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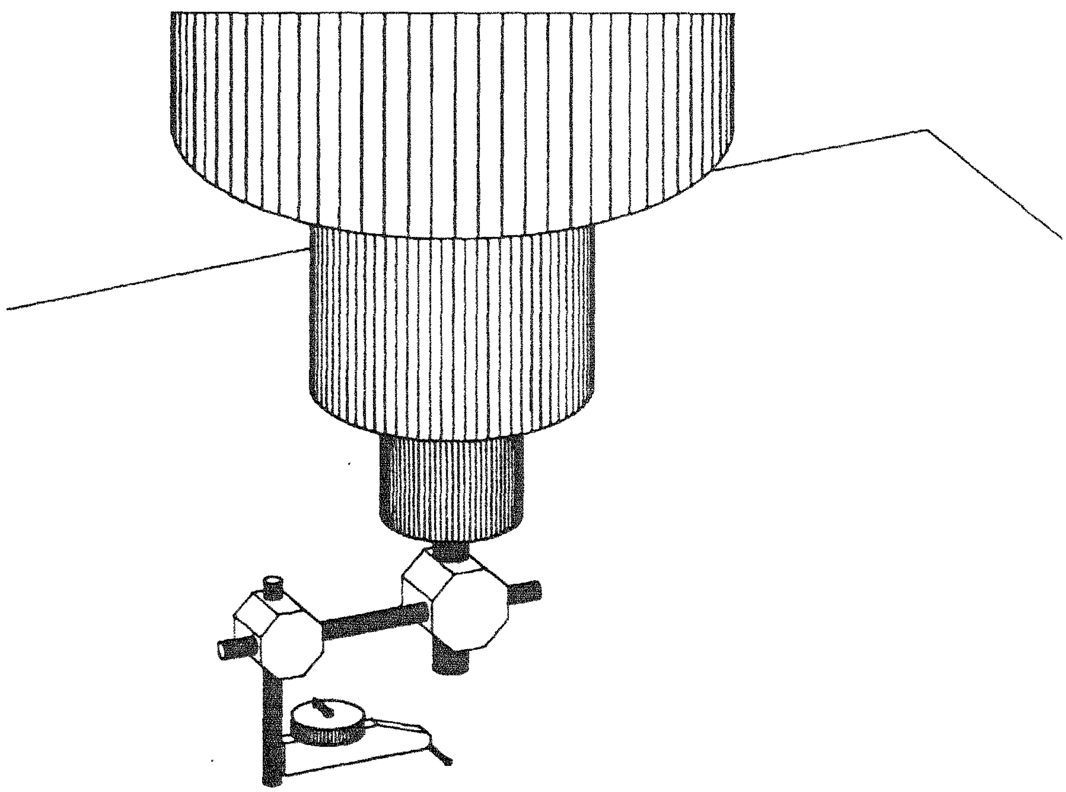
CNC Router Evaluation Procedures

Edward L. Adams
Everette D. Rast
Neal D. Bennett



Abstract

The lack of procedures for evaluating computer numerically controlled (CNC) routers makes it difficult for the buyers and sellers of these machines to communicate when trying to determine the best machine for a given production situation. This report provides procedures to evaluate specific machine capabilities as related to production situations. By using the procedures, both the buyers and the sellers will know how the evaluations were made and what the results mean.

The Authors

EDWARD L. ADAMS is a forest products technologist with the Northeastern Forest Experiment Station's Forestry Sciences Laboratory at Princeton, West Virginia. He received a B.S. degree in forest management and an M.S. degree in forest mensuration at West Virginia University. He worked for the USDA Forest Service in Oregon from 1960 to 1963 and joined the Northeastern Station in 1968. He retired in January 1995.

EVERETTE D. RAST is a forest products technologist with the Northeastern Forest Experiment Station's Forestry Sciences Laboratory at Princeton, West Virginia. He received a B.S. degree in forestry from the University of Missouri in 1960 and an M.S. degree in agricultural economics from The Ohio State University in 1970. He joined the USDA Forest Service in 1960 as a forester on the Mendocino National Forest and transferred to the Northeastern Forest Experiment Station, Delaware, Ohio, in 1966. From 1966 to 1987, he was with the log and tree grade project and then the management and utilization alternatives for nonindustrial private forests. In 1987 he was transferred to the Advanced Hardwood Processing and Technical Resource Center.

NEAL D. BENNETT is a general engineer with the Northeastern Forest Experiment Station's Forestry Sciences Laboratory at Princeton, West Virginia. He received a B.S. degree in biology from Concord College, Athens, West Virginia, in 1983 and an A.S. degree in mechanical engineering from Bluefield State College, Bluefield, West Virginia, in 1992. He joined the USDA Forest Service in 1988.

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USDA FOREST SERVICE
5 RADNOR CORP CTR STE 200
PO BOX 6775
RADNOR PA 19087-8775

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Introduction

Managers of furniture and cabinet manufacturing plants have the difficult task of purchasing the best computer numerical controlled (CNC) machines for particular situations. They need machines that will not only perform present tasks but also possible future tasks. Much of the information needed to compare machines is not available in the sales literature. And, because procedures are not available for evaluating the machines, managers find it difficult to communicate with machine dealers in their search for the best machine for the job.

Machine dealers also are concerned about this problem. If a dealer sells a brand "A" CNC router and it does not meet a plant manager's needs, that manager is going to be upset. And, he will probably tell others about his dissatisfaction with the machine. The negative advertising produced by this situation may cause potential buyers to avoid brand "A" when that machine may be exactly what their production situation requires. Thus, both the seller and potential buyers of the brand "A" machine lose.

This paper provides procedures for evaluating CNC routers that can be used to help solve the communication problem between buyers and sellers. By using the procedures, these individuals can, in effect, speak the same language as they try to match machines to production situations. It is not necessary to use all of the procedures when evaluating a router. Only those needed to provide information that is critical to the production situation need to be used. For example, if tool positioning accuracy is only critical in the Z-axis, the only procedures needed are those that measure the ability of the router to position the tool in this axis. The procedures for the X-axis and the Y-axis are not necessary. Also, the procedures do not include recommended tolerances. These values will depend on the individual production situations and must be determined by the machine user.

It should be emphasized that we are not attempting to set evaluation standards for the industry. The purpose of this paper is to provide an objective means for the buyers and sellers of CNC routers to discuss needs in terms of accuracy, repeatability, and suitability for particular production situations. However, if the secondary processing industry decides to develop standards in the future, the procedures presented in this paper could provide a good base to start from.

Following are discussions of the possible uses, the evaluation methods, and the sample results for each evaluation procedure. The procedures are divided into three categories: (1) basic evaluations, (2) spindle/table travel evaluations, and (3) machining evaluations.

List of Abbreviations

CNC	-	computer numerically controlled
CPM	-	cycles per minute
deg	-	degrees of angular measurement
E	-	volts
F	-	Fahrenheit
FLP	-	full load power (kilowatts) requirement of an electric motor
G&M code	-	more or less standard computer code for controlling computer numerically controlled equipment
hp	-	horsepower
Hz	-	hertz (one cycle per second)
I	-	electric current in amperes
IPM	-	inches per minute
kW	-	1000 watts
MDF	-	medium density fiberboard
min	-	minutes of angular measurement
mm	-	millimeters
PC	-	microcomputer
pf	-	power factor (electric motors)
RPM	-	revolutions per minute
sec	-	seconds of angular measurement
TGP	-	turned-ground-polished
thou	-	thousandths of an inch

2.0 Spindle/table Travel Evaluations

2.1 Positioning Accuracy

2.1.1 X-axis Positioning

Purpose—This procedure determines the ability of the router to accurately position a tool in the X-axis in response to the machine controller and its program. Router construction affects positioning, which may be a result of the table moving relative to the spindle or the spindle moving relative to the table. Basically, this reflects the ability of the router's servo motor and ball screw to respond to the instructions from the controller.

Recommended equipment:

- Class II helium-neon laser (interferometer) system with optics for measuring linear displacement. The optics include a beam splitter and two linear reflectors plus the hardware required for mounting them. The system must allow for environmental compensations for air temperature, barometric pressure, and relative humidity. It also should allow for adjustments to be made based on the temperature of the machine scale and the thermal expansion coefficient of the scale material. The scale in this situation is the ball screw used to drive the router table or spindle in the axis to be measured. The laser system must be equivalent to the Renishaw Laser Interferometer System (ML10) by Renishaw Transducer Systems Limited or the HP5528A Laser Measurement System by Hewlett Packard.

- Microcomputer (PC) and software to record and analyze the data. Although the PC and software are not necessary, they greatly facilitate collecting and analyzing the data for this procedure.

Method—Before beginning this evaluation, the servo motor and ball screw that controls the movement in the X-axis should be exercised through at least 20 full cycles. This reduces the error in positioning that can occur due to cold servo motors and ball screws. Once this is done, use the following steps.

Step 1

The router controller is programmed to move the table/spindle in the X-axis. If the ball screw has standard threads, the controller must be programmed to move the table/ spindle 50 mm at a time. If the ball screw has metric threads, the controller must be programmed to move 2 inches at a time. With this movement, the ball screw will not be in the same rotational position for each position measurement of the table/spindle. The table/spindle must travel the full extent of the X-axis in 2-inch or 50-mm increments. However, provide at least 1 inch of extra travel past the two end targets to allow for changing the direction of travel. Pause between each move to allow the measurement of the difference between the distance specified by the controller program and the distance actually moved. The program also must provide for bi-directional travel so that measurements can be taken in both the +X and -X directions. After the measurement is recorded for the last point in a given direction, move the spindle/table ahead 1 inch. Then reverse the direction of travel 1 inch to the finalpoint for the first measurement in the other direction. Examples of these programs and their subroutines, titled LINEAR POSITIONING IN X-AXIS for (STANDARD UNITS) and (METRIC UNITS), are shown in Figure A.1.1 of Appendix A.1.

Step 2

Set up the laser as instructed in the laser user's manual. Figure 2.1 shows an example of the laser optics setup. The laser is aligned down the middle of the table in the X-axis. Assure that adjustments are made in the laser measurements for air temperature, barometric pressure, relative humidity, and thermal expansion of the ball screw material.

Step 3

Measure and record the difference between the controller instructed moves and the actual moves of the table/spindle in both directions in the X-axis. Repeat this procedure for five full forward and reverse cycles.

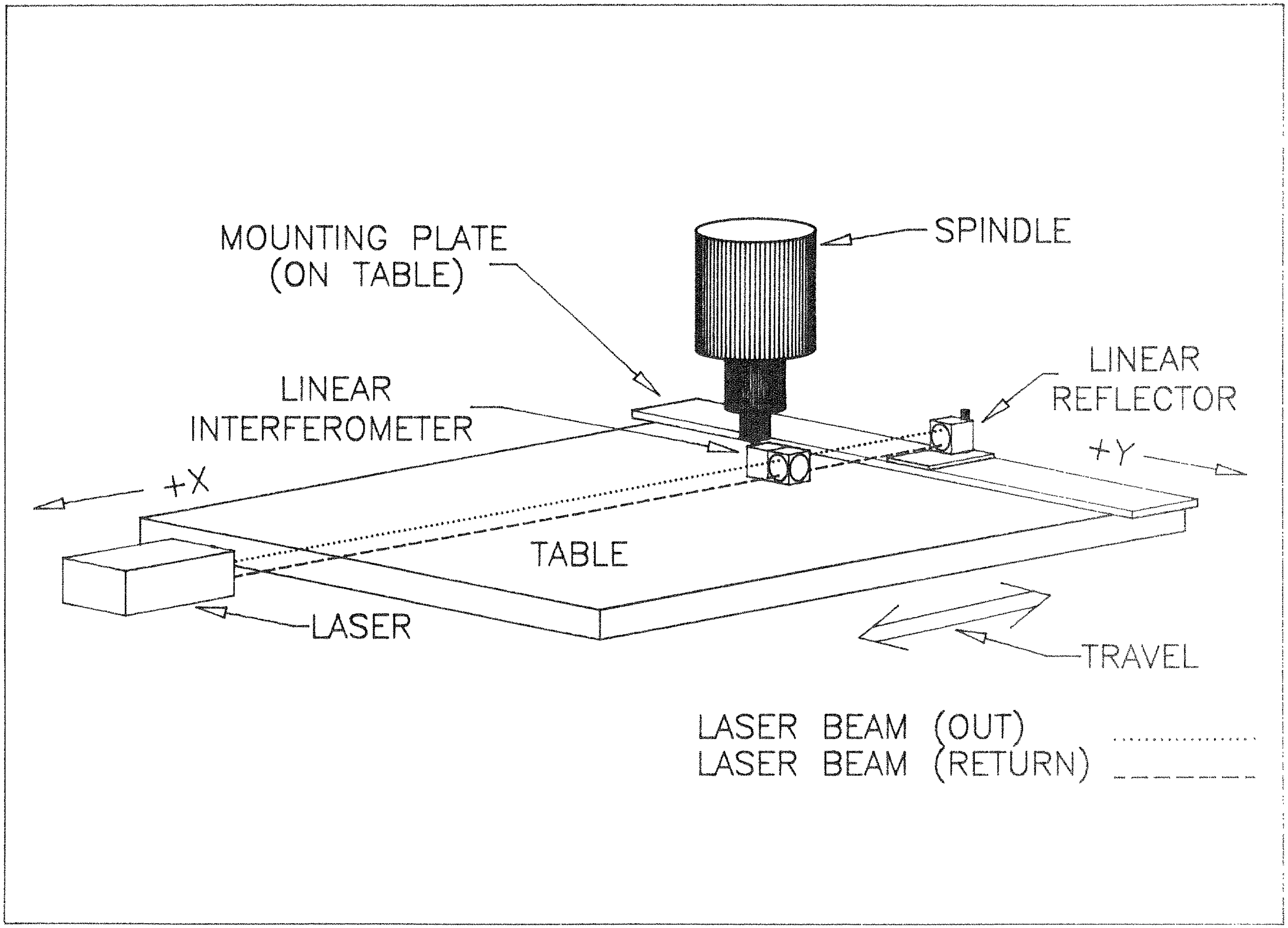


Figure 2.1—Laser setup for measuring positioning accuracy in the X-axis.

Results—Plot a graph based on the German VDI 3441 standard showing the differences between the specified positions and the actual positions of the table/spindle in both the +X and the -X directions. In collecting data, the table was moved 50 mm at a time because the ball screws had standard threads. The error in positioning also was measured in metric units. However, the software used to provide the analysis has the option of converting the data to standard units. Figure 2.2 is an example of the graph with representative statistics. The graph shows mean positional errors in both the positive and negative directions, the bi-directional mean positioning error, and the maximum "±3 sigma" repeatability bands from either direction of travel. Discussion of the data presented below the graph follows:

- Mean Reversal Error (U mean) and Maximum Reversal error (U max) are commonly referred to as 'backlash' or 'lost motion.' They are defined as the difference obtained from the mean values in both directions of travel for each target position.

- Mean Positional Scatter (Ps mean) and Maximum Positional Scatter (Ps max) represents the effect of random deviations in the positional errors at each position along the test axis. They may be regarded as a measure of the uni-directional repeatability.

- Positional Deviation (Pa) is the maximum difference in the mean positional error values of all measured points along the test axis.

- Positional Uncertainty (P) is the total deviation along the test axis and takes into account the values of positional deviation, reversal error, and positional scatter at each point.

The above definitions were taken from the RENISHAW TRANSDUCER SYSTEMS LIMITED, Laser Interferometer System PC10 User Manual.[1]

2.1.2 Y-axis Positioning

Purpose—This procedure determines the ability of the router to accurately position a tool in the Y-axis in response to the machine controller and its program. Router construction affects the positioning, which may be a result of the table moving relative to the spindle or the spindle moving relative to the table. Basically, this reflects the ability of the router's servo motor and ball screw to respond to the instructions from the controller.

Recommended equipment:

- Class II helium-neon laser (interferometer) system with optics for measuring linear displacement. The optics include a beam splitter and two linear reflectors plus the hardware required for mounting them. The system must allow for environmental compensations for air temperature, barometric pressure, and relative humidity. It also should allow for adjustments to be made based on the temperature of the machine scale and the thermal expansion coefficient of the scale material. The scale in this situation is the ball screw used to drive the router table or spindle in the axis to be measured. The laser system must be equivalent to the Renishaw Laser Interferometer System (ML10) by Renishaw Transducer Systems Limited or the HP5528A Laser Measurement System by Hewlett Packard.

- Microcomputer (PC) and software to record and analyze the data. Although the PC and software are not necessary, they greatly facilitate collecting and analyzing the data for this procedure.

Method—Before beginning this evaluation, the servo motor and ball screw that controls the movement in the Y-axis should be exercised through at least 20 full cycles. This reduces the error in positioning that can occur due to cold servo motors and ball screws. Once this is done, use the following steps.

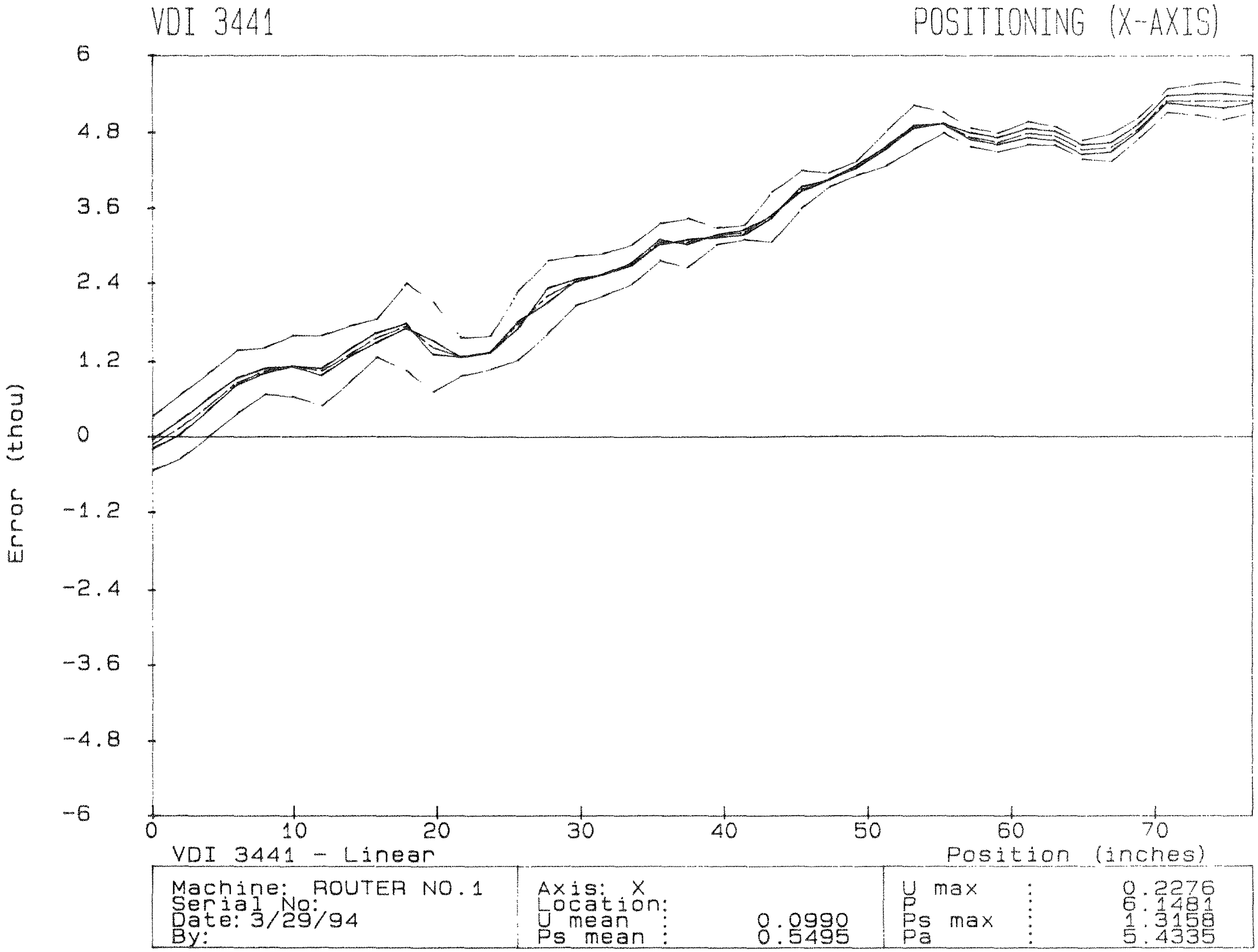


Figure 2.2—Results showing positioning accuracy in the X-axis as measured by laser system.

Step 1

The router controller is programmed to move the table/spindle in the Y-axis. If the ball screw has standard threads, the controller must be programmed to move the table/spindle 50 mm at a time. If the ball screw has metric threads, the controller must be programmed to move 2 inches at a time. With this movement, the ball screw will not be in the same rotational position for each positional measurement of the table/spindle. The table/spindle must travel the full extent of the Y-axis in 2-inch or 50-mm increments. However, provide at least 1 inch of extra travel past the two end targets to allow for changing the direction of travel. Pause between each move to allow the measurement of the difference between the distance specified by the controller program and the distance actually moved. The program also must provide for bi-directional travel so that measurements can be taken in both the +Y and -Y directions. After the measurement is recorded for the last point in a given direction, move the spindle/table ahead 1 inch. Then reverse the direction of travel 1 inch to the final point for the first measurement in the other direction. Examples of these programs and their subroutines, titled LINEAR POSITIONING IN Y-AXIS for (STANDARD UNITS) and (METRIC UNITS), are shown in Figure A.1.1 of Appendix A.1.

Step 2

Set up the laser as instructed in the laser user's manual. Figure 2.3 shows an example of the laser optics setup. Assure that adjustments are made in the laser measurements for air temperature, barometric pressure, relative humidity, and thermal expansion of the ball screw material.

Step 3

Measure and record the difference between the controller instructed moves and the actual moves of the table/spindle in both directions in the Y-axis. Repeat this procedure for five full forward and reverse cycles.

Results—Plot a graph based on the German VDI 3441 standard showing the differences between the specified positions and the actual positions of the table/spindle travel in both the +Y and the -Y directions. In collecting data, the table was moved 50 mm at a time because the ball screws had standard threads. The error in positioning also was measured metric units. However, the software used to provide the analysis has the option of converting the data to standard units. Figure 2.4 is an example of the graph with representative statistics. The graph shows mean positional errors in both the positive and negative directions, the bi-directional mean positioning error, and the maximum "±3 sigma" repeatability bands from either direction of travel. See section 2.1.1 "X-axis Positioning" for a discussion of the data presented at the bottom of the graph.

2.1.3 Z-axis Positioning

Purpose—This procedure determines the ability of the router to accurately position a tool in the Z-axis in response to the machine controller and its program. Router construction affects positioning of which may be a result of the table moving relative to the spindle or the spindle moving relative to the table. Basically, this reflects the ability of the router's servo motor and ball screw to respond to the instructions from the controller.

Recommended equipment:

- Class II helium-neon laser (interferometer) system with optics for measuring linear displacement. The optics include a beam splitter and two linear reflectors plus the hardware required for mounting them. The system must allow for environmental compensations for air temperature, barometric pressure, and relative humidity. It also should allow for adjustments to be made based on the temperature of the machine scale and the thermal expansion coefficient of the scale material. The scale in this situation is the ball screw used to drive the router table or spindle in the axis to be measured. The laser system must be equivalent to the Renishaw Laser Interferometer System (ML10) by Renishaw Transducer Systems Limited or the HP5528A Laser Measurement System by Hewlett Packard.

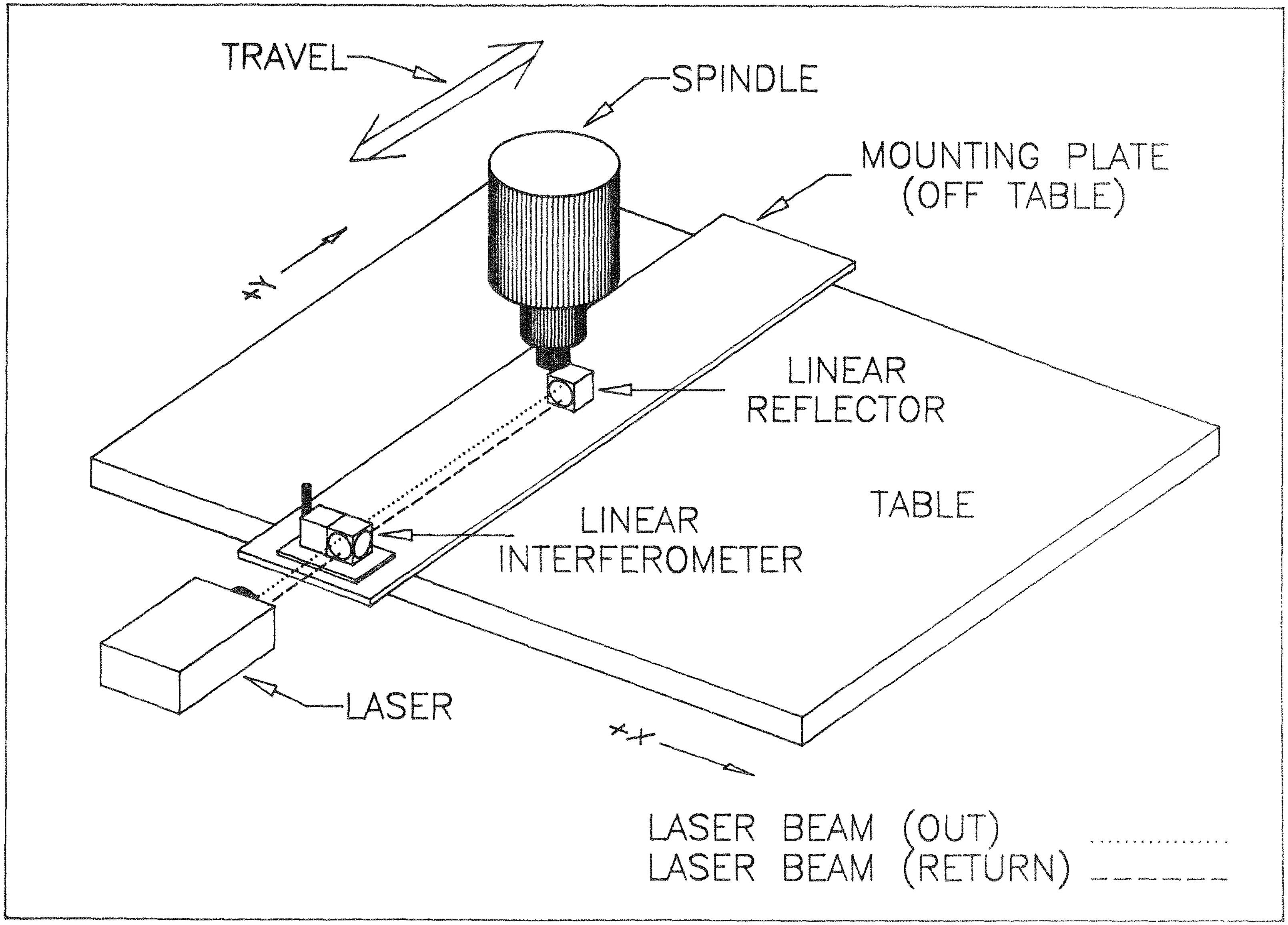


Figure 2.3—Laser setup for measuring positioning accuracy in the Y-axis.

