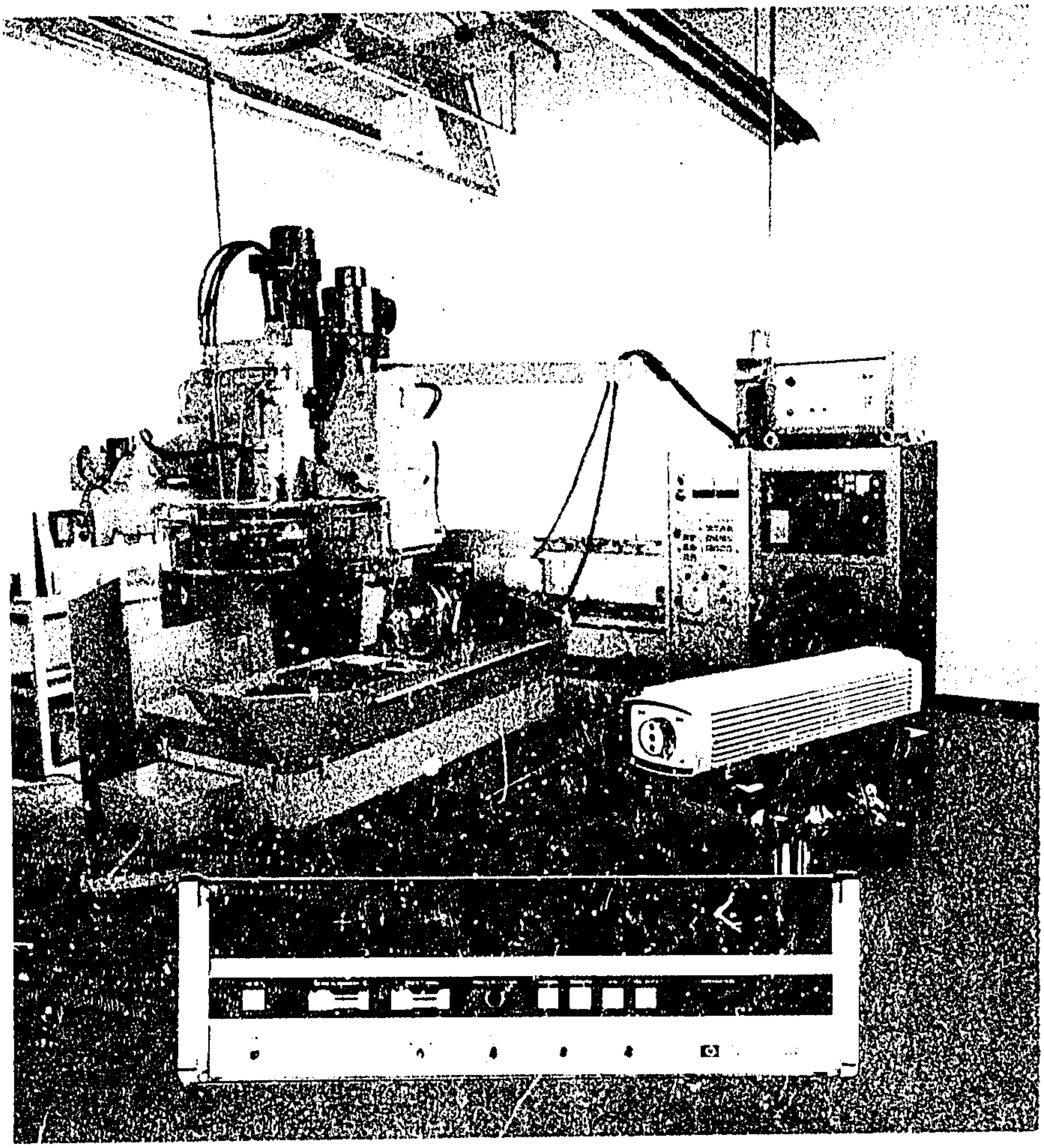
HEWLETT PACKARD

LASER MEASUREMENT SYSTEM

5526A

User's Guide



USER'S GUIDE

5526A
LASER MEASUREMENT SYSTEM

Manual Part No. 05526-90066
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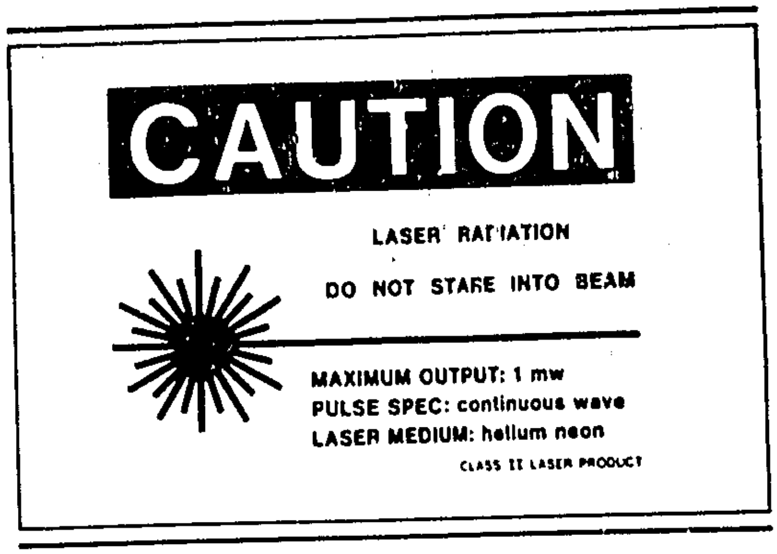
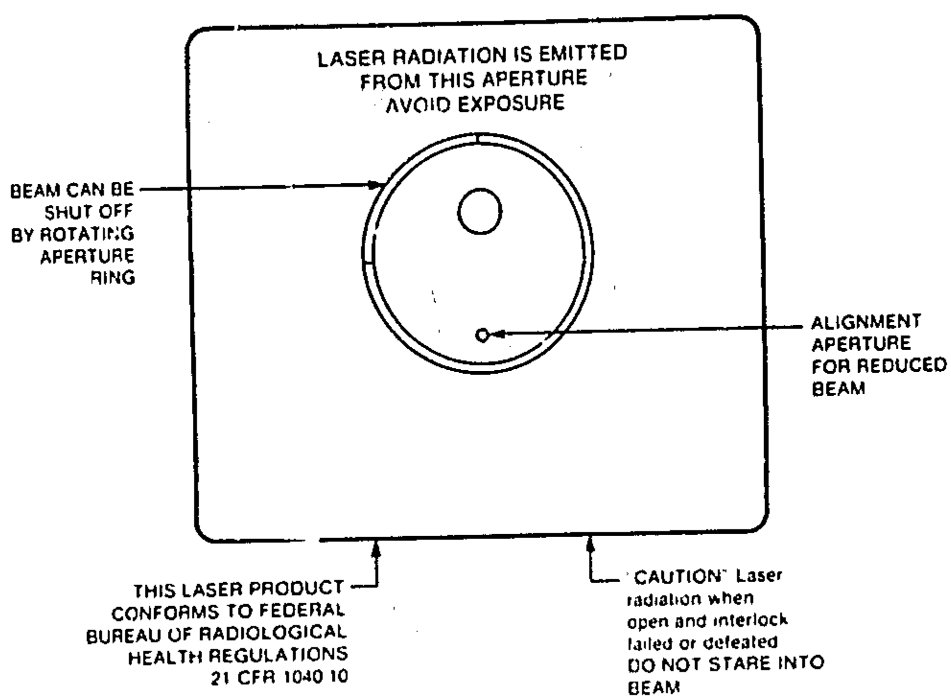
HEWLETT PACKARD

SAFETY PRECAUTIONS

This is a Safety Class I system. This system has been designed and tested according to IEC Publication 348, "Safety Requirements for Electronic Measuring Apparatus". This product is also a Class II Laser Product conforming to Federal Bureau of Radiological Health Regulations 21 CFR 1040.10.





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INTRODUCTION

The objectives of this training manual are to give the reader a:

1) Thorough understanding of how to operate the 5526A system.

   - o How to set up for a good measurement
   - o Correct fixturing of the optics
   - o Accurate alignments
   - o Correct terminology

2) Basic understanding of how the 5526A system works.

   - o Laser interferometry
   - o Laser display functions and features
   - o How the optics measure displacement

3) Basic understanding of how to analytically characterize machine geometry.

   - o The five basic measurements linear, angular, straightness, squareness, parallelism
   - o Measurement accuracy and precision considerations

The presentation of this material is basic to enable the majority of operators to begin geometric calibrations of a machine structure. This large body of measurement knowledge is not commonly known or well understood. To most readers - even experienced machine tool repairmen, the terms, concepts, definitions and procedures are new. The measurement knowledge presented is well established basic machine movement metrology.

SECTION I

SECTION I

DIMENSIONAL METROLOGY (Calibration of a Machine)

THE MEASUREMENT TRIANGLE

A machine calibration is more complex than checking positioning accuracy and precision. How accurate and precise the work a machine can be expected to do, is the result of:

- Environmental temperature of the machine and part.
- Machine response to changing operating and environmental conditions.
- Machine geometry accuracy and precision.
- Machine scale (or calibration) accuracy and precision.

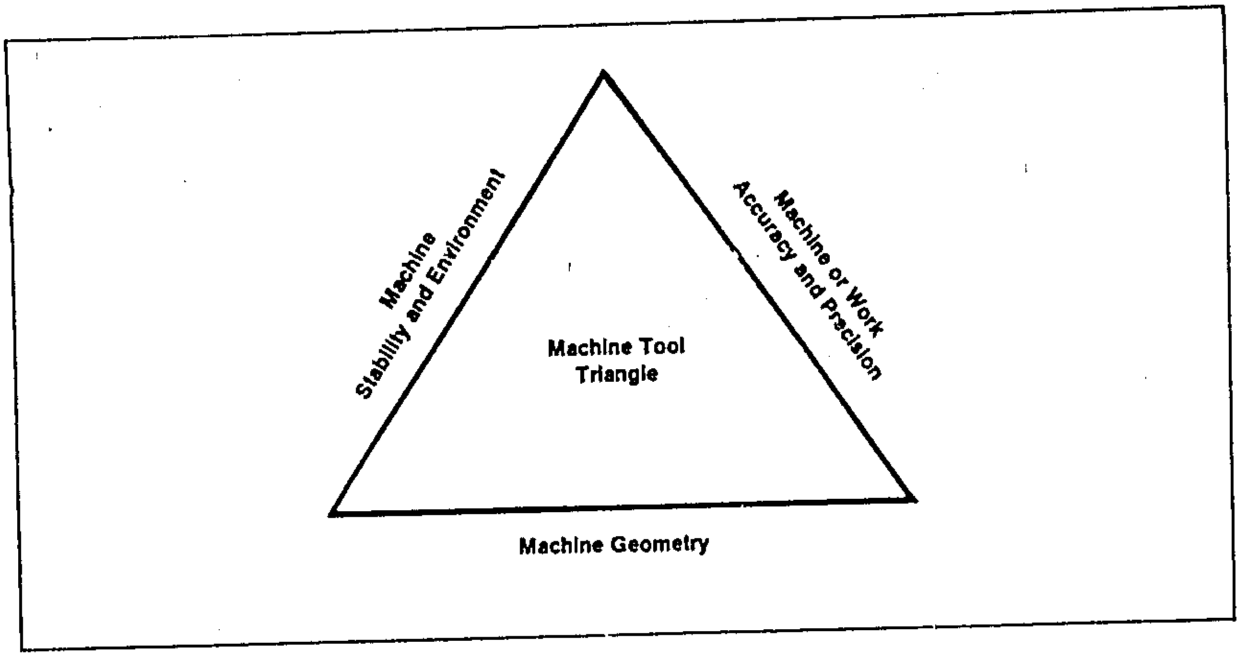


Figure 1-1 THE MEASUREMENT TRIANGLE

These variables form three sides of an equilateral triangle. The sides of the triangle are equally important. Anyone of the three sides can dominate. By knowing any two, the requirements or limits of the third can be determined. Measurements of accuracy and precision are meaningful only when both the environment and geometry are known.

Meaningful results from a machine investigation or calibration depend on a variation of this triangle:

- Required part accuracy and precision
- Typical machine environment and stability, consisting of:
  Typical machine and part temperature.

Typical machine and part production environment.
Typical or critical machine mode of operation.
Typical machine responce to environmental and operating mode changes.

- Machine geometry. The accuracy and precision of all six degrees of freedom in each axis plus squareness and parallelism measured relative to the above typical conditions.

Some machines change radically as the operating conditions change, i.e., the spindle speed of a common lathe. The operating environmental temperature in most machine shops is uncontrolled and can range from below 40 degrees F on cold winter Monday mornings to above 120 degrees F on hot summer afternoons. Machines do not respond to environmental changes in a linear or predictable way. They twist, bend, and generally distort as columns change temperature more rapidly than bases. Most machines are in a constant state of seasonal change. The parts produced are be distorted by distorted machine geometry and the temperature differential between the part and the machine.

Machine geometry is always found at the prevailing operating conditions and environment. These two variables are usually overlooked factors. Machine geometry changes as these variables change. Thus, how much finished parts will vary depends on the range of the environment about the machine and part during all periods when parts are produced - all day - all year.

Summary: Positioning accuracy and precision by themselves are relatively meaningless. Machine geometry is much more meaningful. It includes linear positioning accuracy and precision. Machine geometry, stability and environment must be known to determine the ability of a machine to position accurately and precisely during typical operating conditions.

PRECISION ACCURACY AND RESOLUTION

Be sure you have a good understanding of these terms. They will be used often during measurement discussions. "Accuracy" and "precision" are not interchangeable. The difference in their definition will help to clarify the complexity of making measurements.

PRECISION is often called "Repeatability". For our purposes, it is defined as the average difference among a group of measurements at a target position. In the target analogy in Figure 1-2 below, the average position of the shot grouping is measured as precision. Precision in this case says something about the repeatability of the marksman, his gun and the environment. Precision in laser measurements is similar. Operator skill, machine stability, machine geometry and the environment affect precision.

Accuracy in Figure 1-2 is the measure of how close the shot grouping was to the bull's eye. The shot grouping was more Precise than it was Accurate. When making measurements, Accuracy is how close the measurements agree to a given standard for the measurement (such as the National Bureau of Standards or N.B.S.). Precision, by comparison, is how close the measurements compare to each other.

ACCURACY in linear positioning is the difference between the average position of a group of measurements and the location of the target position for those measurements.

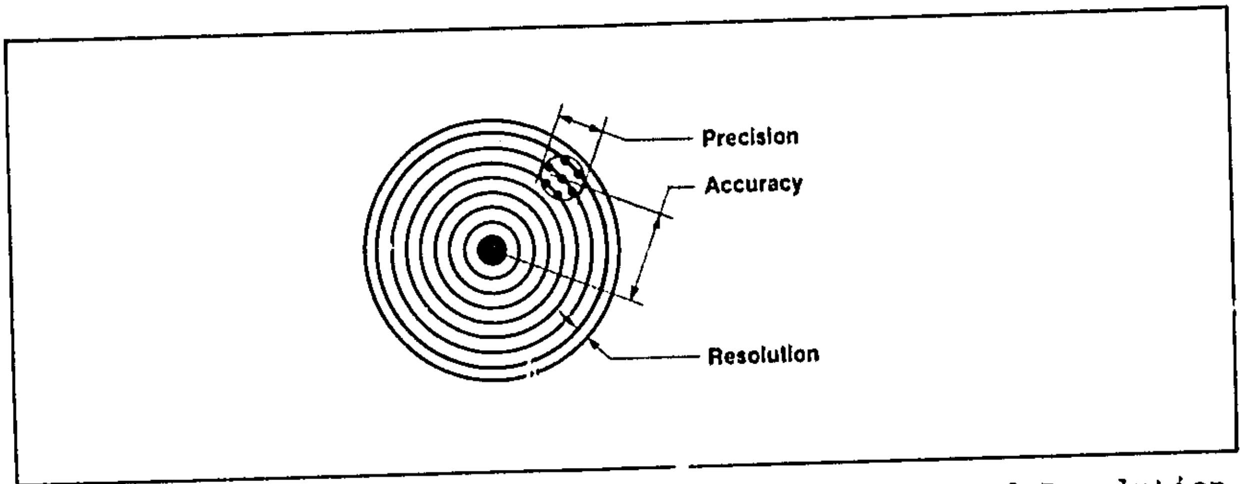


Figure 1-2 Target Example of Accuracy, Precision and Resolution.

Accurate parts are exactly like the drawing for those parts. Precision parts are exactly like each other. A batch of parts, all rejected for the same flaw, are precise but not accurate.

RESOLUTION is the smallest increment of scale. In Figure 1-2, Resolution is the distance between the rings in the target.

5526A LASER MEASUREMENT SYSTEM SPECIFICATIONS FOR LINEAR MEASUREMENT

Accuracy of the 5526A Laser Measurement System is specified as: +/-0.5 ppm (read plus or minus 0.5 part per million) +/-1 count in the last digit on the Laser Display. That means the 5526A will measure linear displacement to better than +/-1/2 millionth of an inch per measured inch +/-one millionth. +/-1/2 ppm is equivalent to:

$$\frac{\pm 1/2 \text{ part}}{1 \text{ million parts}} \text{ or } \pm 0.5 \times 1 \text{ to the 6th part or } \pm 0.00005\%$$

Parts are unitless multipliers like percentages. Whatever the unit: gallons, pints, feet, miles, metres, or inches, +/-1/2 part per million infers that you divide the unit into millionths and for every million millionths you count you'll be accurate to +/-1/2 millionth.

When using the 5510A Automatic Compensator, system accuracy decreases to +/-1.5 ppm +/-1 count in the last digit worst case.

GEOMETRY — DEGREES OF FREEDOM, SQUARENESS, AND PARALLELISM

Diagnosing the accuracy and precision of a multi-axis machine involves the analysis of several complex factors in and between the axes. These factors are grouped by measurement type: linear, angular, straightness, squareness and parallelism. Linear, angular and straightness measurements are used to measure six independent freedoms of movement called the Six Degrees of Freedom. Squareness and parallelism are subsets of straightness.

The Six Degrees of Freedom are:

1. Linear Displacement

Angular displacement about the axis measured.

2. Pitch
3. Yaw
4. Roll

Translational displacement about the axis measured

5. Straightness in the vertical plane
6. Straightness in the horizontal plane

These six variables are used to break down complex movements of a carriage traveling on a pair of ways into factors more easily handled in terms that can be well defined when communicating results or symptoms to others.

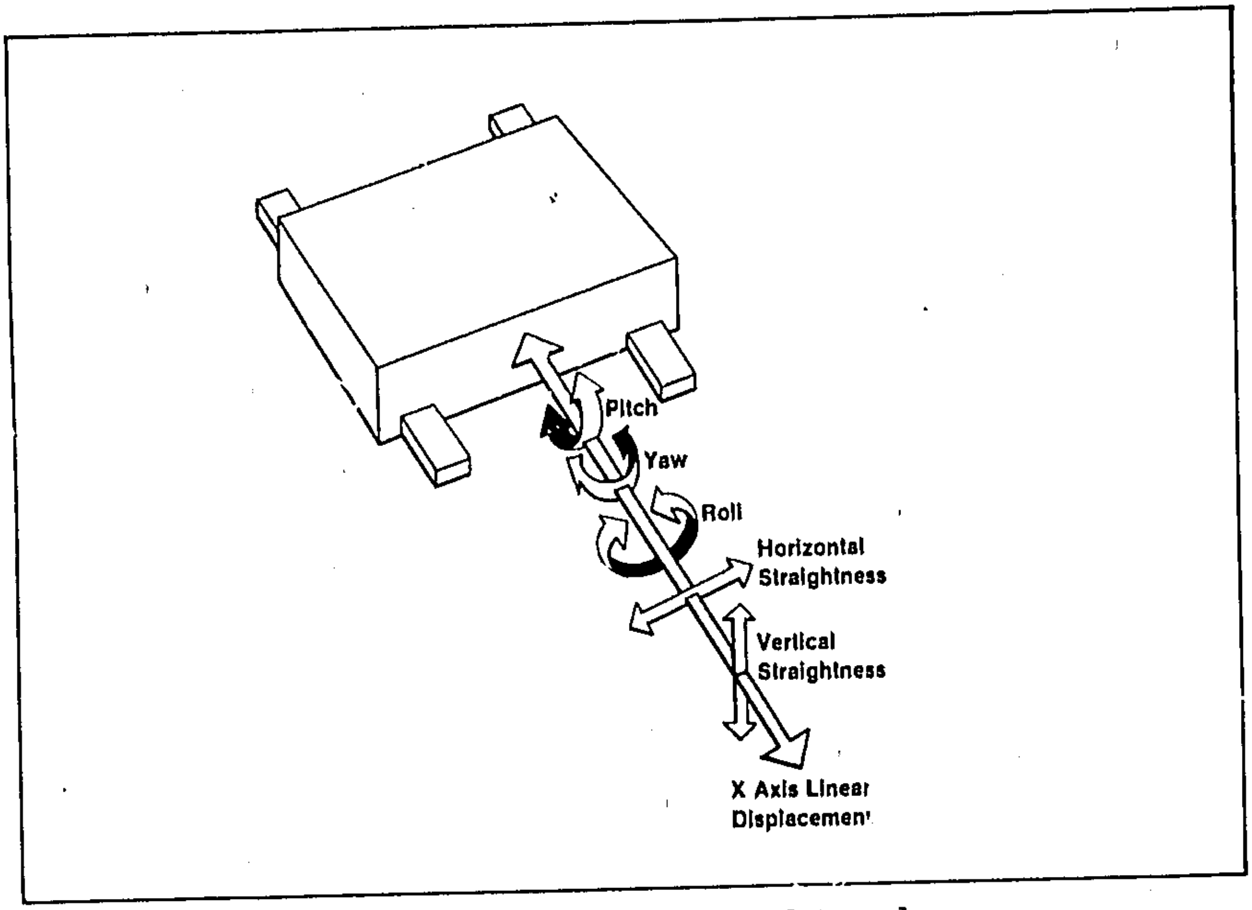


Figure 1-3 Six Degrees of Freedom

Laser geometry measurements are accomplished by three sets of optics named after the type of measurement they perform, Linear Angular, and Straightness. Each set of optics ignores the geometry measured by the other two sets. The 10692B Optical Square is used with the Straightness Optics to measure squareness. The 10693A Vertical Straightness Adapter enables Straightness Measurements in Vertical axes and blind horizontal axes. Squareness and parallelism are computed from two straightness measurements.

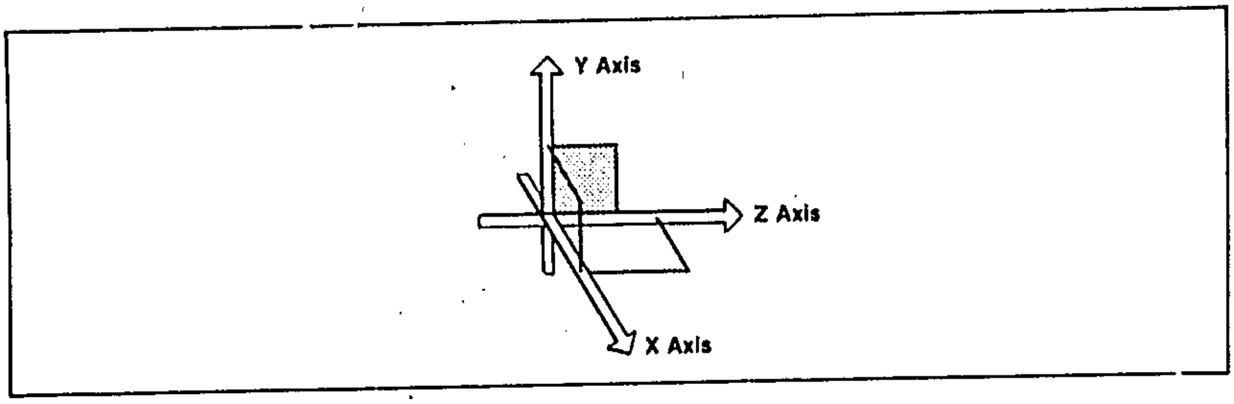


Figure 1-4 Squareness Between Axes

Each of the above variables contributes to positioning precision and backlash. The machine's positioning precision is a composite of these variables at each measurement point. Precision and backlash then can become a significant factor in performing a calibration.

ENVIRONMENTAL TEMPERATURE AND MACHINE USAGE

The objective of a machine tool is to cut parts accurately. Machine temperature changes and temperature differentials will negatively affect the part accuracy .

Machine temperatures will drift depending on the usage and the environmental temperature. The rate of drift will depend on the size and mass of the machine, how open it is to changing air temperature and the temperature difference between the machine and the air. Machines that operate continuously through the day and machines that do not have heat sources that vary during machine process will be more stable than machines that stand idle for part of the day and when in use have motors or hydraulics that generate heat as they perform work. Part accuracy and precision are lowest when the environment is uniform, constant and 20 degrees C (68 degrees F) or when the same as when the machine scales were compensated.

OPERATING UNDER CHANGING TEMPERATURE CONDITIONS

Material temperature compensation is completely accurate only under constant operating conditions. The more unstable the operating conditions the more unpredictable a machine and resulting parts become. The Automatic Compensator can be used to compensate completely for thermal expansion of the part only if the part and the machine are at thermal equilibrium with their environment and at normal operating conditions. Changing the room temperature can result in changing thermal gradients in both the machine and the part. In this case the primary machine errors are due to complex bending effects which result in distorted machine geometry instead of simple thermal expansion.

Machine geometry distortion is extremely difficult if not impossible to describe mathematically, and is equally dfficult to compensate for. Distorted machine geometry changes the pitch, yaw, straightness, parallelism, and squareness of the machine structure and slideways. The resulting errors are not a function of the machine scales. Nor are they directly a function of material temperature. When a machine with good geometry is operated in a poor environment, its accuracy will be limited by its geometry responding to the environment. In this case, the practical solution to better accuracy and precision is to either improve the environment or make the machine less susceptible to environmental changes.

There is no established rule-of-thumb which can be used to estimate allowable temperature variation during a machining or measurement cycle to obtain a given tolerance. One can only predict that a given machine will be most accurate when operated in a constant and uniform temperature environment. If the machine environment is suspected to be poor and part accuracy is critical it is best to run "thermal drift tests" on the machine to determine daily and seasonal environment effects on the part accuracy and precision.

Large machines will tend to change temperature very slowly. The room temperature may change from 65 degrees F to 75 degrees F in 1 hr. but the temperature of a massive machine will lag by a few hours in the most unexposed areas. The most exposed area of a machine tool is often the table,column and head. A 5 degree F increase in a 50 inch machine table will cause the table to grow away from the ball nut and ways by 6.5 ppm/degrees F or 32.5 microinch/in or 7 tenths at the ends of the table. A steel workpiece mounted on the table would not only move with the table but also expand by 32.5 microinch/in. A lead screw has no way of sensing this change in part position and size when it is deap within the machine. Real time compensation is possible when the scale is computer controlled. The most common practice when calibrating or compensating a scale is to arbitrarily pick an operating condition and go with the available ambient temperature.

Summary: To make parts accurately a machine calibration should be done under typical operating conditions and only after pitch, yaw, roll, straightness, squareness, parallelism and velocity have been checked and varified to be good enough to warrent scale calibraton. The use of only one linear precision and accuracy check tion probably will give an inaccurate indication of the overall machine performance . Linear positioning is influenced by many geometry and environmental variables that must be within permissible limits before the machine scales can be usefully calibrated. It is true that a machine can pass a linear positioning accuracy and precision test and not be able to produce accurate or precise parts. A machine will maintain its calibrated accuracy and precision only if the calibration environment and operating conditions are maintained. The calibrated accuracy and precision will change ms the environment and operating conditions

SECTION

II

SECTION II

WAVELENGTHS

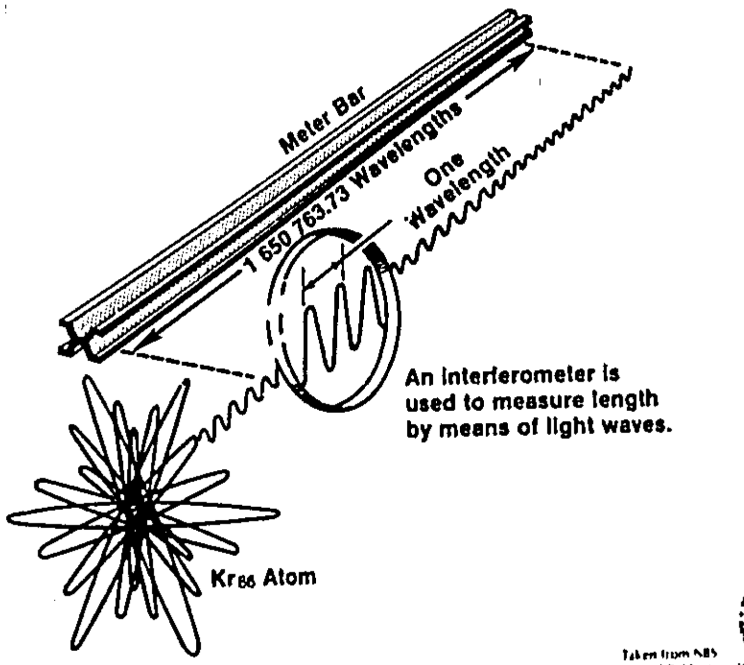


Figure 2-1 The NBS Standard of Length

THE NBS STANDARD

In 1960, the NBS discontinued the use of the Meter Bar as the Standard of length and the Metre as the unit of length. They adopted the wavelength emitted by Krypton 86 under special conditions as the Standard of Length and the Unit of Length. Physical standards had proven to be less stable, less accurate, and more trouble some to duplicate than Wavelength Standards. Krypton 86 was selected as the best wavelength source available at that time. Lasers were first constructed later that same year and proved even more desirable as wavelength sources.

Krypton 86 light waves and laser light waves are used in much the same manner. Thus, the principles and techniques involved are similar. In each case, distance can be measured in terms of wavelengths counted as optics are moved along a measurement path. The light beam becomes a scale and wavelengths are graduations along the scale.

WHAT ARE WAVELENGTHS

Waves are often shown as in Figure 2-1 and Figure 2-2. In these waves, the peaks and valleys repeat at exact intervals. These repeating intervals determine the wavelengths. One wavelength is the distance between similar points on the wave. The Greek letter lambda (λ) is shorthand for wavelength. One half wavelength is half that distance written λ/2, and λ/4 is one fourth wavelength.

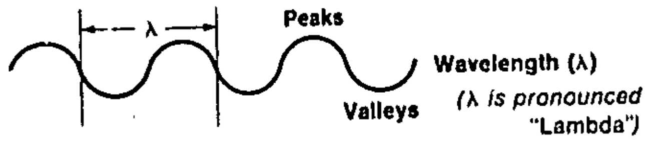


Figure 2-2 A Typical Wave

When the peaks and valleys in two waves are occurring at the same time, the waves are called "In Phase Waves". If these in phase waves are direcced at a common point, (see Figure 2-3) they will combine Constructively. That is, the brightness of the two beams will be combined to form a wave of the same wavelength and with the combined intensity (brightness) of the two criginal waves. This is called Constructive Interference.

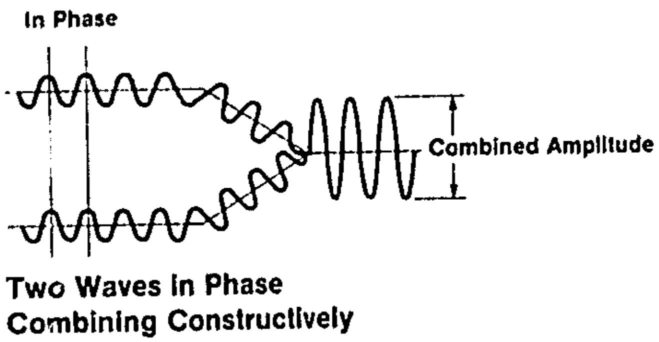


Figure 2-3 Constructive Interference

As shown in Figure 2-4, the opposite effect can also occur. When the peaks and valleys do not occur at the same time, they are Out of Phase. When the peaks in one beam occur at the same time as the valleys in the other beam, the two beams are 180 degrees

Out of Phase. If these two 180 degree waves are directed at a common point, they will combine destructively as in Figure 2-4. If the two combining waves are of equal brightness, they cancel each other completely, and no light will be seen at the common point. This is Destructive Interference.

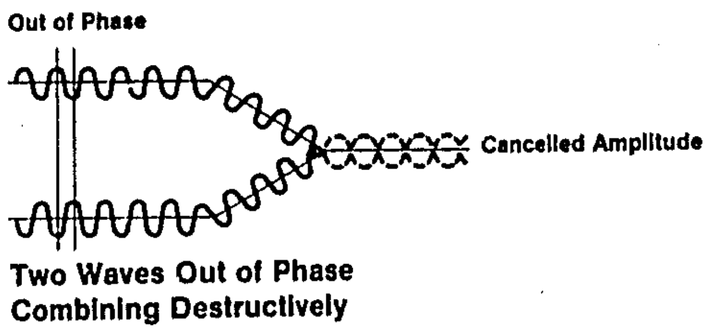


Figure 2-4 Destructive Interference

MICHELSON'S INTERFEROMETER

Light wave interference was first used to measure distances by Michaelson in 1890, using a less than an ideal light source. An ideal light source must produce light with three characteristics not found in sunlight or common light bulbs. The light must be:

1. Monochromatic - all the light must be the same wavelength (or color).

2. Coherent - the waves musts be in phase.

3. Collimated - the waves must travel parallel to each other.

The Michaelson light source was directed to a half-silvered mirror descriptively called a "beam splitter". The beam splitter allowed 50% of the beam to pass through and reflected 50% at an angle depending on the alignment of the beam splitter. In each 50% beam path, Michelson positioned a flat mirror aligned to reflect the beams back on themselves. The returning beams would be recombined at the splitting point.

