RENISHAW
apply innovation™

Environmental compensation of linear laser interferometer readings

by M.A.V. Chapman

Introduction

Laser interferometers are often assumed to automatically provide the ultimate in measurement accuracy. “It’s a laser, so the measurements must be accurate!” However, in reality, the situation is more complex. When measuring linear displacements in air with a laser, the performance of the environmental compensation system is particularly important. The laser and interferometric measurement optics provide very high levels of linear resolution and precision, but it is the environmental compensation unit, (weather station), that is primarily responsible for the system’s measurement accuracy. This paper discusses the importance of environmental compensation in linear interferometry and covers both air refraction and material expansion compensation. It describes in detail Renishaw’s XC-80 environmental compensation unit which automatically compensates the linear displacement readings from Renishaw’s XL-80 laser for variations in air refractive index and material temperature. It also provides advice about the placement of environmental sensors and the selection of material expansion coefficients, depending on the application.

Linear interferometry – the basics

Figure 1 shows a single frequency (homodyne) laser interferometer system with linear optics positioned close together at the “datum” position.

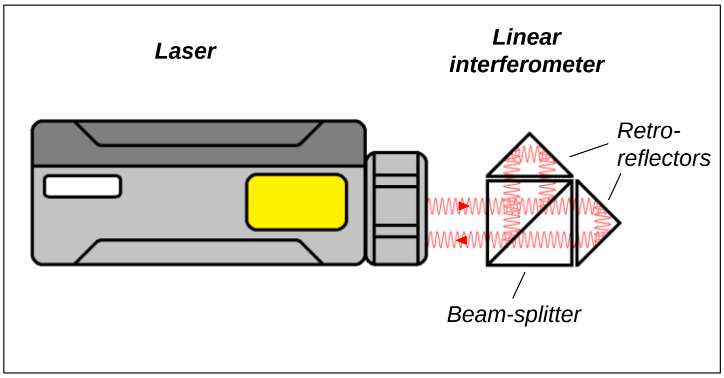

Figure 1

The output beam from the laser is split in two by the beam-splitter. The upper retro-reflector is fixed to the beam-splitter and forms the fixed length reference arm of the interferometer. The other retro-reflector is free to move and forms the measurement arm of the interferometer. The beams reflected by each retro-reflector are recombined at the beam-splitter and returned to the laser where they interfere inside the laser’s fringe detection unit. Whenever the waves in the two returned beams are “in phase”, (as shown in Figure 1), they constructively interfere, producing a “bright” fringe in the detector unit.

In Figure 2 the measurement arm retro-reflector has been moved a distance L away from the beam-splitter, whilst the reference arm retro-reflector has remained fixed to the beam-splitter. Whenever the waves in the two returned beams are 180° out of phase (as illustrated in Figure 2), they will destructively interfere, producing a “dark fringe” in the detector unit. Whether the fringe detector sees a bright or dark fringe (or any brightness level in between) will depend on the relative optical path lengths in the two arms of the interferometer. If the reference arm retro-reflector is fixed then, each time the measurement arm retro-reflector moves a half a wavelength (λ/2)* further away from the beam-splitter, the fringe detector will see a complete bright-dark-bright fringe transition.

**Note: A movement of λ/2 increases the total optical path by λ because the laser beam has to travel back and forth from the retro-reflector.*

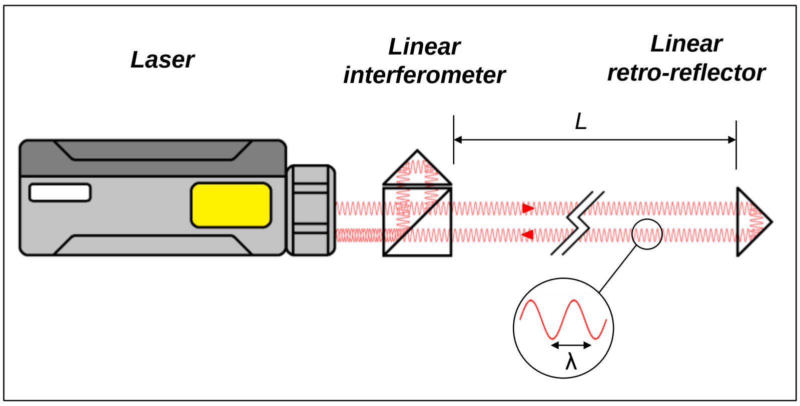

Figure 2

In simple terms* the laser system measures distance by counting the number of complete fringe transitions seen within the detector unit. If the counter is zeroed (datumed) when the optics are together, then the distance L is given by $L = \lambda \times N/2$, where N is the number of bright-dark-bright fringe transitions counted since datum. If the optics were together when the system was datumed, then N is also equal to the number of laser waves added into the outward and return beam path segments of the measurement arm of the interferometer as the optic moved.

** Note - In reality a homodyne laser's fringe detector unit is also able to subdivide the fringes into smaller increments and to determine the direction of travel. This is achieved using multiple fringe photo-detectors, each tuned to detect the brightness of different interference fringe phases.*

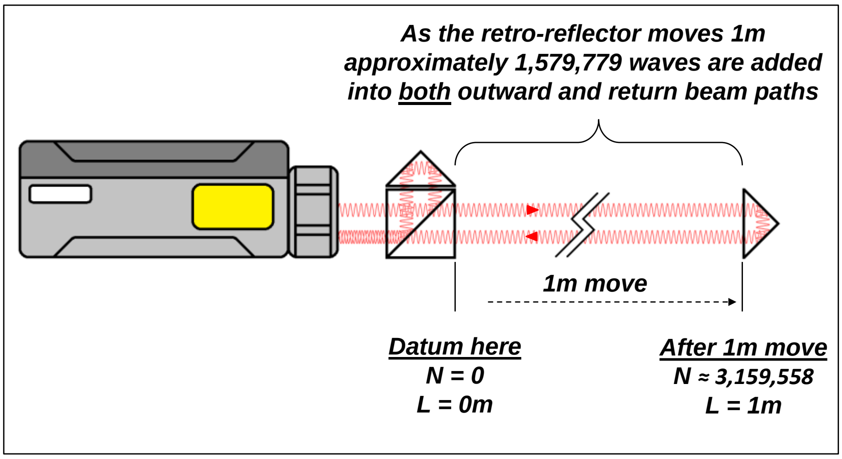

Figure 3

Consider the example shown in Figure 3. If the retro-reflector is moved a distance of 1m after datuming, and the laser wavelength is 0.633µm the counter will have reached a fringe count of approximately 3,159,558, which is equivalent to the number of laser waves that have been added into the gap between the beam-splitter and measurement arm retro-reflector as the reflector moved 1m.

If, for any reason, the number of laser waves in the measurement arm changes, the fringe counter will count up or down accordingly. Obviously this will happen if the measurement arm retro-reflector moves, causing N and the position readout L to change accordingly, correctly indicating any extra movement.

However, the number of waves that fit into the measurement arm also depends on the laser's wavelength in air. If the laser wavelength has altered, this will also alter number of waves that fit into the measurement arm. If the laser system continues to use the original wavelength to calculate distance, using $L = \lambda \times N/2$, the distance readout will be calculated incorrectly, producing an inaccurate reading. But why might the laser wavelength have altered?

Although it is often stated that "the speed of light is constant", in reality it varies depending on the medium it's travelling through. The higher the refractive index of the medium, the slower the speed at which light can travel through it. For example, the speed of light in glass (refractive index 1.4) is around 30% slower than in a vacuum (refractive index 1). As the speed of light changes, its wavelength also changes by a corresponding amount. Although the refractive index of air varies to a much smaller degree, the effect is large enough to seriously compromise the accuracy of linear laser measurements, unless wavelength compensation is applied.

The refractive index of air

Because of the importance of refraction in optical design and metrology, the refractive index of air has been extensively studied (see References 1-5). Figures 4, 5 and 6 show how variations in atmospheric pressure, temperature and relative humidity alter the wavelength of a red 0.633µm wavelength Helium Neon (HeNe) laser. The variations are shown in parts per million (ppm).

The refractive index of a vacuum is exactly 1. The refractive index of standard* air, as seen by a HeNe laser, is around 1.0002714. The laser's wavelength in standard air is therefore about 271ppm shorter than its vacuum wavelength. **Standard air is defined as air with a pressure of 1013.25 mbar, a temperature of 20°C, and a relative humidity of 50%.*

The graphs show how the laser's wavelength varies (in ppm) relative to the wavelength in standard air. (Standard air conditions are shown by the red dot on each graph). So for example, referring to Figure 4, at an atmospheric pressure* of 800 mbar, temperature of 10°C, and humidity of 50%RH a HeNe laser's wavelength will have increased by about +50ppm, relative its wavelength in standard air.

