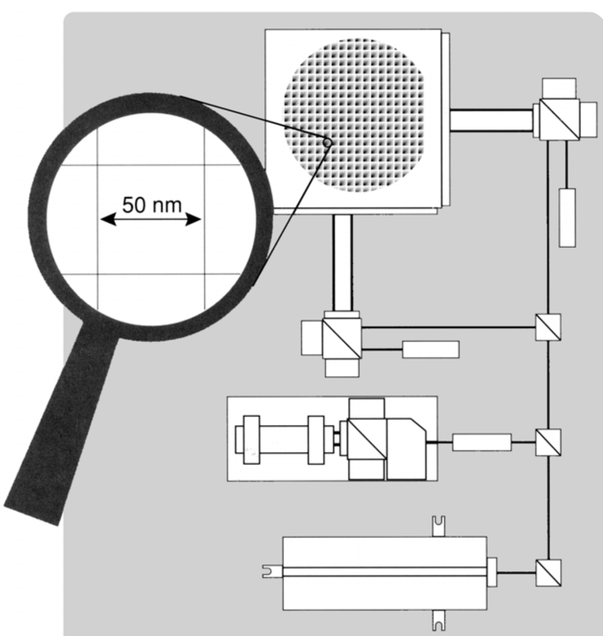
Agilent 5527A/B-2
Achieving Maximum Accuracy and Repeatability

Product Note



With the Agilent 5527A/B Laser Position Transducer System

Agilent Technologies

Purpose of this Product Note

The ability to model the performance of a laser system for a particular application is a valuable tool in achieving the desired performance in precision equipment.

This product note introduces the basic concepts, techniques and principles that determine the overall measurement performance of the Agilent 5527A/B Laser position transducer system. Details are given on how to ascertain the laser system's accuracy and repeatability for a given application.

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Introduction

Since their development, laser interferometer systems have allowed major advances in many manufacturing technologies. Laser interferometers have been incorporated into such manufacturing equipment as lithographic systems, precision cutting machines, and precision measuring machines. This has led to the production of higher density integrated circuits, precision mechanical components, and the ability to make very accurate dimensional measurements.

For many years, the performance of the laser interferometer system exceeded the requirements of such equipment and typically has comprised only a small portion of this equipment's error budget. However, recent advancements in these manufacturing technologies have put increased demands on the performance of the laser interferometer system.

To keep abreast of these demands, Agilent Technologies has conducted research into the error components that affect measurement accuracy and repeatability. Results of this research led to the development of several new products which have improved the performance of Agilent laser transducer systems. Also, as a result of this research, a new method was developed to accurately model the laser system's performance. Modeling laser system performance for a particular application helps designers of precision equipment meet their design goals.

An understanding of each error component in the laser interferometer system will help when using the new modeling technique described in this document. The measurement accuracy and repeatability is determined by summing the error components in the system's error budgets. Before proceeding with the discussion of each component in the accuracy and repeatability error budgets, let's review the definitions of accuracy and repeatability:

Accuracy: The maximum deviation of a measurement from a known standard or true value.

Repeatability: The maximum deviation between measurements under the same conditions and with the same measuring instrument. This also refers to how stable the measurement will be over time.

The components of system accuracy and repeatability

The system measurement accuracy and repeatability error budgets share many of the same error components. System measurement repeatability is divided into short-term and long-term. Short-term repeatability is the measurement stability over a period of time less than one hour; long-term is stability over one hour. The error components that make up the accuracy and repeatability error budgets are shown in figure 1.

Both the accuracy and repeatability error budgets consist of several components, some affected by the operating environment and others by the installation of the system. These error components can be divided into proportional and fixed terms.

Proportional error terms are generally specified in parts-per-million (ppm) and the resulting measurement error is a function of the distance measured by the interferometer system. Fixed terms are noncumulative and the resulting measurement errors are not a function of the measured distance. Fixed terms are given in units of length, such as nanometers or microns.

Error Components By Category	System Error Budgets		
	Accuracy	Long-Term Repeatability	Short-Term Repeatability
Intrinsic			
Laser Wavelength	●	●	●
Electronics Error	●	●	●
Optics Nonlinearity	●	●	●
Environmental			
Atmospheric Compensation	●	●	●
Material Thermal Expansion	●	●	
Optics Thermal Drift	●	●	
Installation			
Deadpath	●	●	●
Abbe' Error	●	●	
Cosine Error	●		

Figure 1. The error components for accuracy, and short and long-term repeatability error budgets.

Environmental and installation error components are the largest contributors to the error budgets. Therefore, careful consideration must be given to installation and implementation of the laser interferometer system to optimize its measurement performance. A more detailed discussion of these error components follows.

Laser wavelength

The laser source of any interferometer system has some type of frequency stabilization to maintain its wavelength accuracy and repeatability. A laser system's accuracy is fundamentally based on the laser's wavelength accuracy. The system's repeatability is based on the laser's wavelength stability.

An interferometer system generates fringes when displacement occurs between the measurement optics of the system. Each fringe generated is equivalent to a fraction of a wavelength of the laser. If the wavelength changes, fringes are generated, thereby giving an apparent distance measurement even without actual displacement. This apparent movement is measurement error.

Both laser wavelength accuracy and stability are specified in parts-per-million of the laser frequency. This is a proportional error, that is, the measurement error is a function of the distance measured. All laser sources for Agilent laser transducer systems have the same wavelength accuracy and stability specifications. These values are specified in a vacuum environment. Lifetime wavelength accuracy for the laser heads is ±0.1 ppm standard and ±0.02 ppm with optional calibration to MIL-STD 45662. Wavelength stability of the laser beads is ±0.02 ppm over their lifetime and ±0.002 ppm over one hour.

Electronics error

Electronics error stems from the method used to extend basic optical measurement resolution in an interferometer system. The basic resolution of an interferometer system is $\lambda/2$ (when using cube-corner optics) and can be electronically or optically extended beyond $\lambda/2$. In an Agilent system, the electronics error is equal to uncertainty of the least resolution count. That is, electronic error equals measurement resolution. This error turns out to be the quantization error of the electronic counter in the system. Other methods of electronic resolution extension can cause jitter and nonlinearity in measurement data, thereby adding additional errors.

The electronics error term is a fixed error and is equal to the least resolution count on Agilent systems.

On the 5527A Laser position transducer system there are three possible measurement resolutions, depending on the interferometers chosen. Figure 2 lists the measurement resolutions for each interferometer available with this system.

Interferometers	System Measurement Resolution
10702A Linear	10. nanometers
10705A Single-Beam	10. nanometers
10706A Plane Mirror	5. nanometers
10706B High Stability Plane Mirror	5. nanometers
10715A Differential	5. nanometers
10716A High Resolution	2.5 nanometers

Figure 2. Agilent 5527A system measurement resolution for each interferometer available.

Optics nonlinearity

The interferometer optical element in a laser interferometer system can contribute to measurement uncertainty because of its inability to perfectly separate the two laser beam components (vertical and horizontal polarizations). This error is referred to as optics nonlinearity and occurs solely as a result of the optical leakage of one component into the other. This error is periodic, with a period of one wavelength of optical path change or a 360° phase shift between the reference and measurement frequencies. Nonlinearity caused by optical leakage affects all interferometer systems, whether they are single-frequency or two-frequency.

Leakage of one laser beam component into the other occurs for two reasons. First, the light leaving any laser source is not perfectly polarized linearly, instead it is slightly elliptical. Second, the interferometer optical element is unable to perfectly separate the two laser beam components.

Figure 3 shows a computed error plot of nonlinearity versus optical path length change for worst-case conditions (when using a linear interferometer). The peak-to-peak phase error is 5.4˚,[1] corresponding to ±4.8 nanometers of distance. Using a statistical model, this value is ±4.2 nanometers. This includes the contribution from the laser head. This nonlinearity error is a fixed term and is different for each interferometer.

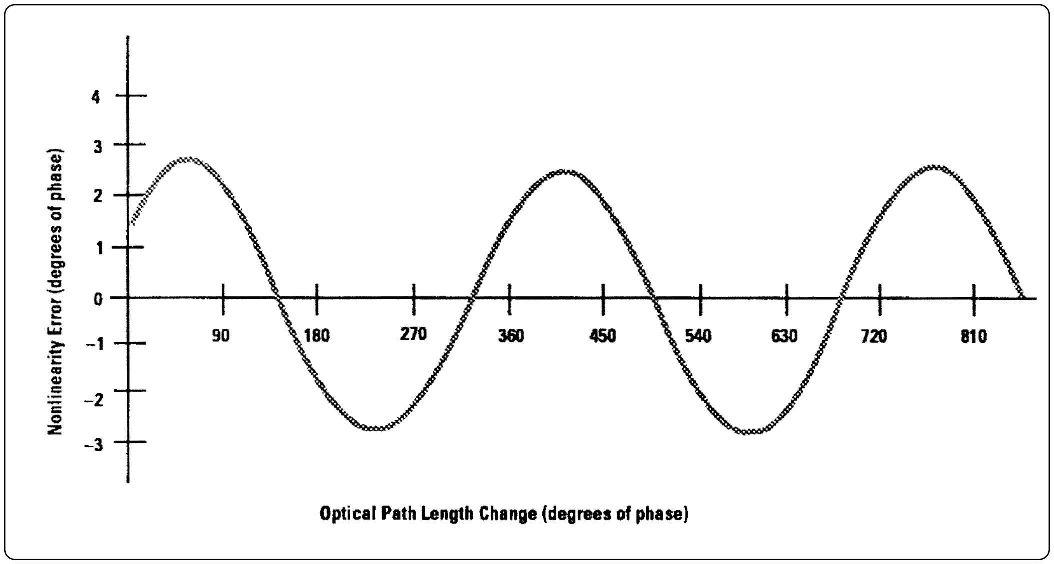

Figure 3. Worst-case error resulting from imperfect separation of the two beam components.

