15

Accuracy and Repeatability

Introduction

This chapter introduces the basic concepts, techniques, and principles that determine the overall measurement performance of Agilent laser measurement systems. Two examples of modeling a laser system's accuracy and repeatability are provided.

Understanding the error components in the laser interferometer system will help you use the modeling technique described in this chapter. 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, review the definitions of accuracy and repeatability given below.

- **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 repeatability. Short-term repeatability is the measurement stability over a period shorter than one hour; long-term repeatability is stability over a period longer than one hour. Error components that make up the accuracy and repeatability error budgets are shown in Table 15-1.

Table 15-1. Error components for accuracy and long- and short-term repeatability error budgets

Error Components by Category	System Error Budgets		
	Accuracy	Long-Term Repeatability	Short-term Repeatability
Intrinsic			
Laser Wavelength	X	X	X
Electronics Error	X	X	X
Optics Nonlinearity	X	X	X
Environmental			
Atmospheric Compensation	X	X	X
Material Thermal Expansion	X	X	
Optics Thermal Drift	X	X	
Installation			
Deadpath Error	X	X	X
Abbé Error	X	X	
Cosine Error	X		

Both the accuracy and the repeatability error budgets have several components. Some of these components are affected by the operating environment, while others are affected by the system installation. The error components can be categorized as either proportional or fixed terms.

Proportional error terms are generally specified in parts-per-million (ppm). The resulting measurement error is a function of the distance measured by the interferometer system.

Fixed error terms are noncumulative. Fixed terms are given in units of length, such as nanometers or microns. The resulting measurement errors are not a function of the measured distance.

Environmental and installation error components are often the largest contributors to the error budgets. Be sure to keep them in mind when designing and installing the laser interferometer system. A more detailed discussion of these error components follows.

Laser wavelength

An interferometer system generates optical fringes when relative movement occurs between the measurement optics of the system. Each fringe generated represents displacement by a fraction of the laser's wavelength. However, fringes are also generated if the laser wavelength changes, causing an apparent distance change measurement even when there is no actual displacement of an optic. This apparent movement is measurement error.

The laser source of any interferometer system has some type of frequency stabilization to maintain its wavelength accuracy and repeatability.

A laser interferometer system's accuracy is fundamentally based on the laser's wavelength accuracy.

The system's repeatability is based on the laser's wavelength stability.

Laser wavelength accuracy and stability are specified in parts-per-million (ppm) of the laser frequency. They are proportional errors; 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.

Lifetime wavelength accuracy for the laser heads is ± 0.1 ppm standard and ± 0.02 ppm with optional calibration.

Wavelength stability of the laser heads is typically ± 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). The resolution can be electronically or optically extended beyond $\lambda/2$.

In an Agilent laser measurement system, the electronics error equals the uncertainty of the least resolution count. That is, electronic error equals the measurement resolution. It is the quantization error of the electronic counter in the system. Other methods of electronic resolution extension can cause jitter and nonlinearity in measurement data, thus adding other errors.

The electronics error term is a fixed error equal to the least resolution count on Agilent systems. When using an Agilent laser measurement system, there are three possible linear measurement resolutions, depending on the interferometer chosen.

Table 15-2 lists the measurement resolutions for each interferometer available with this system when used with:

- the Agilent 10885A PC Axis Board,
- the Agilent 10895A VME Laser Axis Board,
- the Agilent 10897B High Resolution VMEbus Laser Axis Board, or
- the Agilent 10898A High Resolution VMEbus Dual Laser Axis Board

Table 15-2. System measurement resolution for each interferometer

Interferometer		Fundamental Optical Resolution	System Resolution (Note 1)	System Resolution (Note 2)
Agilent 10702A		λ/2 (316.5 nm, 12.5 μin)	λ/64 (10.0 nm, 0.4 μin)	λ/512 (1.2 nm, 0.047 μin)
Agilent 10705A		λ/2 (316.5 nm, 12.5 μin)	λ/64 (10.0 nm, 0.4 μin)	λ/512 (1.2 nm, 0.047 μin)
Agilent 10706A		λ/4 (158.2 nm, 6.2 μin)	λ/128 (5.0 nm, 0.2 μin)	λ/1024 (0.62 nm, 0.024 μin)
Agilent 10706B		λ/4 (158.2 nm, 6.2 μin)	λ/128 (5.0 nm, 0.2 μin)	λ/1024 (0.62 nm, 0.024 μin)
Agilent 10715A		λ/4 (158.2 nm, 6.2 μin)	λ/128 (5.0 nm, 0.2 μin)	λ/1024 (0.62 nm, 0.024 μin)
Agilent 10716A		λ/8 (79.1 nm, 3.1 μin)	λ/256 (2.5 nm, 0.1 μin)	λ/2048 (0.31 nm, 0.012 μin)
Agilent 10719A	Linear	λ/4 (158.2 nm, 6.2 μin)	λ/128 (5.0 nm, 0.2 μin)	λ/1024 (0.62 nm, 0.024 μin)
	Angular	(1.71 arcsec, 8.3 μrad)	(0.05 arcsec, 0.26 μrad)	(0.007 arcsec, 0.03 μrad)
Agilent 10721A	Linear	λ/4 (158.2 nm, 6.2 μin)	λ/128 (5.0 nm, 0.2 μin)	λ/1024 (0.62 nm, 0.024 μin)
	Angular	(2.56 arcsec, 12.4 μrad)	(0.08 arcsec, 0.39 μrad)	(0.01 arcsec, 0.05 μrad)
Agilent 10735A		Three axes, each the same as the Agilent 10706B. See listing above.		
	Linear		λ/128 on three axes	λ/1024 on three axes
	Yaw		0.04 arcsec, 0.2 μrad	0.005 arcsec, 0.025 μrad
	Pitch		0.05 arcsec, 0.24 μrad	0.006 arcsec, 0.03 μrad
Agilent 10736A		Three axes, each the same as the Agilent 10706B. See listing above.		
Agilent 10736A-001		Three axes, each the same as the Agilent 10706B. See listing above.		
Agilent 10766A		λ/2 (316.5 nm, 12.5 μin)	λ/64 (10.0 nm, 0.4 μin)	λ/512 (11.2 nm, 0.047 μin)
Agilent 10770A	Angular	(20.0 arcsec, 97.0 μrad)	(0.63 arcsec, 3.0 μrad)	(0.08 arcsec, 0.38 μrad)

Notes:

1. The system resolution is based on using 32X electronic resolution extension. This is available with the Agilent 10885A and Agilent 10895A.
2. The system resolution is based on using 256X electronic resolution extension. This is available with the Agilent 10897B and Agilent 10898A electronics.
3. The Agilent 10719A interferometer makes a single measurement, which may be either linear or angular (optically subtracted), depending on the installation. The linear and angular measurements are mutually exclusive and therefore not simultaneous.
4. The Agilent 10721A interferometer makes a two adjacent linear measurements which can be subtracted electronically to give an angular measurement with a linear measurement simultaneously.
5. The Agilent 10735A, Agilent 10736A, and Agilent 10736A-001 interferometers, make linear and angular measurements, so they have both linear and angular resolution specifications.

Optics nonlinearity

Optics nonlinearity occurs as a result of the optical leakage of one polarization component into the other.

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).

Optics nonlinearity 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 15-1 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 a worst case peak-to-peak error of 4.8 nanometers of distance. Using a statistical model, the RSS (Root Sum of Squares) value is ±4.2 nanometers worst case peak-to-peak, including the contribution from the laser head. This nonlinearity error is a fixed term and is different for each interferometer.

[1] Quenelle, R.C., Nonlinearity in Interferometer Measurements, Agilent Technologies Journal, p.10, April 1983.

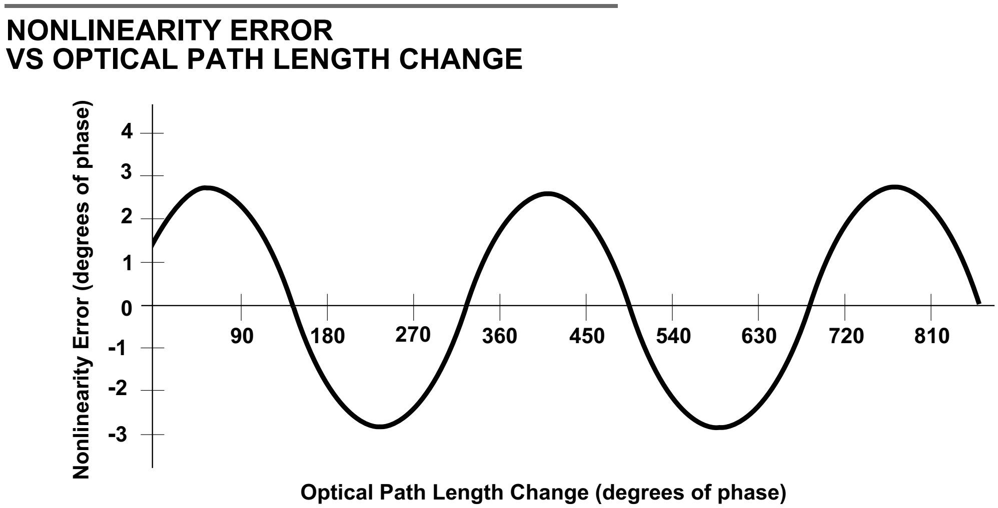

Figure 15-1. Worst-case error resulting from imperfect separation of two beam components

Atmospheric compensation

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

The laser wavelength is specified as the vacuum wavelength, λ_V.

In vacuum, the wavelength is constant (to the degree specified by the stability specification), but in an air atmosphere the wavelength depends on the index-of-refraction of the 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-of-light (WOL) compensation. The index-of-refraction, n, of air is related to λ_V and λ_A by:

$$n = \frac{\lambda_V}{\lambda_A} \qquad (1)$$

Any change in air density, which is a function of air temperature, air pressure, humidity, and composition, affects the index-of-refraction. Thus, a change in air density alters the required compensation of the laser measurement. Without proper compensation, system accuracy and repeatability will be degraded. For example, assuming a standard and homogeneous air composition, a one ppm error will result from any one of the following conditions:

- a 1°C (1.8 °F) 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:

$$\mathrm{WCN} = \frac{\lambda_A}{\lambda_V} \tag{2}$$

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

$$\text{Actual displacement} = (\text{wavelength counts}) \times \mathrm{WCN} \times \lambda_V \tag{3}$$

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.

The 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.

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[2] Barrell, H. & Sears, J.E., (1939)Phil Trans. Roy. Society, A258, 1-64.

[3] Edlen, B., The Refractive Index of Air, Metrologia, 1966, 2, 71-80.
Birch K P, Downs MJ, Metrologia, 1993, 30, 155-162.
Birch K P, Downs MJ, Metrologia, 1994, 31, 315-316.
Estler, W Tyler, Applied Optics 24 #6, 1985, 808-815.

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

- it is an indirect measurement, which is subject to sensor error,
- it is 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.

Agilent laser position transducer systems generally provide two methods of atmospheric compensation.

In the first method, an air sensor is available that: 1) measures air temperature and pressure, 2) allows a selectable humidity setting, and 3) calculates a compensation number for the system. This product, the Agilent 10751C/D Air Sensor, provides a compensation accuracy of ±1.4 ppm and a repeatability better than ±1.4 ppm, depending on the temperature range.

The second method of compensation uses a differential refractometer, the Agilent 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. This means the initial compensation number must be determined from another source, which also determines the compensation accuracy. One popular method for accurately determining the initial compensation number is to measure a known standard or artifact with the laser system on the machine. Alternatively, high-accuracy external sensors or the Agilent 10751C/D Air Sensor can be used to obtain the initial compensation value.

The repeatability of the Agilent 10717A Wavelength Tracker's compensation number is given by the equation:

$$\text{Repeatability} = \pm\left[0.067\,\text{ppm} + \frac{0.06\,\text{ppm}}{\text{degrees C}} \times \Delta T + \frac{0.002\,\text{ppm}}{\text{mmHg}} \times \Delta P\right] \quad (4)$$

This equation shows that the compensation number's repeatability is a function of ambient temperature and pressure. This temperature and pressure dependency is based on the materials used to construct the Agilent 10717A Wavelength Tracker.

Additional information about wavelength-of-light compensation is provided in Chapter 16, “Wavelength-of-Light Compensation Numbers,” of this manual.

Material thermal expansion

Since a part or machine’s dimensions are a function of temperature, a correction for material 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:

$$\text{Material Temperature Compensation} = 1 - \alpha\,(\Delta T) \qquad (5)$$

where:

α = coefficient of linear thermal expansion

$\Delta T = T - 20°C$

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

$$L_1 = L_2\,[\text{Material Temperature Compensation}] \qquad (6)$$

where:

L_1 = length at 20°C

L_2 = length at temperature T

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 specified in parts-per-million.

The material temperature sensor for Agilent laser systems is the Agilent 10757D/E/F Material Temperature Sensor. It has an accuracy of ±0.1°C and a measurement repeatability better than ±0.1°C.

Linear coefficients of expansion for various commonly used materials are presented in Chapter 17, “Material Expansion Coefficients,” of this manual.

Optics thermal drift

In a laser interferometer system, changes in temperature of some optical components during the measurement can cause measurement uncertainty. This effect occurs 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) passing through different amounts of glass, as shown in Figure 15-2.

With a conventional plane mirror interferometer, such as the Agilent 10706A, beam component f_A travels through more glass than does f_B. Beam component f_A makes twice as many trips through the polarizing beam splitter as does f_B. Component f_A also makes two round trips through the quarter-wave plate, whereas f_B does not pass through the quarter-wave plate at all.

