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PRE-INSTALLATION SCAN MEASUREMENTS OF THE AGS BOOSTER ELECTROSTATIC BEAM POSITION MONITORS

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DISCLAIMER

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INTRODUCTION

The performance goal for the AGS Booster Beam Position Monitoring (BPM) system is to measure the absolute position of the beam to $\pm$ 0.5 mm (with a resolution of $\pm$ 0.1 mm), over a 60 mm circular aperture. The detector used is the split-cylinder electrostatic type, which provides a high degree of linearity and excellent low frequency response (Figure 1). For the system to achieve its performance goal, the high-level software requires offset and sensitivity values for each BPM station in the ring, which are used to convert sum and difference voltages into beam position information (differential sensitivity is primarily determined by the detector, while the system offset is a combination of both the detector and its associated signal processing electronics). It is also desirable to have some knowledge of the effects (if any) of thermal cycling on the detector, as well as the overall linearity of the PUEs over the specified aperture. Since the PUE assembly is the most difficult component of the BPM system to remove or modify, measurements of linearity, offset and sensitivity were made on each detector prior to its installation into the Booster.

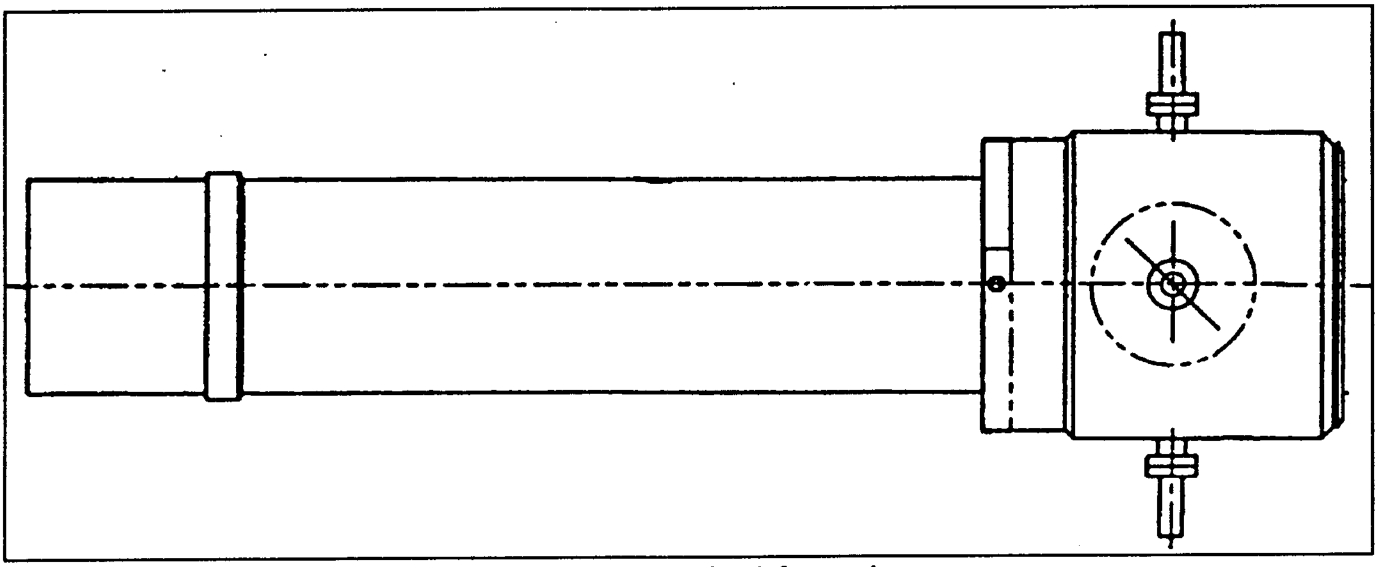


Figure 1. A "completed" detector assembly, as received for testing.

To characterize each detector, a wire of known position (relative to the detector shell) is scanned across the measurement plane. At specified positions, an RF signal is applied to the wire, the voltages on each half of the split-cylinder electrode recorded, and the sum and difference of these voltages computed. A curve fitting routine is then used to find an equation of the form

$$P = K \frac{V_A - V_B}{V_A + V_B} + O \qquad (1)$$

where P is the position (in mm) of the wire

K is the reciprocal of the sensitivity (mm^{-1})

O is the offset (in mm) of the electrical center of the detector with respect to its mechanical center

V_A and V_B are the measured (rms) electrode voltages

The purpose of this technical note is to document and discuss the scan wire tests run on each of the 54 BPM detectors. The outcome of these tests are a reflection only of the quality of the detectors, and do not include any errors introduced into the system by either the installation procedure or by the electronic units at each BPM station. First, sources of error resulting from the construction of the detector itself are identified, and the causes of each is discussed. A description of the actual test set-up used to make the detector measurements follows, and typical data from the tests are presented.

SYSTEM ERRORS RELATED TO THE DETECTOR

Figure 2 is a family tree of mechanical factors related to the detector which contribute to the overall measurement error of the BPM system. These factors can be separated into two groups; errors due to the physical mounting of the detector within the quadrupole and errors that are caused by non-uniformities within the PUE assembly itself.

Errors Associated with Installation

There are three basic sources of misalignment between the detector and its associated quadrupole which diminish the overall position measurement accuracy. They are:

1) rotation of the detector with respect to the quadrupole's coordinate system,

2) longitudinal misalignment with respect to the beam pipe, and

3) physical location changes due to thermal cycling during bakeout.

Since there is no practical method to make scan wire measurements after the detector is already installed, the position error contributed by 1) and 3) cannot be easily measured. The effect of 2), however, is a position offset which can be approximated using a network analyzer after the detectors are installed. The analyzer can be made to drive the calibration ring of the detector while monitoring the difference of the responses from each electrode. It is assumed here that any imbalance of signal from the calibration ring to the plates is relatively small, due to the manufacturing tolerances of the split-cylinder assembly (which includes the calibration ring). No such tolerances were placed on the attachment location of the completed detector assembly to the beam pipe, which strongly affects the relative plate-to-shell capacitances of the two halves of the split-cylinder PUE.

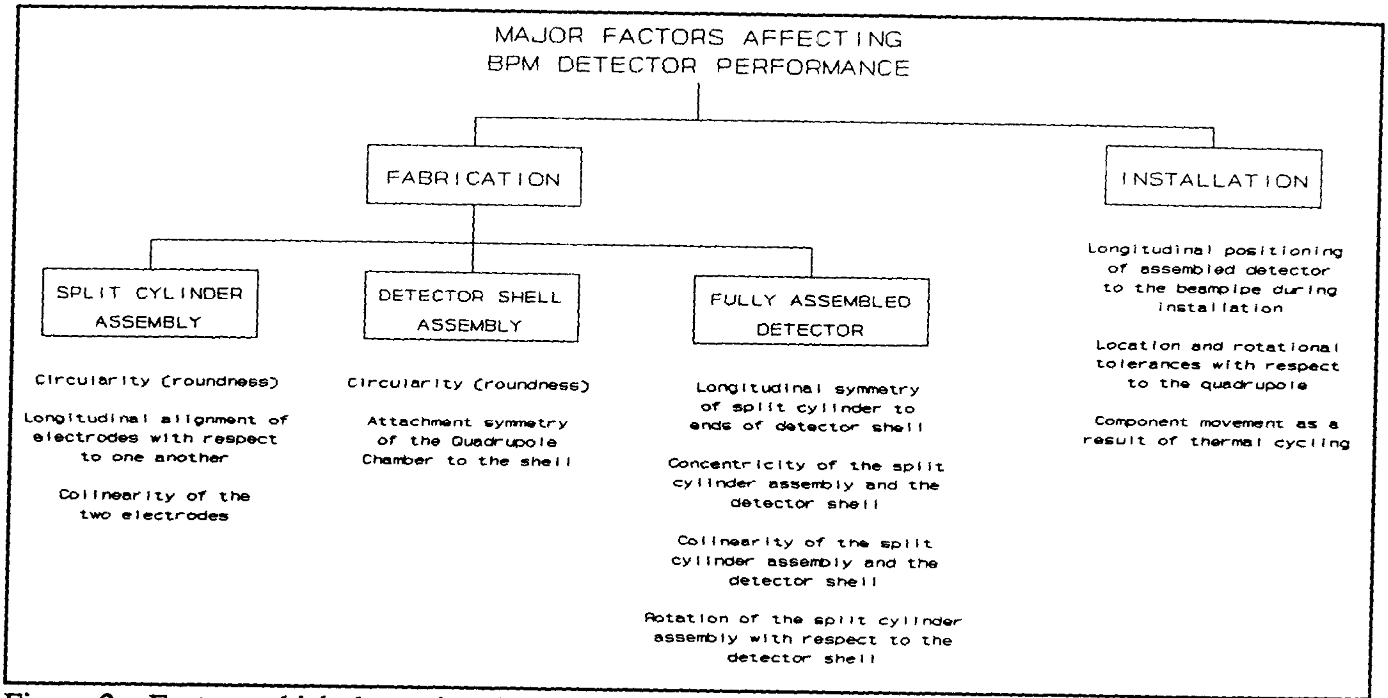


Figure 2. Factors which determine detector-related errors.