Atmospheric compensation

The atmospheric compensation error term is usually the single largest component in the error budgets. The magnitude of this error depends on the accuracy of the compensation method, the atmosphere in which the laser system is operating, and how much the atmospheric conditions change during a measurement.

The wavelength of the laser source is usually specified as the vacuum wavelength λ_v. In vacuum the wavelength is constant, but in atmosphere the wavelength is dependent on the index-of-refraction of this atmosphere.

Since most laser interferometer systems operate in air, it is necessary to correct for the difference between λ_v and the wavelength in air, λ_A. This correction is referred to as atmospheric or wavelength compensation. The index-of-refraction, n, of air is related to λ_v and λ_A by:

$$n = \lambda_v / \lambda_A \qquad (1)$$

Changes in air density, which is a function of air temperature, pressure, humidity, and composition, affect the index-of-refraction, thus altering the required compensation to the interferometric measurement. Without proper compensation, degradation in system accuracy and repeatability will occur. For example, assuming a standard and homogeneous air composition, a one part-per-million error results from any one of the following conditions:

- a 1 ˚C (20F) change in air temperature,
- a 2.5 mm (0.1 inch) of mercury change in air pressure,
- an 80% change in relative humidity.

The wavelength compensation number (WCN) is the inverse of the index-of-refraction, that is;

$$WCN = \lambda_A / \lambda_v \qquad (2)$$

Since the laser interferometer system counts the number of wavelengths of motion traveled, actual displacement can be determined as follows:

$$\text{Actual displacement} = (\text{wavelength counts}) \times WCN \times \lambda_v \qquad (3)$$

This equation shows that uncertainty in the wavelength compensation number directly affects the interferometer measurement. This error is a proportional term and is specified in parts-per-million.

This wavelength compensation number can be derived by a direct measurement of index-of-refraction using a refractometer or by using empirical data. Without a refractometer, it is best simply to measure the air pressure, temperature and relative humidity, and then relate this data to the refractive index using the formulas by Barrel & Sears[2] or Edlen.[3]

The accuracy and repeatability of the compensation number, derived by the empirical method, depends on the accuracy of the formula used and the ability to measure the atmospheric conditions.

The empirical method suffers from the following disadvantages compared to using a refractometer:

- it is an indirect measurement,
- it is only an approximation (good to only 0.05 ppm),
- it is slow in response due to sensor time constants and calculation time,
- it requires periodic calibration of the sensors,
- it ignores air composition changes, such as;
  - Carbon dioxide and
  - Chemical vapors.

The 5527A Laser position transducer system provides two methods of atmospheric compensation. First, an air sensor is available that measures air temperature and pressure, allows a selectable humidity setting and calculates a compensation number for the system. This product, the 10751A Air Sensor, provides a compensation accuracy of ±1.4 ppm and a repeatability better than ±1.4 ppm. The second method of compensation is a differential refractometer, the 10717A Wavelength Tracker. The Wavelength Tracker uses an optical technique to provide compensation repeatability as small as ±0.14 ppm. Since it is a differential refractometer, only changes in the air's index-of-refraction are measured.

Performance of the 10717A Wavelength tracker is given in the following equation for the compensation number's repeatability:

$$\text{Repeatability} = \pm[0.067\text{ ppm} + (0.06\text{ ppm}/^\circ\text{C} \times \Delta T) + (0.002\text{ ppm/mm Hg} \times \Delta P)] \qquad (4)$$

This equation shows that the compensation number's repeatability is a function of ambient temperature and pressure. This temperature and pressure dependency is based upon the materials used to construct this optical device.

Material thermal expansion

Since a part or machine's dimensions are a function of temperature, a correction for expansion or contraction may be required. This correction relates the distance measurement back to a standard temperature of 20 °C (68 °F). To achieve this correction, the temperature of the part or machine (during the time of the measurement) and its coefficient of linear thermal expansion must be known.

The method of correction is to electronically change the effective laser wavelength (e.g., through the controller software) by an amount sufficient to correct for thermal expansion or contraction. This correction or compensation term is known as Material Temperature Compensation and is defined as:

$$\text{Material Temperature Compensation} = 1 - \alpha\,(\Delta t)$$

where:

α = coefficient of linear thermal expansion

$\Delta t = T - 20\ ^\circ\text{C}$

Therefore, the compensated distance measurement (at standard temperature) is:

$$L_1 = L_2\,[\text{Material Temperature Compensation}]$$

where:

L_1 = length at 20 °C

L_2 = length at temperature T (5)

Assuming a known coefficient of thermal expansion, the magnitude of this error is a function of the object's temperature and the temperature sensor's measurement accuracy and repeatability. This error term is also a proportional term and specified in parts-per-million.

The material temperature sensor for the 5527A system is the 10757A Material Temperature Sensor. It has an accuracy of ±0.1 ˚C and a measurement repeatability better than ±0.1 ˚C.

Optics thermal drift

In a laser interferometer system, changes in temperature of some optical components during the measurement can cause measurement uncertainty. This takes place in the measurement optic (the interferometer) in the form of a change in optical path length with temperature. This change in optical path length appears as an apparent distance change.

This optical path length change is caused by the two laser beam components (horizontal and vertical polarizations) not passing through an equal amount of the same glass. This is shown in figure 4. With a conventional plane mirror interferometer, such as the Agilent 10706A, the beam component f_h travels through more glass than does f_v. Beam component f_h makes twice as many trips through the polarizing beam splitter as does f_v. It also makes two round trips through the quarter-wave plate.

When a change in temperature occurs, the physical size of the optical elements and their index-of-refraction will change, both contributing to an apparent distance change. This type of interferometer has a typical thermal drift value of 0.5 microns/˚C. This measurement error is a fixed value and is only a function of the interferometer temperature, not the distance measured.

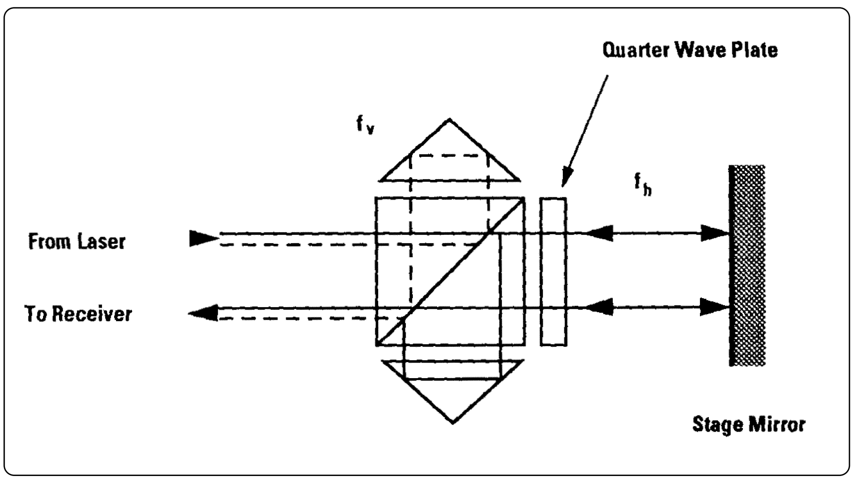

Figure 4. Conventional plane mirror interferometer with unequal path lengths that result in optics thermal drift.

Optical thermal drift can be reduced by either controlling the temperature of the measurement environment, or by using interferometers that are insensitive to temperature changes. To reduce the temperature sensitivity of an interferometer, the beam components need to travel through the same type and amount of glass.

Three interferometers available for Agilent laser transducer systems significantly reduce the optics thermal drift error. The first is the Agilent 10715A Differential interferometer, which has a thermal drift on the order of fractions of a nanometer per °C.[4] The second is the Agilent 10706B High stability plane mirror interferometer, and the third is the Agilent 10716A High resolution interferometer. Both the 10706B and 10716A have a thermal drift 1/12 that of a conventional plane mirror interferometer, typically 0.04 microns/°C.

Figure 5 shows an optical schematic of the 10706B High stability plane mirror interferometer. In this interferometer, the reference beam cube comer has been replaced with a quarter-wave plate with a high-reflectance coating on the back. This optical design allows the measurement and reference beams to have the same optical path lengths in the glass, thus essentially eliminating measurement errors caused by temperature changes of the optics.

The optical path length for both beams may vary somewhat due to mechanical tolerances in the thickness of the quarter-wave plates. Also, the geometry and size of the beam splitter may affect the optical path lengths. These small variations result in the small thermal drift of the High stability plane mirror interferometer. Since either optical path length may be longer than the other, depending on the actual optical elements used, the thermal drift may be positive or negative.

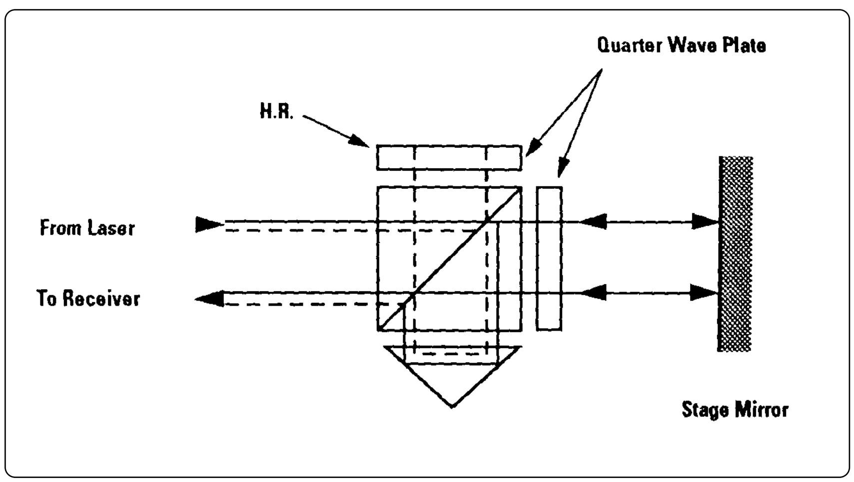

Figure 5. Optical schematic for the Agilent 10706B High stability plane mirror interferometer. Equal beam paths in the interferometer significantly reduce the optics thermal drift.