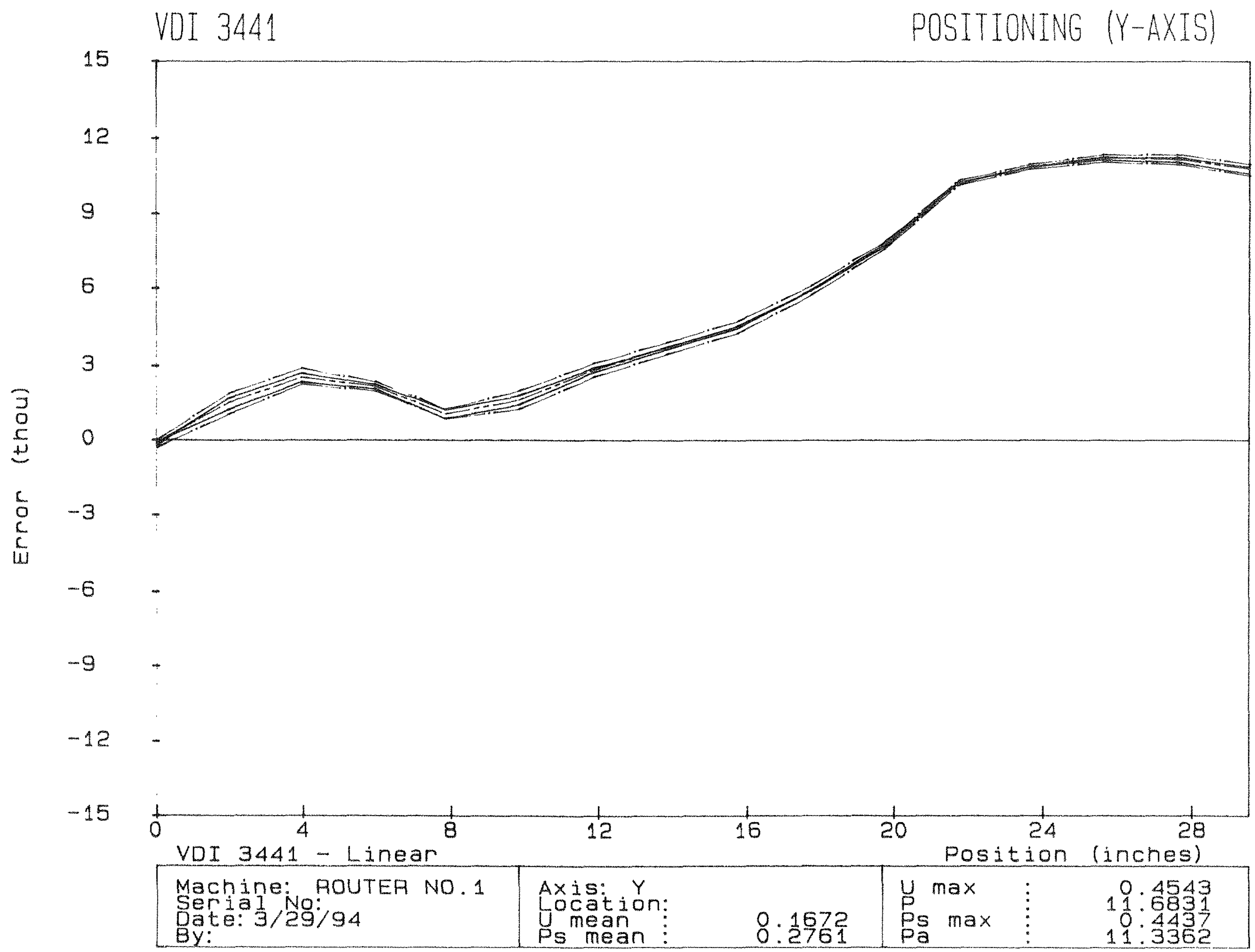


Figure 2.4—Results showing positioning accuracy in the Y-axis as measured by laser system.

- Microcomputer (PC) and software to record and analyze the data. Although the PC and software are not necessary, they greatly facilitate collecting and analyzing the data for this procedure.

Method—Before beginning this evaluation, the servo motor and ball screw that controls the movement in the Z-axis should be exercised through at least 20 full cycles. This reduces the error in positioning that can occur due to cold servo motors and ball screws. Once this is done, use the following steps.

Step 1

The router controller is programmed to move the table/spindle in the Z-axis. If the ball screw has standard threads, the controller must be programmed to move the table/spindle 6 mm at a time. If the ball screw has metric threads, the controller must be programmed to move 0.25 inch at a time. With this movement, the ball screw will not be in the same rotational position for each position measurement of the table/spindle. The table/spindle must travel the full extent of the Z-axis in 0.25-inch or 6 mm increments. However, provide at least 0.25 inch of extra travel past the two end targets to allow for changing the direction of travel. Pause between each move to allow the measurement of the difference between the distance specified by the controller program and the distance actually moved. The program also must provide for bi-directional travel so that measurements can be taken in both the +Z and -Z directions. After the measurement is recorded for the last point in a given direction, move the spindle/table ahead 0.25 inch. Then reverse the direction of travel 0.25 inch to the final point for the first measurement in the other direction. Examples of these programs and their subroutines, titled LINEAR POSITIONING IN Z-AXIS for (STANDARD UNITS) and (METRIC UNITS), are shown in Figure A.1.1 of Appendix A.1.

Step 2

Set up the laser as instructed in the laser user's manual. Figure 2.5 shows an example of the laser optics setup. Assure that adjustments are made in the laser measurements for air temperature, barometric pressure, relative humidity, and thermal expansion of the ball screw material.

Step 3

Measure and record the difference between the controller instructed moves and the actual moves of the table/spindle in both directions in the Z-axis. Repeat this procedure for five full forward and reverse cycles.

Results—Plot a graph based on the German VDI 3441 standard showing the differences between the specified positions and the actual positions of the table/spindle travel in both the +Z and the -Z directions. In collecting data, the table was moved 6 mm at a time because the ball screws had standard threads. The error in positioning also was measured in metric units. However, the software used to provide the analysis has the option of converting the data to standard units. Figure 2.6 is an example of the graph with representative statistics. The graph shows mean positional errors in both the positive and negative directions, the bi-directional mean positioning error, and the maximum "±3 sigma" repeatability bands from either direction of travel. See section 2.1.1 "X-axis Positioning" for a discussion of the data presented at the bottom of the graphic plot.

2.2 Feed Rate Accuracy

2.2.1 X-axis Feed Rate Accuracy

Purpose—This procedure determines the ability of the router to provide accurate tool feed rates in the X-axis as set by the machine controller and its program. Router construction affects the feed, which may be a result of the table moving relative to the spindle or the spindle moving relative to the table. Basically, this reflects the ability of the router's servo motor and ball screw to respond to the instructions from the controller.

Recommended equipment:

- Class II helium-neon laser (interferometer) system with optics for measuring linear velocity. The optics (same as those used for linear displacement) include a beam splitter and two linear reflectors plus the hardware required for mounting them. The

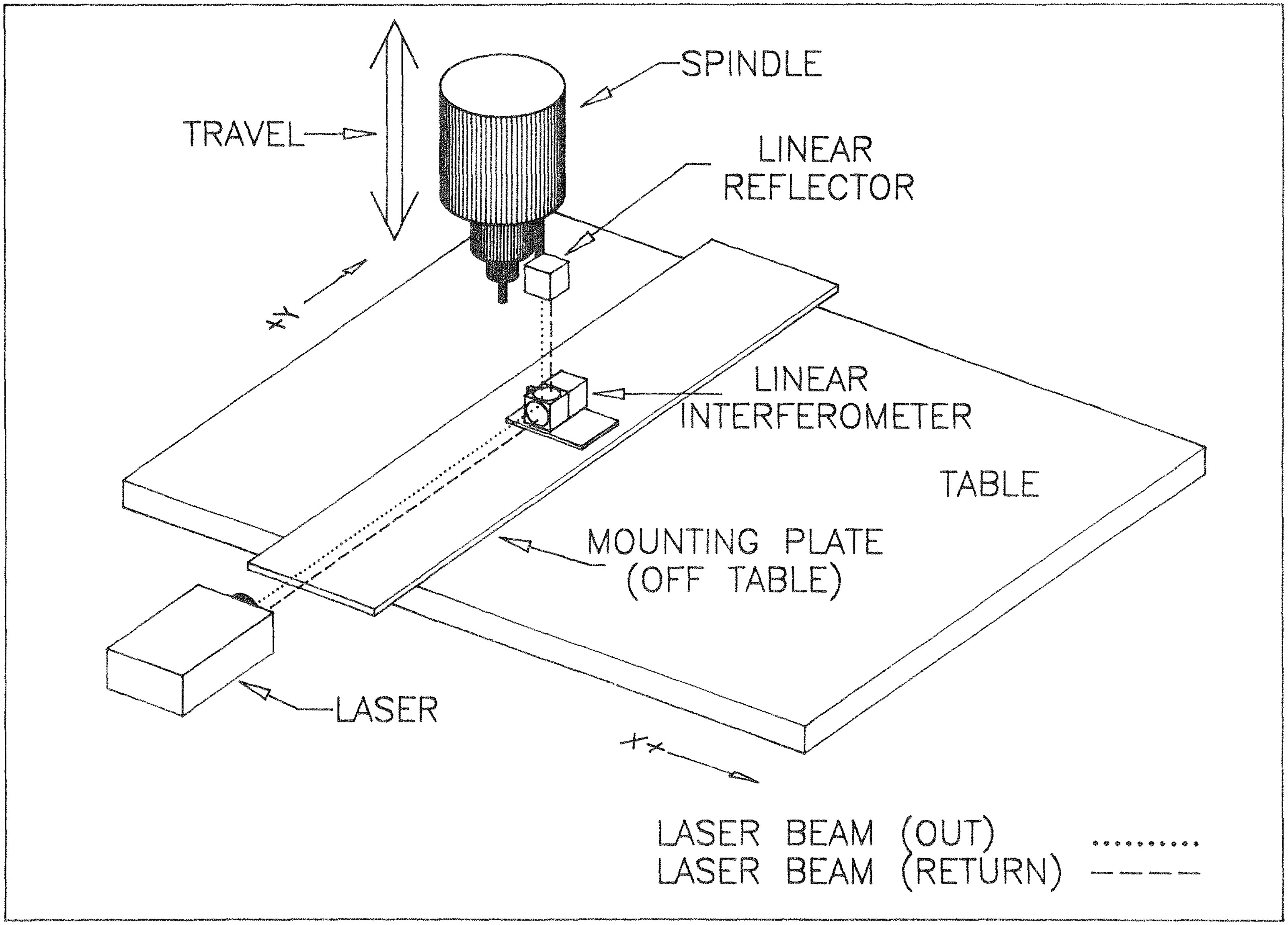


Figure 2.5—Laser setup for measuring positioning accuracy in the Z-axis.

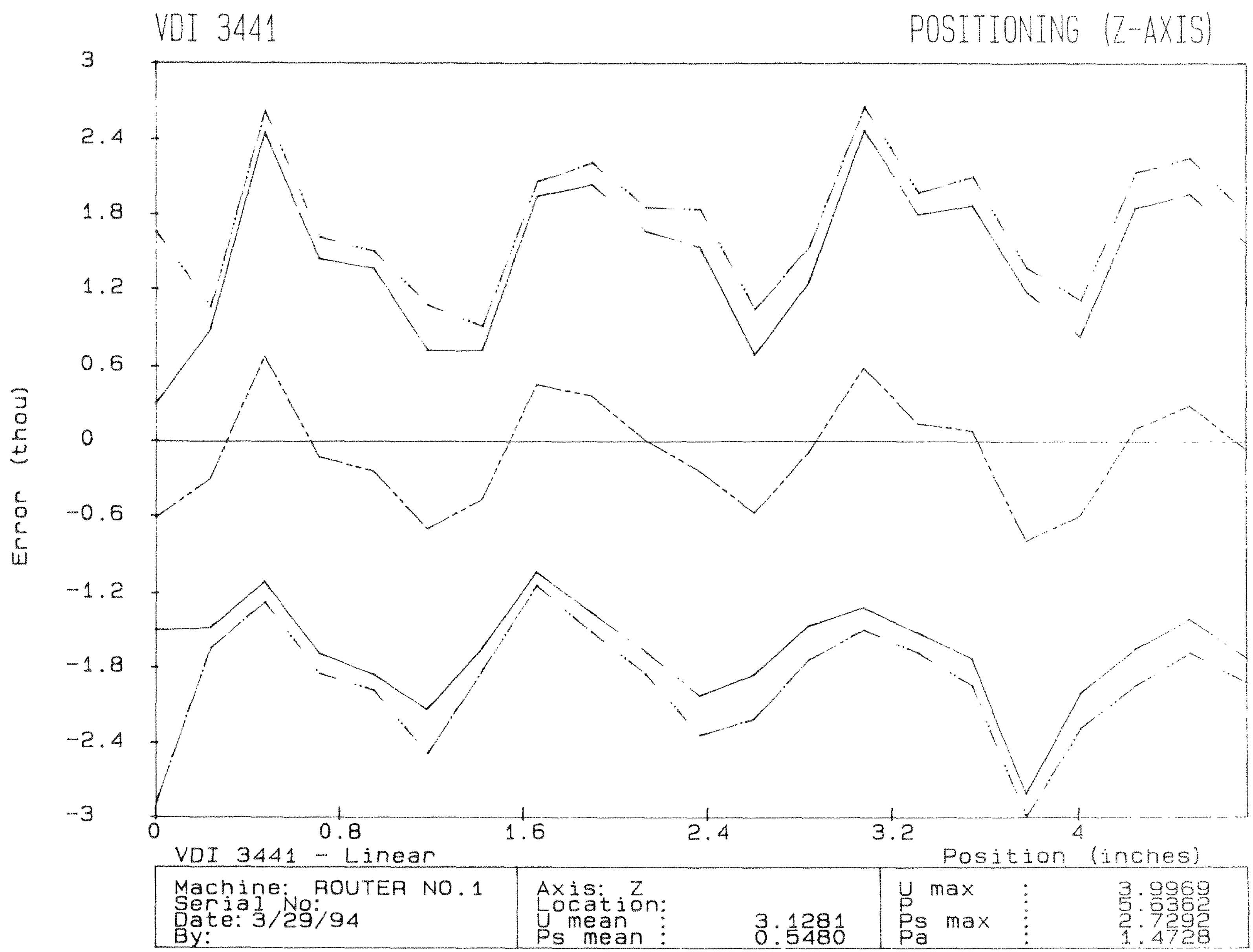


Figure 2.6—Results showing positioning accuracy in the Z-axis as measured by laser system.

system must allow for environmental compensations for air temperature, barometric pressure, and relative humidity. It also should allow for adjustments to be made based on the temperature of the machine scale and the thermal expansion coefficient of the scale material. The scale in this situation is the ball screw used to drive the router table or spindle in the axis to be measured. The laser system must be equivalent to the Renishaw Laser Interferometer System (ML10) by Renishaw Transducer Systems Limited or the HP5528A Laser Measurement System by Hewlett Packard.

- Microcomputer (PC) and software to record and analyze the data. Although the PC and software are not necessary, they greatly facilitate collecting and analyzing the data for this procedure.

Method—Before beginning this evaluation, the servo motor and ball screw that controls the movement in the X-axis should be exercised through at least 20 full cycles. This is done so that measurements are not taken on a cold servo motor and ball screw. Once this is done, use the following steps.

Step 1
Develop a program for the controller that moves the table/spindle the full length of travel in the X-axis at a feed rate of 50 inches per minute and then returns to the start position. Have the program repeat this procedure for feed rate increments of 50 inches per minute (that is, 100, 150, and so on) until the maximum X-axis feed rate is reached. An example of this program and its subroutine, titled SAMPLE FEED RATE PROGRAMS (X-AXIS), is shown in Figure A.2.1 of Appendix A.2.

Step 2
Set up and align the laser as instructed in the laser user's manual. Figure 2.7 shows an example of the laser optics setup. The laser is aligned down the middle of the table in the X-axis. Assure that adjustments are made for air temperature, barometric pressure, relative humidity, and thermal expansion of the ball screw material.

Step 3
Run the controller program and record the laser measured feed rate at the midpoint of table/spindle travel for each feed rate set up in the controller program.

Result—Plot a graph of the differences between the specified feed rate and the actual feed rate of the table/spindle travel. Figure 2.8 shows an example of such a plot.

2.2.2 Y-axis Feed Rate Accuracy

Purpose—This procedure determines the ability of the router to provide accurate tool feed rates in the Y-axis as set by the machine controller and its program. Router construction affects the feed which may be as a result of the table moving relative to the spindle or the spindle moving relative to the table. Basically, this reflects the ability of the router's servo motor and ball screw to respond to the instructions from the controller.

Recommended equipment:

- Class II helium-neon laser (interferometer) system with optics for measuring linear velocity. The optics (same as those used for linear displacement) include a beam splitter and two linear reflectors plus the hardware required for mounting them. The system must allow for environmental compensations for air temperature, barometric pressure, and relative humidity. It also should allow for adjustments to be made based on the temperature of the machine scale and the thermal expansion coefficient of the scale material. The scale in this situation is the ball screw used to drive the router table or spindle in the axis to be measured. The laser system must be equivalent to the Renishaw Laser Interferometer System (ML10) by Renishaw Transducer Systems Limited or the HP5528A Laser Measurement System by Hewlett Packard.

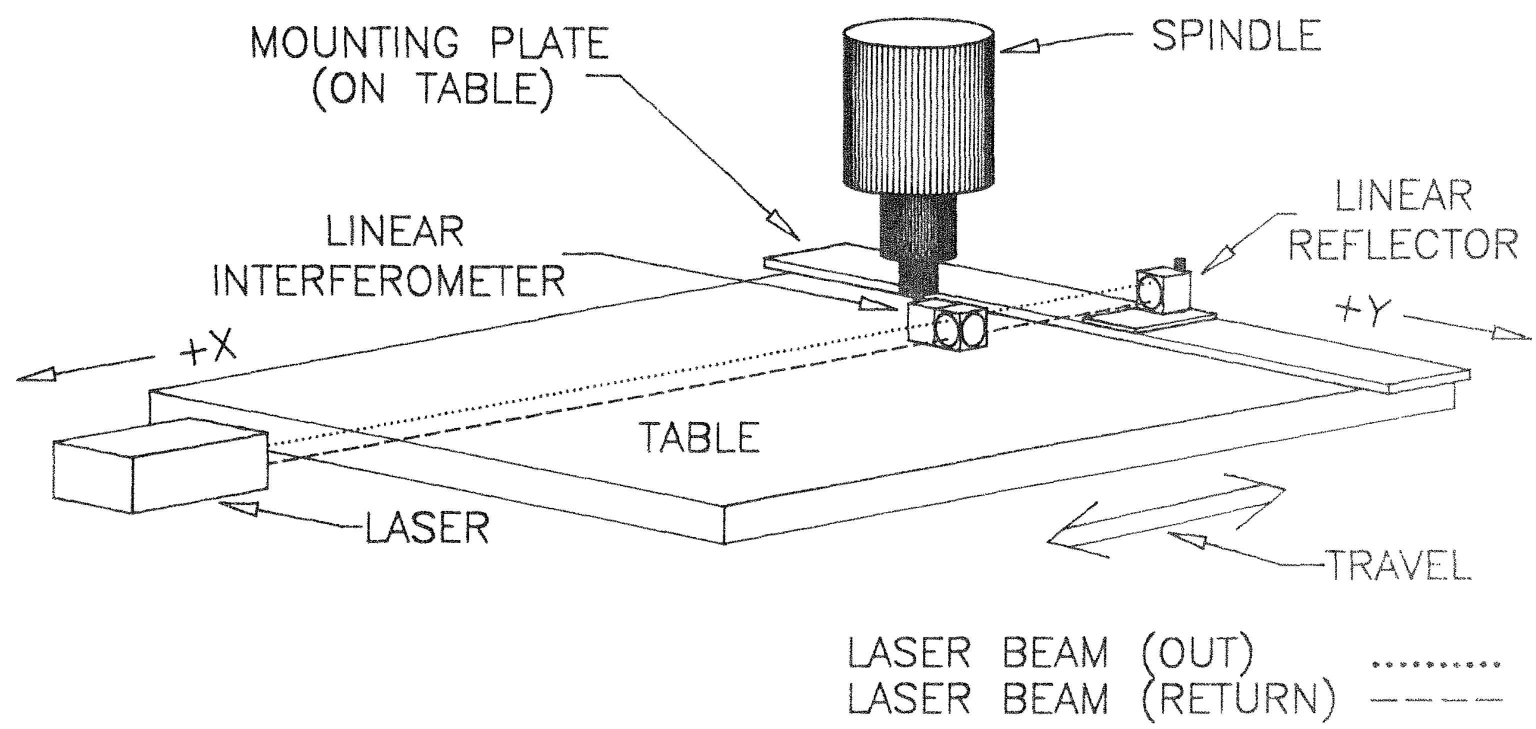


Figure 2.7—Laser setup for measuring feed rate accuracy in the X-axis.

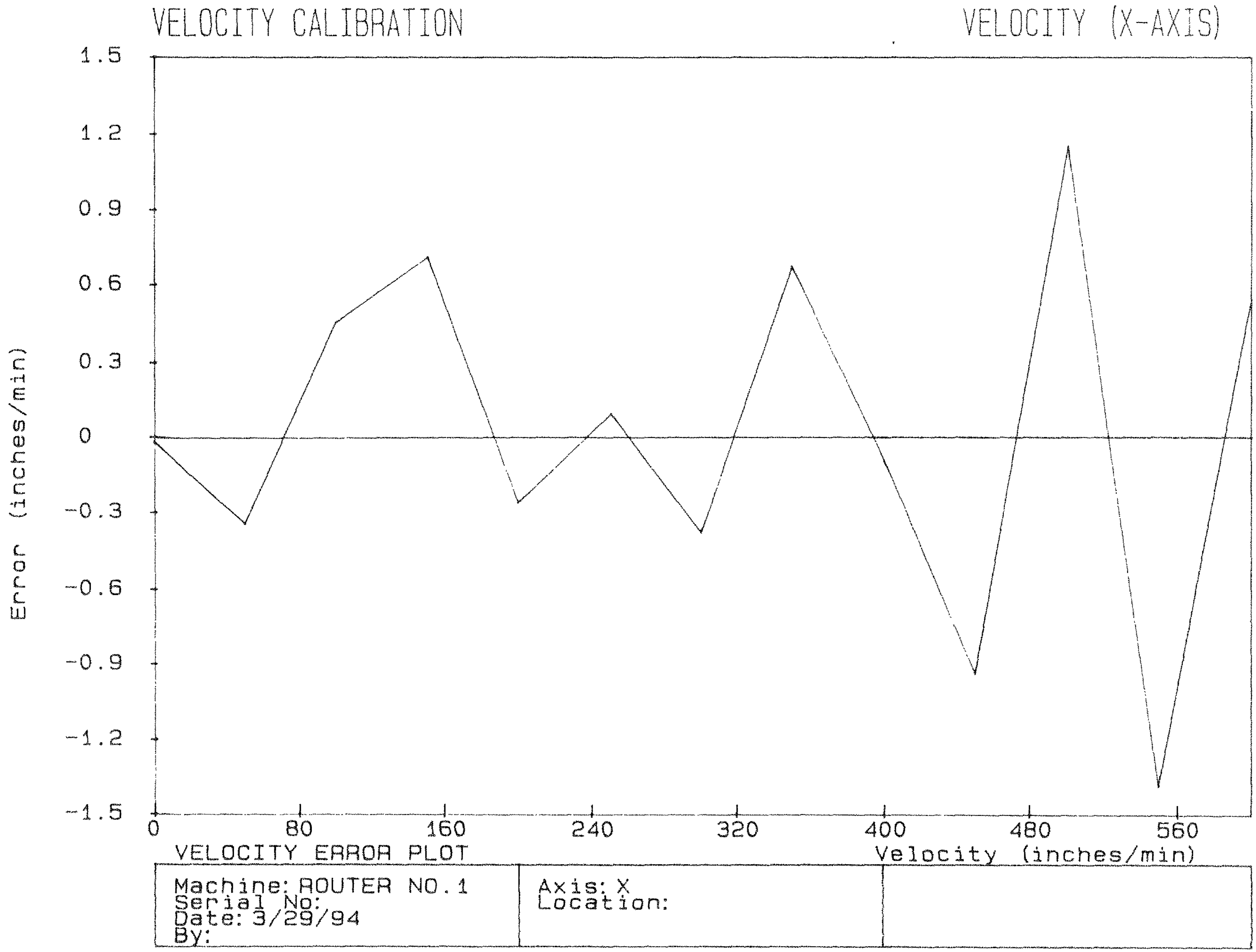


Figure 2.8—Results showing feed rate accuracy in the X-axis as measured by laser system.

- Microcomputer (PC) and software to record and analyze the data. Although the PC and software are not necessary, they greatly facilitate collecting and analyzing the data for this procedure.

Method—Before beginning this evaluation, the servo motor and ball screw that controls the movement in the Y-axis should be exercised through at least 20 full cycles. This is done so that measurements are not taken on a cold servo motor and ball screw. Once this is done, use the following steps.

Step 1
Develop a program for the controller that moves the table/spindle the full length of travel in the Y-axis at a feed rate of 50 inches per minute and then returns to the start position. Have the program repeat this procedure for feed rate increments of 50 inches per minute (that is, 100, 150, and so on) until the maximum Y-axis feed rate is reached. An example of this program and its subroutine, titled SAMPLE FEED RATE PROGRAMS (Y-AXIS), is shown in Figure A.2.1 of Appendix A.2.

Step 2
Set up and align the laser as instructed in the laser user's manual. Figure 2.9 shows an example of the laser optics setup. Assure that adjustments are made for air temperature, barometric pressure, relative humidity, and thermal expansion of the ball screw material.

Step 3
Run the controller program and record the laser measured feed rate at the midpoint of table/spindle travel for each feed rate set up in the controller program.

Results—Plot a graph of the differences between the specified feed rate and the actual feed rate of the table/spindle travel. Figure 2.10 shows an example of such a plot.

2.2.3 Z-axis Feed Rate Accuracy

Purpose—This procedure determines the ability of the router to provide accurate tool feed rates in the Z-axis as set by the machine controller and its program. Router construction affects the feed, which may be a result of the table moving relative to the spindle or the spindle moving relative to the table. Basically, this reflects the ability of the router's servo motor and ball screw to respond to the instructions from the controller.

Recommended equipment:

- Class II helium-neon laser (interferometer) system with optics for measuring linear velocity. The optics (same as those used for linear displacement) include a beam splitter and two linear reflectors plus the hardware required for mounting them. The system must allow for environmental compensations for air temperature, barometric pressure, and relative humidity. It also should allow for adjustments to be made based on the temperature of the machine scale and the thermal expansion coefficient of the scale material. The scale in this situation is the ball screw used to drive the router table or spindle in the axis to be measured. The laser system must be equivalent to the Renishaw Laser Interferometer System (ML10) by Renishaw Transducer Systems Limited or the HP5528A Laser Measurement System by Hewlett Packard.

- Microcomputer (PC) and software to record and analyze the data. Although the PC and software are not necessary, they greatly facilitate collecting and analyzing the data for this procedure.