**Note that air pressure varies according to both the local weather conditions, and the altitude above sea level. For example, 1013 mbar is a typical sea level pressure, whereas 900mbar is typical pressure at an altitude of 1,000m.*

Figure 4 shows that the laser's wavelength depends on the air pressure with a range of sensitivities from -0.24 ppm/mbar to -0.29 ppm/mbar, depending on the temperature. As the air pressure rises, the laser's wavelength decreases. At conditions close to those of standard air, the sensitivity is about -0.27 ppm/mbar.

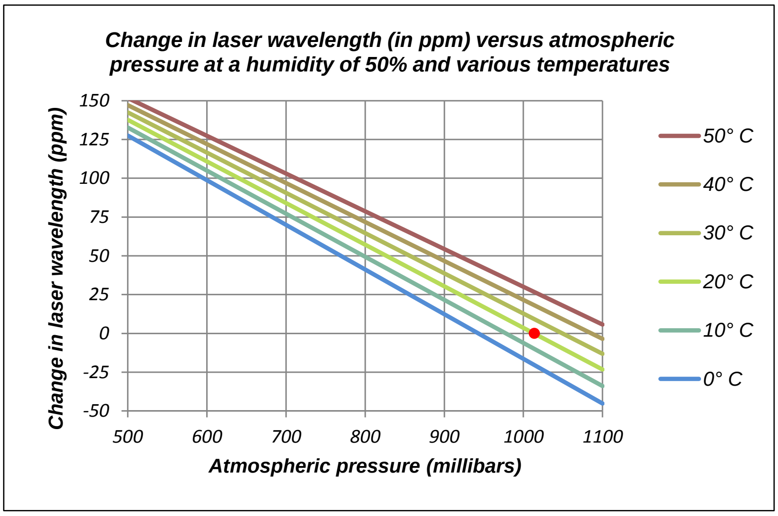

Figure 4

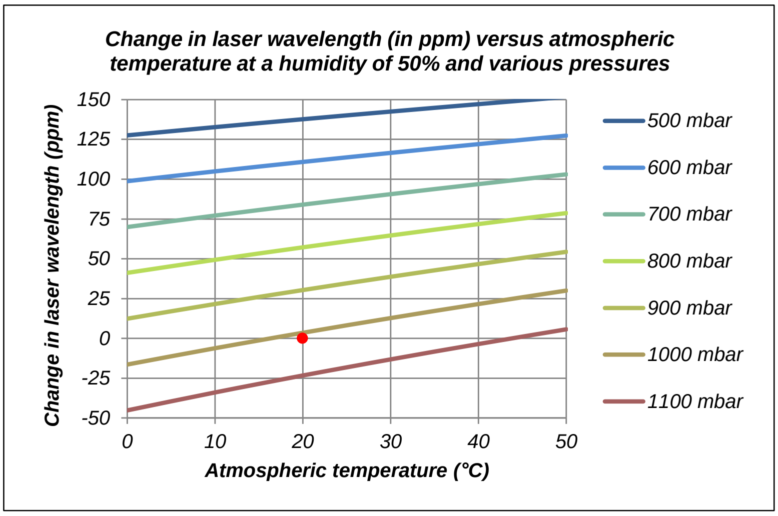

Figure 5

Figure 5 shows that the laser's wavelength also depends on the air temperature with a range of sensitivities from +0.5ppm/°C to +1.0ppm/°C, depending on the pressure. As the air temperature rises, the laser's wavelength increases. At conditions close to those of standard air, the sensitivity is about +0.96ppm/°C.

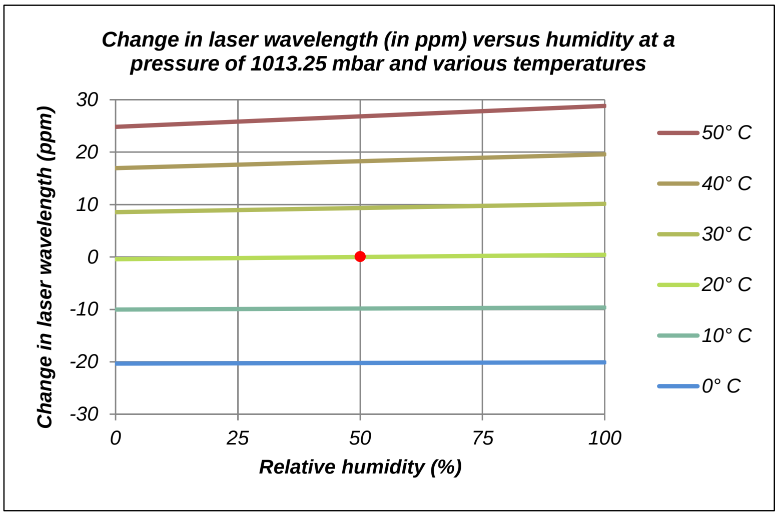

Figure 6

Figure 6 shows that the laser's wavelength also depends on the relative humidity with a range of sensitivities from +0.02 to +0.4ppm for every 10% rise in air humidity, with a strong dependence on the air's temperature. The sensitivity to variations in humidity is negligible at low temperatures but becomes increasingly significant at higher temperatures because warm air can absorb much more water vapour. The more water the air contains, the longer the laser's wavelength becomes. At conditions close to those of standard air, the sensitivity is about +0.1ppm/10%RH.

These graphs and sensitivities make it easy to roughly estimate* the potential laser measurement errors that can be caused by variations in local atmospheric conditions. **For a more accurate method refer to Appendix 2.*

Consider the following example.

Suppose the laser wavelength λ (which is used to calculate linear displacements using the equation L = λ × N/2) is defined at standard conditions and is not altered (i.e. no compensation is applied). Now suppose linear measurements are taken when the local air pressure is 900 mbar, the air temperature is 25°C and the humidity is 60%. The error in the uncompensated laser reading can be estimated using the inverse* of the sensitivities stated above. **The sensitivities above define how the laser wavelength changes with changes in air temperature, pressure and humidity. However, if the laser wavelength increases, the number of fringes counted (N) for a given movement will fall, hence the uncompensated laser reading will decrease.*

Error due to air pressure	-113.25mbar × (+0.27ppm/mbar)	-30.6 ppm
Error due to air temperature	+5°C × (-0.96ppm/°C)	-4.8 ppm
Error due to air humidity	+10% × (-0.1ppm/10%RH)	-0.1 ppm
	TOTAL ERROR	**-35.5 ppm**

Given that it is often taken for granted that linear measurements taken with a laser interferometer are accurate to around 1μm/m or 1ppm, ("it's a laser, so the measurements must be accurate!"), the above example makes it clear just how crucial it is to accurately compensate for air refraction effects to meet such accuracy expectations.

Air refraction compensation

As indicated by Figures 4, 5 and 6, the relationship between air temperature, pressure and relative humidity and the refractive index is quite complex. Fortunately this relationship has been studied extensively, and there are now several established equations that can be used to accurately estimate the refractive index of air if the temperature, pressure and humidity are known. The most well know of these was published in 1966 and is known as the Edlén equation (see Reference 2). This equation was updated in 1993 & 4 by Birch and Downs (References 3 & 4). An alternative equation was published by Ciddor in 1996 (Reference 1). Most laser systems use either the "Updated Edlén Equation" or the "Ciddor Equation" to calculate the air's refractive index. Under normal environmental conditions both equations offer similar levels of accuracy. A useful review of these equations and "refractive index calculators" can be found at NIST's Metrology Toolbox website (see Reference 5).

The complete equations are rather complex and beyond the scope of this paper. However, NIST's Metrology Toolbox provides a slightly lower accuracy, simpler, "pocket calculator friendly" version which can be used with 0.633µm HeNe lasers;

$$n_{air} = 1 + ((7.86e\text{-}5 \times P)/(273 + T)) - 1.5e\text{-}11 \times H \times (T^2 + 160)$$

Where n_{air} = air refractive index, T = air temperature in °C, H = % relative humidity and P = air pressure in mbar. This equation can be useful for estimating potential measurement errors over wider ranges of temperature, pressure and humidity than the sensitivities at conditions close to standard air, quoted above, will allow. This is described in more detail in Appendix 2.