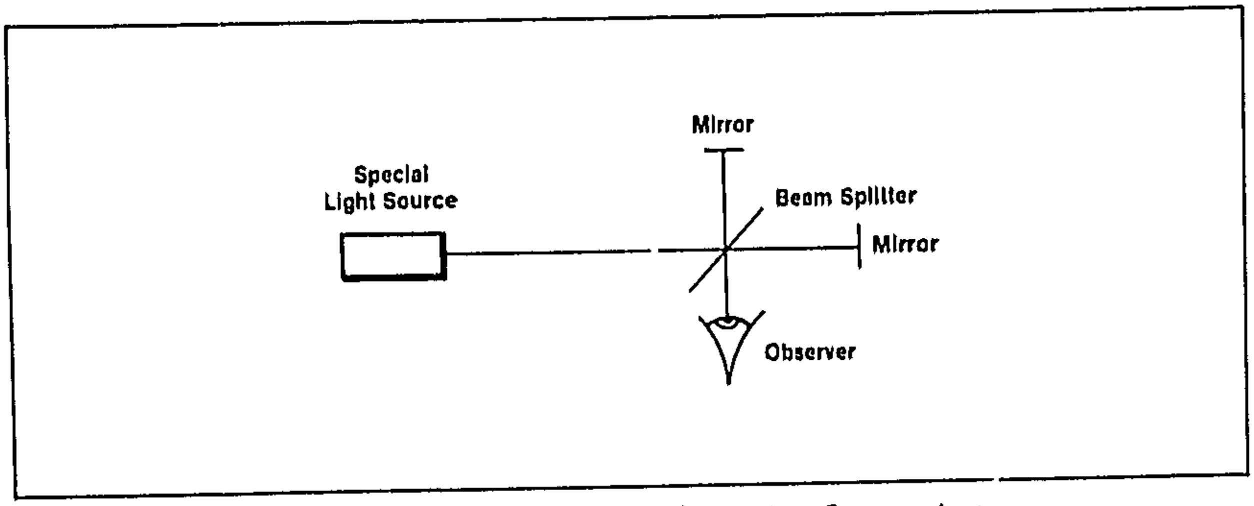


Figure 2-5 Michelson's Interferometer

When the mirrors are equal distance from the splitting point, the beam paths will be the same. The beams will return "In Phase" at the splitting point, combine constructively, and a bright spot will be seen by an observer as in Figure 2-5. As one mirror is moved, that beam path will change and the phase relationship between the returning beams will change. If the mirror is moved $\lambda/4$ away from the beam splitter, the beam will travel an extra $\lambda/4$ both out and back for a total of $\lambda/2$ increase in beam path. This beam will have an increased path length of $\lambda/2$ more than the unchanged beam. Its peak will be $\lambda/2$ behind or 180 degrees Out of Phase with the unchanged beam and the two beams will combine destructively. The observer will see a bright spot change gradually to a very dim spot or to no spot at all. As the mirror continues out to $\lambda/2$, the spot will get increasingly brighter to maximum brightness again. The spot transition from bright to bright is counted as an increment of scale for a resolution of $\lambda/2$.

Michelson's setup had several drawbacks. Among them: noncoherent light, poorly collimated light source, excessive heat, and mirror-beam-beam splitter alignment difficulty during a measurement. The problems Michelson encountered required averaging of several measurements to provide precision.

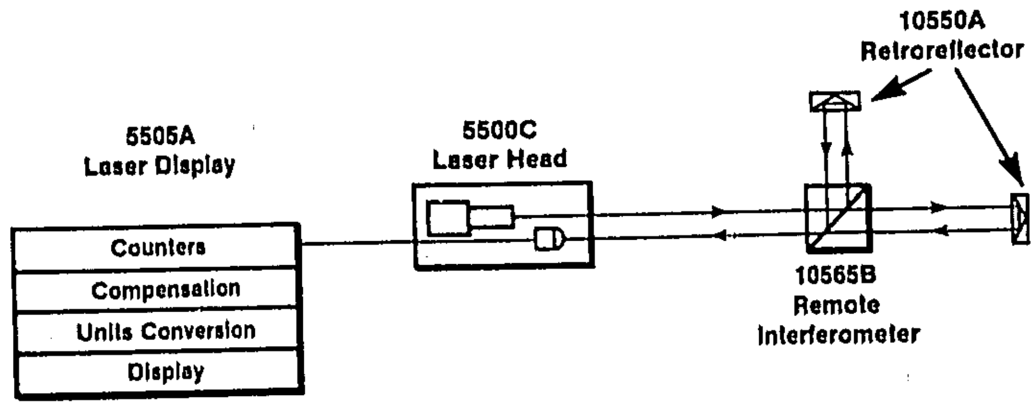


Figure 2-6 5526A Laser Measurement System

HP'S LASER INTERFEROMETER

With the Laser as a light source and through Hewlett-Packard's innovations, Michelson's Interferometer was improved upon to allow convenient use in an industrial environment. The light waves originate in the Laser Head using a rugged long life laser tube. A laser is used because it naturally produces the three important characteristics needed for interferometry. The light produced is: Monochromatic, Coherent and Collimated.

The laser beam is split by the beam splitter Interferometer into two components. One component passes through and the other is reflected perpedicularly. Cube corner Retroreflectors are used in place of plane mirrows because they always return the beam parallel to the incombing beam path. Small rotations or perpendicular movements of the Retroreflectors will not affect the accuracy of the measurement.

The cube corner Retroreflectors offset the beams and return them to the Interferometer where Constructive and Destructive Interference takes place. One Retroreflector is usually free to move independently of the Interferometer. The other Retroreflector is usually attached to the Interferometer and called the Reference Retroreflector or the two are referred to as the Interferometer.

The Laser Beam Path between the Interferometer and the Reference Retroreflector is the Reference Beam Path. The Laser Beam Path between the Interferometer and the Movable Retroreflector is the Measurement Beam Path. By physically positioning the Retroreflectors and Interferometer, the returning beams are recombined at a common point inside the Interferometer. At this point interference can be thought of as occurring basically the same way as in a Michelson Interferometer. (See Figure 3-5 and Figure 3-6). The Return Beams will overlap and return to the Laser Head where a Photo Detector will convert the $\lambda/2$ light information to electronic signals which are fed to the Laser Display. The elecectronic signals are converted to the number of $\lambda/4$'s counted during a movement of the optics (either the Interferometer or the Retroreflector or both). The $\lambda/4$'s are stored in Counters. Measurements are accomplished by:

1. Accumulating in the Counters the number of $\lambda/4$'s detected during a measurement.

2. Compensating the number of $\lambda/4$'s stored for the density of air. Material expansion or contraction due to temperature of the the part being measured.

3. Compensating the number of $\lambda/4$'s stored for the temperature of the material being mearsured.

4. Converting the Compensated $\lambda/4$'s into more common units, either inches or millimetres.

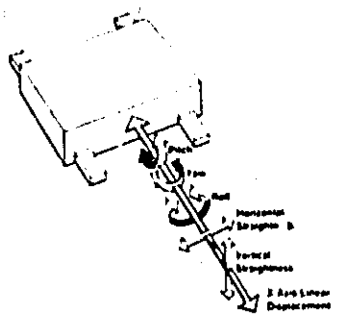
5. Displaying the compensated and converted $\lambda/4$'s or displaying directly from the counters Uncompensated and Unconverted the number of $\lambda/4$'s stored in the counter.

SECTION III

SECTION III

LINEAR MEASUREMENT CONSIDERATIONS

MACHINE GEOMETRY



Six Degrees of Freedom

- Ultimately determines machine accuracy and precision.

1. Linear Displacement

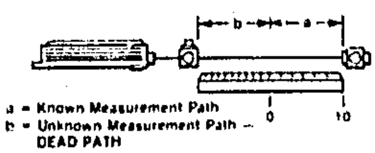
Angular Displacement

2. Pitch
3. Yaw
4. Roll

Perpendicular Displacement

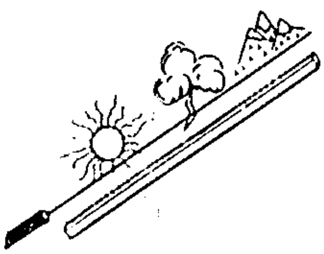
5. Vertical Straightness
6. Horizontal Straightness

DEAD PATH ERROR



- Two necessary contributors:
  1. Some distance between the Interferometer and Retroreflector when Zero Point is Reset — DEAD PATH.
  2. A change in the Velocity of Light or Thermal Expansion. EFFECT: Length a can be compensated BUT Length b cannot. Zero will move as scale changes by b × Δ Compensation #.
- Minimize DEAD PATH — set Zero with Optics together.

VELOCITY OF LIGHT

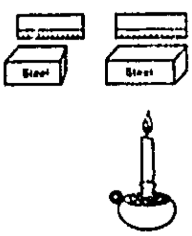


- Constant only in a vacuum.
- Measurements vary 1 ppm for each:

  Air temperature change of 2°F.
  Air pressure change of; 0.1 in Hg.
  Humidity changes of 30%.

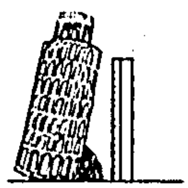
- Corrected with manual or automatic compensation.
- Automatic compensation maintains ± 1.5ppm measurement accuracy during measurements.

THERMAL EXPANSION



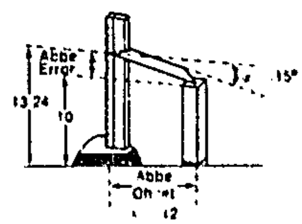
- Linear measurements "Unless Otherwise Stated" are referenced to 68°F.
- Part and Scale MUST be at 68°F or scale reading compensated for temperature and coefficient of expansion.

COSINE ERROR



- Misalignment of scale axis to measurement axis.
- Minimized with proper alignment.
- "Visual" alignment if measured length is OVER 23 inches.
- "Linear Alignment Accuracy Check" if UNDER 20 inches.
- Causes short measurements with laser.

ABBE ERROR



- Two necessary contributors:
  1. Abbe offset — distance between scale axis and measurement axis.
  2. Angular displacement of part during linear displacement of part.
- "Rule of Thumb" abbe error in μins. = angular error in arcseconds × 5 × abbe offset in inches. 54000 × 5 × 12 = 3.24 in.
- Minimized by positioning scale axis as close as possible to desired measurement axis.

WAVELENGTH COMPENSATION

The speed of light changes as light travels through mediums of differing densities. The Laser Beam travels through air which has a density that varies with changes in temperature, pressure and humidity. This change in the speed of light changes the wavelength of the laser light which correspondingly changes the number of λ/4's counted along a given distance.

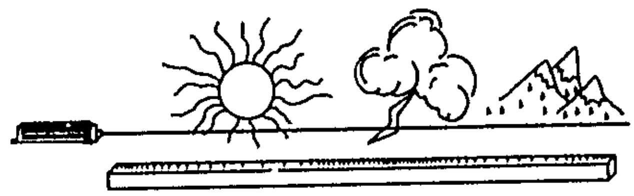


Figure 3-1 WAVELENGTH IS SPEED OF LIGHT DEPENDENT

This change can be corrected for by multiplying the number of λ/4's stored in the counters by the Compensation Factor. In a vacuum, where the speed of light is the fastest, the Compensation Factor is 1.000, so no correction is made to the λ/4's. As the density of air increases, the speed of light decreases, which correspondingly decreases the laser wavelength, and the number of λ/4's counted in a given distance increases. To correct the number of λ/4's, the Compensation Factor will always be less than one. In the range of air temperature, pressure and humidity in which we normally work, the Compensation Factor will be between ".9999999" and ".9990000". This Compensation Factor is applied in three ways. Manually with the Compensation Factor Handbook, manually with the computer program supplied in the CalculatorPlotter option metrology package, and automatically with the 5510A Automatic Compensator.

MANUAL COMPENSATION -- AIR ONLY

The Manual Compensation Factor is entered via the Thumbwheel Switches behind the flip-down door on the front right hand side of the 5505A Laser Display.

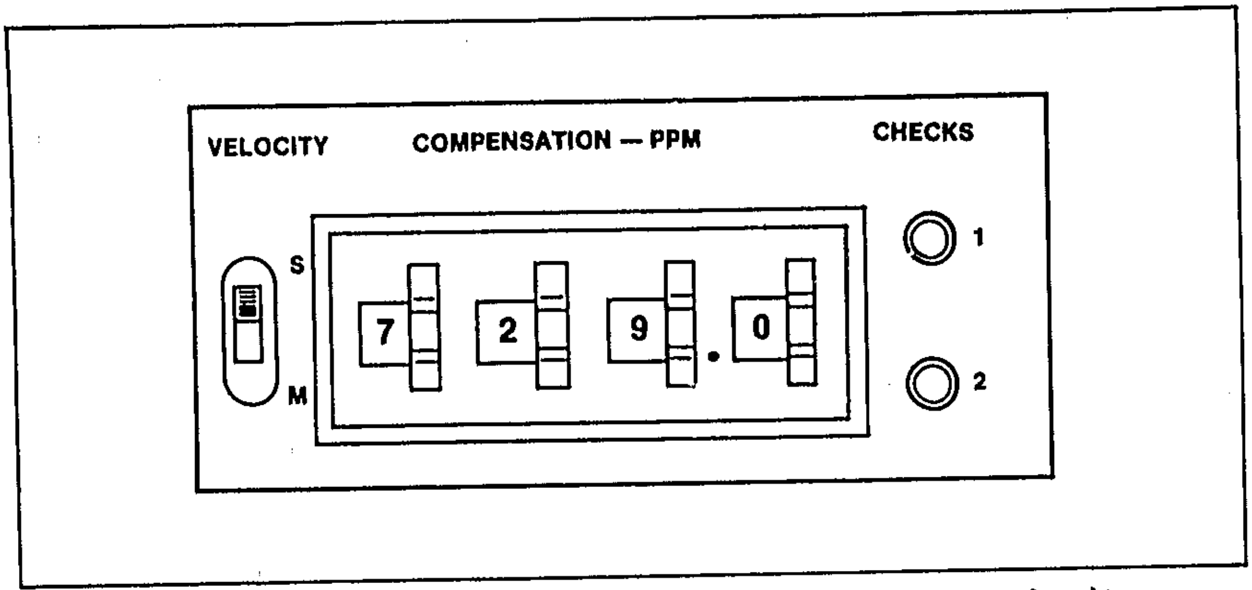


Figure 3-2 Compensation Thumbwheel Switches, Velocity Time Units Switch and Checks Buttons

The number that is entered on the Thumbwheel Switches can be found in the Compensation Factor Handbook, or with the Metrology Program package. The air temperature, pressure and humidity are cross-referenced in the Compensation Factor Handbook to find the Air Only Compensation Factor in parts per million. The Air Only Compensation Factor will compensate the laser beam for changes in the velocity of light to measure accurately in the atmosphere just measured. From that value it will change 1 ppm for every:

1 degree C (2 degrees F)

2.5 mm Hg (0.1 inches Hg)

30% change in humidity

The Air Only Compensation Factor WILL NOT compensate the laser beam for material or machine temperature other than 20 degrees C (68 degrees F). See Material Temperature Compensation and refer to the Compensation Factor Handbook for more details.

MATERIAL TEMPERATURE COMPENSATION FOR THERMAL EXPANSION

All materials expand and contract with changes in temperature. As a result, if a part is measured at two different temperatures, two dimensions will result. The change in dimensions of each type of material differ as a function of temperature and can be measured and given a number which is called the Coefficiant of Expansion.

To determine the true size of a part, it must be measured at the reference temperature of 20 degrees C (68 degrees F) "unless otherwise stated" on the part drawing. To determine the true size of a part at some other temperature, the temperature and coefficient of expansion of the part must be known. To make a part at some other temperature the machine and scale must change proportionately so that when the part is measured at 68 degrees F it is the desired size.

MATERIAL	ppm/°F	ppm/°C
Aluminum	12.8	23.1
Brass	10.8	19.4
Steel	6.5	11.7
Granite	5.0	11.00
Cast Iron	5.7	10.5
Pyrex Glass	1.8	3.2
INVAR	0.70-1.1	0-2

Typical Coefficients of Expansion

Table 3-1 Typical Coefficients of Expansion

Table 3-1 compares several materials and their Coefficients of Expansion. These are approximations only. There are many variables that determine the actual value for a specific part or material. Some of these are the alloy, type or amount of heat treatment, grain structure and structural mix of the materials in a complex part or machine. Seldom can the Coefficient of Expansion be estimated more accurately than one ppm unless it is actually measured for a particular sample.

MANUAL MATERIAL TEMPERATURE COMPENSATION

When the Air Only Compensation Factor is used to correct the counted $\lambda/4$'s, the 5526A display presents a measurement accurate for 20 degrees C, (68 degrees F). At this Reference Temperature, no further Compensation is required. When the part or machine is not at 20 degrees C (68 degrees F), the $\lambda/4$'s counted to measure the length of the part must be compensated for that part temperature. For example, a steel part with a Coefficient of Expansion of 6.8 ppm/degree F heated to 88 degrees F will be larger in all dimensions by 20 degrees F x 6.8 ppm/degrees F or 136 ppm (136 millionths/inch) than when it was at 68 degrees F. If the 5526A displayed value is compensated for air only it will measure the part as being 136 ppm too large. A ten inch part would appear to be 0.00136 inches too long.

Fortunately, we can tell the 5526A to measure 136 ppm larger to compensate for this part by subtracting 136 ppm from the Air Only Compensation Factor previously entered in the Thumbwheel Switches. The 5526A will then be totally compensated to correct the measurement of that part at that temperature and at the previously measured Air Temperature, Pressure and Humidity. This is called the Total Compensation Number.

WHERE TO SENSE MATERIAL TEMPERATURE

The purpose of a machine tool calibration is to determine if the machine wil produce parts accurately and precisely. More accurately, it is to determine if the machine geometry is sufficiently accurate and precise to transfer the machine scale accuracy and precision to produce parts of specified accuracy and precision, when measured at 68 degrees F.

Scales are basically very stupid. They don't know:

If the machine geometry is good enough to accurately transfer their positioning information to make good parts.

If the machine geometry is changing because of temperature differentials.

The temperature of the stock they are trying to make into accurate parts when measured at at 68 degrees F.

Part accuracy is quickly lost when temperature differentials are magnified by environmental changes. When a scale is warmer than the part, the machine geometry will be directed to make a larger than necessary part. When coefficients of expansion (CE) differentials exist between the scale, part and the machine structure, the scale cannot accurately compensate for the differences in the part and machine size with environmental temperature changes.

For example:

A glass scale with a CE of 5.0ppm/degrees F at 80 degrees F will be 5X(80-68)=5X12=60ppm larger than when at 68 degrees F.

An aluminum part with a CE of 13.0 ppm/degree F at 80 degrees will be 13X12=156ppm larger.

A steel machine with a CE of 6.5ppm/degree F at 80 degrees will be 6.5X12=78ppm larger.

A 20 in. part produced by a glass scale, both at 80 degees F, will be 156-60=96ppmX20in.=1920microin. too small, considering only the scale and part CE differential. If this combination existed in a steel machine, the machine would compensate for an additional 6.5-5=1.5ppmX12=18ppm at 80 degrees. This would help the part accuracy by only 18X20=360 micro in. This 20 in. aluminum part will be 0.001560 too small, when measured at 68 degrees F.

Even with perfect machine geometry, a machine cannot produce accurate parts when:

The entire machine, scale and part are not at 68 degrees, or

They are not at the calibration temperature, or

Unless the scale is computer controlled and it knows what the machine and part, temperature and CE are.

Most machines operate in non-temperature controlled shops. temperatures of the machine and part can vary by 80 degrees F in the midwest and northeastern United States. When the part and the scale CE's and temperatures are the same (and the machine geometry is good), there is no problem in accuracy. But typically the scale is a lead screw-resolver that heats up as it works. Or, the scale is protected from open air and does not change temperature as rapidly as the part. In both cases, part accuracy is limited by the inability of the scale to change appropriately with the part.

A partial answer is simple lead screw (scale) compensation. The scale can be computer compensated to produce accurate parts at a selected operating condition and part temperature. A drawback is when the temperature changes in the part or machine, the scale is unaware of the change.

A bonus of scale compensation is that Abbe errors are cancelled along the calibration axis.

Even when a machine is operated at thermal equilibrium in a constant environment,the part and different components of the machine can be at different temperatures. When determining positioning accuracy, the temperature to measure is the part temperature. In order to minimize errors, measure material temperature at the workpiece position. For example, on a milling machine, if the workpiece is clamped to a table, measure the table temperature. To adequately support the weight of a part the machine is designed to carry a specified limited part mass and the table should be much more massive than the part -- if not distortion of the machine geometry will result. The mass of the table will control the workpiece temperature in most situations. It is generally accepted that the table temperature at operating conditions will be indicative of the temperature of the workpiece at operating temperature.

On turning machines this may not be the case since the workpiece is held in a rotating spindle. It is necessary to determine empirically which accessible machine member is the closest in temperature to the workpiece at the specified machine operating conditions or at the specified calibration condition.

When machine and part temperature compensation is not available, part accuracy and precision will change from the calibrated accuracy and precision, in responce to environmental and operational changes. If accurate and precise parts are desired, machines should be in temperature controlled invironments, with uniform air flow.

The problem is in temperature differentials. Both air and machine induced temperature differentials must be minimized. They cause the machine, part and the scale to be different sizes as the temperature varies along the length, width and heigth of the machine and part. To compensate, the scale must know the part temperature where and when the work is being done - real time real location scale compensation.

COSINE ERRROR

Cosine error results from misalignment of the scale axis to the desired measurement axis. In the case of a caliper, Figure 3-3, the scale axis is aligned parallel to the measurement axis through the perpendicularity of the caliper jaws. Measuring between two points on an object provides us with an obvious measurement axis and alignment of the measurement axis in the caliper jaws is easily seen as an accuracy consideration. The name for the error that results when the measurement axis and the scale axis are not parallel is Cosine error.

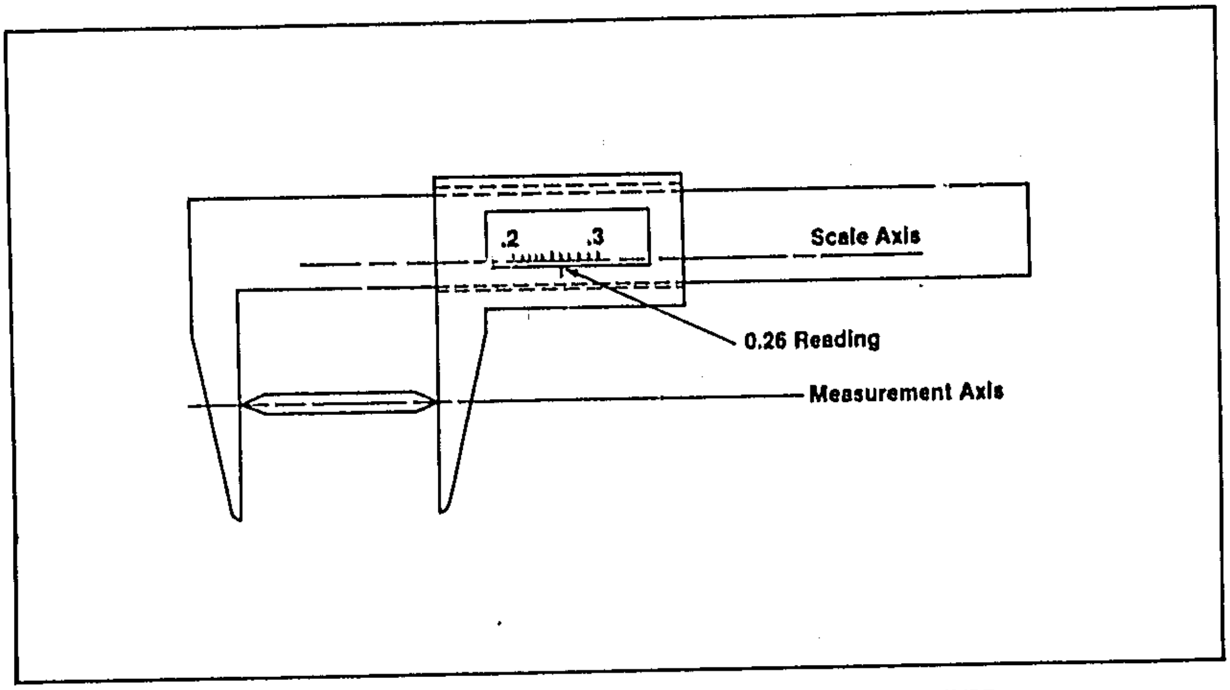


Figure 3-3 COSINE ERRORS AND THE CALIPER

Cosine error is not as obvious when operating the linear interferometer primarily because the scale is 7.6 mm (0.3 in) wide and graduated in .01 micrometre (.1 microinch) invisible increments. See Figure 3-4.

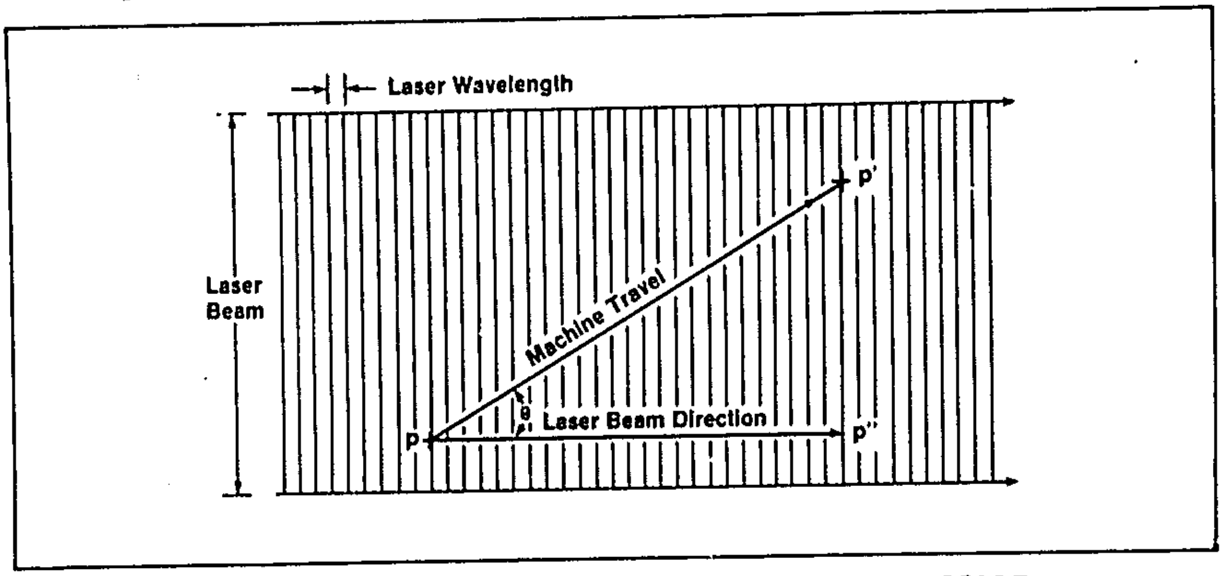


Figure 3-4 COSINE ERROR AND THE LASER SCALE

The linear interferometer will count along the path of the laser beam from P to P" when actually the machine travel is the longer path P to P'. The linear interferometer will always measure short when Cosine error is significant.

Cosine error is minimized with accurate alignments. The objective of an accurate alignment is to have the laser beam parallel to the axis of travel. Accurate linear measurements can be obtained only when the laser beam is parallel to the axis of travel. The Laser Measurement System will tolerate up to 95% loss of the Laser beam, so it is possible for the retroreflector or interferometer to move more than 0.3 inch across the laser beam during a measurement, and still return enough signal for operation. This lateral displacement is the result of angular misalignment between the desired measurement axis and the scale axis. It reduces the accuracy of a linear measurement proportionately to the angle and inversely proportional to the distance measured.

When cosine error is large enough, it can be seen as a changeing distance between the return dots at the Laser Head Turret during an alignment. (See Figure 3-5).

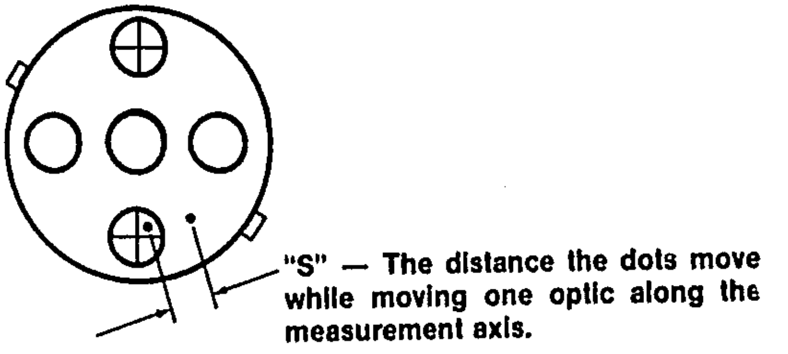


Figure 3-5 A Visual Indication of Cosine Error

If distance S changes as the optics are moved along the axis of travel, Cosine error is presert.

There are two basic alignment procedures: 1. Visual; 2. Autoreflection. Autoreflection can be used if there are convenient and accurately square axes or surfaces available. Visual can be used for over 10 inches of travel by observing the return dot overlap over the entire length of travel and below 10 inches of travel when followed by a Linear Alignment Accuracy Check. See Section 10 for alignment procedures.

ABBE ERROR

The most overlooked problem in machine tools is Abbe error. Abbe Errors result from 1) angular rotation between the Scale Axis and the Measurement Axis during a measurement and, 2) some distance separating the Scale Axis and Measurement Axis. The error increases with the angle of rotation and the distance separating the two axes. The distance between the axes is called the Abbe offset. Abbe error is minimized by positioning the scale axis as close as possible to the Measurement Axis and maintaining angular components (Pitch, Yaw, Roll) to a minimum.

Angular motions are often unaviodable. A simple caliper as in Figure 3-6 requires some tolerance between the sliding jaw and the beam if the jaw is to slide along the beam.

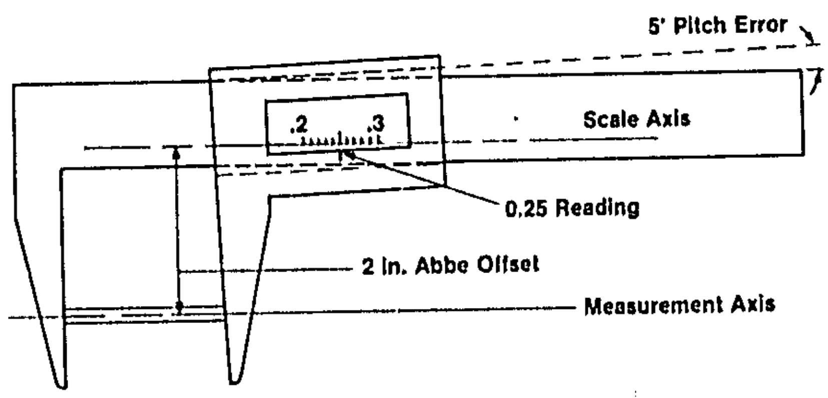


Figure 3-6 Caliper Example of Abbe Error

This tolerance allows the slide to be rotated slightly allowing the indicator mark to move on the beam scale indicating a shorter than true measurement. This error will increase as the Abbe offset increases. A non-straight beam surface will also contribute to rotation of the jaw.

In Linear positioning checks there are usually two Abbe offsets to be considered, one between the machine scale axis and the machine tool travel axis to be checked and the other between the machine tool travel axis to be checked and the laser scale axis during the calibration.

The former is inherent to the machine under calibration and cannot be avoided. The latter usually can be avoided. A major attribute of the Laser Interferometer is that any tool path can be checked, therefore the exact tool path must be specified with respect to Abbe offsets to the machine scales for the resultant data to be meaningful or repeatable. The resultant axis is the Calibration Axis.

Abbe errors can be cancelled allong the calibration axes of a mahine when scale compensation is available. The calibration axes should be located in the most critical positioning area of the machine working area. Once compensated, the machine will position most accurately along the calibration axes. Positioning accuracy will decrease away from the calibration axes. Worst accuracy will be at the greatest Abbe offsets from the calibration axes.

DEADPATH ERROR

Deadpath is a segment of the Laser measurement path between the Interferometer and the Retroreflector that is not measured and stored in the Laser Display counters. This results from resetting to zero with the optics separated by this dead path and then making a measurement. The unmeasured segment of the Laser Beam path cannot be compensated since it is not stored in the counters. The changes in the velocity of light require a change in the Compensation number. In Figure 6-8 the Beam Path is L1 + L2 but only L2 is stored in the Laser Display. Changes in L1 cannot be compensated. The apparent Position of L2 will move with the zero point as L1 expands and contracts with changes in the velocity of light.

Deadpath errors are minimized when zero is established with the Interferometer and Retroreflector as close together as possible.

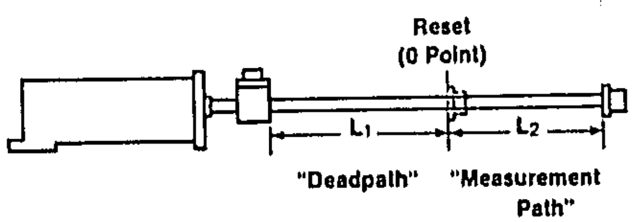


Figure 3-7 Deadpath

FIXTURING

Fixture whenever possible to position one optic where a part mounts and the other optic where a tool mounts to simulate as closely as possible the actual working conditions. Fixturing that does not reflect actual operating conditions should be avoided. Fixturing or mounting posts should be rigid and as short as possible to avoid amplifying vibrations. The Optics should be positioned so that the axis of the Laser Beam is as close and as parallel as possible to the Measurement Axis (the axis of exactly what is to be measured) to avoid cosine error and abbe error.

Fixturing should allow the Interferometer and the Retroreflector to be as close as possible when resetting to zero to avoid dead-path error and to minimize the time required to accomplish Beam Alignment. If the optics can be fixtured closer than 2.54 cm (1 inch) apart, Linear Alignment can be accomplished in a minimum of time.

CLEANING THE OPTICS

A good rule for the exposed glass surfaces is Never Let Anything Touch Them. Fingerprints will collect dust and dirt which will reduce the beam intensity by attentuating and dispersing the Beam. (Notice dim return dots about Laser Head Turret). Cleaning the optics should be avoided unless the signal intensity is noticeably reduced as indicated by the Beam Alignment Meter. Or when the return dots from finger prints are confused with retro-reflector return dots. If cleaning is necessary, you must be careful to avoid rubbing particles into the antireflective lens coating. Permanent reduction of the signal intensity will result. Particles can be rinsed with a gentle stream of pure industrial grade ethanol or methanol from a squirt bottle. A paper stick cotton swab with alcohol dripped on the cotton will absorb oil, cushion, and collect particles. Rotate the swab as its lightly moved along the optical surface. Throw it away when it has been rotated 360 degrees. Several swabs may be needed to clean one window.

Contaminated alcohol will leave a film on the window. Avoid alcohol contamination by following these precautions:

1. Use only new, previously unopened containers. Alcohol absorbs water if left exposed to air, that will leave water deposits when the alcohol evaporates.

2. Transfer the alcohol to a squirt bottle that can be capped airtight.

3. Never transfer alcohol BACK into the container.

4. Drip alcohol onto the swab, do not dip the swab into the alcohol container (as this may contaminate the alcohol).

SECTION

IV

SECTION IV

ANGULAR MEASUREMENTS

The Angular optics will measure angles of rotation up to 20 degrees in one plane and are unaffected by rotation in perpendicular planes up to the point where beam alignment is lost. The common uses for the Angular optics are:

1. Pitch and Yaw determinations - investigation of rotational freedoms in machine geometries and the determination of resulting linear displacement errors called Abbe errors and the range of squareness and precision.

2. Surface flatness, straightness of a line along a surface, and Straightness of a way.

3. Calibration of Rotary tables, indexing tables and rotary encoders.

PITCH AND YAW DETERMINATIONS

Abbe errors are linear positioning errors caused by angular freedoms and Abbe offsets. Many devices that incorporate linear positioning in the course of their work are affected by Abbe errors.

Machine tools position a tool relative to a part by means of machine scales (lead screws, inductosyn scales, rotary encoders, graduated scales, laser interferometers) that track the tool positioning through mechanical linkages. The linkages present Abbe offsets that produce Abbe errors when acted upon by pitch or yaw. When a machine tool is calibrated and the linear positioning scale compensated for accuracy, Abbe errors are cancelled along the axis of calibration.