Errors Produced by the Detector Itself

The mechanical precision of the detector has a large effect on the overall BPM measurement accuracy. The following situations can arise due to asymmetries within the PUE assembly:

1) The electrical and mechanical centers of the detector do not coincide (constant offset independent of beam position).

2) The electrical center offset (with respect to mechanical center) is beam position dependent.

3) The differential sensitivities of the detectors vary from unit to unit.

4) The plate voltage does not vary linearly with respect to the beam (or scan wire) position.

A difference between the electrical and mechanical centers is commonly referred to as the offset of the detector. Offset occurs when the capacitance between each electrode and the detector shell is not equal. For example, certain "out of round" conditions of either the split-cylinder assembly or the detector shell could manifest themselves as an offset, if the net capacity of one electrode to the detector shell is greater than that of the opposite electrode (assuming no other offset effects). If the split cylinder is not coaxial with the shell, this could also show up as an offset error. Figure 3 shows a few of the possible situations where a component of position offset arises due to unequal plate capacitances. (All illustrations assume the split cylinder and shell to be collinear.) In the figure, the "Offset Component" column refers to a mechanical offset, whereas an electrical offset is defined as *an inequality of electrode capacitances*. It is the net balance of plate capacitances that matters; several effects could occur

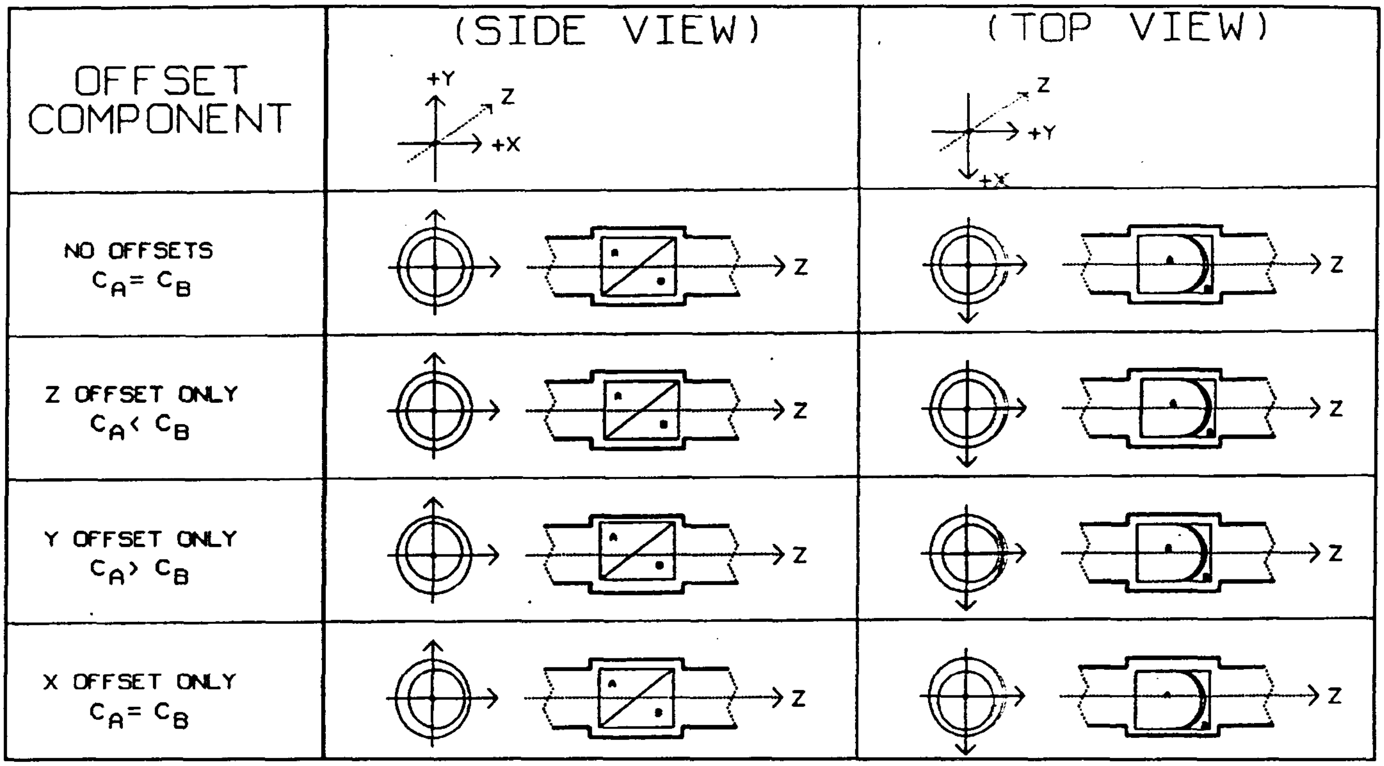


Figure 3. Some examples of non-concentric split cylinder and shell assemblies.

simultaneously, having a canceling effect. (An example is the bottom illustration in Figure 3.) In addition, capacitance loading of the plates (produced by the front-end electronics) is a significant contributing factor not included here.

It is possible, however, for a detector to have an offset which is a function of beam position. This occurs when the transverse coordinate system of the split cylinder does not coincide with that of the detector shell (this of course assumes the shell contains the reference orientation, and is perfectly locked to the quadrupole). When the split cylinder is rotated within the shell, any given beam position has associated with it both a horizontal and a vertical offset component as shown in Figure 4. This effect must be minimized before installation of the detector, since the resulting error cannot easily be corrected by the software.

Variations of the detector differential sensitivity occur when the gap size between each half of the split cylinder varies from unit to unit. The gap distance directly affects the inter-plate capacitance, as well as the capacitance between each plate and the detector shell. For example, a wider gap would result in a smaller value of plate-to-plate capacitance, but a larger plate-to-shell capacitance — the converse is also true. It is the interaction of these capacitances which determines the differential sensitivity. (It is interesting to note that the AGS Booster detector has an inter-plate capacitance which is of the same order of magnitude as its electrode-to-shell capacitance.) Scan wire tests allow a value for the differential sensitivity of each detector to be measured. (The differential sensitivity is equivalent to $1/K$, where K is from equation (1) above.) In principle, conversion of BPM system sum and difference voltages to actual beam positions can be made more accurate if the high-level software uses "detector specific" values for K. Since this value represents the slope of a line, the improvement in the accuracy of the beam position computation that would result from the use of detector specific values is proportional to the actual position of the beam relative to the center of the detector.

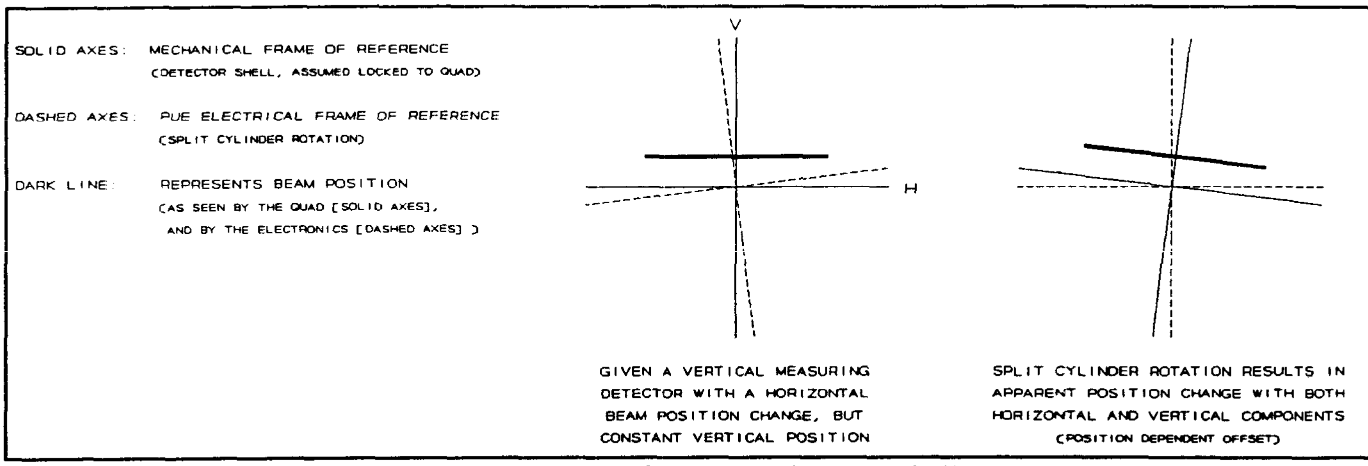


Figure 4. Effect of split cylinder rotation (relative to the detector shell).

It is not necessary that the high-level software correct for nonlinearities of plate voltage with respect to beam position, since the detector design used has been found to be extremely linear over a wide operating aperture, as shown below. In this case, the scan wire measurements are more of a "Pass-Fail" type of test than a method of gathering correction data.

DESCRIPTION OF THE SCAN WIRE TESTS

The primary purpose of the scan wire tests is to provide some degree of Quality Control on the detector assemblies before they are installed. The linearity, sensitivity and rotational characteristics of each detector assembly have been archived for possible enhancement of the accuracy at a later date.