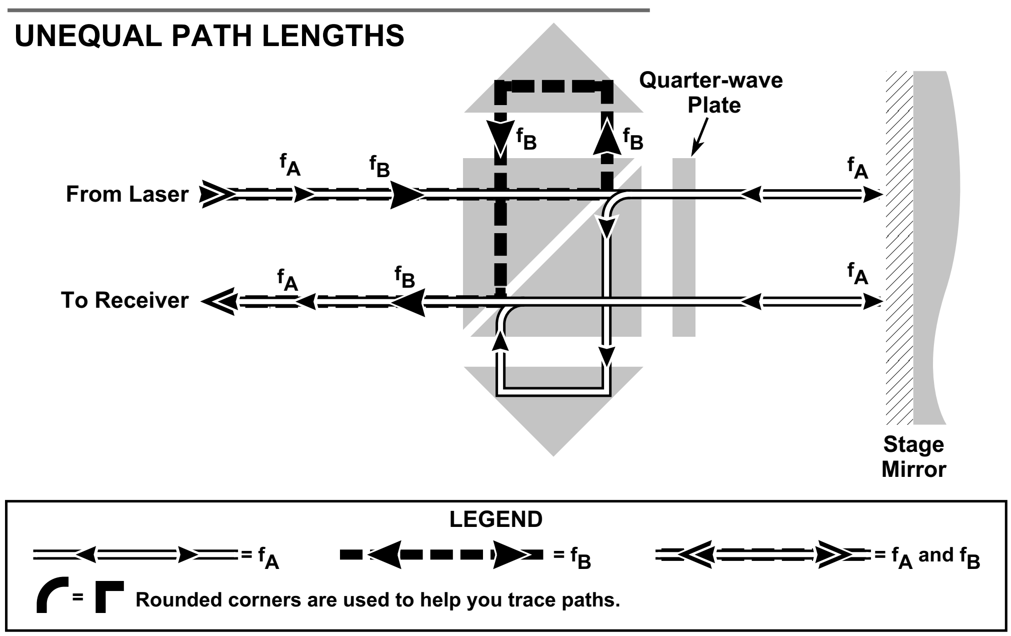

Figure 15-2. Conventional plane mirror interferometer with unequal path lengths that result in optics thermal drift

When a change in temperature occurs, the physical size of the optical elements changes, as does their index-of-refraction. Both changes contribute to an apparent change in distance. This type of interferometer has a typical thermal drift value of 0.5 micron per degree C. This measurement error is a fixed value and is only a function of the change in interferometer temperature, not the distance measured.

Optics 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.

Several interferometers available for Agilent laser measurement systems significantly reduce the optics thermal drift error.

- The Agilent 10715A Differential Interferometer has a thermal drift on the order of fractions of a nanometer per °C[4].
- The Agilent 10706B High Stability Plane Mirror Interferometer has a thermal drift, optics that of a conventional plane mirror interferometer, typically 0.04 micron/°C. Other interferometers incorporating a similar high-stability design include the Agilent 10716A, Agilent 10719A, Agilent 10721A, Agilent 10735A, and Agilent 10736A.

Figure 15-3 is an optical schematic of the Agilent 10706B High Stability Plane Mirror Interferometer. In the Agilent 10706B, the reference beam cube comer has been replaced by 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, essentially eliminating measurement errors caused by temperature changes of the optics.

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[4] Baldwin, D.R. & Siddall, G.J., A double pass attachment for the linear and plane mirror interferometer, Proc. SPIE, Vol. 480, p.78-83, 1984.

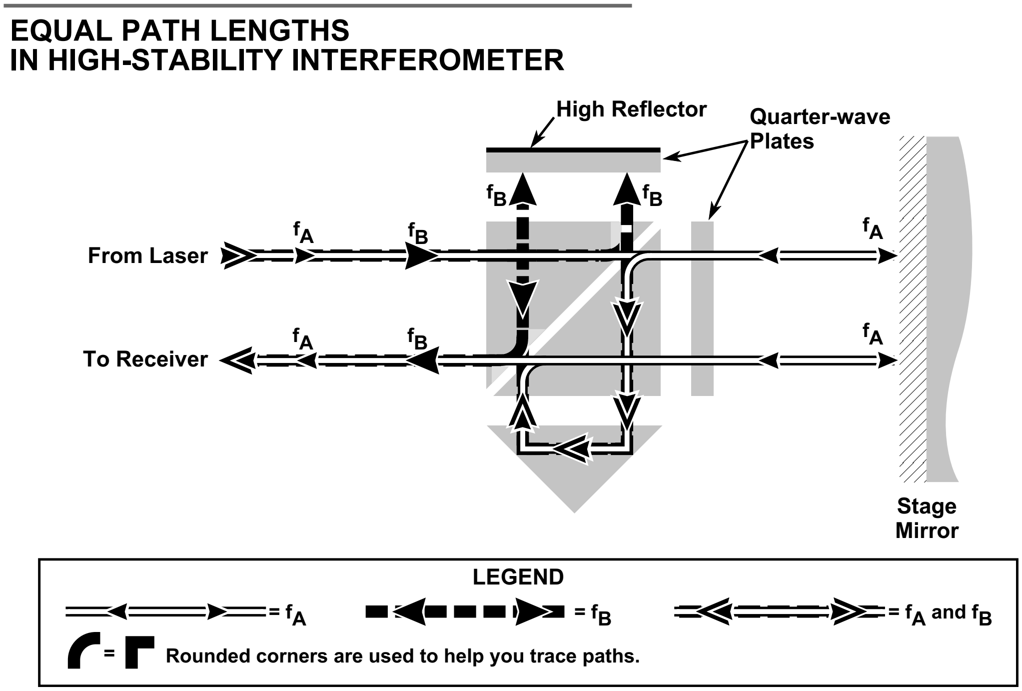

Figure 15-3. Agilent 10706B High Stability Plane Mirror Interferometer Beam Paths

The optical path lengths for the two beams may differ slightly, due to the normal dimensional tolerances in the thicknesses of the quarter-wave plates and in the geometry of the beam splitter. These small variations result in the small thermal drift of the Agilent 10706B. 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 15-4 is a plot of the thermal drift performance of the Agilent 10706B, Agilent 10716A, and Agilent 10715A interferometers as compared to a conventional plane mirror interferometer.

- The left vertical scale is thermal drift in microns.
- The right vertical scale is the interferometer's temperature in °C.
- The horizontal scale is time.
- The thermal drift of the conventional plane mirror interferometer (Agilent 10706A) closely tracks the optics temperature changes at a rate of approximately 0.5 micron per °C.
- The Agilent 10715A shows essentially zero drift.

- The Agilent 10706B and Agilent 10716A show much smaller drift than the conventional plane mirror interferometer, typically 0.04 micron per degree C.

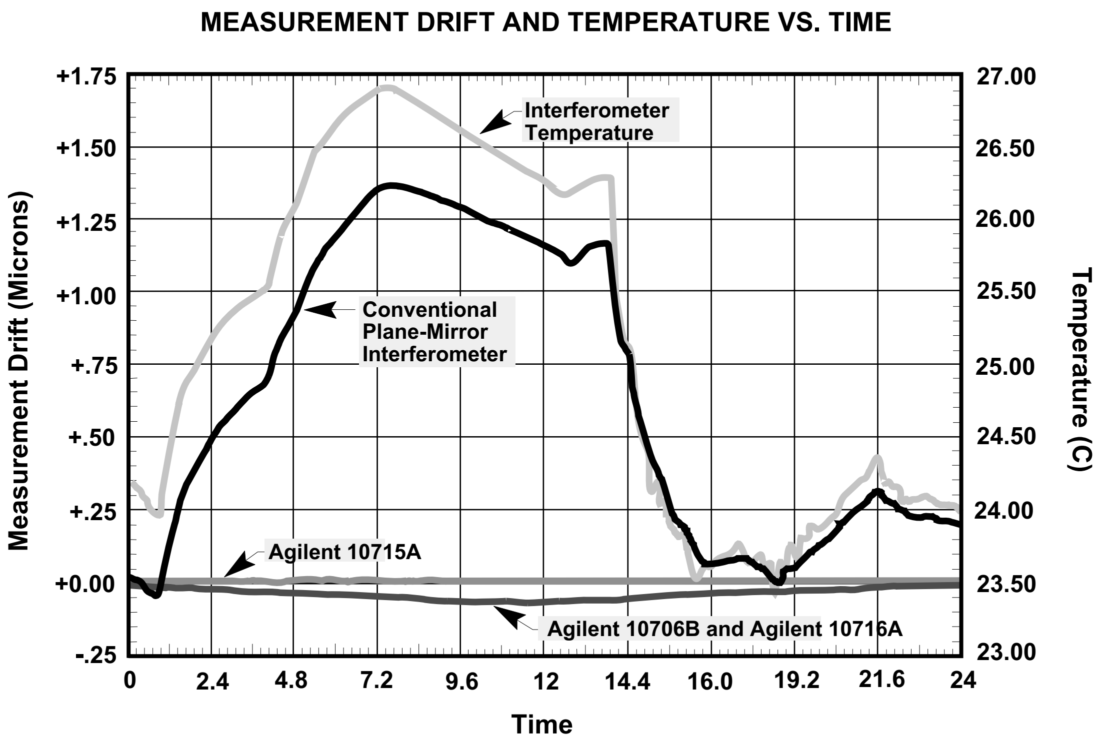

Figure 15-4. Comparison of optics thermal drift between Interferometers

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 its “zero” position (the position at which the laser system is reset).

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

Figure 15-5(A) 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_B, and the measurement component is f_A. The f_A optical path is longer than the f_B path, by “D”. Assume that the measurement reflector, a cube-corner in this example, moves the distance “L” (see Figure 15-5(B)) to a new position and comes to rest.

Assume that, while the cube corner is at rest, the environmental conditions surrounding the laser beam change. The laser beam wavelength changes over the entire path (D + L) due to these environmental changes, and so should be compensated. Since a laser interferometer system measures only “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.

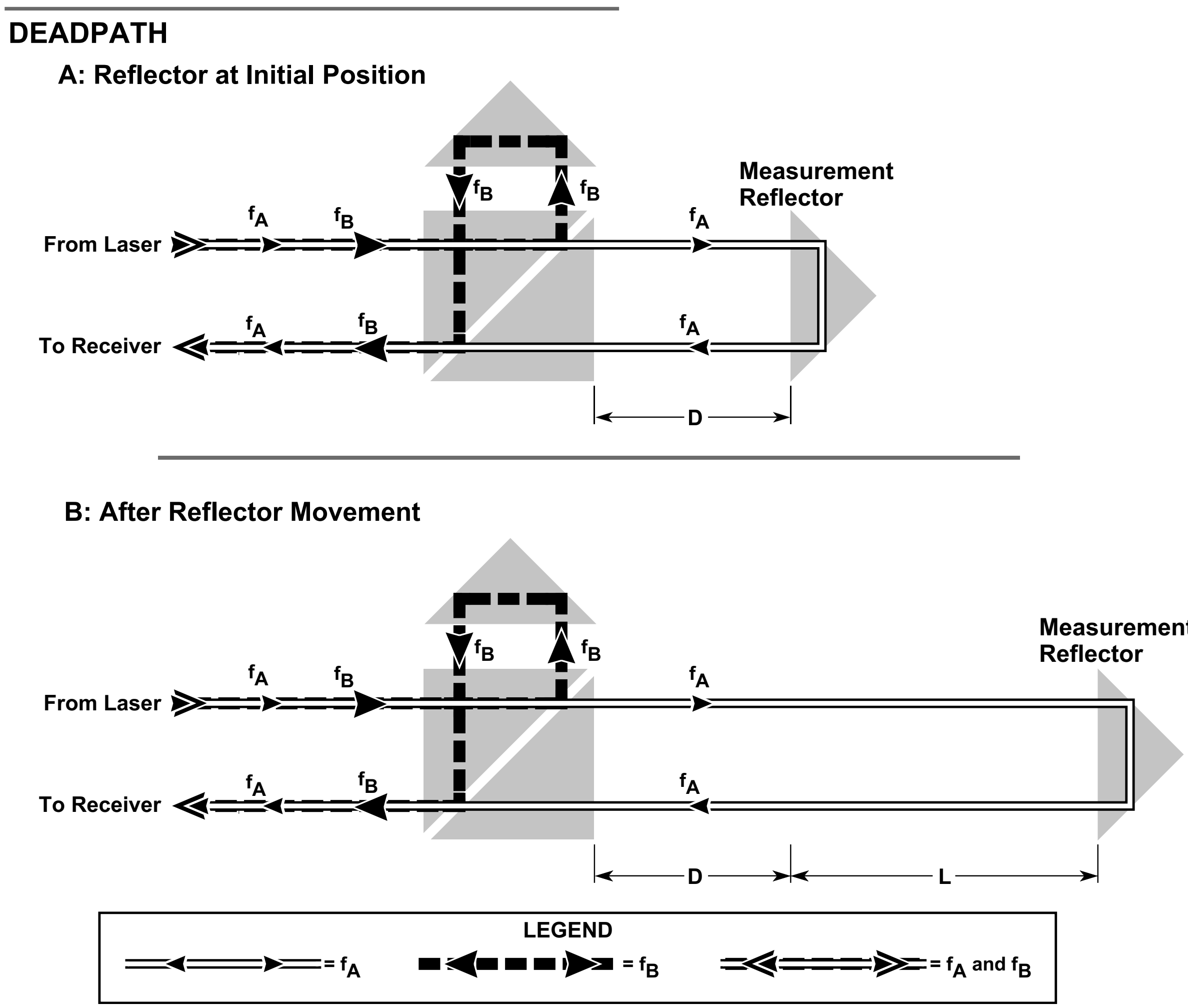

Figure 15-5. Deadpath caused by unequal lengths from initial point

Deadpath error can be represented as:

$$\text{Deadpath Error} = \text{Deadpath distance} \times \Delta\text{WCN} \qquad (7)$$

where:

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

Deadpath effects should be considered when designing a laser interferometer into an application or when using it.