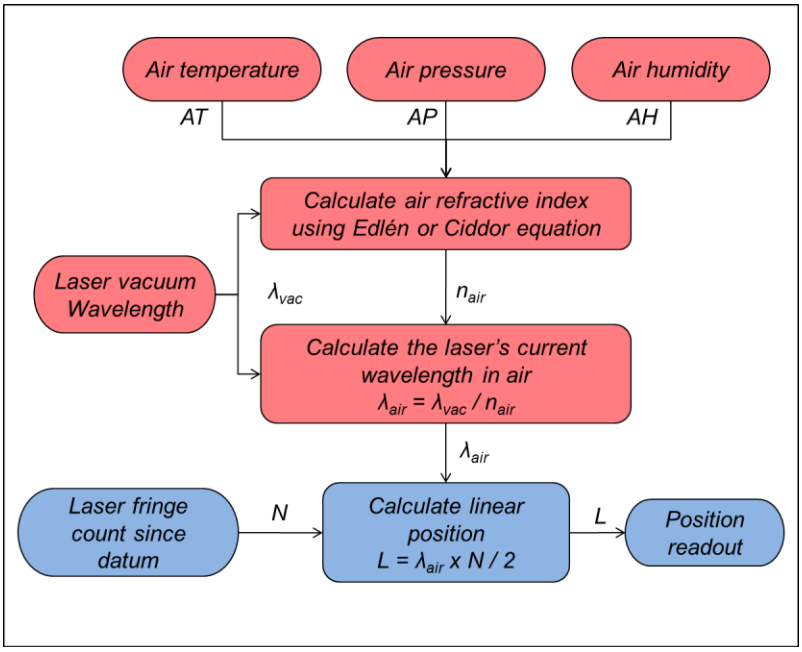

Figure 7

Figure 7 shows how the Updated Edlén or Ciddor equation can be used to compensate the laser reading for variations in the atmospheric conditions. The red coloured cells are associated with calculating the laser's current wavelength. The blue cells are associated with calculating the laser position readout.

Firstly, local values for air pressure, temperature and humidity are determined using sensors. The system uses these to calculate the air's refractive index n_{air} using the Edlén or Ciddor equation. Using n_{air} and the laser's vacuum wavelength λ_{vac} ,the system calculates an "environmentally compensated" laser wavelength, λ_{air}. Then, instead of multiplying the fringe count by a default laser wavelength λ, the system uses the environmentally compensated wavelength λ_{air}. Therefore, if the laser wavelength rises (for example), the fringe count N (for a given linear displacement L) will fall, but the value of λ_{air} calculated from the sensor readings should rise by a corresponding amount, so that the "environmentally compensated" position given by $L = \lambda_{air} \times N / 2$ remains nominally constant and accurate.

Automatic environmental compensation with XC-80

Renishaw's XL-80 Laser Interferometer System can automatically compensate linear readings for the effects of changes in local atmospheric conditions by using the XC-80 environmental compensation unit and sensors, shown in Figure 8. The XC-80 contains processing electronics, and the air pressure and relative humidity sensors. External air and material* temperature sensors are connected via cables. Figure 9 shows how the components are connected. **Note the use of material temperature sensors for thermal expansion compensation is covered later.*

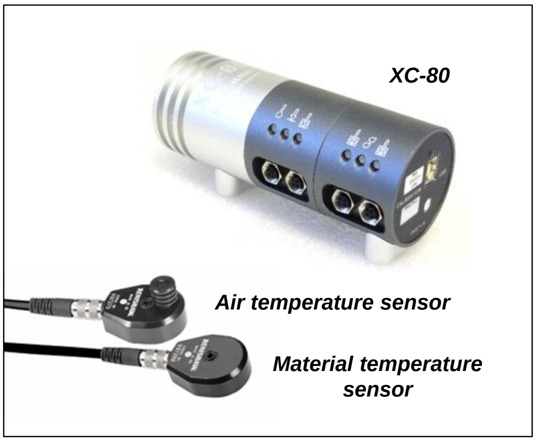

Figure 8

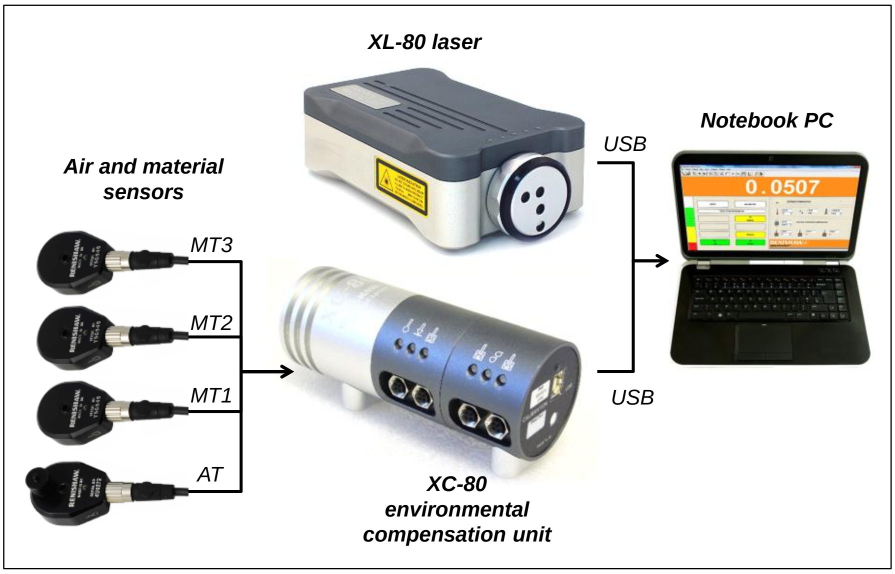

Figure 9

Each external material and air temperature sensor contains an analogue temperature sensing element and a digital processing unit. Every sensor is individually calibrated at the factory and contains an error map to ensure accuracy is maintained over the full measuring range. The analogue reading from the temperature sensing element is digitised and error corrected (using the error map) before being sent digitally over the sensor network to the XC-80. Digital transmission provides immunity to electrical noise and cable resistance, thereby ensuring data integrity and allowing sensor leads to be extended if necessary.

The XC-80 contains the error mapped air pressure sensor and a relative humidity sensor, and further digital processing electronics. One of the most demanding measurements is that of atmospheric pressure because of the accuracy required (±1 mbar) over a wide range of operating pressures (650-1150 mbar) and temperatures (0-40°C). Renishaw utilise very high quality pressure sensors to ensure long term stability and reliability. Every pressure sensor is individually calibrated at the factory against rising and falling pressures and temperatures (most commercially available pressure sensors are sensitive to temperature and show hysteresis). The results are used to produce a 3D error map which is stored inside the XC-80 to ensure accuracy is maintained over the full range of operating pressure and temperature.

Figure 10 shows an example error plot for an XC-80 pressure sensor, against both temperature and pressure, after error mapping. In this example the error ranges from 0 to ±0.32 millibars. *Note that this accuracy plot excludes the uncertainty of measurement of the calibration rig.*

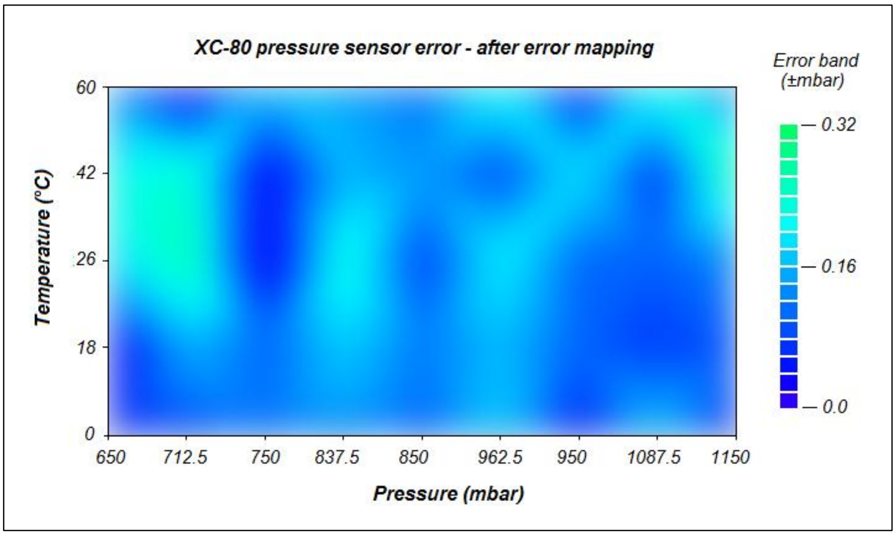

Figure 10

The XC-80's calibrated sensor accuracies are shown in the Table in Figure 11. All figures are quoted to an expanded uncertainty of K=2 (95% confidence level).

XC-80 measurement accuracies and ranges		
Measurement	*Accuracy*	*Range*
Air temperature	*±0.2°C*	*0 - 40°C*
Air Pressure	*±1 mbar*	*650 - 1150 mbar*
Air humidity	*±6% RH*	*0 - 95% non condensing*
Material temperature	*±0.1°C*	*0 - 55°C*

Figure 11

The XC-80 transmits the environmental sensor readings digitally to the PC over USB with an update rate of one sensor reading every 7 seconds, giving a complete environmental update (from up to 6 active sensors) every 42 seconds.