A set of scan wire measurements consists of five scans, each with 51 data points. The reference position (mechanical zero) is measured before and after each scan as an accuracy verification, bringing to 261 the total number of data points obtained during each measurement set. From the completed set of scans it is possible to observe the effects (if any) of split-cylinder rotation and position-dependent offset. In addition, the linearity, differential sensitivity and offset characteristics of the detector under test can be determined. The resulting offset value is somewhat misleading, however, since the final capacitance balance of the PUEs cannot be known until the detector is installed into the beam pipe.

Three separate scan sets are performed for each detector. The first is done following its initial assembly and is used as baseline data (for later comparisons). The second set is done after welding in place the L-brackets which hold the split cylinder together. The third and final set of measurements is performed after firing the completed PUE assembly at 900 °C. If the detector can withstand firing and maintain its accuracy afterward, then there is a high level of confidence that the normal 300 °C bakeouts will not cause difficulties.

The large amount of data required for each detector (783 total data points per assembly) coupled with the requirement for 54 detectors, justified the need for an automated test set-up. The repetitive nature of these measurements makes them tedious, time consuming and prone to operator error. A computer is well suited to handle the acquisition, file handling and reduction of the large amounts of data involved. In addition, a motorized table under computer control can provide rapid, precise manipulation of the scan wire.

Test Set-up

After the split cylinder and calibration ring have been carefully assembled, the unit is inserted into the pick-up electrode body. The pick-up electrode body is itself part of the vacuum chamber. It has openings for the four coaxial signal feed-throughs as well as mounting holes to allow the BPM to be precisely positioned in the Booster quadrupoles. The pick-up electrode bodies come in three lengths — designated short, intermediate, and long.

The split cylinder is inserted into one end of the pick-up electrode body. This end is left open until it is welded to the flange that reduces the diameter of the chamber to that which passes through the quadrupoles. As a consequence, one of the halves of the split cylinder does not see the electrical environment it sees after being installed. Therefore, it is necessary to attempt to produce an electrically similar configuration using an extension which consists of a short tube and a flange. The junction between the extension and the pick-up electrode body is wrapped with grounding braid that is secured by means of hose clamps. Four springs go from the extension to the feed-throughs to hold the extension tightly against the pick-up electrode body.

After the extension has been attached, the pick-up electrode body is positioned vertically on a stand. Short rods are inserted into the same mounting holes which allow the BPM to be precisely mounted in the quadrupoles. These rods accurately position the pick-up electrode body on the mounting stand and prevent it from moving.

In order to obtain the scan measurement data, a signal wire is dropped through the inside of the pick-up electrode body. The wire (a 10-mil diameter piano wire) is connected to a 180 Ω terminating resistor and is then placed under tension produced by a strong spring. The signal wire is strung between the two arms of a large C-shaped support. The C-shaped support itself is mounted to the platform of an X-Y Cross Table.

A program running on a Hewlett Packard 9836S workstation/instrument controller automates the measurement process. (The HP 9836 is the predecessor of the HP Series 200 Model 236 workstation and is largely software compatible with the later models.) The primary measuring instrument is the HP 3577A Network Analyzer. The RF output port of the HP 3577A provides the signal, and the A and B receiver ports measure the r.m.s. voltage on the each half of the split cylinder of the pick-up electrode assembly. The Network Analyzer, the HP 9876A thermal printer, and the HP 9133XV disc drive are connected to the workstation using the HP-IB interface buss (IEEE-488). The equipment used is schematically indicated in Figure 5.

The X-Y Table Controller is attached to one of two RS-232C interfaces on the workstation. A complete scan consists of 261 measurements. By convention, the plane of highest sensitivity is designated y. The aperture is scanned at five x positions (-50, -30, 0, +30, +50). At each of the x positions, a measurement is taken every 2 mm from y = -50 mm to y = +50 mm (51 measurements). In addition to these 255 measurements, the wire is moved to (0,0) between each x position scan and at the beginning and the end of the entire measurement process, thus giving 6 additional measurements at position (0,0).

Since the process is largely automated the technician need not devote all his time to supervising the operation, but can engage in other tasks nearby. In order to maximize this capability, a text-to-speech convertor is used. The program announces the movement of the wire to each new measurement position by stating the new location. If these regular auditory signals cease, the technician knows that the

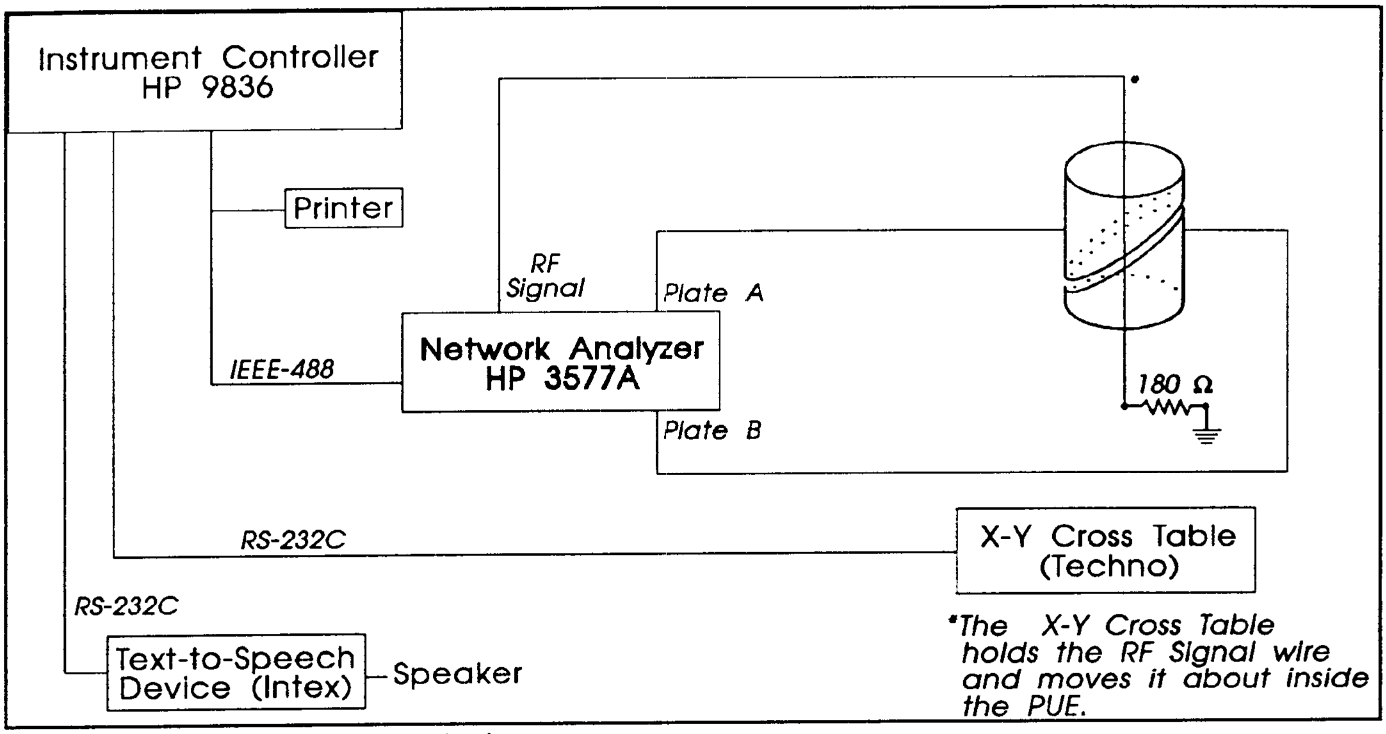


Figure 5. Set-up for the scanned wire measurements.

measurement device needs attention. In addition, a distinctive series of tones are produced at the end of the measurement to alert the technician that the measurement data is ready for analysis and inspection, and that a new pick-up electrode body may be placed on the stand.

If the X-Y Cross Table Controller returns an error, indicating perhaps that it failed to move to the position specified, or if the Controller fails to complete a movement within the expected time, the program causes a vocal annunciation of an error condition and screen messages give possible corrective procedures that will allow the measurements to resume without having to restart the procedure. Verbal instructions are also provided (these are supplemented or repeated by screen messages) for the less frequent tasks. These include the once daily calibration of the HP 3577A Network Analyzer and the preparation of new flexible discs for data storage.

For each of the 261 measurements, the Network Analyzer records and displays 401 data points representing the r.m.s. voltage magnitude of the signals at its A and B receiver inputs. (These 401 measurements are called a "trace".) The program retrieves these values and computes the average, the difference between the maximum and minimum measurement, and the standard deviation for the two signals. These three values for each channel are stored on removable flexible discs along with the coordinates of the wire position.

The program also uses this information, as well as the repeated measurements at (0,0), to ascertain that the cables have been connected appropriately. When a problem is suspected, the operator is verbally requested to check the cable connections.

The procedure for calibrating the HP 3577A Network Analyzer for the particular set-up in use is an integral part of the program. The program assists this process by drawing on the screen of the Network Analyzer a diagram of how the cables are to be connected for each step of the calibration process. In addition, the program assigns one of the function keys on the Network Analyzer as a "Ready?" key that is to be pressed after the proper connections have been made for each step.