Table 15-3 lists the minimum-deadpath mirror position(s), and the deadpath values, for Agilent interferometers.

Table 15-3. Deadpath mirror positions and values for Agilent interferometers

Interferometer	Mirror Position for Minimal Deadpath	Deadpath Value
Agilent 10702A	Zero-deadpath condition exists when the measurement cube corner is flush with the interferometer's measurement face.	Distance between interferometer measurement face and cube corner face at measurement “zero” position.
Agilent 10705A	Zero-deadpath condition exists when the measurement cube corner is flush with the interferometer's; measurement face.	Distance between interferometer measurement face and cube corner face at measurement “zero” position.
Agilent 10706A	Zero-deadpath condition cannot be achieved with this interferometer. Because of interferometer design, zero-deadpath would require that measurement reflector be inside the interferometer 7.62 mm (0.300 inch) behind the measurement face.	Distance between interferometer measurement face and cube corner face at measurement “zero” position plus 7.62 mm (0.300 inch).
Agilent 10706B	Zero-deadpath condition exists when the measurement mirror is flush with the interferometer's; measurement face.	Distance between interferometer measurement face and cube corner face at measurement “zero” position.
Agilent 10715A	Zero-deadpath condition cannot be achieved with this interferometer design because the reference and measurement mirrors cannot be coplanar.	Distance between front face of reference mirror and front face of measurement mirror.
Agilent 10716A	Zero-deadpath condition exists when the measurement mirror is flush with the interferometer's; measurement face.	Distance between interferometer measurement face and measurement mirror, at measurement “zero” position.
Agilent 10719A	Zero-deadpath condition exists when the measurement mirror is 19.05 mm (0.750 inch) farther from the interferometer's measurement face than the reference mirror is.	M - R - 19.05 (metric),- or - M - R - 0.750 (English), - where: M = Measurement Mirror distance from interferometer* R = Reference Mirror distance from interferometer* *at measurement “zero” position
Agilent 10721A	Zero-deadpath condition exists when the measurement mirror is 19.05 mm (0.750 inch) farther from the interferometer's measurement face than the reference mirror is.	M - R - 19.05 (metric),- or - M - R - 0.750 (English), - where: M = Measurement Mirror distance from interferometer* R = Reference Mirror distance from interferometer* *at measurement “zero” position

Table 15-3. Deadpath mirror positions and values for Agilent interferometers (Continued)

Interferometer	Mirror Position for Minimal Deadpath	Deadpath Value
Agilent 10735A	Zero-deadpath condition cannot be achieved with this interferometer. Because of interferometer design, zero-deadpath would require that measurement reflector be inside the interferometer, 6.59 mm (0.259 inch) behind the measurement face.	Distance between interferometer measurement face and cube corner face at measurement “zero” position plus 6.59 mm (0.259 inch).
Agilent 10736A	Zero-deadpath condition cannot be achieved with this interferometer. Because of interferometer design, zero-deadpath would require that measurement reflector be inside the interferometer, 6.59 mm (0.259 inch) behind the measurement face.	Distance between interferometer measurement face and cube corner face at measurement “zero” position plus 6.59 mm (0.259 inch).
Agilent 10736A-001	Zero-deadpath condition cannot be achieved with this interferometer. Because of interferometer design, zero-deadpath would require that measurement reflector be inside the interferometer. For measurement axis #1 or measurement axis #3, zero-deadpath would require that the measurement reflector be inside the interferometer 6.59 mm (0.259 inch) behind the measurement face. For the bent measurement axis (measurement axis #2), zero-deadpath would require that the measurement reflector be inside the interferometer, 34.42 mm (1.355 inches) behind the measurement face.	For measurement axis #1 or measurement axis #3, distance between interferometer measurement face and measurement mirror, at measurement “zero” position, plus 6.59 mm (0.259 inch) behind the measurement face. For the bent measurement axis (measurement axis #2, distance between interferometer’s beam bender measurement face and measurement mirror, at measurement “zero” position, plus 34.42 mm (1.355 inches).
Agilent 10776A	Zero-deadpath condition exists when the measurement cube corner is flush with the interferometer’s measurement face.	Distance between interferometer measurement face and cube corner face at measurement “zero” position.
Agilent 10770A	Zero-deadpath condition exists when the angular reflector face is parallel to the interferometer’s measurement face.	Difference in beam path lengths between interferometer and angular reflector, at measurement “zero” position.
Agilent 10774A	When used with the straightness reflector, the reference and measurement beam paths are the same length in air.	Deadpath does not exist.
Agilent 10775A	When used with the straightness reflector, the reference and measurement beam paths are the same length in air.	Deadpath does not exist.

During system design, there are two key approaches to minimizing deadpath effects.

- One approach is to locate the stationary optic (typically the interferometer) as close as possible to the "zero" point of the moving optic. The zero point is established at the time the laser system is reset.

This will minimize or eliminate deadpath in most applications. This is shown in Figure 15-6, which shows how to eliminate deadpath in a basic optical layout for an interferometer system.

OPTICAL CONFIGURATION WITH AND WITHOUT DEADPATH

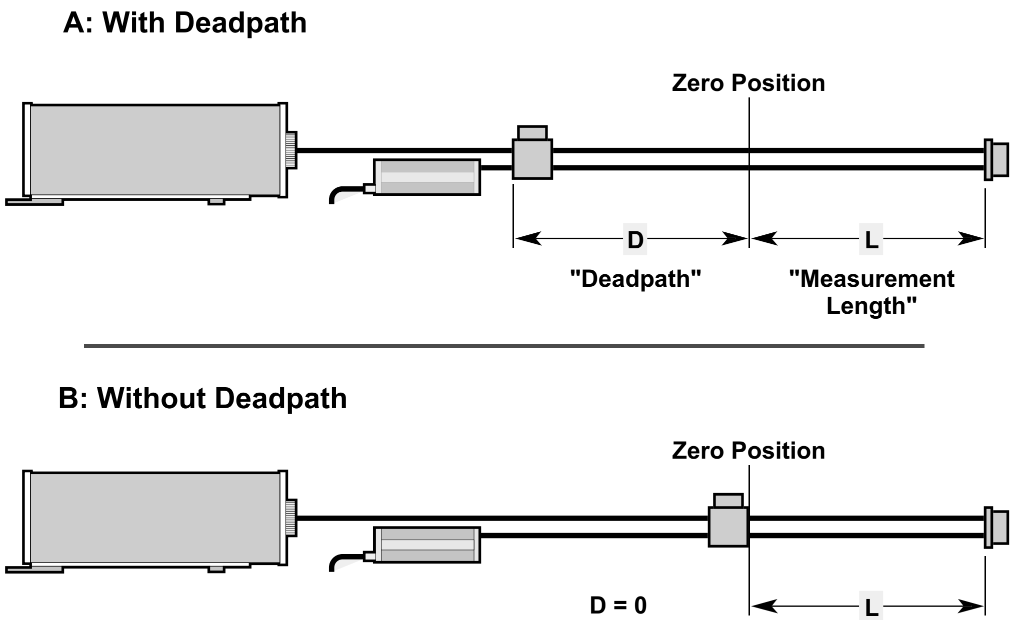

Figure 15-6. Optical configuration with and without deadpath

NOTE

It is important to understand that the zero-deadpath condition occurs when the reference and measurement optical paths have equal length. For some interferometers, this may NOT correspond simply to bringing the interferometer and measurement mirror as close as possible. For example, due to the differential design of the Agilent 10719A and Agilent 10721A interferometers, the zero-deadpath condition occurs when the mirror is 19 mm (0.750 inch) FARTHER from the interferometer than the reference mirror is located. This condition makes the reference and measurement path lengths equal because the reference beam travels an additional 19 mm (0.750 inch) inside the interferometer.

- The second approach is to choose an interferometer model which permits the minimum deadpath in the installation, wherever possible. While Agilent interferometers can usually be installed with essentially zero deadpath, the application itself sometimes imposes constraints. For example, in some cases, the Agilent 10715A may be the interferometer of choice because it has a remote reference mirror which minimizes deadpath when the interferometer itself cannot be located at the zero point.

During use of the interferometer system, there are two alternative methods to minimize deadpath effects.

- The first method is to always move the moving optic (typically the measurement reflector) to the position where the deadpath distance is zero (that is, where measurement path length equals reference path length), before resetting the laser system. This aligns the machine's "zero" point to the zero-deadpath position. If you always do this, no further compensation will be required.
- The second method — which you should use when it is not possible to align the machine's "zero" point to the zero-deadpath position at reset — is to provide deadpath compensation via software in the system controller.

Note that when using the Agilent 10719A in its angle-measuring configuration, the software correction is the only method possible since the measurement and reference path lengths are inherently unequal by 19.05 mm (0.750 inch).

By expanding Equation 3, the corrected actual displacement can be represented as:

Actual displacement = [(Accumulated Counts + Deadpath Counts) :

$$\times \frac{\lambda v}{R} \times WCN_1 \Big] - \text{Deadpath distance} \tag{8}$$

"Accumulated counts" is the displacement measured in units of LRCs (Least Resolution Counts). "Deadpath counts" is the deadpath distance in terms of compensated LRCs (using the initial compensation number, WCN0) "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.

In most cases, when you enter a deadpath distance into the software, a positive value corresponds to the case in which the measurement path length is longer than the reference path length. However, for the Agilent 10719A and Agilent 10721A differential interferometers, the deadpath distance sign depends on the measurement mirror position during reset. For example, if the measurement and reference mirrors are located coplanar during reset, the deadpath distance is –19 mm (–0.750 inch).

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:

$$\text{Deadpath Correction Error} = \text{Deadpath Distance} \times \text{Wavelength Compensation Number Repeatability} \quad (9)$$

The error in measuring the deadpath distance can generally 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 parts-per-million. However, the measurement error is a function of deadpath distance, rather than the distance measured by the interferometer.

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

Abbé error

Abbé error was first described by Dr. Ernst Abbé 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, Abbé error occurs when the measuring point of interest is displaced from the actual measuring scale location and unwanted angular motion occurs in the positioning system.

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

$$\text{Abbé error} = \text{offset distance} \times \text{tangent of offset angle} = A_0 \tan\theta$$

Figure 15-7 shows an example of Abbé error, and illustrates the requirements for minimizing angular error and minimizing offset of the scale from the measurement path. In Figure 15-7(A), the carriage is positioned by a leadscrew and the measurement axis is at the leadscrew centerline. This figure illustrates the displacement (Abbé) error E, which is generated at the measurement probe tip due to unwanted angular motion (θ) of the carriage during the measurement. Figure 15-7(B) shows the same carriage motion as Figure 15-7(A), but with the measurement axis coincident with the probe path. Here, the measurement system measures the actual displacement, thus no Abbé error exists. In general, reducing the Abbé offset will reduce sensitivity to unwanted angular motions.

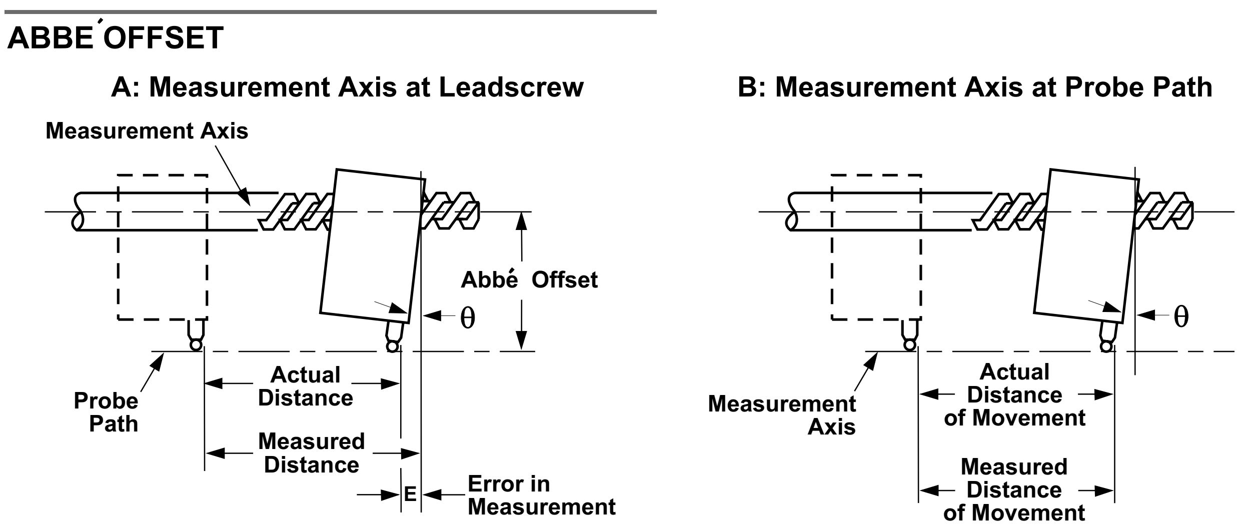

Figure 15-7. Abbé error

As a general rule, Abbé error is approximately 0.1 micron per 20 mm of offset for each arc-second of angular motion. Abbé error can occur with any type of displacement transducer.

In high-accuracy applications where it is not possible to completely eliminate the Abbé effect, you may measure the unwanted angular displacement directly, and then correct for Abbé errors via software. A variety of interferometers can serve this purpose — particularly the Agilent 10719A (when used as an angle-measuring optic), the Agilent 10735A, or the Agilent 10736A, for plane mirror of X-Y stage applications.