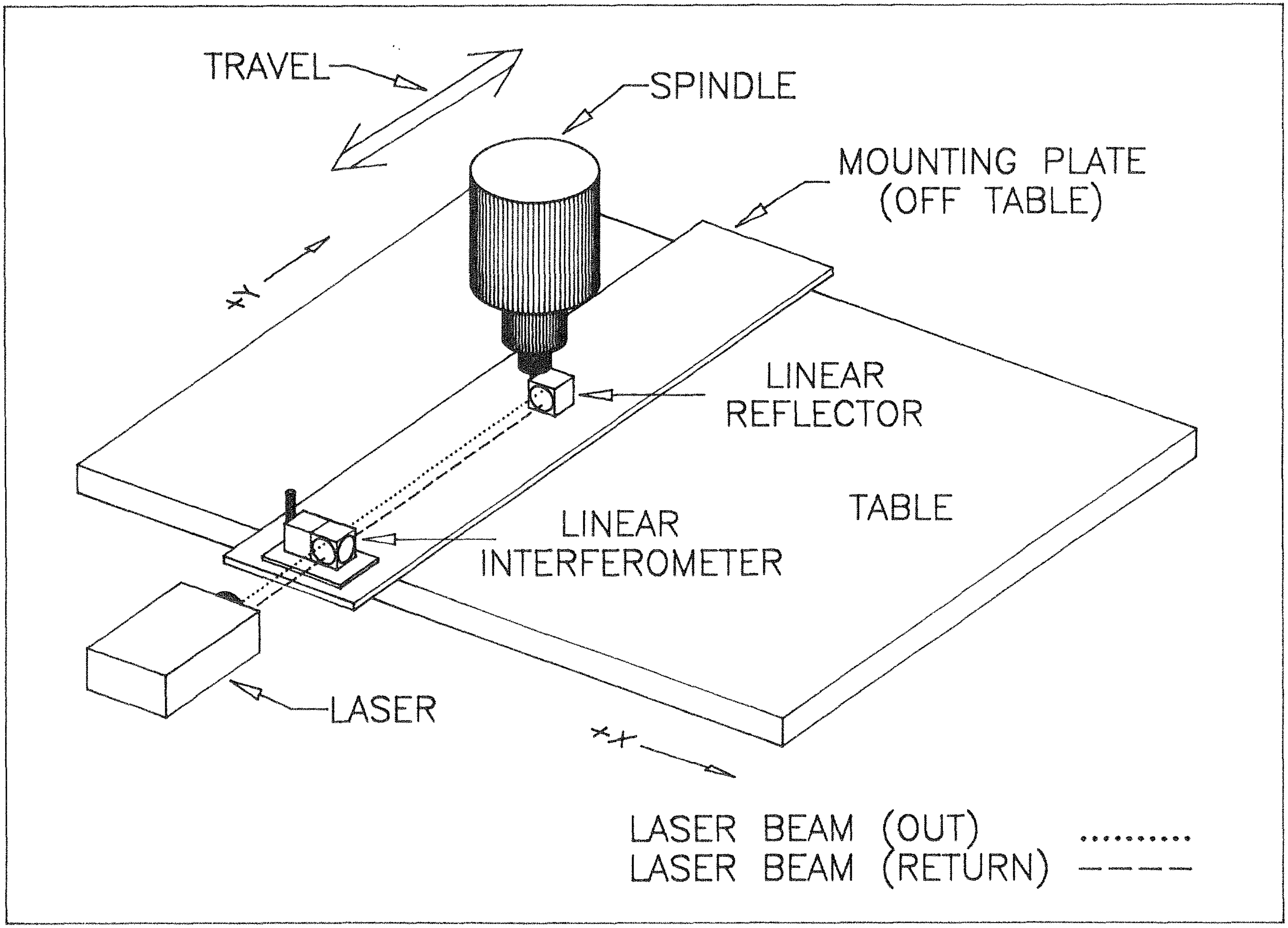


Figure 2.9—Laser setup for measuring feed rate accuracy in the Y-axis.

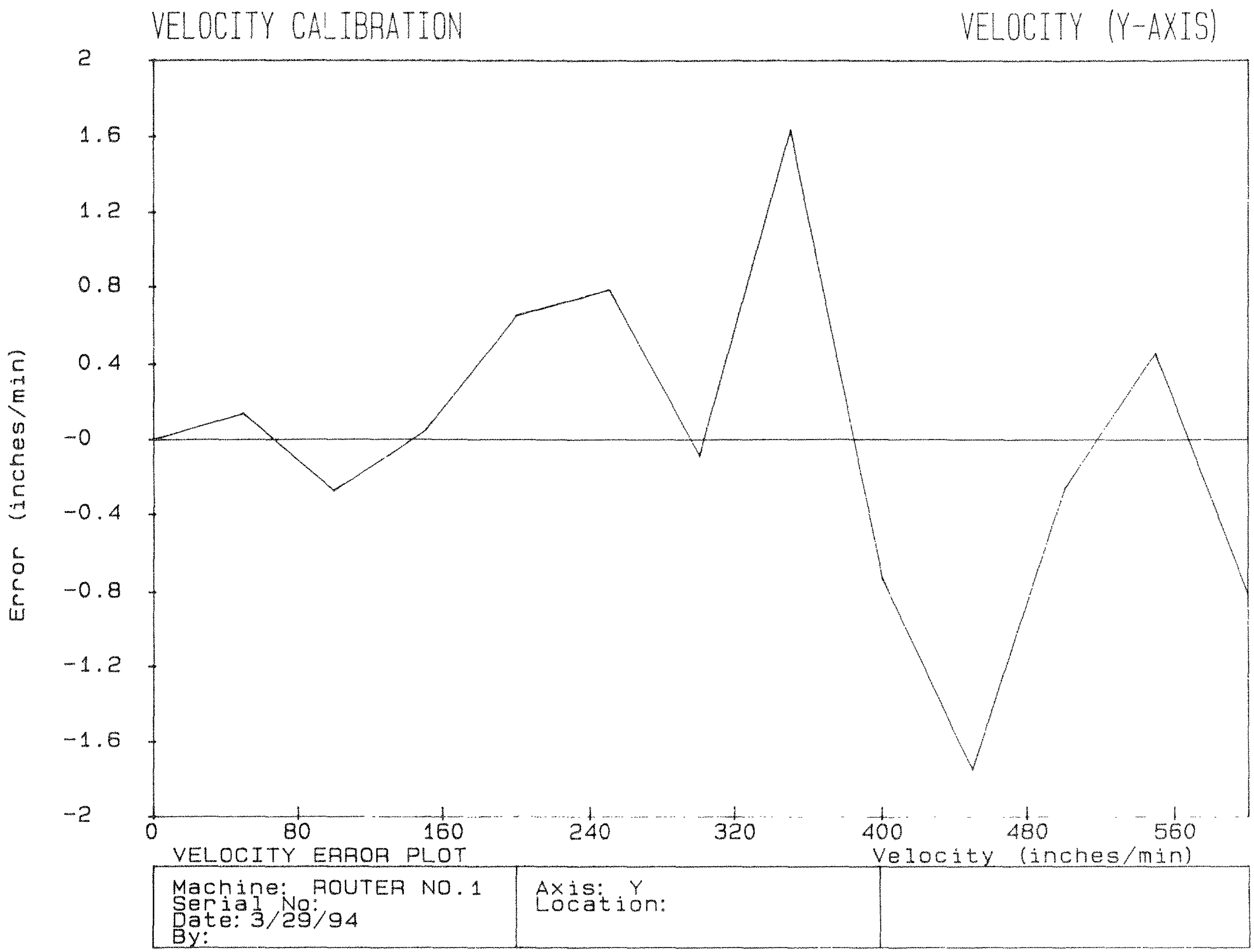


Figure 2.10—Results showing feed rate accuracy in the Y-axis as measured by laser system.

Method—Before beginning this evaluation, the servo motor and ball screw that controls the movement in the Z-axis should be exercised through at least 20 full cycles. This is done so that measurements are not taken on a cold servo motor and ball screw. Once this is done, use the following steps.

Step 1

Develop a program for the controller that moves the table/spindle the full length of travel in the Z-axis at a feed rate of 50 inches per minute and then returns to the start position. Have the program repeat this procedure for feed rate increments of 50 inches per minutes (that is, 100, 150, and so on) until the maximum Z-axis feed rate is reached. An example of this program and its subroutine, titled SAMPLE FEED RATE PROGRAMS (Z-AXIS), is shown in Figure A.2.1 of Appendix A.2.

Step 2

Set up and align the laser as instructed in the laser user's manual. Figure 2.11 shows an example of the laser optics setup. Assure that adjustments are made for air temperature, barometric pressure, relative humidity, and thermal expansion of the ball screw material.

Step 3

Run the controller program and record the laser measured feed rate at the midpoint of table/spindle travel for each feed rate set up in the controller program.

Results—Plot a graph of the differences between the specified feed rate and the actual feed rate of the table/spindle travel. Figure 2.12 shows an example of such a plot.

2.3 Straightness

2.3.1 X-axis Straightness (Horizontal & Vertical Planes)

Purpose—This procedure determines the ability of the router to move a cutting tool in a straight line when moving in both the horizontal and vertical planes of the X-axis. Router construction affects the movement, which may be a result of the table moving relative to the spindle or the spindle moving relative to the table. Basically, this reflects the straightness and alignment of the ways used to guide the table/spindle.

Recommended equipment:

- Class II helium-neon laser (interferometer) system with optics for measuring linear straightness. The optics include a straightness interferometer and straightness reflector plus the hardware required for mounting them. It is not necessary to make environmental compensations for air temperature, barometric pressure, and relative humidity. However, follow the recommendations of the laser manufacturer concerning air turbulence, heaters, and air fans. The laser system must be equivalent to the Renishaw Laser Interferometer System (ML10) by Renishaw Transducer Systems Limited or the HP5528A Laser Measurement System by Hewlett Packard.

- Microcomputer (PC) and software to record and analyze the data. Although the PC and software are not necessary, they greatly facilitate collecting and analyzing the data for this procedure.

Method—Before beginning this evaluation, the servo motor and ball screw that controls the movement in the X-axis should be exercised through at least 20 full cycles. This reduces the error in positioning for data collection that can occur due to cold servo motors and ball screws. Once this is done, use the following steps.

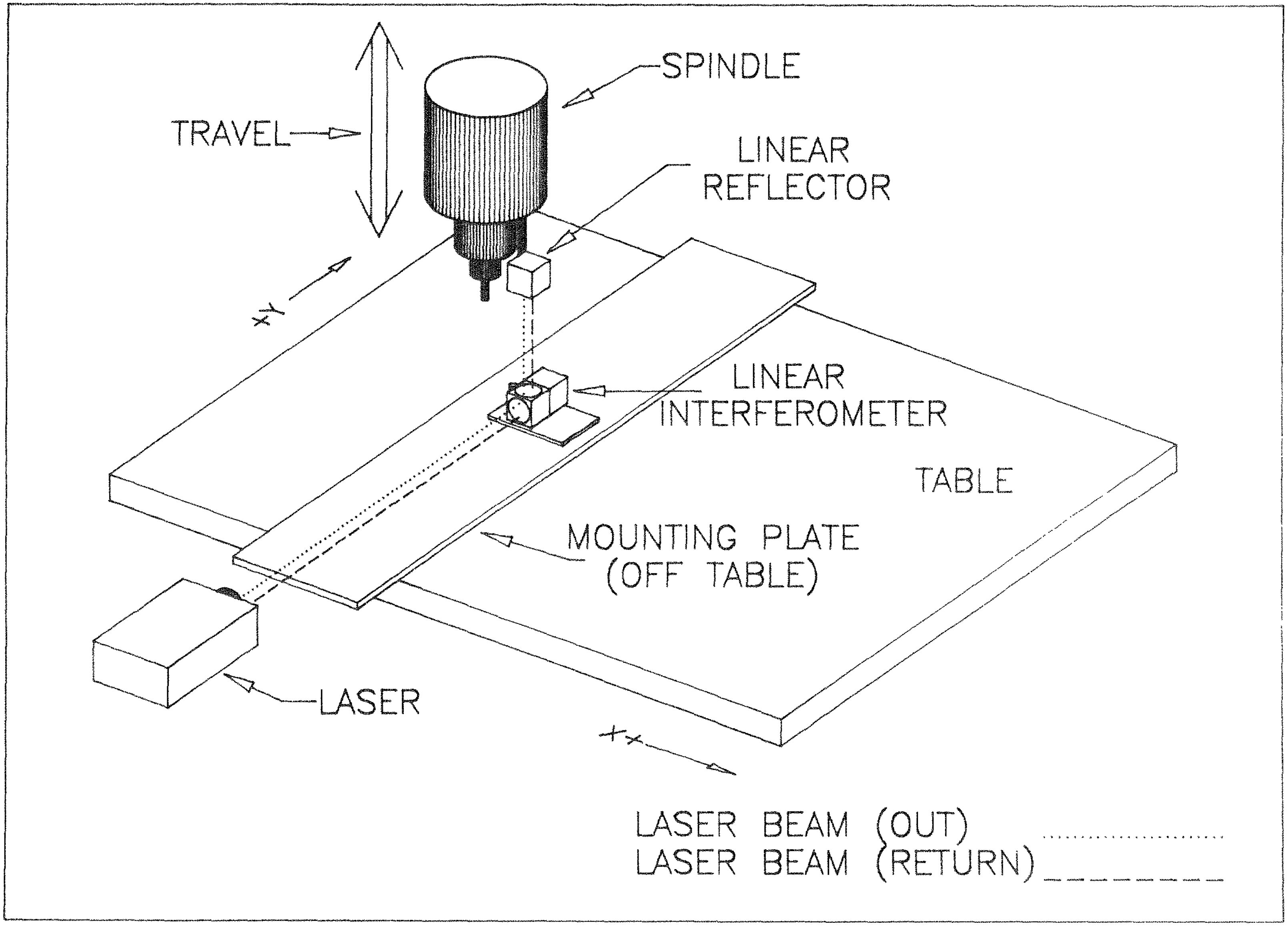


Figure 2.11—Laser setup for measuring feed rate accuracy in the Z-axis.

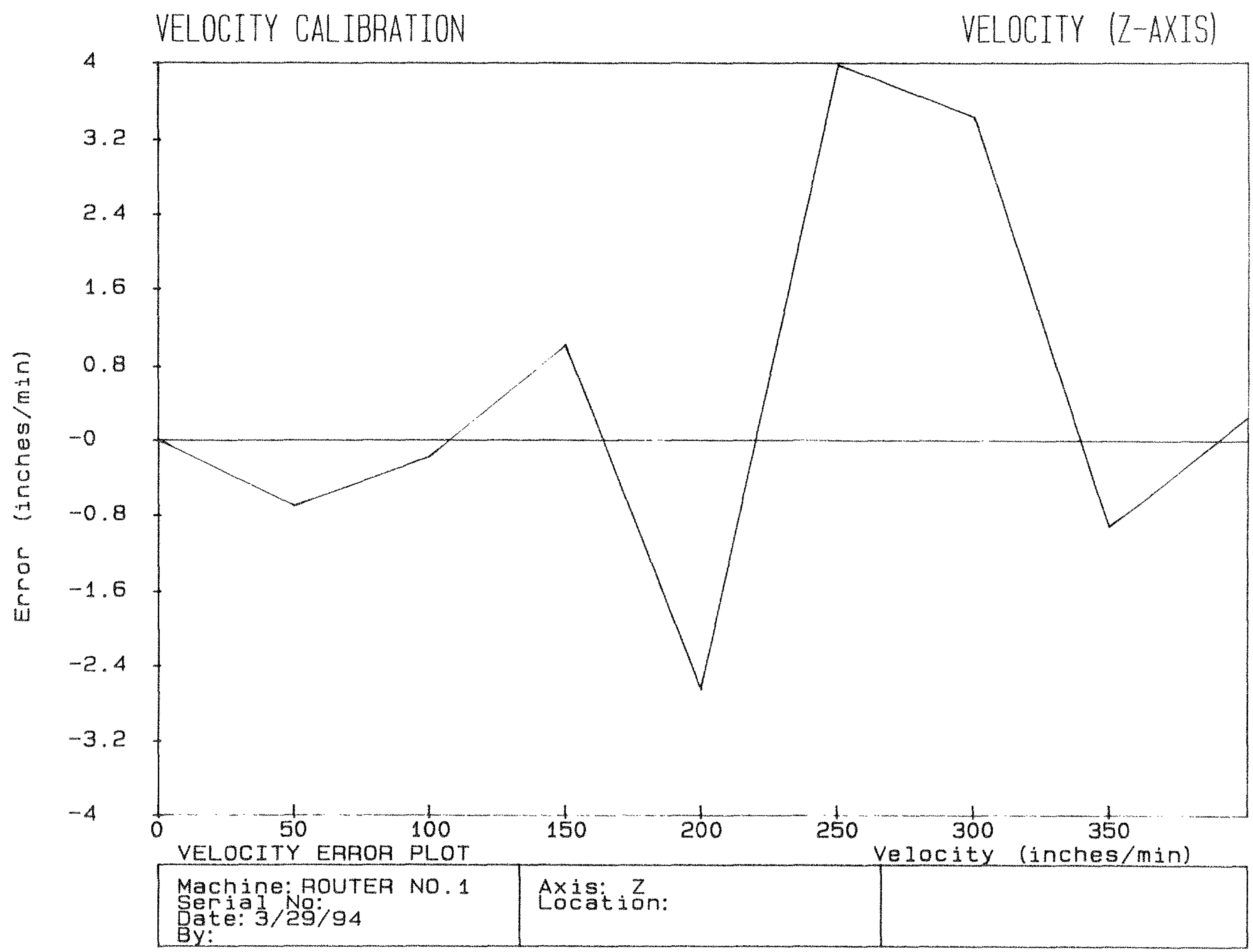


Figure 2.12—Results showing feed rate accuracy in the Z-axis as measured by laser system.

Step 1

Develop a program for the controller that moves the table/spindle the full length of the X-axis in 2-inch increments. However, provide at least 1 inch of extra travel past the two end targets to allow for changing the direction of travel. Pause between each move to allow the measurement of the deviation in straightness of travel. The program also must provide for bi-directional travel so that measurements can be taken in both the +X and -X directions. After the measurement is recorded for the last point in a given direction, move the spindle/table ahead 1 inch. Then reverse the direction of travel 1 inch to the final point for the first measurement in the other direction. An example of this program and its subroutines, titled LINEAR POSITIONING IN X-AXIS (STANDARD UNITS), is shown in Figure A.1.1 of Appendix A.1.

Step 2

Set up and align the laser for determining straightness in the horizontal plane as shown in Figure 2.13. The laser is aligned down the middle of the table in the X-axis. Be sure to follow the instructions in the laser user's manual concerning air turbulence, heaters, and air fans.

Step 3

Measure and record the deviation in straightness of travel at the start point and at the end of each 2-inch move in both the +X and the -X directions. Repeat this procedure for five full forward and reverse cycles.

Step 4

Move the straightness interferometer to the -X end of the table as shown in Figure 2.14 and repeat Step 3.

Step 5

Repeat Steps 2, 3, and 4 with the laser set up for determining straightness of travel in the vertical plane as shown in Figures 2.15 and 2.16.

Results—Plot graphs based on the British Standard (BS 4656, Part 16) showing least-squares fits of the straightness errors in table/spindle travel for both the +X and the -X directions. These plots are provided for straightness errors in both the horizontal and vertical planes. Figures 2.17 and 2.18 show examples of the plots and representative statistics for straightness in the horizontal plane with the straightness interferometer positioned at both the +X and -X ends of the table. Figures 2.19 and 2.20 show examples of the plots and representative statistics for straightness in the vertical plane with the straightness interferometer positioned at both the +X and -X ends of the table. These outputs indicate the straightness of the ways for the entire length of travel. The first two plots show the mean straightness errors in both the positive and negative directions along with the "±3 sigma" repeatability bands. The third plot shows both the positive and negative mean straightness errors along with the combined repeatability bands. A discussion of the data presented at the bottom of the graph follows:

- Accuracy is the difference between the maximum and minimum values of the mean plus 3 standard deviations and the mean minus 3 standard deviations, respectively, regardless of travel direction.

- Uni-directional Repeatability (Uni-dir. Rep) is the maximum value of the difference between the mean plus 3 standard deviations and the mean minus 3 standard deviations at any given point, within either direction of travel.

- Bi-directional Repeatability (Bi-dir. Rep) is the maximum value of the difference between the mean plus 3 standard deviations and the mean minus 3 standard deviations at any given point, within both directions of travel. The two maximum values can be taken from different directions of travel.

- Mean Reversal Error (Mean rev) is the mean value of the differences between the mean straightness errors for the two directions of travel.

Text continues on page 53

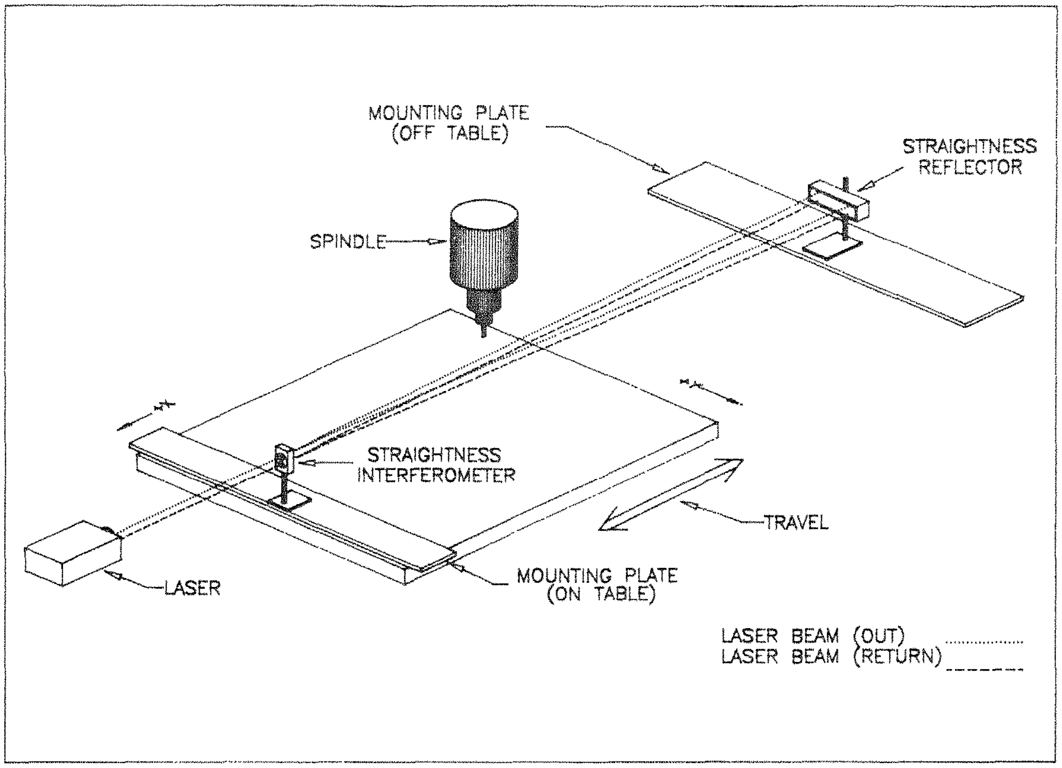


Figure 2.13—Laser setup for measuring horizontal straightness in the X-axis travel with straightness interferometer at the +X end of table.

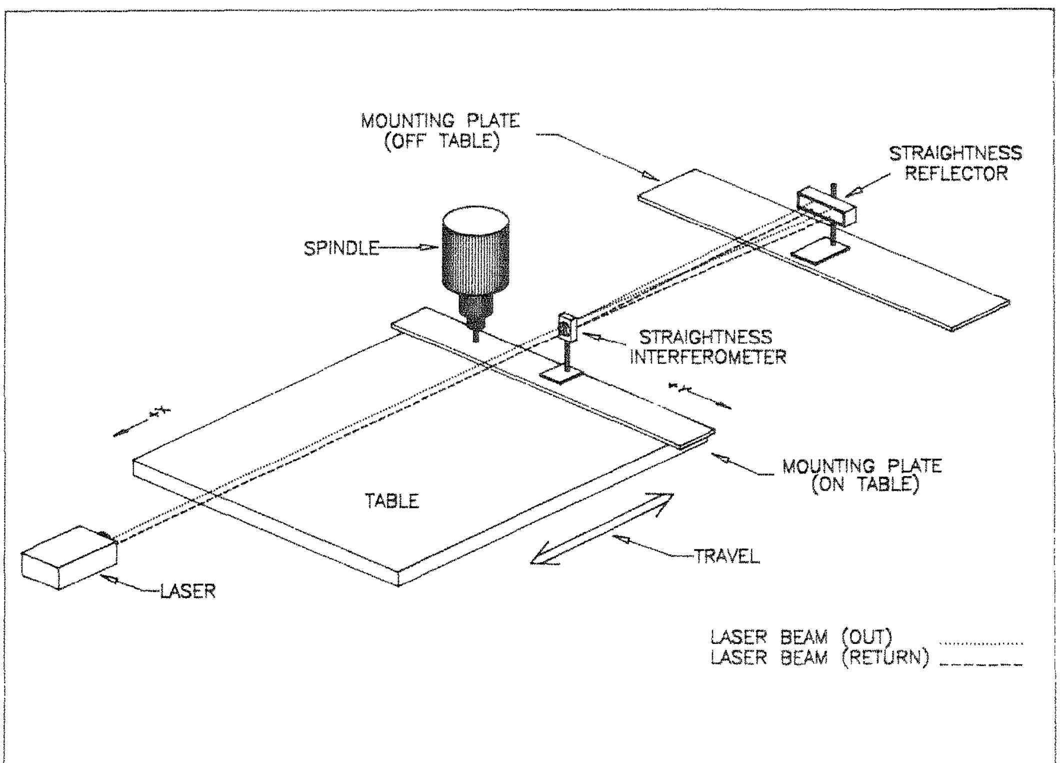


Figure 2.14—Laser setup for measuring horizontal straightness in the X-axis travel with straightness interferometer at the -X end of table.

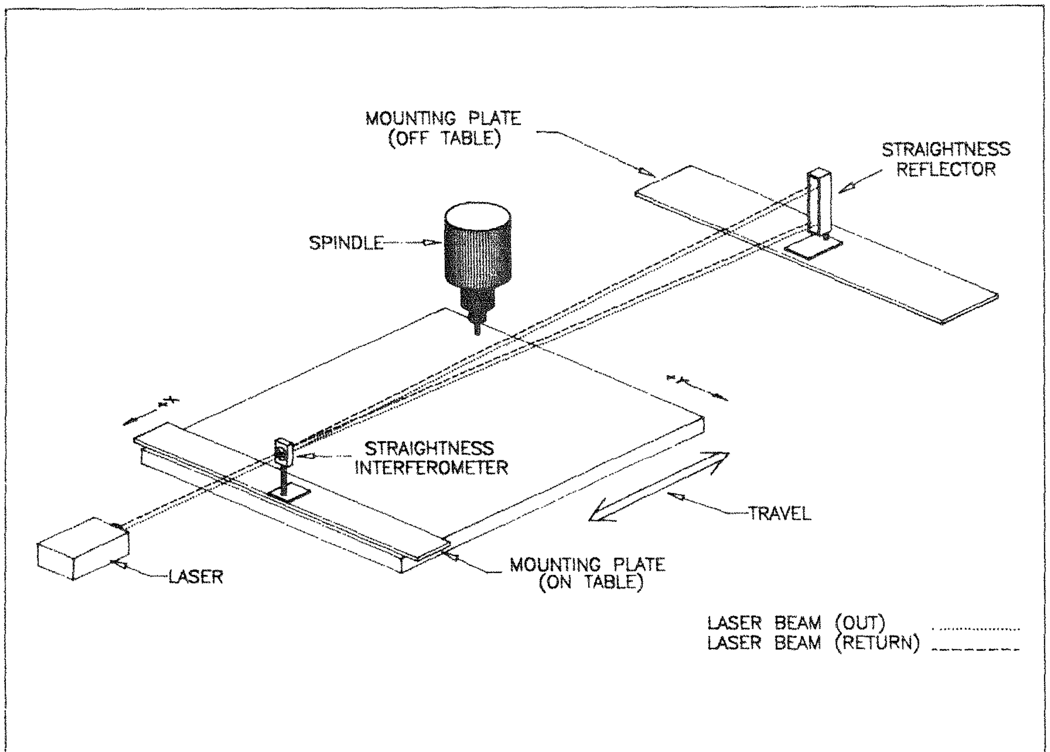


Figure 2.15—Laser setup for measuring vertical straightness in the X-axis travel with straightness interferometer at the +X end of table.