Figure 6 is a plot of the thermal drift performance of the 10706B, 10716A and 10715A interferometers as compared to a conventional plane mirror interferometer. The left vertical scale is thermal drift in microns. The Tight vertical scale is the interferometer's temperature in ˚C. The horizontal scale is time. The thermal drift of the conventional plane mirror interferometer closely tracks the optics temperature changes at a rate of approximately 0.5 microns/˚C. The 10715A shows essentially zero drift. The 10706B and 10716A show much smaller drift than the conventional plane mirror interferometer, approximately 0.04 microns/˚C.

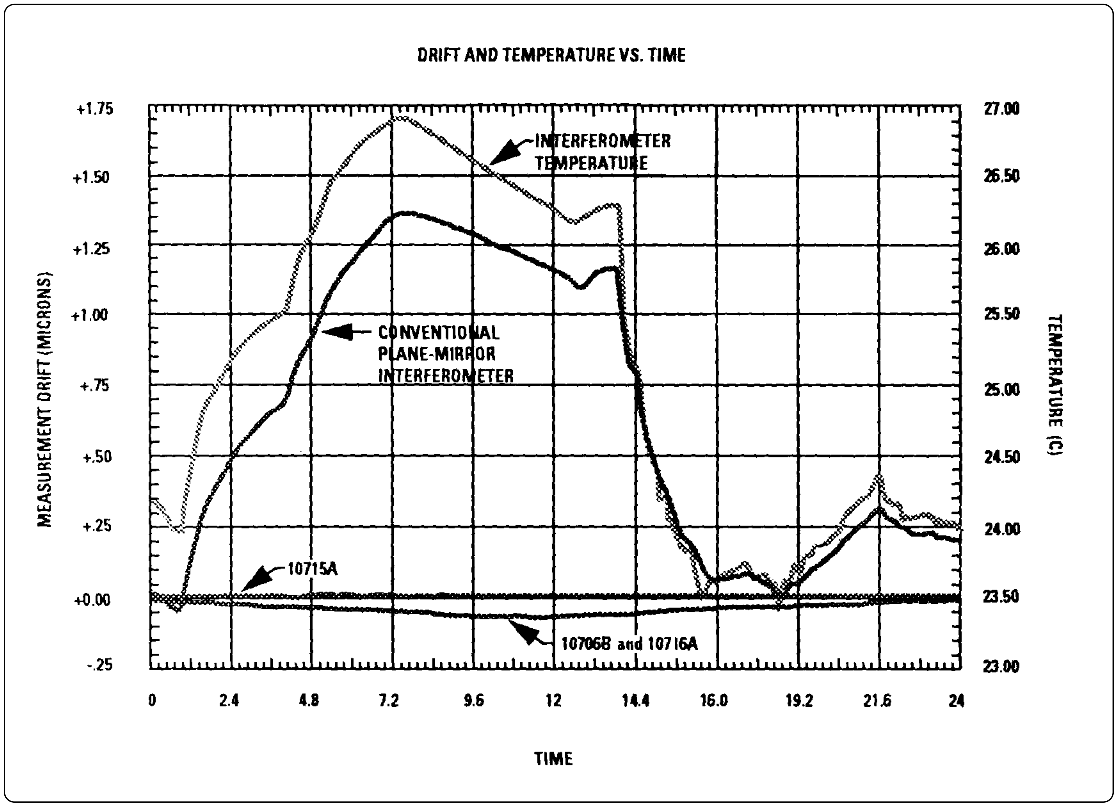

Figure 6. Optics thermal drift comparison between different interferometers.

Deadpath error

Deadpath error is caused by an uncompensated length of the laser beam between the interferometer and the measurement reflector, with the positioning stage or machine at zero position.

The deadpath distance is the difference in optical path length of the reference and measurement components of the laser beam, at the zero position. These unequal beam components can produce a measurement error, if not properly compensated for during changing environmental conditions.

Figure 7A shows the unequal path lengths for a conventional linear interferometer. The deadpath length is designated as “D”. In this diagram, the reference component is f_v, and the measurement component is f_h. The component f_h has a longer optical path length than component f_v, by a distance “D”. Assume the measurement reflector, a cube-corner in this example, moves a distance “L” (see figure 7B) to a new position and comes to rest. Since a laser interferometer system only measures “wavelengths of motion”, which involves only the distance “L”, the system will not correct for the wavelength change over “D”. This will result in an apparent shift in the zero position on the machine. This zero shift is deadpath error and occurs whenever environmental conditions change during a measurement.

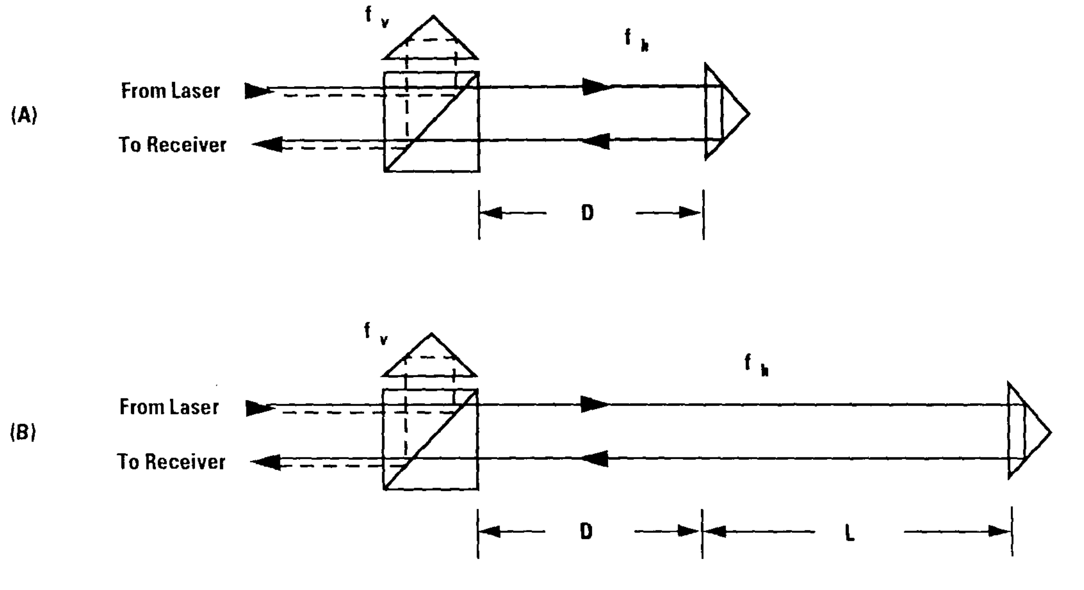

Figure 7. Deadpath caused by unequal lengths from initial point.

Deadpath error can be represented as:

$$\text{Deadpath Error} = \text{Deadpath distance} \times \Delta\text{WCN} \qquad (6)$$

where:

ΔWCN = Change in wavelength compensation number during the measurement time.

Figure 8 shows a basic optical layout of a laser interferometer system. In figure 8A, deadpath occurs as length “D”, the distance between the interferometer and the zero point.

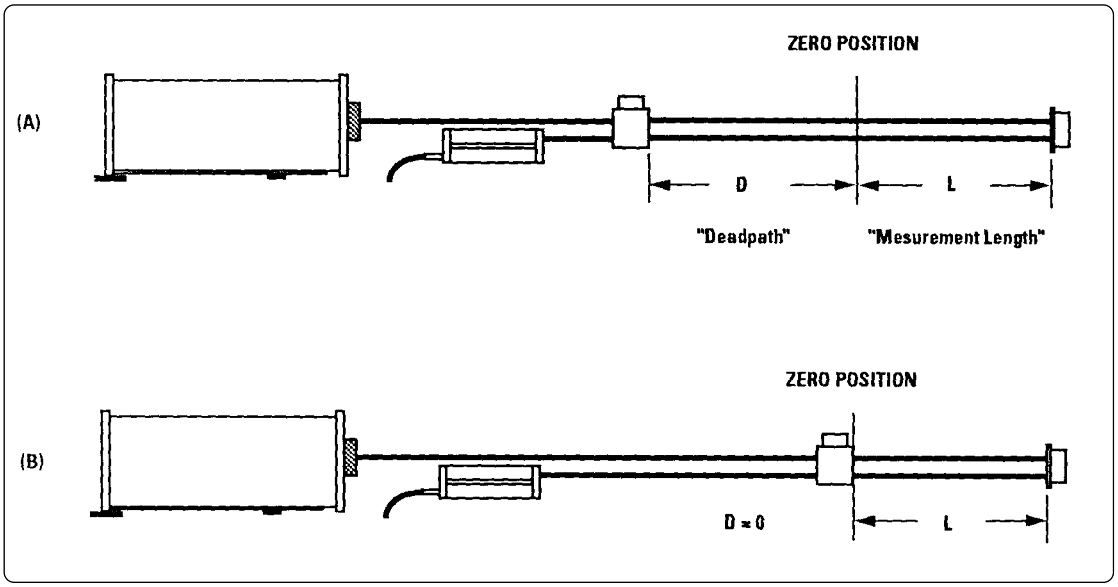

Figure 8. Optical configuration with and without deadpath.

