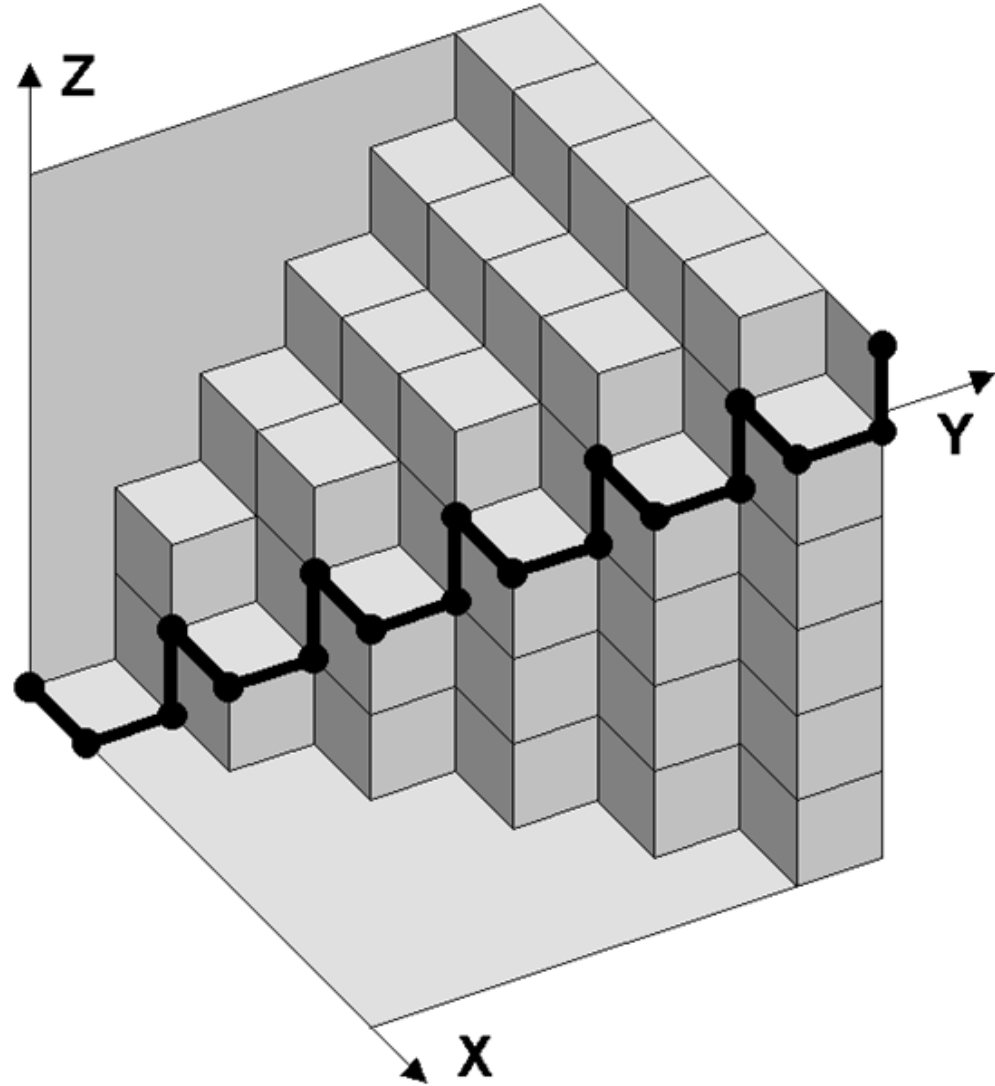


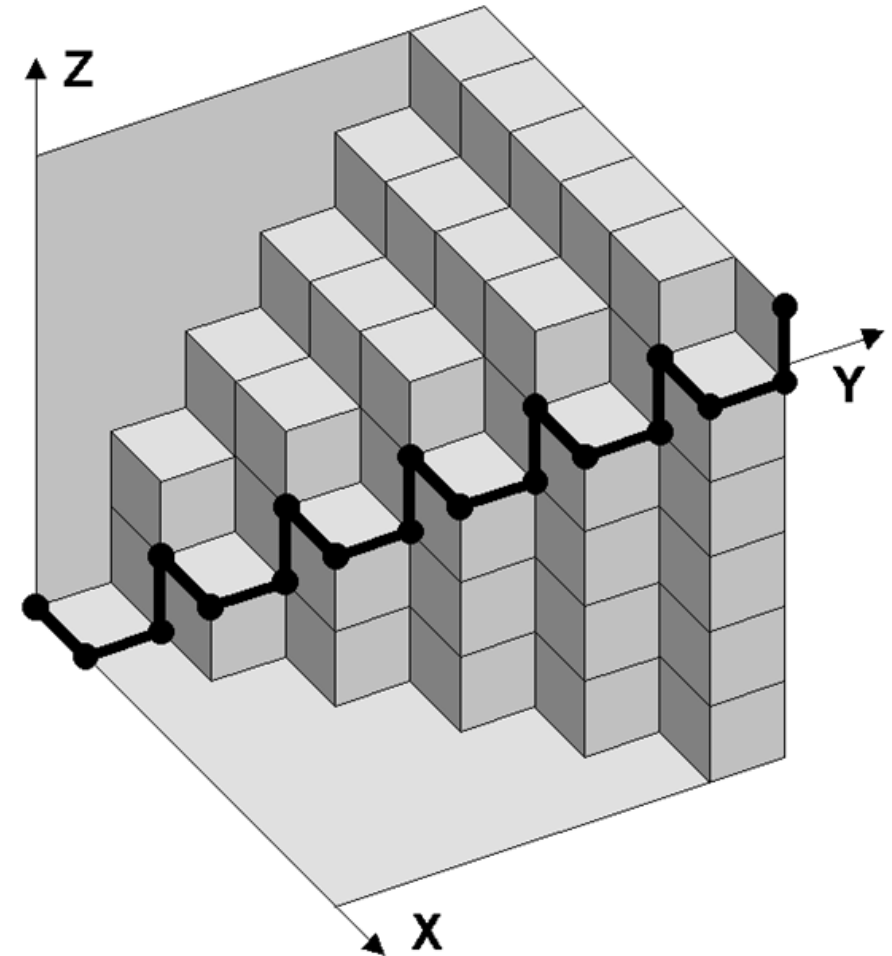
# Laser step diagonal testing

*H-5650-2057-01-B*



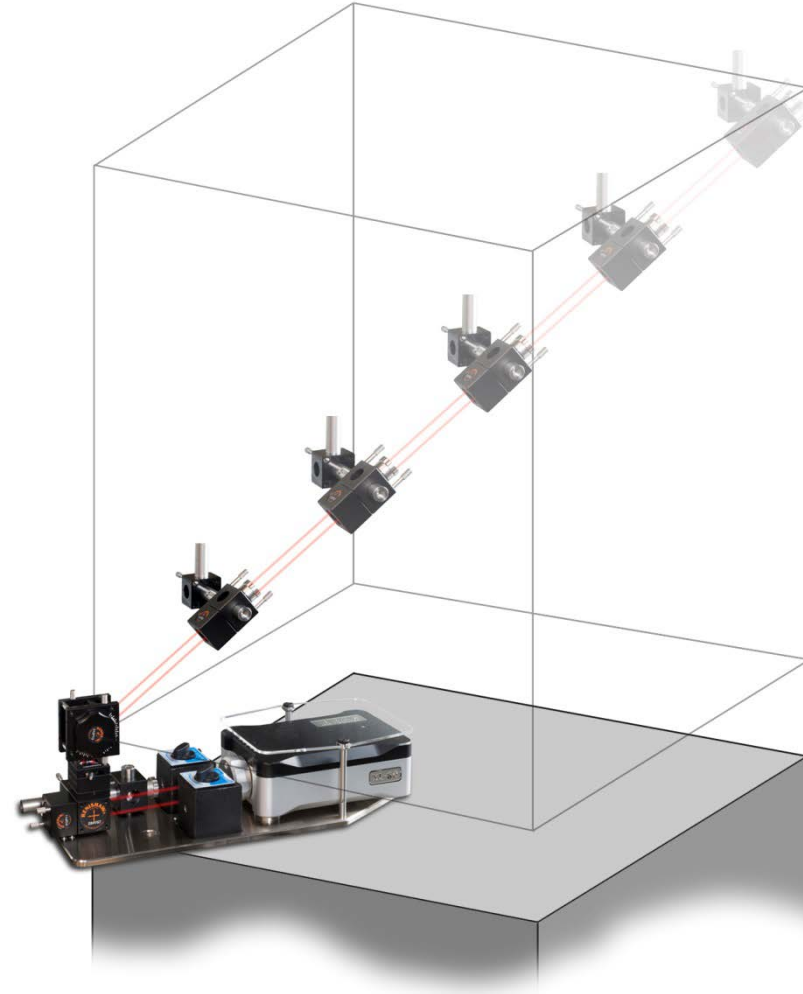
# Introduction

- This presentation reviews the step or vector diagonal measurement method for machine calibration.