Three of the six degrees are the angular freedoms of pitch, yaw and roll. These three freedoms contribute to four machine tool positioning errors, Abbe errors, Straightness of travel errors, parallelism errors and Squareness errors.

Abbe errors can be determined and even compensated for by measuring pitch and yaw. The error caused by roll is by definition a straightness error and no Abbe error is generated by roll. Pitch and yaw can contribute to straightness errors which are not measured by the Angular optics. Straightness of travel, parallelism and squareness are measured by the Straightness optics. The range of parallelism and squareness is also measured with the Angular optics.

ANGULAR OPTICS DESCRIPTION

The Angular optics consist of: Two 10556A Retroreflectors mounted in one 10559A Retroreflector mount, A 10565B Interferometer, and one 10558A Beam Bender. The Interferometer/Beam Bender splits the laser beam into two beams that exit parallel (in two planes) and separated by 2.0625 in., see Figure 4-1. The parallel beams are returned to the Interferometer/Beam Bender by the Retroreflectors and recombine in the Interferometer. The two parallel laser beam paths form two linear measurement paths separated by 2.0625 in.

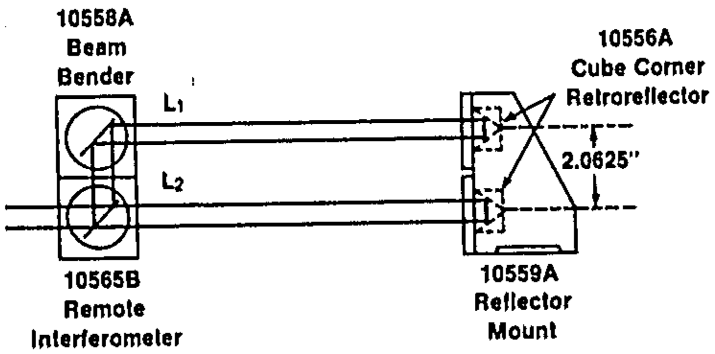


Figure 4-1. Laser Beam Paths through the Angular Optics

When rotation is encountered, the Interferometer will detect the change in one beam path length with respect to the other. This resultant measurement is proportional to the beam separation and the angle of rotation. The displayed value is L1 minus L2 in the desired units selected by the units switch. In Figure 4-2 it can be seen that L1-L2 and d are the opposite and hypotenuse sides of a right triangle. By choosing the dimension of 2.0625 inches for d, L1-L2 will approximate the magnitude of the angle in arc seconds at the rate of one arc second per 10 uin. on the Laser Display.

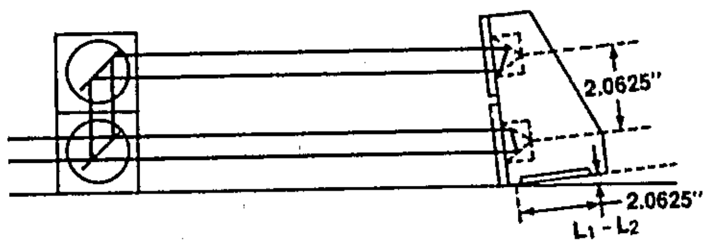


Figure 4-2. Flatness Measurement

ANGULAR OPTICS ASSEMBLY

The angular optics are assembled as in Figure 4-3. The 10559A Reflector Mount is used to accurately hold the two 10556A Retroreflectors of the Linear optics. The 10558A Beam Bender is wrung and squared to the 10565B Remote Interferometer, then locked together with 4 slot head screws.

Wringing is accomplished by pressing two flat and highly polished surfaces together with enough pressure to displace the air between them. A thin oil film or alcohol film is often used and recommended to help displace the air.

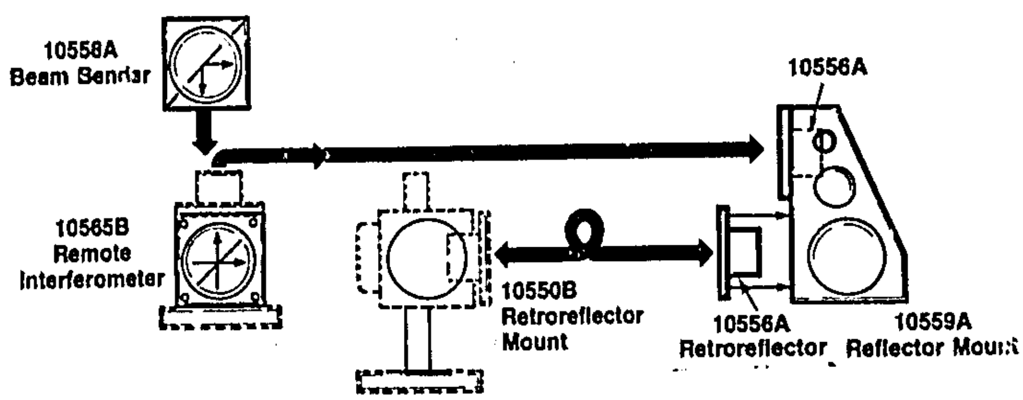


Figure 4-3 Angular Optics Assembly

NOTES

1. Wringing should not be attempted if burrs, dents or scratches are apparent. Surface defects must be removed by a qualified person to insure correct spacing and parallelism of the laser beams.
2. The cylindrical surfaces on the back of the Retroreflectors are precision ground to insure spacing and parallelism. Plastic covers are provided to protect these surfaces and should be used any time the Retroreflectors are not mounted in the 10559A Retroreflector Mount.
3. Care should be taken in fitting Retroreflector into the Retroreflector Mount. Damage can result by forcing an incorrect fit.
4. Do not warm the Retroreflectors with respect to the Retroreflector Mount. The expansion of the Retroreflectors could produce an interference fit.

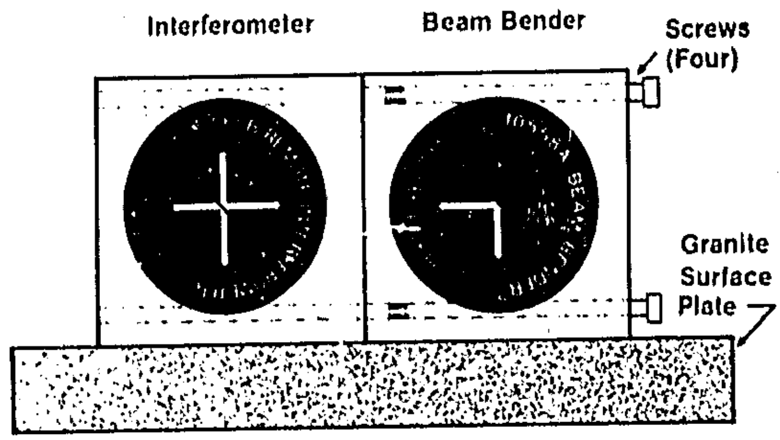


Figure 4-4 Wringing of the Angular Optics

Figure 4-4 shows the correct orientation of the Interferometer and Beam Bender prior to wringing. Carefully clean the mating surfaces with alcohol and a clean, soft, lintless wipe. A thin film of oil or alcohol can then be applied to aid in wringing. Slide the Beam Bender onto the top of the Interferometer. Press the Beam Bender and Interferometer together forcing any trapped air from between the mating surfaces. Slowly rotate the Beam Bender while maintaining wringing pressure. The correct alignment of the Beam Bender and Interferometer can be accomplished by pressing the wrung optics down on a clean inspection grade surface plate. Lock the optics together only finger tight with 4 slot head screws provided. Do not over tighten. To insure that tightening the screws has not changed the orientation of the optics, press down on the corners of the optics. No rocking should be detected.

VISUAL ALIGNMENT OF BEAM BENDER AND INTERFEROMETER

When a surface plate in good condition is not available, the correct alignment can be determined by setting up as shown in figure 4-5 or 5-1. Follow the Angular Setup and Alignment procedure. Mount the Reflector Mount at the near end of travel to obtain a return dot at the desired Return Port. Position the Interferometer/Beam Bender in the laser beam as close to the Reflector Mount as possible and obtain a second return dot. Rotate the Interferometer/Beam Bender as a unit to overlap the dots as much as possible. Move the Reflector Mount away from the Interferometer as far as possible, 10 ft. or more is preferred. The return dots should remain overlapped. If not, rotate the Beam Bender to overlap the dots horizontally. Perfect vertical overlap may not be possible. Retighten the slot head screws. Move one optic toward the other until they are as near as possible. The dots should remain overlapped. If not, repeat the above procedure.

When maximum overlap is attained perform the following Assembly and Accuracy checks.

ASSEMBLY AND ACCURACY CHECKS

Place the Angular optics on a clean Lab grade surface plate. Align the optics, following the Angular Setup and Alignment Procedure, along a straightedge in good lab condition and adjust the laser head to maintain beam alignment while moving the optics along the straightedge. A 12 inch straightedge is sufficient. See Figure 4-5. Press Reset on the Laser Display.

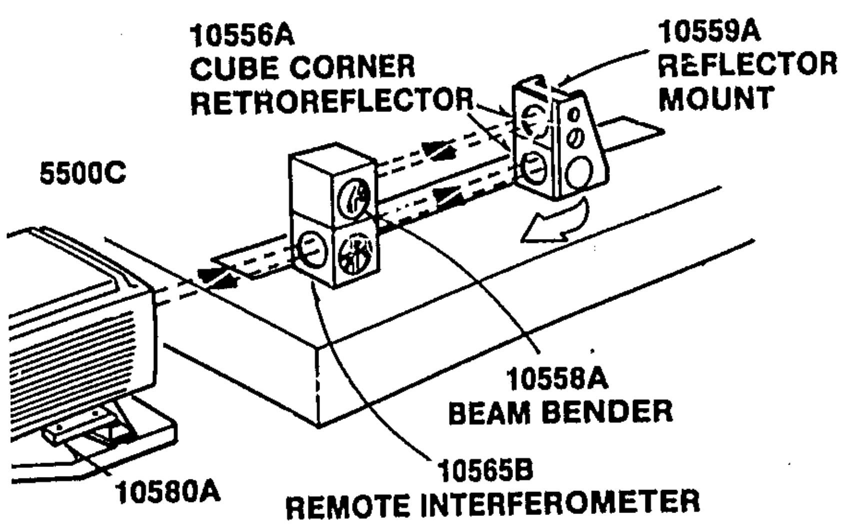


Figure 4-5. Angular Optics Accuracy Checks

While maintaining the front foot of the Reflector Mount against the straight edge, rotate the rear foot 0.100000 in. (2.54mm) away from the straight edge. For accuracy use a gage block. The Laser Display should accumulate <100 uin (2.54um). This test checks the centering of the Retroreflectors in the 10556A Assembly and the 10559A Reflector Mount.

Remove the gage block and place the Reflector Mount flush against the straight edge. The Laser Display should read zero. If not, insure clean contacting surfaces and repeat the above until precision is established.

Press Reset on the Laser Display. Slowly move both ends of the Reflector Mount away from the straight edge by 0.100,000 inches (2.54mm). The Laser Display should accumulate <10 uin (2.54um). This procedure checks the parallel alignment of the two laser beams exiting from the Interferometer/Beam Bender. If this test fails, check the return dot overlap at the Laser Head Turret with the optics as far apart as possible using the Reduced Aperature and Alignment Target. The dots should be overlapped at least in the horizontal plane. If not, follow the Visual Alignment of Beam Bender to Interferometer procedure above and recheck. If the check cannot be passed the optics will measure angles and flatness inaccurately. The wringing surfaces should be closely inspected and the problem rectified before measurements are attempted.

ANGULAR MEASUREMENT CONSIDERATIONS

ARC SECONDS DIRECT READ OUT

Arc seconds are indicated directly on the Laser Display only when units of inches has been selected on the Laser Display Units Switch

ACCURACY

Accuracy of the angular optics is limited to four factors:

1. Approximation of the displayed value to arc seconds.
2. Separation of the laser measurement paths L1 and L2.
3. Parallelism of the laser measurement paths L1 and L2.
4. Thermal stability of the optics during a measurement.

THERMAL EXPANSION

External heat sources should be avoided and sufficient thermal equilibrium reached before using the Angular optics. Measurement error can result from thermal expansion of a measuring instrument during a measurement. Non-typical measurements will result if non-typical operating conditions exist during the measurements.

Thermal stability of the Interferometer/Beam Bender and Reflector Mount can significantly affect measurement accuracy and precision. The 2.0625 beam spacing will change by 11 ppm/degree C (5.5 ppm/degree F) or the coefficient of expansion of the 416 stainless steel housings of the Beam Bender and Interferometer. A 1.0 degree F increase or decrease in temperature of the Interferometer/Beam Bender during a measurement will result in a 1.1 arc second error.

Always insure sufficient thermal stability to obtain the desired accuracy before dimensional measurements are attempted.

MEASUREMENT TIME INTERVAL

Due to outside influences affecting most measurements, the time interval required for the measurement should be as short as possible. Angular measurements are included in this rule. The angular optics give optimal results when measurement times are short.

FIXTURING

Most machines are safely assumed to be two or more rigid structures, with freedom of movement between two or more of the structures. Rotation of one rigid structure will result in all points on that structure rotating equally. The rotation will be equally measured anywhere on that structure with respect to another structure. Care should be taken that the desired measurement is accomplished. Rotation is a relative measurement in that one optic is mounted on a machine member to measure rotation relative to another machine member on which the other optic must be mounted (referenced).

Fixturing must be rigid, as short as possible, and indicative of how the machine is used. One optic is mounted in the tool position as a tool would mount. The other optic is mounted where a part would mount. This is the safest way to measure when in doubt of correct mounting.

NON-CONSIDERATIONS FOR ANGULAR

BEAM ALIGNMENT-COSINE ERROR

Beam alignment as indicated by the Beam Alignment Meter on the Laser Display need only be sufficiently into the green region (greater than 5% usable signal) during the measurement to prevent a Zero Reset by the automatic reset function of the Reset button on the Laser Display. Cosine Error does not affect the accuracy of measurements using the Angular optics.

ABBE ERROR

Abbe offsets have no effect on the accuracy of angular measurements. Machines typically measured or investigated with the Angular optics are designed to resist flex. Stresses great enough to cause flexing of a machine typically reduce the accuracy, shorten the life expectancy and should be avoided. A non-flexible or Rigid Body will rotate all points on its structure equally and the position of the optics on a rigid body has no effect on the resulting rotational data.

DEADPATH ERROR

The angular optics effectively eliminate dead path error due to the differential nature of the measurement technique.

COMPENSATION

Compensation and dead path error are related in that changes in the density of air result in Linear measurement errors. When using the Angular optics changes in one measurement path (L1) due to changes in the density of air are cancelled by equal changes in the other measurement path (L2). During the measurement only the difference between L1 and L2 is measured and displayed. Velocity of light differences in L1 and L2 are therefore very small compared to the one part per thousand angular optics accuracy specification. For this reason, the Laser Display Thumb Wheel Switches and the Automatic Compensator have no affect on measurement accuracy.

SECTION

V - VI

SECTION V

PITCH AND YAW MEASUREMENTS

Pitch is measured when the optics are mounted in the vertical plane. Yaw is measured when the optics are in the horizontal plane. When measuring Pitch, the optics are insensitive to Yaw and vice versa.

Many types of machines have parts that are required to travel in straight lines from one point to another along an axis. It is usually required that the part move in a straight line in that axis. The truth upon close inspection is that machine parts do not travel in straight and direct paths from point to point. They rotate and translate during their journey. Both positioning accuracy and precision depend on how well the table rotation and translation is controlled as it is positioned.

Angular errors affect linear positioning accuracy and precision, squareness precision and range, and can contribute to straightness errors. Squareness is not a fixed number. It varies as the machine positions. The change in squareness is called range. The range of a machine's squareness is pitch and yaw. For example: A table traveling in X below a vertical spindle is checked for squareness with respect to the Z spindle axis at the center X position. The result is +2.5 arcsec out of square, (2.5X5=12.5 microin./in. or 125tenths/ft.). As the table travels it also pitches a total of +2+/-1 arcsec (0.00012/ft.); 1 arcsec to each side of the table center position,+/-1 arcsec. If squareness is checked at either end of travel it will be different by +1 arcsec on one side and -1 arcsec on the other, most of the time. The +/-1 indicates the pitch or squareness precision.

The measured squareness in the center of travel would be called the squareness accuracy. The +/-1 arcsec is the squareness range. If squareness is checked several times at the center position it will be different each time by +/-1. That is the squareness precision.

Squareness range also has precision. Squareness Range precision is the precision of an angular measurement.

From the above example, the specification for squareness would be Squareness of X to Z = 2.5 arcsec, Range = +/-1 arcsec, Precision = +/-1 arcsec.

Conclusion: When a machine has pitch, yaw, or roll, the squareness is changing. The linear scales do not know about this changing geometry and position the machine inaccurately. The magnitude of the linear inaccuracy (Abbe error) is proportionate to the angular change and the distance between the scale, (or calibration axis) and the work position (Abbe offset).

The angular optics are insensitive to linear displacement or straightness displacemant (translation). Straightness errors are measured by the Straightness optics. The out of straightness experienced in cutting or measuring parts as a result of pitch, yaw, and roll, is measured by the Straightness optics as part of the total out of straightness error perpendicular to the axis under investigation.

PITCH AND YAW EFFECTS ON LINEAR POSITIONING

Angular displacement of a machine table will cause a linear positioning error that increases proportionatly as the distance between the machine scale or axis of linear calibration and the working position (cutting point) increases. The magnitude and repeatability of Pitch and Yaw will accurately determine the best and worst case positioning accuracy and precision at any point within the machine working area, and in a minimum of measurements,

How well a multi-axis machine positions near its table top is very different from how it positions away from the table top. Depending on the Abbe effect. The best case linear positioning accuracy will usually be the machine path closest to the scale for a particular axis, unless the machine scale was compensated along some other calibration axis.

To determine how accurately and precisely a machine will position at some Abbe offset, the following steps can be taken.

1. Determine the location of the calibraion axis or the machine scale for the individual axis of travel. Inside lower edge of the work area is assumed for the following examples. Also assumed: x and y are horizontal and the z axis is vertical, as in Figure 5-1.

2. Perform an x axis linear positioning check for accuracy and precision at a defined position on the machine table, preferably with the minimum Abbe offset to the machine scale or along a most often used machine path. This axis is the x axis Calibration Axis.

   A. Abbe's law tells us that the best case positioning accuracy of a machine tool will be the machine path closest to the machine scale - minimum Abbe offset between the machine scale and tool axis. When scale compensation is available the best case positioning accuracy will be along the calibration axes.

B. By definition, precision cannot be determined by one or two runs of positioning checks. Several runs must be made for an adequate statistical sample. Five is often used, seven is recommended by the NMTBA.

National Machine Tool Builders Association (7901 West Park Drive, McLean, Virginia, 22101, (703) 893-2900), Definition and Evaluation of Accuracy and Repeatability for Numerically Controlled Machine Tools.

If the Calculator plotter option is available, the data for each run can be formatted and recorded with the General Error program. Accuracy and Precision is then plotted with the Statistical Error Analysis program.

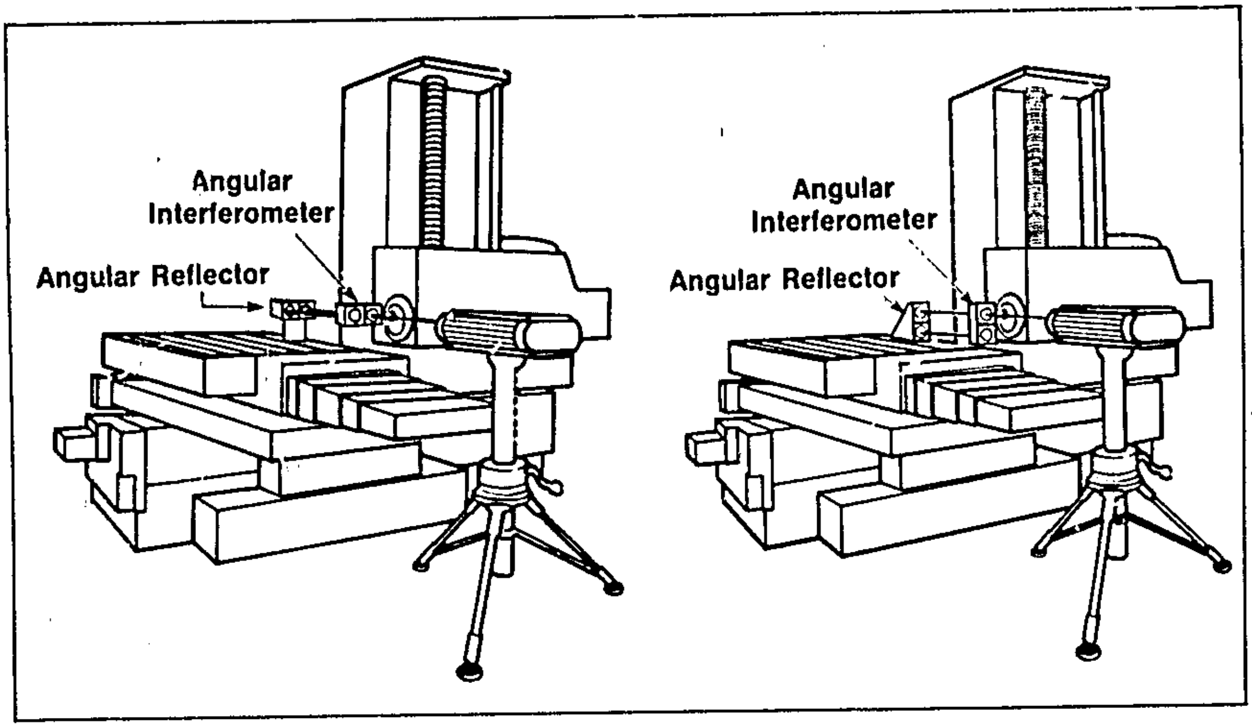


Figure 5-1. Measurement Setups for Pitch and Yaw

3. Position the Angular optics to measure Pitch along the same axis checked in Step 1 (do not reposition the Laser head and/or Tripod). The inside lower edge of the work area has been assumed.

A. It is helpful to plot, sketch or otherwise note the exact position of this calibration axis and the maximum(s) found. It will be used later to predict worst case positioning accuracy and precision. positioning

B. Again, precision of any measurement cannot be determined by one run of data! At least a check of the maximum pitch and the repeatability of Pitch at that location should be determined and recorded.

C. Be sure to determine what the sign of the data means relative to the machine movement and positioning accuracy.

4. Repeat #3 collecting the Yaw data.

NOTE

This pitch and yaw data also is the range of the machine's squareness. The squareness of X and Z will change by pitch value. X to Y squareness will change by the yaw value.

5. Determine the Abbe offsets.

A. Determine the remaining lengths of machine travel in the Y and Z axes.

6. Multiply the maximum angular errors and their precision (in arc seconds) by 5. Example: Pitch of +4 +/- 2 arc seconds +4 +/-2 x 5 = +20 +/-10 uin/in.

The result is maximum linear positioning Abbe error and precision in the x axis per inch of z axis travel from the Calibration axis.

Multiply again by Z axis the Abbe offset in inches found in #5 above. The result is the linear positioning Abbe error in X at the extreme of machine travel in Z.

7. Add this Abbe error from #6 to the positioning accuracy and precision found at the same x axis coordinate position recorded in #2. The result is the worst case positioning accuracy and precision in the x axis along the inside upper edge of the working area.

8. To determine the x axis positioning Accuracy and Precision along the outside lower edge of the working area repeat #6 & 7 for the x axis Yaw and the Abbe offset in the y axis --

Yaw x 5[Y Abbe offset] = Yaw Abbe error in X

9. To determine the outside upper edge accuracy and precision, algebraically add the values found in 7 & 8. This will be the worst case positioning in x anywhere in the working area of this machine when the machine is calibrated at the inside lower edge of the work zone.

NOTE

The extreme Abbe offsets from the machine scale or the calibration axis will always result in worst positioning ability.

SECTION VI

FLATNESS MEASUREMENTS

The flatness of a surface such as a surface plate or a machine way can be quickly determined with the angular optics and the calculator plotter option. (Flatness of a way can also be measured with the Straightness optics, see Section 14).

By spacing foot pads on the base of the 10559A Reflector Mount at the same spacing as the distance between the laser beams, when the rear foot pad is raised one uin., the upper Retroreflector will also move one uin. with respect to the lower Retroreflector. This shortens laser measurement path L1 with respect to L2 by one uin. This is shown in Figure 6-1.

Application Note 156-2 explains briefly how the Angular optics are used to collect the necessary data to calibrate a surface plate.

NOTE

Proper preparation of the surface plate prior to calibration and reworking of the surface plate is beyond the scope of this manual or the 156-2 Application Note.

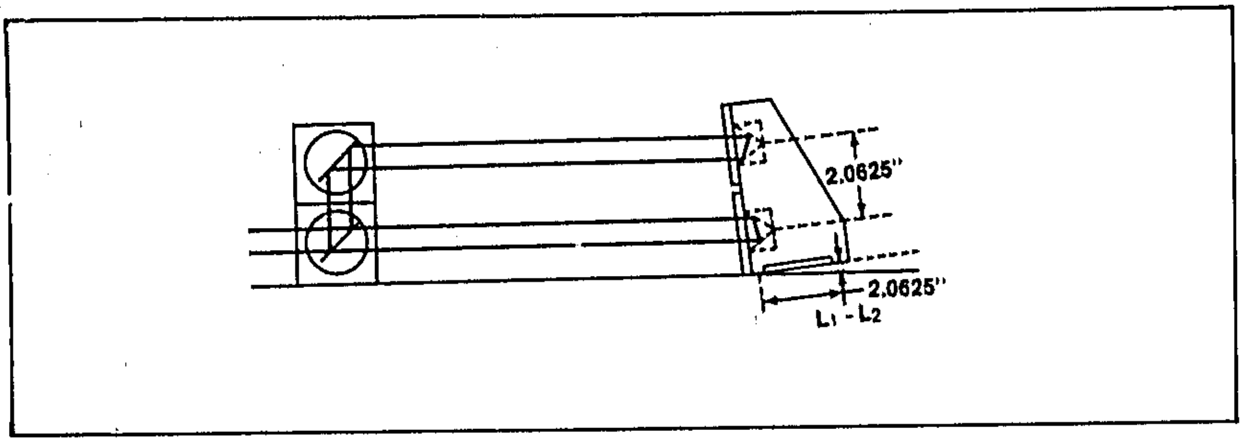


Figure 6-1. Flatness Me surement

Flatness measurements are obtained by intergrating a series of measurements taken as the Angular optics follow surface variations along a measurement path. Figure 6-2 describes the process of taking measurements for flatness. Position A is the Reset position and relative zero elevation. The Reflector Mount is moved "one foot pad spacing" to position B where the front foot rests where the back foot was is position A or zero. The new height of the rear foot at position B will be displayed and should be recorded. At position C the Reflector Mount front foot will now be where the rear foot was in position B and the back foot will be at a new height above or below that in position B. The value of C is algebraically added to B (and A, if A has a value other than zero) to find the total distance above or below zero. This process is continued to the end of the measurement path, each new foot height is algebraically added to the previous total. This is the same method used with an auto columnator and used in the Moody Method. Other methods are sometimes used for flatness, however the calculator plotter software includes only the Moody method.

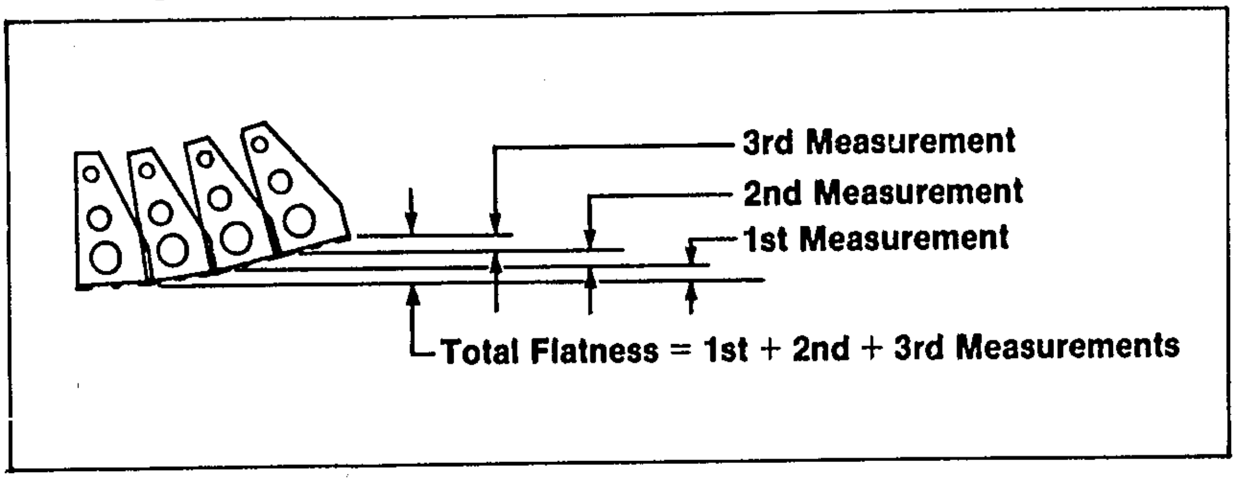


Figure 6-2. Integrating a Curve

SECTION

VII

SECTION VII

ROTARY TABLE CALIBRATION

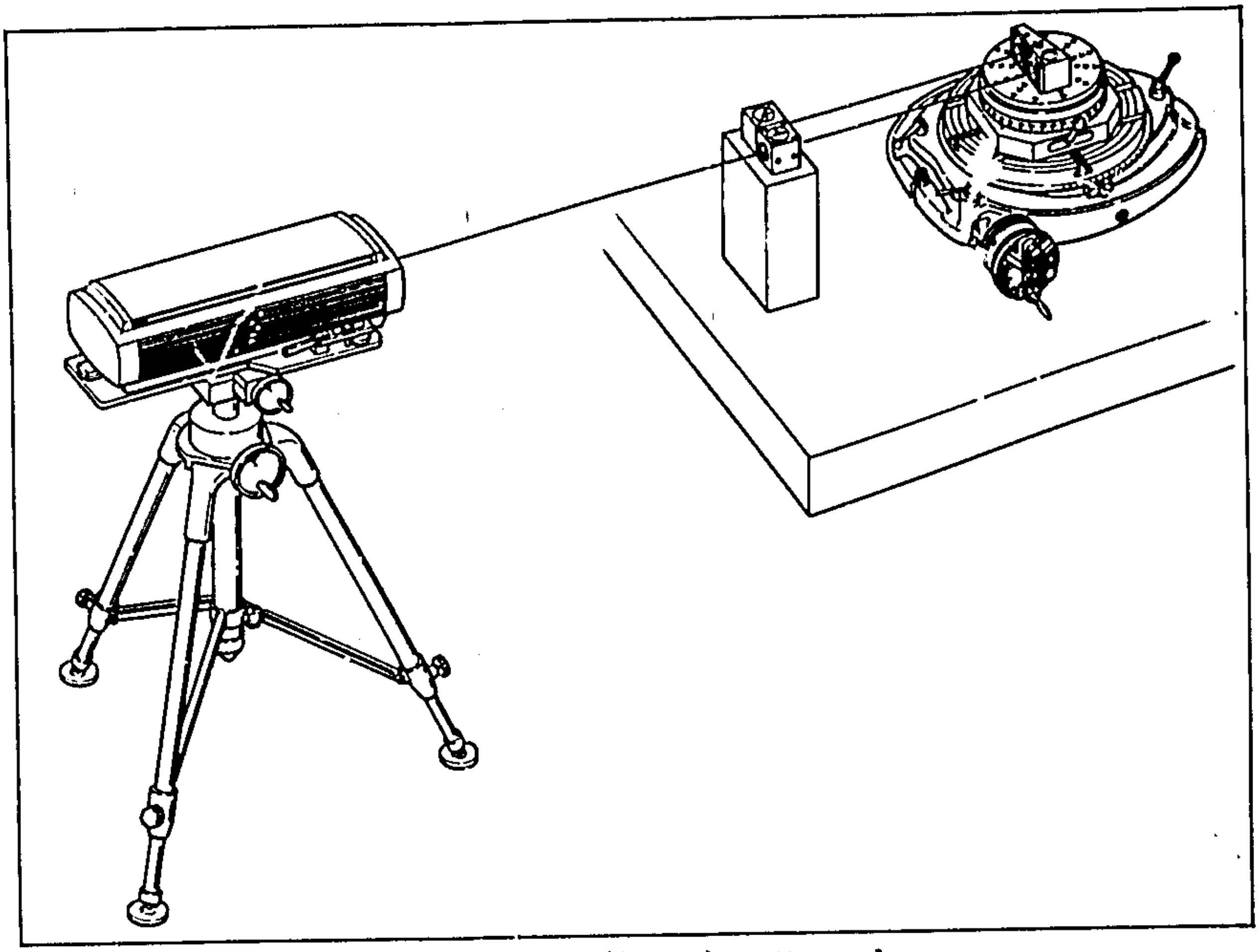


Figure 7-1. Rotary Table Calibration Example

Beam alignment is established by the following steps:

1) Align the Laser Head with Autoreflector to a mirror positioned on the uppermost table top shown in Figure 7-1 and relatively perpendicular to the table top. Alignment is necessary only to insure sufficient signal strength during the measurements.

2) Assemble the Angular optics

3) Position the Reflector Mount on the top table to return the Laser beam to the desired Return Port from one of the Retroreflectors. A short plug gage of the appropriate diameter will center the Reflector on most rotary table centers.

4) Position the Interferometer/Beam Bender to return the overlapped return beams.

5) Rotate either table to find the center of the Beam Alignment Meter Needle Peak. Maximum measurement rotation is table rotation to each side of this position.

6) One procedure is to zero both tables and rotate the Reflector Mount to a low but safe Beam Alignment Meter reading in the direction opposite test rotating. The table under test is rotated through a test region of +/- 10 degrees. The Beam Alignment Meter will peak and drop down. Stop before Alignment is lost. Refinement of the optics position and alignment may be necessary to attain maximum angular range.

7) At the end of each +/- 10 degrees test region, rotate the reference table back through the alignment peak to return the Laser Display to Zero. This process can be automated with user generated software, the calculator plotter system, and motorized tables. The Angular optics are used as the master angular scale and each return to zero. For manual calibrations the table used to zero the Laser Display need not be accurate, or totally illuminated.

MANUAL CHANGES

HEWLETT PACKARD — MANUAL CHANGES

MANUAL DESCRIPTION

INSTRUMENT: 5526A Opt. 210

SERIAL PREFIX: NA

DATE PRINTED: September, 1975
HP PART NO: 05526-90030
MICROFICHE NO: 05526-90031

CHANGE DATE December 16, 1975

(This change supersedes all earlier dated changes)

- Make all changes listed as ERRATA.
- Check the following table for your instrument's serial prefix or serial number and make listed change(s) to manual.