X-Y Table Accuracy

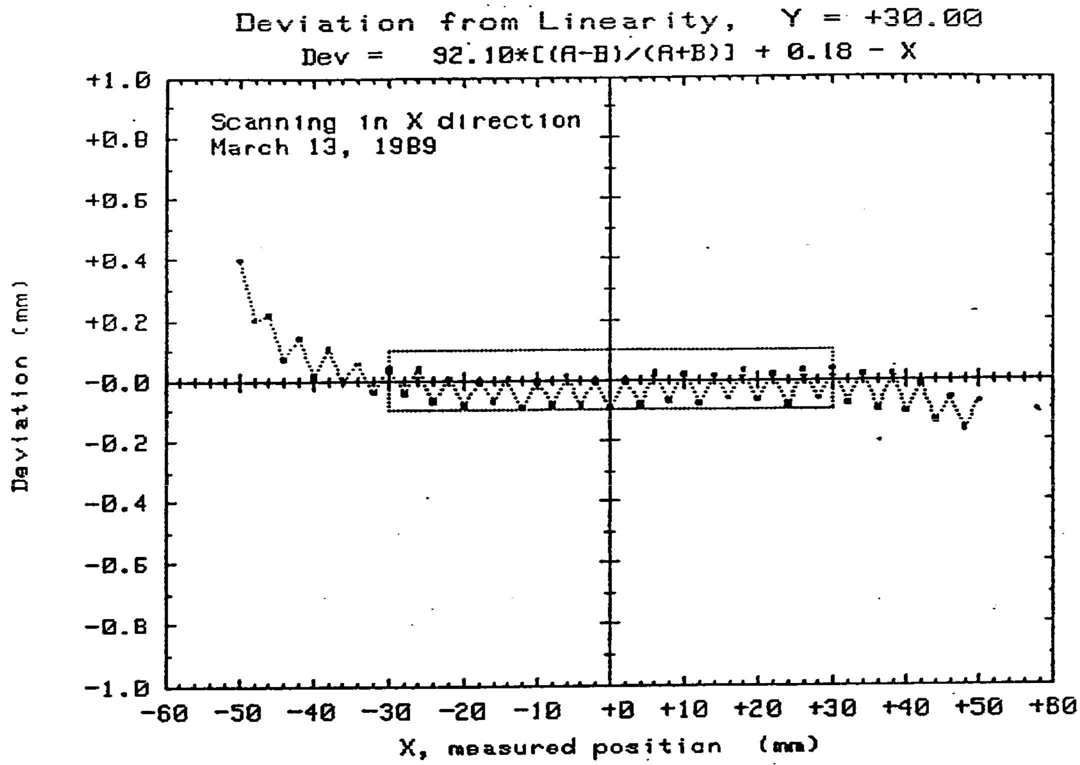
The X-Y Cross Arm Table (Techno Model HL32SBM2298) is an economical model and can not provide a continuous indication of its position. In fact, the table controller only knows when the platform has reached a single location on each of the axes, and this single location must be at one of the extremes of the arm movement. The controller knows that this position has been reached by the opening of a micro-switch when a protrusion mounted to the platform contacts it. All positions are then relative to the position of the platform when the switch on each axis opens. This position is known as the "Home" position. The controller sends pulses to the two stepper motors to drive a lead screw which in turn moves the platform relative to the Home position. There are 100 pulses/mm.

It was necessary for the Home switches to be moved to a position that kept the wire from touching the inside of the PUE body. This position is at about $x=-52$ mm, $y=+52$ mm. When the table is commanded to Home, the platform moves at the programmed acceleration until the switches are struck, so the switches must be mounted securely. The manufacturer specifies the accuracy of the homing operation to be ± 0.01 mm. In addition to this must be added the accuracy of determining the Home position relative to the position of the center of stand that holds PUE body.

The center of the stand (relative to the Home position) is determined by use of a special centering fixture. The centering fixture is placed on the stand in place of the PUE body. The signal wire is dropped through a small hole in the fixture and made taut. Two micrometers are mounted over the center hole on a vertical bar. The micrometers are spaced 10 inches apart. Since it is known that the true center is about 52 mm away from the Home position, the wire is commanded to move to that location, and the deviation of the center of the wire (the wire has a radius of about 5 mils) from the true center is determined using the micrometers. Originally, it was difficult to determine when the micrometer just touched the wire. Later, a hand-held digital voltmeter was used. The digital voltmeter is placed on the MΩ resistance scale, one lead is connected to the wire and another to the centering fixture. The vertical mounting of two micrometers allows the C-shaped support to be adjusted to make the wire perpendicular to the stand.

After the wire has been centered along one axis and made perpendicular in that plane, the centering fixture is rotated 90° and the procedure is repeated for the other axis. The process is both tedious and lengthy. The wire was considered centered when repeatable to ± 0.08 mm.

In addition to the difficulty of centering the wire, there was initially some jitter in the movement of the table platform itself. It was determined that this was due to either a bowing of the lead screw or to a loose fit that allowed the platform to tilt first to one side and then the other as it progressed along the lead screw. The effect was seen in the plots of the deviation of the data from a straight line where it manifested itself as a periodic variation instead of a smooth curve (see Figure 6). This problem was solved by dismantling the entire X-Y Table and reassembling it with attention being given to making everything tight.



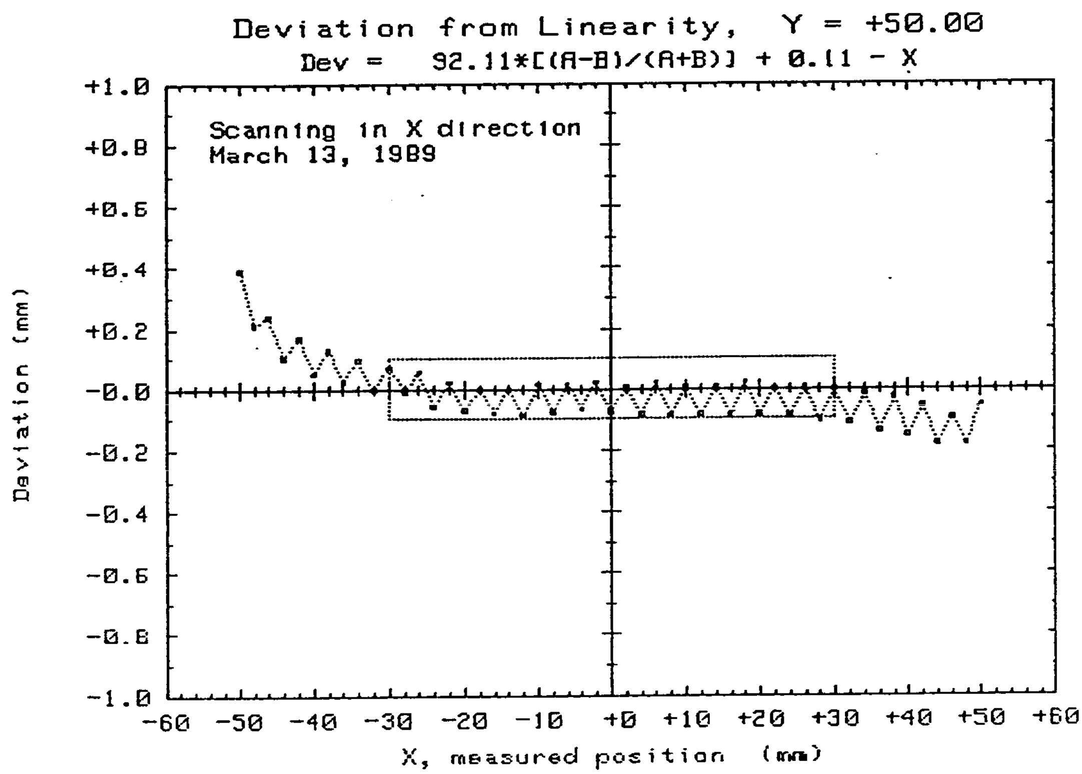


FIGURE 6. ERROR DUE TO LEAD SCREW OF X/Y TABLE. (PITCH OF LEAD SCREW IS 4mm/360 deg AND MEASUREMENTS ARE SPACED EVERY 2mm).

RESULTS OF TESTS

Immediately after the data has been taken and stored, it is analyzed. All of the results are plotted and a robust straight line fit is made to each of the five data sets (one for each of the five x positions) for the points which fall within -30 mm $< y <$ +30 mm. The fits are two parameter fits (slope and offset) of $(V_A - V_B)/(V_A + V_B)$ as a function of the programmed y position, where V_A and V_B are the magnitudes of the voltages on plates A and B of the PUE, respectively. A robust fit is one based on minimizing the absolute deviations rather than the squares of the deviations (the fit is ***not*** a least-squares fit). It has the advantage of being less sensitive to outlying points which frequently appear in data taken under real laboratory conditions.[1] A final fit is performed for the same range of y values, but combining all the points in this range for the three central x scans (-30, 0, +30). The deviations from a straight line are plotted in all cases.

