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# The benefits of remote interferometry for linear, angular and straightness measurements.

## INTRODUCTION

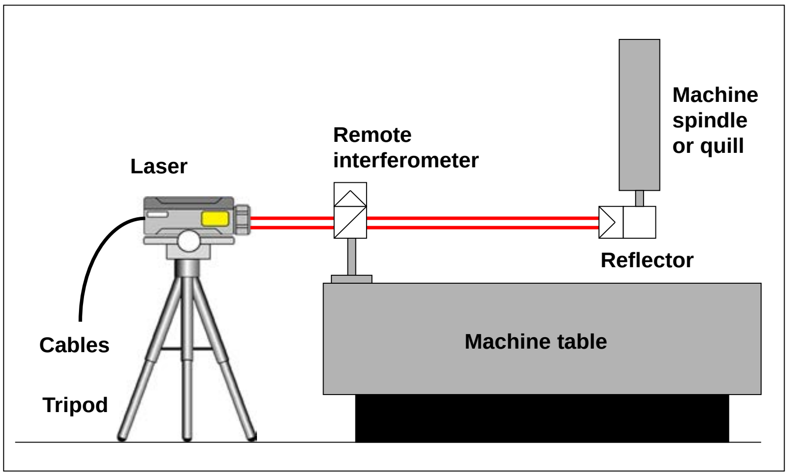


*Figure 1 - Linear measurement with remote interferometer*

For many years the industry standard method of measuring machine tool or CMM accuracy utilised a free-standing laser on a tripod, in combination with a remote (i.e. separate) interferometer and reflector optics, mounted directly to the machine table and spindle. Linear, angular (pitch and yaw) or straightness measurements, between table and spindle, can then be made interferometrically with the appropriate choice of interferometer optics. The design of Renishaw's XL-80 laser interferometer system is based on this long established and proven measurement method. Figure 1 illustrates a typical setup for linear measurements using this method.

Various alternative designs of laser measuring systems are now available, but some of them depart from this measurement methodology in one or two key areas.

1) They use a linear interferometer optic that is combined with the laser head (either internally or externally). The laser head is then mounted directly onto the machine (rather than on a tripod).

2) They use electronic targets, (not interferometers), to measure pitch, yaw and straightness errors, and some offer simultaneous measurement of linear, angle and straightness.

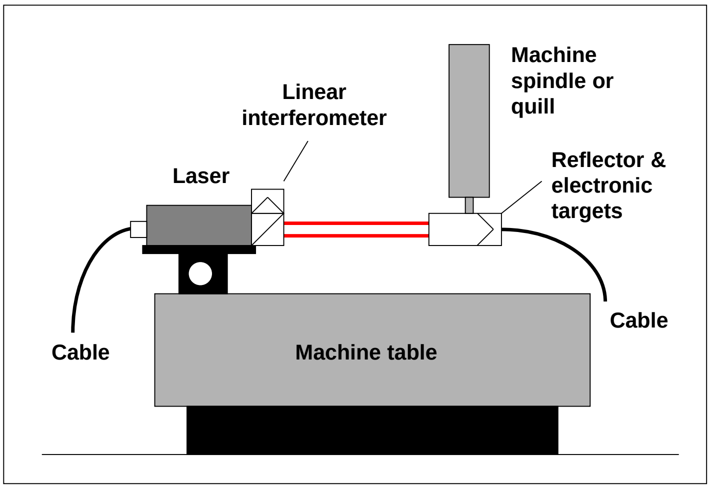


*Figure 2 - Linear measurement (alternative method)*

A schematic diagram of such a system is shown in Figure 2. These systems appear to offer benefits of easier set-up, increased portability and significantly reduced measurement time, (particularly if electronic targets and a linear interferometer are used to provide simultaneous linear, angular and straightness readouts). However, this may be at the expense of measurement accuracy and stability.

This whitepaper examines each measurement mode (linear, angular and straightness) and explains the benefits of taking measurements interferometrically, with remote interferometer optics and the laser mounted on a tripod. It also draws attention to the importance of the environmental compensation system for linear measurement accuracy.

## INTERFEROMETER MEASUREMENTS

There are number of benefits of using a tripod mounted laser, with only the remote interferometer optics mounted directly to the machine.