In most applications, deadpath errors can be minimized by reducing the distance "D", as shown in figure 8B. Here the interferometer is located at the machine's zero point of travel. In applications where the interferometer cannot be located at the machine's zero position, a correction for the deadpath distance "D", may be accomplished in software on a controller. By expanding equation 3, on page 9, the corrected actual displacement can be represented as:

$$\text{Actual displacement} = [(\text{Accumulated Counts} + \text{Deadpath Counts}) \times (\lambda_v/R) \times WCN_1] - \text{Deadpath distance} \quad (7)$$

The "accumulated counts" is the displacement measured in units of LRCs (Least Resolution Counts). The "deadpath counts" is the deadpath distance in terms of compensated LRCs (using the initial compensation number, WCN_0). "λ_v/R" is equal to the LRC in units of length, where "R" is the amount of resolution extension. The compensation number at the time of measurement is WCN_1.

Even with this correction, a small error still remains because of the repeatability of the compensation number determination. This deadpath correction error is given as:

$$\text{Deadpath correction error} = \text{Deadpath Distance} \times \text{Wavelength Compensation Number Repeatability} \quad (8)$$

The error in measuring the deadpath distance can be ignored if its measurement tolerance is within ±0.5 mm. Deadpath error and deadpath correction error are both proportional values that are specified in ppm's. However, the measurement error is a function of deadpath distance, rather than the measured distance by the interferometer.

Using the 10717A Wavelength tracker and software correction, the deadpath correction error will be less than ±(0.14 ppm × deadpath distance).

Abbe′ error

Abbe′ error was first described by Dr. Ernst Abbe′ of Zeiss:

> "If errors of parallax are to be avoided, the measuring system must be placed co-axially (in line with) the line in which displacement (giving length) is to be measured on the work-piece."

In simple terms, Abbe′ error occurs when the measuring point of interest is displaced from the actual measuring scale location, and when angular errors exist in the positioning system.

Abbe′ error makes the indicated position either shorter or longer than the actual position, depending on the angular offset. The Abbe′ error is a fixed term and can be represented as:

$$\begin{aligned}\text{Abbe}' \text{ error} &= \text{offset distance} \times \text{tangent of offset angle} \\ &= A_0 \tan(\theta)\end{aligned} \tag{9}$$

Figure 9 shows an example of Abbe′ error, and illustrates the requirements for minimizing angular error and placement of the measurement path. In figure 9A, the carriage is positioned by a leadscrew and the measurement axis is at the leadscrew centerline. This figure illustrates the displacement (Abbe′) error E, which is generated at the measurement probe tip due to angular motion (θ) of the carriage. Figure 9B shows the same carriage motion as figure 9A, but with the measurement axis coincident with the probe path. Here the measurement system measures the actual displacement, and thus no Abbe′ error exists.

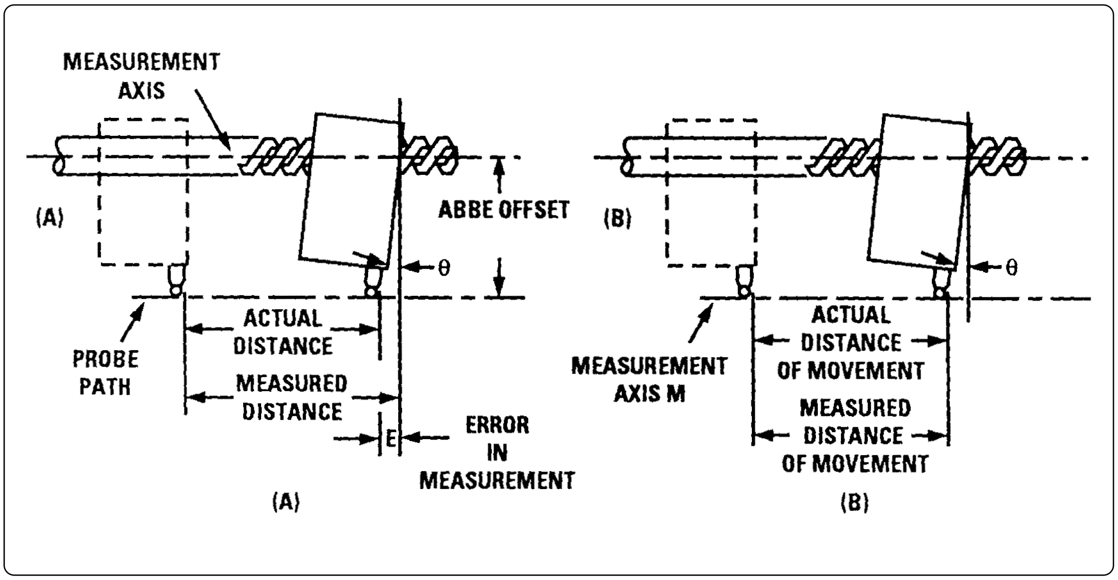

Figure 9. Illustration of Abbe′ error.

As a general rule, this error is approximately 0.1 micron per 20 mm of offset for each arcsecond of angular motion. Abbe′ error can occur with any type of displacement transducer.

Cosine error

Misalignment of the measurement axis (the laser beam) to the mechanical axis of motion, results in an error between the measured distance and the actual distance traveled. This is called cosine error, because its magnitude is proportional to the cosine of the angle of misalignment. The cosine error is common to all position transducers, If the alignment of the laser is maintained over time, there will be no change in the cosine error. Therefore, cosine error is part of the accuracy budget but not the repeatability budget.

Figure 10 illustrates cosine error using a ruler as a scale, with an angle θ between the measurement axis and the scale axis. Measured length L is related to scale length L_s by:

$$L = L_s \cos \theta \qquad (10)$$

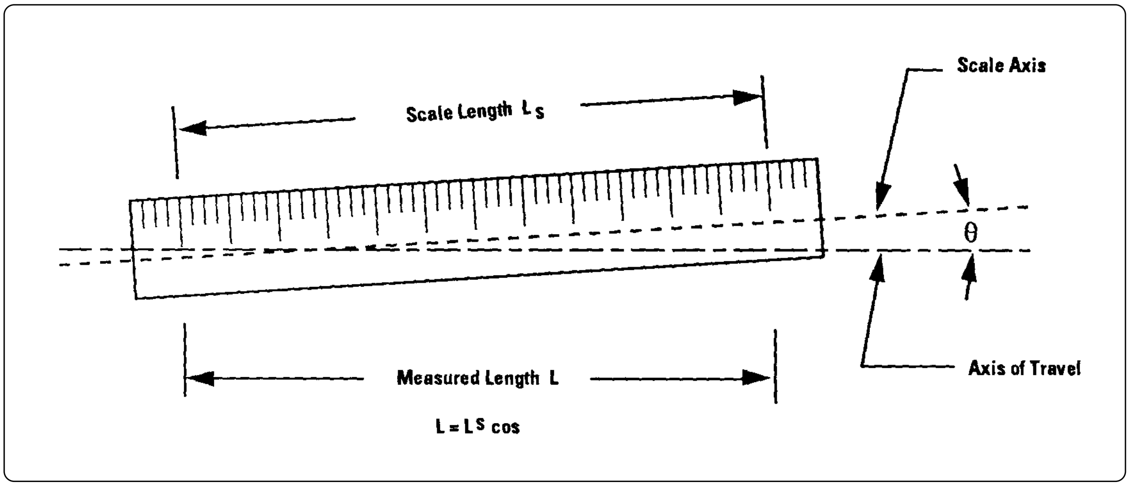

Figure 10. Scale misalignment causing cosine error.

Cosine error is a proportional term, that is, the resulting measurement error is a function of the distance measured by the interferometer. Therefore, the cosine error can be represented, in parts-per-million as:

$$\text{Cosine error in ppm} = [1 - \cos\theta] \times 10^6$$

It can be eliminated by orienting the laser beam parallel to the actual axis of travel. Care should be taken in aligning the laser beam and system optics to minimize the possibility of cosine error. By following the proper alignment procedures for each type of interferometer, cosine error can be minimized. For example, with interferometers using plane mirror reflectors (10706A/B, 10715A, 10716A), the resulting cosine error is less than 0.05 ppm. With interferometers that use cube corner reflectors (10702A, 10705A), the cosine error in ppm's, is approximately equal to $31250/L^2$, where L is the measured distance in millimeters.

Determining system accuracy and repeatability

The measurement accuracy and repeatability of a laser interferometer system is determined by summing all the error components previously discussed. The error components used to determine the measurement repeatability are a subset of the accuracy components.

Figure 11 shows the list of components for these error budgets and bow the totals are determined. As shown in figure 11, the only differences between the two error budgets are the laser wavelength terms, and the cosine error not being included in the repeatability budget.

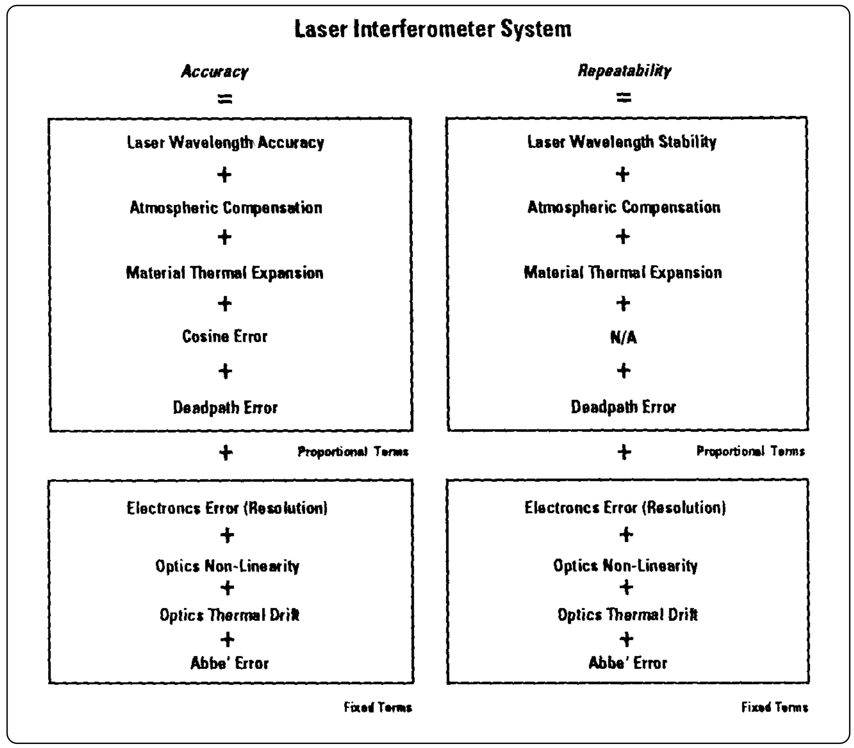

Figure 11. Laser Interferometer System Accuracy and Repeatability Error Budgets.