IF YOUR INSTRUMENT HAS SERIAL PREFIX OR SERIAL NUMBER	MAKE THE FOLLOWING CHANGES TO YOUR MANUAL	IF YOUR INSTRUMENT HAS SERIAL PREFIX OR SERIAL NUMBER	MAKE THE FOLLOWING CHANGES TO YOUR MANUAL

► NEW OR REVISED ITEM

► ERRATA

Page ii (Reverse side of Title Page) Add:

TABLE OF CONTENTS

Insert the following attached "A" reprinted pages in manual:

8A, 9A, 12A, 13A, 17A, 20A, 24A, 25A, 29A, 33A, 43A, 44A, 50A, 55A, 59A, 68A, 69A, 70A

PROGRAM LISTING

```
0:
CFG 2;CFG 13;
ENT "METRIC?",Z;
IF FLG 13;SFG 2⊢
1:
CFG 13;ENT "EDIT
 DATA?",Z;IF
FLG 13;TBL 4⊢
2:
21→B;2.0625→Y;
FXD 0⊢
3:
CFG 13;ENT "LI
NE NO?",Z;Z→X⊢
4:
IF FLG 13;GTO 36
⊢
5:
1→R19;IF 0>X;-X→
X;-1→R19⊢
6:
IF (X>4)+(1>X);
JMP -3⊢
7:
X+10→A;IF RA=0;
GTO +3⊢
8:
GSB "A"⊢
9:
A→B;X+10→A⊢
10:
ENT "FOOT SPACIN
G?",Y⊢
11:
R19*Y/2.0625→R19
⊢
12:
IF FLG 2;JMP 2⊢
13:
R19/25.4→R19⊢
14:
CFG 1;CFG 13;
ENT "KEYBOARD IN
PUT?",Z⊢
15:
IF FLG 13;SFG 1⊢
16:
0→RA→R5;0→RB;-1→
Z⊢
17:
IF FLG 1;JMP 4⊢
18:
CFG 13;ENT "DATA
?",R(B+1→B)⊢
19:
IF FLG 13;JMP 7⊢
20:
JMP 3⊢
21:
RED 3,R(B+1→B),R
B⊢
22:
IF Z=0;JMP 4⊢
23:
PRT RB⊢
24:
RB*R19→RB⊢
25:
JMP -8⊢
26:
(B-R5+1)*1E3+RA→
RA⊢
27:
SPC 2;R5→A;0→Z⊢
28:
RA+Z→RA→Z;JMP (A
+1→A)>B⊢
29:
R5→A⊢
30:
RB/(B-A)→R1⊢
31:
0→Z⊢
32:
RA-Z*R1→RA;Z+1→Z
;JMP (A+1→A)>B⊢
33:
R5→A;B-A+1→C⊢
34:
0→Z;GSB "L"⊢
35:
B+1→B;GTO 3⊢
36:
1→X→R20⊢
37:
GSB "M"⊢
38:
RA-R1→RA;JMP (A+
1→A)>B⊢
39:
IF X=1;2→X;JMP -
2⊢
40:
1→X⊢
41:
GSB "A"⊢
42:
RA→R(X*2-1)⊢
43:
RB→R(X*2)⊢
44:
IF X=1;2→X;JMP -
3⊢
45:
3→X;R3→Y;R1→Z;
GSB "E"⊢
46:
4→X;R3→Y;R2→Z;
GSB "E"⊢
47:
5→X;R2→Y;R4→Z;
GSB "E"⊢
48:
6→X;R1→Y;R4→Z;
GSB "E"⊢
49:
3→X⊢
50:
GSB "M"⊢
51:
R1→RX;IF (X+1→X)
≤6;JMP -1⊢
52:
7→X;R4→Y;R6→Z;
GSB "E"⊢
53:
8→X;R3→Y;R5→Z;
GSB "E"⊢
54:
7→X⊢
55:
GSB "M"⊢
56:
R1→RX;IF X=7;8→X
;JMP -1⊢
57:
21→A;RA→X→Y;R20→
B⊢
58:
IF X>RA;RA→X⊢
59:
IF RA>Y;RA→Y⊢
```

```
60:
IF (A+1→A)<B;
JMP -2⊢
61:
ABS (X-Y)→R1⊢
62:
PRT "CLOSURE ERR
OR","LINE 7",R7,
"LINE 8",R8,"MAX
 ELEV",R1;SPC 8⊢
63:
21→A⊢
64:
RA-X→RA;JMP (A+1
→A)>B⊢
65:
1→X→Z⊢
66:
CFG 13;ENT "PRIN
T?UT?",Z⊢
67:
IF FLG 13;JMP 5⊢
68:
GSB "A"⊢
69:
GSB "L"⊢
70:
IF (X+1→X)<8;
JMP -2⊢
71:
SPC 10⊢
72:
CFG 13;ENT "RECO
RD DATA?",Z⊢
73:
IF FLG 13;JMP 3⊢
74:
R20→B;ENT "FILE
NO?",Z⊢
75:
→RCF Z,R0,R210⊢
76:
GTO 0⊢
77:
"A"⊢
78:
A+10→B;INT (RB/1
E3)→C⊢
79:
RB-C*1E3→A⊢
80:
IF (A+C-1→B)>R20
;B→R20⊢
81:
RET ⊢
82:
"L"⊢
83:
PRT "LINE",X,""⊢
84:
PRT RA;JMP (A+1→
A)>B⊢
85:
PRT "",C;SPC 3⊢
86:
RET ⊢
87:
"E"⊢
88:
A→R7;GSB "A"⊢
89:
Y-RA→R9⊢
90:
(Z-RB-R9)/(C-1)→
RB⊢
91:
RA+R9+R7*RB→RA;R
7+1→R7;JMP (A+1→
A)>B⊢
92:
RET ⊢
93:
"M"⊢
94:
GSB "A"⊢
95:
(A+B)/2→Z;RZ→R1⊢
96:
IF Z-INT Z>0;(RZ
+R(Z+1))/2→R1⊢
97:
RET ⊢
98:
END ⊢
Σ19408
R227
```

```
0:
FXD 0;PEN ;35→R2
⊢
1:
ENT "TILT ANGLE?
",R2⊢
2:
COS R2→R19;SIN R
2→R20;10→R2⊢
3:
ENT "ROT. ANGLE?
",R2;COS R2→X;
SIN (-R2)→Y⊢
4:
X+Y→R9;X-Y→R10⊢
5:
SCL -110R9,110R1
0,-10,(110R9+110
R10)R20+30;LTR 0
,0,211⊢
6:
0→X→Y→Z;GSB "P"⊢
7:
100→X;GSB "P"⊢
8:
100→Y;GSB "P"⊢
9:
0→X;GSB "P"⊢
10:
0→Y;GSB "P"⊢
11:
100→X→Y;GSB "P"⊢
12:
PEN ;50→Y;GSB "P
"⊢
13:
0→X;GSB "P"⊢
14:
PEN ;100→Y;GSB "
P"⊢
15:
100→X;0→Y;GSB "P
"⊢
16:
PEN ;50→X;GSB "P
"⊢
17:
100→Y;GSB "P"⊢
18:
PEN ;50→X;0→Y;-R
1/4→Z;GSB "P"⊢
19:
PLT "CLOSURE 7
   ";PLT R3⊢
20:
PEN ;-R1/2→Z;
GSB "P"⊢
21:
PLT "CLOSURE 8
   ";PLT R8⊢
22:
PEN ;-R1*3/4→Z;
GSB "P"⊢
23:
PLT "MAX EL
   ";PLT R1⊢
24:
PLT 1E3,1E3;DSP
"CHANGE PEN?";
STP ⊢
25:
PEN ;1→X;0→R3;10
0→R4⊢
26:
100→R5;0→R6;GSB
"L"⊢
27:
PEN ;2→X;100→R3→
R4⊢
28:
0→R5→R6;GSB "L"⊢
29:
PEN ;3→X;100→R3→
R4⊢
30:
0→R5;100→R6;GSB
"L"⊢
31:
PEN ;4→X;100→R3→
R4⊢
32:
100→R5;0→R6;GSB
"L"⊢
33:
PEN ;5→X;100→R3;
0→R4⊢
34:
0→R5→R6;GSB "L"⊢
35:
PEN ;6→X;0→R3;10
0→R4⊢
36:
0→R5→R6;GSB "L"⊢
37:
PEN ;7→X;100→R3;
50→R4⊢
38:
0→R5;50→R6;GSB "
L"⊢
39:
PEN ;8→X;50→R3;1
00→R4⊢
40:
50→R5;0→R6;GSB "
L"⊢
41:
PEN ;LTR 140,175
;STP ⊢
42:
"P"⊢
43:
PLT X*R10-Y*R9,(
X*R9+Y*R10)*R20+
Z*30/R1⊢
44:
RET ⊢
```

```
45:
"L":GSB "A"⊦
46:
(R5-R3)/(C-1)→R0
⊦
47:
(R6-R4)/(C-1)→R2
⊦
48:
RA→Z;R3→X;R4→Y⊦
49:
GSB "P"⊦
50:
0→Z;GSB "P"⊦
51:
RA→Z;GSB "P"⊦
52:
R3+R0→R3⊦
53:
R4+R2→R4⊦
54:
A+1→A;IF A≤B;
JMP -6⊦
55:
RET ⊦
56:
"A":X+10→R0⊦
57:
INT (RR0/1000)→C
;RR0-C*1000→A;A+
C-1→B⊦
58:
RET ⊦
59:
END ⊦
Σ2310
R269
```

```
0:
CFG 1⊢
1:
CFG 13;ENT "POSI
TIVE DATA?",Z;
IF FLG 13;R1/2→R
3→R4;SFG 1;JMP 2
⊢
2:
0→R3;R1→R4⊢
3:
FXD 0;SCL -10,11
0,-10,110⊢
4:
CFG 13⊢
5:
ENT "LINES ?",A⊢
6:
IF FLG 13;JMP 4⊢
7:
PEN ;PLT 0,0;
PLT 0,100;PLT 10
0,100;PLT 100,0;
PLT 0,0;PLT 100,
100;PEN ;PLT 0,1
00;PLT 100,0⊢
8:
PEN ;PLT 100,50;
PLT 0,50;PEN ;
PLT 50,100;PLT 5
0,0;PEN ;AXE -10
,-10;AXE 110,110
⊢
9:
DSP "CHANGE PEN?
";STP ⊢
10:
1→X;GSB "A"⊢
11:
0→X;100→Y;100/C→
Z;A-1→A⊢
12:
LTR X,Y,211;PLT
RA-R3;X+Z→X;Y-Z→
Y;JMP (A+1→A)>B+
1⊢
13:
2→X;GSB "A"⊢
14:
100→X→Y;100/C→Z;
A-1→A⊢
15:
LTR X,Y;PLT RA-R
3;X-Z→X;Y-Z→Y;
JMP (A+1→A)>B+1⊢
16:
3→X;GSB "A"⊢
17:
100/C→Z;(100→Y)-
Z→X⊢
18:
LTR X,Y;PLT RA-R
3;X-Z→X;JMP (A+1
→A)>B⊢
19:
4→X;GSB "A"⊢
20:
100/C→Z;(100→X)-
Z→Y⊢
21:
LTR X,Y;PLT RA-R
3;Y-Z→Y;JMP (A+1
→A)>B⊢
22:
5→X;GSB "A"⊢
23:
0→Y;100-(100/C→Z
)→X⊢
24:
LTR X,Y;PLT RA-R
3;X-Z→X;JMP (A+1
→A)>B⊢
25:
6→X;GSB "A"⊢
26:
0→X;100-(100/C→Z
)→Y⊢
27:
LTR X,Y;PLT RA-R
3;Y-Z→Y;JMP (A+1
→A)>B⊢
28:
7→X;GSB "A"⊢
29:
50→Y;100-(100/C→
Z)→X⊢
30:
LTR X,Y;PLT RA-R
3;X-Z→X;IF A+1=R
2;A+1→A;X-Z→X⊢
31:
A+1→A;IF A<B;
JMP -1⊢
32:
8→X;GSB "A"⊢
33:
50→X;100-(100/C/
2)→Y⊢
34:
LTR X,Y;PLT RA-R
3;Y-Z→Y;IF A+1=R
2;A+1→A;Y-Z→Y⊢
35:
A+1→A;IF A<B;
JMP -1⊢
36:
LTR 70,55;PLT "C
LOSURE ";PLT R7;
LTR 55,85,211;
PLT "CLOSURE ";
PLT R8⊢
37:
IF FLG 1;LTR 46,
-8;PLT "MAX DEV
+/- ";PLT R4;
JMP 2⊢
38:
LTR 46,-8;PLT "M
AX EL ";PLT R4⊢
39:
PEN ;PLT 47,110;
PLT 57,110;PLT 5
7,107;PLT 47,107
;PLT 47,110⊢
40:
PLT 1E3,1E3;STP
⊢
41:
"A";GSB "A"⊢
42:
(A+B)/2→R2⊢
43:
IF R2-INT R2>0;0
→R2;RET ⊢
44:
RET ⊢
45:
"A";X+10→R0⊢
46:
INT (RR0/1000)→C
;(RR0-C*1000+1→A
)+(C-1→C)-2→B⊢
47:
RET ⊢
48:
END ⊢
Σ2903
R266
```

PROGRAM LISTING

```
0:
CFG 1;CFG 2;CFG
3;2.0625→Y;FXD 6
⊢
1:
CFG 13;ENT "RADI
ANS?",Z⊢
2:
IF FLG 13;TBL 1;
JMP 2⊢
3:
TBL 2;SFG 3;JMP
4⊢
4:
CFG 13;ENT "ARCS
ECONDS?",Z⊢
5:
IF FLG 13;JMP 2⊢
6:
SFG 2⊢
7:
CFG 13;ENT "KEYB
OARD INPUT?",Z;
IF FLG 13;SFG 1⊢
8:
IF FLG 1;JMP 10⊢
9:
CFG 13;ENT "DATA
?",R0⊢
10:
IF FLG 13;JMP -1
0⊢
11:
ASN (R0/Y)→R1⊢
12:
IF FLG 2;R1*3600
→R1⊢
13:
PRT "INPUT",R0⊢
14:
IF FLG 3;PRT "RA
DIANS",R1;JMP 3⊢
15:
IF FLG 2;PRT "AR
CSECONDS",R1;
JMP 2⊢
16:
PRT "DEGREES",R1
⊢
17:
SPC 1;JMP -9⊢
18:
-1→Z;RED 3,R0,R0
;R0*0.000001→R0⊢
19:
IF Z=0;JMP -13⊢
20:
JMP -9⊢
21:
END ⊢
S485
R371
```

```
0:
FXD 1⊢
1:
PRT "IS COMPENSA
TION"⊢
2:
PRT "FACTOR TO B
E"⊢
3:
PRT "COMPUTED US
ING"⊢
4:
PRT "ENGLISH OR"
⊢
5:
PRT "METRIC UNIT
S ?"⊢
6:
SPC 2⊢
7:
PRT "INPUT 0 ON"
⊢
8:
PRT "KEYBOARD FO
R"⊢
9:
PRT "ENGLISH UNI
TS"⊢
10:
SPC 2⊢
11:
ENT "ENG OR METR
IC ?",Z;IF FLG 1
3=0;SFG 1⊢
12:
SPC 3⊢
13:
PRT "  COMPENSAT
ION"⊢
14:
PRT "     FACTOR
"⊢
15:
SPC 1⊢
16:
IF FLG 1;GTO 63⊢
17:
PRT "  METRIC UN
ITS"⊢
18:
TBL 4;TBL 5⊢
19:
SPC 2⊢
20:
ENT "AIR TEMP?",
R1⊢
21:
PRT "AIR TEMPERA
TURE"⊢
22:
PRT R1⊢
23:
SPC 1⊢
24:
ENT "AIR PRESSUR
E?",R2⊢
25:
PRT "AIR PRESSUR
E"⊢
26:
PRT R2⊢
27:
ENT "HUMIDITY %
?",R3⊢
28:
SPC 1⊢
29:
PRT "HUMIDITY"⊢
30:
PRT R3⊢
31:
SPC 1⊢
32:
IF FLG 1;GTO 65⊢
33:
ENT "EXP COEFF P
PM/C ?",R4;IF R4
=0;GTO 52⊢
34:
IF R4≠0;PRT "EXP
 COEFF PPM/C"⊢
35:
PRT R4⊢
36:
SPC 1⊢
37:
CFG 13;ENT "MAT'
L TEMP1?",Z;IF
FLG 13;IF FLG 1;
68→R8;GTO 69⊢
38:
IF FLG 13;20→R8;
GTO 52⊢
39:
PRT "MAT'L TEMP1
",Z→R5⊢
40:
SPC 1⊢
41:
CFG 13;ENT "MAT'
L TEMP2?",Z;IF
FLG 13;1→X;GTO 5
0⊢
42:
PRT "MAT'L TEMP2
"⊢
43:
PRT Z→R6⊢
44:
SPC 1⊢
45:
CFG 13;ENT "MAT'
L TEMP3?",Z;IF
FLG 13;2→X;GTO 5
0⊢
46:
Z→R7;3→X⊢
47:
PRT "MAT'L TEMP3
"⊢
48:
PRT R7⊢
49:
SPC 1⊢
50:
(R5+R6+R7)/X→R8⊢
51:
IF FLG 1;GTO 69⊢
52:
.3836391*R2*(1+1
E-6*R2*(.817-.01
33*R1))/(1+.0036
61*R1)→R9⊢
53:
R9-3.033*(.001*R
3)*EXP (.057627*
R1)→R11⊢
54:
1E12/(R11+1E6)-9
99000→R12⊢
55:
IF R4=0;R12→R13;
GTO 60⊢
```

```
56:
IF FLG 1;GTO 72⊦
57:
R12-(R8-20)*R4→R
14⊦
58:
IF FLG 1=0;R14→R
13⊦
59:
SPC 1⊦
60:
PRT "THUMBWHEEL
SET"⊦
61:
PRT R13;SPC 8;
GTO 74⊦
62:
GTO 18⊦
63:
PRT " ENGLISH UN
ITS"⊦
64:
GTO 18⊦
65:
CFG 13;ENT "EXP
COEFF PPM/F ?",Z
;IF FLG 13;GTO 6
9⊦
66:
PRT " EXP COEFF
PPM/F"⊦
67:
PRT Z→R4⊦
68:
GTO 37⊦
69:
9.7443*R2*(1+1E-
6*R2*(26.7-.187*
R1))/(.934915+.0
020388*R1)→R9⊦
70:
R9-1.089*(.001*R
3)*EXP (.032015*
R1)→R11⊦
71:
GTO 54⊦
72:
R12-(R8-60)*R4→R
13⊦
73:
GTO 58⊦
74:
STP ⊦
75:
END ⊦
*25728
R251
```

```
0:
CFG 1;CFG 2;CFG
3⊢
1:
FXD 6;CFG 13;
ENT "XMAX?",Z;
IF FLG 13;SFG 1⊢
2:
Z→R0;0.01→R1;0.0
05→R2;0.001→R4;0
.0005→R5;0.00001
→R6⊢
3:
CFG 13;ENT "NORM
AL MODE?",Z;IF
FLG 13;R4→R1;R5→
R2;0.000001→R6⊢
4:
CFG 13;ENT "METR
IC?",Z;IF FLG 13
;JMP 2⊢
5:
10*R1→R1;10*R2→R
2;10*R6→R6⊢
6:
CFG 13;ENT "PRIN
TOUT?",Z;IF FLG
13;SFG 2⊢
7:
IF FLG 1;JMP 5⊢
8:
SCL 0,R0,-R2,R2⊢
9:
PLT 0,-R2;PLT 0,
R2;PEN ;PLT 0,.9
*R2;PLT .01*R0,.
9*R2⊢
10:
PEN ;PLT 0,-.9*R
2;PLT .01*R0,-.9
*R2;PEN ;PLT 0,0
;PLT R0,0⊢
11:
LTR .02*R0,.91*R
2,221;PLT R2;
LTR .02*R0,-.94*
R2;PLT -R2⊢
12:
CFG 13;ENT "KEYB
OARD INPUT?",Z;
IF FLG 13;SFG 3⊢
13:
-1→Z;0→R3→R7⊢
14:
IF FLG 3;RED 3,X
,X⊢
15:
IF FLG 3;IF Z=0;
GTO 28⊢
16:
IF FLG 3;R6*X→X;
JMP 3⊢
17:
CFG 13;ENT "DATA
?",Z;IF FLG 13;
GTO 28⊢
18:
Z→X⊢
19:
X*(1/R1)→Y;INT Y
→Y;Y*R1→Y⊢
20:
X-Y→B;IF B>R2;B-
R1→B;Y+R1→Y⊢
21:
IF FLG 2;JMP 2⊢
22:
PRT "COMMAND",Y,
"ERROR",B;SPC 2⊢
23:
IF FLG 1;JMP 4⊢
24:
IF B>R2;R2→B;
JMP 2⊢
25:
IF B≤-R2;-R2→B⊢
26:
PLT R7,.9*R3;
PLT Y,.9*R3;PLT
Y,.9*B;PEN ;B→R3
;Y→R7⊢
27:
GTO 14⊢
28:
PEN ;SPC 8;STP ⊢
29:
END ⊢
Σ31388
R317
```

```
0:
CFG 1;CFG 2;CFG
3;0→Y;1→R6;FXD 1
⊢
1:
CFG 13;ENT "PLOT
?",Z;IF FLG 13;
SFG 1;JMP 2⊢
2:
ENT "XMAX?",R0;
ENT "YMAX?",R2⊢
3:
ENT "DELTA X?",R
1⊢
4:
CFG 13;ENT "NORM
AL MODE?",Z;IF
FLG 13;.1→R6⊢
5:
CFG 13;ENT "PRIN
TOUT?",Z;IF FLG
13;SFG 2⊢
6:
IF FLG 1;JMP 5⊢
7:
SCL 0,R0,-R2,R2⊢
8:
PLT 0,-R2;PLT 0,
R2;PEN ;PLT 0,.9
*R2;PLT .01*R0,.
9*R2⊢
9:
PEN ;PLT 0,-.9*R
2;PLT .01*R0,-.9
*R2;PEN ;PLT 0,0
;PLT R0,0⊢
10:
LTR .02*R0,.91*R
2,221;PLT R2;
LTR .02*R0,-.94*
R2;PLT -R2⊢
11:
CFG 13;ENT "KEYB
OARD INPUT?",Z;
IF FLG 13;SFG 3⊢
12:
-1→Z;0→R3→R4⊢
13:
IF FLG 3;RED 3,X
;X⊢
14:
IF FLG 3;IF Z=0;
GTO 23⊢
15:
IF FLG 3;R6*X→X;
JMP 3⊢
16:
CFG 13;ENT "DATA
?",Z;IF FLG 13;
GTO 23⊢
17:
Z→X⊢
18:
IF FLG 2;JMP 2⊢
19:
PRT "COMMAND",Y,
"ERROR",X;SPC 2⊢
20:
IF FLG 1;JMP 2⊢
21:
PLT R4,.9*R3;
PLT Y,.9*R3;PLT
Y,.9*X;PEN ;X→R3
;Y→R4⊢
22:
Y+R1→Y;GTO 13⊢
23:
PEN ;STP ⊢
24:
END ⊢
29308
R339
```

```
0:
TBL 4;SFG 3;FXD 0;1→R9;ENT "CAL. NO.?",R9⊢
1:
CFG 1;CFG 2;ENT "AXIS?",R10⊢
2:
ENT "N?",R1;ENT "DELTA X?",R2⊢
3:
CFG 13;ENT "PLOT ?",Z;IF FLG 13;JMP 2⊢
4:
SFG 1⊢
5:
CFG 13;ENT "WORD INPUT?",Z;IF FLG 13;SFG 2⊢
6:
-1→Y;11→B;1→R0;PRT "AXIS",R10;SPC 1;PRT "INPUT DATA"⊢
7:
0→Z;IF FLG 2;JMP 5⊢
8:
IF Z=R1;JMP 9⊢
9:
ENT "DATA?",A;Z+1→Z⊢
10:
A/R9→A;PRT A;A+R6→RB;IF Y≤0;B+1→B;JMP -2⊢
11:
B-1→B;JMP -3⊢
12:
IF Z=R1;JMP 5⊢
13:
RED 3,X,X;X/R9→X⊢
14:
Z+1→Z⊢
15:
PRT X;X+RB→RB;IF Y≤0;B+1→B;JMP -3⊢
16:
B-1→B;JMP -4⊢
17:
CFG 13;SPC 4;ENT "MORE DATA?",Z;IF FLG 13;JMP 5⊢
18:
CFG 13;ENT "DIRECTION?",Z⊢
19:
IF Z≤0;IF Y≤0;1→Y;B-1→B;JMP 2⊢
20:
11→B;-1→Y⊢
21:
R0+1→R0;GTO 7⊢
22:
11→B⊢
23:
RB/R0→RB;B+1→B;IF B-11=R1;JMP 2⊢
24:
JMP -1⊢
25:
GSB "L"⊢
26:
11→B;PRT "STRAIGHTNESS"⊢
27:
PRT RB;B+1→B;IF B-11=R1;JMP 2⊢
28:
JMP -1⊢
29:
SPC 2;GSB "S"⊢
30:
IF FLG 1;GSB "P"⊢
31:
IF FLG 3;CFG 3;JMP 3⊢
32:
GSB "SQ"⊢
33:
JMP 7⊢
34:
CFG 13;ENT "PARALLELISM?",Z;IF FLG 13;JMP 2⊢
35:
SFG 4;JMP 2⊢
36:
CFG 13;ENT "SQUARENESS?",Z;IF FLG 13;JMP 4⊢
37:
11→B⊢
38:
0→RB;B+1→B;IF B>140;GTO 1⊢
39:
JMP -1⊢
40:
STP ⊢
41:
"L":CFG 13;ENT "LST SQ LINE?",Z;IF FLG 13;JMP 14⊢
42:
0→R3→R4→R5→R6;11→B⊢
43:
R4+RB→R4;R5+RB*R2*(B-11)→R5;(B-11)*R2+R3→R3⊢
44:
(B-11)*(B-11)*R2*R2+R6→R6;B+1→B⊢
45:
IF B-11=R1;JMP 2⊢
46:
JMP -3⊢
47:
(R4*R3-R1*R5)/(R3*R3-R1*R6)→R7⊢
48:
(R4-R7*R3)/R1→C⊢
49:
IF FLG 3;R7→R8⊢
50:
11→B;0→A⊢
51:
RB-(R7*A+C)→RB⊢
52:
A+R2→A;B+1→B⊢
53:
IF B-11=R1;RET ⊢
54:
JMP -3⊢
55:
(R(R1+10)-R11)/(R1*R2-R2)→R7;R11→C⊢
```

```
56:
JMP -7⊢
57:
"S"⊢
58:
11→B;RB→A→C⊢
59:
IF RB>A;RB→A⊢
60:
IF RB<C;RB→C⊢
61:
B+1→B;IF B-11=R1
;JMP 2⊢
62:
JMP -3⊢
63:
PRT "MAX DEV=",A
;SPC 1;PRT "MIN
DEV=",C;SPC 3;
IF FLG 1;JMP 2⊢
64:
RET ⊢
65:
IF ABS C>A;-C→A⊢
66:
ENT "SCALE?",A⊢
67:
SCL 0,R1*R2,-A,A
⊢
68:
IF FLG 3;JMP 2⊢
69:
JMP 11⊢
70:
PEN ;PLT 0,-A;
PLT 0,-.05*A;
PEN ;PLT 0,.05*A
;PLT 0,A;PEN ⊢
71:
PLT 0,A/2;PLT R1
*R2,A/2;PEN ⊢
72:
PLT R1*R2,-A/2;
PLT 0,-A/2;PEN ⊢
73:
PLT 0,.8A;PLT .0
1*R1*R2,.8A;PEN
⊢
74:
PLT 0,.2A;PLT .0
1*R1*R2,.2A;PEN
⊢
75:
PLT 0,-.2A;PLT .
01*R1*R2,-.2A;
PEN ⊢
76:
PLT 0,-.8A;PLT .
01*R1*R2,-.8A;
PEN ⊢
77:
LTR .01*R1*R2,.8
A,211;PLT A⊢
78:
LTR .01*R1*R2,.2
A;PLT -A⊢
79:
LTR .01*R1*R2,.9
*A;PLT "AXIS ";
PLT R10⊢
80:
IF FLG 3;JMP 4⊢
81:
LTR .01*R1*R2,-.
2A;PLT A⊢
82:
LTR .01*R1*R2,-.
8A;PLT -A⊢
83:
LTR .01*R1*R2,-.
9*A;PLT "AXIS "
;PLT R10⊢
84:
RET ⊢
85:
"P"⊢
86:
11→B;0→X;A/2→A⊢
87:
IF FLG 3;-A→A⊢
88:
PLT X,0.6*RB/2-A
;X+R2→X;B+1→B;
IF B-11=R1;JMP 2
⊢
89:
JMP -1⊢
90:
PEN ;PLT 0,0;
PEN ⊢
91:
RET ⊢
92:
"S";ATN (R7*1E-
6)→A;ATN (R8*1E-
6)→C;(A+C)*3600→
X;FXD 1⊢
93:
IF FLG 4;JMP 6⊢
94:
0→Z;ENT "PRINT E
RROR?",Z⊢
95:
X*2→X⊢
96:
PRT "SQUARENESS=",X
,"ARCSCDS";SPC 8
⊢
97:
IF FLG 1;LTR .3*
R1*R2,0;PLT "SQU
ARENESS ";PLT X
⊢
98:
JMP 3⊢
99:
PRT "PRLLISM=",X
/2,"ARCSCDS";
SPC 3⊢
100:
IF FLG 1;LTR .3*
R1*R2,1;PLT "PAR
ALLELISM ";PLT
X/2⊢
101:
IF FLG 1;PLT "
ARCSECONDS";LTR
R1*R2,A⊢
102:
RET ⊢
R6134
R156
```

```
0:
CFG 1;CFG 2;CFG
3;CFG 13;ENT "PL
OT?",Z;IF FLG 13
;CFG 1;JMP 2⊢
1:
ENT "XMIN?",R0;
ENT "XMAX?",R1⊢
2:
ENT "NSTART?",C;
Z+20→B→C⊢
3:
ENT "NMAX?",R4;
FXD 0;PRT "NSTAR
T",Z,"NMAX",R4;
SPC 4⊢
4:
CFG 13;ENT "PRIN
TOUT?",Z;IF FLG
13;SFG 2⊢
5:
CFG 13;ENT "STOR
E ERRORS?",Z;IF
FLG 13;SFG 3⊢
6:
IF FLG 1;JMP 5⊢
7:
SCL 0,R1,-R0,R0;
FXD 6⊢
8:
PEN ;PLT 0,-R0;
PLT 0,R0;PEN ;
PLT 0,.9*R0;PLT
.01*R1,.9*R0;
PEN ⊢
9:
PLT 0,-.9*R0;
PLT .01*R1,-.9*R
0;PEN ;PLT 0,0;
PLT R1,0⊢
10:
LTR .85*R1,.91*R
0,221;PLT R0;
LTR .82*R1,-.96*
R0;PLT -R0⊢
11:
0→R2→A⊢
12:
CFG 13;ENT "COMM
AND?",Z;IF FLG 1
3;JMP 2⊢
13:
Z→RB;FXD 0;PRT "
COMMAND",B-20;
SPC 0;FXD 6;PRT
Z;B+1→B;SPC 1;
JMP -1⊢
14:
CFG 13;ENT "RECO
RD COMMANDS?",Z;
IF FLG 13;JMP 2⊢
15:
ENT "FILE NO?",Z
;→RCF Z,R0,R260⊢
16:
C→B⊢
17:
CFG 13;ENT "KEYB
OARD INPUT?",Z;
IF FLG 13;SFG 4;
JMP 3⊢
18:
ENT "DATA?",Z,
IF FLG 13;PEN ;
JMP 1[illegible]⊢
19:
Z→X;JMP 5⊢
20:
.00001→R3;CFG 13
;ENT "NORMAL MOD
E?",Z;IF FLG 13;
.000001→R3⊢
21:
-1→Z⊢
22:
RED 3,Y,X;R3*X→X
⊢
23:
IF Z=0;PEN ;JMP
12⊢
24:
X-RB→Y;IF FLG 1;
JMP 2⊢
25:
IF ABS Y>R0;PRT
"SCALE ERROR"⊢
26:
IF FLG 2;JMP 3⊢
27:
FXD 0;PRT "N",B-
20⊢
28:
FXD 6;PRT "COMMA
ND",RB,"ERROR",Y
;SPC 2⊢
29:
IF FLG 1;JMP 2⊢
30:
PLT A,.9*R2;PLT
RB,.9*R2;PLT RB,
.9*Y;Y→R2;PEN ⊢
31:
RB→A;IF FLG 3;
JMP 2⊢
32:
Y*1E6→RB⊢
33:
B+1→B;IF FLG 4;
JMP -11⊢
34:
JMP -16⊢
35:
CFG 13;ENT "RECO
RD DATA?",Z;IF
FLG 13;JMP 2⊢
36:
ENT "FILE NO?",Z
;→RCF Z,R0,R190⊢
37:
CFG 13;ENT "MORE
DATA?",Z;IF
FLG 13;JMP 4⊢
38:
CFG 13;ENT "CLEA
R DATA?",Z;IF
FLG 13;JMP 2⊢
39:
TBL 4⊢
40:
GTO 0⊢
41:
SFG 6;STP ⊢
42:
END ⊢
Σ1175
R281
```