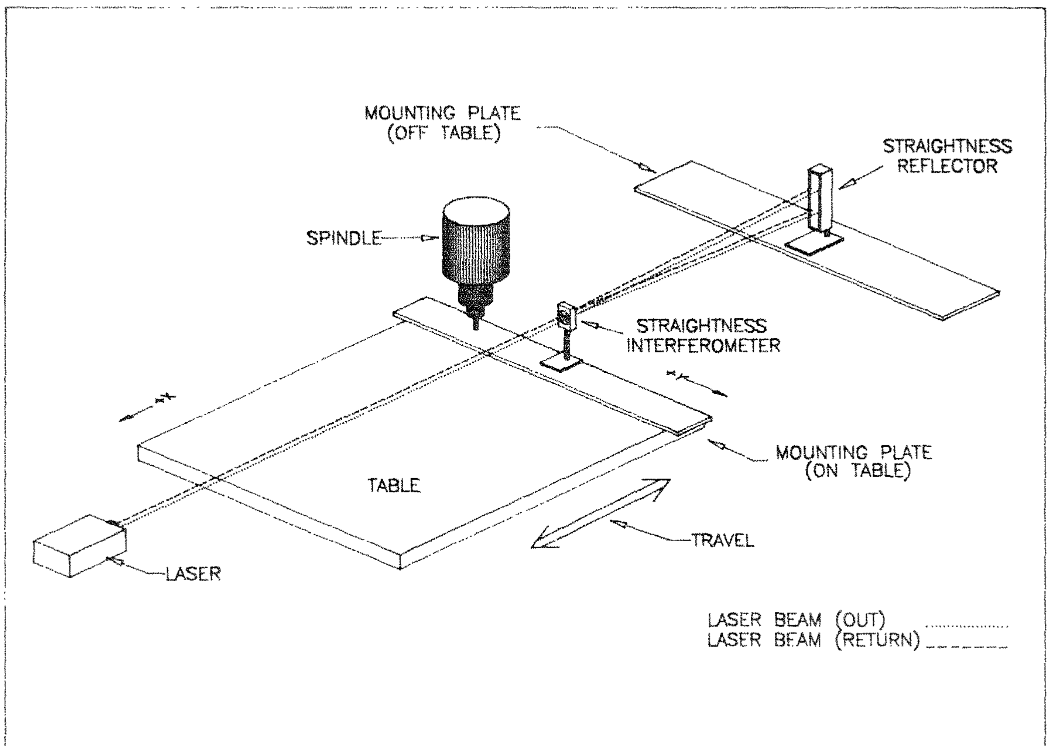
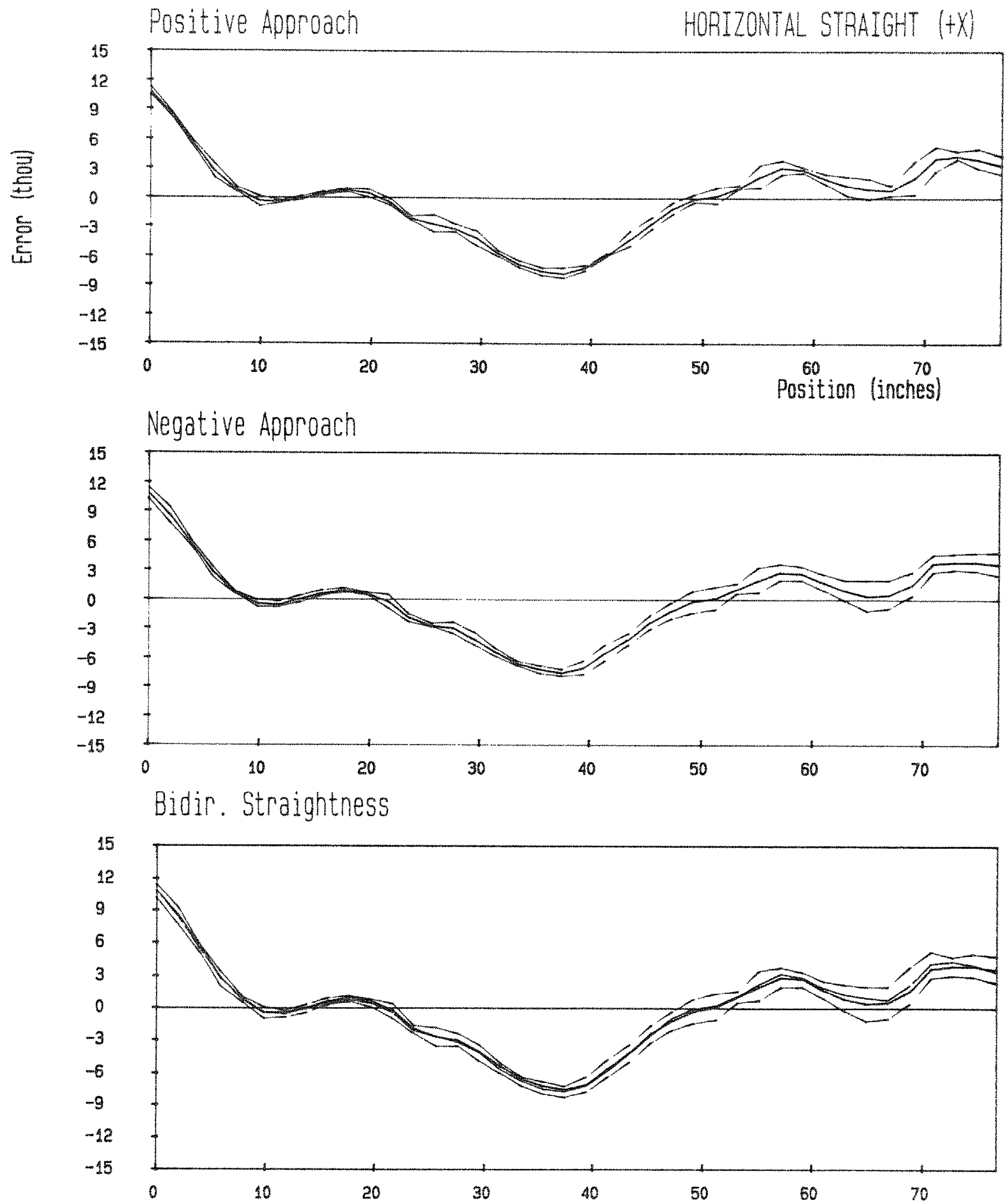


Figure 2.16—Laser setup for measuring vertical straightness in the X-axis travel with straightness interferometer at the -X end of table.



Machine: ROUTER NO.1	Axis: X	Accuracy: 19.6924
Serial No:	Location: +X END	Uni-dir. Rep: 3.4048
Date: 3/29/94	Slope: 21.48 ARCSEC	Bi-dir. Rep: 3.4099
By:	Str. Error : 18.5760	Mean rev: 0.0242

Figure 2.17—Results showing horizontal straightness in the X-axis travel with the straightness interferometer at the +X end of table.

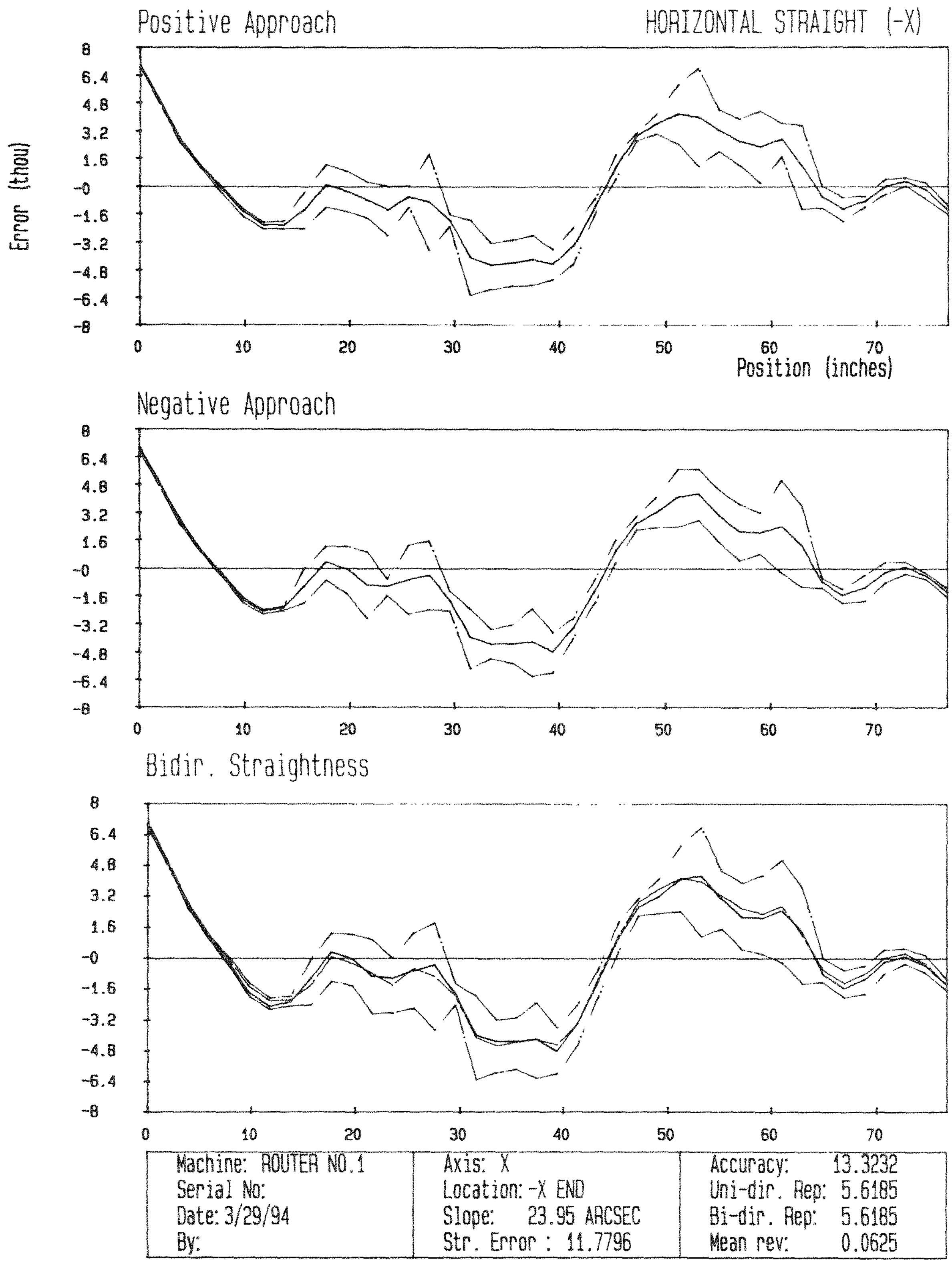
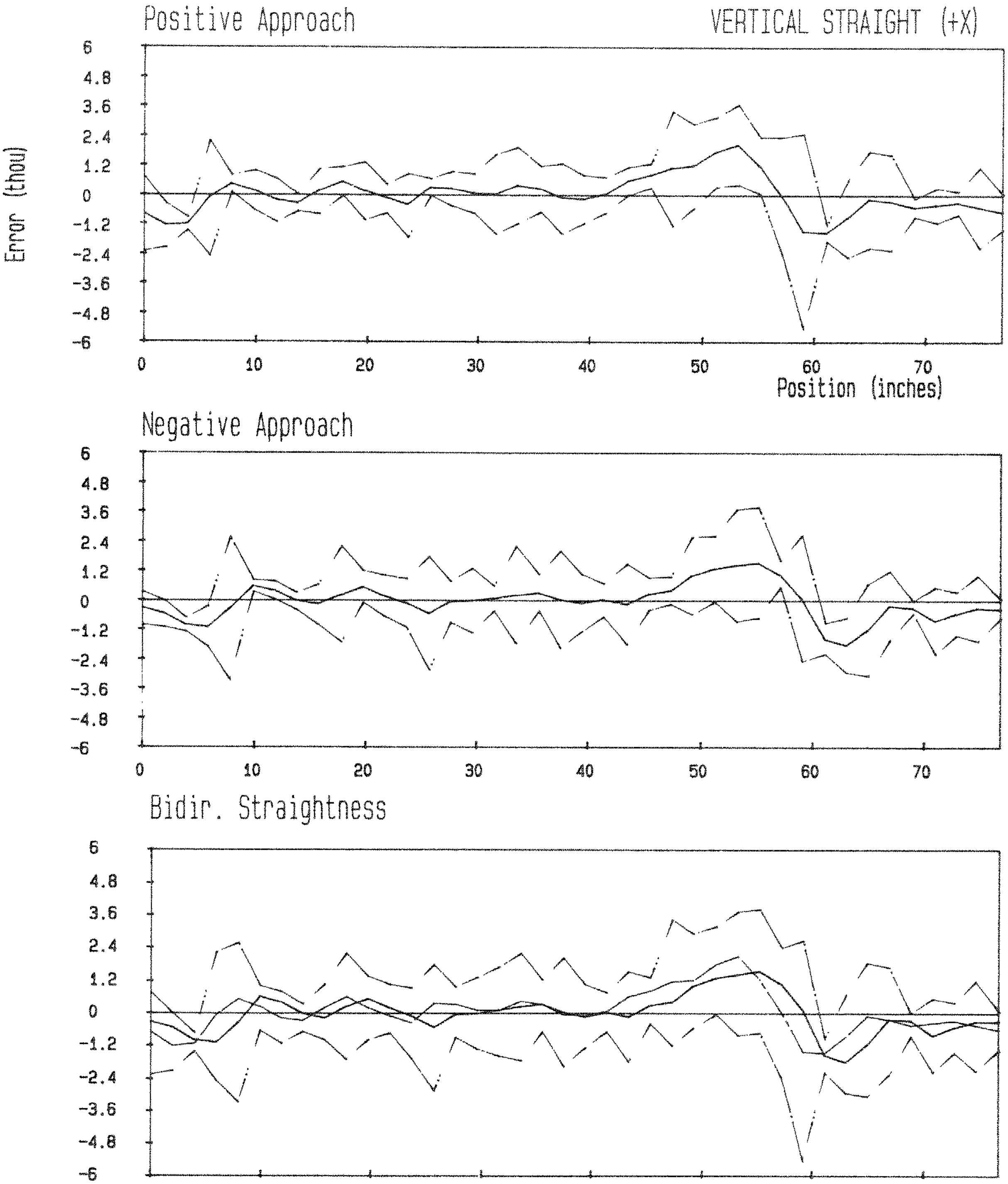


Figure 2.18—Results showing horizontal straightness in the X-axis travel with the straightness interferometer at the -X end of table.



Machine: ROUTER NO.1	Axis: X	Accuracy: 9.2451
Serial No:	Location: +X END	Uni-dir. Rep: 7.9595
Date: 3/29/94	Slope: 3.78 ARCSEC	Bi-dir. Rep: 8.0818
By:	Str. Error : 3.8898	Mean rev: 0.0573

Figure 2.19—Results showing vertical straightness in the X-axis travel with the straightness interferometer at the +X end of table.

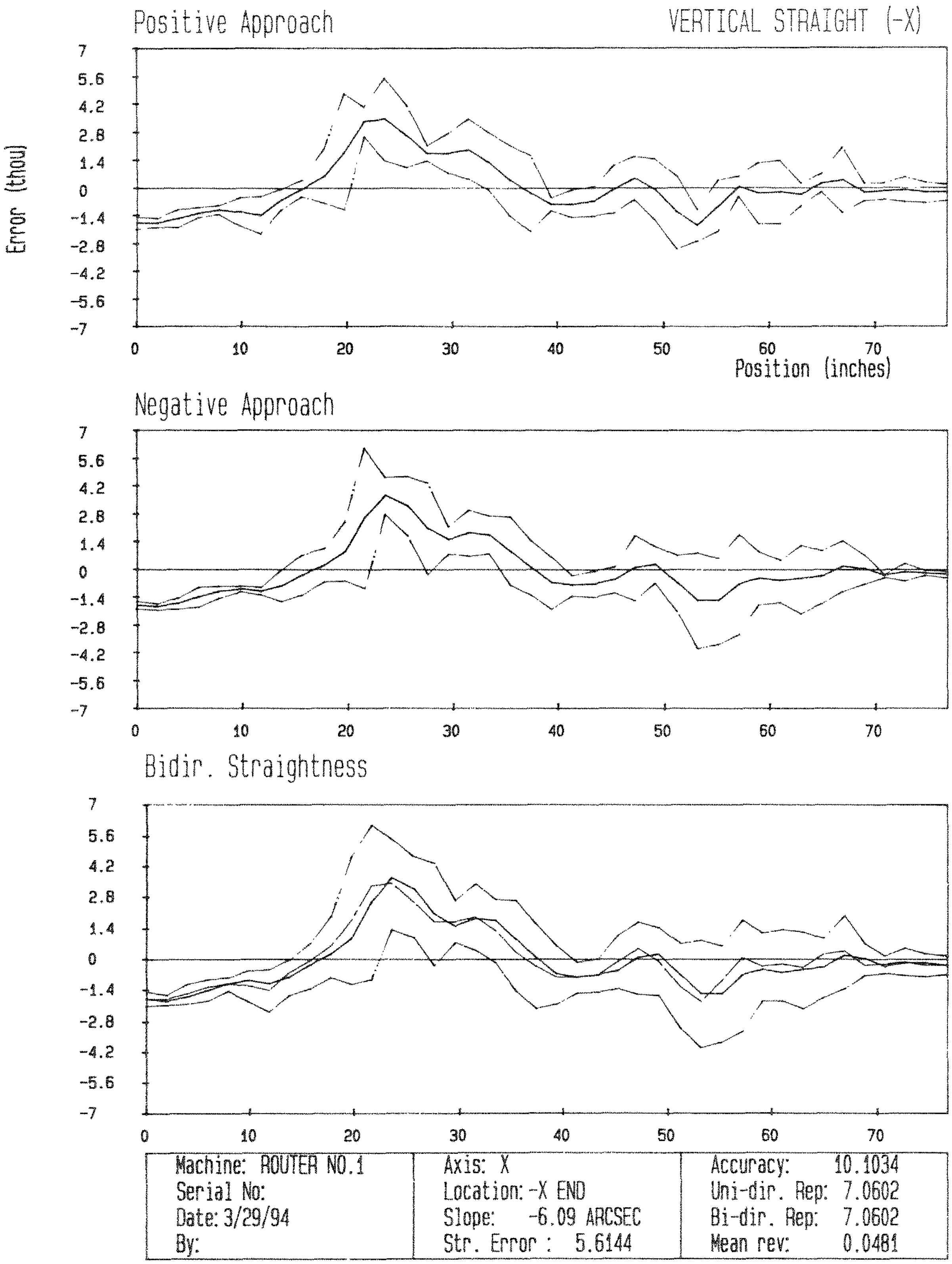


Figure 2.20—Results showing vertical straightness in the X-axis travel with the straightness interferometer at the -X end of table.

- Slope is the misalignment angle between the laser beam used for data capture and the straightness datum as determined by the analysis.

- Straightness Error (Str. Error) is the sum of the maximum and minimum excursions of the mean straightness errors from the straightness datum defined by the analysis.

The above definitions were taken from the RENISHAW TRANSDUCER SYSTEMS LIMITED, Laser Interferometer System PC10 User Manual.[1]

2.3.2 Y-axis Straightness (Horizontal & Vertical Planes)

Purpose—This procedure determines the ability of the router to move a cutting tool in a straight line when moving in both the horizontal and vertical planes of the Y-axis. Router construction affects the movement, which may be a result of the table moving relative to the spindle or the spindle moving relative to the table. Basically, this reflects the straightness and alignment of the ways used to guide the table/spindle.

Recommended equipment:

- Class II helium-neon laser (interferometer) system with optics for measuring linear straightness. The optics include a straightness interferometer and straightness reflector plus the hardware required for mounting them. It is not necessary to make environmental compensations for air temperature, barometric pressure, and relative humidity. However, follow the recommendations of the laser manufacturer concerning air turbulence, heaters, and air fans. The laser system must be equivalent to the Renishaw Laser Interferometer System (ML10) by Renishaw Transducer Systems Limited or the HP5528A Laser Measurement System by Hewlett Packard.

- Microcomputer (PC) and software to record and analyze the data. Although the PC and software are not necessary, they greatly facilitate collecting and analyzing the data for this procedure.

Method—Before beginning this evaluation, the servo motor and ball screw that control the movement in the Y-axis should be exercised through at least 20 full cycles. This reduces the error in positioning for data collection that can occur due to cold servo motors and ball screws. Once this is done, use the following steps.

Step 1

Develop a program for the controller that moves the table/spindle the full length of the Y-axis in 2-inch increments. However, provide at least 1 inch of extra travel past the two end targets to allow for changing the direction of travel. Pause between each move to allow the measurement of the deviation in straightness of travel. The program also must provide for bi-directional travel so that measurements can be taken in both the +Y and -Y directions. After the measurement is recorded for the last point in a given direction, move the spindle/table ahead 1 inch. Then reverse the direction of travel 1 inch to the final point for the first measurement in the other direction. An example of this program and its subroutines, titled LINEAR POSITIONING IN Y-AXIS (STANDARD UNITS), are shown in Figure A.1.1 of Appendix A.1.

Step 2

Set up and align the laser for determining straightness in the horizontal plane as shown in Figure 2.21. Be sure to follow the instructions in the laser user's manual concerning air turbulence, heaters, and air fans.

Step 3

Measure and record the deviation in straightness of travel at the start point and at the end of each 2-inch move in both the +Y and the -Y directions. Repeat this procedure for five full forward and reverse cycles.

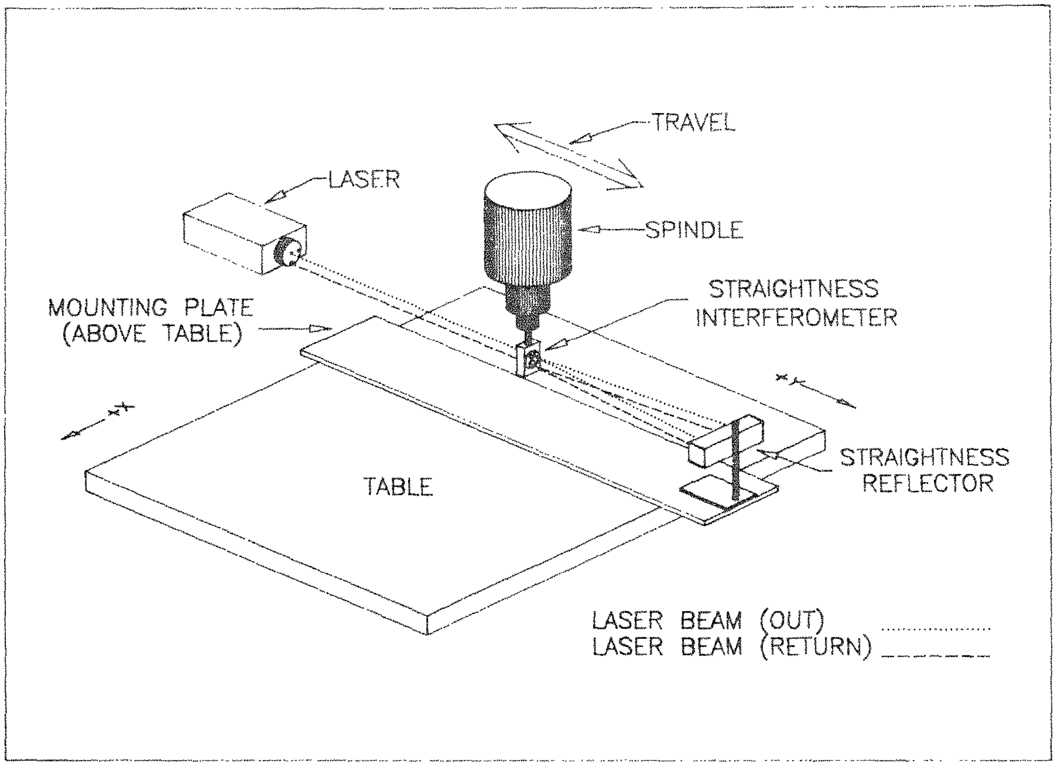


Figure 2.21—Laser setup for measuring horizontal straightness in the Y-axis travel.

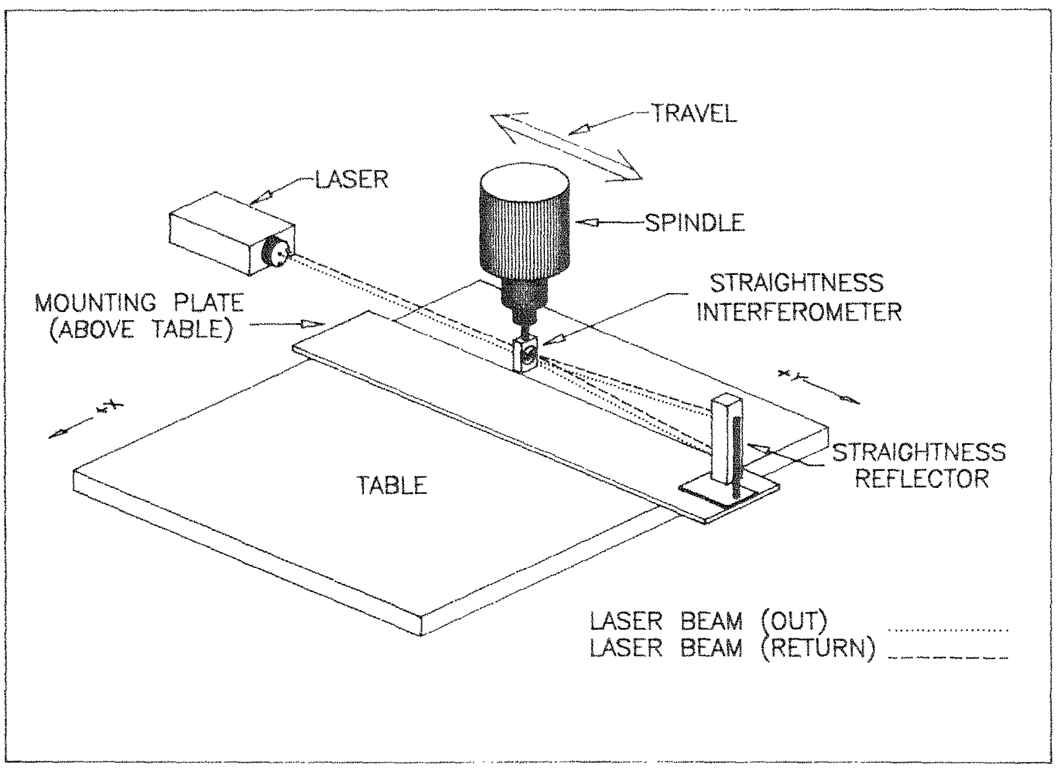
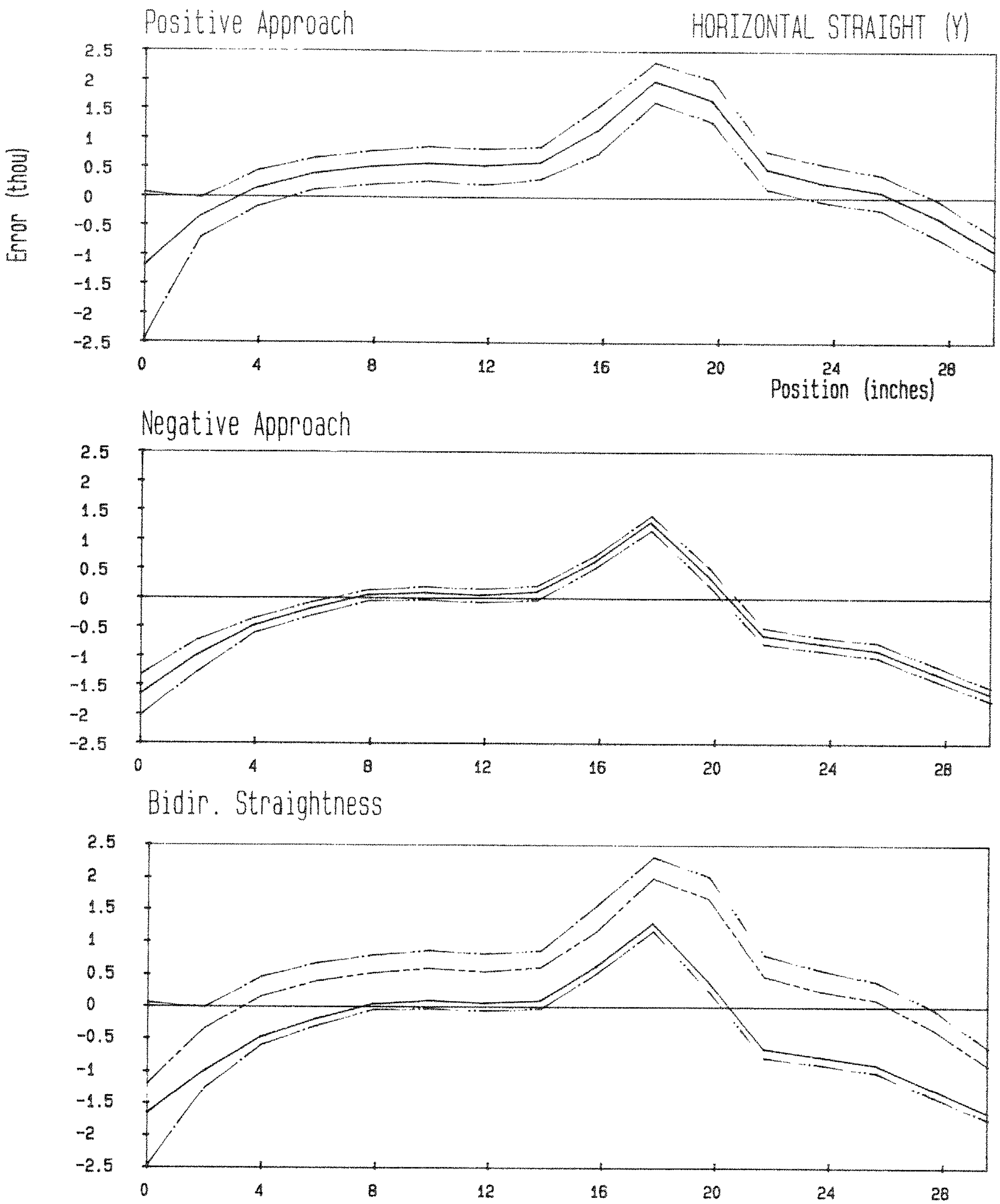
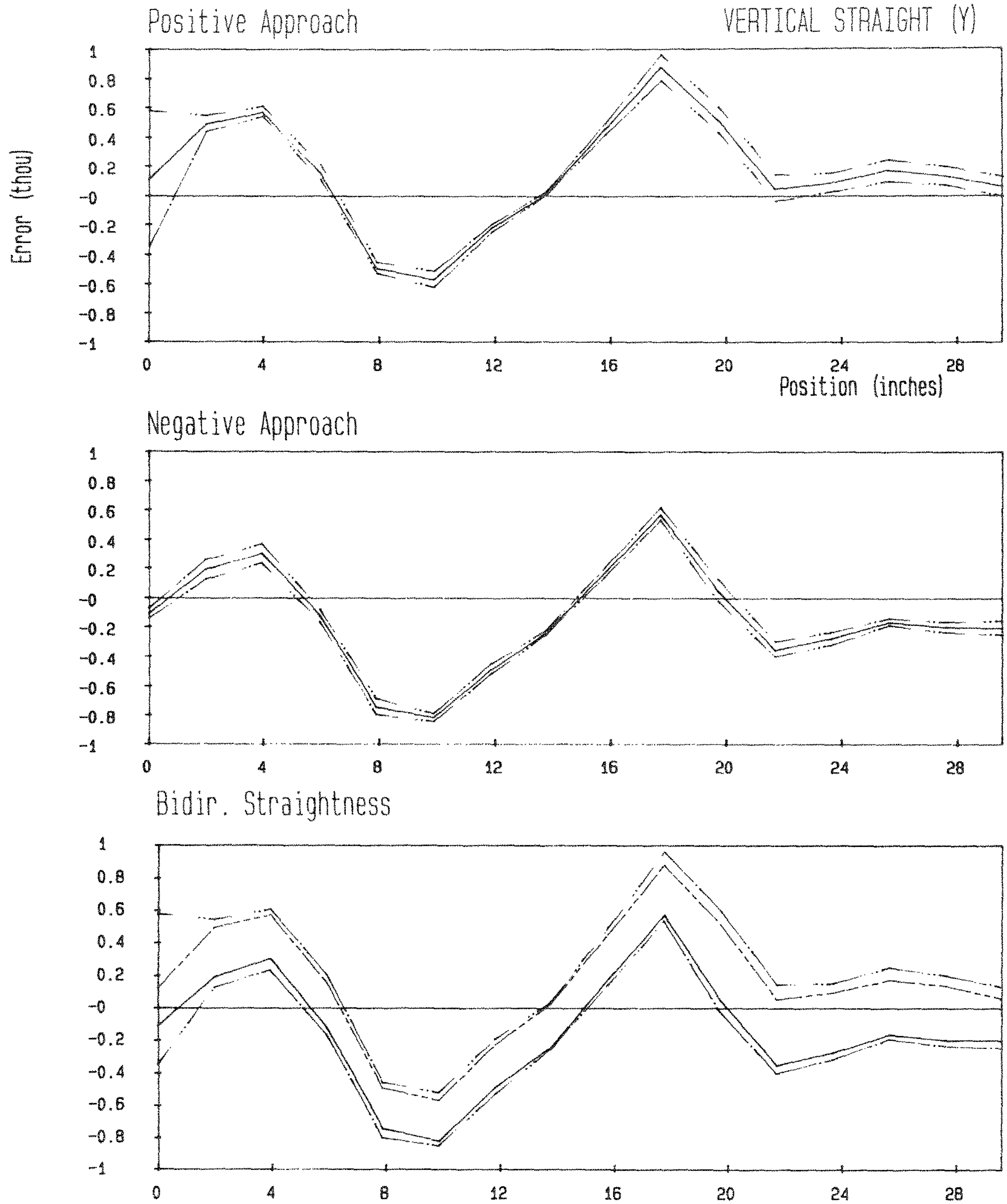