The PC also receives the laser status and fringe count, N, over USB from the XL-80 laser at a maximum update rate of 50KHz. Renishaw's LaserXL software uses the air sensor readings from XC-80 and the Ciddor equation to calculate the local air refractive index and hence the current XL-80 laser wavelength in air, λ_{air}. The distance L is then calculated using the equation $L = \lambda_{air} \times N/2$ thereby automatically compensating the laser reading for local variations in the refractive index of air.

The effectiveness of air refraction compensation with XC-80 is illustrated by considering a simple example. Suppose laser measurements are being taken at an altitude of 100m above sea level, where the local air temperature is 25°C and the relative humidity is 70%, and the sea level air pressure is 970mbar. There is nothing particularly extreme or unusual in these conditions.

The atmospheric pressure at an altitude of 100m will be about 12mbar below that at sea level, giving a local pressure of 958mbar. Using the simple NIST equation shows that the refractive index of air under these conditions (958mbar, 25°C, 70%RH) is about 1.0002519. Whereas, the refractive index of standard air (at which the default XL-80 laser's air wavelength is defined) is about 1.0002714. The fractional difference between these two refractive indices (and hence the associated laser wavelengths) is almost 20ppm. So, under these conditions, if environmental compensation is not carried out, the linear position readout would contain a measurement error of around 20ppm or 20µm/m.

However, if refractive index compensation is correctly applied, using the air sensor readings from XC-80, the system's linear measurement error will fall below 0.5ppm (0.5µm/m). An improvement in accuracy of around 40 times! The difference between these uncompensated and compensated accuracies is shown graphically in Figure 12. It's interesting to note that the dominant source of error in the uncompensated results is atmospheric pressure (due to the combined effects of the altitude and the weather). The second most significant source of error is the air temperature. The most insignificant error is the laser frequency accuracy. This clearly illustrates just how important environmental compensation is. Note that the accuracy improvements shown in Figure 12 assume that the sensors are suitably positioned and have had time to respond to any changes in the environment. Automatic environmental compensation is not a "universal panacea" which allows accurate measurement irrespective of the environment. For best results it is important that the environment is reasonably stable and the sensors have been positioned in the vicinity of the measurement laser beam and away from localised heat sources etc.

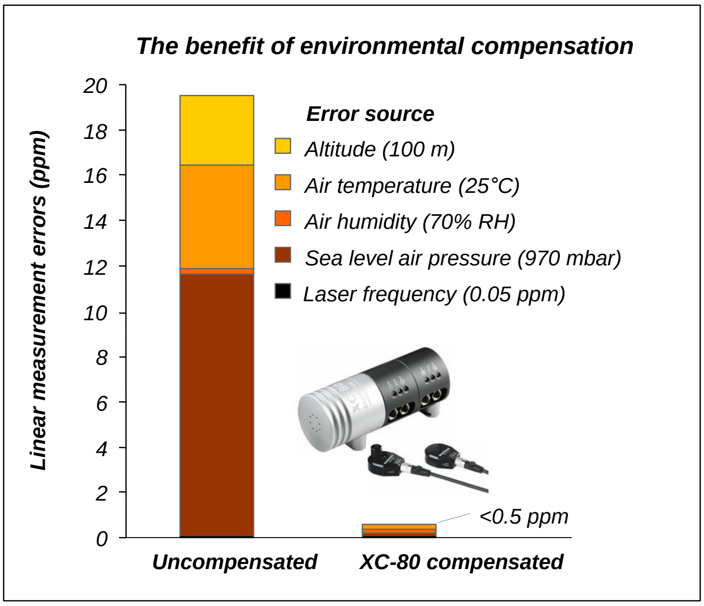

Figure 12

For reference, the table in Figure 13 shows the reduction in air pressure and refractive index with increasing altitude above sea level. It also shows (in ppm) the change in laser wavelength this induces, relative to the wavelength at sea level. Day to day/seasonal atmospheric pressure variations due to the weather are typically 100-150millibars. These will cause an additional variation in laser wavelength of around 25-40 ppm.

Variation in air pressure and refractive index with altidude above sea level (at 20°C and 50%RH)			
Altitude (m)	Pressure (mbar)	Refractive index n	Change (ppm)
0	1013.25	1.0002714	0
500	954.6	1.0002557	-16
1000	898.7	1.0002407	-31
1500	845.6	1.0002264	-45
2000	795.0	1.0002128	-59
2500	746.8	1.0001999	-71
3000	701.1	1.0001877	-84
3500	657.6	1.0001760	-95
4000	616.4	1.0001649	-106
4500	577.3	1.0001544	-117
5000	540.2	1.0001445	-127

Figure 13

Material expansion compensation

Most engineering materials, components and machines will expand or contract with changes in temperature. Therefore the dimensions of high precision engineering components, machine tools and CMMs are usually defined at a specific reference temperature. The international reference temperature used by the calibration community is 20°C (68°F).

However, when dimensions are being checked, (for example with a laser interferometer system), it is often the case that the temperature is not 20°C. One way to avoid this problem is to take the item being checked into a 20°C temperature controlled room. However, in many cases this is impractical and the dimensions have to be measured "in situ". In order to handle this, Renishaw's XL-80 laser interferometer system includes the facility to compensate the linear readings using a manually entered material expansion coefficient and the temperature from up to three material temperature sensors. This process is called material expansion compensation. The objective of the process is to estimate the linear laser readings that would have been obtained if the measurements had been carried out at the international reference temperature of 20°C.

Suppose the laser is being used to verify the accuracy of a 0.5m long linear encoder which is made of glass with a linear expansion coefficient of 6ppm/°C, as illustrated in Figure 14. The accuracy of the linear encoder is specified as being within ±1μm over its full length at a temperature of 20°C. However, the encoder is fitted inside a machine that cannot be moved and the encoder's temperature is currently 22°C. The linear encoder (if unconstrained) will therefore have expanded by 0.5m × 6ppm/°C × 2°C = 6μm over its full length. If the laser system is used to check the encoder's accuracy <u>without applying material expansion compensation</u>, the results will appear to show that the encoder's accuracy (as shown by the red line in Figure 15) is outside specification.

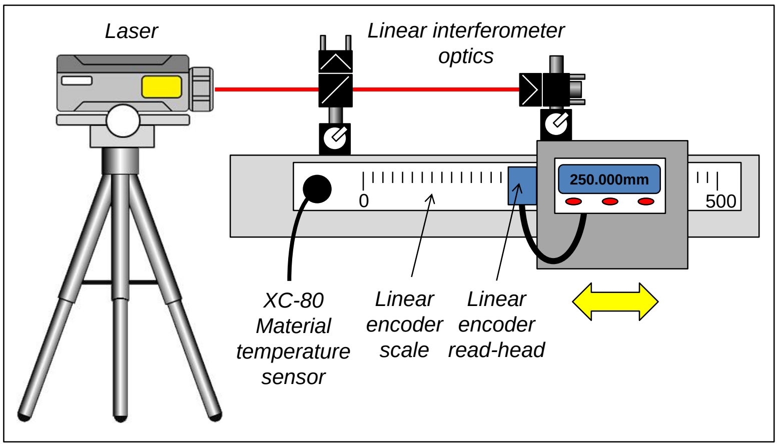

Figure 14

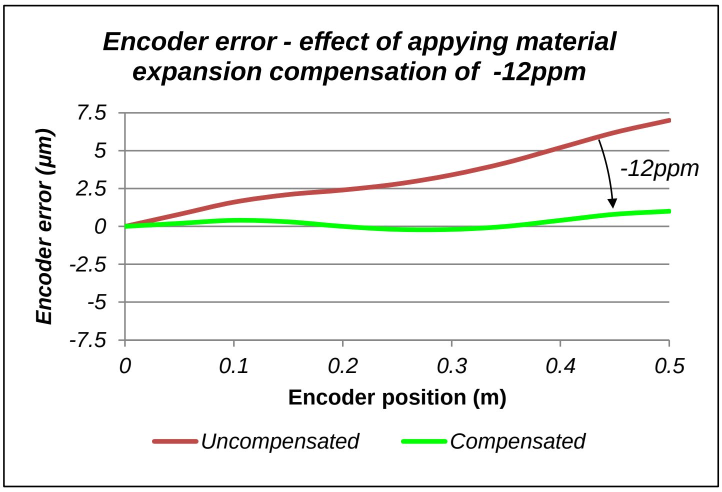

Figure 15

However, if a Renishaw XC-80 environmental compensation unit with a material temperature sensor is used to measure the encoder's temperature, and a linear expansion coefficient of 6ppm/°C is entered into the software, the system will automatically apply material expansion compensation. If the material temperature is measured as 22°C, then the system will apply a correction to the laser readout data of -6ppm/°C × 2°C = -12ppm. So, for example, if the uncompensated laser reading is 500.007mm, a correction of -6μm will be applied to give compensated laser reading of 500.001mm. If applied correctly, material expansion compensation adds an equal and opposite correction which cancels out the thermal expansion of the encoder, thereby giving a good estimate of what the laser measurement would have been if the encoder had been measured at 20°C. The corrected data is illustrated by the green line in Figure 15, which now shows the encoder is just within specification.