PROGRAM LISTING

```
0:
CFG 1;CFG 2;CFG
3;CFG 4;FXD 0⊢
1:
ENT "PTS/RUN?",R
2;ENT "RUNS?",R3
⊢
2:
CFG 13;ENT "PLOT
?",Z;IF FLG 13;
JMP 6⊢
3:
SFG 4;ENT "YMAX?
",R17;ENT "XMAX?
",R18;SCL 0,1.1*
R18,-1.2*R17,1.2
*R17;JMP 5⊢
4:
"A";PEN ;PLT 0,-
R17;PLT 0,R17;
PEN ⊢
5:
PLT 0,0;PLT R18,
0;PEN ;PLT 0,0;
PEN ⊢
6:
PLT 0,R17;PLT .0
5*R18,R17;LTR .0
6*R18,1.03*R17,2
11;PLT R17⊢
7:
PLT 0,-R17;PLT .
05*R18,-R17;LTR
.06*R18,-1.05;PL
7;PLT -R17;RET ⊢
8:
21→B→R7;CFG 13;
ENT "KEYBOARD IN
PUT?",Z;IF FLG 1
3;JMP 3⊢
9:
CFG 13;ENT "DATA
?",Z;IF FLG 13;
JMP 2⊢
10:
Z→RB;PRT RB;B+1→
B;JMP -1⊢
11:
CFG 13;ENT "UNID
IRECTIONAL?",Z;
IF FLG 13;JMP 2⊢
12:
SFG 1⊢
13:
CFG 13;ENT "BIDI
RECTIONAL?",Z;
IF FLG 13;JMP 2⊢
14:
SFG 2⊢
15:
CFG 13;ENT "DATA
 FORMAT?",Z;IF
FLG 13;SFG 3;
GSB "SHFL"⊢
16:
IF FLG 1;GSB "UN
I"⊢
17:
IF FLG 2;GSB "BI
D"⊢
18:
SPC 8;STP ⊢
19:
"SHFL";1→A⊢
20:
R7+(2*A-1)*R2→R5
;R5+R2-1→R6⊢
21:
RR5→B;RR6→C;C→RR
5;B→RR6⊢
22:
R5+1→R5;R6-1→R6⊢
23:
IF R6≤R5;JMP 2⊢
24:
JMP -3⊢
25:
A+1→A;IF 2*A-1>R
3;RET ⊢
26:
JMP -6⊢
27:
"C";PRT "
N=",R9;SPC 1⊢
28:
PRT "     MEAN="
,R0;SPC 1⊢
29:
PRT "3*STD DEV="
,R1;RET ⊢
30:
"BID";CFG 3;PRT
"BIDIRECTIONAL";
DSP "CHNG PLOT?"
;STP ⊢
31:
GSB "B"⊢
32:
RET ⊢
33:
"UNI";PRT "UNIDI
RECTIONAL"⊢
34:
"B";1→X→Y→Z;R7→R
6→B;IF FLG 4;
GSB "A"⊢
35:
0→R0→R1→R9→R10→R
11⊢
36:
FXD 0;PRT "    P
OINT=",Z;SPC 1⊢
37:
ENT "COMMAND?",R
15;FXD 6;PRT "
COMMAND=",R15;
PRT "     DATA="
⊢
38:
RB+R10→R10;RBRB+
R11→R11;R9+1→R9;
FXD 0;PRT RB⊢
39:
IF FLG 4;LTR R15
,RB,211;PLT "X"⊢
40:
IF FLG 3;B+2→R5→
B;JMP 2⊢
41:
B+R2→B⊢
42:
IF B>R7-1+R2*R3;
R8+1→R8→B;JMP 2⊢
43:
JMP -5⊢
44:
R10/R9→R0;(R11-R
10*R10/R9)/(R9-1
)→R1;3*√R1→R1⊢
```

```
45:
IF FLG 4;LTR R15
,R0+R1;PLT "0";
LTR R15,R0;PLT "
0";LTR R15,R0-R1
;PLT "0"⊢
46:
IF X>0;-1→X;JMP
3⊢
47:
IF FLG 4;PLT R16
,R12;PLT R15,R0+
R1;PEN ;PLT R16,
R13;PLT R15,R0;
PEN ⊢
48:
IF FLG 4;PLT R16
,R14;PLT R15,R0-
R1;PEN ⊢
49:
R0+R1→R12;R0→R13
;R0-R1→R14;R15→R
16⊢
50:
GSB "C"⊢
51:
SPC 4;Z+1→Z⊢
52:
IF Y>0;IF R8>R7+
R2-1;JMP 3⊢
53:
IF R8>R7+2*R2-1;
JMP 2⊢
54:
JMP -19⊢
55:
IF FLG 0;-Y→Y;
JMP 2⊢
56:
RET ⊢
57:
IF Y>0;RET ⊢
58:
R7+R2→R8→B;SPC 4
;PRT "REV DIRECT
ION";SPC 2;1→Z⊢
59:
DSP "CHNG PLOT?"
;STP ⊢
60:
IF FLG 4;GSB "A"
⊢
61:
1→X;JMP -26⊢
62:
END ⊢
Σ24107
R214
```

PROGRAM LISTING

```
0:
PRT "PART 1";
SPC ⊢
1:
PRT "  VDI 3254"
⊢
2:
FXD 0;1→B;SPC 3;
PRT "NUMBER OF",
"POSITIONS"⊢
3:
ENT "M",R0;IF R0
<9;DSP "  M MIN
10";DSP ;DSP ;"
DSP ;DSP ;JMP 0⊢
4:
IF R0>42;DSP "M
 MAX 42";DSP ;
DSP ;DSP ;DSP ;
GTO -1⊢
5:
PRT "M";R0;SPC 2
;PRT "NO. OF MEA
S CYC";ENT "N",R
(R0+1)→Y;PRT "N"
,Y;SPC 2⊢
6:
1.128→B;IF Y>2;1
.693→B;IF Y>3;2.
059→B;IF Y>4;2.3
26→B;IF Y>5;2.53
4→B⊢
7:
IF Y>6;2.704→B;
IF Y>7;2.847→B;
IF Y>8;ENT "N>8,
 DN ?",B⊢
8:
B→R(R0+2);PRT "D
ESIRED POSITIONS
","(IN MM)";FXD
1;0→A⊢
9:
A+1→A;ENT "DES.
POSITION?",RA;
PRT RA;GSB "Z"⊢
10:
IF A≠R0;GTO -1⊢
11:
SPC ;PRT "ENTER"
;PRT "DATA CASSE
TTE"⊢
12:
GTO 8;ENT "FILE
NO?",Z;RCF Z,R0
,R(R0+2);GTO +6⊢
13:
"Z";0→C⊢
14:
IF (C+5→C)=A;
SPC ;RET ⊢
15:
IF (C+5→C)=A;
SPC 2;RET ⊢
16:
IF C>45;RET ⊢
17:
GTO -3⊢
18:
SPC 9;DSP 0⊢
19:
END ⊢
22483
R344
```

```
0:
PRT "PART 2"⊢
1:
SPC ;PRT "  VDI
3254";SPC ;PRT "
DATE";FXD 2;ENT
"DATE",Z;PRT Z;
FXD 0⊢
2:
PRT 1974;PRT "MA
CH NO.";ENT "MAC
H NO.?",Z;PRT Z⊢
3:
DSP "DATA CASSET
TE";DSP ;DSP ;
DSP ;GTO 4;ENT "
FILE NO?",Z;LDF
Z,R0,R(R0+2)⊢
4:
FXD 0;1→B;SPC 3;
PRT "NO. OF POSI
TIONS","M",R0;
SPC 2⊢
5:
PRT "NO. OF MEAS
. CYC","N",R(R0+
1)→Y→R(7R0+1);
SPC 2⊢
6:
R(R0+2)→R(7R0+2)
;PRT "DESIRED PO
SITIONS","(IN MM
)";FXD 2;0→A⊢
7:
A+1→A;PRT RA;
GSB "Z"⊢
8:
IF A≠R0;GTO -1⊢
9:
SPC 3;PRT "MEASU
RED DATA","(IN
UM)";0→C;DSP "TA
KE DATA";STP ⊢
10:
0→A;SPC ;FXD 0;
PRT "RUN NO.";B;
SPC 1;FXD 2;PRT
"DIRECTION +"⊢
11:
A+1→A;1→X;GSB "M
"⊢
12:
GSB "Z"⊢
13:
IF A≠R0;GTO -2⊢
14:
SPC 2;PRT "DIREC
TION -"⊢
15:
4→X;GSB "M"⊢
16:
A-1→A;GSB "Z"⊢
17:
IF A≠0;GTO -2⊢
18:
B+1→B;IF B≤Y;
GTO -8⊢
19:
R(7R0+2)→B;SPC 3
;PRT "RESULTS";
SPC 3;DSP "PROG
CASSETTE?";STP ⊢
20:
GTO 0;LDF 14;
GTO 0⊢
21:
"M";RED 3,Z,C;
JMP Z=0⊢
22:
C/1E4→C;PRT (C-R
A)1E3→C⊢
```

```
23:
XR0+A→X;X+R0→Z;
IF B=1;0→RX;C→RZ
→R(Z+R0)⊢
24:
C+RX→RX;IF C>RZ;
C→RZ⊢
25:
IF C<R(Z+R0);C→R
(Z+R0)⊢
26:
RET ⊢
27:
"Z":0→C⊢
28:
IF (C+5→C)=A;
SPC ;RET ⊢
29:
IF (C+5→C)=A;
SPC 2;RET ⊢
30:
IF C>45;RET ⊢
31:
GTO -3⊢
32:
END ⊢
Σ22447
R311
```

```
0:
PRT "PART 3";
SPC ⊢
1:
PRT "CALCULATION
","WITH BACKLASH
";SPC 3⊢
2:
0→A→R8→R9→R10;1E
9→R3→R5→R7;-1E9→
R2→R4→R6⊢
3:
"R":A+1→A;R0+A→Y
;4R0+A→Z⊢
4:
RY/R(7R0+A)→RY→X
;IF X>R2;X→R2⊢
5:
IF X<R3;X→R3⊢
6:
RZ/R(7R0+1)→RZ→X
;IF X>R4;X→R4⊢
7:
IF X<R5;X→R5⊢
8:
(RY+RZ)/2→C;IF C
>R6;C→R6⊢
9:
IF C<R7;C→R7⊢
10:
RY-RZ→C;√(CC)+R8
→R8⊢
11:
2R0+A→Y;5R0+A→Z⊢
12:
RY-R(R0+Y)→X;√(X
X)+R9→R9⊢
13:
RZ-R(R0+Z)→X;√(X
X)+R10→R10;C→RY⊢
14:
IF A=R0;GTO "R"⊢
15:
R2-R3→A;√(AA)→A;
(R2+R3)/2→R3;A→R
2⊢
16:
R4-R5→A;√(AA)→A;
(R4+R5)/2→R5;A→R
4⊢
17:
FXD 2;PRT "BACKL
ASH"," U",R8/R0→
R8⊢
18:
SPC 2;PRT "AVE.
SPREAD"," R +",R
9/R0→R9⊢
19:
PRT " R -",R10/R
0→R10;SPC 2;PRT
"STANDARD DEV"⊢
20:
PRT " S +",R9/B→
R9;PRT " S -",R1
0/B→R10⊢
21:
SPC 2;PRT "AVE.
STND. DEV."," S",
(R9+R10)/2⊢
22:
SPC 2;PRT "RANGE
 OF DEV"," R PU"
,R8+3(R9+R10)→Z;
SPC 2⊢
23:
R6-R7→X;PRT "ABS
 ACCURACY"," TEU
",√(XX)+Z⊢
24:
SPC 2;PRT "AVE D
EV OF POS"," A U
",(R6+R7)/2⊢
25:
SPC 3;PRT "WITHO
UT","BACKLASH";
SPC 2;PRT "RANGE
 OF DEV"⊢
26:
PRT " R P +",6R9
,""," R P -",6R1
0;SPC 2⊢
27:
PRT "ABS. ACCURA
CY"," TE +",R2+6
R9," TE -",R4+6R
10⊢
28:
SPC 2;PRT "AVE.
POS. DEV."," A +
",R3;PRT " A -",
R5;SPC 9⊢
29:
END ⊢
Σ10404
R296
```

```
0:
PRT "PART 4";
SPC ;PRT "  VDI
3254"⊢
1:
CFG 1;CFG 2;CFG
13;FXD 2⊢
2:
ENT "WITH BACKLA
SH?",Z;IF FLG 13
;SFG 1⊢
3:
IF FLG 1;0→R6;
JMP 2⊢
4:
R8/2→R6⊢
5:
ENT "YMAX?",Y⊢
```

```
6:
SCL 0,R0,-1.1*Y,
1.1*Y⊢
7:
AXE 0,0,1,10;
LTR R0,Y,211;PLT
Y⊢
8:
LTR 0,-Y;PLT -Y;
PLT 0,0;PEN ⊢
9:
IF FLG 1;IF FLG
2;LTR 1,1.05*Y;
PLT "UNI -";JMP
3⊢
10:
IF FLG 1;LTR 1,1
.05*Y;PLT "UNI +
";JMP 2⊢
11:
LTR 1,1.05*Y;
PLT "BID"⊢
12:
0→A;1→X⊢
13:
A+1→A;GSB "POS"⊢
14:
GSB "NEG"⊢
15:
IF FLG 1;IF FLG
2;JMP 4⊢
16:
IF FLG 1;JMP 2⊢
17:
(R1+R2)/2→C;1.5*
(R9+R10)→R7;JMP
3⊢
18:
R1→C;3*R9→R7;
JMP 2⊢
19:
R2→C;3*R10→R7⊢
20:
LTR A-1,C+R6+R7+
R(2R0+1),111;
PLT "O"⊢
21:
IF FLG 1;JMP 2⊢
22:
LTR A-1,C+R6+R(2
R0+2);PLT "+"⊢
23:
LTR A-1,C;PLT "X
"⊢
24:
IF FLG 1;JMP 2⊢
25:
LTR A-1,C-R6-R(2
R0+3);PLT "+"⊢
26:
LTR A-1,C-R6-R7-
R(2R0+4);PLT "O"
⊢
27:
IF X≠1;0→X;C→B;
JMP 9⊢
28:
PLT A-2,R(2R0+1)
-C+B;PLT A-1,R(2
R0+1);PEN ⊢
29:
IF FLG 1;JMP 2⊢
30:
PLT A-2,R(2R0+2)
-C+B;PLT A-1,R(2
R0+2);PEN ⊢
31:
PLT A-2,B;PLT A-
1,C;PEN ⊢
32:
IF FLG 1;JMP 2⊢
33:
PLT A-2,R(2R0+3)
-C+B;PLT A-1,R(2
R0+3);PEN ⊢
34:
PLT A-2,R(2R0+4)
-C+B;PLT A-1,R(2
R0+4);PEN ⊢
35:
C→B;IF A=R0;JMP
2⊢
36:
GTO 13⊢
37:
IF FLG 1;IF FLG
2;GTO 0⊢
38:
IF FLG 1;SFG 2;
DSP "CHANGE PLOT
?";STP ;GTO 5⊢
39:
GTO 0⊢
40:
"POS":R0+A→Y;RY→
R1;RET ⊢
41:
"NEG":4*R0+A→Y;R
Y→R2;RET ⊢
42:
END ⊢
Σ14142
R301
```

SECTION

VIII

SECTION VIII

STRAIGHTNESS MEASUREMENTS

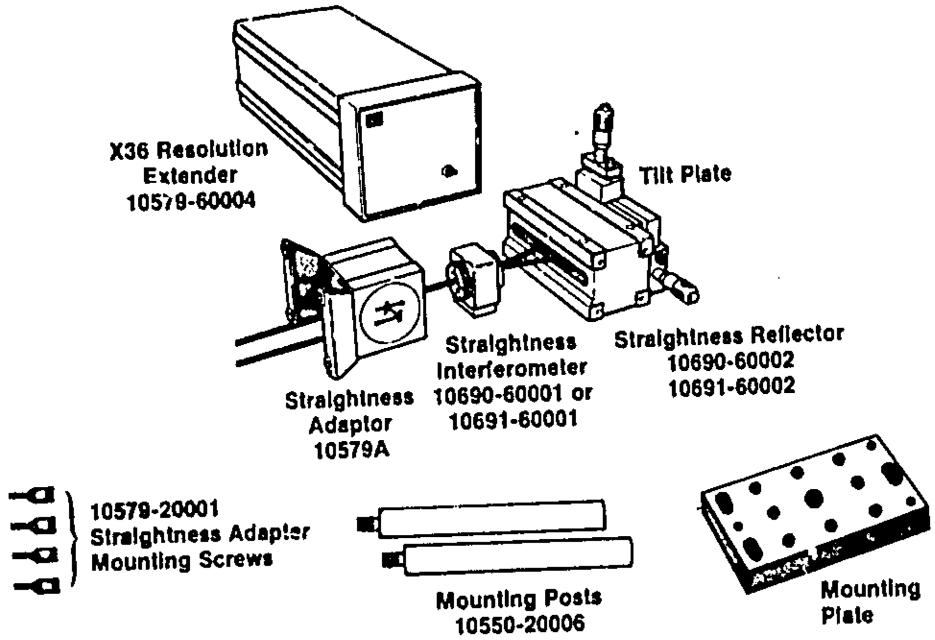


Figure 8-1. Straightness Optics

Straightness of travel, the fifth and sixth degrees of freedom is measured by the 10690A Short-Range Straightness optics and the 10691A Long-Range Straightness optics. Both sets of optics measure movements perpendicular to a linear axis. The straightness optics do not measure linear or angular movements.

Many types of machines have parts that are required to travel in straight (linear) paths. Close inspection will show that machines do not travel perfectly straight. They also rotate and translate. Translation is movement perdendicular to the inspected axis. Rotation can contribute to straightness when the rotational pivot point is not under the work point. The angular contribution to straightness depends on the exact locations of the pivot point and the work point. Straightness of travel is directly measured at the work point by the Straightness optics.

Out of straight travel results in parts that have slots that are too deap, too shallow, or that bow left or right. It is measured traditionally by mounting a reference part in the form of a reference straight edge, where the part would mount. An indicator mounts in the tool position or work point. As the machine is moved from point A to point B the indicator will show deviations of the work point with respect to the reference straight edge.

The position of the indicator and straight edge for straightness of travel measurements is of primary importance. If the positions are reversed the resulting measurement may not be indicative of how the machine makes or measures parts. Multispindle machines are an exception. Table travel must be in a flat plane when work is done at more than one point simultainiously. Angular components will cause straightness to be different at each work point.

The Straightness optics take the place of the above indicator and reference straightedge. The Straightness Reflector in effect holds one end of a long, invisible, straight line and mounts where a part could mount. The Interferometer performs as an indicator and mounts where an indicator or tool would mount.

STRAIGHTNESS OPTICS FUNCTIONAL OPERATION

The Straightness optics measure displacement perpendicular to the axis of travel with respect to a reference straight line called the Reference Bisector, shown in Figure 8-2. Relative perpendicular displacement as displayed on the Laser Display is the displacement between the Straightness Interferometer and the Reference Bisector.

NOTE

Trying to use the Theory of Operation, and the divergent laser beams, to perform alignments or measurements can seriously impede an operator's progress in using the optics and/or incorrectly influence the interpretation of the resulting data. The following functional explanation of operation will explain the proper use of the Straightness optics.

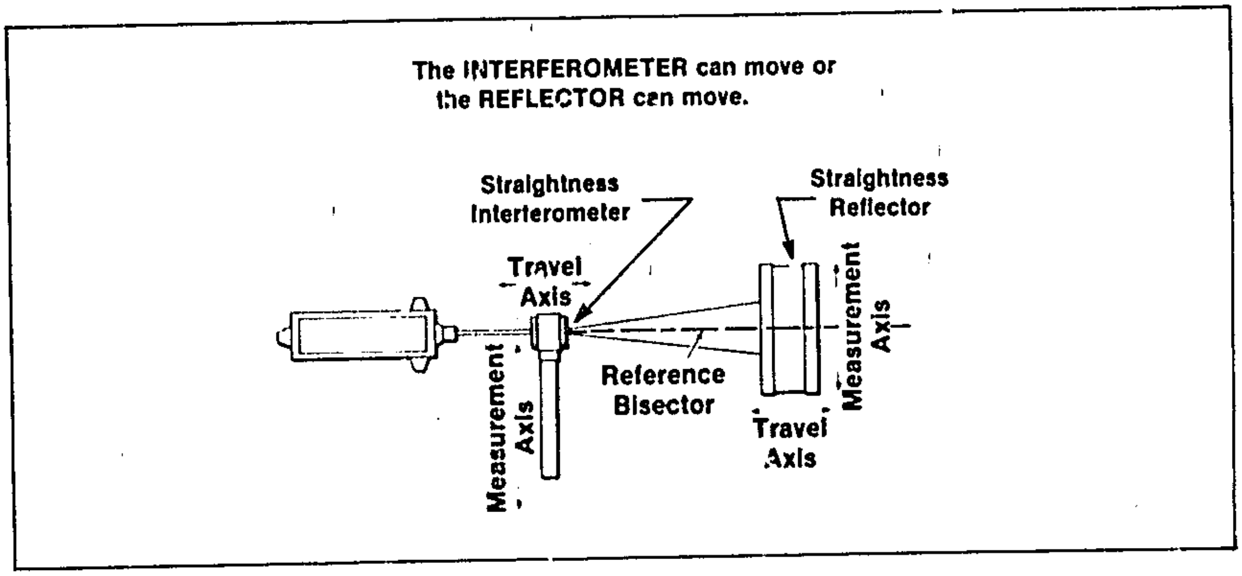


Figure 8-2. The Reference Bisector

When using the Straightness optics for straightness of travel measurements:

THE STRAIGHTNESS REFLECTOR IS MOUNTED WHERE THE PART WOULD MOUNT.

THE REFERENCE BISECTOR IS ALIGNED TO THE AXIS OF TRAVEL.

THE INTERFEROMETER IS MOUNTED WHERE THE WORK IS DONE OR WHERE THE INDICATOR OR TOOL WOULD MOUNT.

In operation, the optical straight edge is the Reference Bisector. Measurements take place between it and a zero reset point inside the Straightness Interferometer. The Straightness optics are used in the same manner as a straight edge and an inspection indicator, as in Figure 8-3.

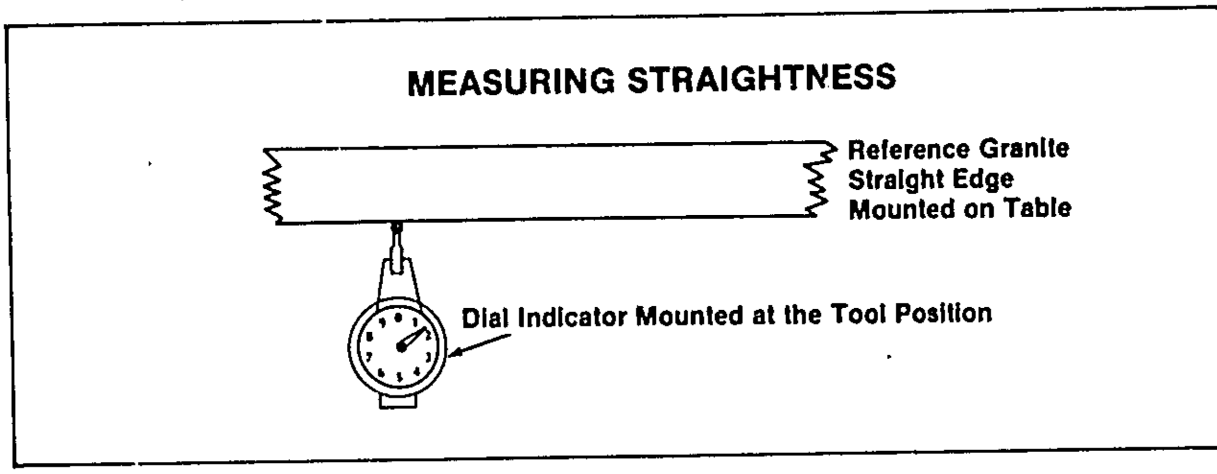


Figure 8-3. The Mechanical Equivalent of the Straightness Optics

STRAIGHTNESS MEASUREMENT CONSIDERATIONS

Straightness measurements are subject to various types of errors which can be broken down into the catagories of systematic errors (repeating) and random (non-repeating) errors.

SYSTEMATIC ERROR CONSIDERATIONS

Thermal Expansion

External heat sources should be avoided, or isolated from the machine. Thermal equilibrium should be reached at a typical operating condition of the machine before dimensional measurements are attempted. Measurement errors can result from thermal expansion for three reasons.

1. Thermal expansion during the measurement.

2. Non-typical environmental conditions during the measurement.

3. Non-typical machine operating conditions during the measurement.

Measurements taken while the environment is changing will reflect how parts would change with the environmental change. If your measurements are to reflect how parts are made and the environment changes during part process, the total range of the change should be determined during all times when parts are processed. The machine should be checked during specific limited environments , one at a time. The range of the data will be indicative of how parts would be made. Part accuracy and precision suffer when the environment changes.

Straightness Reflector Flatness

The accuracy limit of the HP Straightness Optics is directly related to the difference in flatness of the two plane mirrors that serve as the reflector. For example, suppose one of the mirrors is flat but the other is convex by a small amount, C, as shown in Figure 8-4. Even through the straightness interferometer were to travel in a straight path with respect to the mirror axis, the optical path length of F1 would be shortened by an amount equal to C with respect to the optical path of F2, and this would be interpreted by the interferometer as "out of straightness" of the interferometer travel.

The straightness optics therefore rely on the flatness of the reflector mirrors as its straightness reference. Fortunately, extremely accurate optical flats are available. Laboratory-grade flats are typically accurate to within one microinch per foot. The specified accuracy of the HP Straightness option is +/-5 microinches / foot. This accuracy can be improved to the limit of linearity of laser beam wave length by rotating the Straightness Reflector through 180 degrees and making a second pass which is equivalent to reversal of a straightedge.

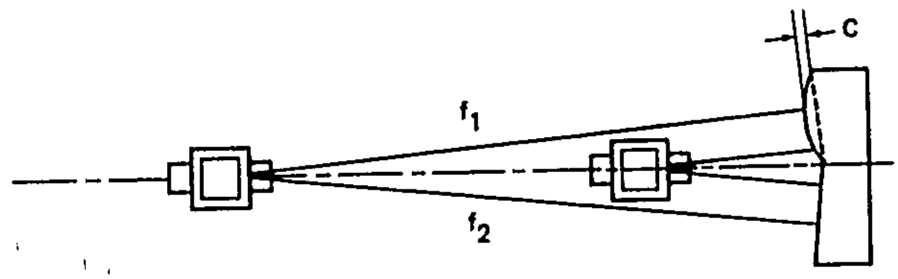


Figure 8-4. Mirror Flatness

RANDOM ERRORS

Vibration

Mounting and fixturing of the Straightness optics is extremely important when vibration is encountered during a measurement. Vibration can cause machine movements that result in straightness measurements as the Straightness optics vibrate. The rate and magnitude of vibration will determine the rate of change (slew rate) of the straightness data received by the Laser Display. The slew rate of the Laser Display when using the Straightness optics is reduced to as much as 20 inches per minute. Slew rates of greater than 20 inches per minute can cause the Laser Display to Reset. The three basic symptoms of vibration are listed below:

1. The Laser Display reading will drift randomly when the optics appear to be at rest.
2. When the machine is shut down the drifting stops.
3. As the distance increases between the optics the drifting also increases. Symptoms one and three can also be caused by turbulence covered later under Turbulance.

NOTE

When machine vibration cannot be reduced by proper fixtures and alignment to a level that allows laser measurements, the vibration may be imparing the part accuracy and precision.

Fixturing

Fixturing is primary in reducing the drifting caused by vibration. The Reference Bisector is held at one end by the Straightness Reflector. The other end is free to move in response to flexing of the fixturing used to mount the Straightness Reflector. The resultant vibration of the Reference Bisector will increase away from the Straightness Reflection. Improper fixturing will amplify vibration of the optics and increase the display drifting. Long linkages suspending the optics from the machine should be avoided. Soft wood wedges or special locking clamps may be required to hold non-locking spindles in position. A hose clamp and an "O" ring are often effective. Fixturing of the Straightness Reflector should be short, ridged, and direct. An angle plate is the perferred mounting fixture for most applications.

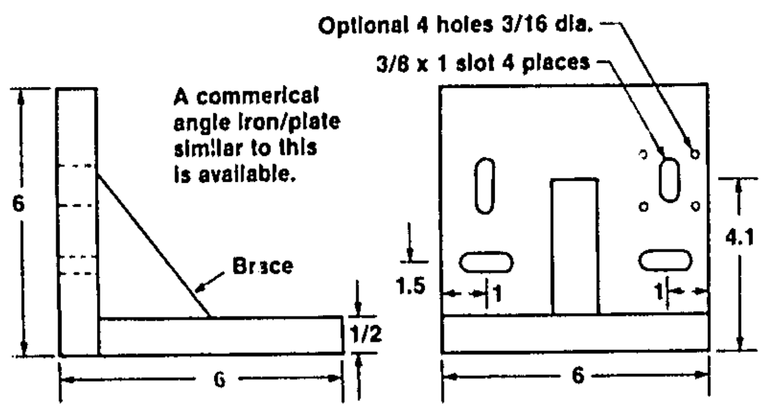


Figure 8-5. Angle Plate. The Most Common Fixturing for the Straightness Reflector

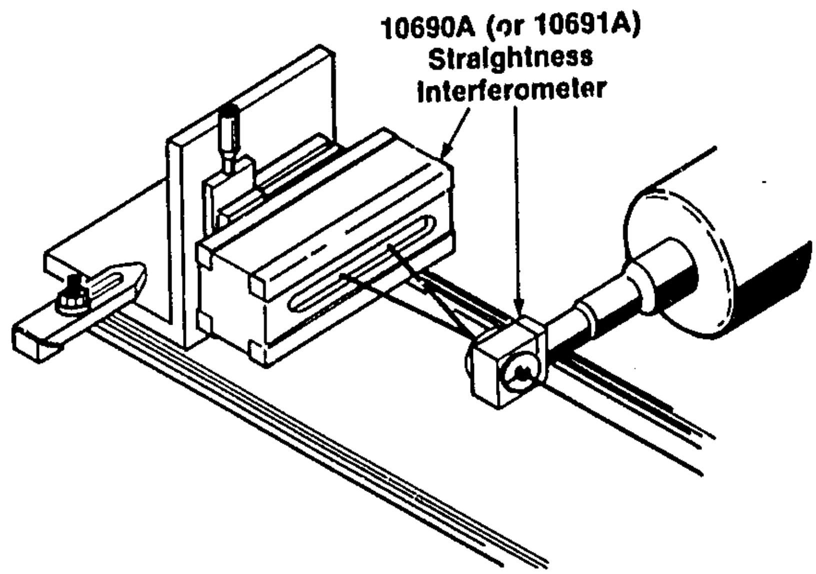


Figure 8-6. Straightness Optics Mounted in a Typical Application

In Figure 8-5 vibration in the machine would have a minimal effect on the Laser Display reading. The following points can be used to minimize unacceptable vibration caused display drifting.

A. With the machine on, feel the vibration at the Straightness Reflector and on the Interferometer, then follow the vibration to the machine by touching parts of the fixturing. If the magnitude of the vibration changes significantly the fixturing should be changed accordingly to reduce the vibration at the optics.

B. The angle plate and machine table should have smooth mating surfaces to prevent rocking.

C. Tap on the angle plate to check for angle plate induced drifting.

D. The angle plate must be tightly clamped to the machine table.

E. Tap on the Straightness Reflector to check the rigidity of the Tilt plate. Under conditions of severe vibration the Tilt plate may be replaced with a base plate or mount the Straightness Reflector directly to the angle plate with 4, 8-32 screws.

When vibration is as small as fixturing will allow but still objectionable the calculator/plotter metrology software allows for averaging of successive runs of straightness data and the averaging of successive averages. Averaging is explained in the following turbulance section. Machine movements perpendicular to the axis of travel can be severe enough to cause the Laser Display to Reset during measurements. This may indicate wear or mechanical interference within the machine or drive train. To check Straightness under these severe conditions:

1. Perform the most accurate alignment possible and remove all slope.

2. Reduce feed rates to the slowest affordable.

3. Start the machine then press Reset to begin taking data after a possible abrupt start.

4. Use hand cranks if available.

5. Last resort when Reset can not be maintained:
   Shock mount the angle plate and toe clamps by placing a 1/4 to 1/2 in. urathane or silicone foam rubber mat under the angle plate and pads under the toe clamps. Compress the rubber by 1&/4 to 1/2 thickness. Watch for creep in the rubber pads that may allow the angle plate to rotate and change the position of the Reference Bisector during a measurement. This mounting isolation is intended for lower accuracy, lower precision, high vibration work only.

Turbulence

Laser Display drifting and even Reset can be caused by air turbulance. Turbulant air is air of varing temperatures. The laser beams are defracted as they pass through air of one temperature into air of another temperature. The defraction causes physical movements of the laser beam which are detected and displayed as a drifting straightness number. The turbulance drifting of the Laser Display will increase:

1. As air temperature differentials increase

2. Length of measurement increases

Turbulance and vibration are responsible for the same symptom of a drifting Laser Display. To isolate turbulance from vibration turn off the machine. If the drifting remains touch the optics. If vibration is preceivable the machine may not be full off or vibration is entering the machine from other sources. The magnitude of drift caused by vibration can be reduced as explained above under Vibration.

If no vibration can be detected but the drifting continues direct a fan along the measurement path to mix and homogenize the air temperature. The fan should be large enough to be felt along the entire horizontal measurement path (the laser beams between the interferometer and the reflector). Turbulance in the vertical axis is partically cancelled and not as severe as in the horizontal plane.

Causes of Turbulance

Air is an excellent insulator, it does not conduct heat well. Air in the area of accurate production or measurements should be constantly moving to prevent temperature differentials or stratification . Temperature controlled rooms are especially prone to turbulance. The air temperature is often controlled by alternatly pumping in cool and warm air to maintain 20 degrees C or 68 degrees F. The pockets of cool and warm air incompletely mix in the room. For metrology room measurements 4 inch muffin fans may be sufficient to minimize turbulance.

Turbulance in a large shop area is typically not as severe as in temperature controlled rooms but can be caused by several different sources of hot or cold air:

1. The opening of a large door to the outside allowing air currents that rapidly change the air temperature within the shop.

2. Large overhead space heaters that blow hot air to heat the shop. These same blowers can be used to mix the air and decreases turbulance in the summer when the heating element is not used.

3. Mercury vapor lamps that generate columns of heat in the form of infrared radiation. Sodium vapor lamps generate less heat and turbulance.

4. Heat sources on machines such as spindle motor cooling blowers should not direct the hot exhaust toward other parts of the machine or the measurement area.

5. Exhaust f propane fork lifts passing by the measurement area.

If the source of turbulance cannot be eliminated the turbulance can be reduced or eliminated by directing a fan down the measurement path. The fan should be large enough to thoroughly mix all the air along the measurement path.

NOTE

The accuracy and precision of a machine tool is highly dependent on the machine operating environment. The above conditions directly effect part accuracy and precision.

Number of Data Points

When a straightness measurement using the HP Straightness Interferometer System is being performed, it is important to record as many data points as possible during each straightness run. This can best be accomplished by taking measurements "on the fly" using either the Timed Print Mode ** available on the 5505A Laser Display or externally controlling the Laser Measurement System via the Laser Display Rear Panel Aux Connector. Slope must be small compared to the Straightness data when using on the fly techniques and the machine must position accurately to allow accurate slope removal. Each run should be taken with the 5505A Laser Display in the SMOOTH or X10 mode, and least squares, best line fit slope calculation should be made. To minimize effects of remaining air turbulence, 50 to 100 data points should be taken per run.

**To determine the Print Rate (labeled "PRINTS-PLOTS/MIN") on the HP 5505A Display, use the following relation:

$$\text{PRINT RATE} = \frac{\text{Number of Data Points} \times \text{Feed Rate}}{\text{Distance Traveled}}$$

Air turbulane effects are indicated by random non-repeatability of successive runs and can easily be seen by plotting successive runs (using the least squares, best line fit calculation) on the same graph.

NON-CONSIDERATIONS FOR STRAIGHTNESS MEASUREMENTS

ABBE ERROR

Abbe offsets have no effect on Straightness measurements. Machines typically are designed to resist flex. Stresses great enough to cause flexing of a machine typically reduce the accuracy, shorten the life expectancy and should be avoided. A non-flexible or Rigid Body will rotate all points on its structured equally. The position of the Straightness optics on a rigid body has no effect on the resulting data when the straightness convention of a straight edge in the part position and indicator in the tool position is followed.

Abbe Errors are linear positioning errors or in scale errors due to rotation and Abbe offsets. Rotation can also cause linear errors in axes perpendicular to the investigated axis. These errors are by definition straightness errors. Total straightness is measured at the work position by the Straightness optics.

DEADPATH ERROR

The Straightness optics effectively eliminate deadpath error due to the differential nature of the measurement technique. See Compensation below.