Production Outputs

Figures 7 and 8 are the scan results of PUE assembly S/N 038, one of the "best" detectors tested. Figure 7 illustrates the high degree of linearity exhibited by the split cylinder geometry of the PUEs. All five of the x scans are well within $\pm$ 0.1 mm of the offset value for the entire aperture. Figure 8 results when the test wire is scanned in the x direction only. This plot verifies that the detector is relatively insensitive to position changes outside of the intended measurement plane. Note that the offset increases uniformily about zero, indicating that there is no rotation of the split cylinder assembly within the detector shell.

Figure 9 shows the results of a typical production detector. Only the x scans within the originally specified aperture of $\pm$ 30 mm are used as acceptance criteria.

Figures 10 through 12 are plots illustrating a few of the types of detector errors revealed via scan wire measurements (note that not all of the errors shown result in rejection of the detector under test). Detector S/N 005 (Figure 10) was rejected due to the large variation in offsets measured for different x scans. The plots indicate a significant rotation of the split cylinder within the detector shell. In contrast, S/N 021 also exhibited a rotation error (Figure 11), but one not as severe as that of S/N 005; The two x scans outside of the acceptance window are at + 30 and + 50 mm. If one observes only those scans within the specified 60 mm circular aperture, then S/N 021 might very well be accepted without rework.

A large variation in slope (1/K) is depicted in figure 12, the results from detector S/N 039. Although not aesthetically pleasing, the plots do not indicate an unacceptable unit. In fact, the value of the slope at x = -50 mm and at x = +50 mm differs by only 0.7 %. At the $\pm$ 30 mm aperture edges, the slope differs by only 0.4%, which translates to less than 0.5 mm error.

Figure 13 shows the distribution of slopes resulting from the measurement of 60 detectors. The distribution of the measured offsets are shown in Figure 14.

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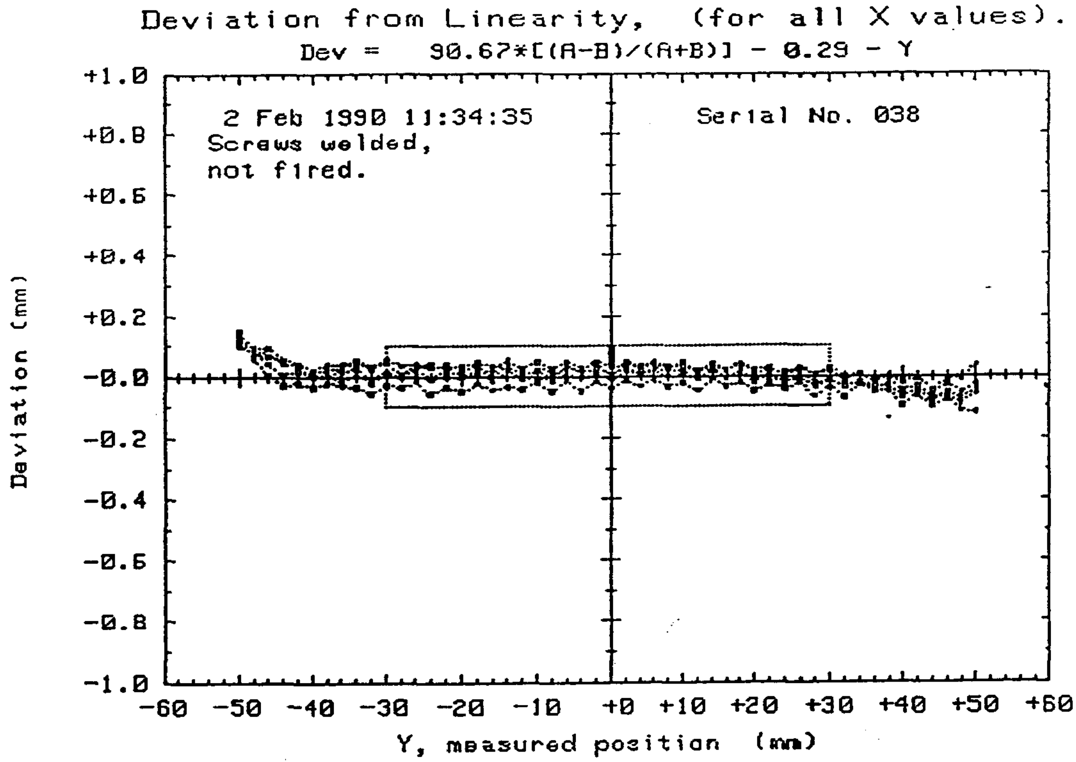
[1]Press, W. H., Flannery, B. P., Teukolsky, S. A., and Vetterling, W. T., *Numerical Recipes*, Cambridge University Press, 1986, pp. 539-546.



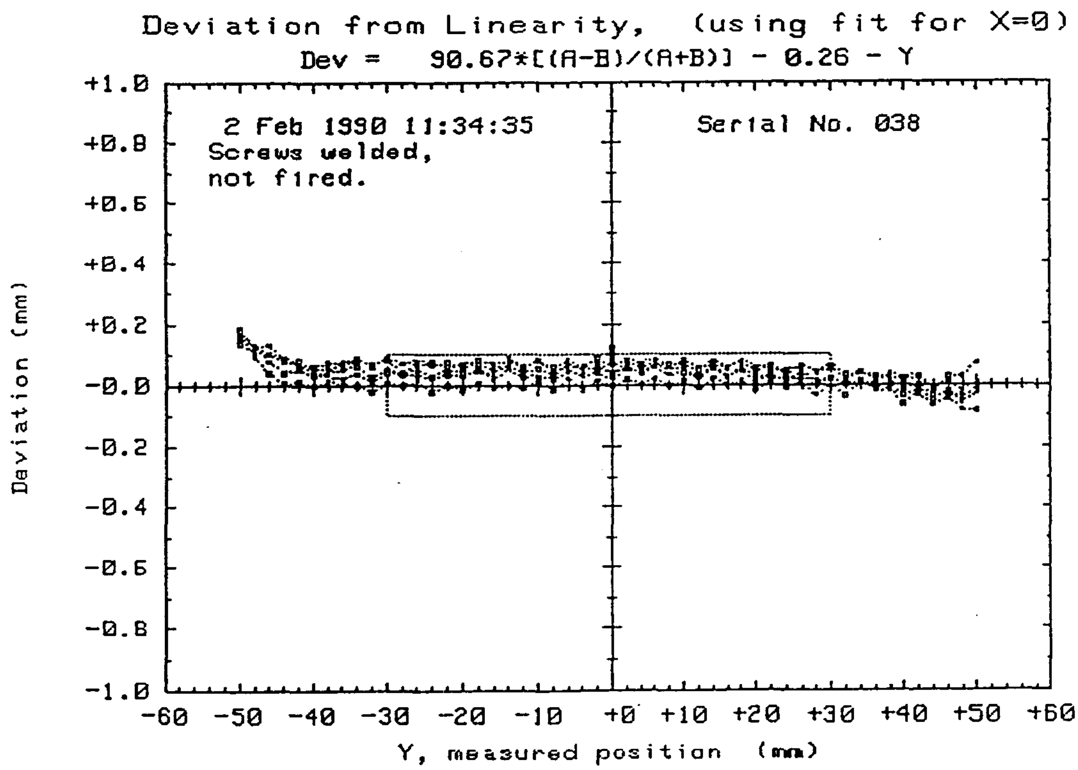


FIGURE 7. RESULTS OF SCAN FOR DETECTOR S/N 038.

X,Y -50.0	-0.47	X,Y -40.0	-0.42
X,Y -30.0	-0.37	X,Y -20.0	-0.34
X,Y -10.0	-0.35	X,Y +0.0	-0.33
X,Y +10.0	-0.35	X,Y +20.0	-0.35
X,Y +30.0	-0.39	X,Y +40.0	-0.45
X,Y +50.0	-0.48		