1. ***The heat generated by the laser is kept away from the interferometer optics.*** The linear interferometer and associated reference arm form the reference point from which all machine movement is measured. Any changes in the interferometer position or in the reference arm length, caused by thermal expansion or contraction, will degrade the accuracy of this measurement. To ensure such changes are kept to an absolute minimum the Renishaw XL-80 system follows good metrology principles by keeping the heat of the laser source away from the measurement optics. Laser systems that use an interferometer inside the laser head, or mounted on the front of the laser head break these principles, and may suffer from significant zero point drift, both during laser warm-up, and if the ambient environment changes. These drifts can be tens of micrometres.

*A Renishaw XL-80 laser system was recently tested using the combined services of the American National Institute of Standards and Technology (NIST) and the UK National Physical Laboratory (NPL). The system was tested in accordance with the new American standard ASME B89.1.8-2011 which evaluates the performance of linear displacement measuring laser interferometers. During this test Renishaw's XL-80 laser system showed a zero point drift of just 0.047$\mu$m. An excellent result.*


*Figure 3 - ASME B89.1.8-2011*

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2. ***The heat generated by the laser is kept away from the machine under test.*** A Helium Neon laser head will dissipate at least 5 watts of heat, (more if it contains power supplies). Placing such a heat source on small, high accuracy machines may cause thermal expansion and distortion of that machine. Although these effects are small, they can degrade the accuracy of results at the micrometre level. Mounting the laser on a tripod, away from the machine, eliminates that possibility.

3. ***The laser head doesn't obstruct axis movement.*** If the laser head is mounted on the machine, its size may reduce the available range of travel of the axis under test. If the laser is mounted on a tripod, the only items mounted on the machine are the small interferometer optics, which will usually have less effect on axis travel.

4. **_Beam alignment adjustments can be made outside the machine._** If the laser is mounted inside the machine, all laser beam alignment adjustments have to be made inside the machine. Machine geometry and guards may make this difficult to achieve. The Renishaw XL-80 laser system allows adjustments to be made externally (using the tripod stage controls to move the laser), or internally (using the unique Renishaw LS350 beam steering optic mounted directly to the interferometer). This allows the user to choose the easiest method of adjustment, according to the design of the machine under test.

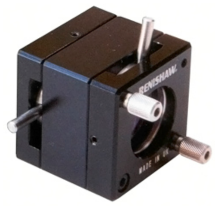


*Figure 4 - LS350 beam steerer*

5. **_No trailing cables inside the machine._** The laser head requires power and signal cables, but interferometer optics don't. Mounting the laser on an external tripod, with just the optics inside the machine, avoids the need to route these power and signal cables into the moving machine, and prevents problems of snagging or dragging these cables which can cause damage or measurement error.

6. **_Lower sensitivity to degradations in laser beam quality._** Internal optical reflections and dust, dirt and fingerprints on glass components can cause weak interference and diffraction patterns within the laser beam, and a diffuse halo around it. These have minimal effect on a laser interferometer system (until they are so severe that they reduce the signal strength to levels where measurement becomes impossible). However, in the case of an electronic target these effects can disrupt the position of the beam "centre of intensity" and light in the halo may miss the target altogether. Both of these can produce significant errors in measurement. This makes it particularly important to keep the optical surfaces scrupulously clean in order to maintain optimum measurement accuracy.

If thermal drift has been eliminated (see points 1 and 2 above) the accuracy of linear measurements depends primarily on the performance of the weather station and not the laser. Changes in atmospheric temperature, pressure and humidity all alter the laser wavelength, and must be compensated for in order to achieve high accuracy. The accuracy of the weather station sensors over the full range of operation is therefore critical. For example, to ensure that each individual sensor contributes less than ±0.5 ppm of error to the wavelength compensation (and hence to the linear measurement accuracy), the sensor accuracies in the table below are required.

| Sensor accuracy required | |
|---|---|
| Air Pressure | Better than ± 1.5 mBar ( ± 1 mm Hg) |
| Air Temperature | Better than ± 0.5 °C ( ± 1 °F) |
| Air Humidity | Better ± 20% RH |

*For more information on the importance of environmental compensation, refer to Renishaw's whitepaper "TE329: Environmental compensation of linear laser interferometer readings".*