Figure 16 shows how material expansion compensation is applied. The red coloured cell is the result of calculating the laser's current wavelength (refer back to Figure 7). The yellow cells are associated with calculating the material expansion compensation. The blue cells are associated with calculating the laser's position readout. Note that instead of multiplying half the fringe count, N/2, by λ_{air} (as shown in the blue cells in Figure 7) the system now uses an "environment factor" EF (as shown by the blue cells in Figure 16). This environment factor is very similar to the laser wavelength, λ_{air}, except it contains a small adjustment to compensate for material expansion. Multiplying N/2 by EF therefore provides compensation for both air refraction and material expansion effects.

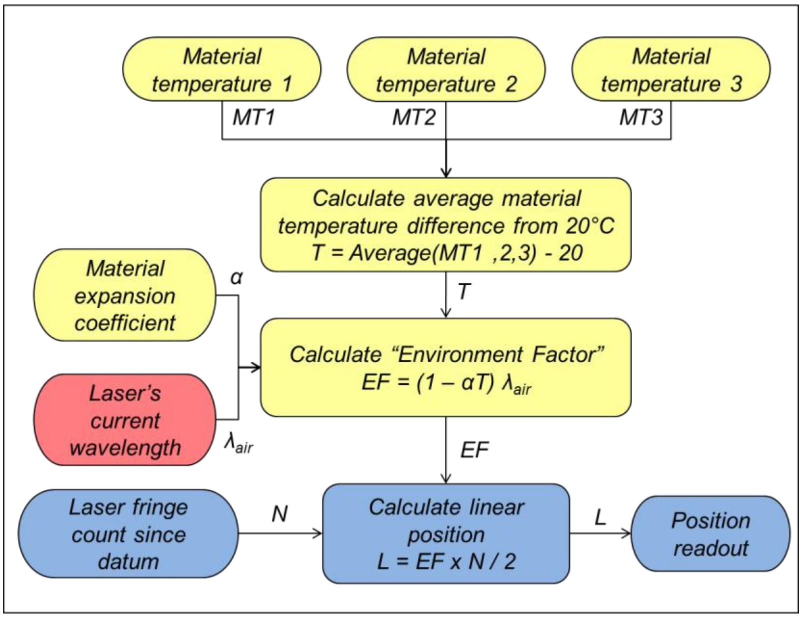

Figure 16

The expanded equation, which applies both air and material expansion compensation to linear laser readings can therefore be written as;

$$L = (1 - \alpha T) \times \lambda_{air} \times N / 2 \quad \text{..........Equation 1}$$

Where L is the laser readout, N is the number of laser fringes counted since the system was datumed, α is the material expansion coefficient entered by the user, T is the difference between the average material temperature and 20°C, and λ_{air} is the current air refractive index calculated using the Edlén or Ciddor equation from the air temperature, pressure and humidity.

Material expansion coefficients

Material expansion compensation can have a significant effect on measurement accuracy. The linear expansion coefficients of most steels are close to 10ppm/°C and machine shops are often above 25°C (and the machines themselves are usually warmer still). If linear measurements are carried out under such conditions, the errors due to material expansion can easily exceed 50ppm (50µm/m). This section gives advice on the selection of the coefficient of material expansion with particular emphasis on the measurement of the positioning accuracy of machine tools.

It is important to select the correct coefficient of expansion during linear laser measurements, particularly if the material temperature is not close to 20°C. For example, if the true expansion coefficient is 5ppm/°C but a value of

Material	Application	Expansion coefficient (ppm/°C)
Iron/steel	Machine structural elements, rack and pinion drives, ballscrews	11.7
Aluminum alloy	Lightweight CMM machine structures	22
Glass	Glass scale linear encoders	6-11
Granite	Machine structures and tables	8
Concrete	Machine Foundations	12
Invar	Low expansion encoders/structures	<2
Zerodur glass	"Zero" expansion encoders/structures	<0.2

Figure 17

6ppm/°C is entered in the software, then an additional measurement error of 1ppm will be incurred for every 1°C the material temperature is away from 20°C. When calibrating a machine tool or an XY stage's positioning accuracy, the expansion coefficient of the axis feedback system is usually required and is ideally taken from the manufacturer's data. If this is not available, Figure 17 shows a table of typical expansion coefficients for a variety of materials used in construction of machine tools, XY stages, and their position feedback systems.

Notes:

1) When trying to identify the expansion coefficient, care needs to be taken where there are two materials with different coefficients fixed together. For example, in the case of a rack and pinion feedback system, the expansion coefficient may be closer to the cast iron rail to which the rack is fixed. In the case of large gantry machines with floor mounted rails, the expansion coefficient of the rail may be reduced by the restraining action of the concrete foundations.

2) Expansion coefficients of materials can vary with composition and heat treatment. It is therefore often difficult to obtain a highly accurate value. The accuracy of this coefficient becomes increasingly important the further away from 20°C the calibration is being performed. If an accurate coefficient is not available, then measurement errors can be reduced by calibrating at a temperature close to 20°C.

3) If a machine is always used to process work-piece materials with significantly different expansion coefficients to those of the feedback system, (for example, aluminium alloys, carbon composites, ceramics, flat panel glass substrates, silicon wafers etc.), it may be beneficial to use the expansion coefficient of the work-piece and not of the machine feedback system. Although this will not give a calibration that represents the performance of the machine at 20°C, it can improve the accuracy of the work-pieces when they are returned to 20°C for measurement. This topic is covered in more detail under Objective 4 in the next sub-section.

Sensor location

This section gives advice on the placement of environmental sensors.

Air temperature sensor - Locate the air temperature sensor close to the measurement arm laser beam, ideally about halfway along it. Avoid placing it in warm air plumes rising from motors, power supplies etc., or in direct sunlight.

Air pressure & humidity - These sensors are both located inside XC-80 which should be placed horizontally, with a height difference of no more than 3m to the measurement laser beam.

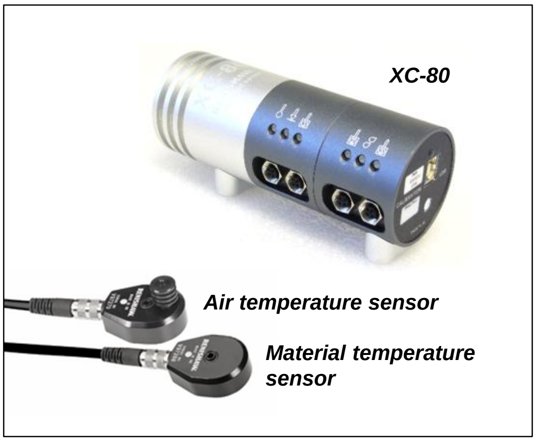

Figure 18

Material temperature sensors - The topic of where to put material temperature sensors on a machine tool during laser calibration is often the subject of some debate. The first step is to decide on the primary objective for performing material expansion compensation. This is typically one of the four objectives described in ASME B89.1.8-2011 Appendix C (see Reference 6) and as shown on the following table;

Objective 1	To perform a calibration in accordance with a National or International Machine Acceptance Standard.
Objective 2	To estimate the linear positioning accuracy that would be obtained if the machine was operated in an ambient environment of 20°C
Objective 3	To estimate the linear accuracy that the machine feedback system could achieve, if the feedback system was at a temperature of 20°C
Objective 4	To estimate the accuracy of parts that the machine can produce, when those parts are returned to 20°C for inspection

The differences between these objectives are often significant, particularly if the machine's position feedback system gets hot during machine operation (for example a ball-screw), or if the work-piece expansion coefficient is significantly different from that of the position feedback system, (for example, an aluminium work-piece on a machine with glass scale linear encoders). The following paragraphs make recommendations about material temperature sensor placement and material expansion coefficient selection, depending on the objective selected.

Objective 1 - To calibrate the accuracy of the machine in accordance with a National or International Standard. The procedure defined in the standard should be followed. This should cover where to place the material sensor, what expansion coefficient to use, and what machine warm up cycle to perform. If a thermal drift test is also defined in the Standard, this should also be included.