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 error is called cosine error, because its magnitude is proportional to the cosine of the angle of misalignment. Cosine error is common to all position transducers. If the laser alignment is unchanged over time, the cosine error will not change. Therefore, cosine error is part of the accuracy budget, but not part of the repeatability budget. Figure 15-8 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:

$$L = L_s \cos \theta \qquad (11)$$

COSINE ERROR

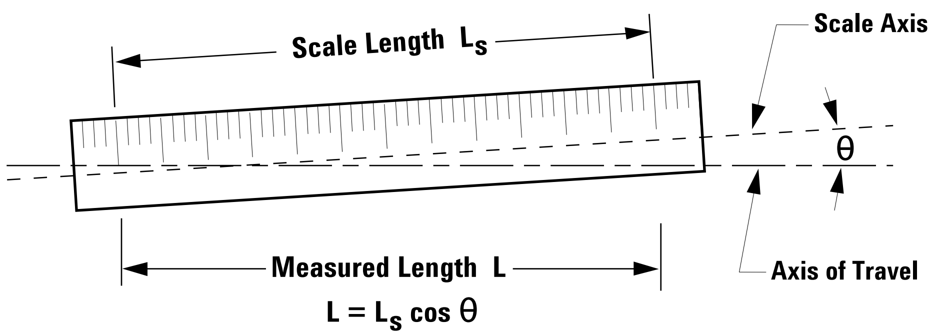

Figure 15-8. Cosine error

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:

$$\text{Cosine error in ppm} = (1 - \cos \theta) \times 10^6 \qquad (12)$$

Cosine error can be eliminated by taking care to orient the measurement laser beam parallel to the actual axis of travel. Use the proper alignment procedures for each type of interferometer. For example:

- with interferometers using plane mirror reflectors (Agilent 10706A/B, Agilent 10715A, Agilent 10716A), the resulting cosine error is less than 0.05 ppm.
- with interferometers that use cube comer reflectors (Agilent 10702A, Agilent 10705A), the cosine error in parts-per-million is approximately equal to 31250/L2, where L is the measured distance in millimeters.

Determining System Accuracy and Repeatability

The measurement accuracy and repeatability of a laser interferometer system are 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. Table 15-4 shows the list of components for these error budgets and how the totals are determined. As shown in Table 15-4, the only differences between the two error budgets are the laser wavelength terms and the cosine error not being part of the repeatability error budget.

Table 15-4. Laser interferometer system accuracy and repeatability error

	Laser Interferometer System	
	Accuracy is the Sum of	**Repeatability is the Sum of**
Proportional Terms	Laser Wavelength Accuracy	Laser Wavelength Stability
	Atmospheric Compensation	Atmospheric Compensation
	Material Thermal Expansion	Material Thermal Expansion
	Cosine Error	not applicable
	Deadpath Error	Deadpath Error
Fixed Terms	Electronics Error (Resolution)	Electronics Error (Resolution)
	Optics Non-Linearity	Optics Non-Linearity
	Optics Thermal Drift	Optics Thermal Drift
	Abbé Error	Abbé Error

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 categorized into proportional terms or fixed terms. The resulting measurement errors from proportional terms are a function of the distance measured. Fixed terms are noncumulative 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 (> l hour) components. For short-term repeatability, only a subset of the total error components is included. Generally, the optics and material thermal effects are negligible over a short period of time, and these components are deleted from the short-term repeatability error budget. Additionally, short-term laser wavelength stability is used instead of long-term wavelength stability, and atmospheric changes, especially pressure, will also be smaller.

Examples — Determining System Accuracy and Repeatability

The examples below illustrate the calculation of measurement accuracy and repeatability of Agilent laser measurement systems 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 measurement 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). Table 15-5 shows a list of parameters needed to calculate each error component.

[5] Steinmetz, C.R., Displacement Measurement Repeatability in Tens of Manometers with Laser Interferometry, Proc. SPIE, Vol. 921, p.406-420, 1988.

Table 15-5. Parameters needed to calculate each error component

System Error Component	Parameters
Laser Wavelength	Measurement Distance (L), Laser Specifications
Atmospheric Compensation	Measurement Distance (L), Environmental Conditions, Compensation Performance
Material Thermal Expansion	Measurement Distance (L), Material Temperature, Material
Cosine Error	Measurement Distance (L), Interferometer Type, Misalignment Angle
Deadpath Error	Deadpath Distance, Environmental Conditions, Compensation Performance
Electronics Error (Resolution)	Interferometer Type, Electronics
Optics Non-Linearity	Interferometer Type
Optics Thermal Drift	Interferometer Type, Temperature Changes
Abbé Error	Abbé Offset, Angular Changes

Precision Coordinate Measuring Machine (CMM) example

The typical configuration for this application is shown in Figure 15-9. It uses Agilent 10716A High Resolution interferometers and the Agilent 10717A Wavelength Tracker. This CMM has a working measurement volume of 1.0 m × 1.0 m × 1.0 m.

Dimensions: see figure below
Maximum distance measured (L): 1.0 m
Deadpath distance (D): 0.1 m
Cosine Error: 0.05 ppm (Agilent 10716A aligned according to procedure in this manual)
Nonlinearity: ±1.0 nm (Agilent 10716A)
Abbé error: none (assume zero offset)
Measurement resolution: ±2.5 nanometers (Agilent 10716A)
ENVIRONMENT:
Temperature: 20 °C ±0.5° (temperature controlled environment)
Pressure: 760 mm Hg ±25 mm Hg (possible storm fronts during measurement, pressure not controlled)
Humidity: 50% ±10% (humidity controlled environment)

LASER SYSTEM CONFIGURATION ON CMM

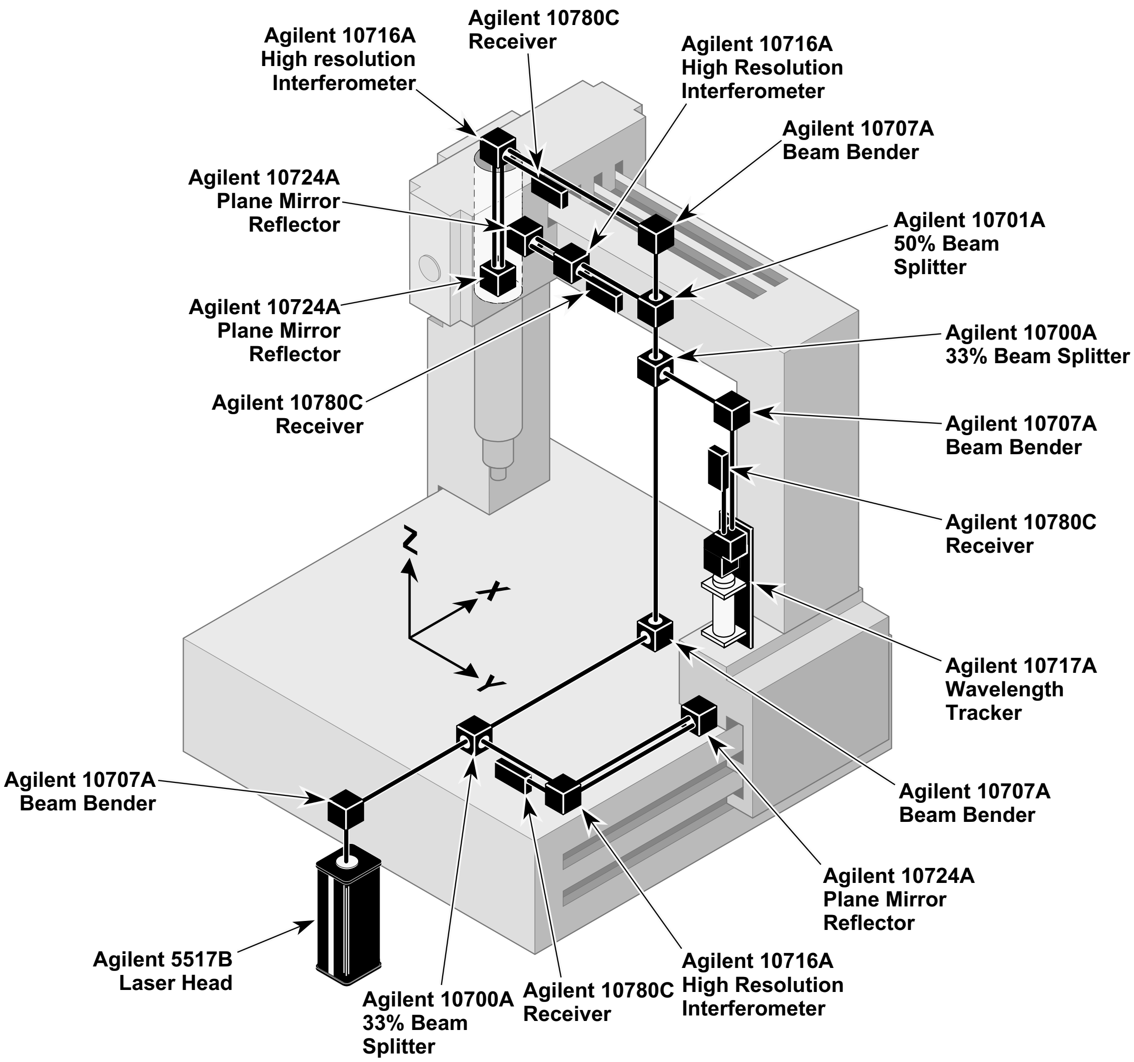

Figure 15-9. Laser system configuration for a precision Coordinate Measuring Machine (CMM)

A list of parameters needed to calculate the system's measurement accuracy and repeatability for this application is provided the following subsections. The laser head and optics' component specifications are taken from this manual, system resolution specifications for Agilent laser transducer electronics (Agilent 10885A, Agilent 10895A, Agilent 10897B, and Agilent 10898A) are taken from the manual of the respective electronic board, and the Agilent 10751C/D Air Sensor and Agilent 10757D/E/F Material Temperature Sensor environmental specifications are provided in this chapter.

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

Laser wavelength error

When using a CMM, both accuracy and long-term repeatability need to be calculated.

Laser Wavelength Stability: ±0.02 ppm (long-term)

This translates to a maximum distance uncertainty of:

Laser Wavelength Stability Error = (1.0 m) $(\pm 0.02 \times 10^{-6})$ (long-term) = ±0.02 micron

Laser Wavelength Accuracy: ±0.02 ppm (with optional calibration)

Laser Wavelength Accuracy Error = (1.0 m) $(\pm 0.02 \times 10^{-6})$ = ±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 (given earlier in this chapter) and the specified environmental conditions, accuracy and repeatability of compensation information from wavelength tracker can be determined.

Compensation accuracy and repeatability =

$$\pm\left[0.067\,\text{ppm} + \frac{0.06\,\text{ppm}}{\text{degree C}} \times 0.5\ \text{degree C} + \frac{0.002\,\text{ppm}}{\text{mm Hg}} \times 25\ \text{mm Hg}\right]$$

$$= \pm 0.15\ \text{ppm}$$

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

Compensation Error = (1.0 m) ($\pm 0.15 \times 10^{-6}$) = ±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 1 m, 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 depends 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 0.5 m part made of steel (α = 0.00 ppm/°C) and using the Agilent 10757D/E/F Material Temperature Sensor, the resulting measurement accuracy and repeatability will be:

$$\begin{aligned}\text{Measurement Accuracy} &= \alpha \times \text{temperature sensor repeatability} \\ &\quad \times \text{part length} \\ &= \frac{10.0\ \text{ppm}}{\text{degree C}}(\pm 0.1\ \text{degree C} \times 0.5\text{m}) \\ &= \pm 0.5\ \text{micron}\end{aligned}$$

The Agilent 10757D/C/E 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, specific errors will not be included in this example. However, this error should be included when calculating the error budget for an actual machine.

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 7 determines the error.

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

With deadpath correction and using Wavelength Tracking Compensation, Equation 9 determines the error.

$$\text{Deadpath correction error} = (0.1\ \text{m})\ (\pm 0.15 \times 10^{-6}) = \pm 0.015\ \text{micron}$$

Electronics error

With Agilent laser interferometer systems, the electronics error equals measurement resolution. When using the Agilent 10716A High Resolution Interferometer, system measurement resolution (for Agilent 10885A, Agilent 10895A, Agilent 10897B, or Agilent 10898A electronics) is:

$$\text{Measurement Resolution} = 0.0025\ \text{micron}$$

Optics nonlinearity

Nonlinearity when using the Agilent 10716A High Resolution Interferometer is ±0.001 micron.

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 Agilent 10716A in this application, typical thermal drift will be:

$$\text{Optics Thermal Drift} = \frac{0.04\ \text{micron}}{\text{degree C}} \times (\pm 0.5\ \text{degree C}) \times \pm\ 0.02\ \text{micron}$$

Abbé error

Since this error term is independent of the type of measurement scale used, but strongly dependent on how the machine is designed and built, specific errors will not be included in this example. However, the errors should be included when calculating the error budget for an actual machine when the Abbé offset is known and angular errors can be measured or estimated.

$$\text{Abbé Error} = 0\ \text{micron (assumed)}$$

Cosine error

If the proper alignment procedure for the Agilent 10716A is followed, the worst-case cosine error is:

Cosine Error = ±0.05 ppm

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

CMM system accuracy calculation

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, but still conservative, system repeatability 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. The results are presented in Table 15-6.

Table 15-6. System accuracy with and without atmospheric compenstation

	System Accuracy Calculation	
	With Atmospheric Compensation ±(microns)	**Without Atmospheric Compensation** ±(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
Abbé 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:

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

Figure 15-10 graphically presents this accuracy data and shows the importance of using atmospheric compensation. Figure 15-11 shows in more detail the relative magnitude of each component when using atmospheric compensation.