All these terms can be directly summed to determine the worst case system accuracy and repeatability. However, taking the vector sum of the individual components, results in a more realistic or typical system performance.[5]

Again, these components are divided into proportional terms and fixed terms. The resulting measurement errors from proportional terms are a function of the distance measured. Fixed terms are non-cumulative and the resulting measurement errors are not a function of the distance measured.

Repeatability error components can also be divided into short-term (< 1 hour) and long-term (> 1 hour) components. For short-term repeatability, only a subset of the total error components is included.

Examples of determining system accuracy and repeatability

The following examples illustrate the calculation of measurement accuracy and repeatability of the 5527A system for two typical applications.

In the first example, the laser system is part of a precision coordinate measuring machine (CMM) and monitors the position of the touch probe on the machine. In this example, accuracy and long-term repeatability will be determined.

In the second example, the laser system is built into an integrated circuit manufacturing system, such as a wafer stepper or inspection machine and controls the position of the wafer stage. For this example, accuracy, long-term repeatability and short-term repeatability will be determined. Short-term repeatability is calculated for the wafer stepper application because process time for wafer exposures is typically very short (<2 minutes).

Figure 12 shows a list of parameters needed to calculate each error component.

System Error Component	Parameters
Laser Wavelength	Measurement Distance (L), Laser Specifications
Atmospheric Compensation	L, Environmental Conditions, Compensation Performance
Material Thermal Expansion	L, Material Temperature, Material
Cosine Error	L, Interferometer type
Deadpath Error	Deadpath distance, Environmental Conditions, Compensation Performance
Electronics Error (Resolution)	Interferometer type
Optics Non-Linearity	Interferometer type
Optics Thermal Drift	Interferometer type, Temperature changes
Abbe' Error	Abbe' Offset, Angular changes

Figure 12. Parameters needed to calculate each error component.

Precision Coordinate Measuring Machine (CMM)

The typical configuration for this application is shown in figure 13. It uses the 10716A High resolution interferometers and the 10717A Wavelength tracker. This CMM has a working measurement volume of 1.0m × 1.0m × 1.0m. Shown below is a list of parameters needed to calculate the system's measurement accuracy and repeatability for this application. Component specifications are taken from the 5527A Laser position transducer specification set:

Maximum distance measured (L): 1.0m
Deadpath distance (D): 0.1m
Cosine error: 0.05 ppm
Non-linearity: ±1.0 nm (10716A)
Abbe′ error: none (assume zero offset)
Measurement resolution: ±2.5 nanometers (10716A)
Environment:
- Temperature: 20 ˚C ±0.5 ˚C (temperature controlled environment)
- Pressure: 760 mmHg ±25 mmHg (possible storm fronts during measurement, pressure not controlled)
- Humidity: 50% ± 10% (humidity controlled environment)

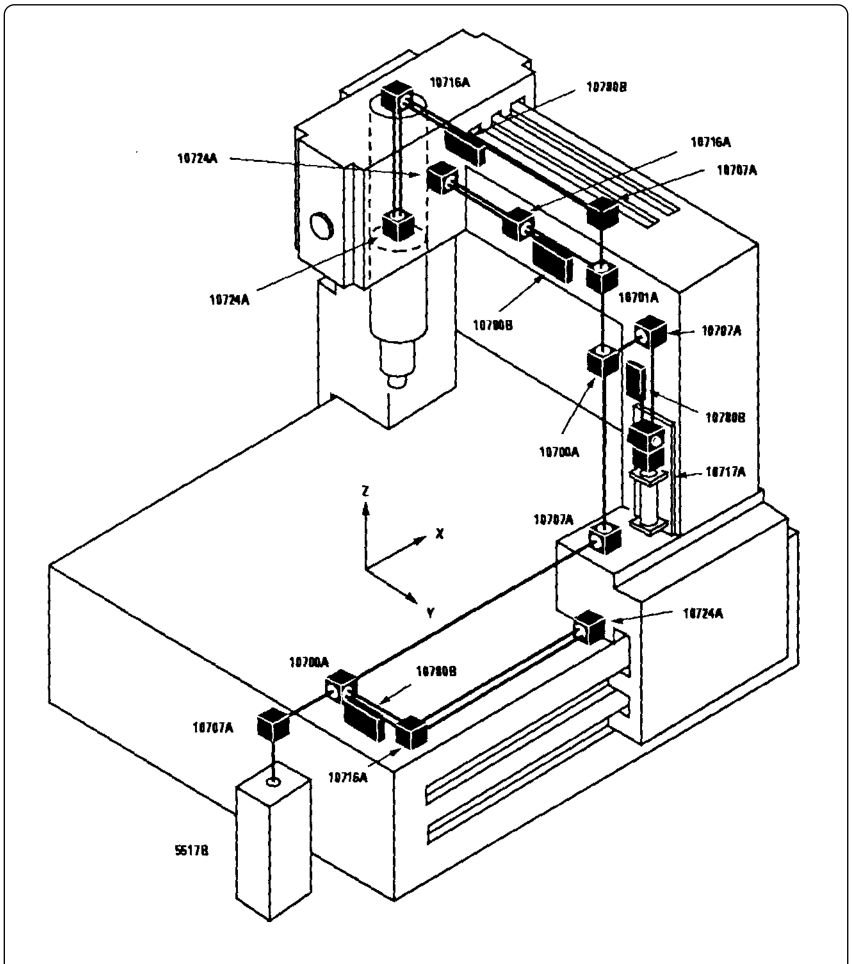

Figure 13. Laser system configuration for a precision CMM.

Each error component is calculated individually and summed in the appropriate error budget to determine system accuracy and repeatability.

Laser wavelength error:

Laser wavelength stability: ±0.02 ppm (long-term)
This translates to a maximum distance uncertainty of:

Laser wavelength stability error = $(1.0\text{m})(\pm 0.02 \times 10^{-6})$
$= \pm 0.02$ micron

Laser wavelength accuracy: ±0.02 ppm (with optional calibration)

Laser wavelength accuracy error: = $(1.0\text{m})(\pm 0.02 \times 10^{-6})$
$= \pm 0.02$ micron

Atmospheric compensation: Since the Wavelength tracker provides relative compensation information, the initial compensation number from another source determines the compensation accuracy. In this example, the initial compensation number is derived from measuring a known artifact or standard with the laser system on the machine. The accuracy of measuring the artifact or standard is the sum of the laser system measurement repeatability, machine repeatability and touch probe accuracy. It is assumed that no error is induced in measuring the artifact. Consequently, in this example, accuracy and repeatability of atmospheric compensation information will be equal.

Using equation 4, on page 10, and the environmental conditions, accuracy and repeatability of compensation information from wavelength tracking compensation can be determined.

Compensation accuracy and repeatability =
$\pm[0.067 \text{ ppm} + (0.06 \text{ ppm}/^\circ\text{C} \times 0.5\ ^\circ\text{C}) + (0.002 \text{ ppm/mm Hg} \times 25 \text{ mm Hg})]$
$= \pm 0.15$ ppm

At maximum distance the position uncertainty, due to compensation, will be:

Compensation error = $(1.0\text{m})(\pm 0.15 \times 10^{-6}) = \pm 0.15$ micron

With no atmospheric compensation, the error would be ±9.0 ppm. This translates to a position uncertainty, at the maximum distance, of 9.0 microns.

Material thermal expansion: On a CMM, with a laser interferometer system used as the position scale, material compensation should be done to the measured part, not the machine. Therefore, the material temperature error term is dependent on the type of material being measured and the specifications of the temperature sensor.

This can be a significant error if the temperature of the part is not tightly controlled or compensation is not adequate. For example, with a 0.5m part made of steel (α = 10.0 ppm/˚C) and using the 10757A Material temperature sensor, the resulting measurement accuracy and repeatability will be:

Measurement accuracy = ($\alpha \times$ temperature sensor repeatability $\times$ part length
= (10.0 ppm/˚C)(±0.1 ˚C $\times$ 0.5m)
= ±0.5 micron

The10757A temperature sensor has a measurement repeatability equal to its accuracy.

Measurement repeatability = ±0.5 micron

Since this error is independent of the type of measurement scale but strongly dependent on the type of material and temperature sensor performance, it will not be included in this analysis.

Material thermal expansion = 0 micron (assumed)

Deadpath error: Deadpath error is a function of deadpath distance, method of compensation, and environmental conditions. With no compensation for deadpath, equation 6, on page 14, determines the error.

Deadpath error = (0.1m)(±9 x 10^{-6}) = 0.9 micron

With deadpath correction and using Wavelength tracking Compensation, equation 8, on page 15, determines the error.