It is not easy to achieve these accuracies, especially over a wide range of environmental conditions. Renishaw's XL-80 laser system including the XC-80 compensator and sensors have been specially designed to provide a total linear measurement system accuracy within ±0.5 ppm (part per million), over the full environmental range of 0-40 °C, 650-1150 mBar, 0-95% RH. If material thermal expansion normalisation is also required, (as recommended in machine calibration standards), then the accuracy of linear measurements will also depend critically on the accuracy of the material temperature sensor system. Renishaw's XC-80 compensator includes a material temperature sensor with an accuracy of ±0.1 °C, over the full operating temperature range of 0-55 °C.

*When a Renishaw XL-80 laser system was tested in accordance with ASME B89.1.8-2011 by NIST and NPL (see note above) it showed a linear measurement accuracy of 0.2 ppm (without material expansion compensation) and 0.24 ppm (including material expansion compensation for steel).*

## ANGULAR MEASUREMENTS

The Renishaw XL-80 laser system uses angular interferometry to measure angle, pitch or yaw. Referring to Figure 5, the laser system measures relative changes between the lengths $L_1$ and $L_2$, and from these computes the angle using the equation shown.

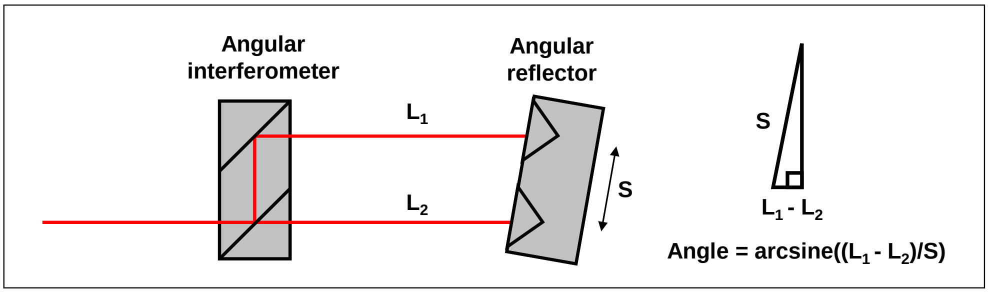


*Figure 5 - Interferometric angle measurement*

*For more detailed technical information on interferometric angular measurement, refer to the Renishaw whitepaper entitled "TE326: Interferometric angle measurement and the hardware options available from Renishaw".*

An alternative measurement method is to focus the laser beam onto an electronic target using a lens and measure where the beam strikes the target and divide by the lens focal length (see Figure 6).

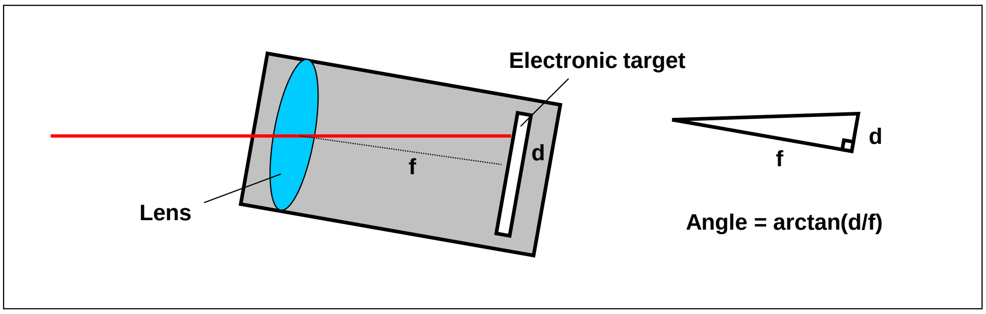


*Figure 6 - Angular measurement with electronic target*

Although two axis electronic targets can be used to allow simultaneous measurement of pitch and yaw, the interferometer offers a number of advantages.