COMPENSATION

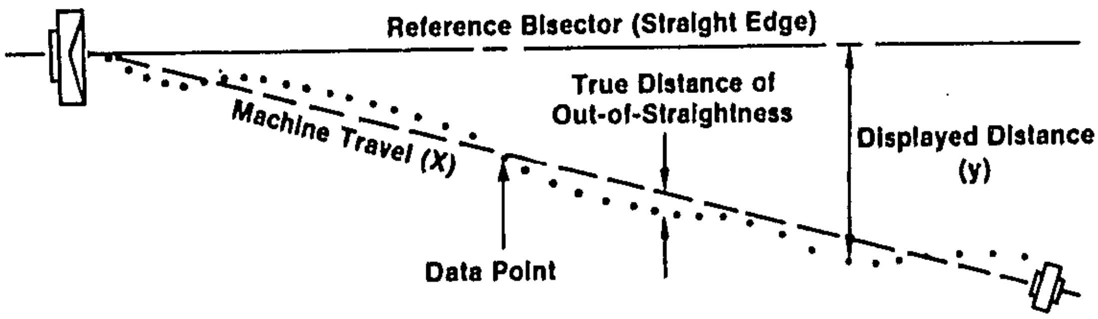
Compensation and deadpath error are related in that changes in the density of air can result in linear measurement errors. When using the Straightness optics density of air changes in one measurement path are cancelled by equal changes in the other measurement path. During a measurement only the difference between the measurement path is displayed. Velocity of light differences in the measurement paths are therefore very small compared to the very small actual measurement length. For this reason, the Laser Display Thumb Wheel Switches and the Automatic Compensator have no affect on measurement accuracy.

BEAM ALIGNMENT-COSINE ERROR

Beam alignment, as indicated by the Beam Alignment Meter on the Laser Display need only be sufficiently in to the green region to prevent Reset by the Reset button on the Laser Display. Cosine Error can exist when using the Straightness optics in that the optics must be oriented to the vertical or horizontal planes and not in between.

SLOPE OF THE DATA

In Straightness Measurements when the optics are not perfectly aligned to the axis of travel the Straightness Reflector is not directing the Reference Bisector along a path parallel to the axis of travel as shown in Figure 8-7. During a measurement pass the Interferometer moves with the machine along the axis travel. The Laser Display will show the distance from the Reference Bisector to the new location of the Interferometer at each reading. The resulting data points are shown spaced about the Axis of Travel.



rm = data slope = rise over run = Y/X

- Misalignment of Reference Bisector results in a data slope as the Interferometer measures displacement from the Axis of Travel to the Reference Bisector.

Figure 8-7. Data Slope

This is analogous to indicating a straightedge to a machine axis. During the first pass the indicator will nove into or away from the straight edge. The pointer on a dial indicator will show increasingly smaller or larger numbers.

The are three ways to remove the slope from the straightness data:

1. Calculator reduction and plot of data.

2. Manual mathematic reduction and plot of data.

3. Align the slope out with a zero-end-point-fit.

Alignment of the Reference Bisector may be necessary if the slope becomes great enough to Reset the Laser Display before the end of travel is reached, and when "on the fly" measurement is used.

It is possible to have about 0.20 inches of slope and not loose beam ailgnment. The Straightness Optics Alignment Procedure explains how to manually realign the Reference Bisector to minimize slope. This should be attempted to gain familiarity with the optics.

Reducing the slope will reduce the possibility of loosing beam alignment during a measuremnt due to vibration and turbulance. Slope is removed mathematically by calculating the least squares best line fit through the data points. The slope of the line is often referred to as the rise over the run, of so many micro inches over the distance of travel of so many inches. This is how squareness and parallelism is usually specified, u inches per inch. One degree equals 180 tenths in ten inches, one minute is 3 tenths in one inch, and one second of arc is 5 u inch per inch

The rise is subtracted from the data at each command position. The remainder is straightness error. The command position is the run at each data point. Accurate command positioning is the important to the accuracy of the straightness measurement. The greater the slope the more accurately the machine must be positioned to the desired command position. When "on the fly" short-range measurements are performed slope must be minimized to insure accurate slope removal.

STRAIGHTNESS MEASUREMENT EXAMPLES

There are four basic measurements possible with the Straightness optics:

1. Straightness of a linear axis of travel

2. Straightness of a line along a surface.

3. Parallelism between

   a) two linear axes of travel.

   b) two lines along two surfaces

   c) a linear axis to a line along a surface

   d) a linear axis to a rotational axis

4. Squareness between

   (b) two lines along two surfaces

   (c) a linear axis to a line along a surface

   (d) a linear axis to a rotational axis

SECTION

IX - X

SECTION IX

SQUARENESS MEASUREMENTS

The 10690A and 10691A Straightness optics can be used to measure squareness when combined with a 10692B Optical Square shown in Figure 9-1. Straightness is measured in each of two perpendicular axes with respect to a common Reference Bisector. The Reference Bisector is bent 90 degrees by the 10692B Optical Square. Each straightness measurement results in straightness data and a data slope. The difference between the slope in each axis is the squareness of the two axes.

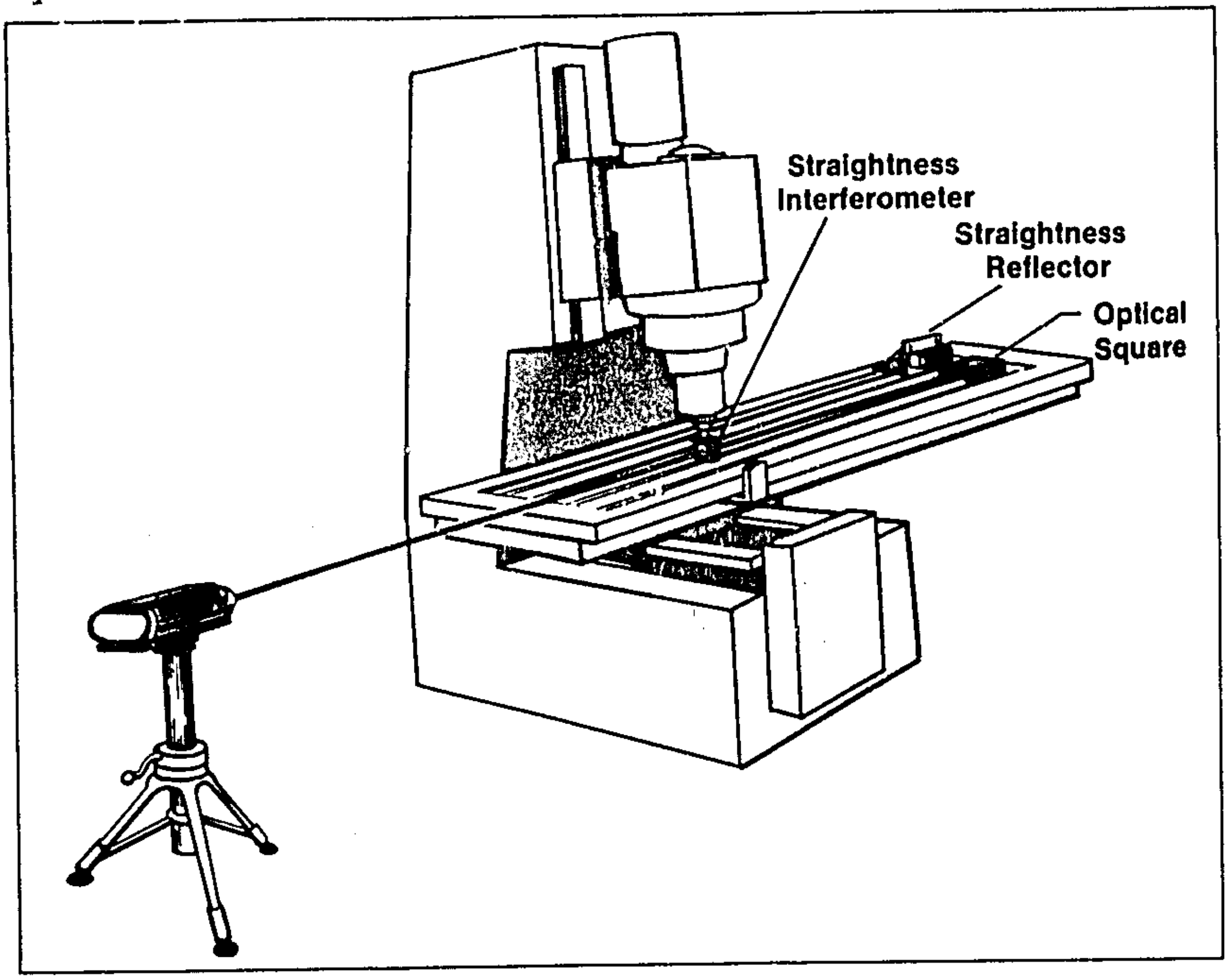


Figure 9-1. Squareness X to Y

Figure 9-2 illustrates the Reference Bisector aligned parallel to one of two perpendicular axes. The straigtness data for the first measured axis is typical of a zero-end-point-fit, where the end points are adjusted to be at or very near zero. This results in a zero or low value slope.

Axis two is shown in Figure 9-3 with straightness data slope. If axis two were square to axis one the slope magnitude and sign for each axis would be equal.

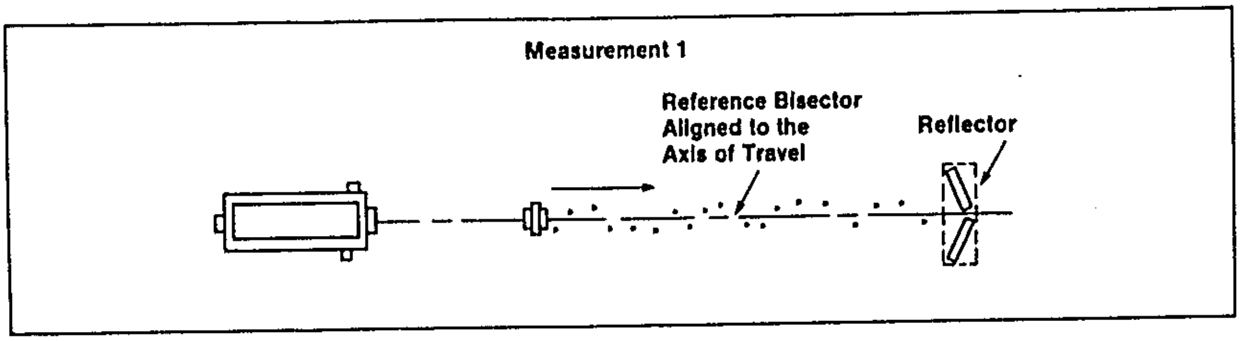


Figure 9-2. Squareness Measurement One: Straightness in X

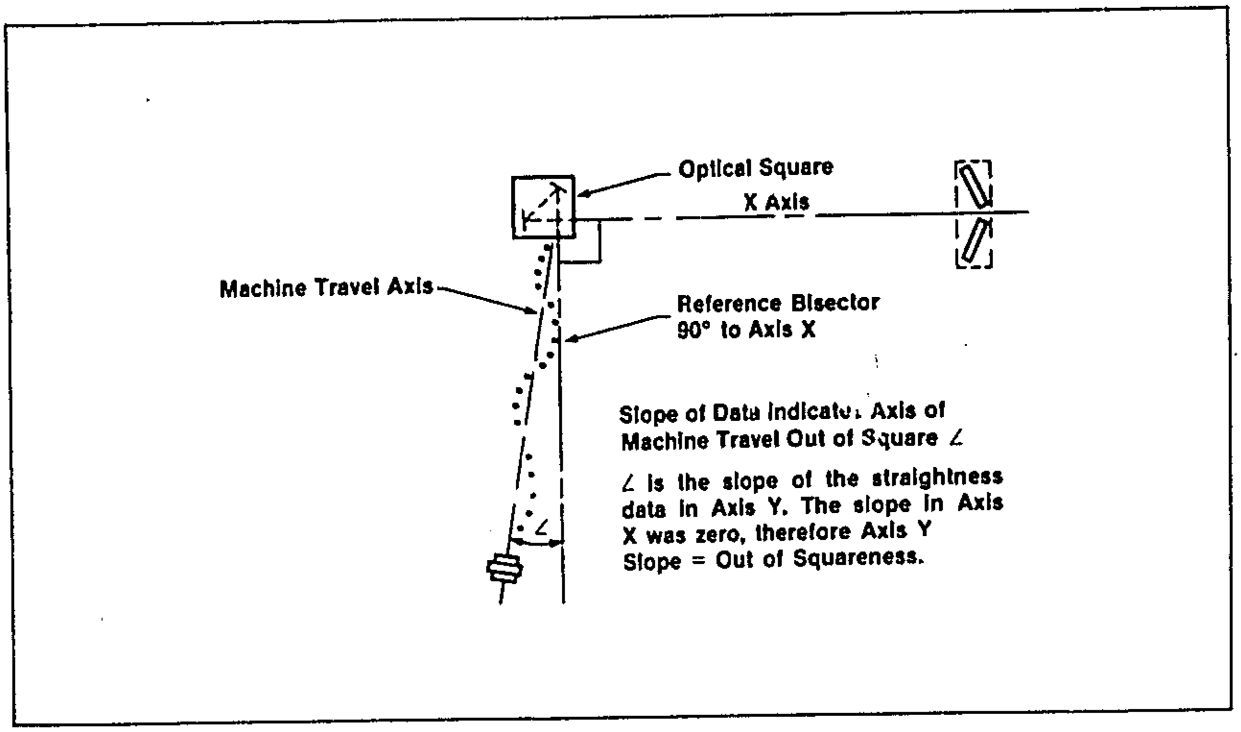


Figure 9-3. Squareness Measurement Two: Straightness in Y

When axis two is not square to axis one, data can appear as in Figure 9-3. The data slope indicates non squareness. Figure 9-4 describes the relationship between squareness in arc seconds and the often-used tenths-per-inch notation.

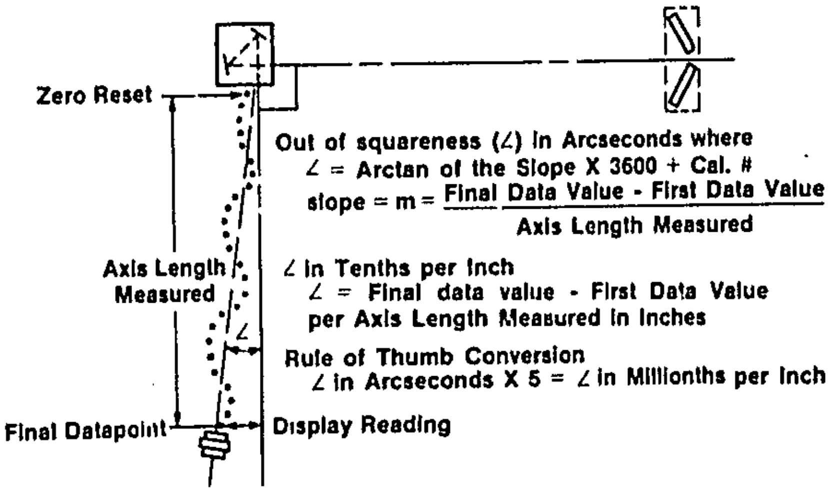


Figure 9-4. Squareness in Tenths-Per-Inch

DATA SLOPE

Slope as in Figure 9-3 and Figure 9-4 is also called rise-over-run and typically specified in units of tenths per foot or millionths per inch. Slope is equivalent to an angle in degrees, minutes or seconds. Seconds of arc convert to typical slope units by the rule of thumb that one arc second is about 5 millionths rise over a one inch run, or 5 uin per in.

Slope need not be totally removed from the straightness data when mathematical reduction is used or when the straightness of each axis is not desired. The calculator/plotter will remove the slope from the straightness data, plot the straightness data, and store the slope of the first axis as angle A and the second axis as angle B. Squareness is computed by subtracting angle A from angle B. The calibration error of the Optical Square is added and the result printed on the paper tape. A third plot is drawn of both Axis 1 and Axis 2 straightness and the squareness is printed between.

DIRECTION OF TRAVEL AND DATA SIGN

Sign of the data and direction of travel are important for the correct squareness result. The method used to collect squareness data is similar to but more versatile than collecting data with a granite square and a dial indicator. In fact the calculator/-plotter will accept data manually through keyboard entry from a dial indicator and plot the resulting straightness and squareness in the same format as from the Straightness Optics and Optical Square. Pictorial descriptions of how to collect the squareness data is presented in Figure 9-7 in the 10692-90002 Optical Square manual, the Calculator/Plotter Metrology manual and in the 156-5 Application Note.

NOTE

When first learning to make squareness measurements with the interferometer system the following principles can be followed.

Direction of Travel:

Take data of both axes starting at the apex of the square being measured.

Sign of the Data:

If the data is positive into the square in axis one then it should be positive out of the square for axis two as when working with a granite square and pressing the Indicator into the square.

To determine the sign of the data with a moving Straightness Reflector, press gently on the Straightness Reflector, (the orientation of the Reference Bisector may be disturbed). When the Interferometer is the moving optic press on the Interferometer or move the machine so that the Interferometer moves into the square being measured.

NOTE

Rotation of the Interferometer will reverse the sign of the data. A good rule is to face the polished Bezel toward the incoming laser beam and the non-polished Bezel toward the Straightness Reflector.

SECTION X

VERTICAL AXIS STRAIGHTNESS, SQUARENESS AND OTHER USES OF THE VERTICAL STRAIGHTNESS ADAPTER

Vertical axis measurements and some horizontal measurements require the use of a beam u-turning optic to direct the beam along the desired measurement path. U-turning of the laser beam is accomplished by the 10693A Vertical Straightness Adaptor shown in Figure 10-1

Figure 10-1. Vertical Straightness Adapter with Interferometer

A large cube corner is the glass optic emploided. The aluminum housing allows mounting of the Straightness Interferometer on the Vertical Straightness Adaptor. Straightness measurements require that the Reference Bisector be located where the part would mount. The Vertical Straightness adaptor allows this to be done. However, the application is not restricted to vertical axis measurements. Measurements of squareness, parallelism, spindle ram droop, horizontal boring and milling machine spindle axis straightness and many other measurements are accomplished using the Vertical Straightness Adaptor, Straightness optics and the Optical Square. Many of the applications are easy to visualize and setup. A selection of typical setups are pictured in Application Note 156-4 pages 15-17. Shown in Figure 10-2 is the setup that allows measurements of vertical axis straightness, squareness, and parallelism. This setup is very common and much used for machine tool calibration.

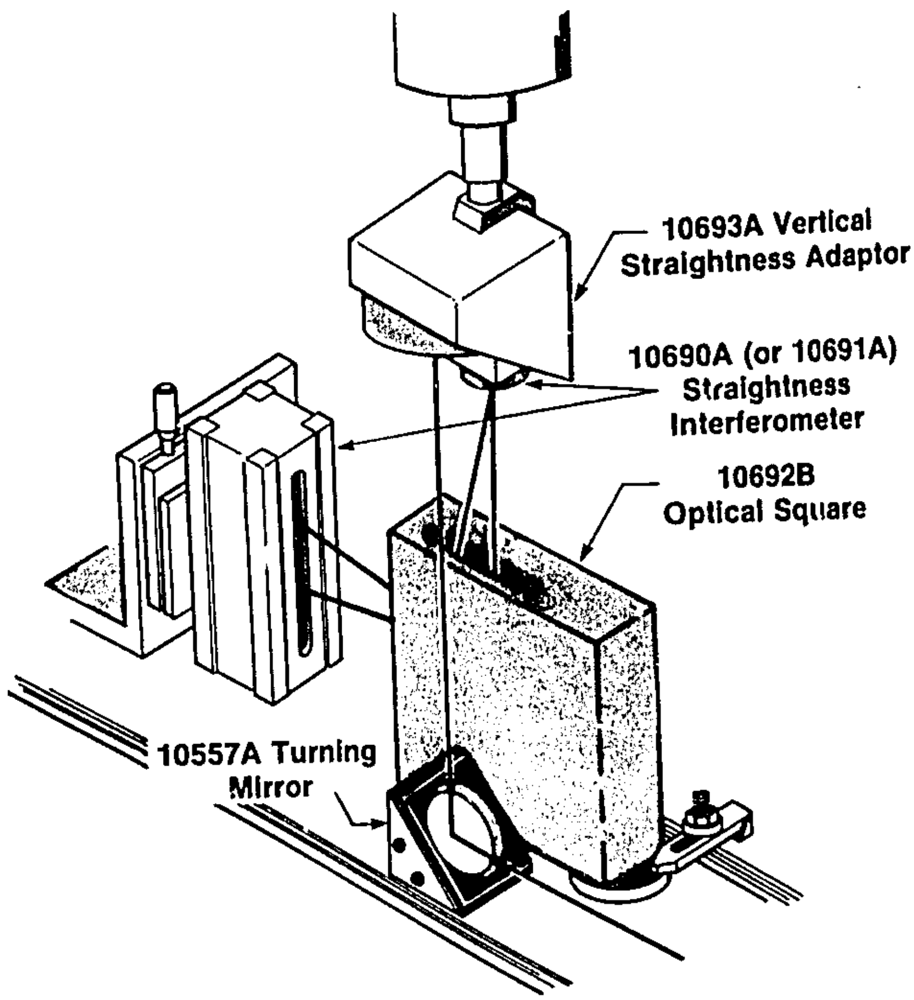


Figure 10-2. Straightness in a Vertical Axis by Using the Vertical Straightness Adaptor

Calibration or geometric characterization of horizontal and vertical machine tools and coordinate measuring machines can be accomplished with only two Laser Head positions. The number of measurements depends on the number of axes. For a 4 axis Vertical boring machine six measurements of straightness are taken from both the x axis and the y axis positions of the Laser Head. In each case straightness in the vertical axis is the first setup and measurement. The second measurement does not require a new setup. It is straightness of the second vertical axis. The result of the two straightness measurements is parallelism of the ram axis to the spindle head axis. Rotational parallelism cannot be measured with this setup, the Straightness Reflector would necessarily be mounted in the spindle.

A third measurement would duplicate the spindle head straightness and is used to determine squareness of the spindle head axis to the table axis of x. To measure the z-x squareness all the optics except the Straightness Reflector are removed from the machine. The fourth measurement would be the x axis table travel with respect to the spindle. For this measurement the Laser Head is aligned to the Straightness Reflector which is in effect supporting the base leg of our reference square. Beam alignment is established as in an ordinary straightness alignment.

Again, the position of the Straightness Reflector cannot be disturbed once the last z axis measurement is complete.

When squareness adjustments are to be made to the vertical axis and on most measuring machines a different setup is recommended. It requires a sturdy column like the adjustable granite square in Figure 10-3 to hold the Straightness Reflector high above the table. This setup allows measurement of both axes with no change in setup or fixturing. The column should be tall enough to allow measurement of the vertical axis plus six inches to prevent loss of beam alignment at the near end of travel. It should be rigid enough not to amplify vibration. The Straightness Reflector is mounted to direct the Reference Bisector down into the Optical Square where it is bent 90 degrees and directed parallel to the x or y axis.

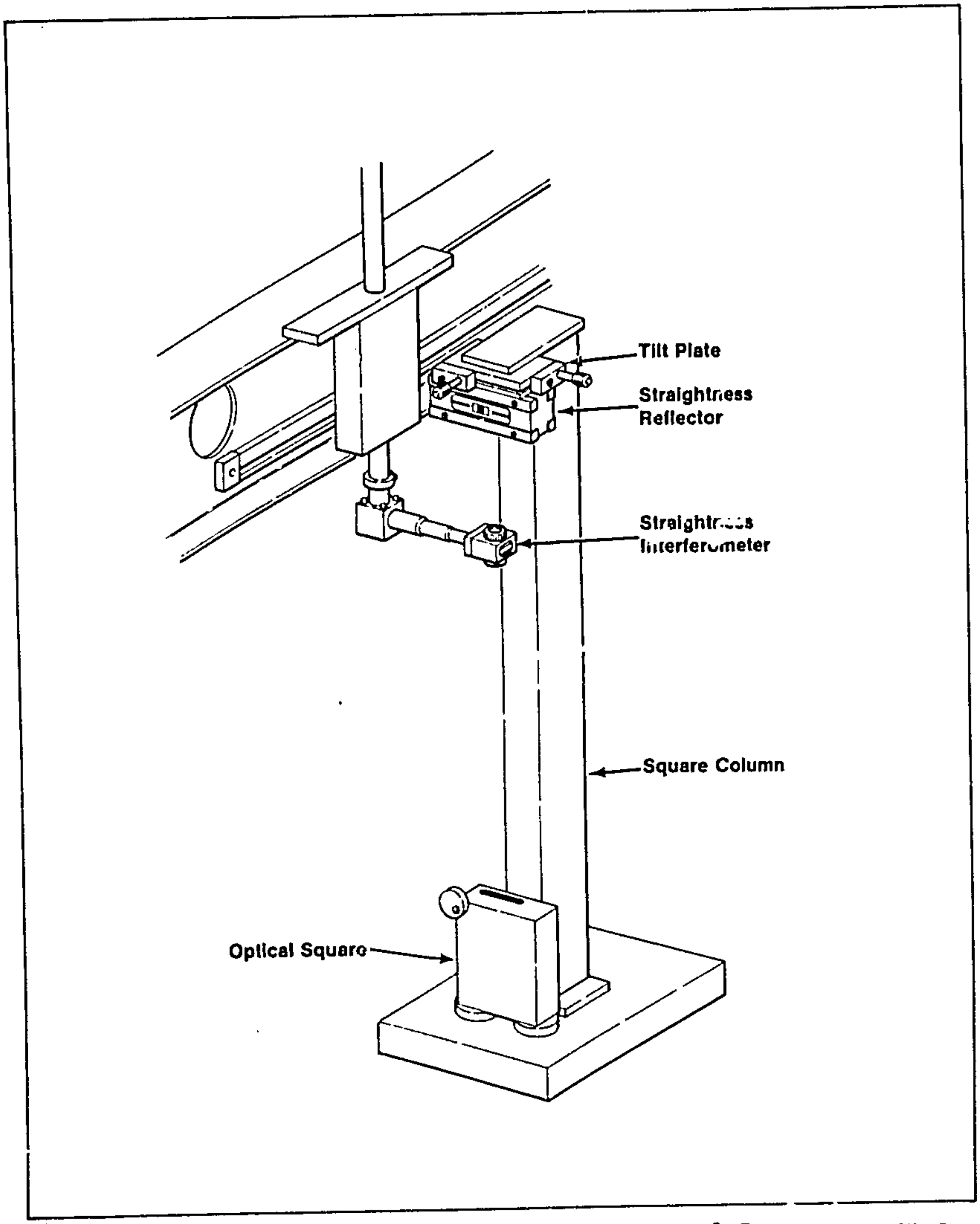


Figure 10-3. Typical Setup for Straightness and Squareness on a Coordinate Measuring Machine or Construction of a Machine Tool

SECTION XI

SECTION XI

LINEAR MEASUREMENT SETUP AND ALIGNMENT PROCEDURE

ALIGNMENT METHOD CHOICE

Two methods can be used to align the laser interferometer: Visual or Autoreflection. The alignment method selected depends on several factors: convenience, speed, and availability of accessories. Visual alignment can be used for measurements longer than 10 inches. Below 10 inches of travel, Autoreflection or Visual can be used when followed by the Alignment Accuracy Check. Use the reduced aperture during alignment for less than 30 feet.

"Near" and "Far" Ends of Travel For this manual are definded here as:

- o "Near end of travel" means the Remote Interferometer and Retroreflector (cube corner) are at the points of measurement where they are nearest to each other.
- o "Far end of travel" means the Remote Interferometer and Retroreflector are at the points of measurements where they are farthest from each other.

BASIC "VISUAL" ALIGNMENT METHOD

In the "visual" alignment method the Laser Head, Remote Interferometer and Retroreflector are adjusted so at the near and far ends of travel the reflected laser beam return spots remain centered on the cross hair target covering the selected return port on the Laser Head Turret. (The complete procedure is described later).

BASIC "AUTOREFLECTION" ALIGNMENT METHOD

In the "autoreflection" alignment method a plane mirror reflector such as the Model 10557A Turning Mirror is mechanically aligned with its reflecting face perpendicular both vertically and horizontally to the measurement line of travel. Then the Laser Head is set up at least 20 inches from the mirror and adjusted so the laser beam is reflected by the mirror back to the center exit port of the Laser Head Turret. Autoreflection depends on the availability of a perpendicular axis square to 0.0008 inch over 2 inches of travel or a similarly square or parallel reference surface to indicate the plane mirror reflector.

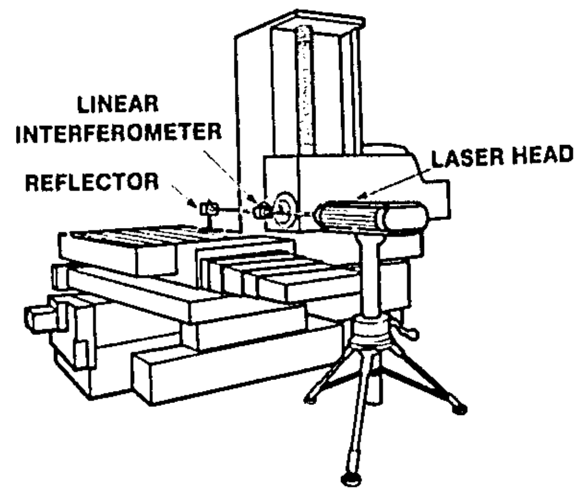


Figure 11-1. Typical Linear Setup

LINEAR MEASUREMENT SETUP AND ALIGNMENT PROCEDURE

INITIAL EQUIPMENT SETUP

1) Transport the necessary equipment to the measurement area.

2) Determine the desired measurements.

3) Position the necessary equipment and Tripod. Positioning the Tripod as explained below and in Figure 11-1 and Figure 11-2.

   a. The position of the equipment should provide convenient access to all controls and ease of operation during the measurements.

   b. The position of the Tripod should be chosen to minimize repositioning to measure other axes. Much time can be saved by eliminating realignment of the Laser Head for each measurement. A machine tool measurement is assumed.

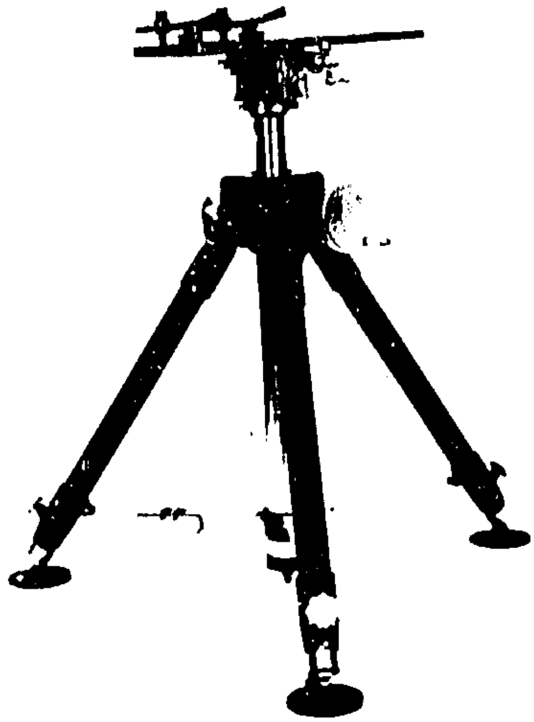


Figure 11-2. Correct 10580A Tripod Setup

4) Position the machine at one end of its travel.

5) Mount the optics

   a. It is usually easiest to mount the Retroreflector where the tool mounts and the Interferometer where the parts mount.

   b. Leave some space between the optics but not more than one inch.

   c. This is the "near end of travel".

   d. Position the optics along the desired measurement axis.

   e. Check the direction of the Interferometer arrows.

   f. Take the necessary precautions to avoid a collision of the optics.

6) Position the Tripod:

   a. With both cranks on the side you will be working from.

b. With two legs toward and parallel to the side of the machine. The third leg will then be parallel to the machine travel or the measurement axis.

c. Loosen the rotational axis locking screw. Rotate the mounting platform to be parallel to the machine travel by comparing the alignment of the platform, third leg, and the machine.

d. Lock the swivel screw tightly. This method of rotation should not be necessary during the alignment unless very coarse rotation is required.

7) Place the Laser Head on the tripod platform. Position one front foot ball in the conical depression and firmly clamp that foot with the toggle clamp.

NOTE

The toggle clamps are reversed to allow the Laser Head to rotate horizontally on the pads under the left and rear feet.

Vertical rotation is provided by the screw in the rear foot of the Laser Head that raises and lowers the back of the Laser Head. Only light pressure should be used to clamp the Laser Head resting on the front round pad.

8) Check that the Laser Head and Display are connected and turned on.

NOTE

Always turn power off before connecting or disconnecting cables. Damage to the electronic components may result.

9) Standing directly behind the Laser Head and tripod, sight down the Laser Head along the machine axis of travel. Position the Laser Head and tripod to direct the Laser Beam down the desired measurement path and into the window of the Interferometer.

a. Translate the Laser Head with the side cranks to direct the Laser into the window of the Interferometer. Rotation should be avoided if the Laser Head appears to be parallel to the measurement axis.

b. The Retroreflector attached to the Interferometer should return a dot that is visible on the face of the Laser Head turret. This dot is termed the "Interferometer dot". If no dot is seen check the Interferometer arrows. A second dot may be present from the Retroreflector not attached to the Interferometer; this is the "Retroreflector" dot.

10) Rotate the turret to position a cross hair target over the desired return port and reduce the beam diameter with the small aperture. This helps to resolve the actual position of the center of the return dots.

VISUAL ALIGNMENT PROCEDURE

The Visual Alignment procedure in brief is to:

- o Position the optics at the "near end of travel".
- o Carefully overlap the return dots. Rotation of the Laser Head has no effect at the "near end of travel".
- o At the "far end of travel" where the optics are at the maximum separation, overlap the dots again by translating the Laser Head first, then rotating it. When misalignment is sufficient the dots will separate as the optics separate and possibly be lost before the end of travel.

The detailed step-by-step procedure is as follows:

1) Place a piece of paper in the gap between the optics to block the beam to the Retroreflector. The remaining dot at the turret is the Interferometer dot. Translate the Laser Head to position the dot at the center of the cross hair target covering the desired Return Port. Remove the paper. If a second dot is not visible, reposition the Retroreflector until a second dot is visible at the Laser Head Turret.

2) Position the Retroreflector to very accurately overlap the two return dots.

NOTE

Rotation of either optical component to accompish the overlap is permissible. The squareness of the optics has no bearing on accuracy or the alignment to this axis. However do not rotate so far as to clip the beam passing through the optics. Also, when mounting the Interferometer in a spindle, rotation about the spindle axis will determine if a perpendicular axis can be measured without excessive realignment to that axis.

When the dots are perfectly overlapped interrupting the laser beam between the Interferometer and Retroreflector will cause a distinctive "blinking" of the return dots.

3) Once the dots are accurately overlapped and near the center of the cross hair target, with the optics at the near end of travel, traverse the machine along the measurement path toward the far end of travel. The dots will separate if cosine error is present as in Figure 11-3. Stop the machine just before one of the dots starts to disappear, or at the far end of travel.