Deadpath correction error = (0. 1m)(0.15 x 10^{-6})
= ±0.015 micron

Electronics error: On Agilent laser interferometer systems, the electronics error equals measurement resolution. When using the 10716A High resolution interferometer, measurement resolution for the system is:

Measurement resolution = 0.0025 micron

Optics non-Linearity: Non-linearity when using the High resolution interferometer is ±0.001 microns.

Optics thermal drift: This error term should be included when determining long-term repeatability. The error depends on the degree of thermal cycling that the interferometer experiences. With the High resolution interferometer, thermal drift will be:

$$\begin{aligned}\text{Optics thermal drift} &= (0.04\ \text{microns}/^\circ\text{C})(\pm 0.5\ ^\circ\text{C}) \\ &= \pm 0.02\ \text{micron}\end{aligned}$$

Abbe′ error: Since this error term is independent of the type of measurement scales used, but strongly dependent on how the machine is designed and built, it is ignored in this analysis.

Abbe′ error = 0 micron (assumed)

Cosine error: If the proper alignment procedure for the High resolution interferometer is followed, the worst case cosine error is:

Cosine error = ±0.05 ppm

Cosine error (in microns) = (±0.05 ppm)(1.0m) = ±0.05 micron

Now, the appropriate components can be summed together to obtain system measurement accuracy and repeatability. Worst case system accuracy and repeatability is determined by directly summing these components. However, a more realistic system repeatability, but still conservative, is the vector sum (RSS, Root Sum of Squares) of the individual components. System accuracy and repeatability will be calculated with and without atmospheric compensation to show the importance of compensating for changes in atmospheric conditions.

System accuracy calculation

	With atmospheric compensation	**Without atmospheric compensation**
	±(microns)	±(microns)
Laser wavelength error	0.02	0.02
Compensation error	0.15*	9.0*
Material thermal expansion	0.0	0.0
Deadpath error	0.015*	0.90*
Electronics error	0.0025	0.0025
Optics non-linearity	0.001	0.001
Optics thermal drift	0.02	0.02
Abbe′ error	0.0	0.0
Cosine error	0.05#	0.05#
Direct sum total	±0.26 micron	±9.99 microns
RSS sum where *'s are not independent and # is an offset.	±0.22 micron	±9.95 microns

The following equation is used to calculate the RSS sum:

$$\text{RSS sum} = [(\text{sum of squares of independent terms}) + (\text{sum of not independent terms}^2)]^{1/2} + \text{offset}$$

Figure 14 graphically presents this accuracy data and shows the importance of using atmospheric compensation. Figure 15 shows in more detail the relative magnitude of each component when using atmospheric compensation.

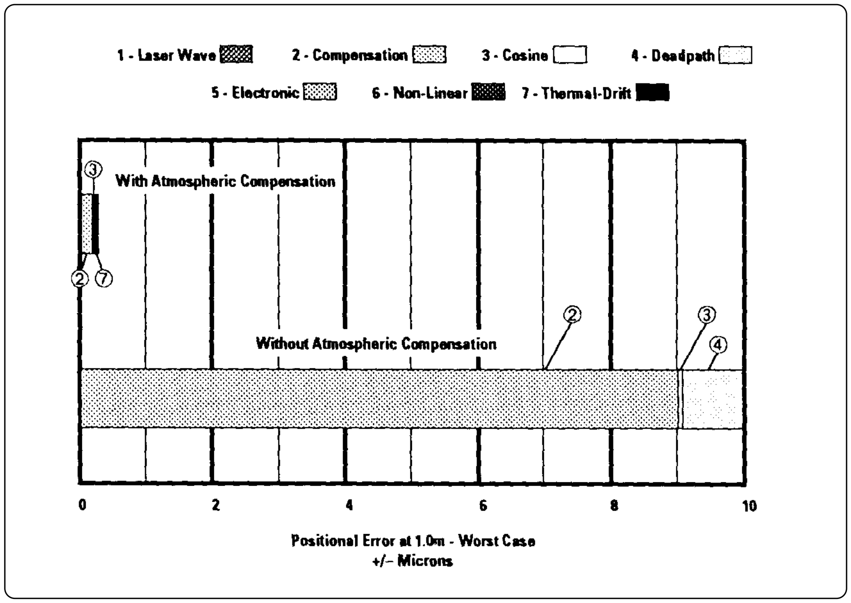

Figure 14. Worst case system accuracy with and without atmospheric compensation for the CMM example.

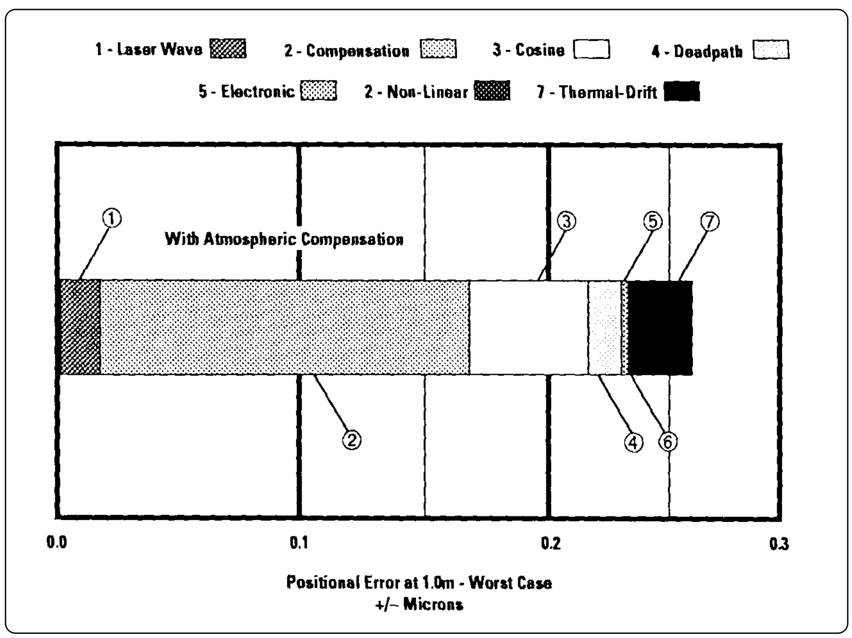

Figure 15. Worst case system accuracy with atmospheric compensation for the CMM example.

System repeatability calculation

Calculation of system long-term repeatability in this example is the same as system accuracy except that the cosine error term (±0.05 microns) is not included. Therefore, system repeatability in this example will be:

	With atmospheric compensation	**Without atmospheric compensation**
Direct Sum Total	±0.21 micron	±9.94 microns
RSS sum	±0.17 micron	±9.90 microns

Figure 16 shows a graph of this repeatability data. Again it shows the importance of atmospheric compensation. Figure 17 shows in more detail the repeatability data with atmospheric compensation.

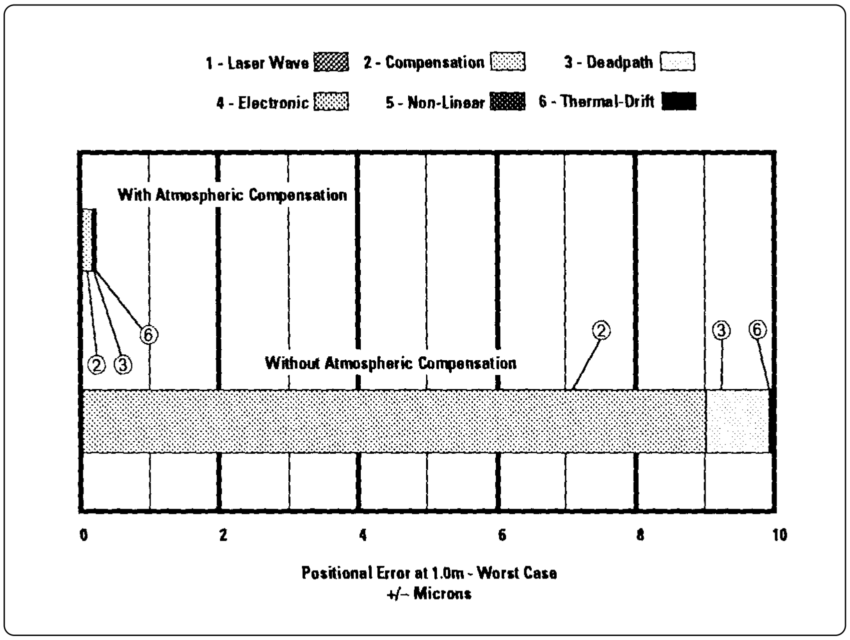

Figure 16. Worst case system repeatability with and without atmospheric compensation for the CMM example.

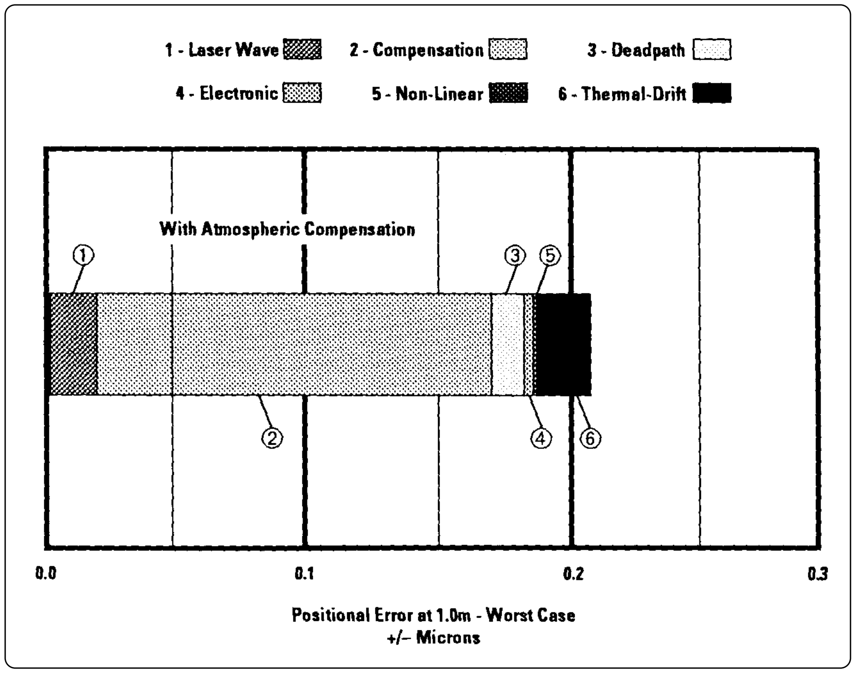

Figure 17. Worst case system repeatability with atmospheric compensation for the CMM example.