Objective 2 - To estimate accuracy of the machine if it was operated in 20°C environment. This is often the objective during machine build, sign off, commissioning or recalibration. This Objective is, in many cases the same as Objective 1. To meet this objective, the material temperature sensor(s) should be placed on the table of the machine or on some other massive part of the machine structure that is NOT close to any sources of heat such as motors, gearboxes etc. The material expansion coefficient should be set to that of the feedback system. Note: It is a common misconception that material sensors should always be placed on the ball-screw, or feedback system. Whilst this is true for Objective 3, it is often not the case for Objective 2, as the following example illustrates.

Suppose a machine is being calibrated in a shop at 25°C but, because of heat generated by machine operation, the ball-screw is 5°C warmer, at 30°C. If the material sensor is placed on (or very close to) the ball-screw, the laser readings will be compensated to estimate the readings that would have been obtained if the ball-screw was operating at 20°C. However, if the machine was being operated in an environment at 20°C, the ball-screw would NOT be at 20°C. The heat generated by operation of the screw and the motor would still be there, so the ball-screw temperature would still be about 5°C warmer than ambient (i.e. 25°C). Putting the material sensor on the ball-screw will therefore result in over compensation. It is better to place the sensor on a massive part of the machine to give a temperature reading related to the average ambient temperature around the machine over the last few hours.

Objective 3 - To estimate accuracy of machine feedback system if it was at 20°C. This is particularly useful for diagnosing faults in the machine's position feedback system. Perhaps the machine has failed calibration against Objective 1 or 2, and the accuracy of the feedback system at 20°C now needs verifying. To meet this objective the laser beam should be aligned as close to the axis of the feedback system as possible (to minimize Abbe offset error). If there is an Abbe offset, then the axis pitch and or yaw should also be checked. The material temperature sensor(s) should be placed on (or very near to) the feedback system and the expansion coefficient should be set to that of the feedback system.

Objective 4 - To estimate the accuracy of parts that the machine can produce, when those parts are returned to 20°C for inspection. This procedure is particularly useful for optimising the dimensional accuracy of machined parts produced in non-temperature controlled shops, where machine position feedback system and work-piece expansion coefficients differ significantly. The material thermal expansion coefficient should be set match that of the work-piece material. The material temperature sensor(s) should be located to measure a temperature similar to that expected of the work-piece. (This is often on the table of the machine, but other factors like the type of coolant system employed and the metal removal rates may need to be considered). Care should also be taken to perform this type of calibration under typical conditions, and it can only be truly effective if the temperature and expansion coefficients of the various work-pieces are relatively consistent.

Other precautions - Be careful to ensure there is good thermal contact between the material temperature sensor and the material being measured. Flat, bare material surfaces are best.

If the air and machine temperatures are significantly different, then it is also likely that there are significant temperature differences between material surface and core temperatures. Under these circumstances care should be taken to locate the material temperature sensors where they will measure the core temperature.

Machine tool temperature will often rise during operation. It is recommended to perform a warm up sequence of moves before calibration starts, so that this effect is included.

Dead path errors

In order for Equation 1 (see page 10) to effectively compensate linear measurements taken in unstable environments, it is important that N (the fringe count) nominally reflects the separation between the optics in the measurement arm of the interferometer. For example, if the separation doubles, then N should nominally double too, and when N=0 the optics should be close together. This is easily achieved if the laser is datumed (i.e. N is set to 0) when the optics are close together.

If linear optics are not close together when the laser system is datumed, and the environment subsequently changes, then the laser reading will show a small drift in the datum position. This drift often comprises of two components, an air dead path error and a material dead path error.

Air dead path error

Consider the example shown by Figure 19. Suppose the laser system is datumed where the encoder readout is 0.000mm, but with a “dead path” separation D between the measurement arm optics. At this position N = 0 and the laser position readout will therefore also be 0.000mm. Now suppose the air’s refractive index changes by +1ppm. This will cause the laser wavelength to shorten by 1ppm causing a 1ppm increase in the number of waves that fit into the gap D between the measurement optics. The fringe count N, will increase accordingly, and the laser’s position readout will drift away from zero by 1ppm $\times$ D. This is referred to as an “air

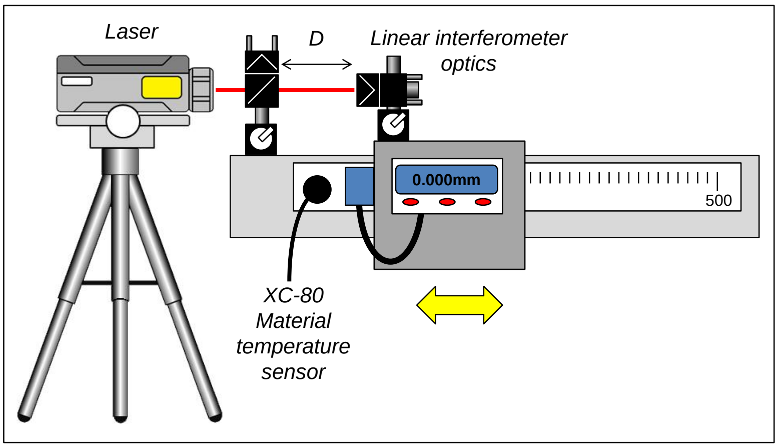

Figure 19

dead path error". Even if the environmental compensation unit has correctly calculated the laser's new wavelength, the air refraction compensation will barely have any effect since N is almost zero (instead of being $2D/\lambda_{air}$). Effectively, the system doesn't "see" that there is extra air in the measurement arm and hence doesn't compensate for changes in the wavelength of the laser in that portion of the beam.

The general equation for the Air Dead Path Error is as follows;

$$E_{ADP} = D \times (\lambda_{air} - \lambda_0) / \lambda_0$$

Where E_{ADP} is the air dead path error, D is the separation between the optics at datum (i.e. the dead path), λ_{air} is the current laser wavelength, and λ_0 was the laser wavelength when the system was datumed. Using this equation and assuming changes relative to standard air, it is possible to estimate the dead path error, per metre of air dead path, as follows.

0.27µm error per mbar change in air pressure since datum.

0.96µm error per °C change in air temperature since datum.

0.1µm error per 10% change in relative humidity since datum.

This makes it clear that air dead path errors are typically quite small and, if the measurement arm optics are positioned such that D is less than 10mm when the system is datumed, the air dead path error is negligible.

Note that some laser systems have software that allows the user to manually enter the air dead path and the software will then make an additional correction. Renishaw's LaserXL software doesn't allow this for two reasons.

1) There is a risk of the user getting the sign convention wrong. Depending on the direction sense of the movement and the arrangement of the optics, the dead path may need to be entered as a positive or negative value. If the sign is entered incorrectly the error will be doubled instead of removed.

2) It is good metrology practice to fix the optics closely and directly to the points of interest thereby minimising extraneous air and material "dead" paths. Indeed material dead path errors are typically much more important as the next section shows. Not providing a software correction therefore encourages good metrology practice.

Material Dead Path Error

Consider again the example shown by Figure 19. The laser system is again datumed where the encoder readout is 0.000mm, and with a "dead path" separation D between the measurement arm optics. At this position N = 0 and the laser position readout will again be 0.000mm. Now suppose the temperature of the machine changes by +1°C and suppose the material has an expansion coefficient of around 10ppm/°C. This expansion will cause the measurement arm optics to move further apart by roughly 10ppm × D causing a 10ppm increase in the number of waves that fit into the gap D between the measurement optics. The fringe count N, will increase accordingly, and the laser's position readout will drift away from zero by 10ppm × D. Note that this "material dead path error" is 10 times larger than the air dead path error produced by a 1°C change in air temperature. Even if the environmental compensation unit has correctly calculated a new environment factor EF, applying material expansion compensation will barely have any effect since N is almost zero (instead of being 2D / EF). Effectively, the system doesn't "see" that there is extra material in the measurement arm and hence doesn't compensate for its thermal expansion or contraction.

The general equation for Material Dead Path Error is, $E_{MDP} = D \times \alpha \times T$

Where E_{MDP} is the material dead path error, D is the separation between the optics at datum (i.e. the dead path), α is the linear coefficient of expansion of the material in the dead path, T is the change in temperature of the material since the system was datumed. For example, if the material expansion coefficient is 10ppm/°C, the dead path error is, 10µm per metre of material dead path, per °C change in material temperature since datum.

This makes it clear that material dead path errors are potentially much more significant than air dead path errors. Because the materials in the "dead path" may not be the same as the item being measured and their temperatures may vary independently, simple software correction is not practical. The best approach is to apply good metrology practices, i.e.

- minimise the material dead path by fixing optics closely and directly to the point of interest
- minimise any changes in material temperature during measurement by stabilising the temperature and/or completing the measurements swiftly.
- minimise the optics separation when the system is datumed by using a reading preset or by using the beam-splitter as the moving optic, as described in the next two sections.