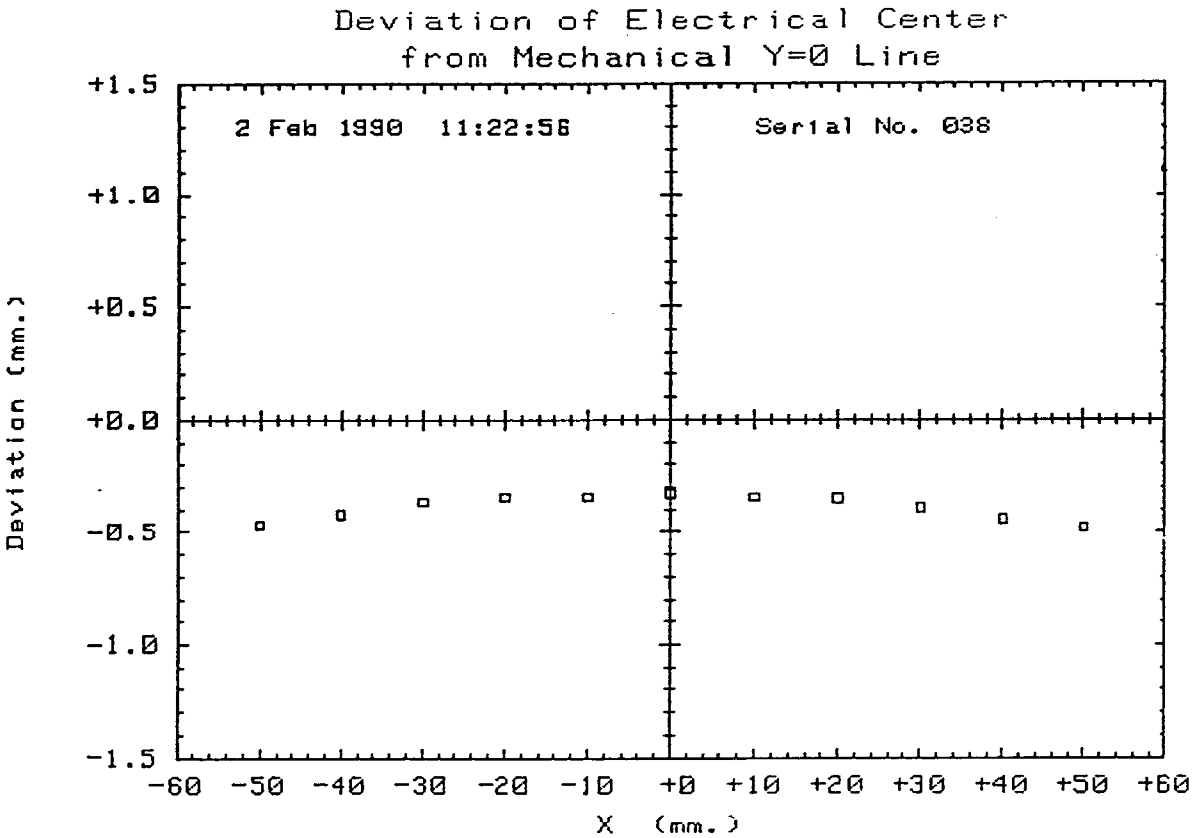


FIGURE 8. RESULTS FROM SCAN IN DIRECTION PERPENDICULAR TO MEASUREMENT PLANE (S/N 038).

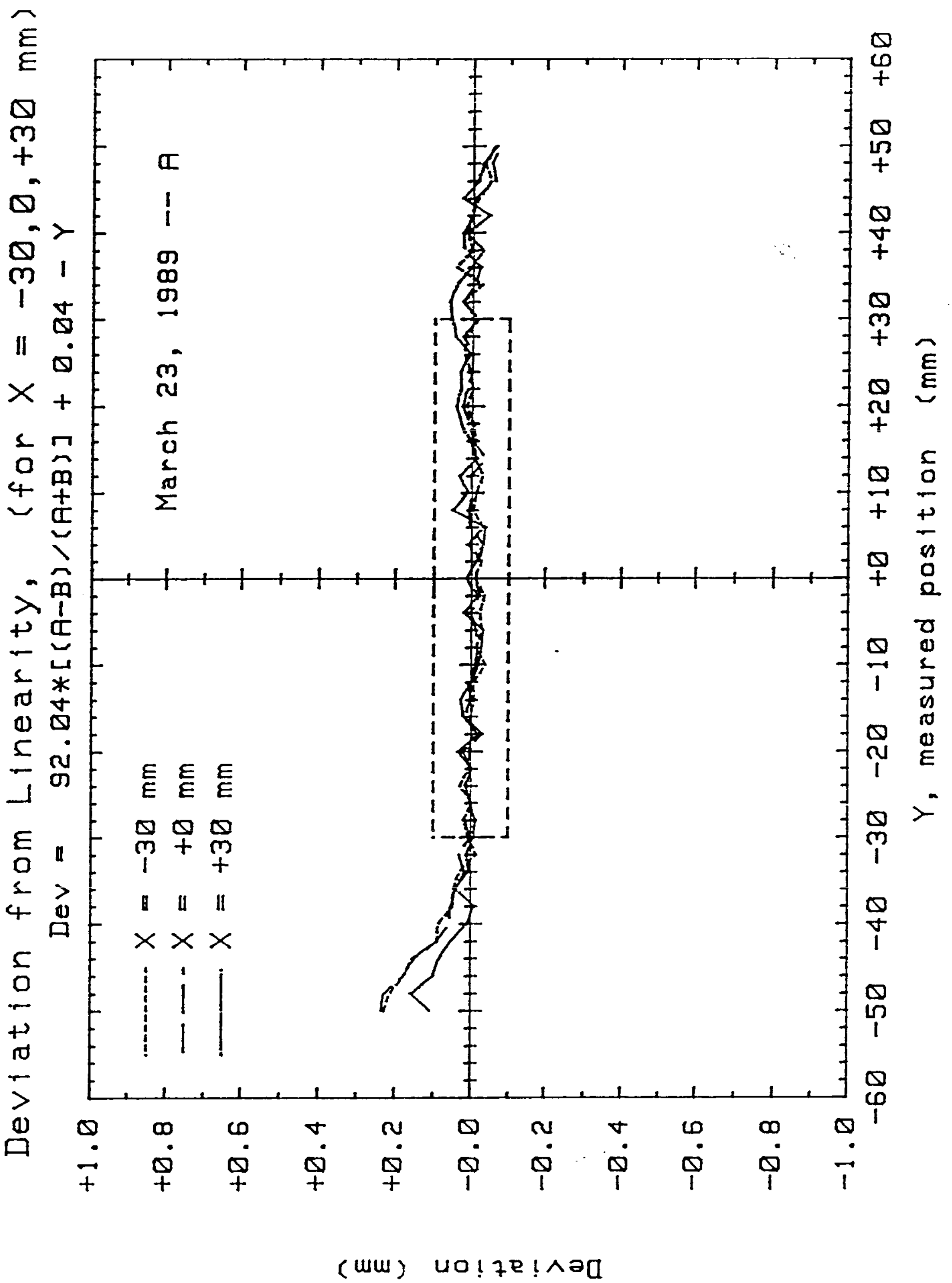
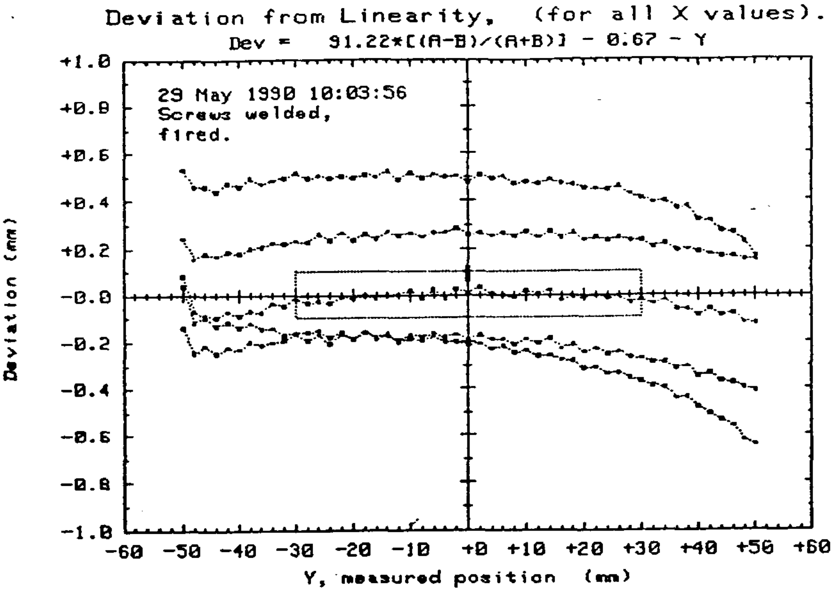
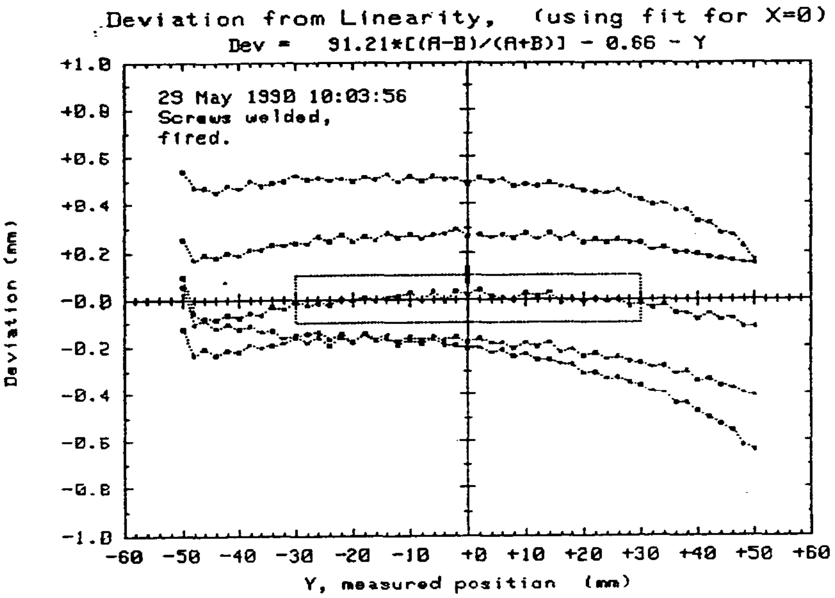


FIGURE 9. TYPICAL ACCEPTANCE DATA.