I.C. Wafer stepper

In this example, the laser system is built into an Integrated circuit wafer stepper and controls the position of the wafer stage. Typical configuration for this application is shown in figure 18. It uses 10706B High stability plane mirror interferometers and an 10717A Wavelength tracker. The following is a list of parameters needed to calculate the system accuracy and repeatability. Component specifications are taken from the 5527A specifications set.

Maximum distance measured (L): 0.2m
Deadpath distance (D): 0.1m
Cosine error: 0.05 ppm
Non-linearity: ±2.2 nm (Agilent 10706B)
Abbe′ error: none (assume zero offset)
Measurement resolution: ±5 nanometers (plane mirror optics)
Environment:
Temperature: 20 ˚C ±0.1 ˚C (temperature controlled environment)
Pressure: 760 mmHg ±25 mmHg (possible storm fronts during measurement, pressure not controlled)
Humidity: 50% ±10% (humidity controlled environment)

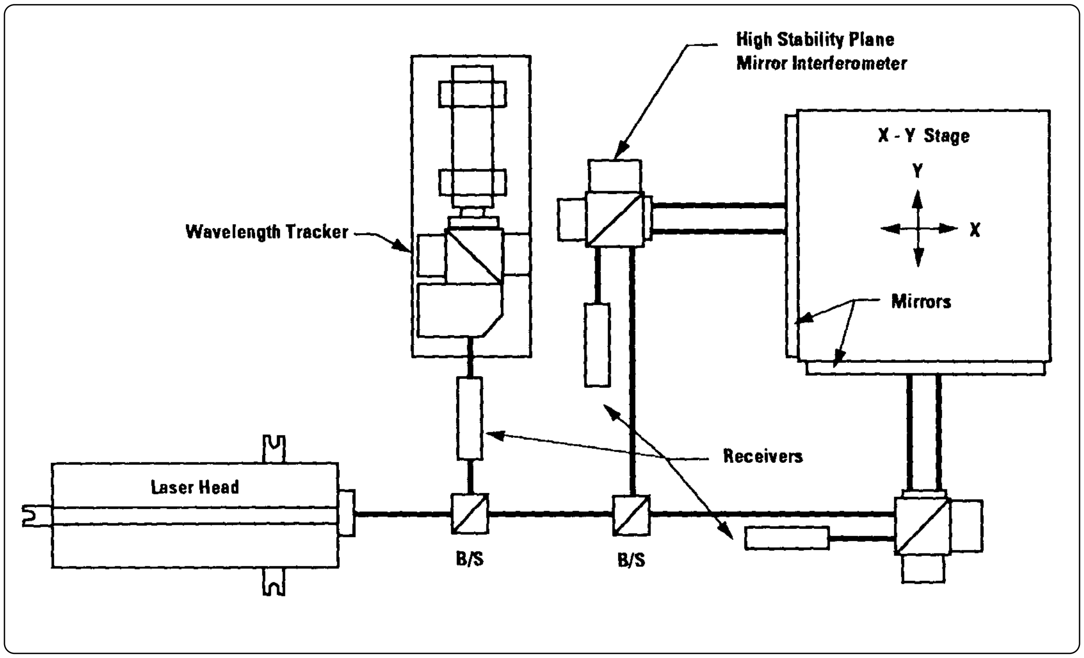

Figure 18. Laser system configuration for an I.C. wafer stepper.

Each error component will be calculated individually and then summed to determine system repeatability.

Lager wavelength error:

Laser wavelength stability: ±0.002 ppm (short-term)
This translates to a maximum distance error of:

Laser wavelength Stability error ± (0.2m)(±0.002 × 10^{-6})
= ±0.0004 micron (short-term)

Laser wavelength stability: ±0.02 ppm (long-term)

Laser wavelength stability error = (0.2m)(±0.02 × 10^{-6})
= ±0.004 micron (long-term)

Laser wavelength accuracy: ±0.02 ppm (with optional calibration)

Laser wavelength accuracy error = (0.2m)(±0.02 × 10^{-6})
= ± 0.004 micron

Atmospheric compensation: Since the Wavelength tracker provides relative compensation information, the initial compensation number from another source determines the compensation accuracy. In this example, the initial compensation number is derived from measuring a known artifact or standard with the laser system. The accuracy of measuring the artifact is the sum of the laser system measurement repeatability, machine repeatability and the accuracy of the alignment mark sensing system. It is assumed that no error is induced in measuring the artifact on the machine. Consequently, in this example accuracy and repeatability of the atmospheric compensation information will be equal.

Using equation 4, on page 10, and environmental conditions, accuracy and repeatability of compensation information from the Wavelength Tracker can be determined.

Compensation accuracy and repeatability
$\pm[0.067 \text{ ppm} + (0.06 \text{ ppm}/^\circ\text{C} \times 0.1\ ^\circ\text{C}) + (0.002 \text{ ppm/mm Hg} \times 25 \text{ mm Hg})]$
$= \pm\ 0.14 \text{ ppm}$

At maximum distance the position error, due to compensation, will be:

Compensation error = $(0.2\text{m} \times \pm 0.14 \times 10^{-6}) = \pm 0.028$ micron

With no atmospheric compensation the error would be ±9.0 ppm. This translates into a position error of 1.8 microns.

Material thermal expansion: This error depends on the machine design and the position that is measured or controlled. On a wafer stepper, the wafer is positioned relative to the optical column. If placement of the measurement axes allows measurement between the wafer and optical column, then material temperature effects may be ignored. This assumes the material expansion in the measurement path is equal to that in the reference path.

Material thermal expansion = 0 micron (assumed)

Deadpath error: Deadpath error is a function of deadpath distance, method of compensation, and environmental conditions. With no compensation for deadpath, equation 6, on page 14, determines the error.

Deadpath error = $(0.1\text{m})(\pm 9 \times 10^{-6}) = \pm 0.9$ micron

With deadpath correction and the use of the Wavelength tracker, equation 8, on page 15, determines the error.

Deadpath correction error = $(0.1\text{m})(\pm 0.14 \times 10^{-6}) = \pm 0.014$ micron

Electronics error: On Agilent laser interferometer systems, the electronics error equals the measurement resolution. When using the 10706B High stability plane mirror interferometer, measurement resolution for the system is:

Measurement resolution = 0.005 micron

Optics non-linearity: Non-linearity when using the High stability plane mirror interferometer is ±0.0022 micron.

Optics thermal drift: If measurement repeatability of this piece of equipment is important, then the effects of thermal changes of the interferometer should be included. With the High Stability Plane Mirror Interferometer, thermal drift will be:

Optics thermal drift = (0.04 microns/˚C)(±0.1 ˚C)
= ±0.004 micron

Abbe′ error: In X-Y stage applications, it is usually easy to have the interferometer measurement axis in line with the wafer. Therefore, Abbe′ offset will be zero and no Abbe′ error will occur.

Abbe′ error = 0 micron

Cosine error: If the proper alignment procedure for the High stability plane mirror interferometer is followed, the worst case cosine error is:

Cosine error = ±0.05 ppm

Cosine error (in microns) = (±0.05 ppm)(0.2m)
= ±0.01 micron

Now, the appropriate components can be summed together to obtain system measurement accuracy and repeatability. The worst case system accuracy and repeatability is determined by directly summing these components. However, a more realistic system repeatability, but still conservative, is the vector sum (RSS, Root Sum of Squares) of the individual components. System accuracy and repeatability will be calculated with and without atmospheric compensation.

System accuracy calculation

	With atmospheric compensation	Without atmospheric compensation
	±(microns)	±(microns)
Laser wavelength error	0.004	0.004
Compensation error	0.028 *	1.8*
Material thermal expansion	0.0	0.0
Deadpath error	0.014 *	0.90*
Electronics error	0.005	0.005
Optics non-linearity	0.0022	0.0022
Optics thermal drift	0.004	0.004
Abbe′ error	0.0	0.0
Cosine error	0.01#	0.01#
Direct sum total	±0.067 micron	±2.725 microns
RSS sum where *'s are not independent and # is an offset.	±0.053 micron	±2.710 microns

The following equation is used to calculate the RSS sum:

$$\text{RSS sum} = [(\text{sum of squares of independent terms}) + (\text{sum of not independent terms})^2]^{1/2} + \text{offset}$$

Figure 19 graphically presents this accuracy data and shows the importance of using atmospheric compensation. Figure 20 shows in more detail the relative magnitude of each error component when using atmospheric compensation.

Another potential source of error that should be included in the total accuracy budget is the flatness of the measurement mirrors. In X-Y stage applications, long mirrors are attached to two of the stage's sides, as shown in figure 18. This error occurs because the mirrors are not perfectly flat and, therefore, a measurement change occurs in one axis as the other axis is moved. Since a mirror flatness of $\lambda/20$ is recommended for correct operation of the laser system, this would induce a maximum measurement error of 0.03 micron. This measurement error can be compensated for if the mirror flatness is mapped and corrected in software on the controller.