Figure 2.22—Laser setup for measuring vertical straightness in the Y-axis travel.



Machine: ROUTER NO.1	Axis: Y	Accuracy: 4.7801
Serial No:	Location:	Uni-dir. Rep: 2.5129
Date: 3/29/94	Slope: -6.15 ARCSEC	Bi-dir. Rep: 2.5129
By:	Str. Error : 3.6357	Mean rev: 0.7170

Figure 2.23—Results showing horizontal straightness in the Y-axis travel.



Machine: ROUTER NO.1	Axis: Y	Accuracy: 1.8083
Serial No:	Location:	Uni-dir. Rep: 0.9304
Date: 3/29/94	Slope: 0.93 ARCSEC	Bi-dir. Rep: 0.9304
By:	Str. Error : 1.6944	Mean rev: 0.3020

Figure 2.24—Results showing vertical straightness in the Y-axis travel.

Step 4

Repeat Steps 2 and 3 with the laser set up for determining straightness of travel in the vertical plane as shown in Figure 2.22.

Results—Plot graphs based on the British Standard (BS 4656, Part 16) showing least-squares fit of the straightness errors in table/spindle travel for both the +Y and the -Y directions. Figure 2.23 shows an example of the plot and representative statistics for straightness in the horizontal plane. Figure 2.24 shows an example of the plot and representative statistics for straightness in the vertical plane. The first two plots show the mean straightness errors in both the positive and negative directions along with the "±3 sigma" repeatability bands. The third plot shows both the positive and negative mean straightness errors along with the combined repeatability bands. See section 2.3.1 "X-axis Straightness (Horizontal & Vertical Plane)" for a discussion of the data presented at the bottom of the graph.

2.3.3 Z-axis Straightness (XZ- & YZ-Planes)

Purpose—This procedure determines the ability of the router to move a cutting tool in a straight line when moving in both the XZ-plane and YZ-plane of the Z-axis. Router construction affects the movement, which may be a result of the table moving relative to the spindle or the spindle moving relative to the table. Basically, this reflects the straightness and alignment of the ways used to guide the table/spindle.

Recommended equipment:

- Class II helium-neon laser (interferometer) system with optics for measuring linear straightness. The optics include a straightness interferometer, straightness reflector, vertical turning mirror, and a retroreflector plus the hardware required for mounting them. It is not necessary to make environmental compensations for air temperature, barometric pressure, and relative humidity. However, follow the recommendations of the laser manufacturer concerning air turbulence, heaters, and air fans. The laser system must be equivalent to the Renishaw Laser Interferometer System (ML10) by Renishaw Transducer Systems Limited or the HP5528A Laser Measurement System by Hewlett Packard.

- Microcomputer (PC) and software to record and analyze the data. Although the PC and software are not necessary, they greatly facilitate collecting and analyzing the data for this procedure.

Method—Before beginning thisevaluation, the servo motor and ball screw that control the movement in the Z-axis should be exercised through at least 20 full cycles. This reduces the error in positioning for data collection that can occur due to cold servo motors and ball screws. Once this is done, use the following steps.

Step 1

Develop a program for the controller that moves the table/spindle the full length of the Z-axis in 0.25-inch increments. However, provide at least 0.25 inch of extra travel past the two end targets to allow for changing the direction of travel. Pause between each move to allow the measurement of the deviation in straightness of travel. The program also must provide for bi-directional travel so that measurements can be taken in both the +Z and -Z directions. After the measurement is recorded for the last point in a given direction, move the spindle/table ahead 0.25 inch and then the direction of travel reversed the 0.25 inch to the final point for the first measurement in the other direction. An example of this program and its subroutines, titled LINEAR POSITIONING IN Z-AXIS (STANDARD UNITS), are shown in Figure A.1.1 of Appendix A.1.

Step 2

Set up and align the laser for determining straightness in the XZ-plane as shown in Figure 2.25. Be sure to follow the instructions in the laser user's manual concerning air turbulence, heaters, and air fans.

Step 3

Measure and record the deviation in straightness of travel at the start point and at the end of each 0.25 inch move in both the +Z and the -Z directions. Repeat this procedure for five full forward and reverse cycles.

Step 4

Repeat Steps 2 and 3 with the laser set up for determining straightness of travel in the YZ-plane as shown in Figure 2.26.

Results—Plot graphs based on the British Standard (BS 4656, Part 16) showing least-squares fits of the straightness errors in table/spindle travel in both the XZ- and YZ-planes for travel in both the +Z and the -Z directions. Figure 2.27 shows an example of the plot and representative statistics for straightness in the XZ-plane. Figure 2.28 shows an example of the plot and representative statistics for straightness in the YZ-plane. The first two plots show the mean straightness errors in both the positive and negative directions along with the "±3 sigma" repeatability bands. The third plot shows both the positive and negative mean straightness errors along with the combined repeatability bands. See section 2.3.1 "X-axis Straightness (Horizontal & Vertical Plane)" for a discussion of the data presented at the bottom of the graph.

2.4 Pitch and Yaw

2.4.1 X-axis Pitch and Yaw

Purpose—This procedure determines pitch and yaw in the router table/spindle as it moves in the X-axis. Router construction affects the movement, which may be a result of the table moving relative to the spindle or the spindle moving relative to the table. Basically, this reflects the straightness and alignment of the ways used to guide the table/spindle.

Recommended equipment:

- Class II helium-neon laser (interferometer) system with optics for measuring angular (pitch and yaw) deviations. The optics include an angular interferometer and angular reflector. Pitch and yaw measurements do not require environmental compensations for air temperature, barometric pressure, and relative humidity. And, it is not necessary to make adjustments for the thermal expansion of the scale material. The scale in this situation is the ball screw used to drive the router table or spindle in the axis to be measured. However, follow the recommendations of the laser manufacturer concerning air turbulence, heaters, and air fans. The laser system must be equivalent to the Renishaw Laser Interferometer System (ML10) by Renishaw Transducer Systems Limited or the HP5528A Laser Measurement System by Hewlett Packard.

- Microcomputer (PC) and software to record and plot the pitch and yaw information. Although the PC and software are not necessary, they greatly facilitate data collection and plotting for this procedure.

Method—Before beginning this evaluation, the servo motor and ball screw that control the movement in the X-axis should be exercised through at least 20 full cycles. This reduces the error in positioning for data collection that can occur due to cold servo motors and ball screws. Once this is done, use the following steps.

Step 1

Develop a program for the controller that moves the table/spindle the full length of the X-axis in 2-inch increments. However, provide at least 1 inch of extra travel past the two end targets to allow for changing the direction of travel. Pause between each move to allow the measurement of the pitch and yaw. This program also must provide

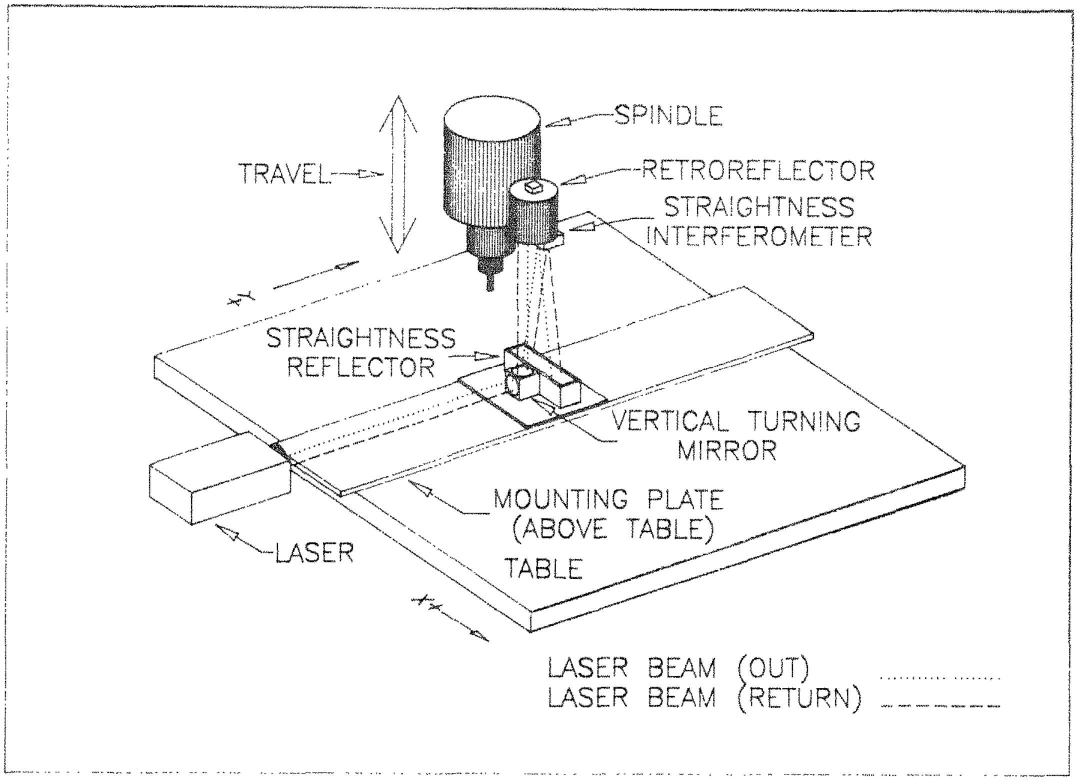


Figure 2.25—Laser setup for measuring straightness of Z-axis travel in the XZ-plane.

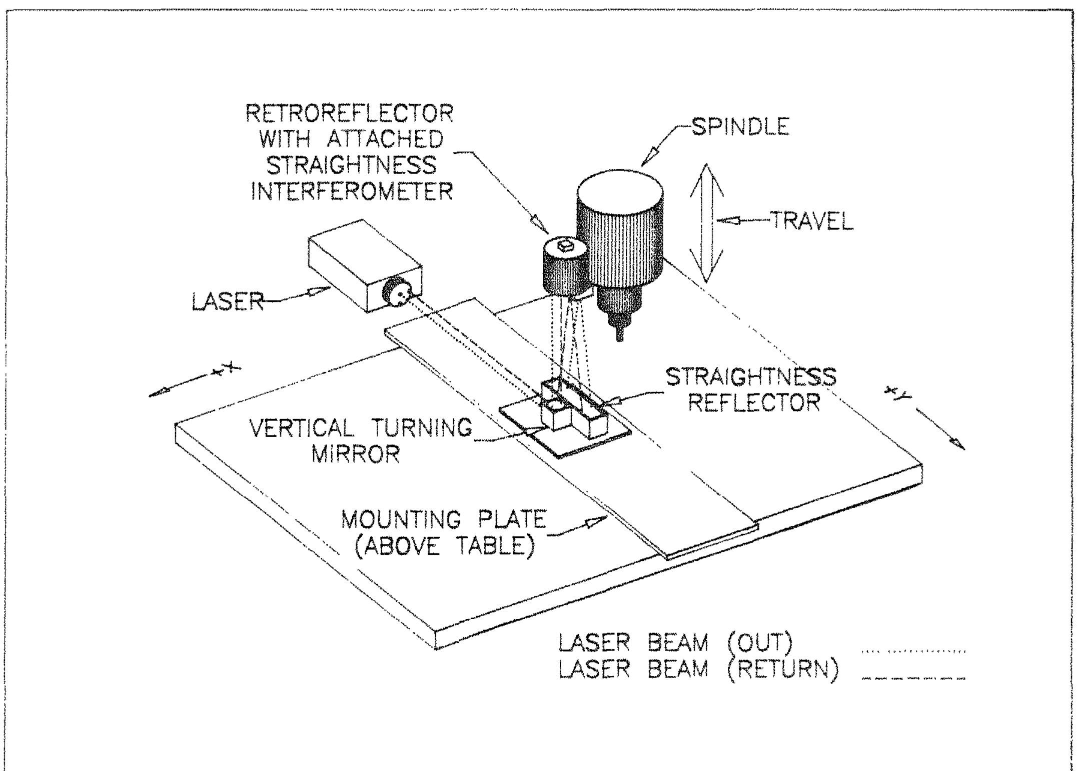


Figure 2.26—Laser setup for measuring straightness of Z-axis travel in the YZ-plane.

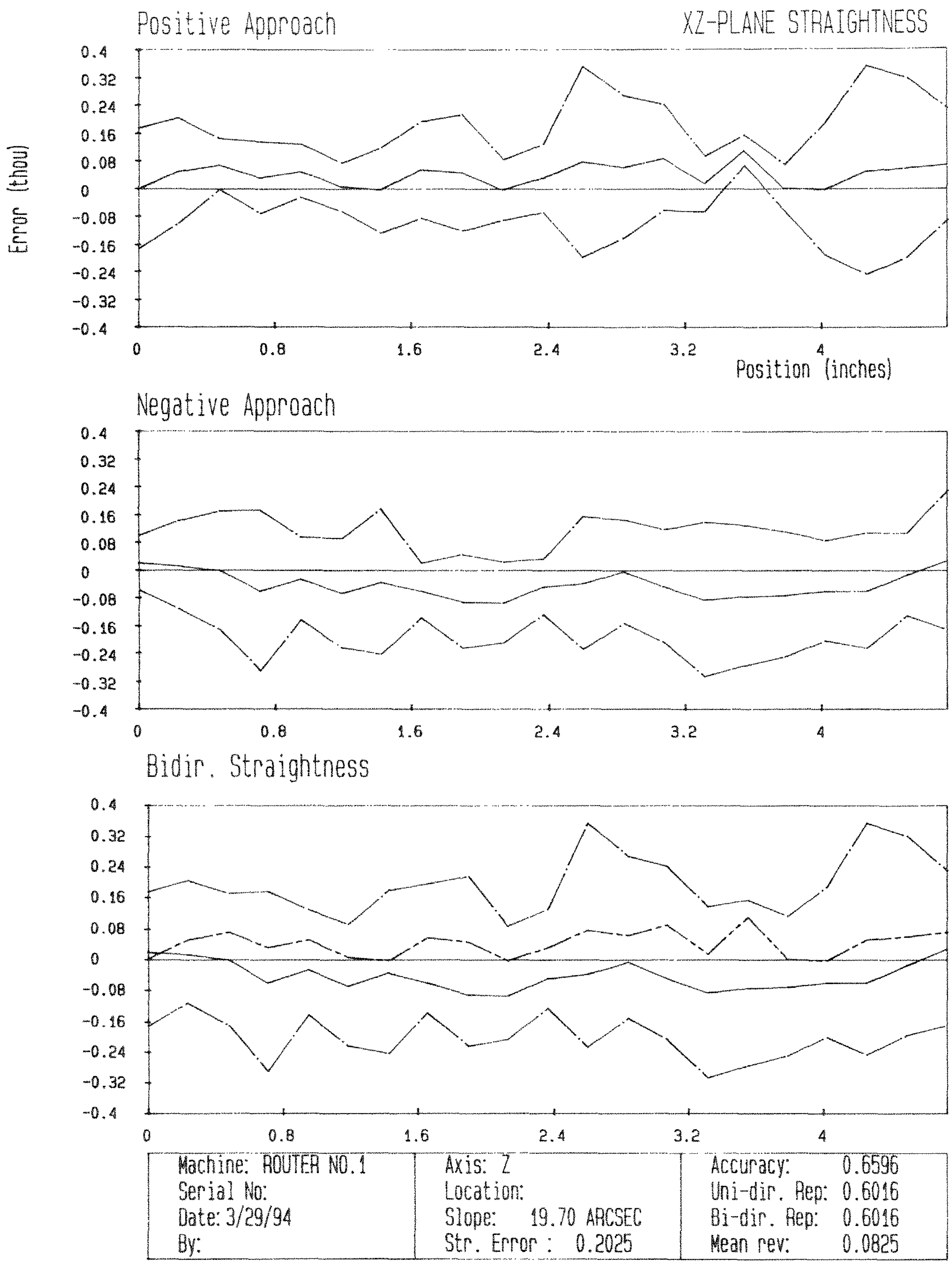


Figure 2.27—Results showing straightness of Z-axis travel in the XZ-plane.

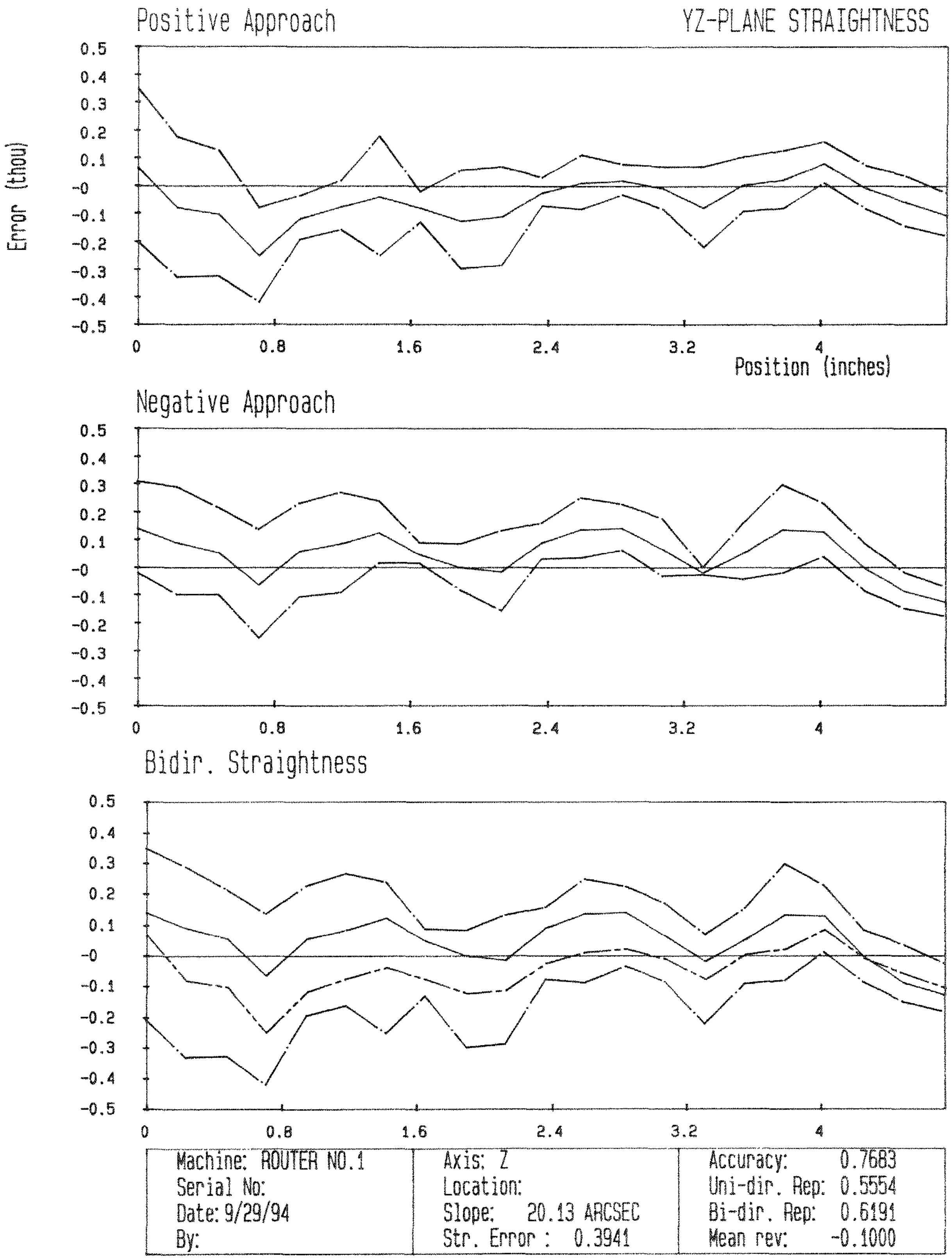


Figure 2.28—Results showing straightness of Z-axis travel in the YZ-plane.

for bi-directional travel so that measurements can be taken in both the +X and -X directions. After the measurement is recorded for the last point in a given direction, move the spindle/table ahead 1 inch. Then reverse the direction of travel the 1 inch to the final point for the first measurement in the other direction. An example of this program and its subroutines, titled LINEAR POSITIONING IN X-AXIS (STANDARD UNITS), is shown in Figure A.1.1 of Appendix A.1.

Step 2
Set up and align the laser for determining pitch as shown in Figure 2.29. The laser is aligned down the middle of the table in the X-axis. Be sure to follow the instructions in the laser user's manual concerning air turbulence, heaters, and air fans.

Step 3
Measure and record the pitch at the start point and at the end of each 2-inch move in both the +X and the -X directions. Repeat this procedure for five full forward and reverse cycles.

Step 4
Repeat Steps 2 and 3 with the laser set up for determining yaw as shown in Figure 2.30.

Results—Plot graphs of the pitch as shown in Figure 2.31. Plot graphs of the yaw as shown in Figure 2.32. Both graphs are to be based on the German VDI 3441 standard. The graphs show mean angular errors in both the positive and negative directions, the bi-directional mean angular error, and the maximum "±3 sigma" repeatability bands from either direction of travel. See section 2.1.1 "X-axis Positioning" for a discussion of the statistics presented at the bottom of the graphic plot.

2.4.2 Y-axis Pitch and Yaw

Purpose—This procedure determines pitch and yaw in the router table/spindle as it moves in the Y-axis. Router construction affects the movement, which may be a result of the table moving relative to the spindle or the spindle moving relative to the table. Basically, this reflects the straightness and alignment of the ways used to guide the table/spindle.

Recommended equipment:

- Class II helium-neon laser (interferometer) system with optics for measuring angular (pitch and yaw) deviations. The optics include an angular interferometer and angular reflector. Pitch and yaw measurements do not require environmental compensations for air temperature, barometric pressure, and relative humidity. And, it is not necessary to make adjustments for the thermal expansion of the scale material. The scale in this situation is the ball screw used to drive the router table or spindle in the axis to be measured. However, follow the recommendations of the laser manufacturer concerning air turbulence, heaters, and air fans. The laser system must be equivalent to the Renishaw Laser Interferometer System (ML10) by Renishaw Transducer Systems Limited or the HP5528A Laser Measurement System by Hewlett Packard.

- Microcomputer (PC) and software to record and plot the pitch and yaw information. Although the PC and software are not necessary, they greatly facilitate data collection and plotting for this procedure.

Method—Before beginning this evaluation, the servo motor and ball screw that control the movement in the Y-axis should be exercised through at least 20 full cycles. This reduces the error in positioning for data collection that can occur due to cold servo motors and ball screws. Once this is done, use the following steps.

Step 1
Develop a program for the controller that moves the table/spindle the full length of the Y-axis in 2-inch increments. However, provide at least 1 inch of extra travel past the two end targets to allow for changing the direction of travel. Pause between each move to allow the measurement of the pitch and yaw. This program also must provide for bi-directional travel so that measurements can be taken in both the +Y and -Y directions.