- It explains the technique and then highlights some fundamental flaws in this method of measurement.
- It is recommended that the introductory Renishaw presentation entitled “Laser diagonal testing” (H-5650-2056) is studied before this one.



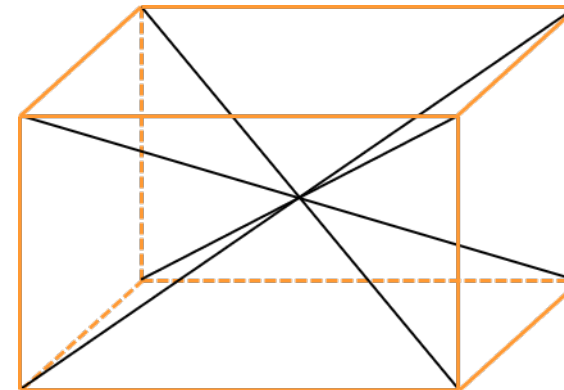
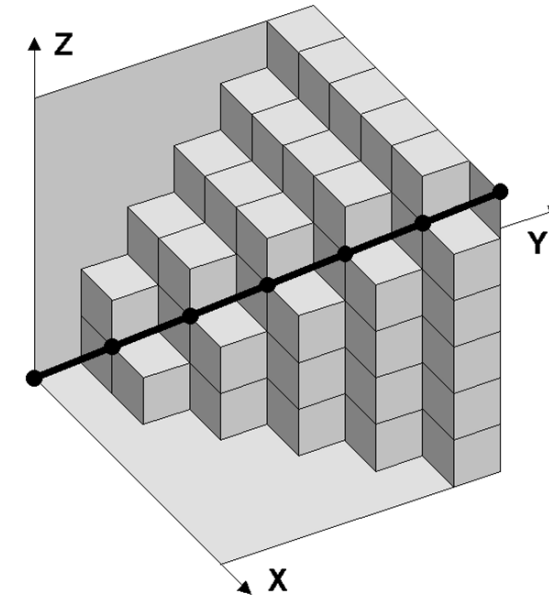
# Laser diagonal tests - B5.54 and ISO230-6