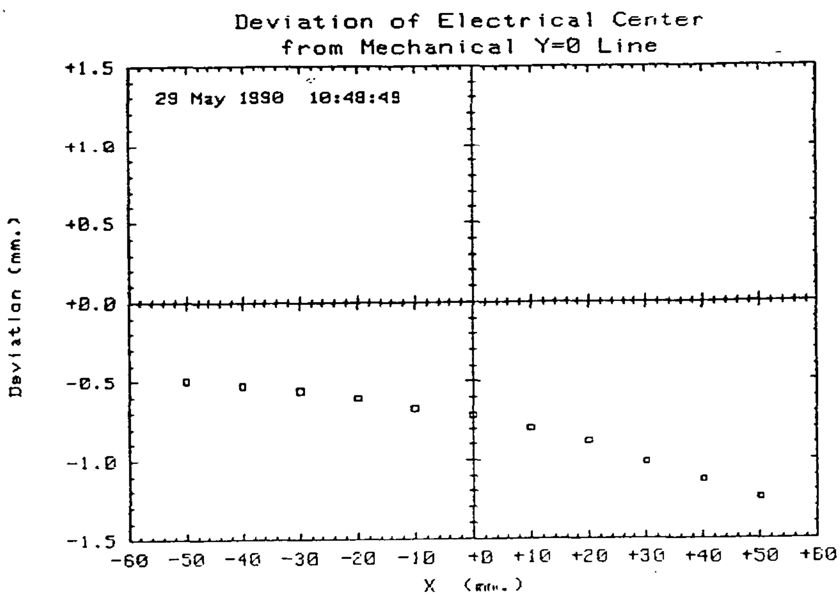


FIGURE 10.

THIS DETECTOR WAS REJECTED, DUE TO A ROTATION OF THE SPLIT CYLINDER ASSY WITHIN THE DETECTOR SHELL.

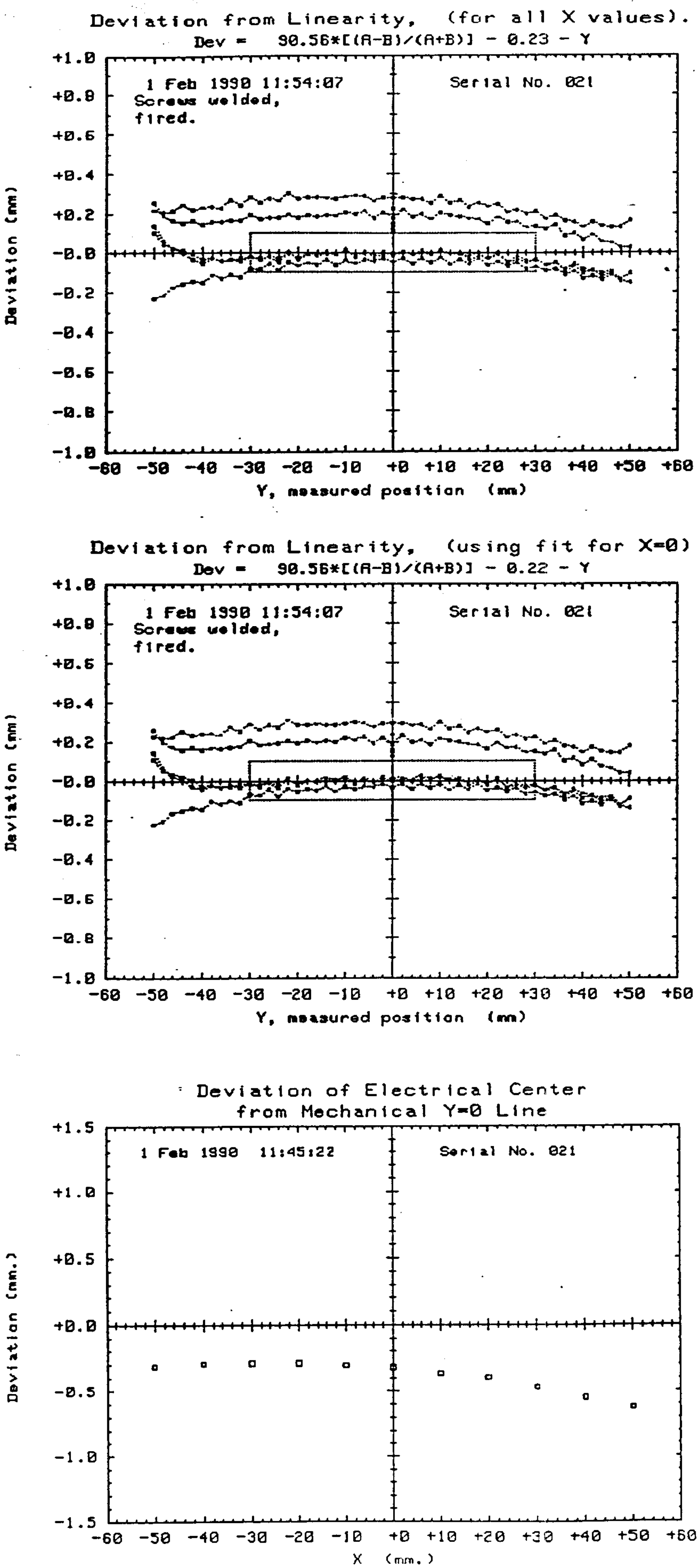


FIGURE 11.

RESULTS OF A DETECTOR EXHIBITING A 'REASONABLY ACCEPTABLE' AMOUNT OF SPLIT CYLINDER ROTATIONAL ERROR.

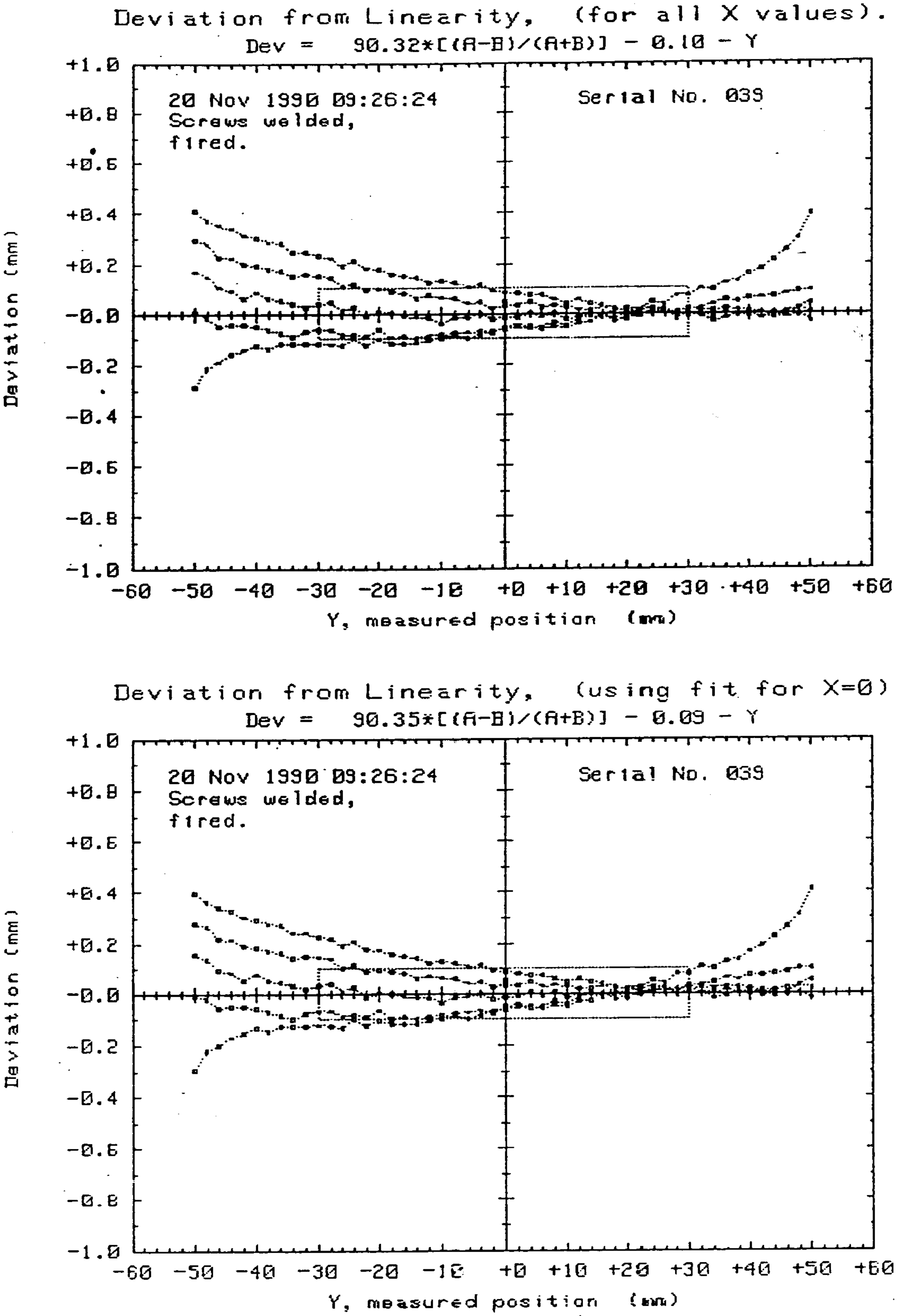


FIGURE 12. DETECTOR WITH A LARGE VARIATION OF SLOPE.