WORST-CASE SYSTEM ACCURACY — CMM EXAMPLE

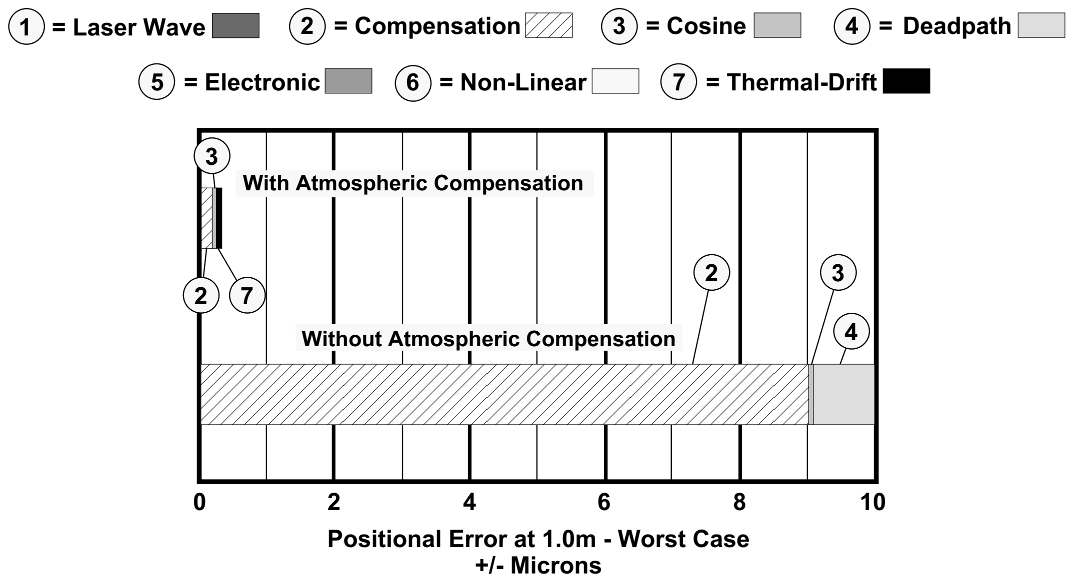

Figure 15-10. Worst-case System Accuracy with and without Atmospheric Compensation for the CMM example

WORST-CASE SYSTEM ACCURACY WITH ATMOSPHERIC COMPENSATION — CMM EXAMPLE

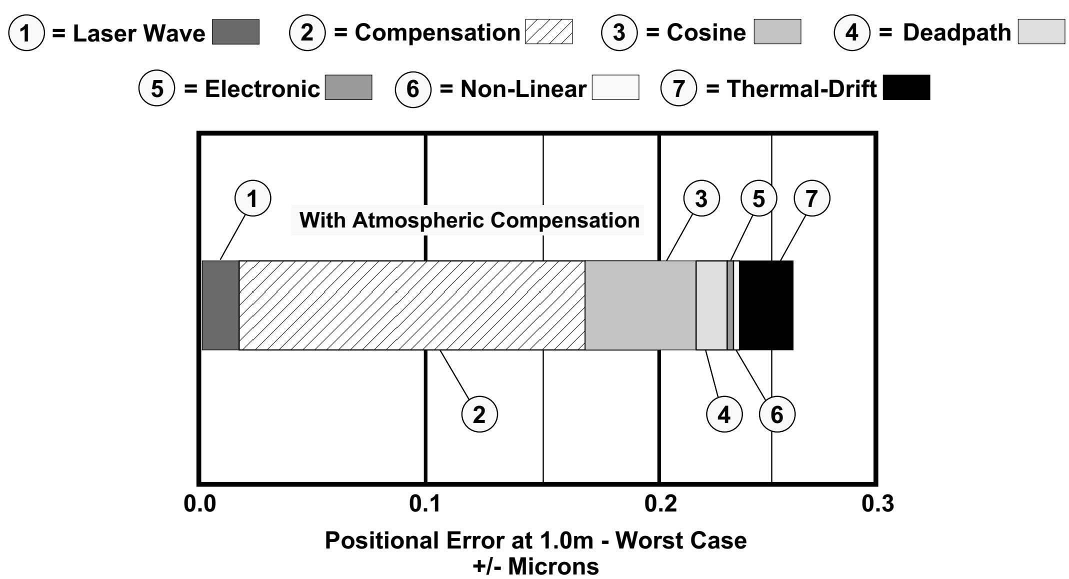

Figure 15-11. Worst-case System Accuracy with Atmospheric Compensation for the CMM example

CMM system repeatability calculation

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

	With Atmospheric Compensation	Without Atmospheric Compensation
Direct Sum Total (Worst Case)	±0.21 micron	±9.94 microns
RSS sum (Typical)	±0.17 micron	±9.90 microns

Figure 15-12 is a graph of the worst-case repeatability. Again it shows the importance of atmospheric compensation. Figure 15-13 shows in more detail the worst-case repeatability with atmospheric compensation.

WORST-CASE SYSTEM REPEATABILITY — CMM EXAMPLE

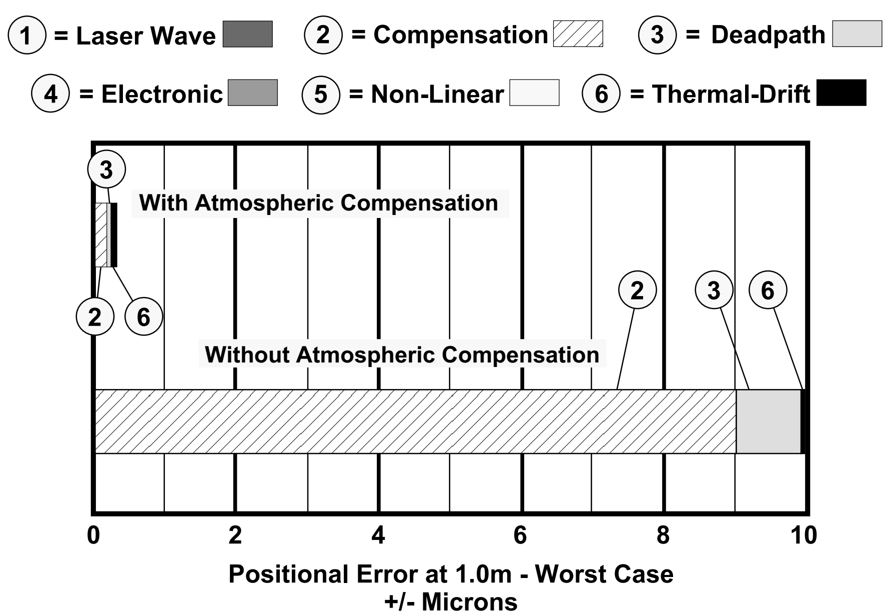

Figure 15-12. Worst-case System Repeatability with and without Atmospheric Compensation for the CMM example

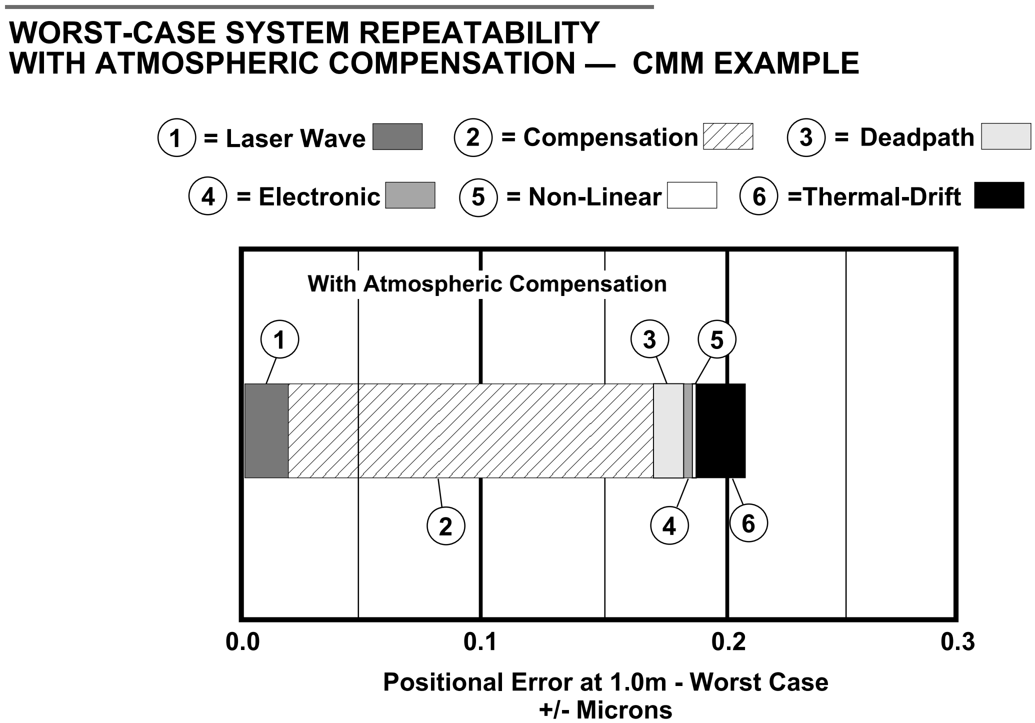

Figure 15-13. Worst-case System Repeatability with Atmospheric Compensation for the CMM example

IC Wafer Stepper example

In this example, the laser system is built into an Integrated Circuit Wafer Stepper and controls the position of the wafer stage. A typical configuration for this application is shown in Figure 15-14. It uses Agilent 10706B High Stability Plane Mirror Interferometers and an Agilent 10717A Wavelength Tracker. Following is a list of parameters needed to calculate the system accuracy and repeatability. The laser head and optics' component specifications are taken from this manual, system resolution specifications for Agilent laser transducer electronics (Agilent 10885A, Agilent 10895A, Agilent 10897B, and Agilent 10898A) are taken from the manual of the respective electronic board, and the Agilent 10751C/D Air Sensor and Agilent 10757D/E/F Material Temperature Sensor environmental specifications are provided in this chapter.

Dimensions: see figure below
Maximum distance measured (L): 0.2 m
Deadpath distance (D): 0.1 m
Cosine Error: 0.05 ppm (Agilent 10706B aligned according to procedure in this manual)
Nonlinearity: ±2.2 nm (Agilent 10706B)
Abbé error: none (assume zero offset)
Measurement resolution: ±5 nanometers (Agilent 10706B)
ENVIRONMENT:
Temperature: 20° C ±0.1° (temperature controlled environment)
Pressure: 760 mm Hg ±25 mm Hg (possible storm fronts during measurement, pressure not controlled)
Humidity: 50% ±10% (humidity controlled environment)

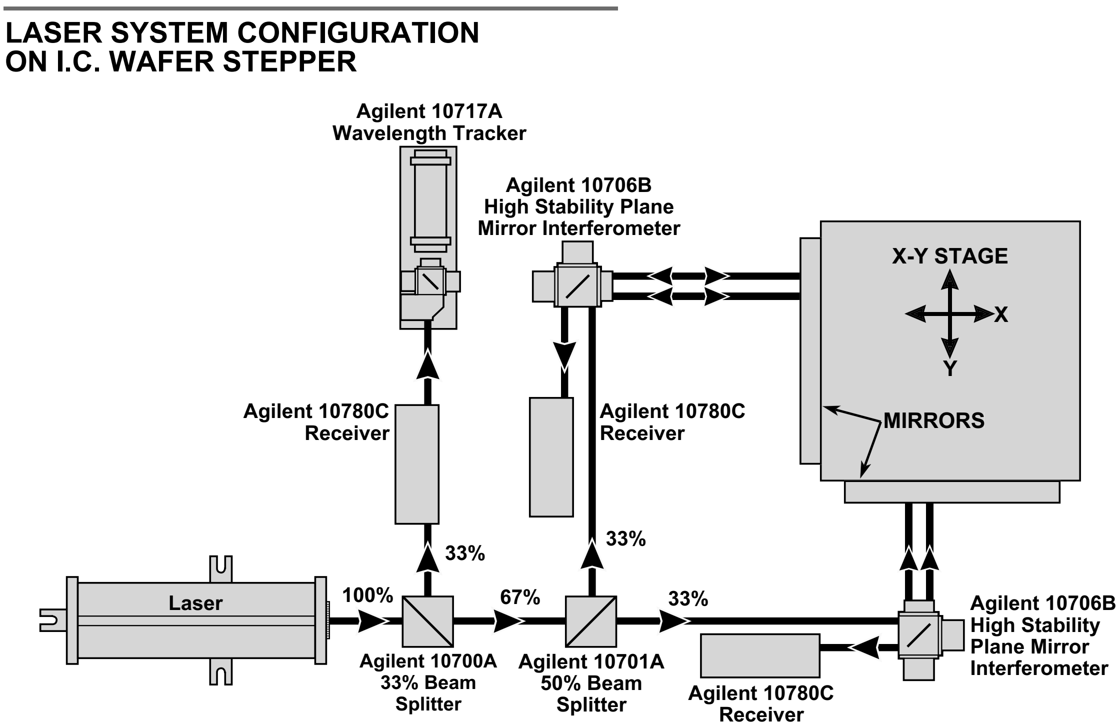

Figure 15-14. Laser System Configuration for an Integrated Circuit Wafer Stepper

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

Laser wavelength error

The time required for an operation by IC fabrication equipment is often only a few minutes. Thus, accuracy, long-term stability, and short-term stability need to be calculated.

