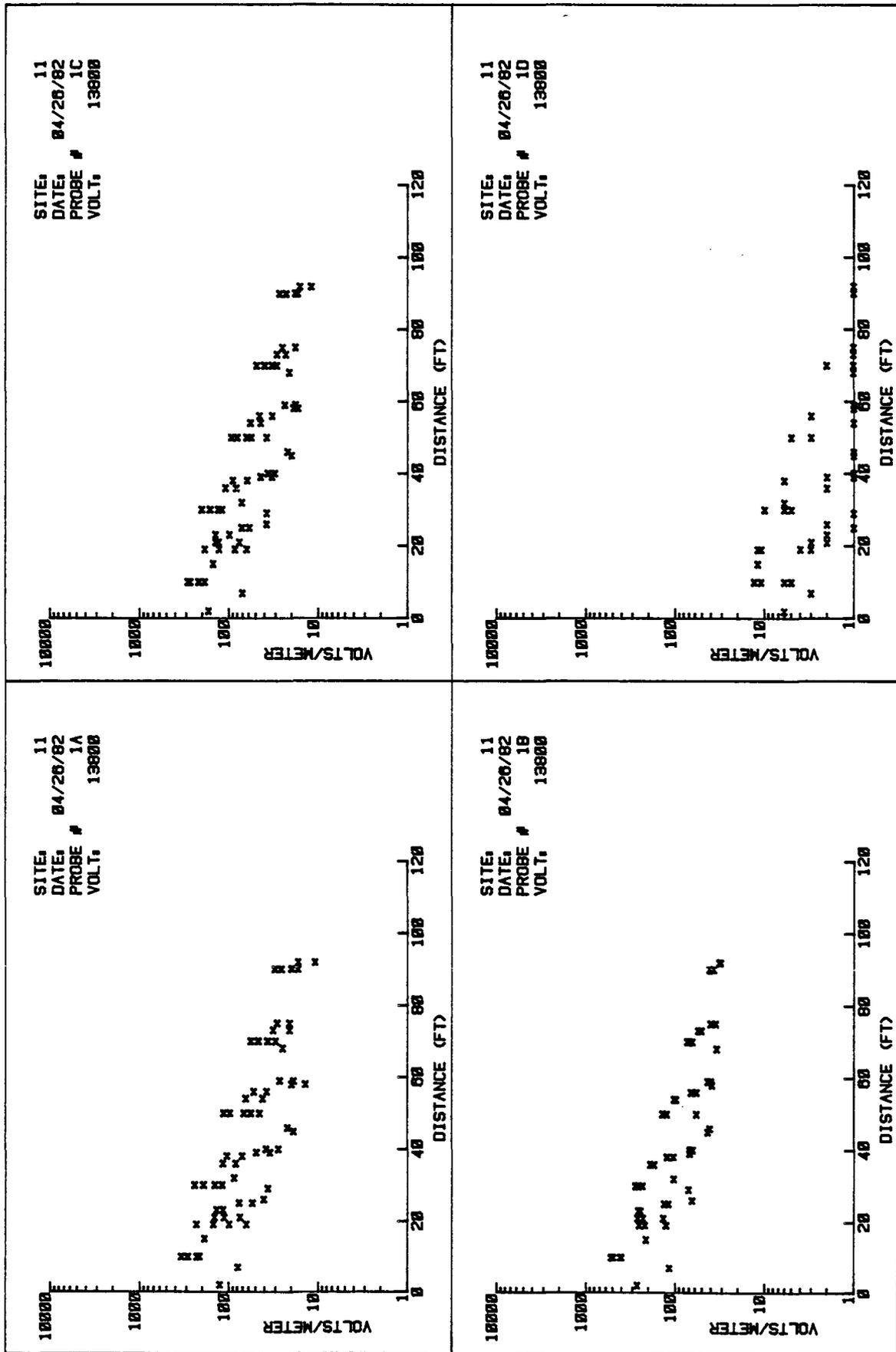FOR PROBE GROUP 1, SITE 15

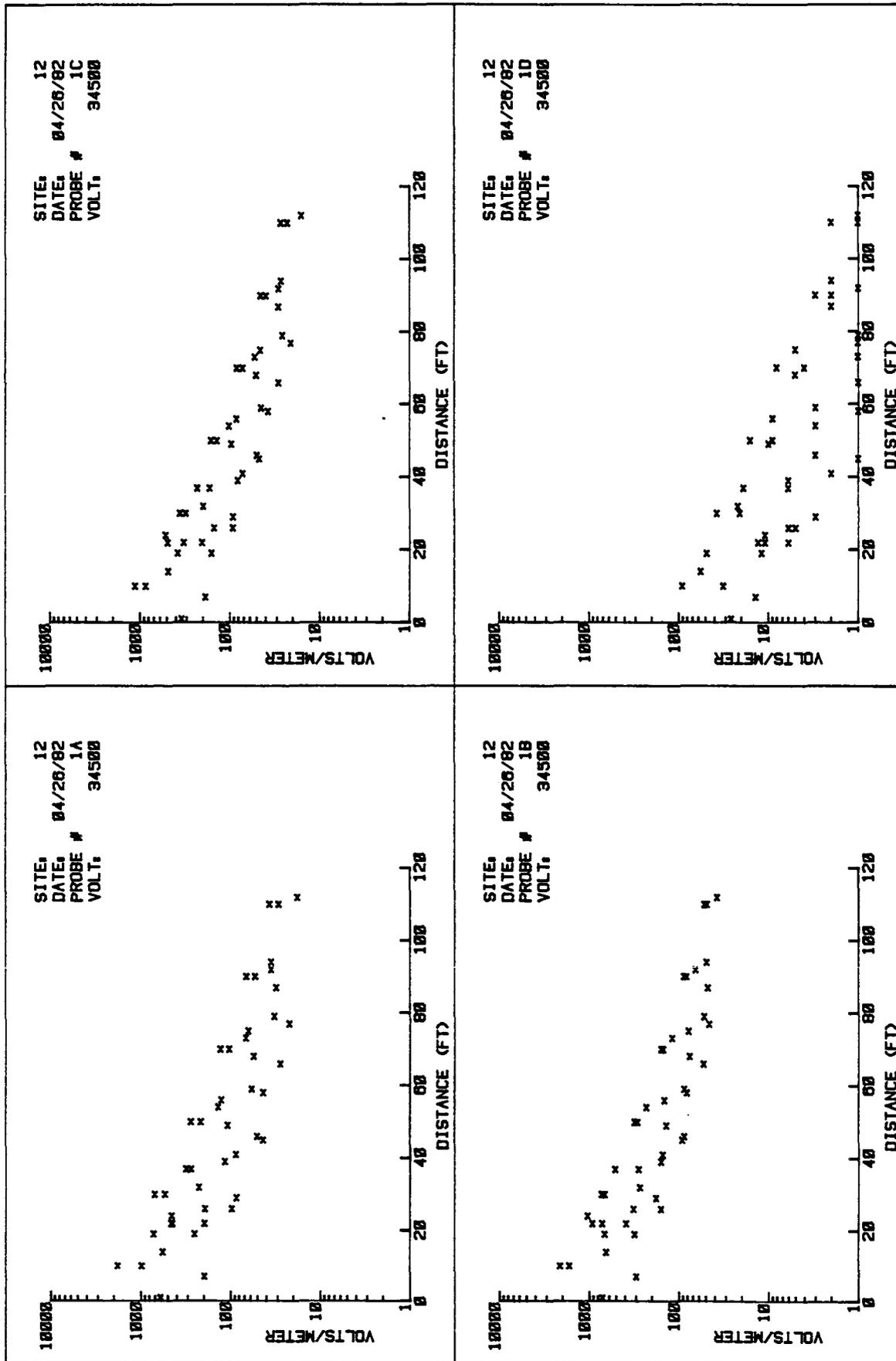FIGURE 45.   DISTRIBUTION OF MEASURED ELECTRIC FIELD STRENGTH vs MISS DISTANCE FOR 13.8KV POWER LINE

FIGURE 46. DISTRIBUTION OF MEASURED ELECTRIC FIELD STRENGTH vs MISS DISTANCE FOR 34.5KV POWER LINE

IV. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

1. Phase I

Several design deficiencies were observed in the three commercial proximity warning devices tested under this contract. These design deficiencies, which vary from device to device, include inadequate overlap in sensitivity ranges, utilization of fragile vacuum tubes and electromechanical parts, excessive sensitivity to temperature, inaudible alarms, and lack of provisions for boom length variations. The elimination of these deficiences is straightforward and within the present state of the art.

In addition, several aspects of the proximity warning device reliability are severely limited by the physical principle (i.e., electrostatic field sensing) on which the devices operate.

Six categories of physical phenomena were observed to produce undesirable performance in the commerically available proximity warning devices. These phenomena included field distortion from multiple power line circuits, electric field polarization effects, sensor shielding by the crane boom, partial boom protection, sensitivity variation with boom orientation, and sensitivity variation with boom extension. The inability of the devices to operate reliably in the presence of multiple power line circuits results from an interaction of the electrostatic field vectors produced by the individual power line circuits and can cause extreme departures from the electrostatic field produced by a single power line circuit. These variations are so diverse and extreme as to render unreliable any device operating on electrostatic field detection principles alone. However, a more sophisticated proximity warning device system can be designed to minimize the above limitations and substantially improve the operational reliability in the vicinity of a <u>single circuit power line</u>.