- Laser body diagonal tests for machining centres are described in B5.54 and ISO 230-6 standards.
- These tests use a laser interferometer to measure the linear positioning accuracy of the machine as it moves along each of its four body diagonals in turn.
- The figure shows a Renishaw XL-80 laser and linear optics aligned, via a steering mirror, to one of four body diagonals.



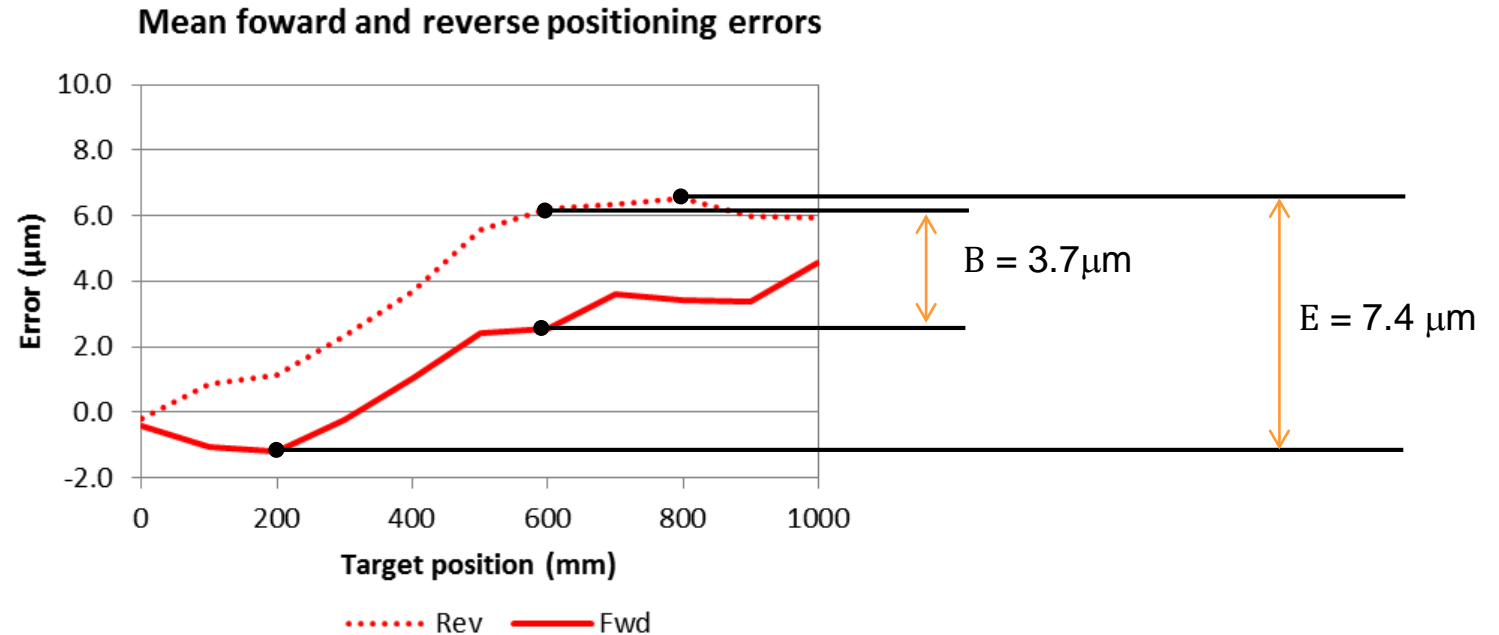
# Laser diagonal tests - B5.54 and ISO230-6

- A number of equi-spaced target positions are defined along each body diagonal.
- The machine is then moved along the diagonal from one target position to the next.
- The laser measures the linear positioning error at each target position.
- The measurement is repeated using 5 bi-directional runs along 4 body diagonals.