Laser Wavelength Stability: ±0.002 ppm (short-term)

This translates to a maximum distance error of:

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

Laser Wavelength Stability: ±0.02 ppm (long-term)

Laser Wavelength Stability Error = 0.2 m (±0.02 × 10^{-6})
(long-term) = ±0.004 micron

Laser Wavelength Accuracy: ±0.02 ppm (with optional calibration)

Laser Wavelength Accuracy Error = 0.2 m (±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 obtained by 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 and the specified environmental conditions, accuracy and repeatability of compensation information from wavelength tracker can be determined.

Compensation accuracy and repeatability =

$$\pm\left[0.067\,\text{ppm} + \frac{0.06\,\text{ppm}}{\text{degree C}} \times 0.1\ \text{degree C} + \frac{0.002\,\text{ppm}}{\text{mm Hg}} \times 25\ \text{mm Hg}\right]$$

= ± 0.14 ppm

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

Compensation Error = (0. 2 m × ±0. 14 × 10^{-6}) = ±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 the measurement axes are placed to allow measurements between the wafer and optical column (for example, using an Agilent 10719A or Agilent 10721A differential interferometer), 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 7 determines the error.

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

With deadpath correction and the use of the wavelength tracker, Equation 9 determines the error.

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

Electronics error

With Agilent laser interferometer systems, the electronics error equals the measurement resolution. When using the Agilent 10706B High Stability Plane Mirror Interferometer, system measurement resolution (for the Agilent 10885A, Agilent 10895A, Agilent 10897B, or Agilent 10898A electronics) is:

Measurement Resolution = 0.005 micron

Optics nonlinearity

Nonlinearity when using the Agilent 10706B High Stability Plane Mirror Interferometer is ±0.0022 micron.

Optics thermal drift

Because the measurement repeatability of this piece of equipment is important, the effects of thermal changes of the interferometer should be included. With the Agilent 10706B High Stability Plane Mirror Interferometer, typical thermal drift will be:

$$\text{Optics Thermal Drift} = \frac{0.04\ \text{micron}}{\text{degree C}} \times (\pm 0.1\ \text{degree C}) = \pm 0.004\ \text{micron}$$

Abbé error

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

Abbé Error = 0 micron

Cosine error

If the proper alignment procedure for the Agilent 10706B 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 × 0.2 m = ±0.01 micron

IC Stepper System accuracy calculation

Now you can sum the appropriate components 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, but still conservative, system repeatability 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. The results are presented in Table 15-7.

Table 15-7. IC Stepper System Accuracy with and without Atmospheric Compenstation

	System Accuracy Calculation	
	With Atmospheric Compensation ±(microns)	**Without Atmospheric Compensation** ±(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
Abbé 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

Use the following equation to calculate the RSS sum:

RS sum = [(sum of squares of independent terms) + (sum of not independent terms^2)]^{½} + offset

Figure 15-15 graphically presents this accuracy data and shows the importance of using atmospheric compensation. Figure 15-16 shows in more detail the relative magnitude of each component when using atmospheric compensation.

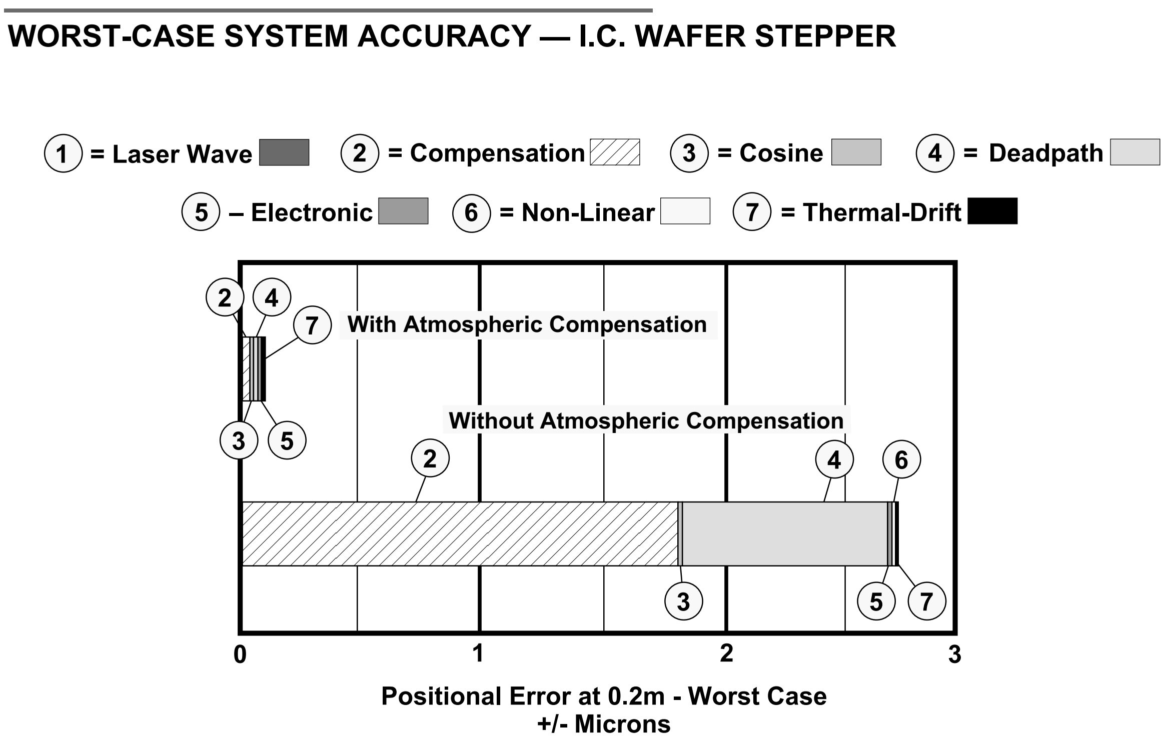

Figure 15-15. Worst-case System Accuracy with and without Atmospheric Compensation for the Wafer Stepper example

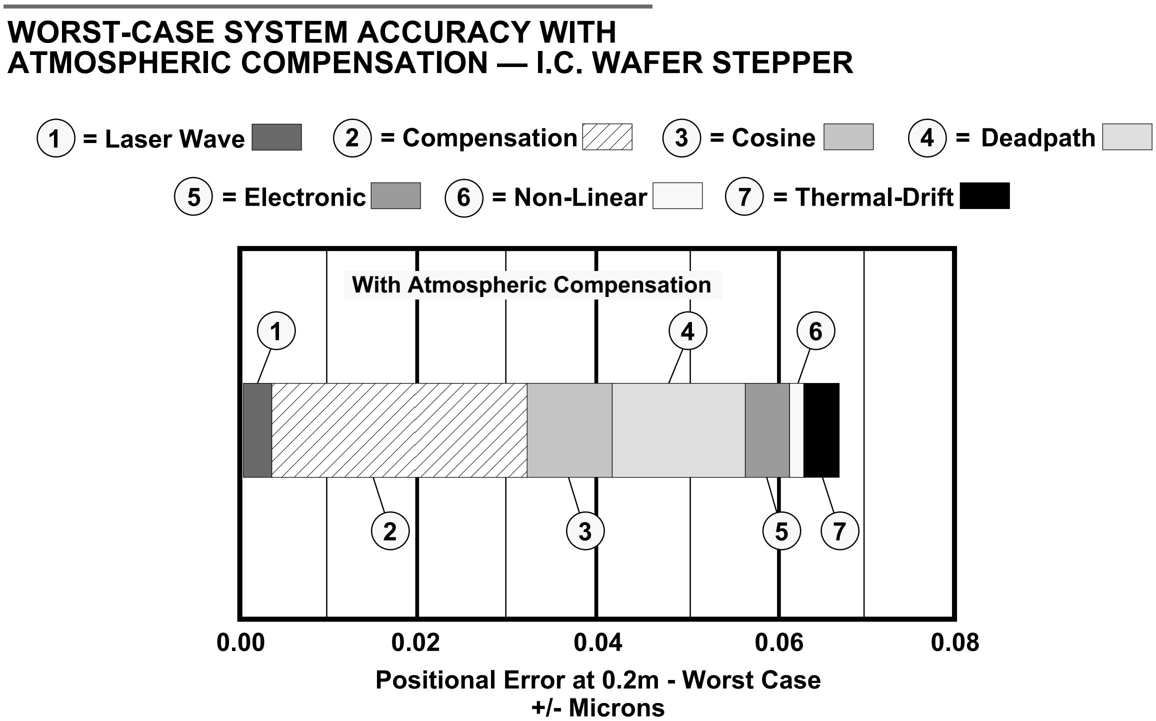

Figure 15-16. Worst-case System Accuracy with Atmospheric Compensation for the Wafer Stepper example

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 sides of the stage, as shown in Figure 15-14. Because the mirrors are not perfectly flat, 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. To compensate for this measurement error, map the mirror flatness, then make the correction via software in the controller.

IC Stepper system repeatability calculations

Long-term repeatability

Calculation of laser system long-term repeatability in this example is the same as system accuracy, except that the cosine error term (±0.01 micron) is not included. Therefore, laser system long-term repeatability will be:

	With Atmospheric Compensation	Without Atmospheric Compensation
Direct Sum Total (Worst Case)	±0.057 micron	±2.715 microns
RSS sum (Typical)	±0.043 micron	±2.710 microns

Figure 15-17 is a graph of the worst-case long-term repeatability. Again, the importance of atmospheric compensation is shown. Figure 15-18 shows in more detail the worst-case long-term repeatability with atmospheric compensation.

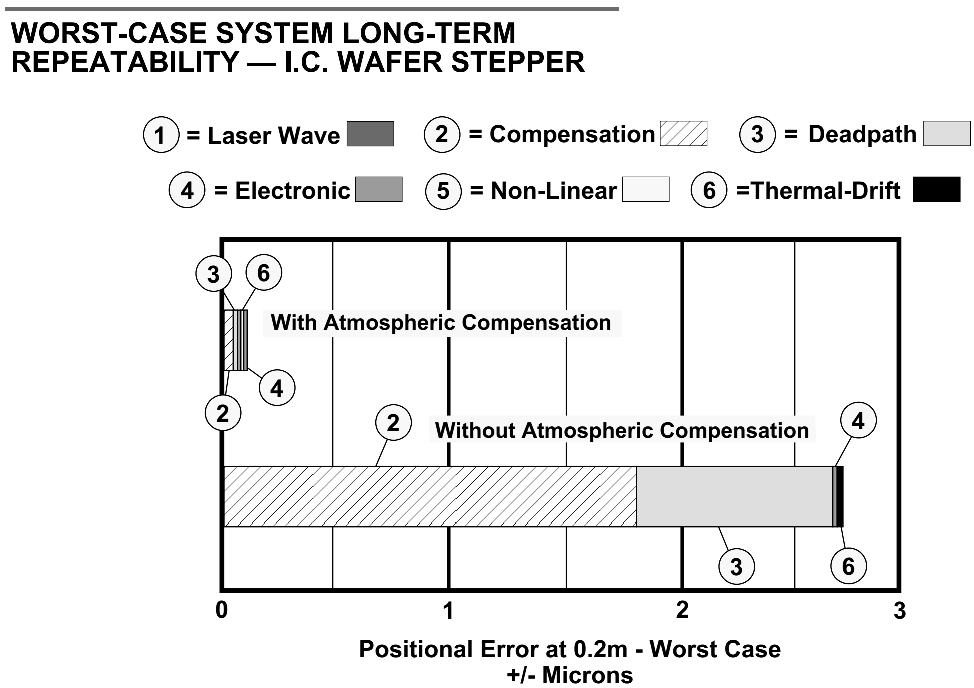

Figure 15-17. Worst-case System Long-term Repeatability with and without Atmospheric Compensation for the Wafer Stepper example

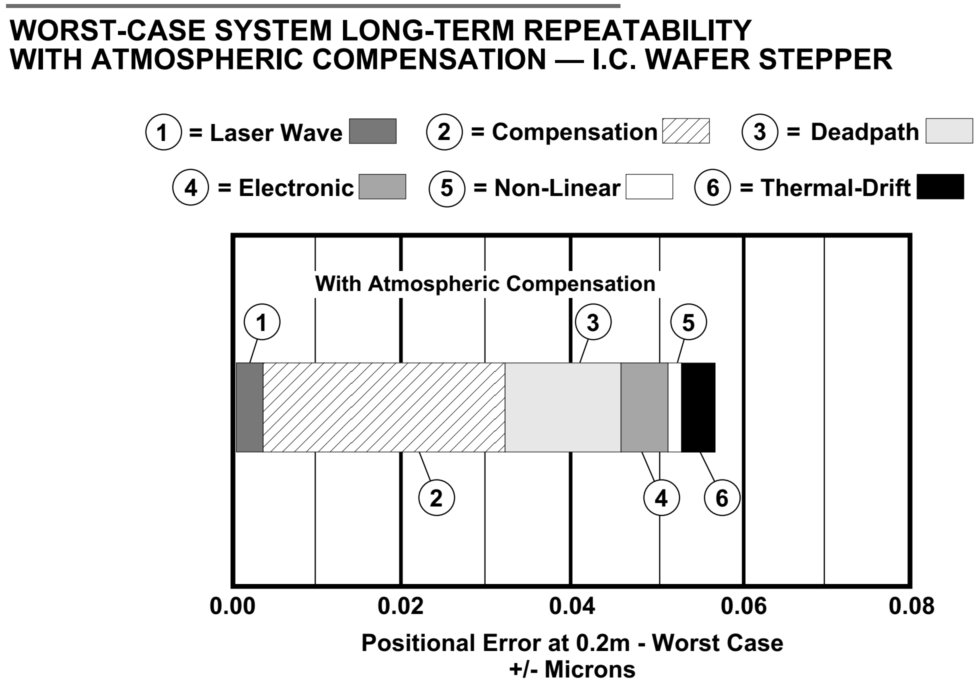

Figure 15-18. Worst-case System Long-term Repeatability with Atmospheric Compensation for the Wafer Stepper example

Short-term repeatability

In this example, calculation of system short-term repeatability is the same as long-term repeatability except: 1) long-term laser wavelength error is replaced by short-term error, and 2) optics thermal drift is not included. The atmospheric compensation error is assumed to be the same. However, under normal operating conditions, atmospheric pressure changes would generally be substantially less than those used in this example for the short periods of interest in IC fabrication.