1) ***Better linearity, range and resolution simplify alignment.*** An electronic target is typically a photo-detector that produces analogue output photocurrents that vary according to where the laser beam strikes the target. Electronic targets cannot match the excellent combination of measurement resolution, linearity and range that an angular interferometer provides. As a result electronic targets have a limited angular range (<0.5°) and often require one or two

small mechanical “offset nulling” screws which must be adjusted, (to ensure the laser beam is near the centre of the target), before measurement can start. This adjustment may be difficult to make if the beam position is not visible from outside the sensor housing, and in the case of a two axis sensor (with simultaneous pitch and yaw outputs), may require a zig-zag search sequence. This is both time consuming and awkward, especially if these screws are difficult to reach from outside the machine. In contrast, the angular interferometer offers excellent resolution, range (10°) and linearity (with arcsine correction). Alignment of interferometer angular optics is fast and simple, with no fine adjustment screws required on the optics.

2) ***Accuracy and traceability.*** Renishaw’s interferometric angle measurements utilise the internationally accepted traceability of the stabilised Helium Neon laser wavelength, in combination with Renishaw’s angular reflector optics, thereby guaranteeing the long term accuracy and performance of the system.

*Figure 7 - Renishaw's angular optics*

Electronic targets measure the beam position electronically, and thus rely on the linearity of response of the electronic target (typically 0.5%) and on the stability of their analogue electronic circuitry. Also they do not utilise the traceability of the laser wavelength.

3) ***Minimal axis payload.*** The mass of Renishaw’s angular reflector assembly (including mounting block and pillar) is about 450 grams. The mass of a sensor head containing a linear retro-reflector, electronic targets, processing electronics and adjustment mechanics, with trailing cable can be 800 grams. This extra mass can increase measurement errors if the machine axis under test has some compliance, (for example when measuring pitch error of the Z-axis of a horizontal arm CMM).

4) ***No trailing cables.*** The angular interferometer and reflector optics need no signal wires or cables. A sensor unit containing electronic targets and electronic circuitry needs power and signal connections that may be provided through trailing cables. If such a unit is fixed to the moving axis of a machine, care needs to be taken to ensure that such cables don’t snag or drag as the axis moves which could cause cable damage or cause angular measurement errors if the axis is compliant (e.g. CMM Z axis).

5) ***Reduced errors from laser pointing instability.*** A correctly designed angular interferometer measures relative angular movement between the interferometer and retro-reflector only, and is largely insensitive to small changes in the pointing direction of the beam from the laser head. This is because lengths $L_1$ and $L_2$ (see Figure 5), are affected equally if the angle of the input beam is changed, and so the effect on $L_1 - L_2$ is negligible.

However, an electronic target based system is just as sensitive to changes in the laser beam direction as it is to pitch and yaw in the axis. If the pointing direction of the output beam from the laser head shifts by 5 arcseconds, then an error of 5 arcseconds will appear directly on the output from the electronic target. This places severe demands on the design of the laser head which must provide an extremely stable beam output direction, even though its temperature may change significantly as it warms up. A laser system that uses remote angular interferometer optics doesn’t have this problem.

6) ***Insensitivity to ambient ligh***t. An electronic target, based on quad cell or PSD (position sensitive detector) technology, provides output signals that indicate the “centre of intensity” of all the light landing on them. (This output is the optical equivalent to a “centre of gravity” in mechanical engineering). If ambient light also reaches the target, it will add to the light from the laser beam, and can shift the “centre of intensity”. It is possible to reject ambient light

variations either by modulating the laser source, or by using a special optical filter that lets only the laser light through. However, if the same laser beam is used for simultaneous linear interferometry, then modulation of the beam is difficult. Also high quality optical band-pass filters, (that let only the laser light through and reject all other wavelengths), are expensive. This results in a trade-off between cost and performance that often ends up compromising system accuracy. An interferometer system is only sensitive to light that has almost exactly the same wavelength and direction as the laser beam, since this is the only light that can optically interfere with the main beam at a frequency the detectors can respond to. In addition, Renishaw’s XL-80 laser head contains a special, differential photodiode fringe detector system that prevents ambient light from causing electrical offsets and fringe interpolation errors.

7) ***Lower sensitivity to stray reflected laser beams.*** External and internal reflections from the various optical surfaces in the system can generate stray laser beams. Normally the optical surfaces are anti-reflection coated to reduce the intensity of these beams. Nevertheless, if these weak beams reach the system’s detectors, they will affect the measurement.