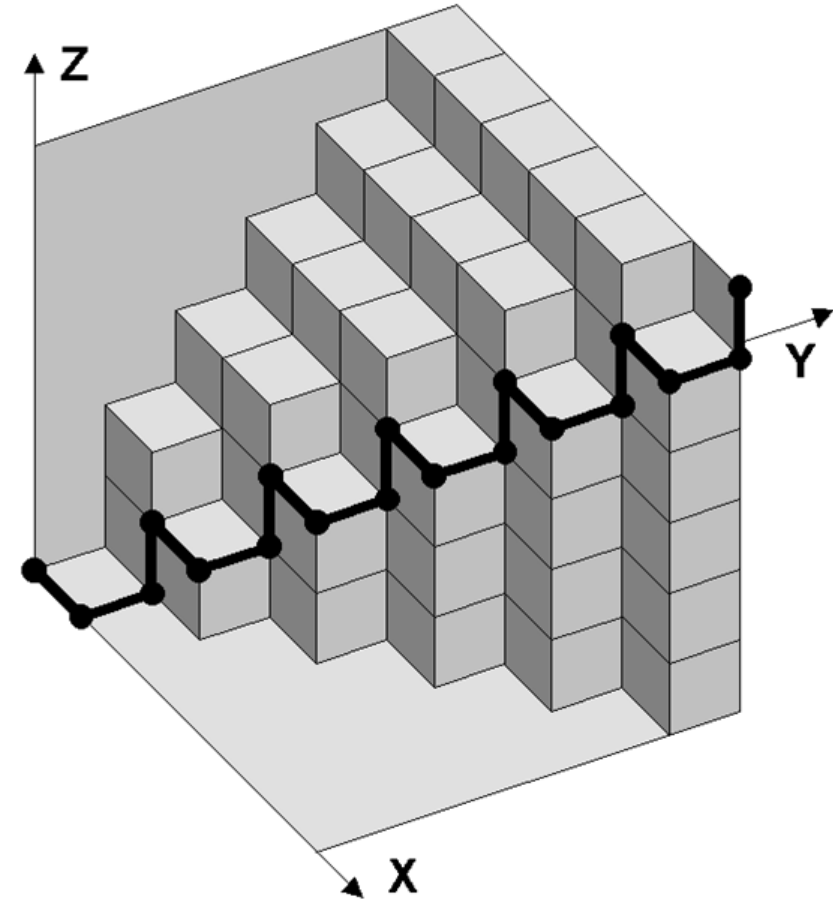
# Laser diagonal tests - presentation of results

- The results are analysed to compute the mean forward and mean reverse errors at each target position along each diagonal.
- These are then inspected to identify the systematic error of positioning ( $E$ ) and the maximum reversal error ( $B$ ) on each diagonal.
- The diagonal systematic deviation ( $E_d$ ) and the diagonal reversal error ( $B_d$ ), for the machine, are obtained by selecting the worst results for  $E$  and  $D$  from the 4 diagonals.

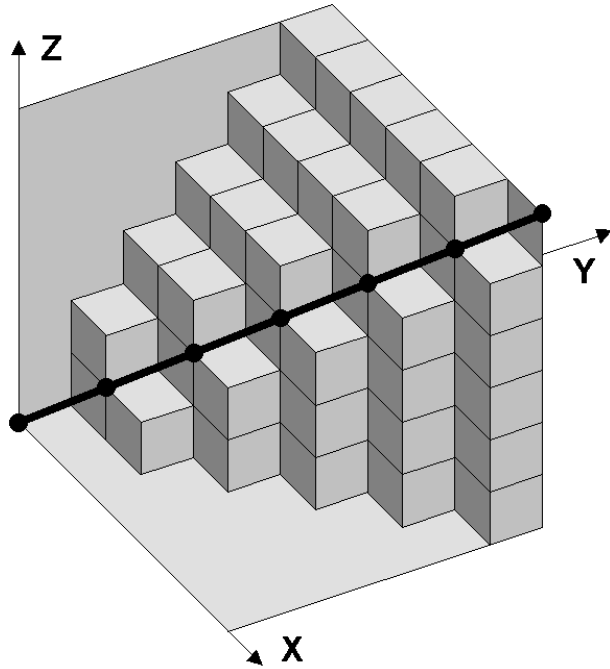


# Laser diagonal tests - step diagonal method

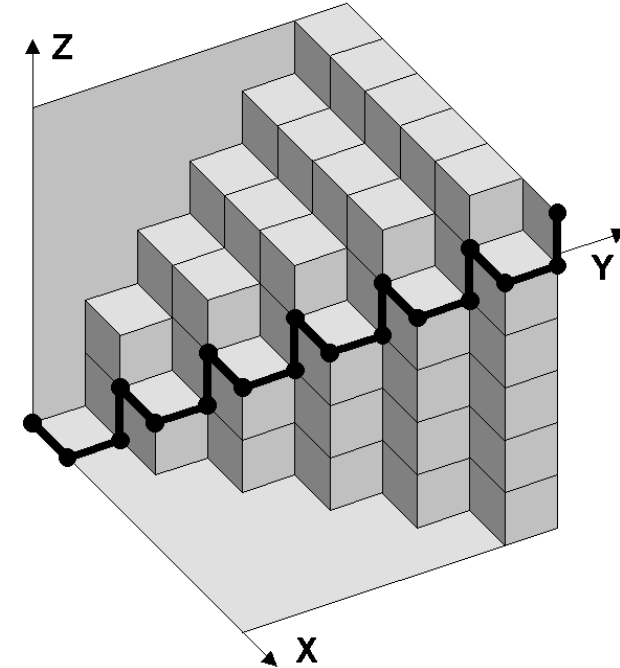
- It has been proposed in a number of technical papers<sup>1,2</sup> that the original laser diagonal test can be enhanced by using a special step sequence to move between target positions on the body diagonals.
- This method is referred to as the step diagonal or vector measurement technique.