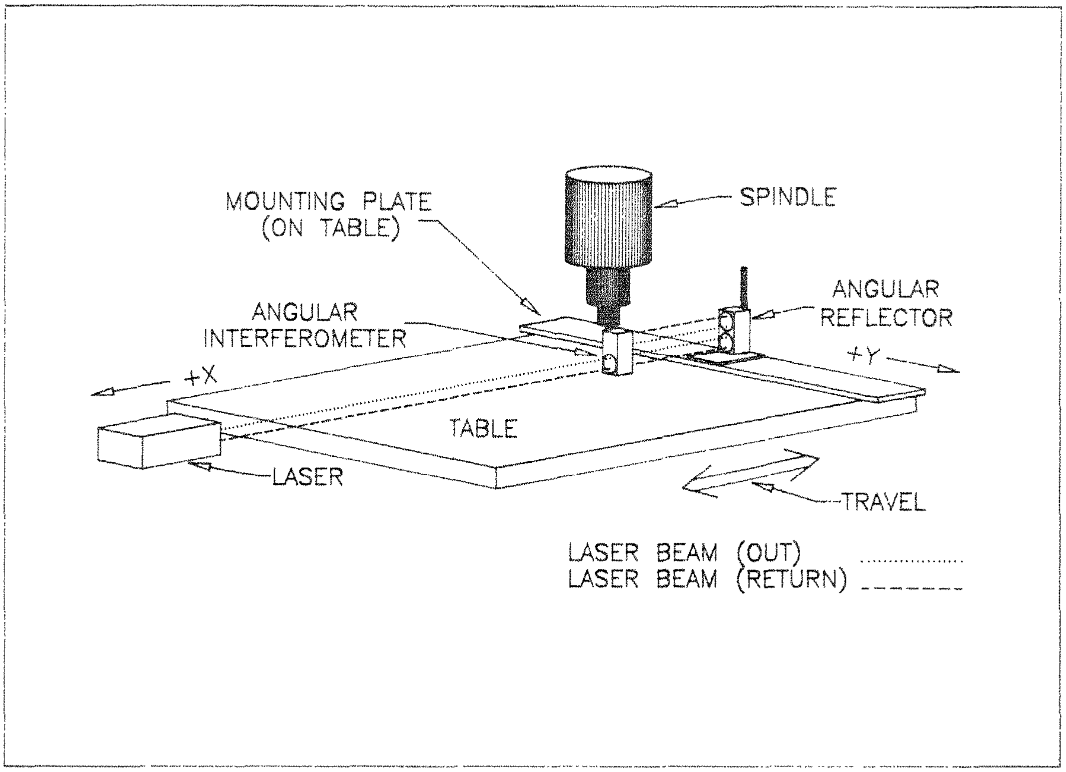


Figure 2.29—Laser setup for measuring pitch in the X-axis travel.

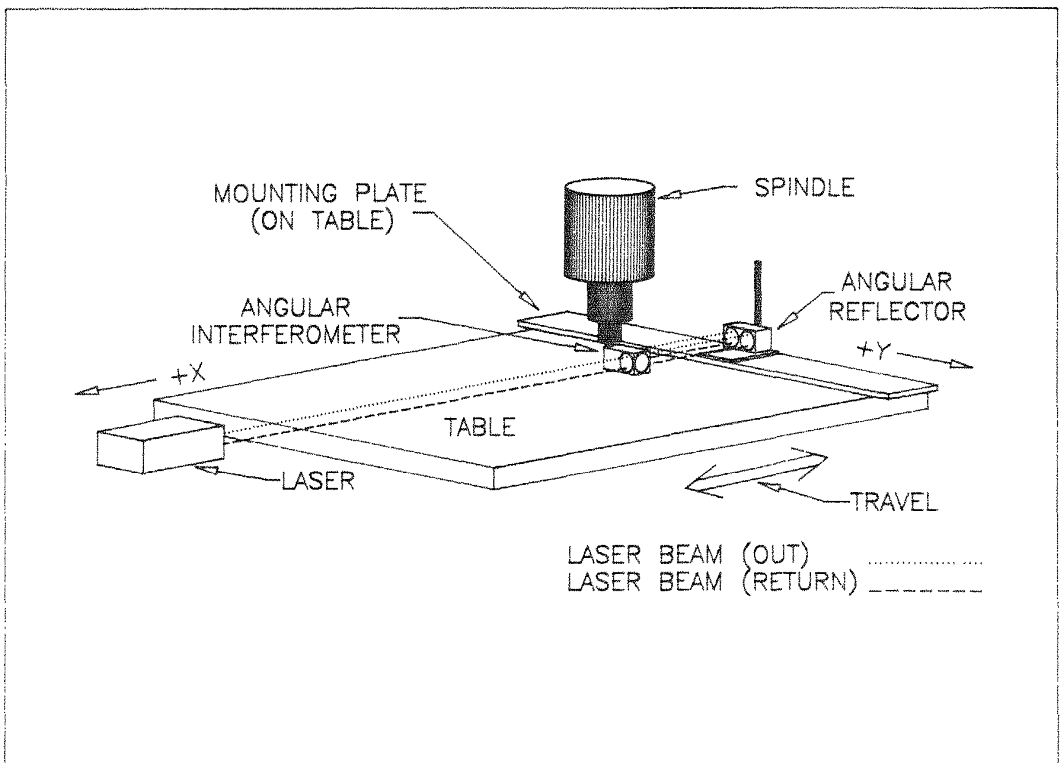


Figure 2.30—Laser setup for measuring yaw in the X-axis travel.

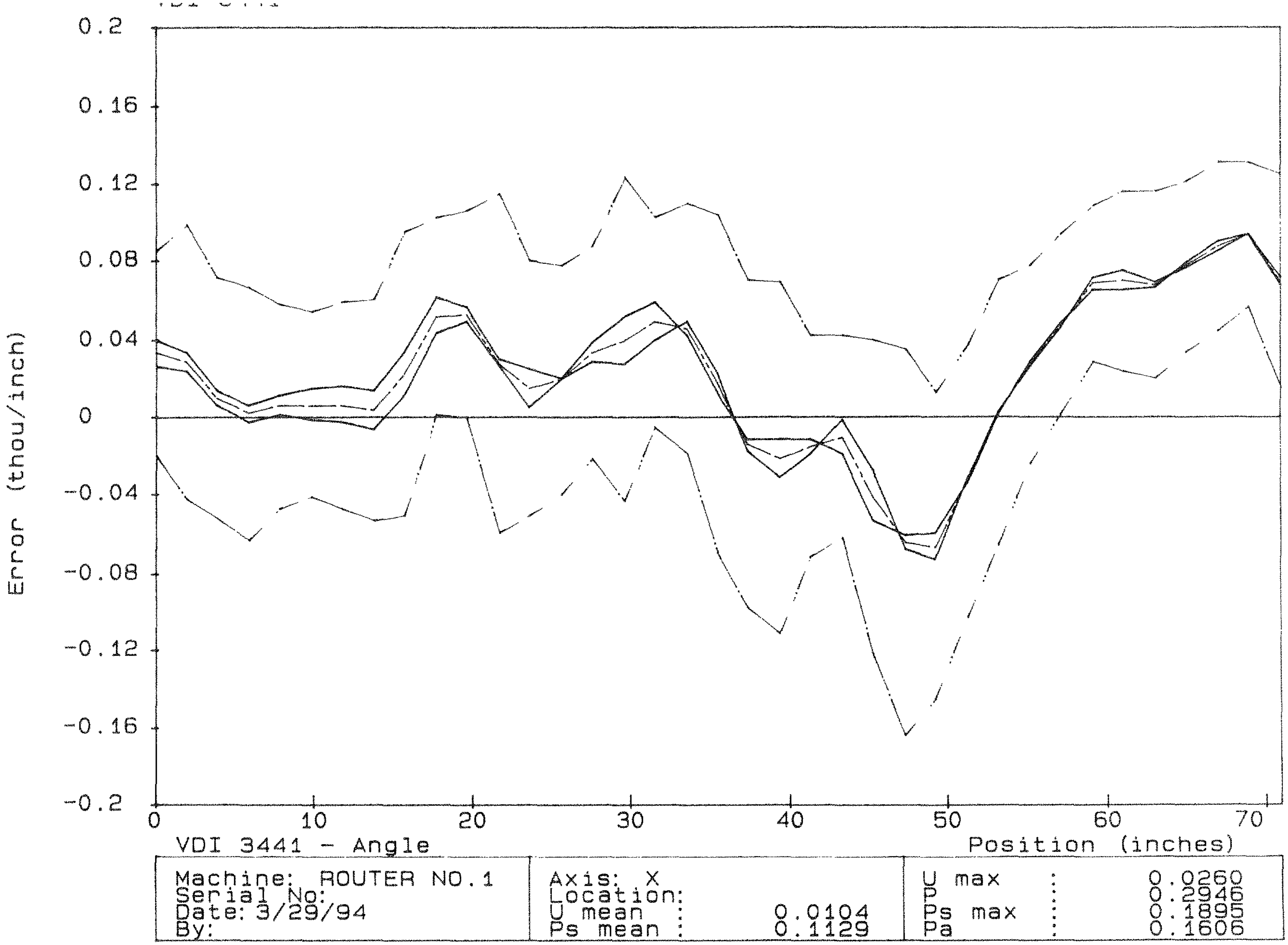


Figure 2.31—Results showing pitch in the X-axis travel.

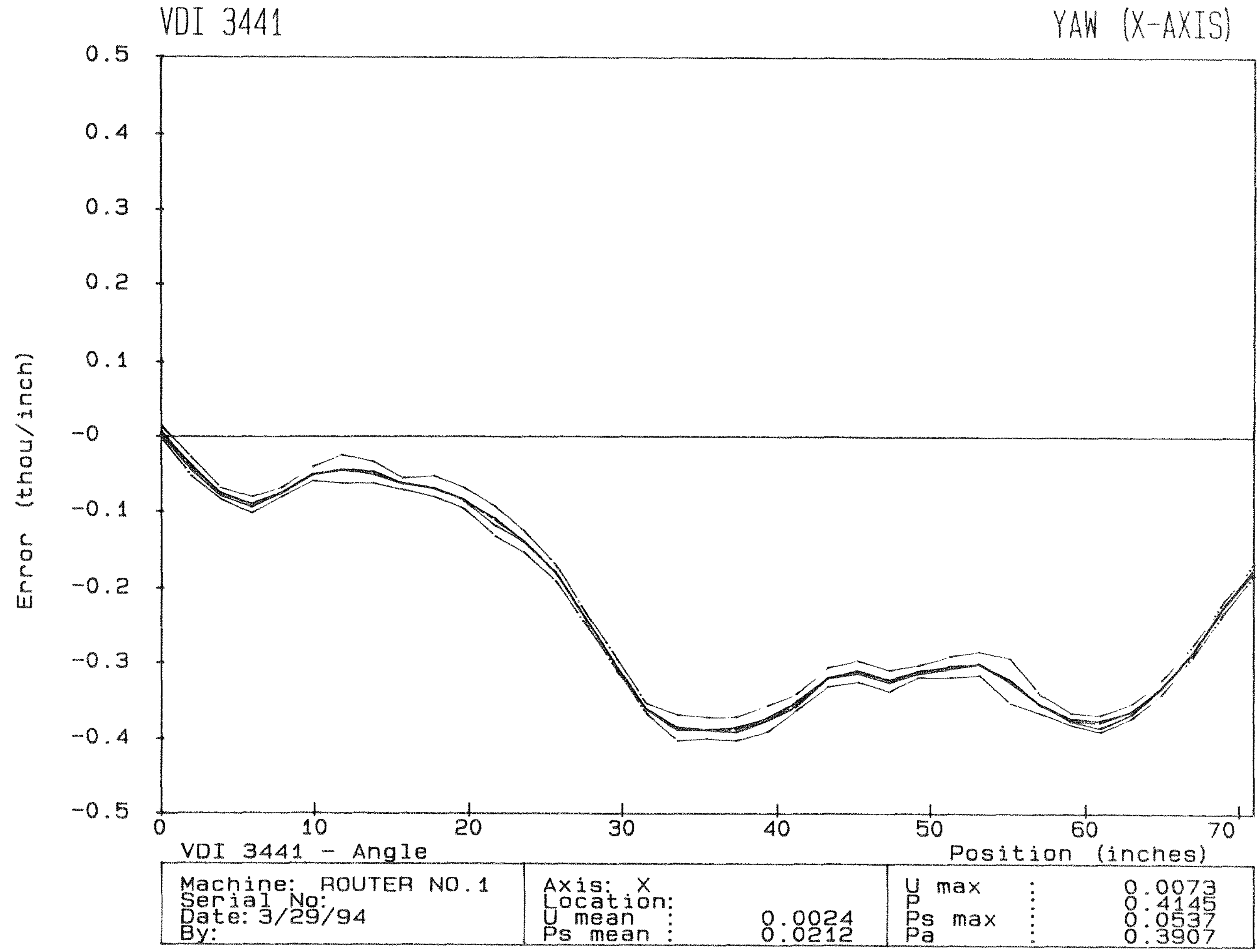


Figure 2.32—Results showing yaw in the X-axis travel.

After the measurement is recorded for the last point in a given direction, move the spindle/table ahead 1 inch. Then reverse the direction of travel 1 inch to the final point for the first measurement in the other direction. An example of this program and its subroutines, titled LINEAR POSITIONING IN Y-AXIS (STANDARD UNITS), is shown in Figure A.1.1 of Appendix A.1.

Step 2

Set up and align the laser for determining pitch as shown in Figure 2.33. If the table moves in the Y-axis, the laser is aligned down the middle of the table in the Y-axis. Be sure to follow the instructions in the laser user's manual concerning air turbulence, heaters, and air fans.

Step 3

Measure and record the pitch at the start point and at the end of each 2-inch move in both the +Y and the -Y directions. Repeat this procedure for five full forward and reverse cycles.

Step 4

Repeat Steps 2 and 3 with the laser set up for determining yaw as shown in Figure 2.34.

Results—Plot graphs of the pitch as shown in Figure 2.35. Plot graphs of the yaw as shown in Figure 2.36. Both graphs are to be based on the German VDI 3441 standard. The graphs show mean angular errors in both the positive and negative directions, the bi-directional mean angular error, and the maximum "±3 sigma" repeatability bands from either direction of travel. See section 2.1.1 "X-axis Positioning" for a discussion of the statistics presented at the bottom of the graphic.

2.4.3 Z-axis Pitch and Yaw

Purpose—This procedure determines pitch and yaw in the router table/spindle as it moves in the Z-axis. Router construction affects the movement, which may be a result of the table moving relative to the spindle or the spindle moving relative to the table. Basically, this reflects the straightness and alignment of the ways used to guide the table/spindle.

Recommended equipment:

- Class II helium-neon laser (interferometer) system with optics for measuring angular (pitch and yaw) deviations. The optics include an angular interferometer and angular reflector. Pitch and yaw measurements do not require environmental compensations for air temperature, barometric pressure, and relative humidity. And, it is not necessary to make adjustments for the thermal expansion of the scale material. The scale in this situation is the ball screw used to drive the router table or spindle in the axis to be measured. However, follow the recommendations of the laser manufacturer concerning air turbulence, heaters, and air fans. The laser system must be equivalent to the Renishaw Laser Interferometer System (ML10) by Renishaw Transducer Systems Limited or the HP5528A Laser Measurement System by Hewlett Packard.

- Microcomputer (PC) and software to record and plot the pitch and yaw information. Although the PC and software are not necessary, they greatly facilitate data collection and plotting for this procedure.

Method—Before beginning this evaluation, the servo motor and ball screw that control the movement in the Z-axis should be exercised through at least 20 full cycles. This reduces the error in positioning for data collection that can occur due to cold servo motors and ball screws. Once this is done, use the following steps.

Step 1

Develop a program for the controller that moves the table/spindle the full length of the Z-axis in 0.25-inch increments. However, provide at least 0.25 inch of extra travel past the two end targets to allow for changing the direction of travel. Pause between each move to allow the measurement of the pitch and yaw. This program also must provide for bi-directional travel so that measurements can be taken in both the +Z and -Z

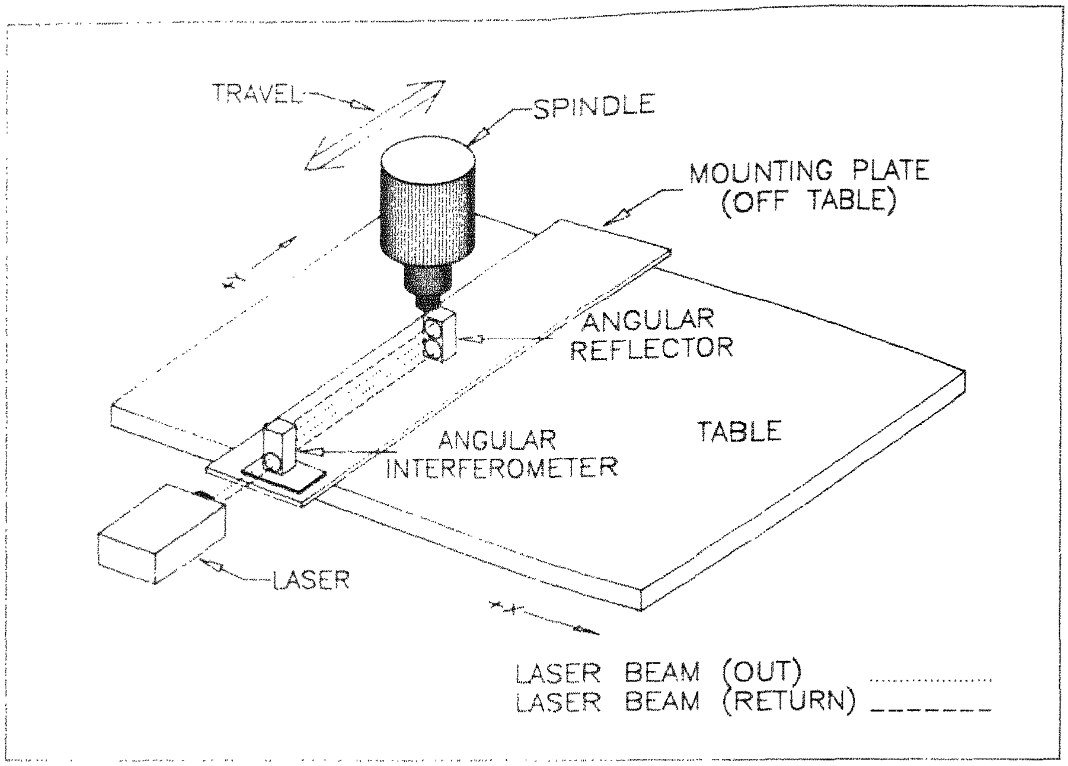


Figure 2.33—Laser setup for measuring pitch in the Y-axis travel.

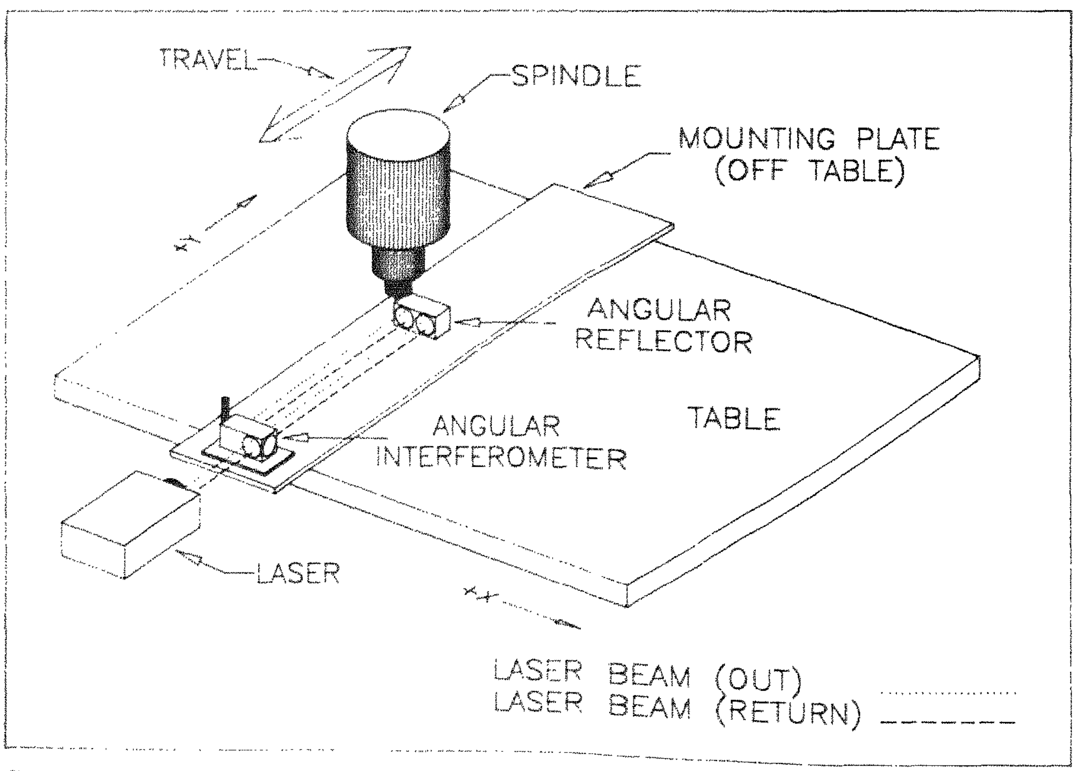


Figure 2.34—Laser setup for measuring yaw in the Y-axis travel.

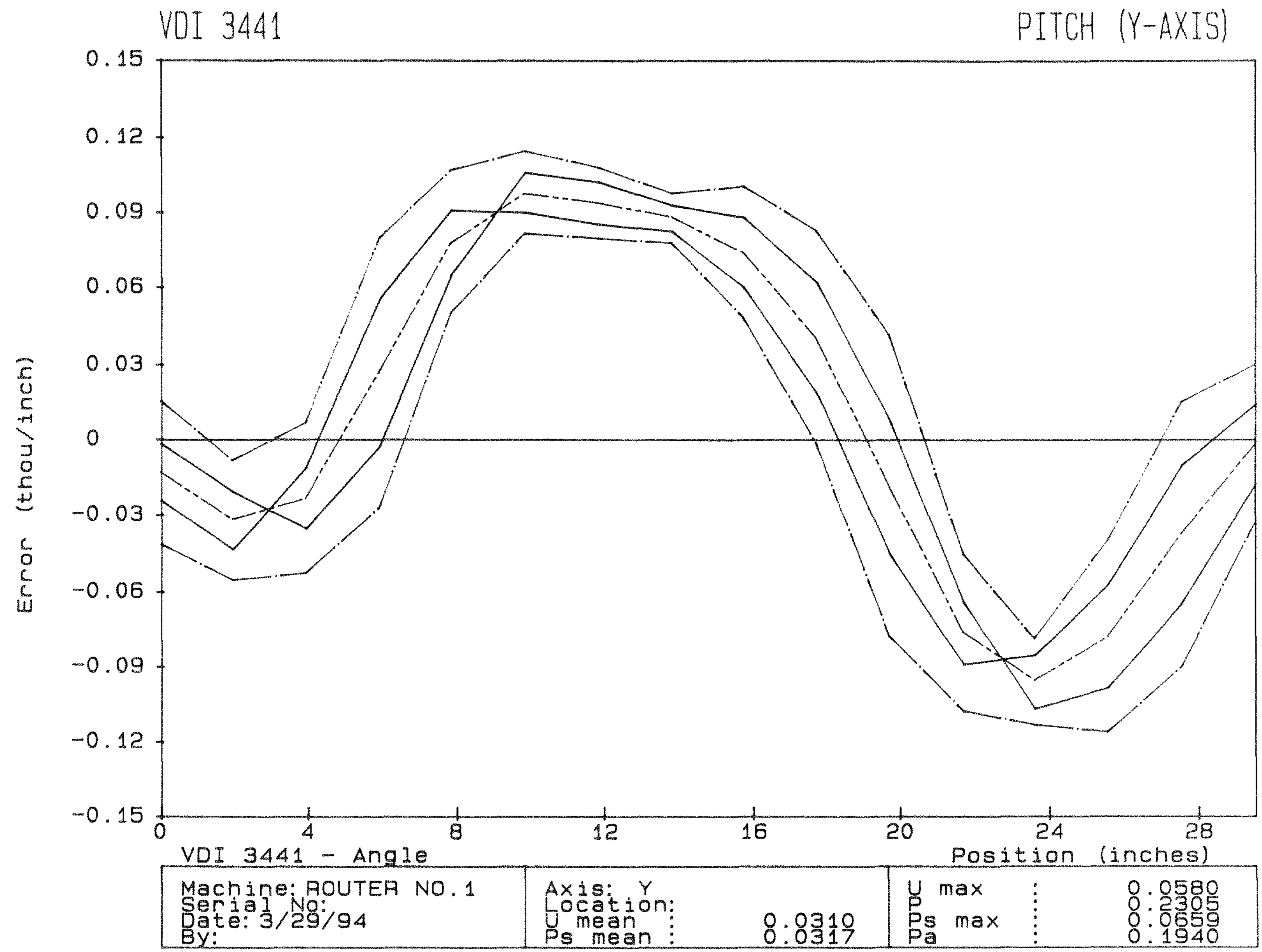
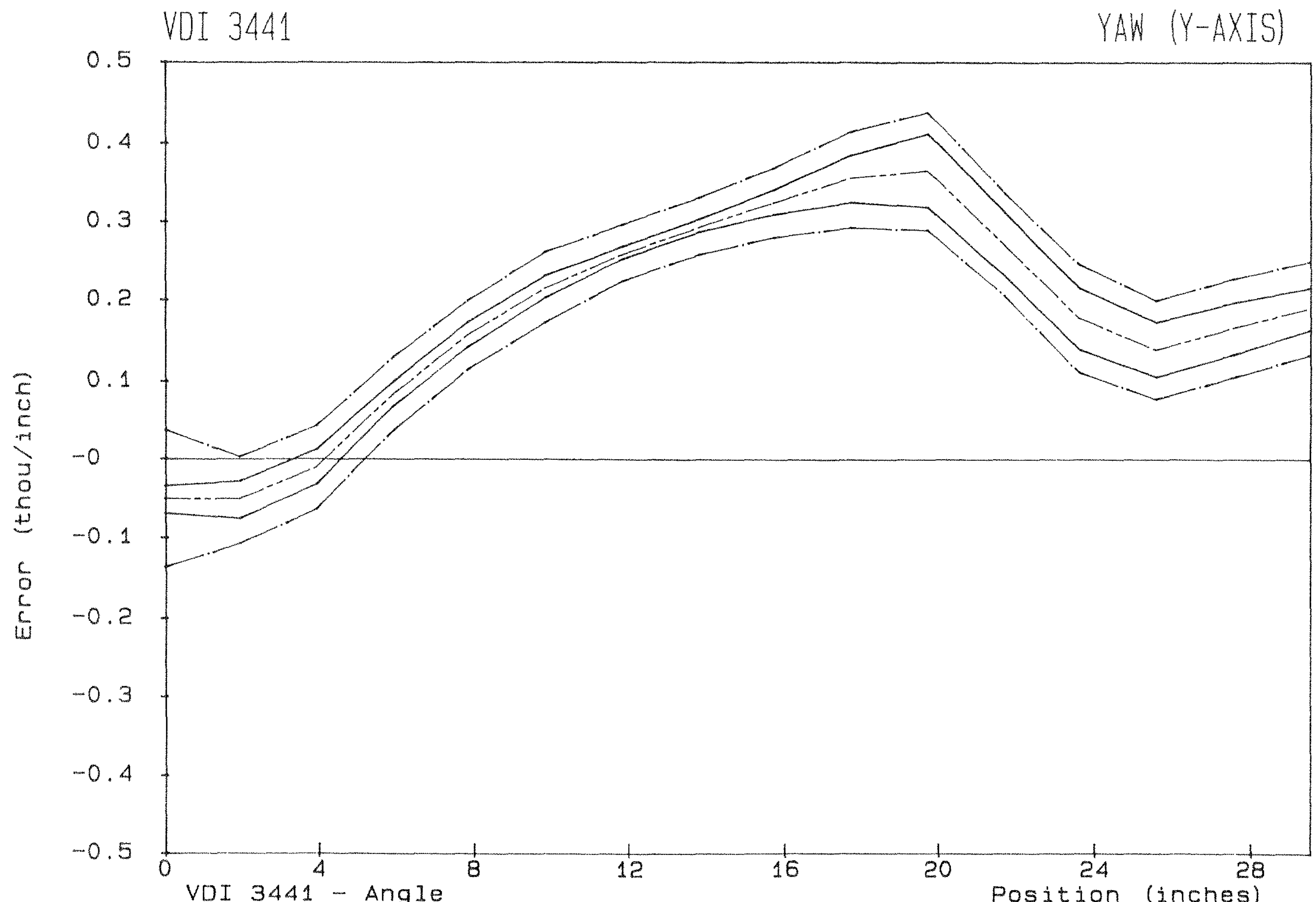


Figure 2.35—Results showing pitch in the Y-axis travel.