   In the case of an interferometer system it is extremely difficult to cause a measurement error with a stray beam, because it must be aligned almost perfectly parallel to the main beam. Even if this does occur, the worst case error for a 0.5% intensity stray beam (typical reflection from an anti-reflection coated surface), is about 1/100th of a fringe, (equivalent to ~0.03 arcseconds in angle measurement mode).

   In the case of an electronic target, the effects are far more severe, and depend on both the intensity of the stray beam and the angle it enters the lens and target assembly. For example, if a 0.5% intensity stray beam enters at an angle of 0.2° to the main beam it will shift the angular output from the target by almost 4 arcseconds! Clearly the effect on an electronic target can be serious so considerable care needs to be taken to eliminate stray reflections, (or to ensure they remain stable during measurement). This is particularly challenging if the electronic target assembly also contains additional optical elements to allow simultaneous linear and straightness measurements, all of which will produce their own stray reflections.

8) ***Much larger angular measurement range***. Renishaw’s angular interferometer provides a measurement range of ±10°, whilst maintaining excellent resolution (0.01 arcseconds), and arcsecond linearity (with arcsine correction).

   Electronic targets typically have an angular measurement of only a fraction of a degree, making them harder to align than an angular interferometer.

   Renishaw’s angular interferometer optics can also be used to measure large angles, and to calibrate rotary axes over any angular increment, to arcsecond accuracy levels, (when combined with Renishaw’s XR20-W rotary axis calibrator).


*Figure 8 - XR20 Rotary axis calibrator*

*For more technical information on rotary axis calibration using Renishaw’s XL-80 laser system, angular optics and the XR20-W rotary axis calibrator refer to the Renishaw whitepaper entitled TE327: Interferometric calibration of rotary axes*.

## STRAIGHTNESS MEASUREMENTS

The Renishaw XL-80 laser system uses a straightness interferometer to measure horizontal or vertical straightness. The laser system measures relative changes in the lengths $L_1$ and $L_2$, and from this computes the straightness error, as shown in Figure 9.

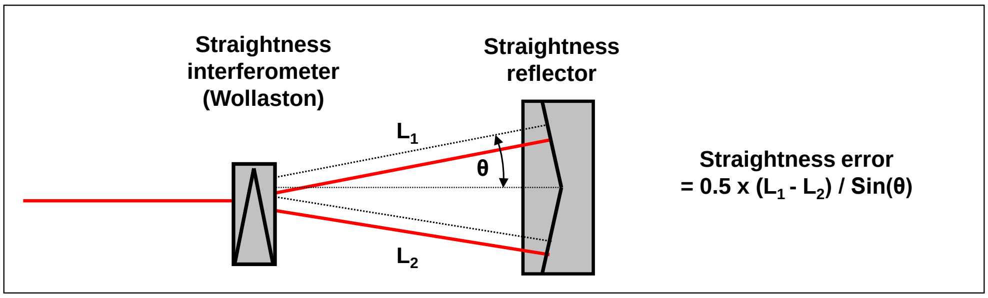


*Figure 9 - Interferometric straightness measurement*

*For more detailed technical information on interferometric straightness measurement, refer to the Renishaw whitepaper entitled "TE325: Interferometric straightness measurement and application to moving table machines".*

An alternative method is to direct the laser beam at an electronic target, and electrically measure where the beam strikes the target, as shown in Figure 10.

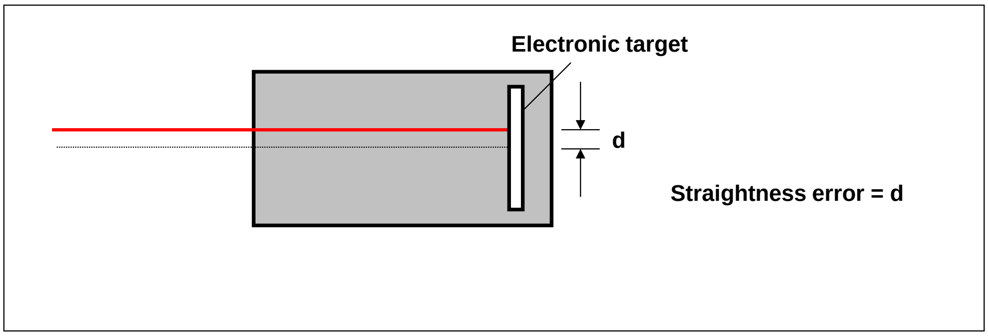


*Figure 10 - Straightness measurement with electronic target*

Although two axis electronic targets can allow simultaneous measurement of horizontal and vertical straightness, and are easier to align, the straightness interferometer offers a number of advantages.