# Laser diagonal tests - step diagonal method



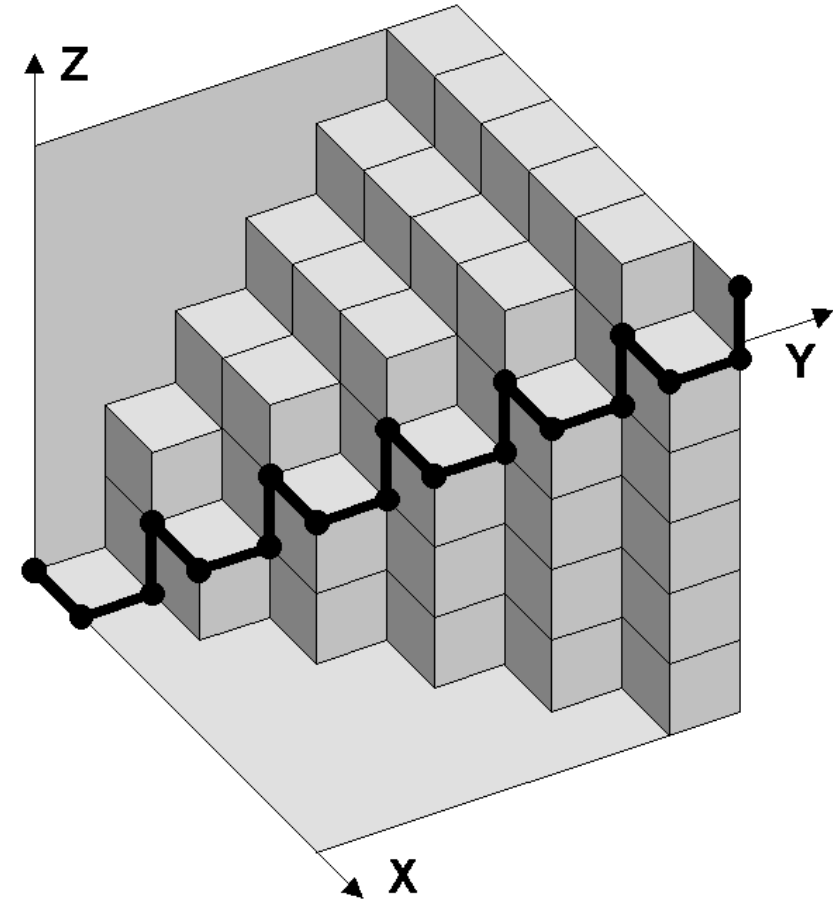
- In the original diagonal test (as described in ISO 230-6 and B5.54) the machine's X, Y and Z axes are moved **simultaneously** in order to move from one target position to the next. A laser reading is taken at each position.



- In the step diagonal test the machine's X, Y and Z axes are moved **individually**, in turn, and a laser reading is taken after each axis movement.

# Laser diagonal tests - step diagonal method

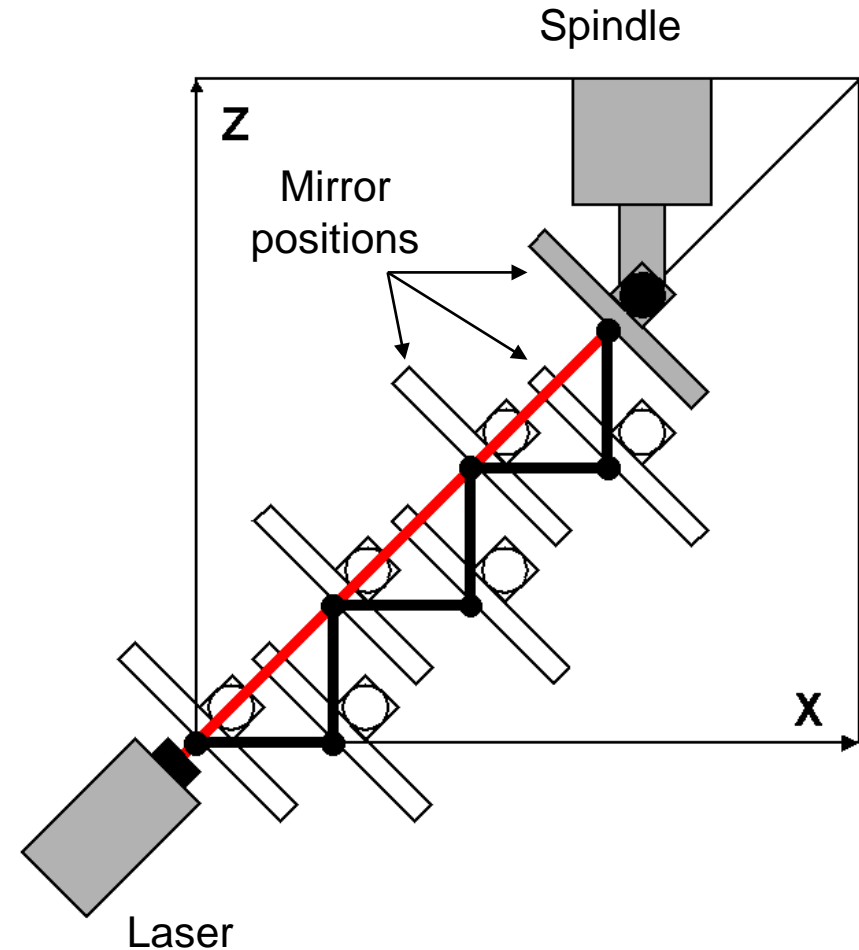
- The step diagonal method therefore takes 3 times as many laser readings as a normal laser diagonal calibration.
- It has been claimed<sup>1,2</sup> that, in addition to the normal diagonal displacement error results, this additional data can be processed to give results for the linear accuracy, straightness and squareness of the machine's X, Y and Z axes.
- However, detailed analysis shows that this is incorrect.
- The reasons for this are given on the following slides.