Elimination of deadpath by presetting the laser reading

Consider a variation on the setup shown in Figure 19. This time the reference (or zero position) of the linear encoder is located at the far end, as shown in Figure 20. However, because of access limitations, the laser and optics cannot be rearranged. In order to handle circumstances like this (where the machine or encoder zero doesn't coincide with the position where the laser's optics are close together) the material and air compensation equation used in Renishaw's LaserXL software contains an extra "preset" term.

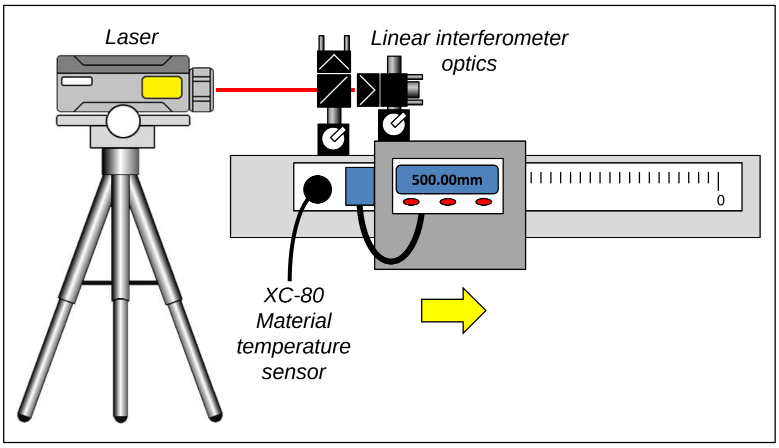

Figure 20

$$L = P + ((1 - \alpha T) \times \lambda_{air} \times N / 2) \text{ ....Equation 2}$$

Where P is a user entered "Preset" that allows the linear laser reading to be offset by a specified amount. Note that the preset is not compensated, it is simply a fixed offset that is added to the compensated laser position before it is displayed.

In the example shown in Figure 20, the correct way to datum the laser and apply the preset is as follows;

1. Move the carriage to the 500mm position of the encoder.
2. Adjust the optics mounts so that the optics are close together as shown in Figure 20.

3. Check the sign convention of the laser reading matches that of the encoder.

4. Datum the laser system. Thus satisfying the requirement the optics are close together when the laser was datumed. *Note: The laser reading will now be 0.000mm and the encoder reading is 500mm.*

5. Move the carriage to the reference or zero position of the encoder. *Note: the encoder reading will now be 0.000mm, and the laser reading will be about -500mm.* (*For example let's assume it's -500.0011mm)*.

6. Enter a preset into the laser software to make the laser and encoder readings agree. *(In this example the user should enter a preset of +500.0011 into the laser software. The laser reading will then jump to 0.0000mm to agree with the encoder readout).*

7. Start calibration. Compensation for any further changes in the environment will now be correctly applied, thereby avoiding the air and material dead path errors that could have arisen if the laser had been datumed with the optics 500mm apart.

Elimination of deadpath by swapping the optics

Another way to datum the system with the optics close together, when the axis zero or reference position is located at the far end away from the laser, is to swap the moving and stationary optics over, as illustrated in Figure 21. In this setup the beam-splitter optic (instead of the retro-reflector) is fixed to the moving carriage, and the retro-reflector is fixed at the far end of the bed. Figure 21 shows the carriage at the datum position with the optics close together, thereby eliminating the air dead path. (However, in this illustration the offset between the optics fixing points and encoder read-head and encoder zero position have increased slightly, which could introduce some material deadpath errors if the temperature changes and the machine bed and moving carriage expand differently). Note that on longer axes (over 10 metres), this arrangement can be more difficult to align because, due to optical manufacturing tolerances, the output beam from the beam-splitter may not be exactly parallel to the input beam.

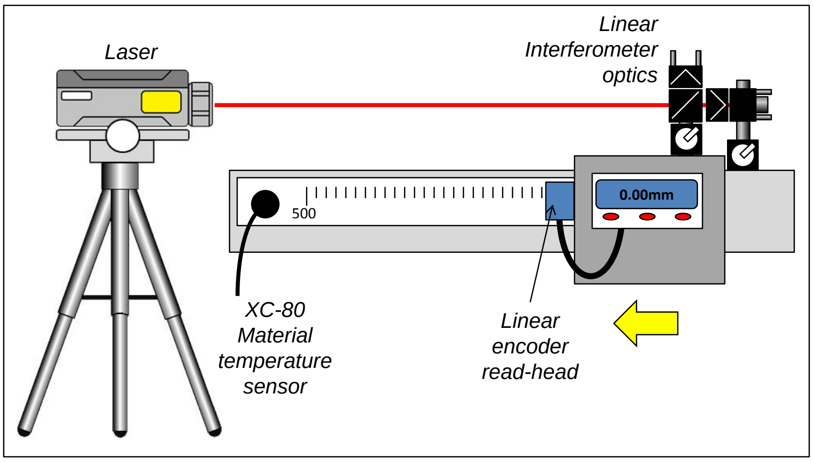

Figure 21

Conclusion

This paper has explained the importance of air refraction and material expansion compensation in ensuring the accuracy of linear laser interferometer measurements. It has detailed the potential errors associated with uncompensated changes in air temperature, pressure and humidity and material expansion. The operation of Renishaw's XC-80 environmental compensation system has been explained and advice provided on how the system is best utilised. For further reading please refer to the References and Appendices below. Appendices 1& 2 provide brief details of alternative methods of environmental compensation. Appendix 3 explains why environmental compensation is not usually required for interferometric angle and straightness measurements.

Appendix 1 – Environmental compensation – alternative methods

This paper has described the use of Renishaw's XC-80 Environmental Compensation Unit to provide automatic air refraction and material expansion compensation. This Appendix gives brief details of some alternative methods.

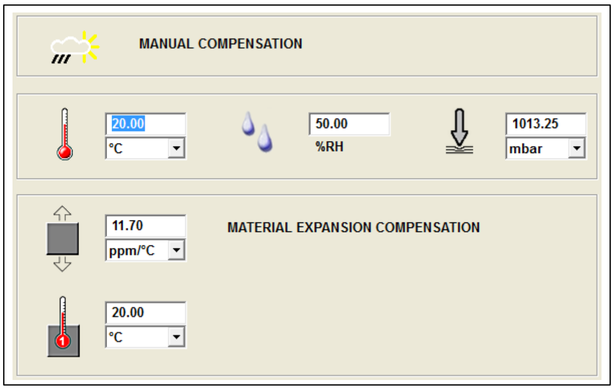

Figure 22

Manual Compensation – If suitable environmental data is available, Renishaw's LaserXL software (see Figure 22) allows the manual (keyboard) entry of air temperature, pressure and humidity as well as a material temperature and an expansion coefficient. Each time the user keys in new environmental data, the compensation applied to the laser reading will be updated. The disadvantage of this approach is that it is not practical to update the compensation frequently, and so is only suitable for stable environments. The advantage of Renishaw's XC-80 system is that the compensation is automatically updated with a new sensor reading every 7 seconds. The XC-80 system also provides all of the sensors needed with suitably high accuracy levels in a compact package.

Air Refractometers – Air refractometers are highly specialised instruments that measure variations in the refractive index of air directly. They typically contain a highly stable, fixed length reference cavity often made of zero expansion glass with mirrors on each end. Changes in the number of laser waves that fit in the cavity are measured directly with a plane mirror linear interferometer. The air in the cavity is at the same temperature, pressure and humidity as the immediate surroundings. There are two basic types. *Tracking refractometers* which only measure variations in refractive index and *Absolute refractometers* which can measure the absolute refractive index and any variations. Refractometers can very quickly determine the variations in refractive index to high accuracy, but they are expensive and cumbersome and require another laser beam for the interferometer. They are typically only used in standards laboratories and in laser position feedback systems within the semiconductor wafer processing machinery. Their response time is much faster than conventional temperature, pressure and humidity sensors can provide. However, this can increase noise in the compensated laser readings as localised variations in air refractive index in the vicinity of the refractometer are immediately applied to the full length of the linear measurement. The slower response of conventional sensors can provide a useful damping in the compensation process as they don't respond to sudden localised changes. Renishaw's laser system does not support environmental input from refractometers.