1) ***Accuracy and traceability.*** The Renishaw straightness interferometer utilises the internationally accepted traceability of the stabilised Helium Neon laser wavelength, in combination with straightness optics including a reflector made from a single, solid block of glass, thereby guaranteeing the long term accuracy and performance of the system.

   Electronic targets measure the beam position electronically, and thus rely on the stability of their analogue electronic circuitry, and do not utilise the traceable laser wavelength.

*Figure 11 - Renishaw's straightness optics*

2) ***Less noise from air turbulence.*** Air temperature changes and gradients can bend a laser beam and change its optical path length. At a range of several meters the beam bending can cause the position of the laser beam to wander visibly. However, the effect on the beam length is much smaller. An interferometer measures straightness by detecting relative changes in lengths of beams $L_1$ and $L_2$. Both of these beams are close together and travel to the reflector and back, so both are affected to a similar degree by macro-scale environmental changes, which therefore cancel.

   An electronic target also suffers from air turbulence noise, but because the system relies on measuring beam position and not length, the noise is expected to be greater. Also because the problem is caused by beam bending, the errors increase significantly at longer range.

   Given the random nature of air turbulence and its unpredictable variation from one machine shop environment to another, the levels of noise that will be seen are hard to predict. But, in general, a laser interferometer is expected to show less straightness measurement noise than an electronic target based system, especially at longer ranges. Unfortunately the time period of this noise may be several minutes, so the use of averaging techniques provides only small improvements unless system response time is seriously compromised. As a result, in many environments, air turbulence noise remains the major limiting factor on the performance of both interferometric and electronic target based systems.

3) ***Better linearity avoids need to manually remove slope.*** Electronic targets have a non-linearity in response (typically 0.5%), especially towards the edges, this often limits the measuring range to a fraction of a millimetre. A straightness interferometer provides a better linearity over a wider measuring range. This allows accurate interferometric results to be taken without the need to manually “remove the slope” by adjusting the optics, since any slope removal required can be done accurately in software.

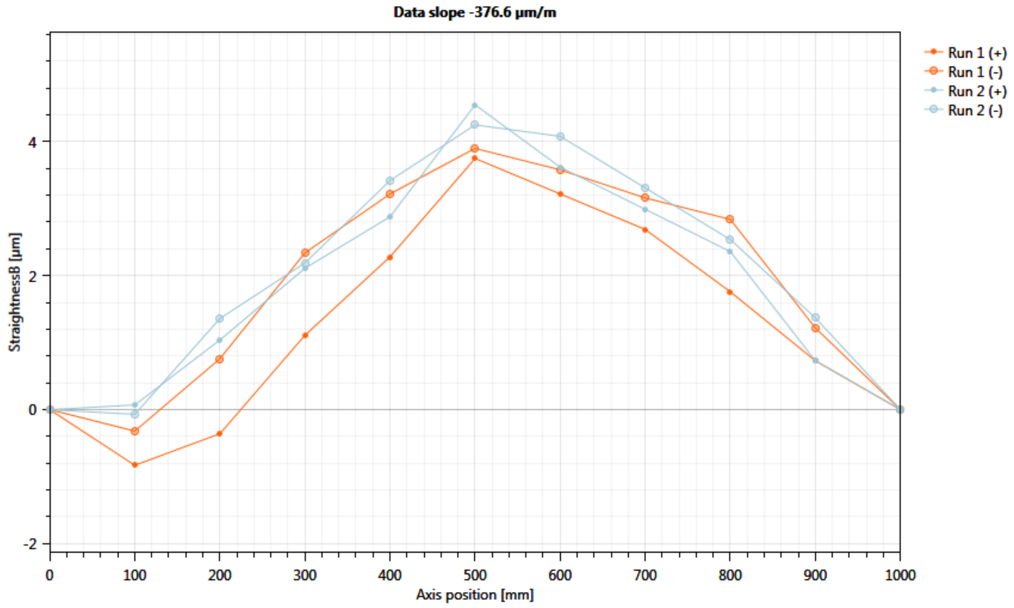


*Figure 12 - Renishaw straightness plot with software slope removal*

However, in order to get the best results from an electronic target, it is best to align the laser beam so it stays close to target centre along the entire axis length, which takes extra time. If this isn’t done, any uncorrected non-linearity in the sensor response will appear superimposed on the straightness results obtained.