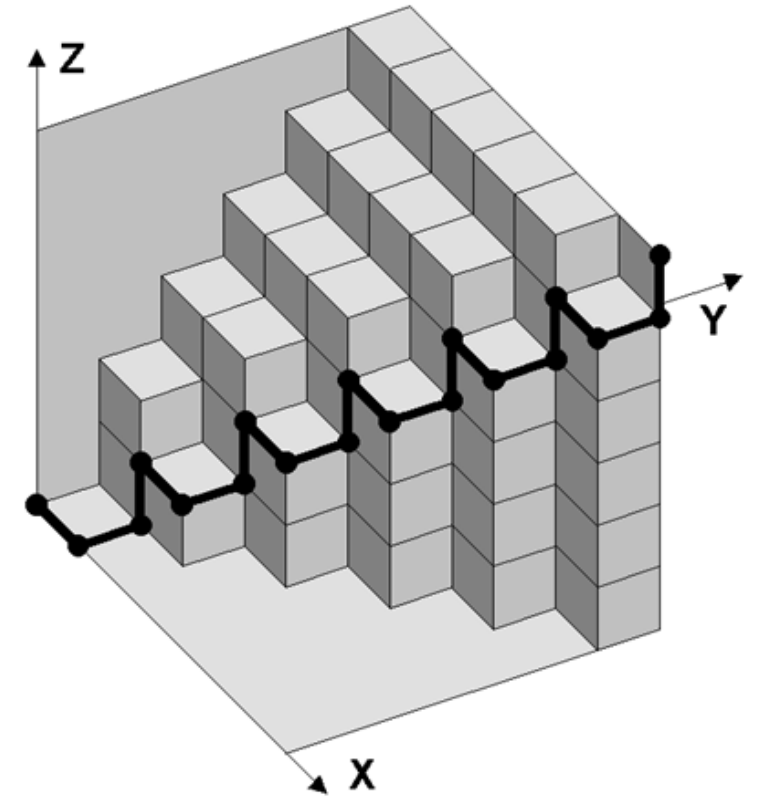
# Step diagonal tests - laser alignment

- In order to maintain alignment of the laser beam (as the machine moves along the stepped diagonal path), the laser is directed onto an angled plane (flat) mirror fixed to the machine spindle.
- The figure shows successive positions of the mirror as it is moved along the diagonal.
- A 2D view is shown for simplicity.
- The laser beam is shown in red.
- The machine movement path is shown as a thick black line.