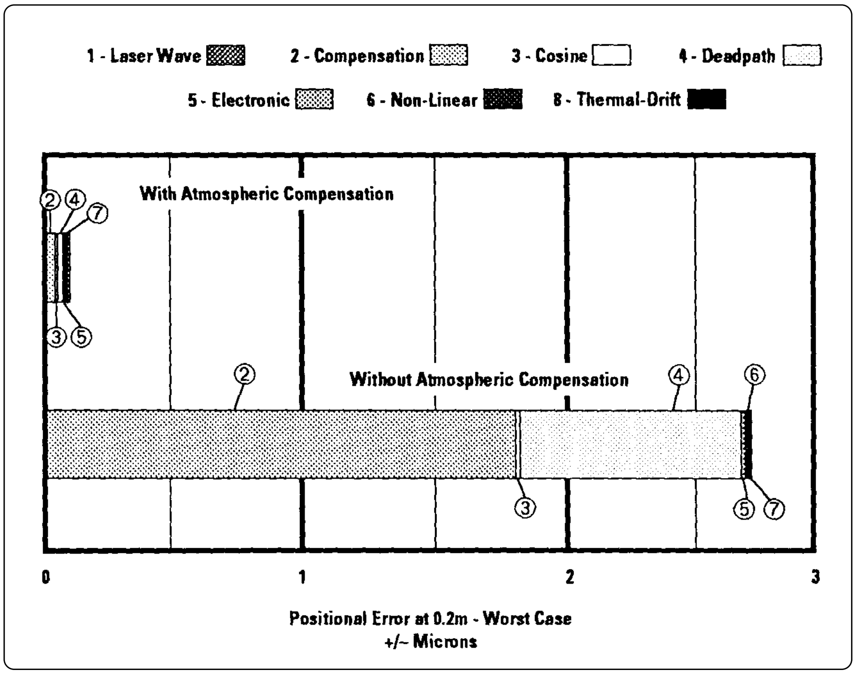

Figure 19. Worst case system accuracy with and without atmospheric compensation for the wafer stepper example.

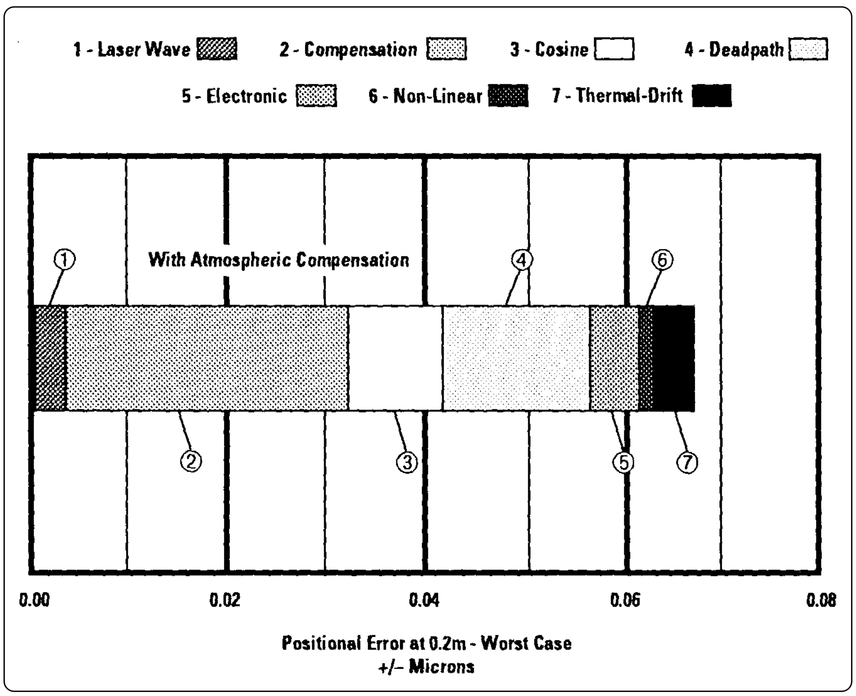

Figure 20. Worst case system accuracy with atmospheric compensation for the wafer stepper example.

System repeatability calculation

Long-term

In this example, the calculation of system long-term repeatability is the same as system accuracy, except the cosine error term (±0.01 microns) is not included. Therefore, system long-term repeatability will be:

	With atmospheric compensation	Without atmospheric compensation
Direct sum total	±0.057 micron	±2.715 microns
RSS sum	±0.043 micron	±2.710 microns

Figures 21 shows a graph of this repeatability data. Again, it shows the importance of atmospheric compensation, figure 22 shows in more detail the repeatability data with atmospheric compensation.

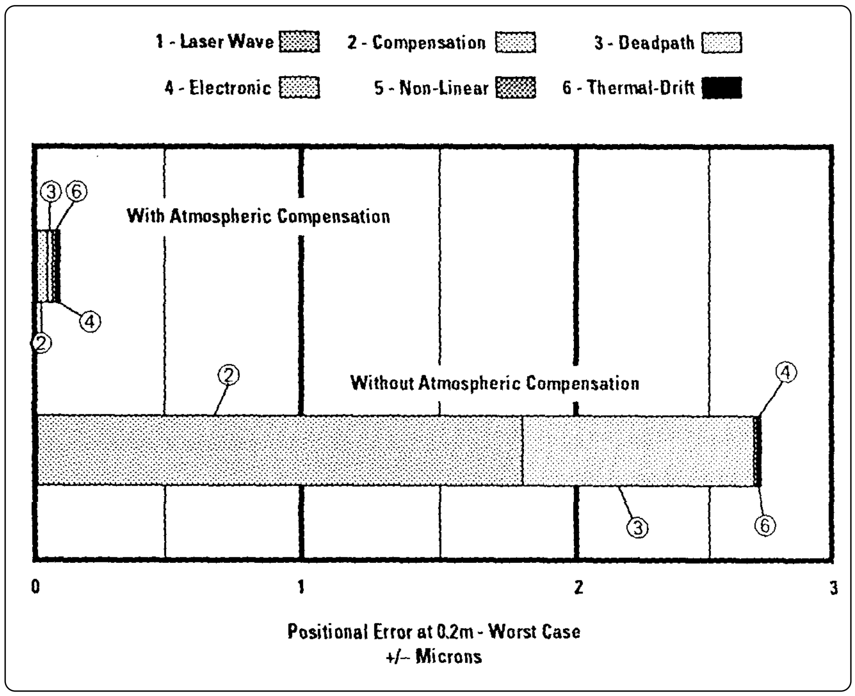

Figure 21. Worst case system long-term repeatability with and without atmospheric compensation for the wafer stepper example.

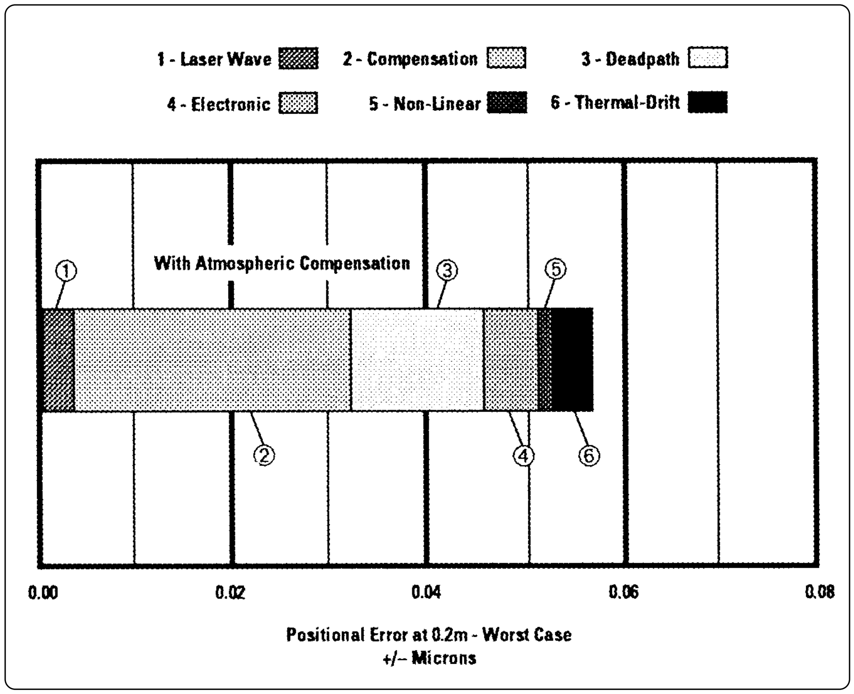

Figure 22. Worst case system long-term repeatability with atmospheric compensation for the wafer stepper example.

Short-term

In this example, calculation of system short-term repeatability is the same as long-term repeatability except that long-term laser wavelength error is replaced by short-term error and optics thermal drift is not included. The atmospheric compensation error is assumed to be the same; however, under normal operating conditions, environmental changes used in this example are unlikely.

	With atmospheric compensation	Without atmospheric compensation
Direct sum total	±0.050 micron	±2.708 microns
RSS sum	±0.042 micron	±2.700 microns

As seen from these values, the difference is only a few nanometers. If the assumed environmental changes are much smaller, then short-term repeatability will be significantly smaller.

Achieving optimum system accuracy and repeatability

In summary, to achieve the optimum measurement accuracy and repeatability from a laser interferometer system in an application, the following four general rules should be followed.

1. Whenever possible make the measurements in a tightly controlled environment. If not, use the appropriate compensation method to correct for atmospheric and material effects.

2. When designing a machine to use a laser interferometer system, minimize both deadpath distances and Abbe′ offsets. If a dead path exists on the machine, correct for it during measurements.

3. For each measurement axis, be sure to properly align optical components during installation to minimize the amount of cosine error.

4. Use the proper components for the particular application. If significant changes in environmental conditions are expected, use automatic compensation and interferometers with minimal thermal drift.

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Printed in USA March 21, 2001
5952-7973

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