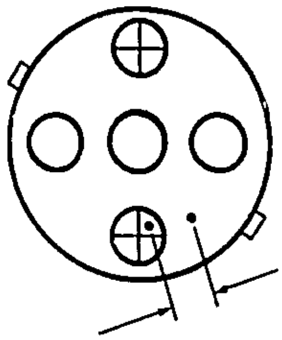


FIGURE 11-3 A Visual Indication of Cosine Error

Block the beam to the Retroreflector. The remaining dot is the Interferometer dot which acts as the point of an arrow formed by mentally drawing a line between the two return dots. The Retroreflector dot acts as the tail of the arrow. The "arrow" points in the direction in which to translate the Laser Head with the side cranks. Translate until one dot is left at the edge of the Turret in the direction of the arrow. One dot will temporarily be lost- the Retroreflector dot.

4) Rotate the Laser Head to bring the dots back across the target by unclamping the left front foot clamp. Then with thumb and forefinger move the rear foot left or right. Stop rotating only when the dots cross or when they reach the other side of the turret. Do not lose both dots outside of the turret until you are sure you can locate them again. (If the arrow was pointing diagonally, work in one axis at a time. Overlap in in one axis then the other. Work in the plane of the two targets on the Turret first).

5) Once the dots are overlapped, translate the Laser Head to position the dot at the center of the cross hairs and return the machine to the near end of travel.

6) If the dots remain overlapped at the near end of travel the alignment is complete. Check the overlap by interrupting the Retroreflector beam with a piece of paper. If the dots are accurately overlapped, proceed to the LINEAR A NMENT ACCURACY CHECK.

If the dots are not overlapped, check below then return to step 1 and repeat the alignment. The dots may have separated at the near end of travel because:

a. The optics changed position on the machine during the alignment -- check the fixturing.

b. Too much space was allowed between the optics at the near end of travel - see step 2 and repeat the alignment.

c. The dots were not accurately overlapped in step 1.

AUTOREFLECTION ALIGNMENT PROCEDURE

The autoreflection alignment procedure can be used if known square or parallel surfaces or axes are available. The alignment accuracy for linear measurements will depend on the perpendicularity of the plane mirror reflecting surface to the measurement axis. Autoreflection is recommended when angular or straightness measurements are to be made and the linear optics will not be used. When linear measurements are to be made, autoreflection should be used only if the measurement path is less than 10 inches followed by a Linear alignment accuracy check. The procedure for linear measurements:

1) Determine the line of travel to be measured. This is the measurement axis. Place the Remote Inteferometer at the near end of the measurement axis with respect to the Laser Head if linear measurements are to be made. The Interferometer laser beam entrance and exit windows should be roughly perpendicular to the measurement axis. Fasten the Remote Interferometer securely. f linear measurements are not to follow, omit the interferometer.

2) Standing behind the Laser Head, position the Laser Head and Tripod so the laser beam is directed into the window on the Remote Inteferometer. The laser beam should be directed in a line as parallel as possible to the measurement axis. As soon as the laser beam enters the Interferometer window a return dot will be visible on the Laser Head Turret.

3) Rotate in the small aperture in the Laser Head Turret to reduce the diameter of the exiting laser beam. This helps to resolve the actual position of the center of the laser beam. Rotate an alignment target over the desired Return Port by rotating the Laser Head Turret.

4) Very carefully adjust the Laser Head with the translation of the Tripod only until the reflected laser beam from the Remote Interferometer is near the middle of the cross hair target. Move the Laser Head only in a line perpendicular to the line of measurement. For this adjustment DO NOT rotate (tilt or turn) the Laser Head.

5) Set a reflecting mirror, such as the HP 10557A Turning Mirror or a gage block surface in the line of measurement so the laser beam is near the center of the mirror. Put the mirror at the far end of measurement travel.

NOTE

The HP Model 10557A Turning Mirror is made with the front surface of the mirror mount parallel with the reflecting surface of the mirror, and the top and bottom surfaces of the mirror mount are perpendicular to the mirror surface. The rear angled surfaces of the mirror mount are at 45 degrees to the front surface and at 90 degrees to the top and bottom surfaces.

6) While measuring with an accurate indicator (an electronic gage is recommended), adjust the mirror so the mirror surface is perpendicular, vertically and horizontally, to the line to be measured. The reflected laser beam should be visible on the Laser Head Front Panel. Fasten the mirror securely only if necessary.

7) Very carefully adjust the Laser Head with rotation by turning it or by raising or lowering the rear foot to center the reflected beam from the mirror on the laser beam Exit Port of the Laser Head. The reflected beam will appear as a "halo" around the small Exit Port.

8) If the Interferometer return dot has moved off the alignment target during rotation of the Laser Head, translate the Laser Head to return it to the center of the desired alignment target.

NOTE

Do NOT move the Laser Head perpendicular to the measurement line, from side to side or up or down, to bring the laser beam from the mirror back to the center aperture (see steps 4 and 7). This will only change the location of the returning Interferometer dot. Do NOT turn the Laser Head or raise or lower the rear foot to put the reflected beam from the Remote Interferometer on the cross hair target of the selected beam return hole (see steps 4 and 7). This will change the location of both dots.

9) If necessary, very carefully repeat steps 4 and 7 to center the reflected laser beam dots. Perform step 7 last.

10) When steps 4,7, and 9 are finished, remove the mirror and replace it with the Retroreflector. If Linear measurements are not to be performed the Interferometer used in Step 1 and Steps 11-16 need not be used or performed.

11) Adjust the Retroreflector so it reflects a return dot to the selected cross hair target on the Laser Head Turret. Adjust the Retroreflector so the return dot from the Retroreflector overlaps the Interferometer return dot and both dots are on the center of the cross hair target.

12) Open the laser beam Exit Port (if covered by the small aperture), and open the selected Return Port on the Laser Head so the reflected laser beams are received by the photo detector. The BEAM ALIGNMENT meter on the Laser Display should indicate in the green area of the scale. Continue with the next step regardless of the meter indication.

13) Slowly move the Retroreflector along the line of measurement to the near end of travel, and note the BEAM ALIGNMENT meter indications during the Retroreflector movement. The BEAM ALIGNMENT should indicate in the green area from the far to the near end of Retroreflector travel.

14) If the BEAM ALIGNMENT meter does not stay in the green area for step 13, recheck the alignment.

15) If the BEAM ALIGNMENT meter stays in the green area for step 13, zero the Display by pressing the display RESET button at the near end of travel.

16) If the preceding steps have been performed properly, the system is ready to check the alignment accuracy.

NOTE

You should always RESET the Laser Display to zero with the Remote Interferometer and Retroreflector at the near end of travel, and then make measurements by increasing the distance between the Remote Interferometer and the Retroreflector to minimize Deadpath error.

LINEAR ALIGNMENT ACCURACY CHECK

The Beam Alignment Meter is a signal strength indicator. It indicates how much of both return dots are being detected by a photo detector in the Laser Head. The Beam Alignment Meter also saturates (the needle pegs at maximum) at about 9 on the meter scale. Cosine error may not be minimum for measurements of less than about 30 inches when the Beam Alignment Meter saturates. For angular and straightness measurements the Beam Alignment Meter is a beam alignment indicator.

Linear measurements of less than about 10 inches require a method of determining that cosine error is sufficiently below the accuracy requirement of the measurement. First, the laser beam must be as parallel as possible (and preferably coaxial) to the measurement axis. This can be accomplished by several means, the quickest and most direct being the Visual alignment.

Procedure

1) Follow the Linear Alignment Setup and Alignment procedure. Overlap the return dots for a perfect blink at both ends of travel.

2) Open the Exit and Return Ports. With the optics at the near end of travel, press the RESET button to establish reference zero.

3) Press the X10 Mode Switch.

4) Move the optics to the far end of travel or a few inches of the measurement length.

5) The Laser Display will show the apparent measurement length which will be shorter than the actual measurement length. While watching the last 3 digits on the Laser Display, rotate the Laser Head in the vertical plane by slowly turning the rear foot adjusting screw on the Laser Head. If the number shown on the Laser Display increases you are rotating in the correct direction. Continue rotation until the number on the Laser Display starts to decrease. Then reverse the rotation to maximize the Laser Display reading.

NOTE

Beam Alignment can be lost if cosine error remained large after the linear alignment. Translation of the Laser Head to re-center the return beams in the desired Return Port will help avoid loss of Beam Alignment. If Beam Alignment is lost during rotation, repeat steps 1 through 5. For long measurements a reading on the Laser Display of a few inches anywhere along the measurement length is sufficient.

6) Once the maximum reading is found by rotating the Laser Head in the vertical axis, unlock the left-hand toe clamp that holds the Laser Head front left foot to the round gage quality footpad. While watching the last 3 digits on the Laser Display, slowly rotate the rear foot of the Laser Head to increase displayed reading to attain the maximum value. Avoid loss of beam alignment by re-centering the returned laser beams with translation of the Laser Head.

   If beam alignment is lost, do the following:

   a. Translate the Laser Head to maximize the Beam Alignment Meter reading.

   b. Insure that sufficient measurement path remains.

   c. Press the RESET button.

   d. Move the optics to store a measurement on the Laser Display.

   e. Continue rotating until the maximum length is found. When the maximum measurement length is found with vertical and horizontal rotation of the Laser Head, cosine error is minimized.

LASER BEAM MAGNETIC TARGET-TEMPLATE

A small aluminum plate with two holes and a magnetic back pad is supplied with the 10565B Remote Interferometer (see Figure 11-4) The two target holes are spaced the same distance as the laser Head The magnetic pad will hold the target-template on a Turning Mirror. help align the beam with the side or the top and bottom beam return ports.

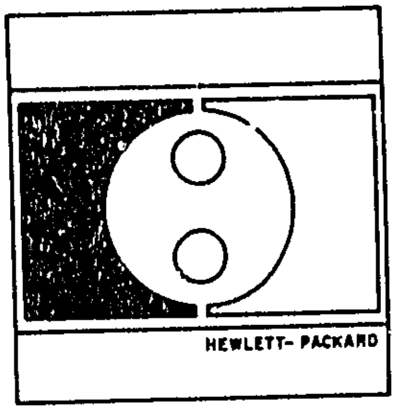


Figure 11-4. Laser Beam Magnetic Target-Template

LINEAR MEASUREMENT
CHECK LIST

1) Set Up Consideration
2) Linear Alignment
3) Compensation

1) Set Up
   [] Determine Desired Information
   [] Consider Abbe Offsets
   [] Minimize Dead Path Error
   [] Economize Set Up

2) Linear Alignment
   [] Select Proper Alignment Procedure -
      o Visual (Machine Travel >10 inches)
      o Visual with Accuracy Check (<10 inches)
   [] Minimize Cosine Error

3) Compensation
   [] Machine at Operating Temperature
   [] Enter Wavelength Compensation
   [] Correct for Material Compensation

SECTION

XII

SECTION XII

ANGULAR MEASUREMENT SETUP AND ALIGNMENT PROCEDURE

1) Initial Equipment Set Up

   A) Transport the necessary equipment to the measurement area.

   B) Determine the desired measurements.

   C) Position the necessary equipment and Tripod. See Figure 12-5.

      1. The desired position of the equipment will provide convenient access to all controls and ease of operation during the measurements.

      2. The desired position of the Tripod should be chosen to minimize repositioning to measure other axes. Much time can be saved by not having to realign the Laser Head for each measurement.

   D) Mount and clamp the Laser Head on the Tripod.

2) Linear Alignment

Align the laser beam to the desired measurement axis by the most convenient method as described in Section 10 Linear Alignment. Laser beam alignment for Angular measurements is not as critical as for Linear measurements.

NOTE

Alignment of the Laser beam to the axis of travel need only be sufficient to allow a Beam Alignment Meter reading anywhere in in the green area of the meter scale. High meter readings will insure maximum measurement lengths and maximum insensitivity to loss of beam alignment due to vibration and turbulence.

3) Angular Optics Assembly

The angular optics are assembled as in Figure 12-1. The 10559A Reflector Mount is used to accurately hold the two 10556A Retroreflectors of the Linear optics. The 10558A Beam Bender is wrung to the 10565B Remote Interferometer, squared to the 10565B Remote Interferometer, then locked together with 4 slot head screws.

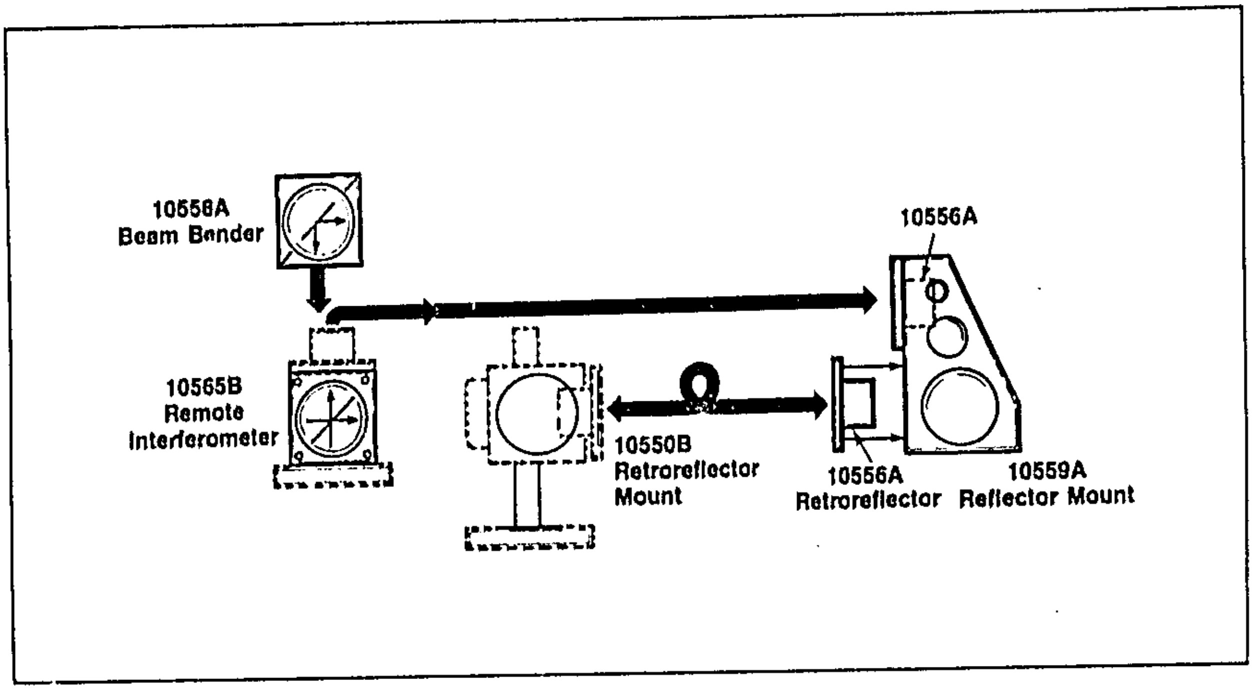


Figure 12-1. Angular Optics Assembly

A) Wringing Procedure

Wringing is accomplished by pressing two flat and highly polished surfaces together with enough pressure to displace the air between them. A thin oil film or alcohol film is often used and recommended to help displace the air.

Figure 12-2 shows the correct orientation of the Interferometer and Beam Bender prior to wringing.

i) Carefully clean the mating surfaces with alcohol and a clean, soft, lintless wipe.

ii) A thin film of oil or alcohol can then be applied to aid in wringing.

iii) Slide the Beam Bender on to the top of the Interferometer.

iv) Press the Beam Bender and Interferometer together forcing any trapped air from between the mating surfaces.

v) Slowly rotate the Beam Bender while maintaining wringing pressure.

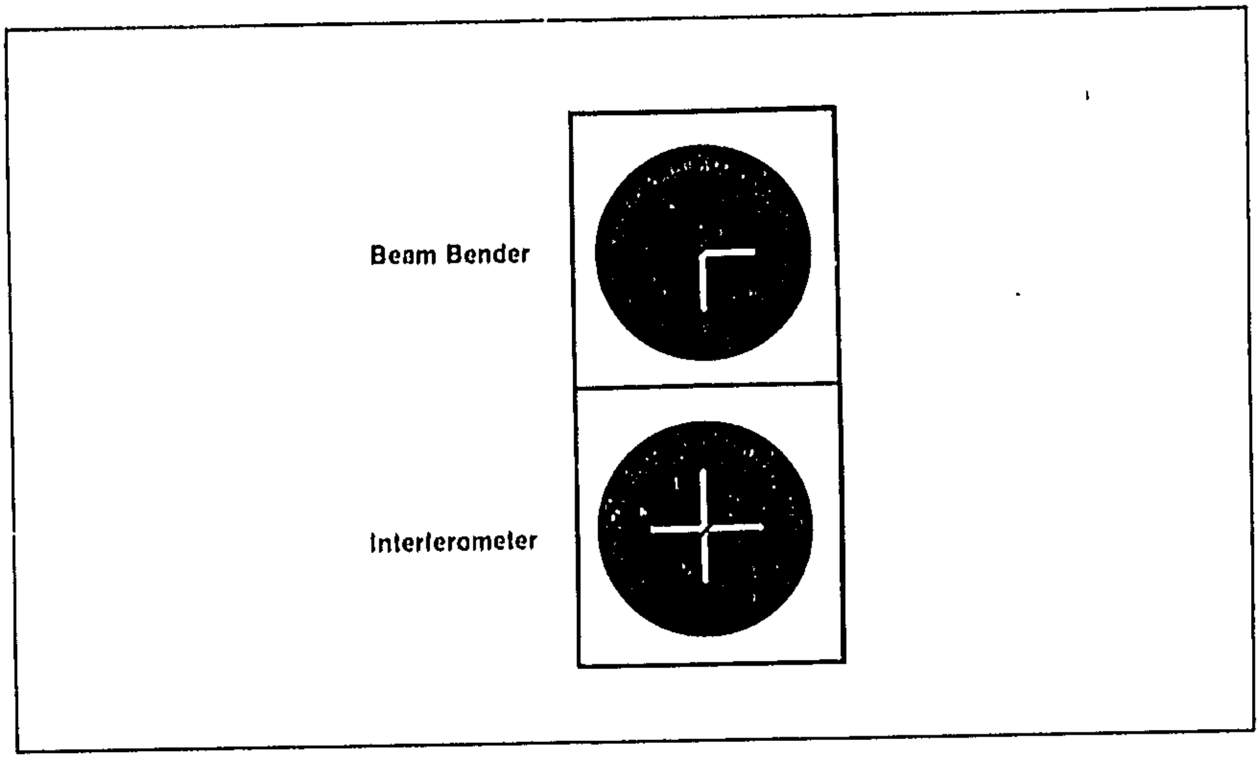


Figure 12-2. Wringing of Beam Bender and Interferometer

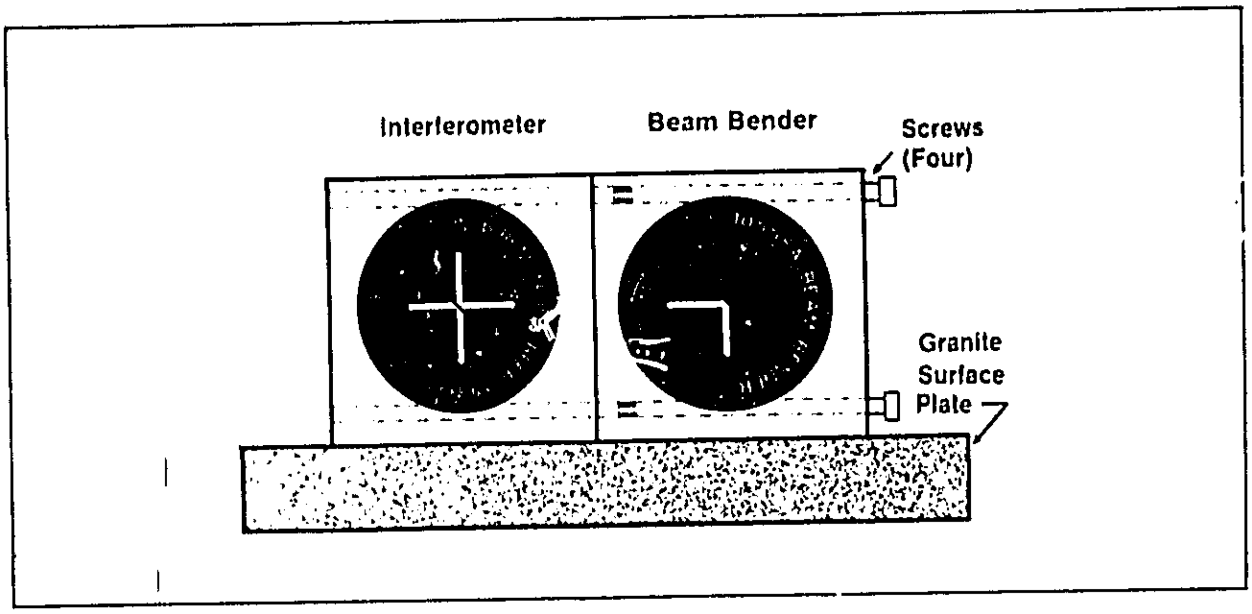


Figure 12-3. Squaring of Beam Bender and Interferometer

NOTES

1) Wringing should not be attempted if burrs, dents or large scratches are apparent. These surface defects must be removed by a qualified person to insure correct spacing and parallelism of the laser beams.

2) The cylindrical surfaces on the back of the Retroreflectors are precision ground to insure spacing and parallelism. Plastic covers are provided to protect these surfaces and should be used any time the Retroreflectors are not mounted in the 10559A Retroreflector Mount.

3) Care should be taken in fitting the Retroreflectors into the Retroreflector Mount; damage can result by forcing an incorrect fit.

4) Do not warm the Retroreflectors with respect to the Retroreflector Mount. The expansion of the Retroreflectors could produce an interference fit.

B) Exiting Beam Parallelism

The correct alignment of the Beam Bender and Interferometer can be accomplished by pressing the wrung optics down on a clean inspection grade surface plate without breaking the wring as shown in Figure 10-2. Lock the optics together only finger tight with 4 slot head screws provided - do not over-tighten. To insure that tightening the screws has not changed the orientation of the optics, press down on the corners of the optics. No rocking should be detected. Perform the Assembly and Accuracy check, step 4.

C) Visual Alignment of Beam Bender to Interferometer

When a surface plate in good condition is not available, the correct alignment of the Interferometer and Beam Bender can be determined in situation by setting up as in Figure 12-4.

i) Follow the Angular Set up and Alignment procedure and set up on a flat surface as in Step 4 Assembly and Accuracy check. See Figure 12-4.

ii) Mount the Reflector Mount at "near end of travel" to obtain a return dot at the desired Return Port using the Alignment target and Reduced Aperture on the Laser Head Turret.

iii) Position the Interferometer/Beam Bender in the laser beam within one inch of the Reflector Mount to obtain a second return dot at the Laser Head.

iv) Loosen the 4 slot head locking screws and slowly rotate the Beam Bender to overlap the dots as much as possible. If a second dot is not apparent, slow rotation of the Beam Bender should produce a second dot. If still no dot, check the orientation of the arrows on the Interferometer.

v) Move the Reflector Mount away from the Interferometer as far as possible. Ten feet or more is preferred. Any means of holding the reflector at a long distance from the Interferometer is usually satisfactory. The return dots should remain overlapped. If not, rotate the Beam Bender to overlap the dots horizontally. Perfect vertical overlap may not be possible. Move the Reflector Mount as far as possible while maintaining both dots at the Laser Head target. Readjust the Beam Bender as necessary.

vi) Retighten the slot head screws. Slide one optic toward the other until they are as near as possible. The dots should remain overlapped. If not, repeat Steps 3-6. A longer separation in Step 5 will give greater resolution. When maximum overlap is attained, perform the following Assembly and Accuracy Check.

4) Assembly and Accuracy Check Place the Angular optics on a suitable flat surface. Align the optics following the Angular Set up and Alignment Procedure along a straight edge and adjust the Laser Head to maintain beam alignment while moving the optics along the straightedge. A 12 inch straightedge is sufficient. See Figure 12-4.

A) Test A

Press Reset on the Laser Display to obtain a zero reading. While maintaining the front foot of the Reflector Mount against the straightedge, rotate the rear foot 0.100,000 in (2.54 mm) away from the straightedge. A guage block is ideal to use. The Laser Display should accumulate <100 uin (2.54 um). This test checks the centering of the Retroreflectors in the 10556A Assembly and the Reflector Mount.

Remove the guage block and place the Reflector Mount flush against the straightedge; the Laser Display should again read nearly zero. If not, insure clean contacting surfaces and repeat the above test until sufficient precision is attained.

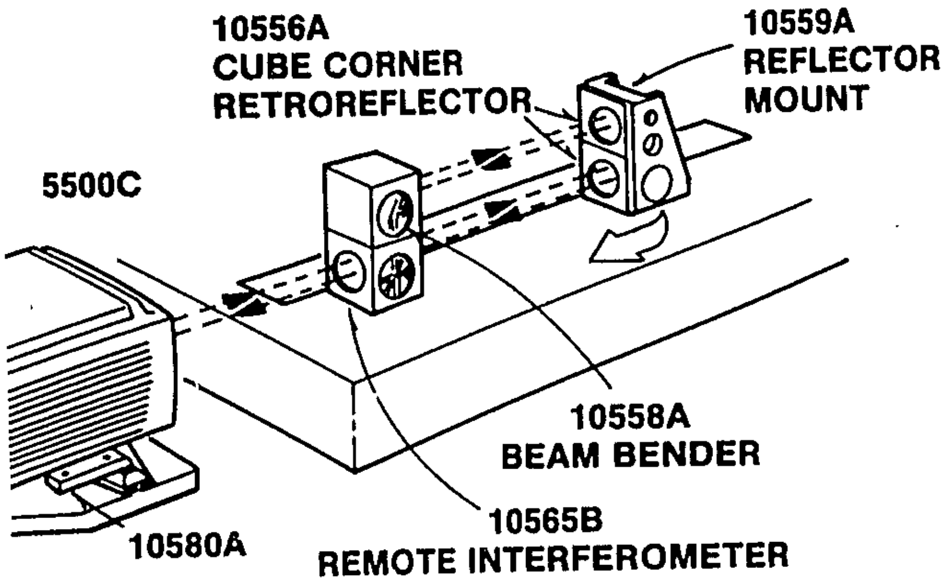


Figure 12-4. Angular Optics Accuracy Check

B) Test B

Press Reset on the Laser Display. Slowly move both ends of the Reflector Mount away from the straightedge by 0.100,000 in (2.54 mm). The Laser Display should accumulate <10 uin (0.254 um). Remove the guage blocks and place the Reflector Mount flush against the straight edge; the Laser Display should again read nearly zero. If not, check the set up and repeat the above test until sufficient precision is attained.

This procedure checks the parallel alignment of the two laser beams exiting from the Interferometer/Beam Bender. If this test fails, check the return dot overlap at the Laser Head Turret with the optics as far apart as possible using the Reduced Aperture and Alignment Target. The dots should be overlapped at least in the horizontal plane. If not, follow Step 3C, Visual Alignment of Beam Bender to Interferometer procedure above. If the check cannot be passed after following Steps 3C and 4B, the optics will measure angles and flatness inaccurately. The wringing surfaces should be closely inspected and the problem rectified before measurements are attempted.

5) Angular Optics Alignment

Insure that Steps 2,3 and 4 have been performed. Position the Reflector in the beam path at the near end of travel to obtain a return beam dot at the desired Return Port. Reduce the beam diameter with the Reduced Aperture and Alignment Target.

6) Position the Interferometer/Beam Bender in the beam path close to the Reflector to obtain a second return beam dot at the Laser Head.

   A) Rotate the Interferometer/Beam Bender to overlap the two dots.

   B) Open the Exit and Return Ports of the Laser Head Turret. The Beam Alignment Meter should indicate in the green.

7) Press Reset and move the optics along the measurement path to ensure Beam Alignment over the entire measurement path. Proceed with the desired measurements.

NOTE

You should ensure that the optics are securely mounted and unable to rotate independently of the machine. The spindle must not rotate. A suitable clamp must be available. A hose clamp and suitable wedging material is usually effective.

ANGULAR MEASUREMENT CHECK LIST

1) Set Up
   [] Determine Desired Information
   [] Economize Set Up

2) Linear Alignment
   [] Select Easiest or Quickest Alignment Procedure
   [] Align Laser Beam to Axis of Travel

3) Angular Alignment
   [] Assembly Accuracy Check
   [] Mount Angular Optics to Place Return Beam on Target at Laser Head
   [] Insure Beam Alignment along entire Axis of Travel

SECTION XIII

STRAIGHTNESS MEASUREMENT SETUP AND ALIGNMENT PROCEDURE

This section should be read before straightness setups and alignments are attempted.

1) INITIAL EQUIPMENT SETUP

   A) Transport the necessary equipment to the site where the Laser measurement will be taken.

   B) Determine the desired measurements.

   C) Position the necessary equipment and Tripod.

      i. The desired position of the equipment will provide convenient access to all controls and ease of operation during the measurements.

      ii. The desired position of the Tripod should be chosen to minimize repositioning to measure other axes. Much time can be saved by not having to completely realign the Laser for each measurement.

   D) Mount and clamp the Laser Head on the Tripod.

2) LINEAR ALIGNMENT

   A) The desired position of the Laser Head and Linear Optics or Turning Mirror for the alignment will be determined by the mounting position of the Straightness optics. Align the Laser beam to the measurement axis by the most convenient method, typically autoreflection.

3) STRAIGHTNESS REFLECTOR ALIGNMENT

   A) Rigidly mount the Straightness Reflector in the horizontal straightness position on the machine:

      i) Where the part would mount.

      ii) As far as possible from the Laser Head.

      iii) So the laser beam enters the slot and impinges on the split in the mirrors.

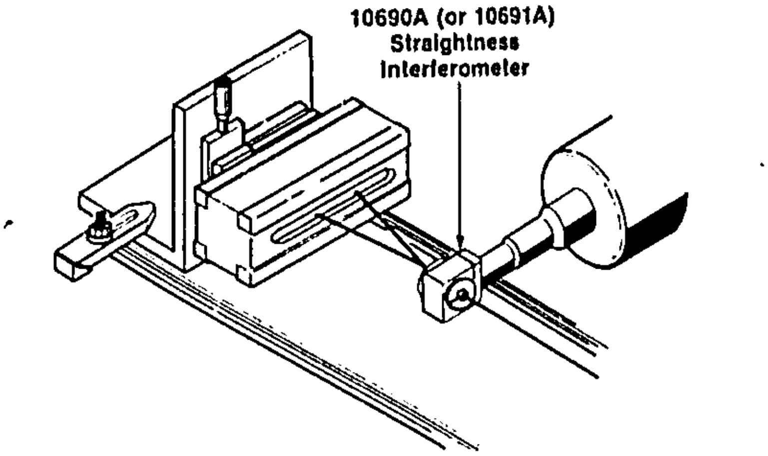


Figure 13-1. Horizontal Straightness-Straightness of X with respect to Z

B) Two semi circular Return Dots will result. Punch a 1/2" hole in the center of a sheet of paper. Insert the paper into the laser beam about three feet from the Straightness Reflector, and allow the laser beam to pass through the 1/2" hole. Adjust the Tilt Plate micrometers until the return dots are equally spaced on each side of the laser beam and in the same plane as seen on the paper.

NOTE

Only one-half of the laser beam is impinging on each mirror, therefore, two one-half dots are returned. The return dots diverge at a small angle. When the dots are adjusted properly, the Straightness Reflector is aligned to the laser beam. The laser was aligned to the machine travel, squareness, or the parallelism of a "T" slot.

4) STRAIGHTNESS INTERFEROMETER ALIGNMENT

A) The Interferometer mounts in the tool position - directly as possible. The mounting post should be as short as possible. Collets are preferred over chucks. The spindle should be locked and free of rotation by some means. A hose clamp and wedging material are usually effective.

NOTE
Rotation of the spindle during straightness measurements will result in cosine errors.

B) Rotate the Interferometer Bezel until the scribeline aligns to the slot in the Straightness Reflector, horizontally in this example.

C) While rotating the Bezel and watching the Laser Head Turret, note that two return dots will rotate across the face of the Laser Head Turret. Overlap the dots with rotation of the Bezel. If two dots cannot be found and overlapped remove the Interferometer and repeat steps 3B thru 4C.

5) FINE ADJUSTMENT OF REFLECTOR AND INTERFEROMETER

A) Reduce the beam diameter with the small aperture.

B) Adjust the Tilt Plate micrometers to halo the return dot about the Exit Port Aperture.

C) Open the Return Port and Exit Port. Carefully mount the Straightness Adaptor on the front panel of the Laser Head by means of the four screw extensions.

D) Follow the laser beam with a piece of paper from the Straightness Adaptor to the Straightness Reflector checking for clipping of the beam that would reduce signal strength. Adjust the optics appropriately. Do not change the angular alignment of the Reflector or Laser Head.

E) Insure that the X36 Resolution Extender is in the cables, and is in Extended. Turn off the Laser Display before connecting or disconnecting any cables.

F) Rotate the Bezel on the Interferometer while watching the return dots on the Laser Head to see how little rotation is necessary to overlap the dots for alignment. Then watch the Beam Alignment Meter and peak it with the bezel. Again, very little rotation is necessary at the peak.

G) Adjust the Tilt Plate for the center of the Beam Alignment Meter peak, rotating the micrometer which is perpendicular to the slot only.

H) Press Reset, and move the optics toward the near end of travel until Beam alignment is about 6 on the Beam Alignment Meter. Translate the Laser Head (do not rotate) in the plane of the Straightness Reflector slot for maximum peak and repeat Step H until the Optics are within 4 in. (3 ft long range) or until maximum travel is attained. Final distance between the optics at near end of travel can be <4 inches, typically one to two inches for short range and <3 ft for long range.

I) Check the optics again for clipping of the beam.

6) MANUAL REDUCTION OF SLOPE (REFERENCE BISECTOR ALIGNMENT)

Maximum slope is about 0.2 inches in any length of travel. Manual reduction of the slope may be necessary and is beneficial if vibration and/or turbulance are severe problems.