Machine: ROUTER NO.1	Axis: Y	U max : 0.0907
Serial No:	Location:	P : 0.5778
Date: 3/29/94	U mean : 0.0477	Ps max : 0.1388
By:	Ps mean : 0.0641	Pa : 0.4158

Figure 2.36—Results showing yaw in the Y-axis travel.

directions. After the measurement is recorded for the last point in a given direction, move the spindle/table ahead 0.25 inch. Then reverse the direction of travel 0.25 inch to the final point for the first measurement in the other direction. An example of this program and its subroutines, titled LINEAR POSITIONING IN Z-AXIS (STANDARD UNITS), is shown in Figure A.1.1 of Appendix A.1.

Step 2
Set up and align the laser for determining pitch as shown in Figure 2.37. If the table moves in the Z-axis, the laser is aligned down the middle of the table in the Z-axis. Be sure to follow the instructions in the laser user's manual concerning air turbulence, heaters, and air fans.

Step 3
Measure and record the pitch at the start point and at the end of each 1/4-inch move in both the +Z and the -Z directions. Repeat this procedure for five full forward and reverse cycles.

Step 4
Repeat Steps 2 and 3 with the laser set up for determining yaw as shown in Figure 2.38.

Results—Plot graphs of the pitch as shown in Figure 2.39. Plot graphs of the yaw as shown in Figure 2.40. Both plots are to be based on the German VDI 3441 standard. The graphs show mean angular errors in both the positive and negative directions, the bi-directional mean angular error, and the maximum "±3 sigma" repeatability bands from either direction of travel. See section 2.1.1 "X-axis Positioning" for a discussion of the data presented at the bottom of the graphics

2.5 Squareness

2.5.1 XY-Plan Squareness

Purpose—This procedure determines the ability of the router to make a right angle movement of the tool in the XY-plane. Router construction affects the movement, which may be a result of the table and/or the spindle moving. Basically, this reflects the straightness and perpendicular alignment of the ways used to guide the table and spindle during movement.

Recommended equipment:

- Class II helium-neon laser (interferometer) system with optics for measuring squareness. The optics include a straightness interferometer, straightness reflector, and optical square. It is not necessary to make environmental compensations for air temperature, barometric pressure, and relative humidity. However, follow the recommendations of the laser manufacturer concerning air turbulence, heaters, and air fans. The laser system must be equivalent to the Renishaw Laser Interferometer System (ML10) by Renishaw Transducer Systems Limited or the HP5528A Laser Measurement System by Hewlett Packard.

- Microcomputer (PC) and software to record and analyze the data. Although the PC and software are not necessary, they greatly facilitate collecting and analyzing the data for this procedure.

Method—Before beginning this evaluation, the servo motors and ball screws that control the movement in both the X-axis and the Y-axis should be exercised through at least 20 full cycles. This reduces the error in positioning for data collection that can occur due to cold servo motors and ball screws. Once this is done, use the following steps.

Step 1
Develop a program for the controller that moves the table/spindle the length of the X-axis in 2-inch increments. However, provide at least 1 inch of extra travel past the two end targets to allow for changing the direction of travel. Pause between each move to allow the measurement of the deviation in straightness of travel. This program also must provide for bi-directional travel so that measurements can be taken in both the +X

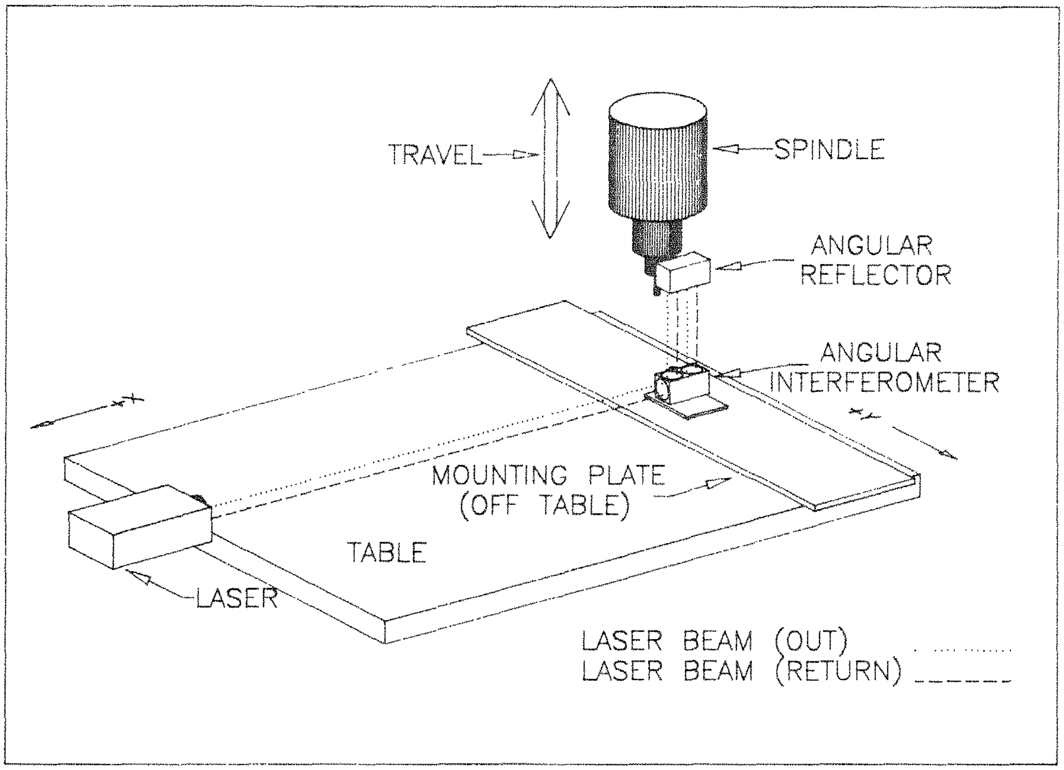


Figure 2.37—Laser setup for measuring pitch in the Z-axis travel.

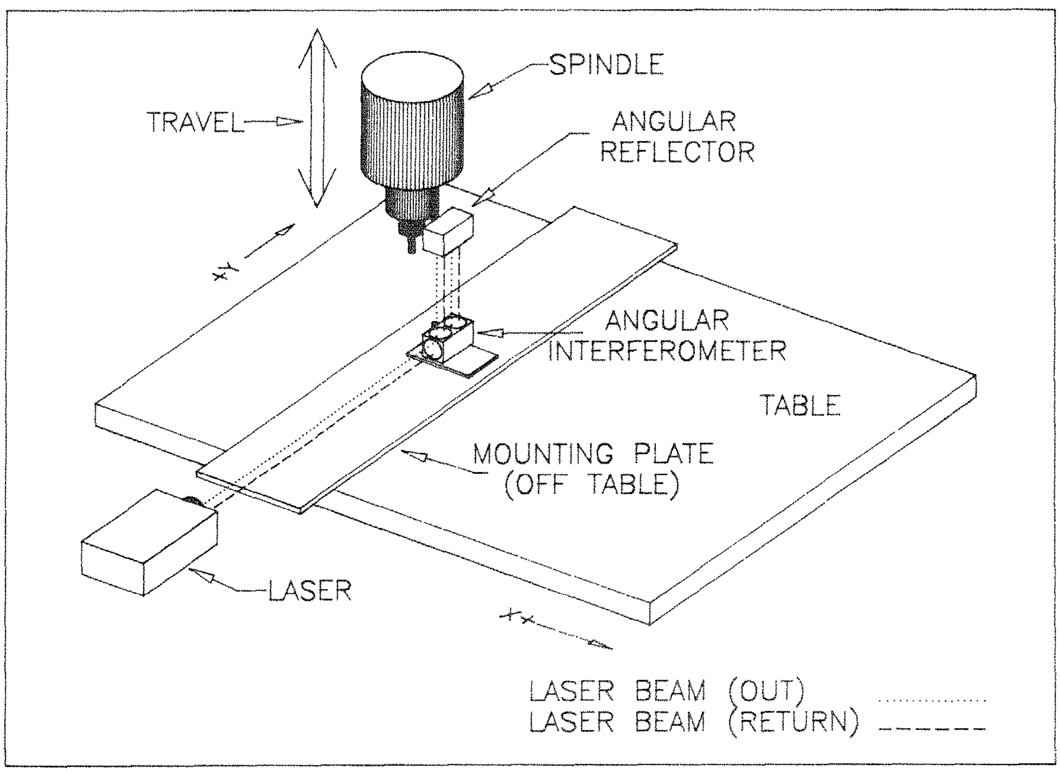
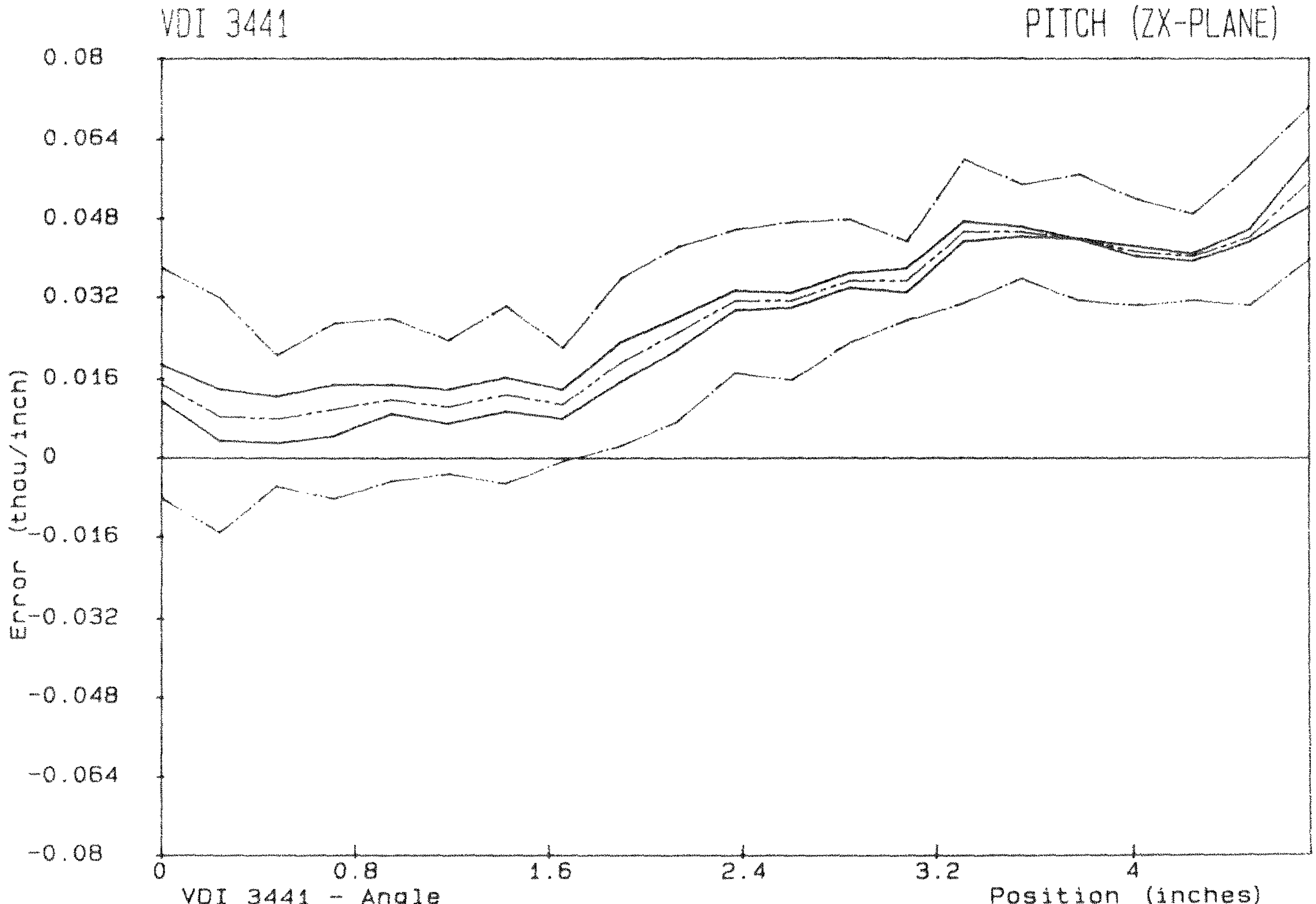


Figure 2.38—Laser setup for measuring yaw in the Z-axis travel.



Machine: ROUTER NO.1	Axis: Z	U max : 0.0102
Serial No:	Location:	P : 0.0858
Date: 3/29/94	U mean : 0.0054	Ps max : 0.0385
By:	Ps mean : 0.0238	Pa : 0.0478

Figure 2.39—Results showing pitch in the Z-axis travel.

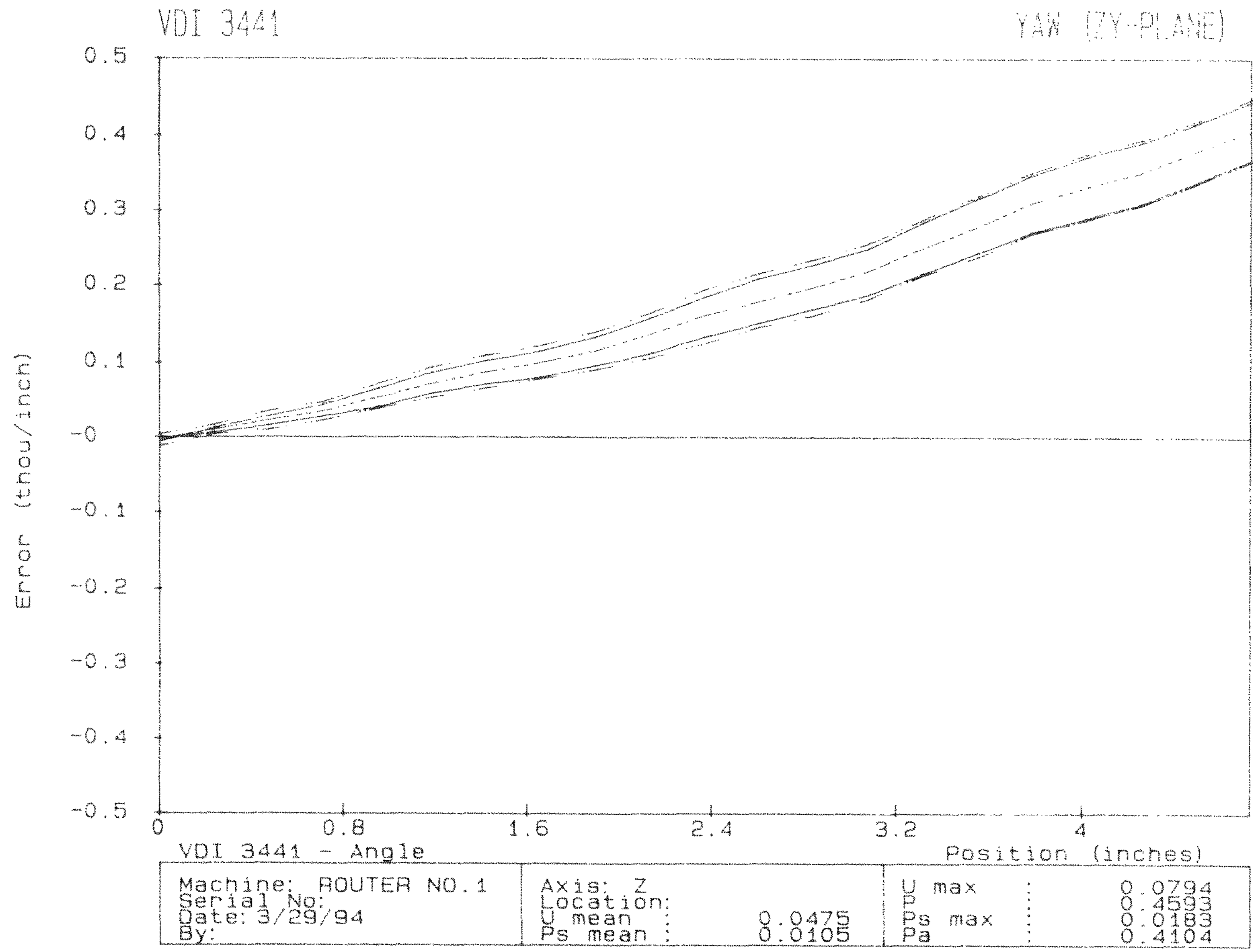


Figure 2.40—Results showing yaw in the Z-axis travel.

and -X directions. An example of this program and its subroutines, titled LINEAR POSITIONING IN X-AXIS (STANDARD UNITS), is shown in Figure A.1.1 of Appendix A.1.

Step 2

Develop a similar program for movement of the table/spindle in the Y-axis. An example of this program and its subroutines titled LINEAR POSITIONING IN Y-AXIS (STANDARD UNITS) is shown in Figure A.1.1 of Appendix A.1.

Step 3

Set up and align the laser for determining squareness of travel in the XY-plane as instructed by the user's manual for your laser. The setup used will depend on whether table and/or the spindle moves. Figure 2.41 shows the first setup for a router with a table that moves in the X-axis and a spindle that moves in the Y-axis. Be sure to follow the instructions in the laser user's manual concerning air turbulence, heaters, and air fans.

Step 4

Running the first program, measure and record the deviation in straightness of travel at the start point and at the end of each 2-inch move in both the +X and the -X directions of the X-axis. Repeat this procedure for five full forward and reverse cycles. After the measurement is recorded for the last point in a given direction, the spindle/table moves ahead 1 inch, and then the direction of travel reverses the 1 inch to the final point for the first measurement in the other direction.

Step 5

Without moving the straightness reflector, make the laser optics setup shown in Figure 2.42. When this is done, run the second program and measure the straightness of travel at the starting point and at the end of each 2-inch move in both the +Y and the -Y directions of the Y-axis. Repeat this procedure for five full forward and reverse cycles.

Results—Plot graphs showing the least squares fit of lines through the measured straightness errors for both the X-axis and the Y-axis. Also, provide a statement of squareness error in arc-seconds and thou/inch between the two lines. Figure 2.43 shows an example of this squareness information. The two graphs in this figure show the least-squares fit for the bi-directional straightness evaluation of the two axes. See section 2.3.1 "X-axis Straightness (Horizontal & Vertical Plane)" for a discussion of the data presented at the bottom of each graph. The bottom of the figure shows the slope of the two axes and the calculation of the squareness error. If the squareness error is positive, the angle between the two axes is greater than 90°.

2.5.2 XZ-Plane Squareness

Purpose—This procedure determines the ability of the router to make a right angle movement of the tool in the XZ-plane. Router construction affects the movement, which may be a result of the table and/or the spindle moving. Basically, this reflects the straightness and perpendicular alignment of the ways used to guide the table and spindle during movement.

Recommended equipment:

- Class II helium-neon laser (interferometer) system with optics for measuring squareness. The optics include a straightness interferometer, straightness reflector, vertical turning mirror, optical square, and retroreflector. It is not necessary to make environmental compensations for air temperature, barometric pressure, and relative humidity. However, follow the recommendations of the laser manufacturer concerning air turbulence, heaters, and air fans. The laser system must be equivalent to the Renishaw Laser Interferometer System (ML10) by Renishaw Transducer Systems Limited or the HP5528A Laser Measurement System by Hewlett Packard.

- Microcomputer (PC) and software to record and analyze the data. Although the PC and software are not necessary, they greatly facilitate collecting and analyzing the data for this procedure.

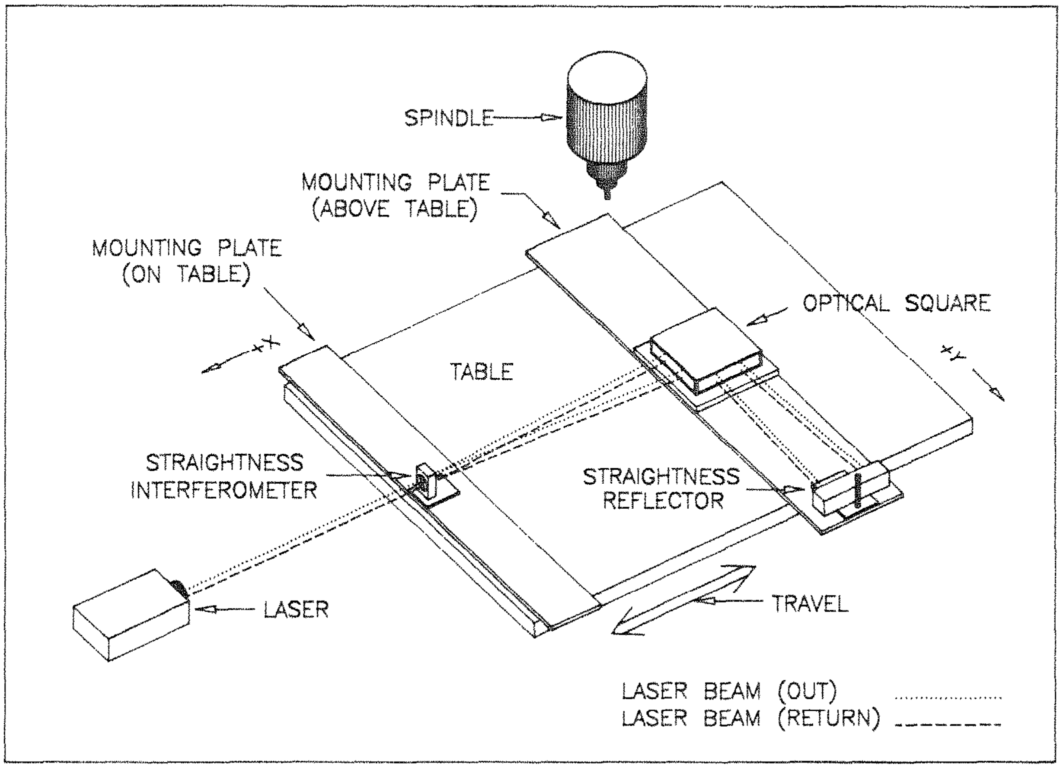


Figure 2.41—First laser setup for measuring squareness of travel in the XY-plan.

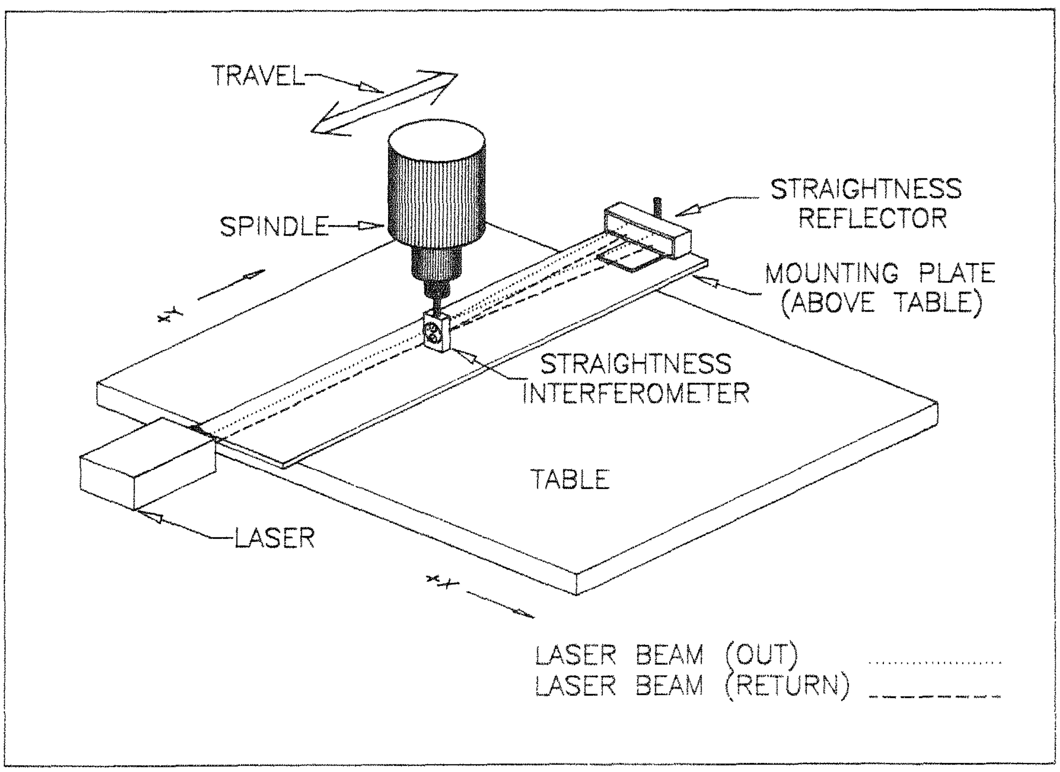
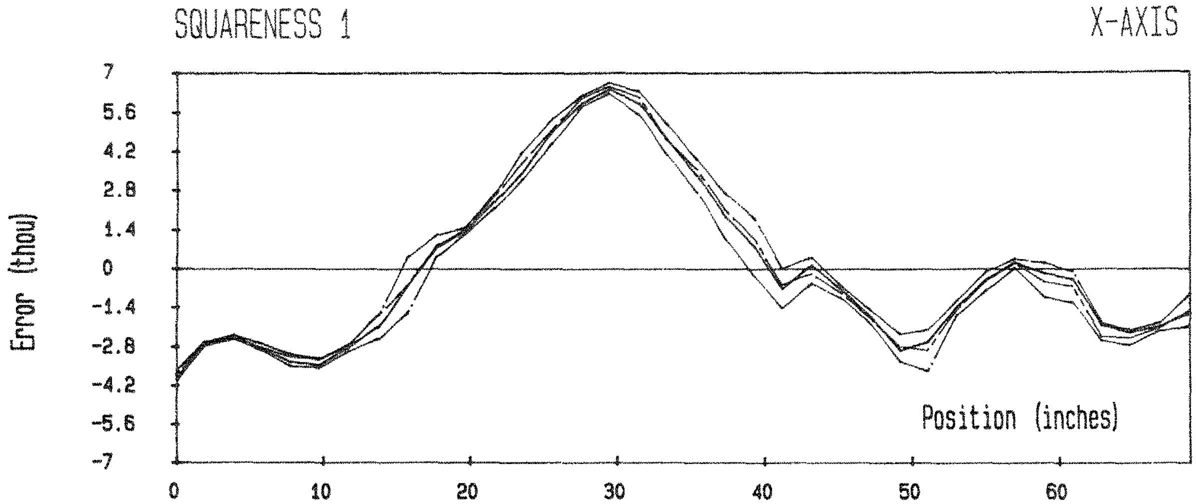
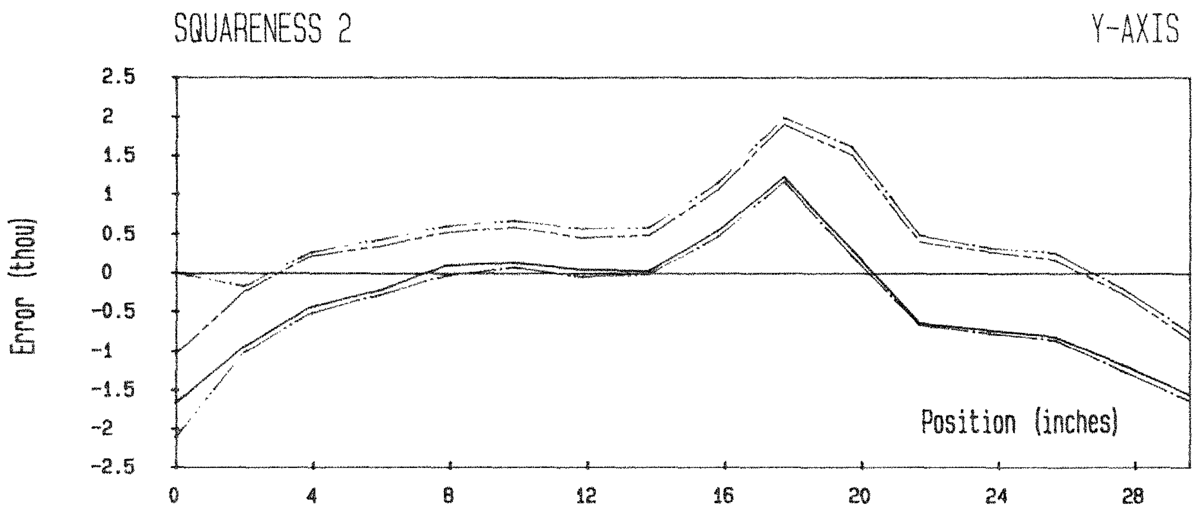


Figure 2.42—Second laser setup for measuring squareness of travel in the XY-plane.