2. Phase II

The Distributed Sensor AC Electrometer designed and developed by SwRI under the Phase II program provides a state-of-the-art automatic data logging device for the measurement of the electrostatic field environment in the presence of high voltage power lines. The incorporation of multiple sensors allows complete mapping of electrostatic field characteristics in the presence of a crane boom and quantifies such factors as polarization, shielding by the crane boom, and sensitivity variations as a function of boom orientation and extension. The distributed processing concept incorporated into the AC electrometer provides maximum accuracy and minimum response time for the field strength measurements. Unique features of the system

such as automatic self-checks of the field probes, data conversion circuits, and the capability for magnetic tape storage of all measured data enhance the usefulness and reliability of the developed equipment group.

Laboratory tests of the Distributed Sensor AC Electrometer using an electrostatic field calibration fixture have demonstrated the design goal dynamic range and measurement accuracy. Dynamic range is in excess of 60 dB with typical field strength measurement accuracy of nominally $\pm 5\%$.

3. **Phase III**

a. **Electrometer Performance**

The Electrometer operated as specified, measuring electric fields about a crane boom in the proximity of various high voltage power lines. The system successfully measured and logged data from 17 sites.

b. **Data Analysis**

Analysis of the measured electrostatic field as a function of crane miss distance demonstrated that a proximity warning device using a single electrostatic sensor would be influenced by the choice of sensor location and would be significantly influenced by the variations of crane boom orientation. The choice of sensor location influences both the absolute level of signal response and the characteristics of signal response vs. distance. The absolute signal response is a concern only when it changes so drastically as to exceed the dynamic range of the system. In contrast, the characteristics of signal response vs. distance are crucial in the reliable operation of a proximity warning device. Sensor placement was shown to have an influence on the undesirable sensitivity to boom orientation. In general, sensors located on either side of the boom were much more sensitive to crane boom azimuth than were sensors placed on top of the crane boom. In addition, sensors placed near the tip of the crane boom were much more sensitive to crane boom elevation than were sensors placed near the crane boom pivot point. As a consequence, a single sensor proximity warning device would be expected to perform more reliably (under the conditions of varying boom elevation and azimuth) whenever the sensor is placed near the boom pivot point.

The measured electric field strength data also demonstrated that a proximity warning device using electrostatic field sensing principles cannot provide a reliable indication of distance to a power line when multiple circuits are present.

The data analysis also showed that the absolute signal response levels are directly influenced by the power line voltage. While the dependence on power line voltage does not directly influence

the reliability of a proximity warning device at any one site, it does indicate a requirement that the proximity warning device be adjustable at each power line site to optimize performance for that site.

The data analysis showed that under typical combinations of crane boom elevation and crane boom azimuth, a best case performance for a single sensor proximity warning device would produce alarms for distances ranging from 20'-60' to the power line depending on the combination of crane boom elevation and azimuth.

B. Recommendations

1. Phase I

a. Recommended Design Objectives for Improved Performance

(1) Minimize Electric Field Polarization Effects

Electric field polarization effects were observed during the tests of all three commercially available devices and arise from the nature of a single sensor/boom configuration to have a maximum sensitivity for a preferred orientation of electrostatic field vector. At positions where the electrostatic field vector is oriented orthogonally to the preferred orientation, the system sensitivity is minimized, allowing the crane boom to be positioned much closer to the power line without producing an alarm. To overcome this difficulty, separately monitored multiple sensors placed on all sides of the crane boom are recommended. In this configuration, even though the electrostatic field vector orientation may be orthogonal to the preferred direction for some sensors, other sensors mounted in positions responding to different preferred field orientations will respond to the electrostatic field.

(2) Eliminate Sensor Shielding by the Crane Boom

Sensor shielding by the crane boom was also observed for all proximity warning devices tested. Whenever the electrostatic field sensor and the electrostatic field source (i.e., the power line) are on opposite sides of the crane boom, the massive conducting structure of the crane boom effectively shields the sensor probe, severely reducing its sensitivity. To eliminate this effect, multiple sensors placed on different sides of the crane boom are recommended, making it impossible for all sensors to be simultaneously in the "shadow" of the crane boom.