	With Atmospheric Compensation	Without Atmospheric Compensation
Direct Sum Total (Worst Case)	±0.050 micron	±2.708 microns
RSS sum (Typical)	±0.042 micron	±2.700 microns

As seen from these values, the difference between system long-term and short-term repeatability is only a few nanometers. If the assumed short-term environmental changes (especially atmospheric pressure) are much smaller, then short-term repeatability will be significantly smaller.

Achieving Optimum System Accuracy and Repeatability

To achieve the best measurement accuracy and repeatability from a laser interferometer system in your application:

1. Whenever possible, make the measurements in a tightly-controlled, stable environment. Also, use the appropriate compensation methods to correct for atmospheric and material temperature effects.
2. When designing a machine to use a laser interferometer system, minimize both deadpath distances and Abbé offsets. If a deadpath 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.

Additional details are presented below.

Minimizing environmental effects

The relative importance of typical atmospheric effects and material temperature errors is shown in Figure 15-19. Measurement errors due to material temperature errors are especially important in many applications. Ideally, all distance measurements with the laser system would be made in a temperature-controlled room held at exactly 20°C (68° F), the standard temperature. Then the machine or part would be at its “true” size and the wavelength compensation number determined earlier could be used directly.

RELATIVE EFFECT OF ERRORS

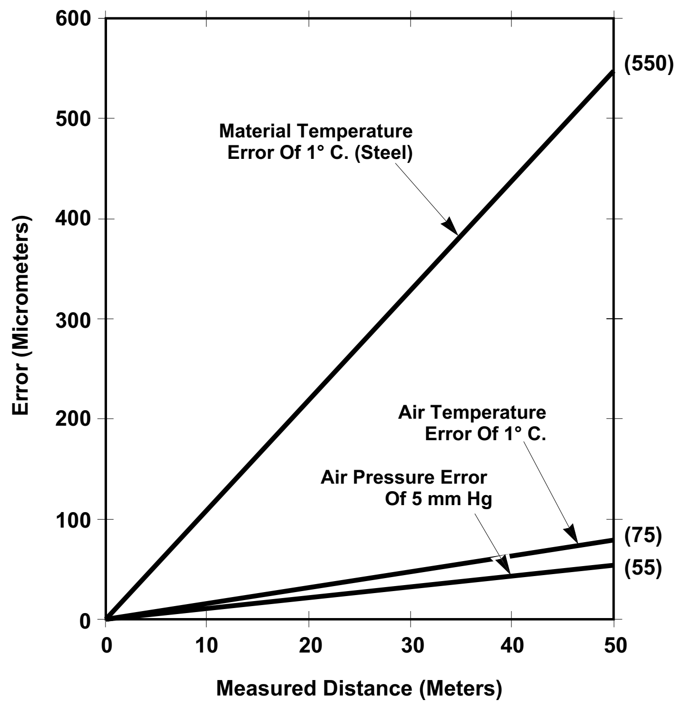

Figure 15-19. Relative effect of errors in atmospheric and material temperature

Laser measurement errors from environmental effects can be corrected by using a combined compensation term called the “Total Compensation Number” or “TCN”. It contains a Wavelength-of-Light compensation term (WCN) and a Material Temperature compensation term (MTC). These terms were described individually earlier in this chapter. The WCN is Equation 2, and the MTC is Equation 5. The TCN is determined from the WCN and MTC as follows:

$$TCN = WCN \times MTC \tag{13}$$

Expanding the WCN and MTC terms, we get:

$$TCN = \overbrace{\frac{\text{air wavelength}}{\text{vacuum wavelength}}}^{\text{WCN}} \times \overbrace{[1 - (\text{Linear Thermal Coefficient}) \times (\text{Material Temperature} - \text{Standard Temperature})]}^{\text{MTC}} \tag{14}$$

The Wavelength-of-Light term compensates for changes in the laser wavelength. The material temperature term corrects the measurement back to standard temperature.

Recall from the earlier section on atmospheric compensation that the laser position transducer counts the number of wavelengths of motion traveled. This measurement can then be corrected for atmospheric effects by multiplying the distance by a correction factor, the WCN. The result was given in Equation 3:

$$\text{Actual Displacement (true position)} = (\text{Wavelength counts}) \times WCN \times \text{vacuum Wavelength} \tag{3}$$

We can now combine the compensation for both atmospheric and material temperature effects and calculate the “true” length of the object at standard 20° C temperature. Using equations (3) and (13) we get:

$$\text{Actual Length} = (\text{Wavelength counts}) \times TCN \times \text{vacuum Wavelength} \tag{15}$$

Laser compensation capability

The laser system electronics can accept a manually-entered Total Compensation Number (TCN) or automatically determine the TCN, if a compensation board is installed.

Manual compensation

For manual compensation, the Total Compensation Number (TCN) is entered through the system controller to the Agilent laser electronics. The TCN can be calculated via Equation 13 or 14. See Chapter 16, "Wavelength-of-Light Compensation Numbers," for Wavelength Compensation numbers and the method to calculate them manually. See Chapter 17, "Material Expansion Coefficients," for information about Material Temperature compensation numbers.

Manual compensation can also be done without deriving or looking up the factors, by using the appropriate Agilent automatic compensation board for the Agilent laser electronics. The compensation board computes compensation factors from the environmental data (atmosphere and machine or part temperature) entered manually through the controller to the Agilent electronics.

Automatic compensation

With most Agilent laser electronics, the necessary information for wavelength compensation can be obtained automatically by using the appropriate Agilent automatic compensator board and environmental sensors. WOL compensation is provided by using either the Agilent 10751C/D Air Sensor to measure air temperature, pressure, and humidity, or the Agilent 10717A Wavelength Tracker to measure the laser wavelength change directly. The Agilent 10757D/E/F Material Temperature Sensor provides the temperature data for the "Material Temperature" term. The Agilent automatic compensation board automatically provides an updated total compensation number (TCN).

The Agilent 10717A Wavelength Tracker and its accompanying Agilent 10780C, Agilent 10780F, Agilent E1708A, or Agilent E1709A receiver provide the Agilent automatic compensation board with information indicating any changes in the laser wavelength. Unlike the air sensor, the wavelength tracker measures relative (differential) changes in the laser wavelength with respect to an initial value. The absolute accuracy is dependent on this initial value. Some methods of determining an initial compensation number are by:

- using an Agilent 10751C/D Air Sensor.
- using look-up tables (such as those in Chapter 16, "Wavelength-of-Light Compensation Numbers," of this manual).
- measuring temperature, pressure and humidity, and then inputting these values into the automatic compensation board.
- measuring a known "standard" length.

To calculate the initial compensation number by measuring a known standard or artifact, use the following formula:

$$\text{Compensation Number} = \frac{\text{Measured length (from laser system on machine)}}{\text{Actual length (from a "Standards" laboratory)}} \qquad (14)$$

NOTE If relative compensation is satisfactory for your application, the default values of initial compensation may be used. See the laser electronics documentation for your system for details.

Sensor placement

To correct for the effects of air conditions on the laser reading, place the Agilent 10717A Wavelength Tracker or Agilent 10751C/D Air Sensor where it can accurately monitor the conditions influencing the laser beam. Mount the sensor as close as possible to the measurement path, so it monitors the condition of these laser beams.

Agilent 10717A Wavelength Tracker

When you use the wavelength tracker, mount the unit on a stable surface so that alignment is maintained.

Agilent 10751C/D Air Sensor

The air sensor should not be placed directly below the measurement beam path because the heat from the air sensor will affect the laser beam. The Agilent 10751C/D Air Sensor base contains a magnet to aid in securing it to magnetic materials. For permanent mounting, fasten the sensor using the #10-32 tapped hole on the bottom of the unit.

AGILENT 10751C/D AIR SENSOR ORIENTATION

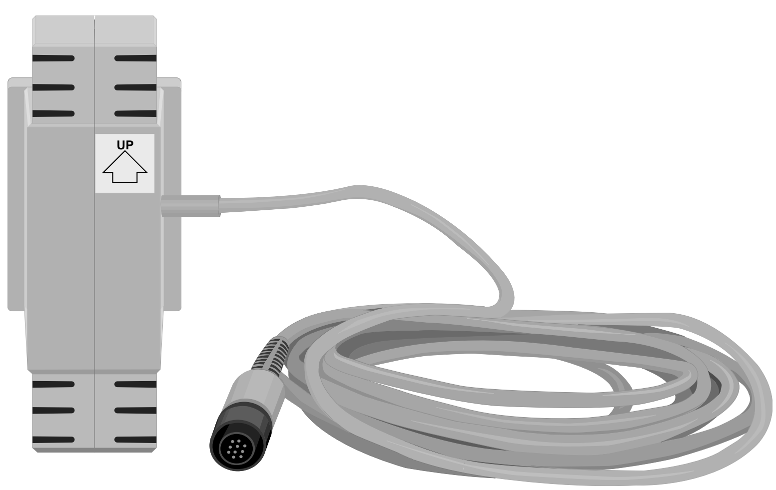

Figure 15-20. Air sensor orientation

NOTE The Air Sensor should be mounted with its arrow pointing up, to maximize accuracy, as shown in Figure 15-20.

Agilent 10757D/E/F Material Temperature Sensor

When monitoring material temperature to account for material expansion, the Agilent 10757D/E/F Material Temperature Sensor should be placed on the part of the machine closest to the workpiece.

The material temperature sensor contains a magnet to aid in securing it to ferrous materials. For permanent mounting, a clamp can be used to secure it. If two material temperature sensors are used, they should be placed to determine the average temperature of the workpiece. After attaching a probe to the workpiece, allow at least 10 minutes for the probe temperature to stabilize at the workpiece temperature.

WOL compensation method comparison

The method of atmospheric (WOL) compensation used is important in determining the overall laser system measurement accuracy. Table 15-8 summarizes the laser system accuracy for various methods of atmospheric compensation as a function of different atmospheric conditions.

Table 15-8. Laser system measurement accuracy comparison*

Environment:
Pressure: 760 mm Hg ±25 mm Hg
Relative Humidity: 50% ±10%

Temperature Control	**±0.1°C**	**±1.0°C**	**±5.0°C**
No Compensation† (at 20°C)	±9.0 ppm	±9.9 ppm	±14.0 ppm
Compensation using Agilent 10751C/D Air Sensor (at 20° C)	±1.4 ppm	±1.5 ppm (typical)	±1.6 ppm
Wavelength Tracking Compensation‡	±0.15 ppm	±0.19 ppm	±0.44 ppm
Measurement in Vacuum	±0.1 ppm	±0.1 ppm	±0.1 ppm

* These accuracy specifications include the laser head term, but exclude electronics accuracy and interferometer nonlinearity terms.

† No compensation means that no correction in compensation number occurs during environmental changes.

‡ System accuracy equals these values (measurement repeatability) plus accuracy of initial compensation value.

Non-Uniform Environments

Compensation for environmental effects is practical only when the material being measured is at a constant temperature, and when the medium through which the measurement laser beam passes is not disturbed (such as by air turbulence).

Changing temperature conditions

Material temperature compensation is accurate only when the part and the machine are at thermal equilibrium with their surroundings. Changing temperature can change thermal gradients in both the machine and the part. In this case, the primary machine errors are due to complex bending effects which distort machine geometry, in addition to simple thermal expansion. These effects are extremely difficult, if not impossible, to describe mathematically.

Changing temperatures also affect the measurement optics, resulting in optics thermal drift as described earlier in this chapter. Therefore, if a machine is operated in a poor environment, its accuracy may be limited by its own geometry, thermal expansion, and optics thermal drift. In this case, the most practical solution is to improve the environment and use optics that are thermally stable.

Air turbulence

Air Turbulence is an important factor to be considered during installation of a laser system. It is usually caused by variations in air temperature. The major effect of air turbulence is reduction of amount of signal at the receiver. This reduction is due to either physical deflection of the laser beam or degradation of the beam's coherence. Excessive air turbulence may cause complete loss of measurement signal. This loss of signal will be detected by the Agilent electronics which will output an error signal.

One application where serious consideration must be given to air turbulence is a temperature-controlled environment. Although it would appear that such an environment would be ideal, temperature-controlled areas often exhibit greater air turbulence than non-controlled areas. This turbulence is caused by incomplete mixing of new air from the temperature control unit with existing air, creating thermal gradients or pockets. Although such environments are good for a machine's thermal stability, the short term fluctuations can cause measurement signal degradation in the laser system.

Reducing air turbulence

In an uncontrolled environment, the effects of air turbulence can be minimized by protecting the laser beam with some type of cover. Since this would normally be done for protection against beam interruption, air turbulence effects will usually not be a significant installation factor in a typical environment.

Protection against air turbulence problems which occur in a controlled environment depends largely on the specific application. For systems such as integrated circuit lithography equipment in small closely-controlled enclosures, it may be sufficient to provide constant air flow over the measurement paths. In other cases, such as large coordinate measuring machines, protecting the laser beams with covers prevents air turbulence effects from interfering with the measurement.