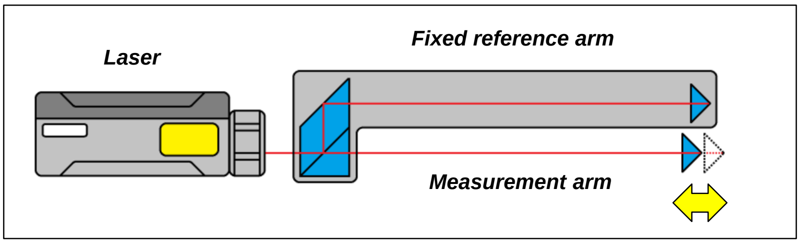

Figure 23

Balanced optical designs - If the optics cannot be located close together when the system is datumed, then a balanced optical layout can be considered. If the reference and measurement arms of the interferometer are similar lengths and exposed to the same air, then changes in the air's refractive index will affect both arms equally. Figure 23 shows one possible arrangement. Instead of a conventional linear beam-splitter the system uses an angular interferometer periscope, to produce parallel reference and measurement laser beams. The long reference arm is either supported on invar (for thermal stability) or on another part of the machine to form a local reference of similar path length to the measurement arm.

Measurement in a controlled environment – If measurements are made in a highly controlled environment then environmental compensation may not be needed. Possibilities include

- measurement in a vacuum
- measurement in air at controlled temperature, pressure and humidity

Appendix 2 - Use of the NIST air refraction equation

As mentioned earlier, NIST's Metrology Toolbox provides a simpler, very slightly lower accuracy, "pocket calculator friendly" alternative to the Edlén and Ciddor equations which can be used with 0.633µm HeNe lasers;

$$n_{air} = 1 + ((7.86e\text{-}5 \times P)/(273 + T)) - 1.5e\text{-}11 \times H \times (T^2 + 160)$$

Where n_{air} = air refractive index, T = air temperature in °C, H = % relative humidity and P = air pressure in mbar. Although this equation is not as accurate as the modified Edlén or Ciddor equations, NIST state that the accuracy should be within ±0.15ppm over 0-35°C, 500-1200 mBar, 0-100% RH with a CO_2 level of 450ppm ±150ppm.

This equation is therefore very useful for estimating environmental compensation errors over a wide range of temperatures, pressures and humidities. Alternatively it can be used to apply air refraction compensation to uncompensated laser readings, as follows;

If air refraction compensation is not applied, Renishaw's laser software will assume that linear laser measurements are being taken in "standard air" with a pressure of 1013.25 mbar, a temperature of 20°C, and a relative humidity of 50%.

Substituting these conditions into the NIST equation gives a refractive index for "standard air".

$$n_{standardair} = 1 + ((7.86e\text{-}5 \times 1013.25)/(273 + 20)) - 1.5e\text{-}11 \times 50 \times (20^2 + 160) = 1.00027139$$

However, if laser measurements are actually being taken in air under different conditions of P, T and H, the current air's refractive index is given by;

$$n_{air} = 1 + ((7.86e\text{-}5 \times P)/(273 + T)) - 1.5e\text{-}11 \times H \times (T^2 + 160)$$

The uncompensated linear laser readings (L) can then be "compensated" by multiplying by the ratio between the two refractive indices using the following equation.

$$L_{compensated} = L_{uncompensated} \times n_{standardair} / n_{air} = L_{uncompensated} \times 1.00027139 / n_{air}$$

NB. The above equation does not make any correction for air dead path errors which may occur in unstable environments if the optics are not datumed whilst close together.

Appendix 3 – Environmental compensation of interferometric angle and straightness measurements

Straightness interferometry – Figure 24 shows a schematic diagram of straightness optics. As can be seen from the figure, the laser beams in arms 1 and 2 of the interferometer are virtually the same length. Therefore any changes in air refractive index affect both arms to virtually the same degree. There is a small imbalance when measuring a large straightness error, and this gives rise to some sensitivity to variations in air refractive index. However, the maximum expected change in refractive index is about 155 ppm (refer to Figures 4,5 & 6) which is equivalent to 0.015%. This is insignificant compared to the specified measurement accuracy of Renishaw's straightness optics which is 0.5% (short range optics) or 2.5% (long range optics) and equates to an error of only 0.15μm when measuring a straightness error of 1mm.

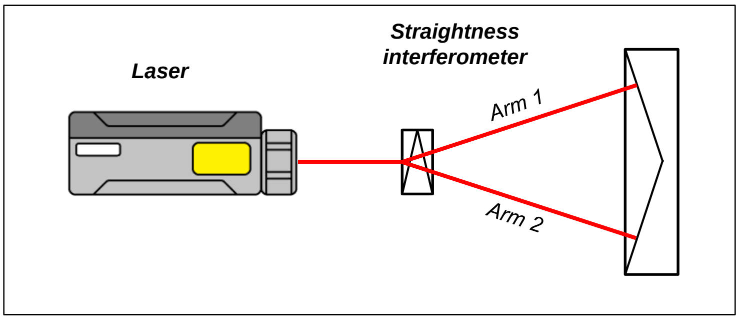

Figure 24

Angular measurement – Figure 25 shows a schematic diagram of angular optics. As can be seen from the figure, the air paths of laser beams in arms 1 and 2 of the interferometer are similar lengths when the reflector is square to the beam. This is typically the case when measuring axis pitch or yaw. If measuring larger angles (up to 10°) there is a small imbalance and this gives rise to some sensitivity to variations in air refractive index. However, as the maximum expected change in refractive index is about 150ppm (0.015%), this is insignificant compared to the specified measurement accuracy of Renishaw's angular optics which is 0.6% (standard angular optics) or 0.2% (for high accuracy angular optics). Finally when measuring a rotary axis using angular optics in combination with Renishaw's XR20-W reference indexer, the optics calibration cycle automatically takes the current air refractive index into account. Further information on this topic can be found in Renishaw Whitepaper TE327 Interferometric calibration of rotary axes (Reference 7).

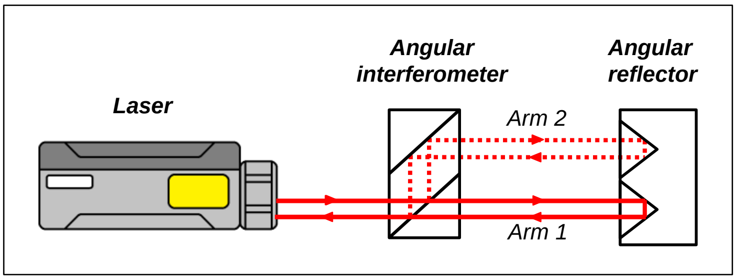

Figure 25

References

1. Phillip E. Ciddor, "Refractive index of air: new equations for the visible and near infrared," Appl. Optics 35, 1566-1573 (1996).

2. B. Edlén, "The refractive index of air," Metrologia 2, 71-80 (1966).

3. K.P. Birch and M.J. Downs, "An updated Edlén equation for the refractive index of air," Metrologia 30, 155-162 (1993).

4. K.P. Birch and M.J. Downs, "Correction to the updated Edlén equation for the refractive index of air," Metrologia 31, 315-316 (1994).

5. NIST Metrology Toolbox http://emtoolbox.nist.gov/Wavelength/Documentation.asp

6. ASME B89.1.8-2011 Performance Evaluation of Displacement Measuring Laser Interferometers. Non-Mandatory Appendix C – Performing Accurate Measurements with a Laser Interferometer System – Best Procedures and Practices. 41-48 (1998)

7. Renishaw Whitepaper TE327 Interferometric calibration of rotary axes

Renishaw plc

New Mills, Wotton-under-Edge,
Gloucestershire GL12 8JR
United Kingdom

T +44 (0) 1453 524524
F +44 (0) 1453 524901
E uk@renishaw.com

www.renishaw.com

RENISHAW
apply innovation™

About Renishaw

Renishaw is an established world leader in engineering technologies, with a strong history of innovation in product development and manufacturing. Since its formation in 1973, the company has supplied leading-edge products that increase process productivity, improve product quality and deliver cost-effective automation solutions.

A worldwide network of subsidiary companies and distributors provides exceptional service and support for its customers.

Products include:

- Additive manufacturing, vacuum casting, and injection moulding technologies for design, prototyping, and production applications
- Advanced material technologies with a variety of applications in multiple fields
- Dental CAD/CAM scanning and milling systems and supply of dental structures
- Encoder systems for high accuracy linear, angle and rotary position feedback
- Fixturing for CMMs (co-ordinate measuring machines) and gauging systems
- Gauging systems for comparative measurement of machined parts
- High speed laser measurement and surveying systems for use in extreme environments
- Laser and ballbar systems for performance measurement and calibration of machines
- Medical devices for neurosurgical applications
- Probe systems and software for job set-up, tool setting and inspection on CNC machine tools
- Raman spectroscopy systems for non-destructive material analysis
- Sensor systems and software for measurement on CMMs
- Styli for CMM and machine tool probe applications

For worldwide contact details, please visit our main website at www.renishaw.com/contact

H-5650-2050-03

Issued: 0717 Part no. H-5650-2050-03-A