(3) Provide Full Boom Protection

Two of the devices tested, under a previous phase of this contract, used short (i.e., "point") sensors and gave

effectively only a sphere of protection about the sensor. Consequently, with the point sensor placed near the boom tip, the base of the crane boom would not be adequately protected and could come into contact with the power line if the boom tip were raised to a high position above the power line. To overcome this limitation, multiple sensor placement along the entire length of the boom is recommended.

(4) <u>Minimize Sensitivity Variation with Boom Orientation</u>

One of the previously tested devices used a distributed sensor and displayed significant sensitivity variation with boom orientation. As the boom was rotated from a position parallel to the power line to a position normal to the power line, the sensitivity decreased severely. To minimize the sensitivity fluctuation with boom orientation, point sensors are recommended.

(5) <u>Eliminate Sensitivity Variations with Boom Extension</u>

The same alarm, which used a distributed sensor, by its design showed decreasing sensitivity with decreasing boom length. To eliminate this variation, point sensors are recommended.

b. <u>Recommended Improved Proximity Warning Device System Design</u>

To incorporate all the features of the above recommended improvements, the improved proximity warning device system must incorporate multiple point sensors distributed around the boom and along the length of the boom. The output of each sensor must be separately monitored to produce an alarm whenever the power line approaches within ten feet (or some other established distance) of that individual sensor. In this way, an approximately uniform distance-sensitivity can be established along the entire length of the boom and on all sides of the boom, regardless of the field orientation, the boom orientation or the boom extension.

In addition, it is recommended that the device incorporate a feature that automatically turns on the device to maximum sensitivity whenever the crane operation begins. This "wake up" sensitivity of the device would be factory adjusted to alarm whenever the crane comes within 50 to 100 feet from a high voltage power line. Such a capability would warn a traveling crane operator that he is coming into the vicinity of a high voltage power line.

To minimize the difficulty of establishing the proper sensitivity at the beginning of operation, it was recommended that the sensitivity adjustment controls be replaced by a single pushbutton switch that activates an automatic sensitivity adjustment.

2. Phase II

It was recommended that the Distributed Sensor AC Electrometer be used for extensive data logging of electrostatic field strengths for a significant sampling of high voltage power line configurations and voltage level parameters. These tests could be accomplished both in controlled environments such as the SwRI radiolocation field laboratories and in practical environments such as the San Antonio local utility and/or Bureau of Mines test facilities. The field strength data recorded on magnetic tape should be reduced by off-line computer processing and compared to theoretical data predicted for each measurement condition.

Results of the above recommended program would provide the Bureau of Mines with a large empirical data base of electrostatic field strength distribution about a variety of high voltage power line configurations. This data in conjunction with theoretical prediction techniques could be used to map other power line configurations not included in this measurement program. Ultimately, the complete data set (both measured and theoretical data) can be used to provide design guidance for commercial manufacturers of crane-mounted proximity warning devices.

3. Phase III

The analysis that was performed under this project concentrated on the performance of a single probe proximity warning device. It is recommended that this data be reanalyzed to determine the performance of a multiple probe proximity warning device. Under this concept, the entire set of 17 probe measurements (or any sub-set of those measurements) would first be independently analyzed for each site to choose an optimum alarm threshold value for that probe. The threshold value would be optimized to produce alarm for any miss distance closer than some specified distance (e.g. 20 feet), regardless of boom orientation. The result of that step of analysis would be a set of 17 threshold values valid for all combinations of boom orientations at that site. Using the set of 17 optimum threshold values, the data for that site would again be reanalyzed to examine each probe signal for each combination of boom elevation and azimuth. Whenever the signal level from any probe is above its associated optimum threshold value, an alarm would be indicated. In this manner, a tabulated list of alarm distances for each combination of boom elevation and azimuth would be established for the collective system of probes, and would demonstrate whether any significant advantage in proximity warning device reliability would be gained from using multiple probes as opposed to single probes. It is suggested that this scheme would minimize the spread of alarm distances that boom orientation variation normally produce in a single sensor system.

The field measurements in this project were taken to quantify the characteristics of electric fields about a crane boom in the vicinity of power lines. The results of the more extensive

analysis proposed above should provide signficant insight into the design and development of a system which better detects the proximity of high voltage power lines.

The application of statistical analysis and field gradient measurements between multiple probes may offer insight into the problems summarized in the conclusions.

Microprocessor technology offers the capability of high speed data analysis which could be integrated into a reliable proximity warning device.

There were several areas in which the system could be improved. These areas include: 1) isolation of signal ground from power ground between field probe and remote processor to improve low level signal accuracy. 2) reduction of temperature sensitivity in electric field probe and master computer electronics, and 3) replacement of present cartridge data recorder with a more reliable data cassette recorder. The estimated cost for a modified and improved master computer is approximately $30,000.