Avoiding thermal gradients

One source of air turbulence, which can affect both the laser system and also the accuracy of the machine itself, is thermal gradients created by localized heat sources (e.g., motors, electromagnetics, lamps, etc.) located on or near the machine. You should shield the measurement path from these types of heat sources. A key benefit of the Agilent 10780F, Agilent E1708A, and Agilent E1709A remote receivers is that they allow remote mounting of the receiver electronics, eliminating its 2 watts of heat from the measurement area. The remote (fiber-optic) pickup is entirely passive and dissipates no heat.

A local heat source which can affect the laser system enough to cause measurement signal loss also tends to degrade the geometric accuracy of the machine through warping or bending. Therefore, you should consider thermally isolating the heat source from the machine as well as the measurement path.

Optics installation effects

When planning the installation of the laser head and optics on a specific machine, important points to remember are:

- Install the interferometer and retroreflector to minimize deadpath errors.
- Align the laser beam path parallel to the axis of motion to minimize cosine errors.
- Select the measurement paths to minimize Abbé error.
- Use thermally stable optics.

These effects are not a concern for the optical axis used for the Agilent 10717A Wavelength Tracker. The components of the wavelength tracker are aligned at the factory to minimize any cosine or Abbé errors.

In many cases, it may not be possible to completely eliminate these sources of error, but every effort should be made to minimize them. The paragraphs below discuss methods of installing and compensating for these errors.

Minimizing deadpath errors

Deadpath error is an error introduced due to an uncompensated length of laser light between the interferometer and the retroreflector when the machine is at its “zero” position.

Deadpath is the difference in optical path lengths between the reference and measurement components of the beam when the positioning stage or machine is at its zero position, as defined by the machine’s coordinate system. Unequal beam components produce an optical path length difference that will not be properly compensated during changing environmental conditions, resulting in a measurement error. The optical path can differ due to unequal path lengths or different optics (thickness or composition) in the beam path.

Deadpath error can be minimized in most applications by a combination of the following:

- Minimize the distance “D”. Mount the interferometer as close to the retroreflector as possible when the machine is at its zero position as defined by its own coordinate system. This minimizes the unequal path length cases.
- Minimize unequal path treatments as much as possible. Minimize the number of optics, such as windows, used in the beam path.
- Use an Agilent 10715A Differential Interferometer or Agilent 10706B High Stability Plane Mirror Interferometer instead of the Agilent 10706A Plane Mirror Interferometer. Some unequal path treatment cannot be avoided with the Agilent 10706A Plane Mirror Interferometer. The other interferometers have negligible difference in their treatments. Figure 15-2 shows that component f_A travels through more glass than does f_B. It makes twice as many trips through the interferometer as does f_A, and also two round trips through the quarter-wave plate. This unequal treatment of f_A and f_B, causes deadpath errors under changing conditions.
- Correct the residual distance “D” in software in the controller.

- Equalize the path lengths of f_B and f_A by moving the reference cube-corner a distance “D” from the interferometer. (See Figure 15-21). Assuming the atmospheric conditions are equivalent and the distances between the cube-corners and the interferometer are equal, this configuration would not have deadpath errors due to unequal path lengths. Take care when using this method of reducing deadpath, because any drift in the position of the reference cube-corner will also show up as a measurement error. This drift can result from non-rigid mounting and thermal expansion, for example.

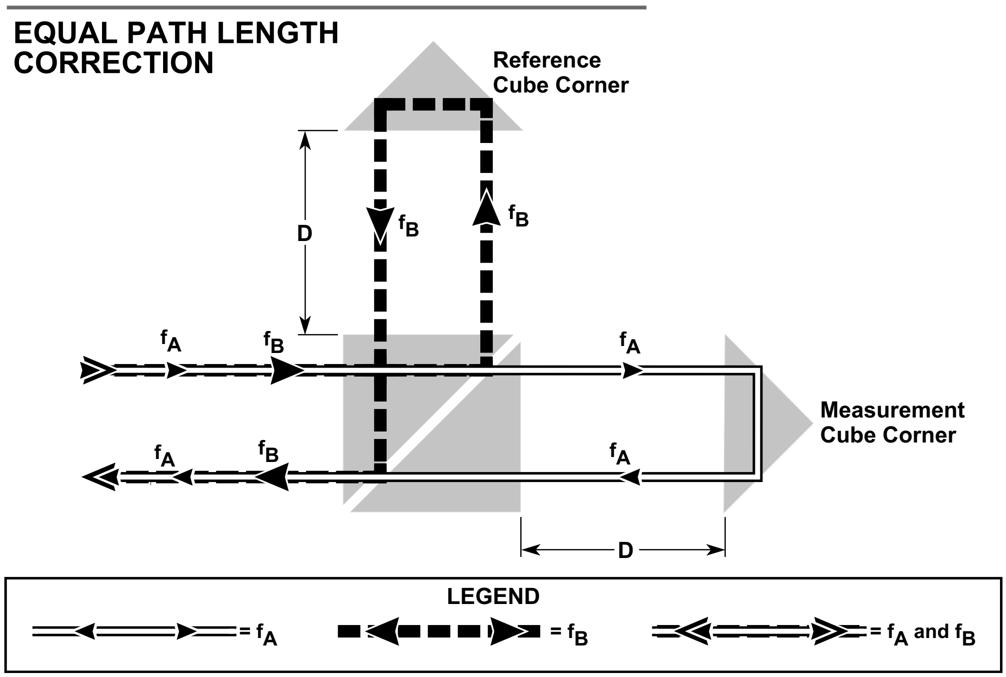

Figure 15-21. Equal path length correction

Compensation for deadpath errors

Correction for deadpath error (unequal path length) is necessary if there is a change in the laser wavelength due to environmental conditions. Compensation for deadpath error can be done by correcting for the deadpath distance “D” in software in the controller. In this case, the general relation:

True Position = Wavelength counts due to motion × vacuum wavelength × TCN

is expanded to be:

True Position = [(Accumulated Counts + Deadpath Counts) × Wavelength Conversion Factor × TCN] - (Deadpath in selected units)

Accumulated raw counts is the actual output from the electronics rather than the number of wavelengths.

For the Agilent 10716A interferometer, a displacement count equals $\lambda/256$, where λ is the wavelength of the laser in air, for Agilent laser electronics.

When using one the interferometers listed below, an actual displacement count is equal to $\lambda/128$, where λ is the wavelength of the laser in air, for Agilent laser electronics:

- Agilent 10706A/B Plane Mirror Interferometer
- Agilent 10715A Differential Interferometer
- Agilent 10719A One-Axis Differential Interferometer
- Agilent 10721A Two-Axis Differential Interferometer
- Agilent 10735A Three-Axis Differential Interferometer
- Agilent 10736A Three-Axis Differential Interferometer
- Agilent 10736A-001 Three-Axis Differential Interferometer with Beam Bender

For the interferometers listed below, a displacement count equals $\lambda/64$.

- Agilent 10702A Linear Interferometer
- Agilent 10766A Linear Interferometer
- Agilent 10705A Single Beam Interferometer

Deadpath counts is the deadpath length, “D”, in terms of counts. These counts have to be appropriate for the optics being used.

You must input the terms "Deadpath Counts" and "deadpath in selected units" with the correct conversion factor. These terms can be determined as follows:

For λ/256 Optics:

$$\text{Deadpath Counts} = \frac{4.0442888 \times 10^5}{\text{Initial TCN}} D$$

For λ/128 Optics:

$$\text{Deadpath Counts} = \frac{2.0221444 \times 10^5}{\text{Initial TCN}} D$$

For λ/64 Optics:

$$\text{Deadpath Counts} = \frac{1.0110722 \times 10^5}{\text{Initial TCN}} D$$

where D is the deadpath distance measured in *millimeters*.

The wavelength conversion factor is also dependent on which measurement optics are used.

For λ/256 optics:

$$\text{Wavelength Conversion Factor} = 2.4726175 \times 10^{-6} \frac{\text{millimeters}}{\text{count}}$$

For λ/128 optics:

$$\text{Wavelength Conversion Factor} = 4.9452351 \times 10^{-6} \frac{\text{millimeters}}{\text{count}}$$

For λ/64 optics:

$$\text{Wavelength Conversion Factor} = 9.8904902 \times 10^{-6} \frac{\text{millimeters}}{\text{count}}$$

The deadpath distance (D) need not be measured with precision. The error in measuring "D" simply shows up as an uncompensated deadpath (ΔD). This value would be much smaller than the error due to D.

The ability to correct for deadpath error in software does not eliminate the necessity of minimizing deadpath for proper location of the interferometer wherever possible. If the deadpath (D) is large compared to the distance traveled (L), then the predominant error is a zero shift due to uncertainty in determining the change in air wavelength and this error cannot be eliminated in software.

Minimizing Abbé error

Abbé offset errors occurs when the measuring point of interest is displaced from the actual measuring scale location and there are angular errors in the positioning system. A very important advantage of laser systems is that the Abbé error evident in almost all positioning systems is very easily reduced.

Abbé offset error will make the indicated position either shorter or longer than the actual position, depending on the angular offset. The amount of measurement error resulting from Abbé offset is:

Offset distance × tangent of offset angle

Figure 15-7 illustrates Abbé error and demonstrates the requirement for minimizing angular error and placement of the measurement path. In Figure 15-7(A), the measurement axis is coincident with the leadscrew centerline and is measuring a displacement of the carriage at the leadscrew. This figure illustrates the displacement error E which is generated at the measurement probe tip due to angular motion (θ) of the carriage. Figure 15-7(B) shows the same carriage motion as Figure 15-7(A) but with the measurement axis coincident with the probe path. In this case, the measurement system measures the actual displacement and there is no offset error.

NOTE

A helpful rule of thumb for approximating the error attributable to angular motion is that for each arcsecond of angular motion, the error introduced is approximately 0.1 micron per 20 mm of offset (5 microinches per inch of offset).

When considering a specific application, make every effort to direct the measurement path as close as possible to the actual work area where the measurement process takes place. In Figure 15-22, a machine slide is shown with the interferometer and retroreflector placed to minimize Abbé error. The measurement axis is placed at approximately the same level as the work table and is also measuring down the center of the machine slide.

MINIMIZE ABBÉ ERROR

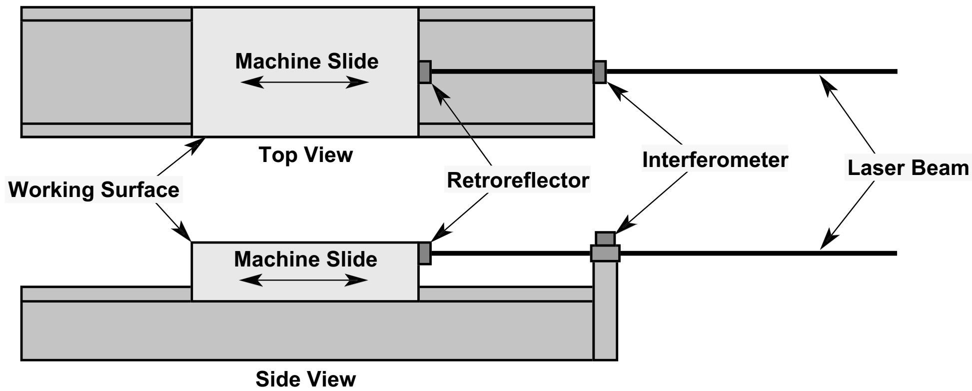

Figure 15-22. Positioning of measurement axis to minimize Abbé error

For X-Y stage applications, the laser system can minimize Abbé errors. Plane mirror interferometers used with plane mirrors, mounted at 90° to each other on the top edges of an X-Y stage, create a very accurate positioning system which eliminates Abbé error. Figure 15-23 shows a typical installation for an X-Y stage. The principal advantage of this type of positioning system is that the measurement in both X and Y axes takes place at the work surface plane. If there are angular errors in the cross slides of the stage, any displacement of the work surface due to these errors is measured by the laser.

X-Y STAGE MEASUREMENT

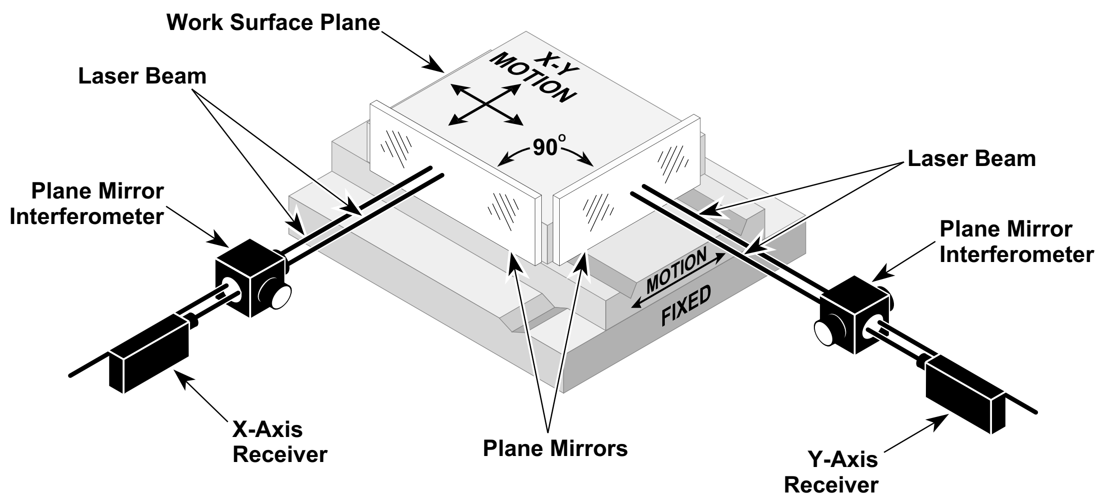

Figure 15-23. X-Y Stage measurement with Agilent 10706A Plane Mirror Interferometer

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