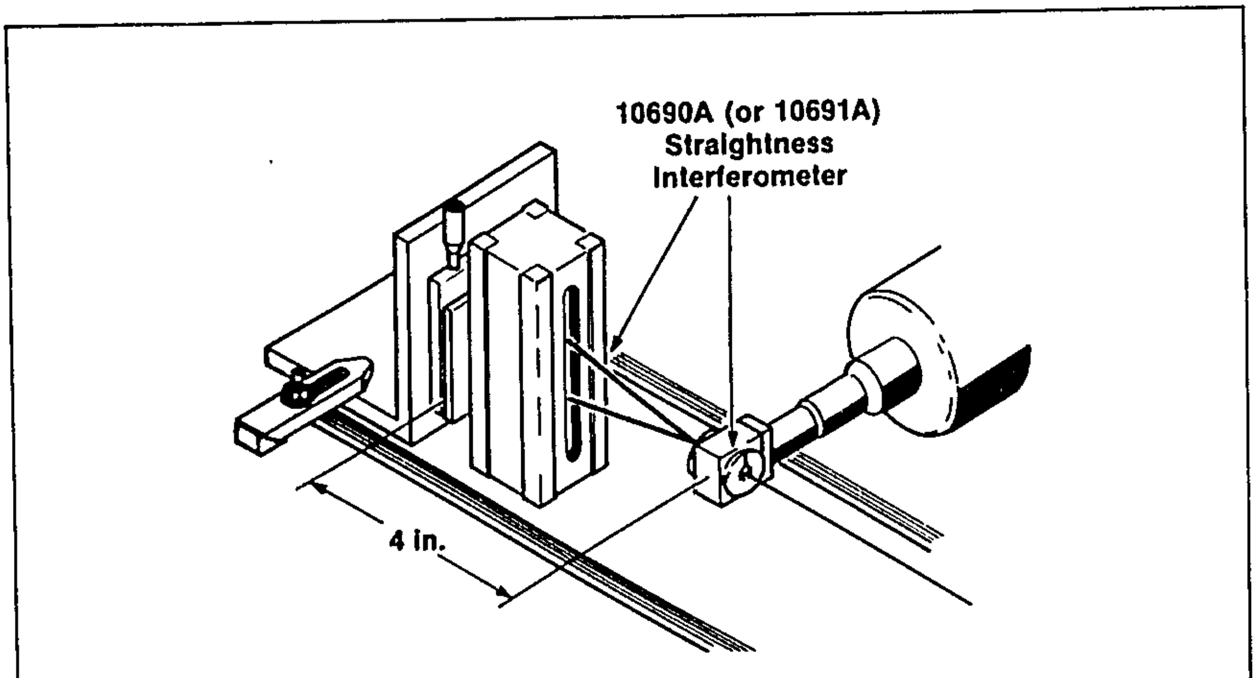


Figure 13-2. Measurement of Distance From Pivot Point to Measurement Zero

A) Reset the Display with the optics at the near end of travel.

B) Measure the distance from the slit in the Tilt Plate to the Interferometer, approximately 4 inches. Record it and label it "r". See Figure 13-2 for example.

C) Traverse the optics to the far end of travel measuring the distance traveled, record it and label it "d".

D) Multiply the Laser Display reading by -r/d.

E) Adjust the Tilt Plate in the plane of the Reflector slot until the Laser Display reads the calculated number. If beam alignment is lost, stop further adjustment, realign the Laser Head to the new reflector position with rotation and translation to regain beam alignment. Check clipping and return to Step A.

F) Reset the Laser Display. Check the slope while returning to the near end of travel. If slope is still unsatisfactory, repeat Steps A-F. If slcpe is satisfactory, alignment is complete.

7) DETERMINE THE SIGN OF THE DATA

8) CONNECT THE CALCULATOR AND PLOTTER IF NOT DONE PREVIOUSLY, AND PLACE PAPER ON THE PLOTTER.

9) CHECK FOR RANDOM ERRORS.

A) Random Errors can be severe enough to interrupt the beam alignment. The Random Errors are:

i) Mechanical Vibration.

ii) Thermal Turbulance.

iii) Abrupt machine movements perpendicular to the Axis of travel. They are more severe at the far end of travel. The source(s) can be isolated by systemtically reducing the error at the source or reducing its symptom as described below.

B) Mechanical Vibration and Machine Movement

1. Reduce any lever arms that may be contained in the mounting fixtures for the Straightness Reflector and Interferometer to minimum length - eliminate them if possible - they amplify vibration.

2. Insure that the Straightness Reflector is solidly mounted preferably on a rigid angle bracket as in Figure 8-5 or remove the Tilt Plate and mount directly to a base plate and clamp the base plate directly to the machine. If straightness alignment has not been attempted before do not remove the tilt plate, alignments can be more difficult without it.

C) Turbulance

1. Turbulance is caused by differing air temperatures along the laser beam measurement path, which result from heat sources like forced air heating and/or cooling outlets, intense light sources that also generate heat along their beam path.

NOTE

Temperature controlled rooms and air conditioned rooms are severe turbulence areas! If the source cannot be directly affected, an appropriate size fan positioned to mix the air along the measurement path can greatly reduce random errors due to thermal turbulence.

D) Abrupt Machine Movements

1. Abrupt machine movements are apparent when beam alignment is lost when a machine is started, stopped or transversed quickly. This indicates a mechanical problem in the table drive system causing out-of-straightness movements at a rate faster than the Laser Display can accept, a minimum of 20 inches per minute.

10) TAKE THE DESIRED STRAIGHTNESS DATA

STRAIGHTNESS MEASUREMENT CHECK LIST

1. SETUP CONSIDERATIONS

   - Determine Desired Information
   - Determine Limits of both Travel and Fixturing
   - Determine Beam Location and Height
   - 10579-60004 Resolution X36 in Cables

2. LINEAR ALIGNMENT

   - Select Convenient Alignment Procedure
   - Laser Beam Accurately Aligned to Machine Travel

3. STRAIGHTNESS REFLECTOR ALIGNMENT

   - Securely Mount Reflector at End of Travel in Part position
   - Adjust Tilt Plate to Center Return Dots About Exit Port or Laser Beam

4. STRAIGHTNESS INTERFEROMETER ALIGNMENT

   - Interferometer is Aprox. Square to Machine in Tool Position
   - With Reduced Aperature Rotate Interferometer Bezels to Overlap Return Dots
   - With Tilt Plate, Position Overlapped Return Dots at Center of Exit Port
   - 10579-60004 Resolution X36 in Straightness
   - Mount Straightness Adaptor on Laser Head
   - Sharp Peak on Beam Alignment Meter with Bezels
   - Adjust tilt Plate for Greatest Peak
   - Insure Alignment over Entire Measurement Path

5. SLOPE ALIGNMENT

   - Adjust Reflector for Zero End Point Fit
   - Adjust Laser and Interferometer for Meter Peak

SECTION

XIV

SECTION XIV

SQUARENESS MEASUREMENT SETUP AND ALIGNMENT PROCEDURE

This setup and alignment procedure should be read before measurements are attempted.

1) INITIAL EQUIPMENT SETUP

A) Transport the necessary equipment to the site where the laser measurements will be taken.

B) Position the equipment and Tripod (see Figure 14-1). The desired location of the equipment will provide convenient access to all controls and ease of operation during the mesurements. The desired location of the Tripod will be chosen by positioning the necessary optics on the machine as described below in C.

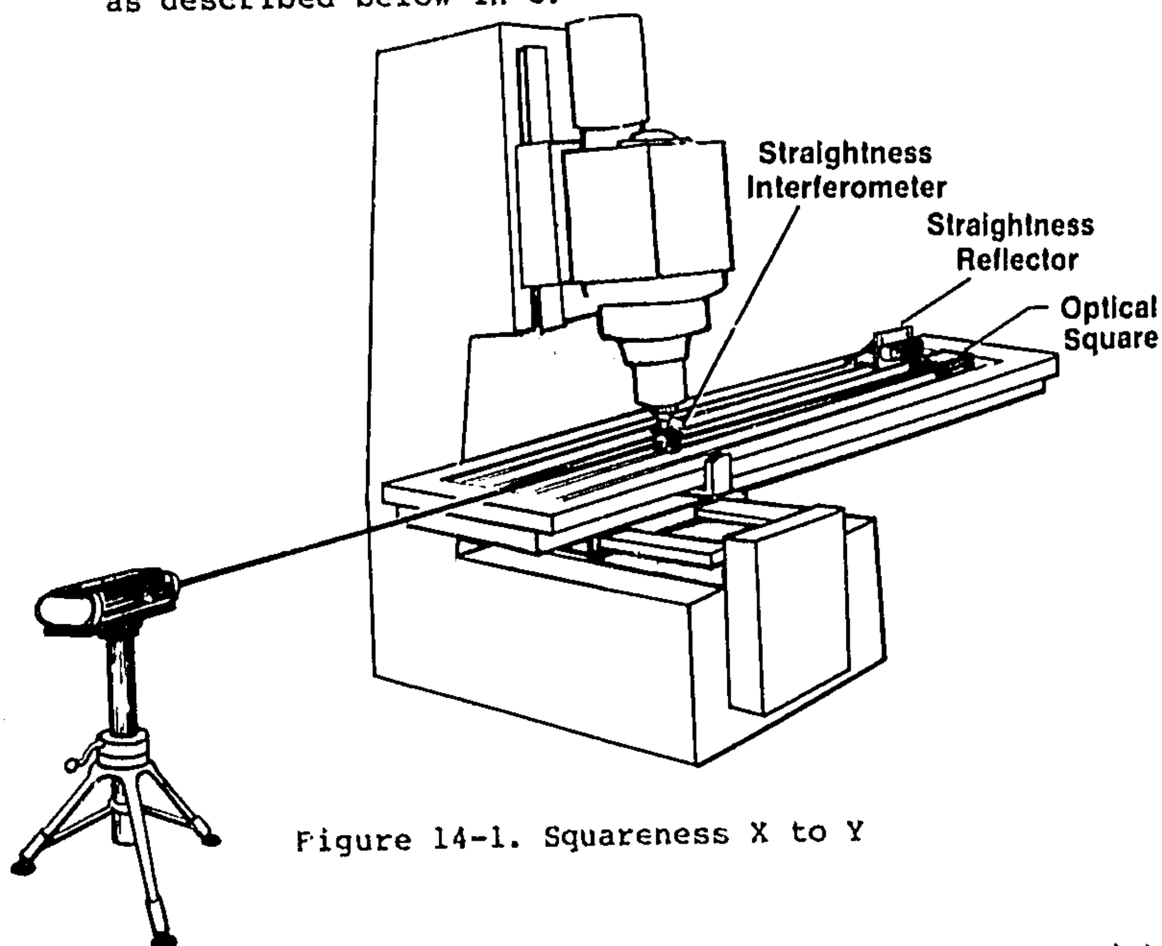


Figure 14-1. Squareness X to Y

C) Mount or determine the mounting position of the Straightness Reflector in the horizontal plane on a sturdy mount that will allow the split in the mirrors to be in the center of the slot in the Optical Square as the Optical Square sits on the table on its three round foot pads or appropriate fixture. See Figure 14-1.

D) Mount or determine the mounting position of the Optical Square to allow the laser beam to pass without clipping. The mounting position of both the Optical Square and the Straightness Reflector must allow both axes to be measured without relocating in any way the Straightness Reflector. Figure 14-1 is an example of a typical horizontal straightness and squareness setup.

2) LINEAR ALIGNMENT

A) The desired position of the Laser Head and Linear Optics or Turning Mirror for the alignment will be determined by the mounting position of the Straightness optics. Position all of the required optics on the machine prior to the Linear Alignment. Align the Laser beam to the measurement axis by the most convenient method, typically Autoreflection.

3) STRAIGHTNESS REFLECTOR ALIGNMENT

A) Rigidly mount the Straightness Reflector in the horizontal straightness position on the machine:

i) Where the part would mount.

ii) As far as possible from the Laser Head.

iii) So the laser beam enters the reflector slot and impinges on the split in the mirrors.

B) Mount the Optical Square to maximize machine travel in the first axis and still allow the Laser beam to be directed into the slot of the Straightness Reflector.

C) Align the Straightness Reflector and Optical Square to the laser beam to allow the laser beam to impinge on the split between the Straightness Reflector mirrors. Reducing the beam diameter with the small aperture may be helpful.

D) Two semi-circular Return Dots will result. Punch a 1/2" hole in the center of a sheet of paper. Insert the paper into the laser beam about three feet from the Straightness Reflector, and allow the laser beam to pass through the 1/2" hole. Adjust the Tilt Plate micrometers until the return dots are equally spaced on each side of the laser beam and in the same plane as seen on the paper.

NOTE

1. Only one half of the laser beam is impinging on each mirror, therefore, two one-half dots are returned diverging at a small angle.

2. When the dots are so adjusted, the Straightness Reflector is aligned to the laser bea... which was aligned to the machine travel or squareness, or parallelism of a "T" slot.
3. Do not adjust the laser head. The laser beam was aligned to the machine and is temporarily the reference to adjust the optics to.
4. Follow the dots as ... as possible for increased resolution.

4) Straightness Interferometer Alignment

A) The Interferometer mounts in the tool position directly as possible. The mounting post should be as short as possible and collets are preferred over chucks. The spindle should be locked and free of rotation by some means.

B) Rotate the Interferometer Bezel until the scribeline is parallel to the slot in the Straightness Reflector - horizontally in this example.

C) While rotating the Bezel and watching the Laser Head Turret, note that two return dots should rotate across the face of the Laser Head Turret. Overlap the dots with rotation of the Bezel. If two dots cannot be found remove the Interferometer and repeat steps 3B thru 4C.

5) Fine Adjustment of Reflector and Interferometer

A) Reduce the beam diameter with the small aperture.

B) Adjust the Tilt Plate micrometers to halo the return dot about the Exit Port Aperture.

C) Open the Return Port and Exit Port. Carefully mount the Straightness Adaptor on the front panel of the Laser Head by means of the four extended screws.

D) Follow the laser beam with a piece of paper from the Straightness Adaptor to the Straightness Reflector checking for clipping of the beam that would reduce signal strength and adjust the optics appropriately. Do not change the angular alignment of the Reflector or Laser Head.

E) Insure that the X36 Resolution Extender is in the cables, and is in Extended. Turn off the Laser Display before connecting or disconnecting any cables.

F) Rotate the Bezel on the Interferometer while watching the return dots on the Laser Head to see how little rotation is necessary for overlapping the dots for alignment. Then watch the Beam Alignment Meter and peak it with the Interferometer Bezel, very little rotation is necessary at the peak which is perpendicular to the slot, for the center of the Beam Alignment Meter peak.

G) Adjust the Tilt Plate, rotating the micrometer which is perpendicular to the slot only, for the center of the beam Alignment Meter peak.

H) Press Reset, and move the optics toward the near end of travel or until Beam alignment is very low. Translate the Laser Head (do not rotate) in the plane of the Reflector slot for maximum peak and repeat Step H if maximum travel is to be measured. Final distance between the optics at near end of travel should be <4 inches, typically one to two inches, and <3 ft for Long Range Straightness optics.

I) Check the optics again for clipping of the beam.

6) MANUAL REDUCTION OF SLOPE (Reference Bisecetor)

(Maximum slope is about 0.2 inches in any length of travel. Manual reduction of the slope may be necessary and is beneficial if vibration and/or turbulance are severe problems).

A) Reset the Display with the optics at the near end of travel.

B) Measure the distance from the split in the Tilt Plate to the Interferometer, approximately 4 inches for short range. Record it and label it "r".

C) Traverse the optics to the far end of travel measuring the distance traveled, record it and label it "d".

D) Multiply the Laser Display reading by-r/d.

E) Adjust the Tilt Plate in the plane of the Straightness Reflector slot until the Laser Display reads the calculated number. (If beam alignment is lost, stop further adjustment. The Reference Bisector is more accurately aligned to the axis of travel than the Laser Head is. Realign the Laser Head to the new Reflector position with rotation and translation to regain beam alignment, check clipping and return to Step A.

NOTE

Returning to Step A can be avoided by readjusting the Laser Head before beam alignment is lost or by remembering the last displayed distance. Reset to zero once beam alignment is regained and continue the necessary absolute distance.

F) Reset the Laser Display and check the slope while returning to the near end of travel. If slope is yet unsatisfactory, repeat Steps A-F. If slope is satisfactory, alignment is complete.

NOTE

Slope is satisfactory when small compared to the straightness data.

7) DETERMINE SIGN CONVENTION AND DIRECTION OF TRAVEL

A) Data starts at apex of square for both axes.

B) Data positive into square for axis one

C) Data positive out of square for axis two.

NOTE

Correct data sign usually requires changing the position of the Direction Sense switch on the Laser Display.

8) Connect the Calculator and Plotter if not done previously. Place paper on the Plotter.

9) Run Straightness in the first axis and plot straightness runs until Random errors are within required limits. Don't forget Sign Conventional.

10) Check for Random Errors.

A) Random Errors can be severe enough to interrupt the beam alignment. The Random Errors are:

i) Mechanical vibration

ii) Thermal Turbulance

iii) Abrupt machine movements perpendicular to the Axis of travel.

They are more severe at the far end of travel. The source(s) can be isolated by systemically reducing the error at the source or reducing its symptom.

B) Mechanical Vibration and Machine Movement

i) Reduce all lever arms that may be included in the mounting fixtures for the Straightness Reflector and Interferometer to minimum length - eliminate them if possible - they amplify vibration.

ii) Insure that the Straightness Reflector is solidly mounted preferably on a rigid angle bracket or remove the Tilt Plate and mount directly to a base plate and clamp the base plate directly to the machine.

NOTE

Slope cannot be removed and alignment may be mor- difficult if the tilt plate is removed.

C) Turbulance

i) Turbulance is caused by differing air temperatures along the laser beam measurement path, which result from heat sources like forced air heating and/or cooling outlets, and intense light sources that generate heat along their beam path.

NOTE

Temperature controlled rooms and air conditioned rooms are severe turbulence areas! If the source cannot be directly affected, an appropriate sized fan positioned to mix the air along the measurement path can greatly reduce random errors due to Thermal Turbulence.

D) Abrupt Machine Movements

i) Abrupt machine movements are apparent when beam alignment is lost as a machine is started, stopped or transversed quickly. This indicates a mechanical problem in the table drive system causing out-of-straightness movements at a rate faster than the Laser Display can accept, or a minimum of 20 inches per minute.

11) If Parallelism is to be checked:

A) Follow parallelism instructions in the Calculator Metrology program package.

B) Run second axis if it is a rotational axis by rotating spindle 180 and reversing the sign of the data with the Direction Sense switch on the Laser Display. If the second axis is a linear axis take a second run of data along the second axis after selecting squareness or multiply the answer from the Parallelism routine by two and do not change the sign of the second axis data if parallelism of two linear axes is measured.

12) If Squareness is desired:

A) Once the first axis Straightness and/or parallelism data is satisfactory, reposition the machine to measure straightness in the second leg of the square. It may be necessary to remove the Optical Square on some machines. Do not disturb the Straightness Reflector!

B) If the Optical Square was removed align the Laser Head to the Straightness Reflector.

C) Mount the Straightness Interferometer in the spindle with the polished Bezel facing in the direction of the Laser Beam as before and insert in the Laser Beam.

D) Establish beam alignment in the second axis - do not adjust the Straightness Reflector!

13) Check the Sign Convention and direction of travel.

14) Take the data for the second axis.

SECTION

XV

SECTION XV

VERTICAL STRAIGHTNESS AND SQUARENESS SETUP AND ALIGNMENT PROCEDURE

1) Initial Equipment Set-up

A) Transport the necessary equipment to the site where the laser measurements will be taken.

B) Position the equipment and Tripod (Figure 10-2). The desired location of the equipment will provide convenient acc.ss to all controls and ease of operation during the measur-eurement-s. The desired location of the Tripod will be chosen by positioning the necessary optics on the machine as below in C.

C) Mount the Straightness Reflector in the vertical plane on a sturdy mount such as in Figure 8-5 that will allow the split in the mirrors to be at the center of the slot in the Optical Square.

D) Position the Optical Square on t table, on two round foot pads, one slot up, one slot towa the Straightness Reflector. The Optical Square slots are offset from center. The side closest to the slot should be toward the front of the machine. Use gauge blocks or parallels in a "T" slot to brace and align the Optical Square parallel to the second axis to be measured.

NO

THIS IS VERY IMPORTANT: Place one or two Base Plates or parallels in a T slot, press the Optical Square against the plate(s), press the Turning Mirror against the Optical Square. The Square can slide against the plates - the Turning Mirror can slide against the square.

E) Position a Turning Mirror on the table in front of the Optical Square. The center of the mirror should be centered with the upper slot in the Optical Square. The Turning Mirror should face away from the Straightness Reflector.

NOTE

Do not allow the Optical Square or Turning Mirror to rotate during alignment adjustments. This could cause excessive slope in the second measurement axis and require setup, alignment and remeasurement of both axes.

F) Mount the Straightness Interferometer in the Vertical Straightness Adaptor, shiny bezel toward the glass. Mount the Vertical Straightness Adapter in the spindle or rail. The Interferometer should be directly over the slot in the Optical Square. The Vertical Straightness Adaptor should extend over the Turning Mirror. The laser beam path should be as in Figure 10-2.

2) LINEAR ALIGNMENT

A) The desired position of the Laser Head and Linear Optics or Turning Mirror for the Alignment will be determined by the mounting position of the straightness optics. Align the Laser beam to the measurement axis by the most convenient method, usually auto reflection using a Turning Mirror indicated to a table T-slot.

3) ALIGNMENT OF TURNING MIRROR, VERTICAL STRAIGHTNESS ADAPTOR AND OPTICAL SQUARE

A) Remove Linear optics if a Visual Alignment was used or the the reflector used for Auto reflection.

B) Insure that the optics are positioned as in 1-C,D,E above, and not rotated once aligned.

C) Follow the beam to the Turning Mirror with a piece of paper. The beam should be centered along the horizontal and vertical centers of the mirror.

D) Follow the beam up to and then out of the Vertical Straightness Adaptor. The beam should pass through the windows in the Straightness Interferometer, without clipping.

E) While holding the Optical Square and Turning Mirror square to the machine, slide the Turning Mirror along the side of the Optical Square to position the laser beam along a center line of the Straightness Interferometer as seen on the Straightness Interferometer in the narrow space between the interferometer and the Vertical Straightness Adaptor.

F) Translate the spindle or the Laser Head or the machine table depending on the setup configuration, to pass the laser beam through the Interferometer without clipping it. Two dots will be visible on top of the Optical Square or seen on a card placed on top of the Optical Square, and centered in the slot on top of the Optical Square. Check that the exiting dots are not clipped. If clipped, the otpics are not square to the machine or the beam alignment is not parallel to the machine, return to Step 2.

G) Once the two dots are established, remove the Interferometer carefully. Alignments should NOT be attempted using the two beam method as described in the Operators Manual.

4) STRAIGHTNESS REFLECTOR ALIGNMENT

A) Rigidly mount the Straightness Reflector in the vertical straightness position as in Figure 14-2 on the machine:

i) Where the part would mount.

ii) As far as possible from the Laser Head.

iii) So the laser beam enters the slot and impinges on the split in the mirrors.

B) Sliding the Optical Square will raise and lower the beam. Take care not to cause rotation of the Optical Square or the Turning Mirror. Their squareness to the machine is paramount to a vertical squareness measurement.

C) Align the Straightness Reflector to the laser beam using a hole in a piece of paper, the reflected half dots, and the Tilt Plate to position the two half dots equal distance from and in the same plane as the incoming laser beam.

5) STRAIGHTNESS INTERFEROMETER ALIGNMENT

A) Mount the Straightness Interferometer in the Vertical Straightness Adaptor with the polished Bezel facing the glass. Overlap the dots on the Turret by rotating the Straightness Interferometer Bezel.

B) Reduce the beam diameter with the small aperture.

C) Adjust the Tilt Plate micrometers to halo the return dot about the Exit Port Aperture. If the return dots cannot be seen at the Laser Head follow the return dots from the Straightness Reflector through the optics adjusting the micrometers accordingly.

D) Open the Return Port and Exit Port. Carefully mount the Straightness Adaptor on the front panel of the Laser Head by means of the four extended screws.

E) Follow the laser beam with a piece of paper from the Straightness Adaptor to the Straightness Reflector checking for a clipped beam that would reduce signal strength and adjust the optics appropriately. Do not change the angular alignment of the Reflector or Laser Head.

F) Insure that the X36 Resolution Extender is in the cables, and is in Extended. Turn off the Laser Display before connecting or disconnecting any cables.

G) Rotate the Interferometer Bezel tc peak the Beam Alignment Meter. Again, very little rotation is necessary at the peak.

H) Adjust the Tilt Plate, rotating the micrometer which is perpendicular to the slot only, for the center of the Beam Alignment Meter peak.

6) Manual Reduction of Slope (Reference Bisector Alignment)

Maximum slope is about 0.2 inches in any length of travel, therefore, manual reduction of the slope may be necessary and is beneficial if vibration and/or turbulance are severe problems.

A) Reset the Display with the optics at the near end of travel.

B) Measure the distance from the slit in the Tilt Plate to the Interferometer, as in Figure 12-4, add 12 in. for the Optical Square. Record and label it "r".

C) Traverse the optics to the far end of travel measuring the distance traveled, record it and label it "d".

D) Multiply the Laser Display reading by -r/d.

E) Adjust the Tilt Plate in the plane of the Reflector slot until the Laser Display reads the calculated number. (If beam alignment is lost, stop further adjustment, realign the Laser Head to the new reflector position with rotation and translation to regain beam alignment, check clipping and return to Step A.

F) Reset the Laser Display and check the slope while returning to the near end of travel. If slope is yet unsatisfactory, repeat Steps A-F. If slope is small with respect to straightness data, alignment is complete.

7) Determine Sign Convention and Direction of Travel

A) Data starts at apex of square for both axes

B) Data positive into square for axis one

C) Data positive out of square for axis two

D) Do not rotate the Interferometer between axes- shiny bezel should always face the incoming laser beam.

8) Connect the Calculator and Plotter if not done previously, and place paper on the Plotter.

9) Run Straightness in Vertical axes and plot straightness runs until Random errors are within required limits. Don't forget Sign Conventional.

10) CHECK FOR RANDOM ERRORS.

A) Random Errors can be severe enough to interrupt the beam alignment. The Random Errors are:

i) Mechanical Vibration

ii) Thermal Turbulance

iii) Abrupt machine movements perpendicular to the Axis of travel. They are more severe at the far end of travel. The source(s) can be isolated by systemically reducing the error at the source or its symptom.

B) Mechanical Vibration and Machine Movement

1. Reduce any lever arms that may be contained in the mounting fixtures for the Straightness Reflector and Interferometer to minimum length eliminate them if possible - they amplify vibration.

2. Insure that the Straightness Reflector is solidly mounted preferably on a rigid angle bracket as in Figure 8-6 or remove the Tilt Plate and mount directly to a base plate and clamp the base plate directly to the machine.

C) Turbulance

1. Turbulance is caused by differing air temperatures along the laser beam measurement path, which result from heat sources like forced air heating and/or cooling outlets, intense light sources that also generate heat along their beam path.

NOTE

Temperature controlled rooms and air conditioned rooms are severe turbulance areas. If the source cannot be directly affected, an appropriate size fan positioned to mix the air along the measurement path can greatly reduce random errors due to Thermal Turbulence.

D) Abrupt Machine Movements

1. Abrupt machine movements are apparent when beam alignment is lost when a machine is started, stopped or transversed quickly. This indicates a mechanical problem in the table drive system causing out-of-straightness movements at a rate faster than the Laser Display can accept, or above a minimum of 20 inches per minute.

11) IF VERTICAL PARALLELISM IS TO BE CHECKED:

A) Follow parallelism instructions in the CalculatorPlotter Metrology program package.

B) Run second axis after selecting squareness or multiply the answer from the Parallelism routine by two. Do not change the sign of the second axis data if parallelism of two linear axes is measured.

12) If Squareness of the Vertical axis to a Horizontal Axis is desired:

A) Once the vertical axis data is satisfactory, remove the Optical Square, Turning Mirror, and Vertical Straighness Adapter. Do not disturb the Straightness Reflector!

B) Align the Laser Head to the Straightness Reflector. Preferably translate the Laser Head and only slight rotation may be necessary.

C) Mount the Straightness Interferometer in the spindle and insert in the Laser Beam, shiny bezel toward the laser head.

D) Establish beam alignment in the second axis - do not adjust the Straightness Reflector!

E) Check the Sign Convention and direction of travel.

13) Take the data for the horizontal axis.

SECTION

XVI

SECTION XVI

CALIBRATION OF A 4-AXIS GENERAL PURPOSE MACHINE TOOL OUTLINE

1) Set up to measure x axis to z axis straightness, squareness and parallelism shown in Figure 10-2.

2) Ask the calculator for straightness. Measure the w axis horizontal straightness. Determine max. and min. of precision. Plot straightness. Slope is stored by the calculator.

3) Ask the calculator for squareness. Measure straightness of the z axis head travel. Determine maximum and minimum of precision. Plot straightness. Slope of z is compared to slope of w. Parallelism is computed and printed.

4) Ask for straightness. Measure straightness of z axis head travel again. Straightness plot will be duplicated. Slope will be duplicated and stored.

5) Set up for straightness of x axis in the vertical plane. All optics are removed except the Straightness Reflector.

6) Ask for squareness. Measure straightness of x axis in vertical plane. Determine maximum and minimum of precision. Plot straightness. Slope of x axis vertical straightness is compared to z axis slope. Squareness is computed and printed.

7) Ask for straightness. Repeat straightness measurement of x axis vertical plane. Straightness will be repeated and plotted. Slope will be stored.

8) Ask for squareness. Remove the Interferometer from the spindle and reposition it on a suitable cart to measure table top flatness in one x axis. See Figure 16-1. Table top flatness is plotted. Slope of table top is compared to x axis of travel slope. Parallelism of table top to table travel in the x axis is computed and printed. Straightness, squareness, and parallelism of the x axis to z axis is now known. Approximate time required: 1 1/2 hours.

9) Set up to measure pitch in the x axis. The Laser Head should not require repositioning or realignment.

10) Measure x axis pitch. Determine minimum and maximum of precision. Record data. Determine and record Abbe offsets. If Roll is desired mount a differential level indicator on the machine. Measure roll and pitch simultaneously.

11) Measure x axis yaw. Determine maximum and minimum of repeatability. Record data. Determine and record Abbe offsets.

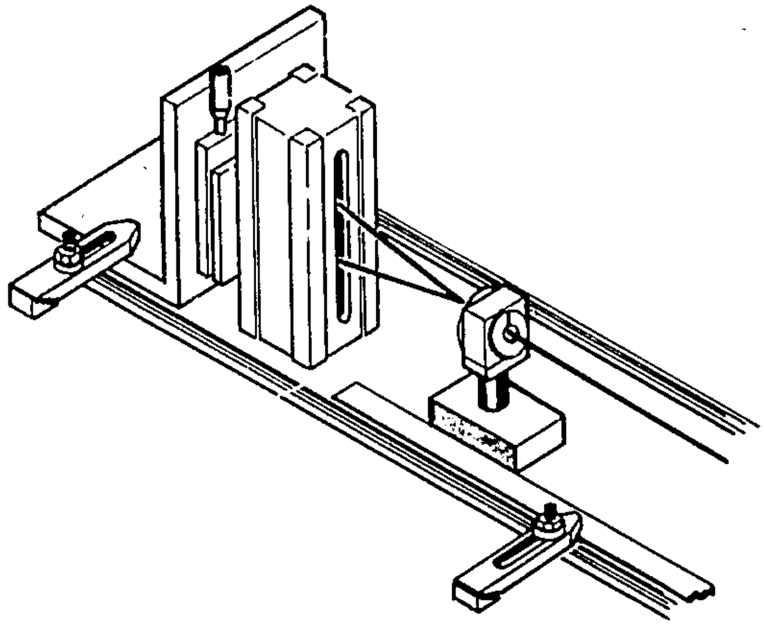


Figure 16-1. Table Top Straightness And Slope

12) Measure w axis Ram yaw. Determine maximum and minimum of precision. Record data.

13) Measure z axis head yaw. Determine maximum and minimum of precision. Record data. Determine and record Abbe offsets.

Four of the eight (or five of the nine if roll was measured) angular measurements are complete. From this data overall positioning accuracy and precision can be predicted. From these measurements precision of the x to z axis squareness is also known. Approximate required time: 1/2 hour. Total elapsed time 2 hours.

14) Depending on the purpose of this calibration the x,z, and w axes linear positioning can be checked and compensated now or in Step 29. Assuming an unknown machine, geometry checks will continue. Set up to measure vertical straightness of the w and z axes and squareness and parallelism in the z,y plane. See Figure 10-2.

15) Measure vertical straightness of the w axis. Determine minimum and maximum of precision. Straightness is plotted. Slope is stored.

16) Ask for squareness. Measure vertical straightness of the z axis. Straightness is plotted. Parallelism is computed from the slopes of the w and z axis in the z-y plane and printed.

17) Ask for straightness. Measure vertical straightness of the z axis once more. Straightness is duplicated and plotted. Slope is duplicated and stored.

18) Ask for squareness. Set up to measure straightness in the y axis vertical plane. Do not reposition the Straightness Reflector.

19) Measure vertical straightness of the y axis. Straightness is plotted. Squareness is computed from the z axis and y axis slopes and printed.

20) Ask for straightness. Measure y axis vertical straightness once more. Straightness is duplicated and plotted. Slope is duplicated and stored.

21) Ask for squareness. Remove the Interferometer from the spindle. Remount it to measure flatness of the machine table top in the y axis. Straightness is plotted. Parallelism of the table top to the y axis of travel is computed and printed.

Straightness, squareness, and parallelism in the plane of y to x is now known. Estimated required time: 1 1/2 hours. Total elapsed time 3 1/2 hours.

22) Set up for angular measurements. No repositioning or realigning of the Laser Head should be necessary.

23) Measure y axis pitch. Determine minimum and maximum of precision. Record data. Determine and record Abbe offsets. If y axis roll is desired measure with a level indicator simultaneously with pitch.

24) Measure y axis yaw. Determine and record minimum and maximum precision. Record data. Determine and record Abbe offsets.

25) Measure w axis pitch. Determine and record minimum and max-

imum repeatability. Record data.

26) Measure z axis pitch. Determine and record minimum and maximum precision. Determine and record Abbe offsets.

All angular components are now known. Precision of the y to z, y to w squareness, and z to w parallellism. Linear accuracy and precision over much of the working area can be determined. Approximate time required: 1/2 hour. Total elapsed time 4 hours.

27) Set up to measure y to z squareness. The Laser Head should not require repositioning or realignment.

28) Measure y axis straightness in the horizontal plane. Determine maximum and minimum of precision. Plot straightness. Slope is stored.

29) Ask for squareness. Measure x axis straightness in the horizontal plane. Determine maximum and minimum of precision. Plot straightness. Squareness of y to z is calculated and printed.

Straightness, squareness and parallelism in all 3 planes are now known. Approximate time required: 1/2 hour. Overall elapsed time 4 1/2 hours.

If the previous geometry measurements indicate that an acceptable machine exists calibration of the linear axis scales can begin. Determine where the location of the calibration axes for the x,y and z axes. Assume that the last position of the Laser Head was in the y axis.

30) Ask for General Error Analysis to determine accuracy and precision. Data will be plotted. Measure linear positioning c the y axis. Store data. Ask for Statistical Error Analysis. Resulting plots will show y axis accuracy, precision, and backlash.

31) Set up to measure linear positioning along the x axis calibration axis. The resulting plots will show x axis linear positioning, accuracy, precision and backlash.

32) Set up to measure linear positioning along the z and/or w axis calibration axis.

33) Repeat Step 29 for the z axis.

34) Repeat Step 29 for the w axis if desired.

Accuracy, precision and backlash are now known for all axes. Estimated time for 14 runs each axis bidirectional 1/2 inch increments on a 30 inch machine: 1 1/2 hours. Overall calibration time 6 hours. This inspection of a machine tool provides graphic analysis of most geometric characteristics that can be analyzed to determine overall ability of the machine to perform a desired function. This data can be effective in software compensation of a machine by a CNC controller to minimize the effects of known geometry errors.