Machine: ROUTER NO.1	Axis: X	Accuracy: 10.7266
Serial No:	Location:	Uni-dir. Rep: 2.0733
Date: 3/29/94	Slope: -8.86 ARCSEC	Bi-dir. Rep: 2.0733
By:	Str. Error : 10.4831	Mean rev: 0.0358



Machine: ROUTER NO.1	Axis: Y	Accuracy: 4.0750
Serial No:	Location:	Uni-dir. Rep: 2.1120
Date: 3/28/93	Slope: -285.12	Bi-dir. Rep: 2.1120
By:	Str. Error : 3.5770	Mean rev: 0.7156

Graph 1: NEWSQUX.STX Slope: -8.86 ARC-SECONDS
Graph 2: NEWSQUY.STY Slope: -285.12 ARC-SECONDS
(Prism error-(-285.12-8.86)) = 292.68 ARC-SECONDS
Squareness error: 292.68 ARC-SECONDS 1.41895 thou/inch

Figure 2.43—Results showing squareness of travel in the XY-plane.

Method—Before beginning this evaluation, the servo motor and ball screw that control the movement in the Z-axis should be exercised through at least 20 full cycles. This reduces the error in positioning for data collection that can occur due to cold servo motors and ball screws. Once this is done, use the following steps.

Step 1

Develop a program for the controller that moves the table/spindle the length of the Z-axis in 0.25-inch increments. However, provide at least 0.25 inch of extra travel past the two end targets to allow for changing the direction of travel. Pause between each move to allow the measurement of the deviation in straightness of travel. This program also must provide for bi-directional travel so that measurements can be taken in both the +Z and -Z directions. An example of this program and its subroutines titled LINEAR POSITIONING IN Z-AXIS (STANDARD UNITS), is shown in Figure A.1.1 of Appendix A.1.

Step 2

Next, develop a similar program for movement of the table/spindle in the X-axis. An example of this program and its subroutines titled LINEAR POSITIONING IN X-AXIS (STANDARD UNITS) is shown in Figure A.1.1 of Appendix A.1.

Step 3

Set up and align the laser for determining squareness of travel in the XZ-plane as instructed by the user's manual for your laser. The setup used will depend on whether table and/or the spindle moves. Figure 2.44 shows the first setup for a router with a table that moves in the X-axis and a spindle that moves in the Z-axis. Be sure to follow the instructions in the laser user's manual concerning air turbulence, heaters, and air fans.

Step 4

Running the first program, measure and record the deviation in straightness of travel at the start point and at the end of each 0.25-inch move in both the +Z and the -Z directions of the Z-axis. Repeat this procedure for five full forward and reverse cycles. After the measurement is recorded for the last point in a given direction, the spindle/table moves ahead 0.25 inch and then the direction of travel reverses the 0.25 inch to the final point for the first measurement in the other direction.

Step 5

Without moving the straightness reflector, make the laser optics setup shown in Figure 2.45. Once this is done, run the second program and measure the straightness of travel at the starting point and at the end of each 2-inch move in both the +X and the -X directions of the X-axis. Repeat this procedure for five full forward and reverse cycles.

Results—Plot graphs showing the least-squares fit of lines through the measured straightness errors for both the X-axis and the Z-axis. Also provide a statement of squareness error in arc-seconds and thou/inch between the two lines. Figure 2.46 shows an example of this squareness information. The two graphs in this figure show the least-squares fit for the bi-directional straightness evaluation of the two axes. See section 2.3.1 "X-axis Straightness (Horizontal & Vertical Plane)" for a discussion of the data presented at the bottom of each graph. The bottom of the figure shows the slope of the two axes and the calculation of the squareness error. If the squareness error is positive, the angle between the two axes is greater than 90°.

2.5.3 YZ-Plane Squareness

Purpose—This procedure determines the ability of the router to make a right angle movement of the tool in the YZ-plane. Router construction affects the movement, which may be a result of the table and/or the spindle moving. Basically, this reflects the straightness and alignment of the ways used to guide the table and spindle during movement.

Recommended equipment:

- Class II helium-neon laser (interferometer) system with optics for measuring squareness. The optics include a straightness interferometer, straightness reflector,

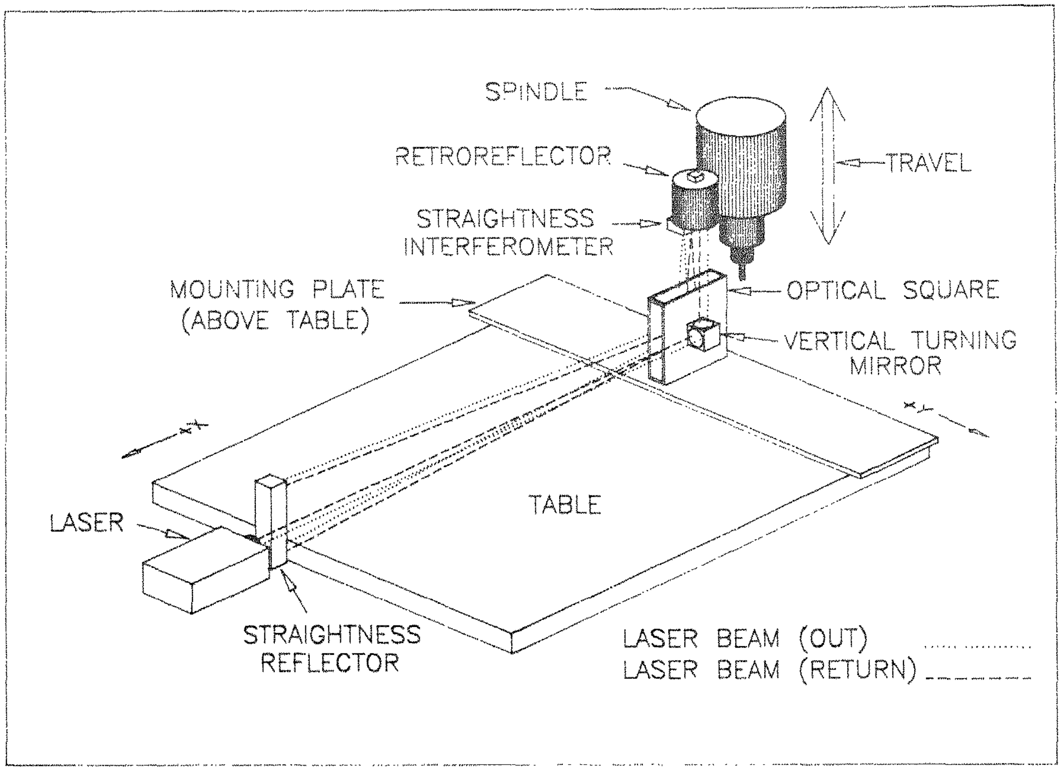


Figure 2.44—First laser setup for measuring squareness of travel in the XZ-plane.

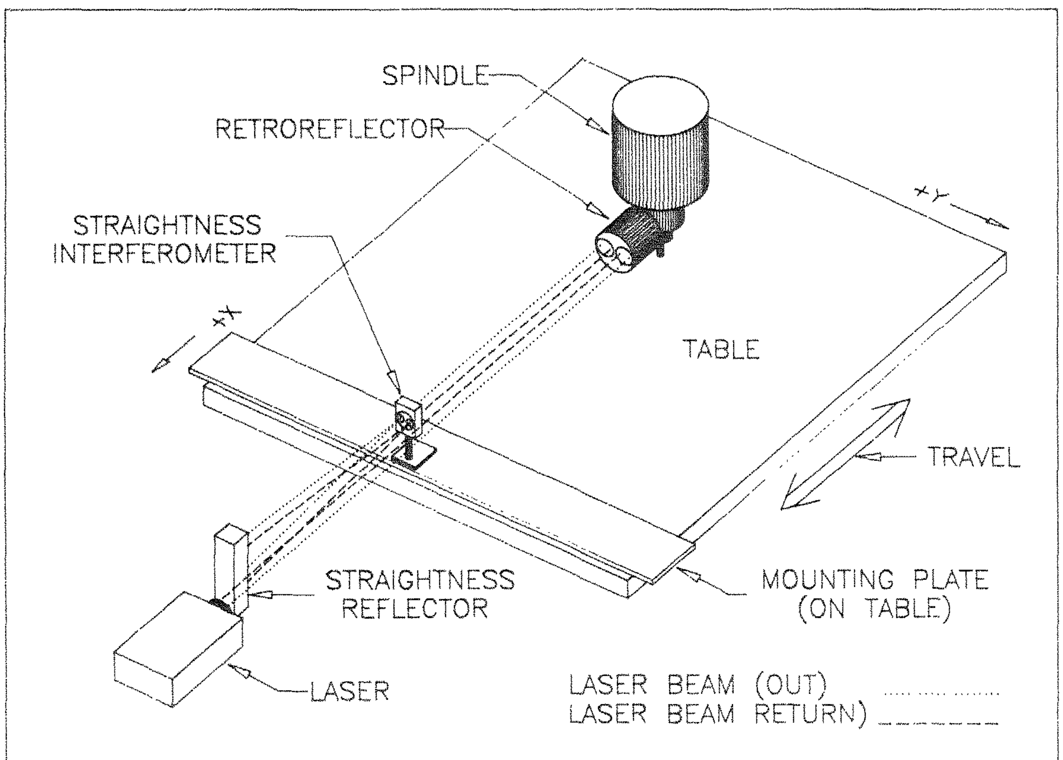
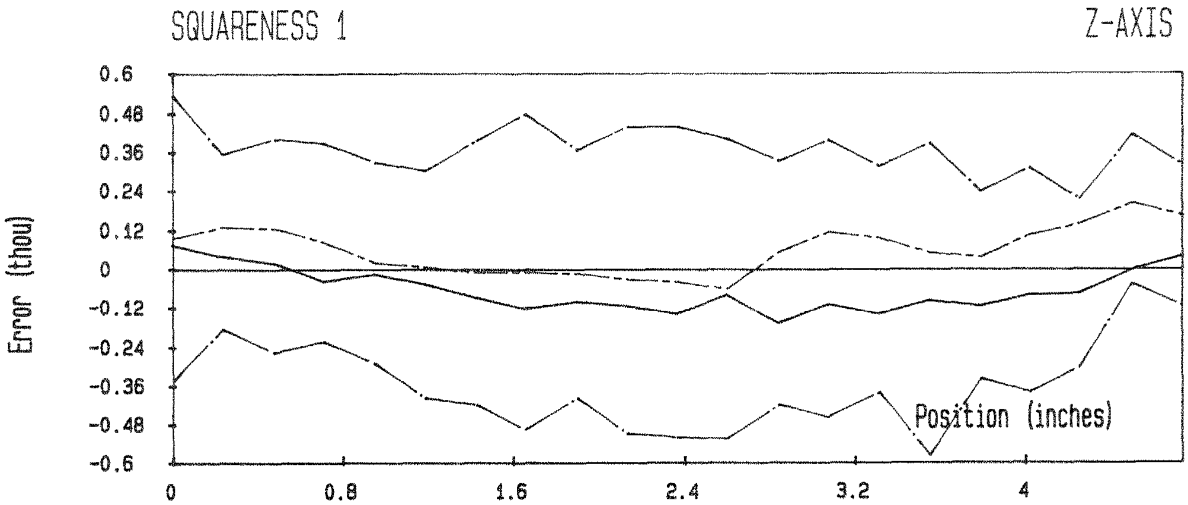
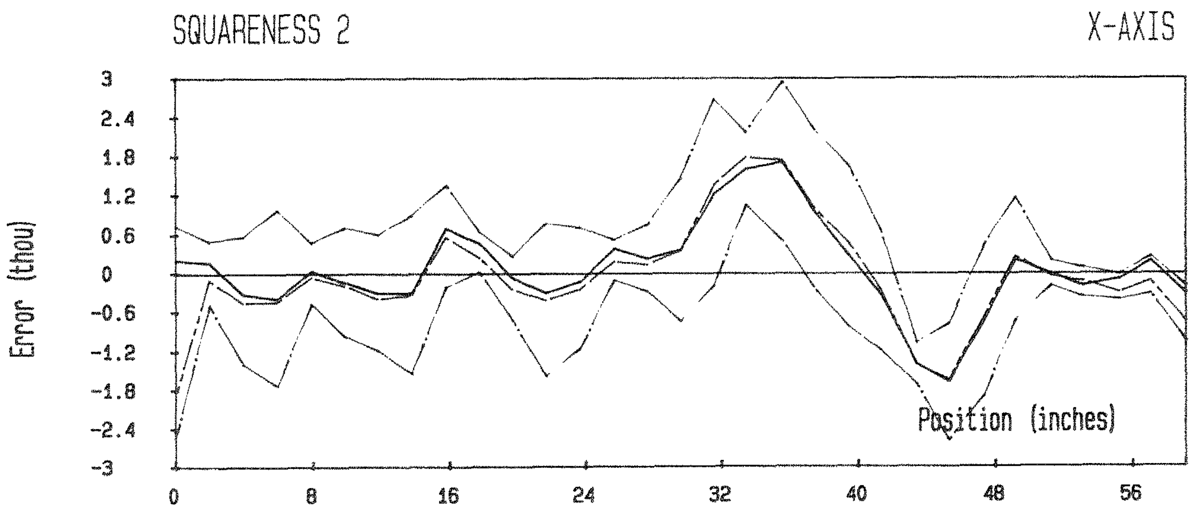


Figure 2.45—Second laser setup for measuring squareness of travel in the XZ-plane.



Machine: ROUTER NO.1	Axis: Z	Accuracy: 1.1055
Serial No:	Location:	Uni-dir. Rep: 0.9696
Date: 3/29/94	Slope: -23.94 ARCSEC	Bi-dir. Rep: 0.9696
By:	Str. Error : 0.3698	Mean rev: 0.1222



Machine: ROUTER NO.1	Axis: X	Accuracy: 5.5322
Serial No:	Location:	Uni-dir. Rep: 2.8316
Date: 3/28/93	Slope: 290.50	Bi-dir. Rep: 3.2650
By:	Str. Error : 3.6675	Mean rev: -0.1389

Graph 1: NEWSQZXZ.STZ Slope: -23.94 ARC-SECONDS
Graph 2: NEWSQZXX.STX Slope: 290.50 ARC-SECONDS
(Prism error-(290.50-23.94)) = -267.86 ARC-SECONDS
Squareness error: -267.86 ARC-SECONDS -1.29864 thou/inch

Figure 2.46—Results showing squareness of travel in the XZ-plane.

vertical turning mirror, optical square, and retroreflector. It is not necessary to make environmental compensations for air temperature, barometric pressure, and relative humidity. However, follow the recommendations of the laser manufacturer concerning air turbulence, heaters, and air fans. The laser system must be equivalent to the Renishaw Laser Interferometer System (ML10) by Renishaw Transducer Systems Limited or the HP5528A Laser Measurement System by Hewlett Packard.

- Microcomputer (PC) and software to record and analyze the data. Although the PC and software are not necessary, they greatly facilitate collecting and analyzing the data for this procedure.

Method—Before beginning this evaluation, the servo motors and ball screws that control the movement in the X-axis and the Z-axis should be exercised through at least 20 full cycles. This reduces the error in positioning for data collection that can occur due to cold servo motors and ball screws. Once this is done, use the following steps.

Step 1
Develop a program for the controller that moves the table/spindle the length of the Z-axis in 0.25-inch increments. However, provide at least 0.25 inch of extra travel past the two end targets to allow for changing the direction of travel. Pause between each move to allow the measurement of the deviation in straightness of travel. This program also must provide for bi-directional travel so that measurements can be taken in both the +Z and -Z directions. An example of this program and its subroutines titled LINEAR POSITIONING IN Z-AXIS (STANDARD UNITS), is shown in Figure A.1.1 of Appendix A.1.

Step 2
Develop a similar program for movement of the table/spindle in the Y-axis. An example of this program and its subroutines titled LINEAR POSITIONING IN Y-AXIS (STANDARD UNITS) is shown in Figure A.1.1 of Appendix A.1.

Step 3
Set up and align the laser for determining squareness of travel in the YZ-plane as instructed by the user's manual for your laser. The setup used will depend on whether table and/or the spindle moves. Figure 2.47 shows the first setup for a router with a spindle that moves in both the Y-axis and the Z-axis. Be sure to follow the instructions in the laser user's manual concerning air turbulence, heaters, and air fans.

Step 4
Running the first program, measure and record the deviation in straightness of travel at the start point and at the end of each 0.25-inch move in both the +Z and the -Z directions of the Z-axis. Repeat this procedure for five full forward and reverse cycles. After the measurement is recorded for the last point in a given direction, the spindle/table moves ahead 0.25 inch and then the direction of travel reverses the 0.25 inch to the final point for the first measurement in the other direction.

Step 5
Without moving the straightness reflector, make the laser optics setup shown in Figure 2.48. Once this is done, run the second program and measure the straightness of travel at the starting point and at the end of each 2-inch move in both the +Y and the -Y directions of the Y-axis. Repeat this procedure for five full forward and reverse cycles.

Results—Plot graphs showing the least-squares fit of lines through the measured straightness errors for both the Y-axis and the Z-axis. Also provide a statement of squareness error in arc-seconds and thou/inch between the two lines. Figure 2.49 shows an example of this squareness information. The two graphs in this figure show the least-squares fit for the bi-directional straightness evaluation of the two axes. See section 2.3.1 "X-axis Straightness (Horizontal & Vertical Plane)" for a discussion of the data presented at the bottom of each graph. The bottom of the figure shows the slope of the two axes and the calculation of the squareness error. If the squareness error is positive, the angle between the two axes is greater than 90°.

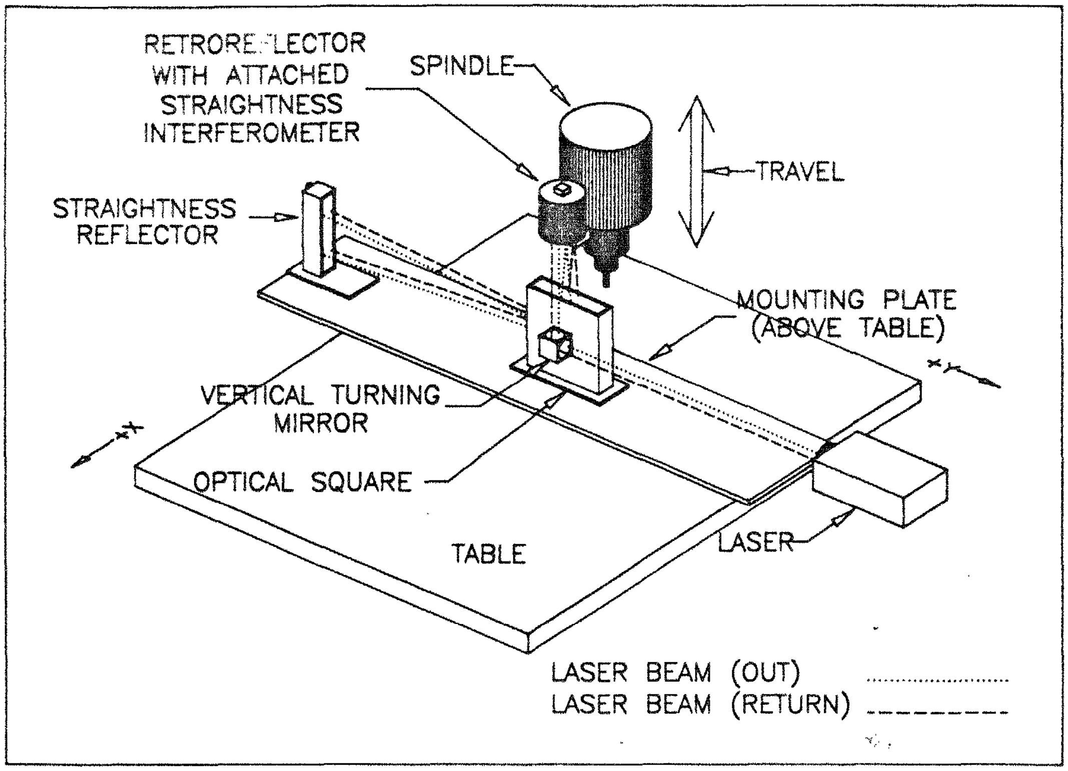


Figure 2.47—First laser setup for measuring squareness of travel in the YZ-plane.

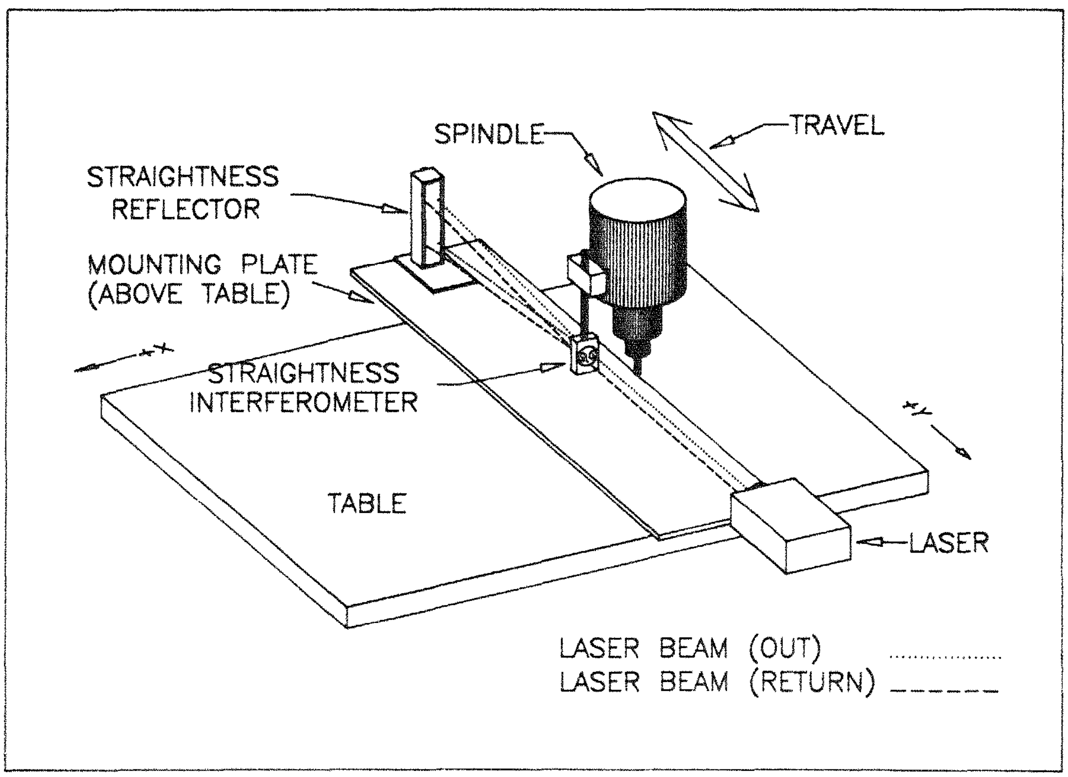
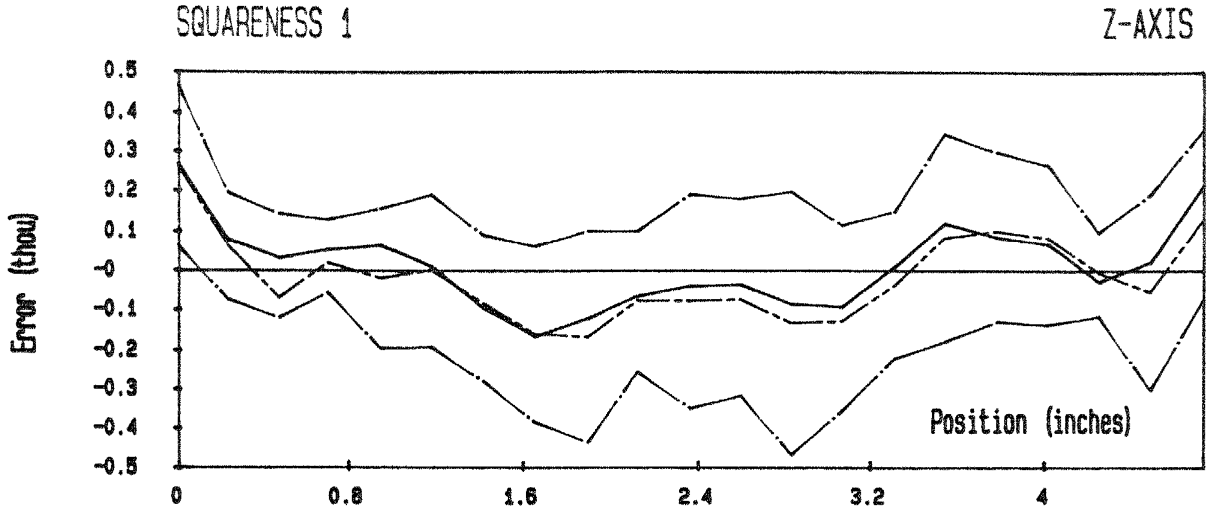
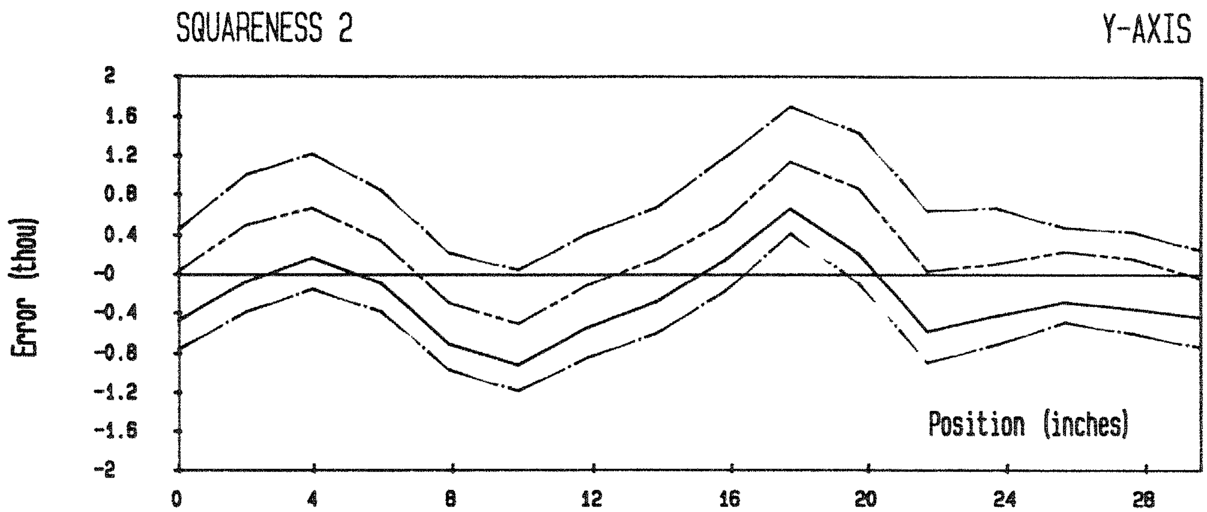


Figure 2.48—Second laser setup for measuring squareness of travel in the YZ-plane.



Machine: ROUTER NO.1	Axis: Y	Accuracy: 0.9308
Serial No:	Location:	Uni-dir. Rep: 0.6644
Date: 3/29/94	Slope: 24.03 ARCSEC	Bi-dir. Rep: 0.6644
By:	Str. Error : 0.4344	Mean rev: -0.0287



Machine: ROUTER NO.1	Axis: Y	Accuracy: 2.8872
Serial No:	Location:	Uni-dir. Rep: 1.3098
Date: 3/28/93	Slope: -385.96	Bi-dir. Rep: 1.5387
By:	Str. Error : 2.0606	Mean rev: 0.4946

Graph 1: NEWSQZYZ.STZ Slope: 24.03 ARC-SECONDS
Graph 2: NEWSQZYY.STY Slope: -385.96 ARC-SECONDS
(Prism error-(-385.96+24.03)) = 360.63 ARC-SECONDS
Squareness error: 360.63 ARC-SECONDS 1.74837 thou/inch

Figure 2.49—Results showing squareness of travel in the YZ-plane.