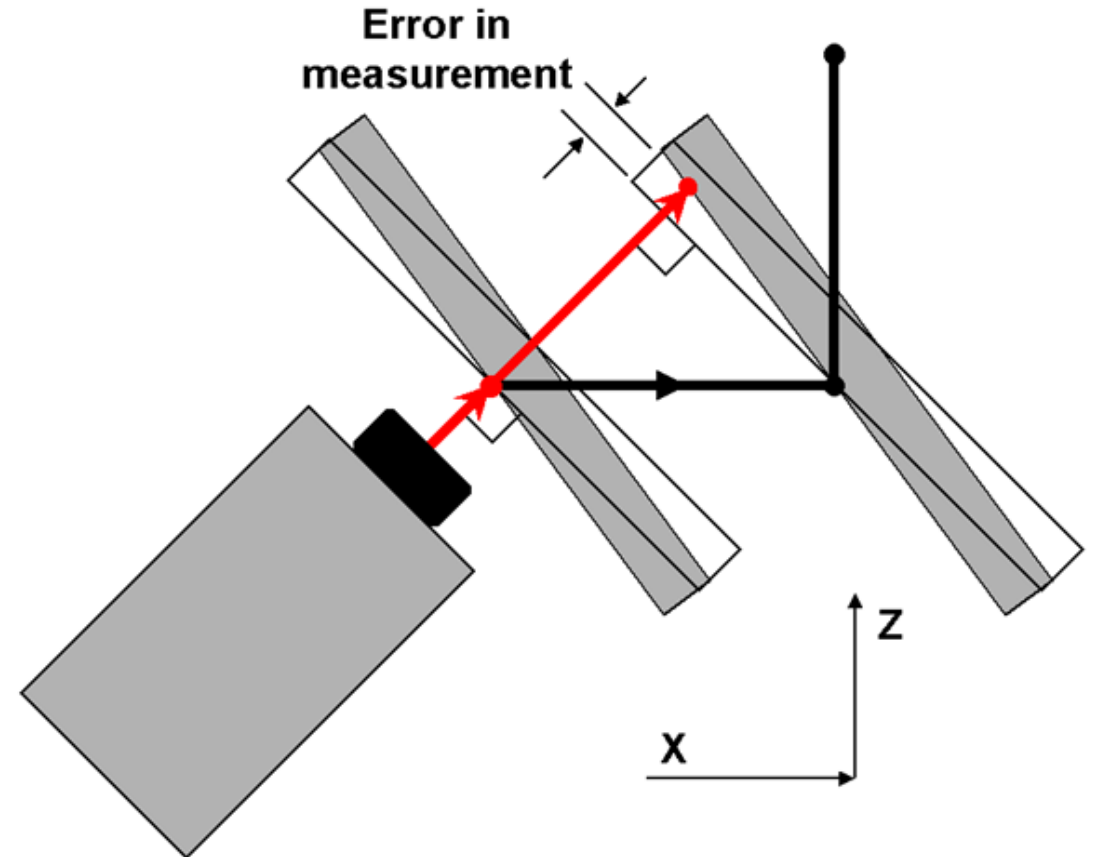
# Step diagonal tests - theory

- If the laser beam and mirror are aligned perfectly and there are no pitch, yaw and roll errors in the machine, then the theory of operation is stated as follows:
  - When the X axis moves the laser will measure the combined effect of errors in the linear and straightness motion of the X axis.
  - When the Y axis moves the laser will measure the combined effect of errors in the linear and straightness motion of the Y axis.
  - Then, when the Z axis moves, the laser will measure the combined effect of errors in the linear and straightness motion of the Z axis.
  - Once data has been taken along all four body diagonals the individual contributions from the linear and straightness errors of each axis, and the squareness errors between the three orthogonal axes can, in theory, be calculated.



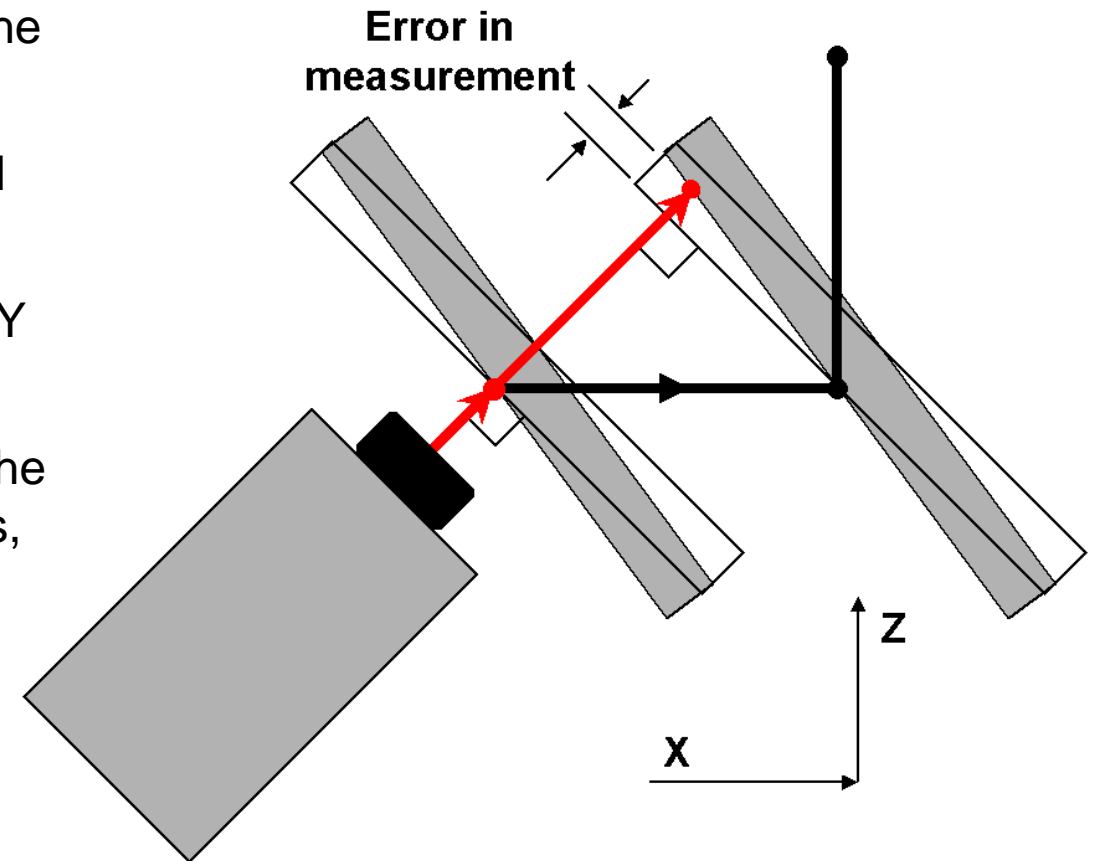
# Step diagonal tests - problems

- However, there are two fundamental problems...
- Firstly, the vast majority of machines do have roll, pitch and yaw errors. These errors will contaminate the results by introducing additional error terms which the proposed calculation methods don't resolve.
- Secondly, (and more importantly), errors in the alignment of the plane mirror and laser beam will introduce additional errors which cannot be separated from linear displacement errors in the X, Y and Z axes of the machine.
- The problem with alignment of the plane mirror is explained in more detail on the next slide.