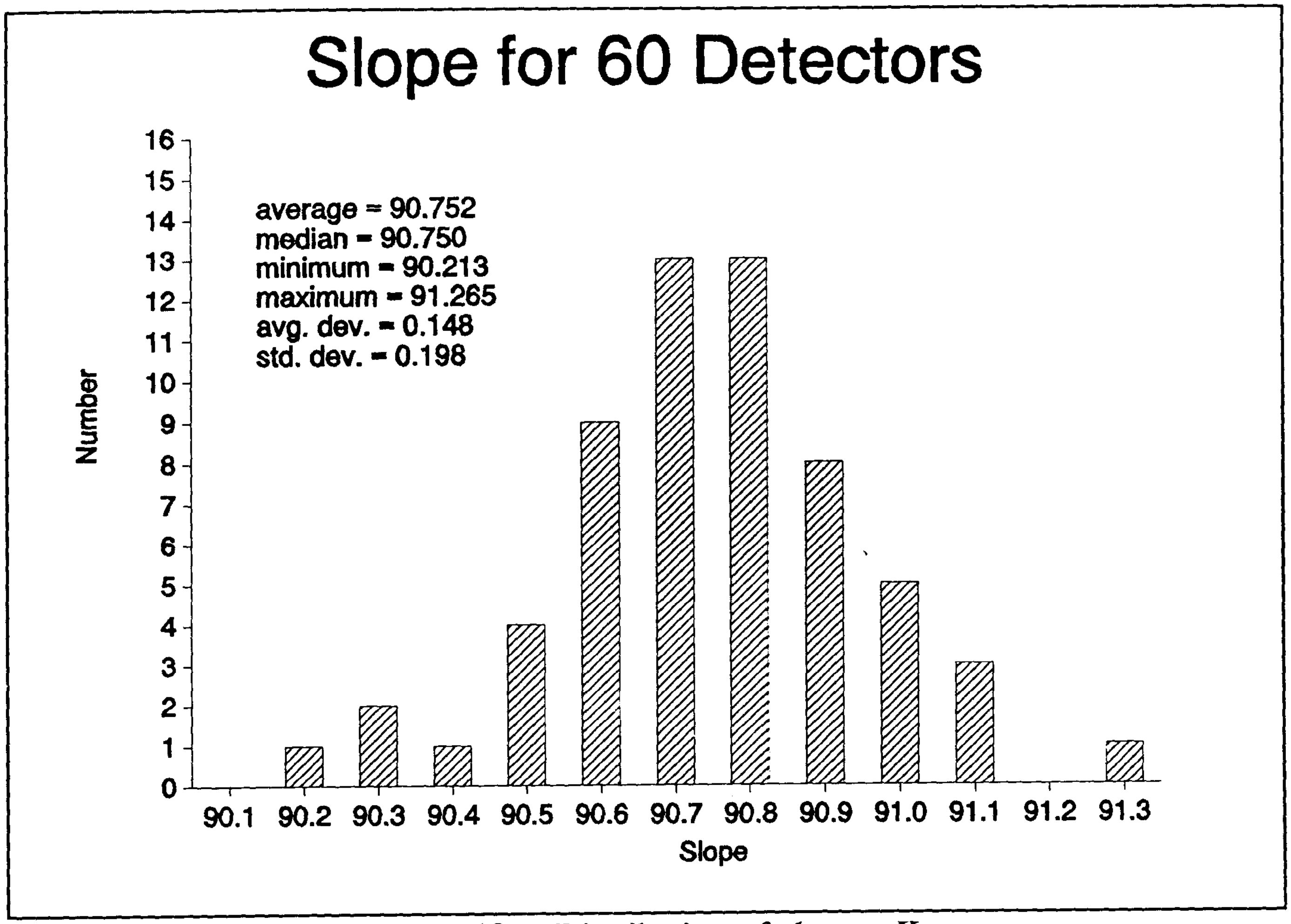


Figure 13. Distribution of slopes, K.

CONCLUDING REMARKS

Scan wire measurements have been run on each of the BPM detectors installed in the Booster. These tests have enabled us to verify the linearity of each detector over a ± 50 mm range, which is larger than the specified operating aperture. The measurements provide a method of "Quality Control" in the production of each of the detectors by revealing:

- rotated split-cylinder assemblies (which would result in position-dependent offsets),
- changes of detector response after firing/bakeout, and
- unacceptable levels of response non-linearity.

A detector exhibiting one or more of the above mentioned "failures" is disassembled, inspected, then reassembled. The unit then gets recycled back into the test sequence. Figures 6 and 7 are histograms showing the statistical distribution of the measured slopes (inverse of the differential sensitivity) and offsets for the 60 detectors measured (note that of these 60 detectors, only 54 are actually used in the Booster). The slopes obtained from the scan wire tests are considered to be baseline data for the detectors, and are "normalized" to the test set-up described in this technical note. The BPM system high-

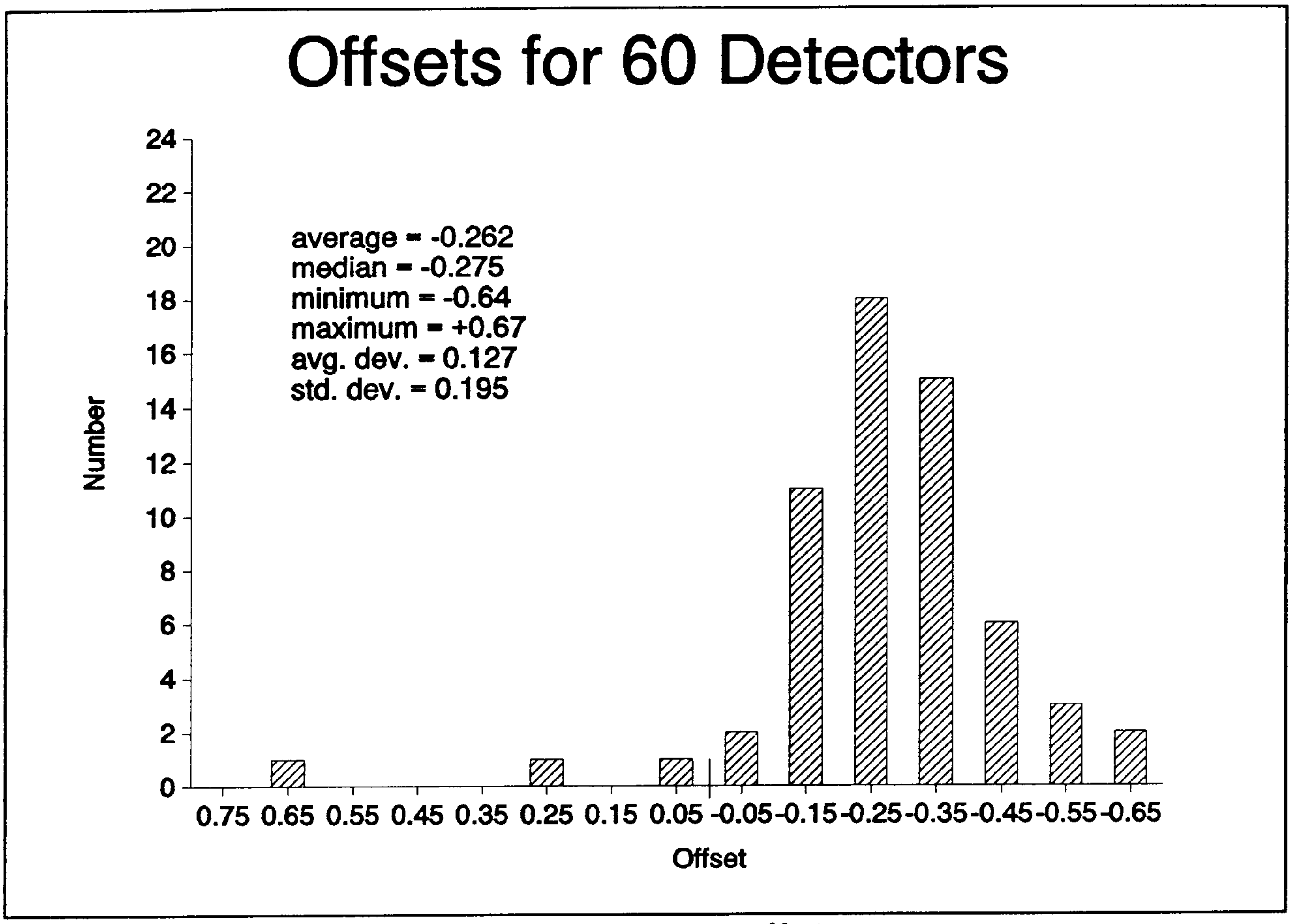


Figure 14. Offsets for the 60 detectors.

level software actually uses two operational values derived from these baseline slopes (the operational values are a function of the external PUE loading due to the front-end electronics). The method used for converting the baseline data to operational values will be presented in a separate Booster Technical Note.