4) ***No trailing cables.*** The straightness interferometer and reflector optics need no signal wires or cables. A sensor unit containing electronic targets and electronic circuitry needs power and signal connections that may be provided through trailing cables. If such a unit is fixed to the moving axis of a machine, care needs to be taken to ensure that such cables don't snag or drag as the axis moves which could cause cable damage or straightness measurement error if the axis is compliant (e.g. CMM Z axis).

5) ***Minimal axis payload***. The mass of Renishaw's straightness interferometer (Wollaston prism) assembly (including mounting pillar) is only 216 grams. The mass of a sensor head containing a linear retro-reflector, electronic targets, electronics and adjustment mechanics and some trailing cable can be 800 grams. This extra mass can cause measurement errors if the machine axis under test has some compliance, (for example when measuring vertical straightness errors of the Z-axis of a horizontal arm CMM). Some straightness interferometer arrangements require the use of a large retroreflector, which makes the weights similar, but still avoids the potential problems from the trailing cable.

6) ***Insensitivity to ambient light.*** The same comments apply in straightness mode as in angular mode (see the previous section).

7) ***Lower sensitivity to stray reflected laser beams.*** External and internal reflections from the various optical surfaces in the system can generate stray beams. Normally the optical surfaces are anti-reflection coated to reduce the intensity of these beams. Nevertheless, if these weak beams reach the system's detectors, they will affect the measurement.

   In the case of a laser interferometer, the effect depends purely on the relative intensities of the main and stray beams. The worst case error induced by a 0.5% intensity stray beam, (reflection from a typical anti-reflection coated surface), is about 1/100th of a fringe, (equivalent to ~0.2μm in short range straightness measurement mode).

   In the case of an electronic target, the effects are far more severe, and depend on both the intensity of the stray beam and where it strikes the target. For example, if a 0.5% intensity stray beam strikes the target 1mm away from the main beam it will shift the straightness output from the target by about 50μm! Clearly the effects on an electronic target can be serious, and considerable care needs to be taken to eliminate stray reflections, (or to ensure they remain stable during measurement). This is particularly challenging if the electronic target assembly also contains all the additional optical elements to allow simultaneous linear and angular measurements, all of which will produce their own stray reflections.

8) ***Reduced errors from laser pointing instability.*** A correctly aligned straightness interferometer only measures relative movement between the interferometer (Wollaston prism) and straightness reflector, and is largely insensitive to the small changes in the pointing direction of the beam from the laser head. This is because lengths $L_1$ and $L_2$ (see Figure 9), are affected equally if the angle of the input beam is changed, and so the effect on $L_1 - L_2$ is negligible. However, an electronic target based system is very sensitive to changes in the laser beam pointing direction, and this sensitivity increases with range. For example, if the pointing direction of the output beam from the laser head shifts by 5 arcseconds, then a shift in straightness reading from the electronic target will be about 25 μm at 1m range, or 100μm at 4m range. This places severe demands on the laser head which must be designed to provide an extremely stable laser beam output direction, even though the temperature of the laser head may change significantly as it warms up. A laser system that uses remote straightness interferometer optics doesn't have this problem.

## CONCLUSION

This whitepaper has shown the benefits that a laser system with remote interferometer optics can provide in terms of accuracy and stability.

Against this, lasers with integral linear interferometers and electronic targets can offer benefits in portability, and ease and speed of use. However, the significant number of additional error sources they are susceptible to raises serious concerns about the accuracy of such systems. Since the prime justification for a laser based calibration system should be the accuracy and repeatability of results, these concerns must be considered carefully when evaluating such systems against fully interferometric systems such as Renishaw's XL-80 laser system.

*Figure 13 - Renishaw's XL-80 laser system with extensive range of fully interferometric measurement optics*

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