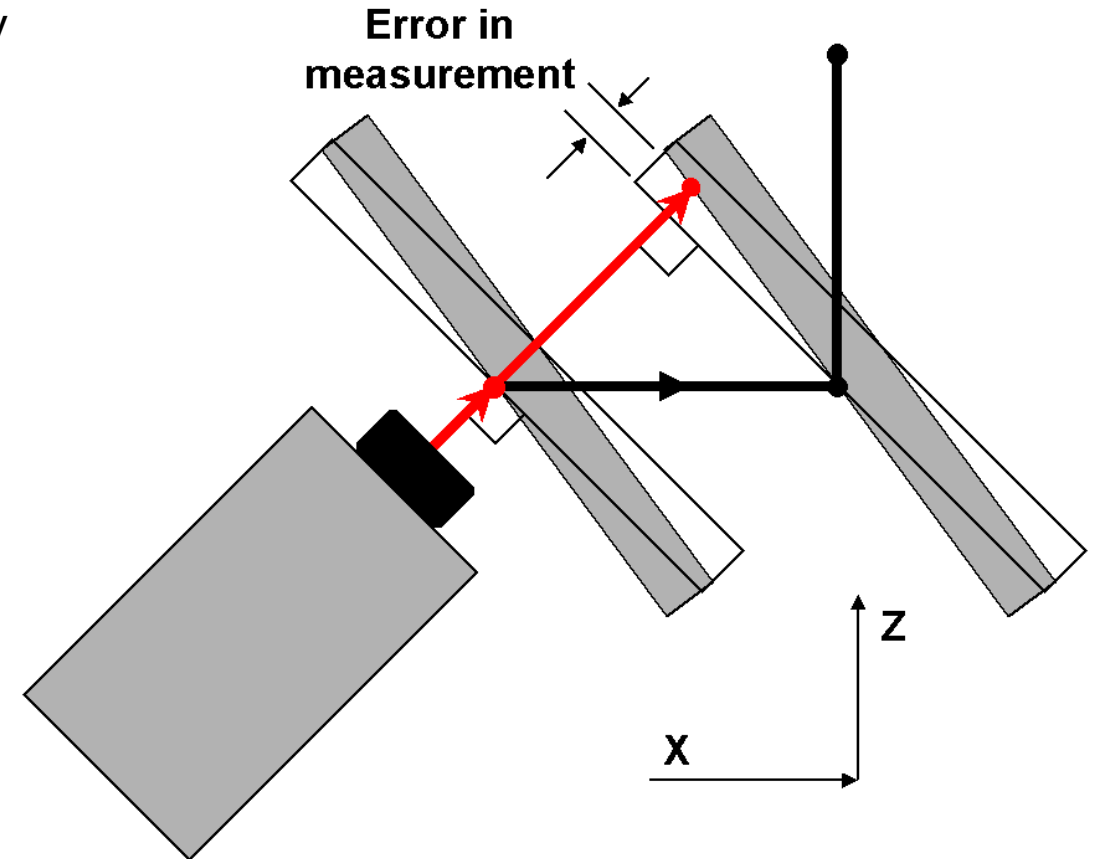
# Step diagonal tests - effect of mirror misalignment

- The figure shows the side view of a laser aligned at 45° to the machine's X and Z axes.
- The movement of a misaligned mirror (shaded) is compared with that of a perfectly aligned mirror (outline).
- The mirror has been misaligned by a small angle about the Y axis. The misalignment has been exaggerated for clarity.
- Note how this mirror misalignment introduces an error into the laser measurement. As the machine moves along the X axis, the laser beam travels across the angled mirror surface.
- **The laser reading is therefore affected by mirror alignment**, as well as by any linear and straightness errors in the axis.



# Step diagonal tests - effect of mirror misalignment

- It might be thought that this error is very small, unfortunately this is not the case, **because the error accumulates.**
- For example,
  - If the plane mirror is misaligned by an angle of just 40 arcseconds or 0.2 mm/m (a typical alignment tolerance) and the X axis step size is 50 mm, then the laser will record an extra 7  $\mu\text{m}$  of displacement during the X axis step movement.
  - In isolation this error seems small. But, because it occurs every time the X axis moves, it accumulates to 140  $\mu\text{m}$  per metre of X axis travel!
- **Therefore even a small amount of mirror misalignment can accumulate to give a large measurement error.**

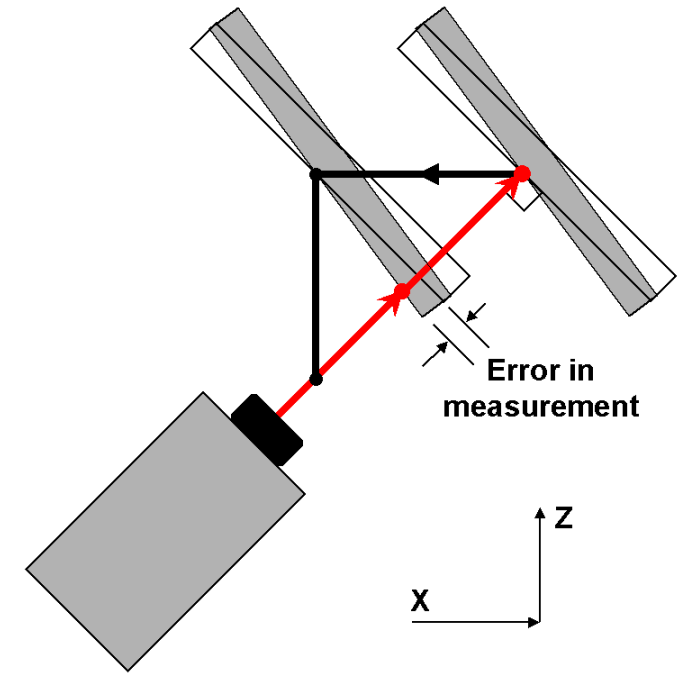
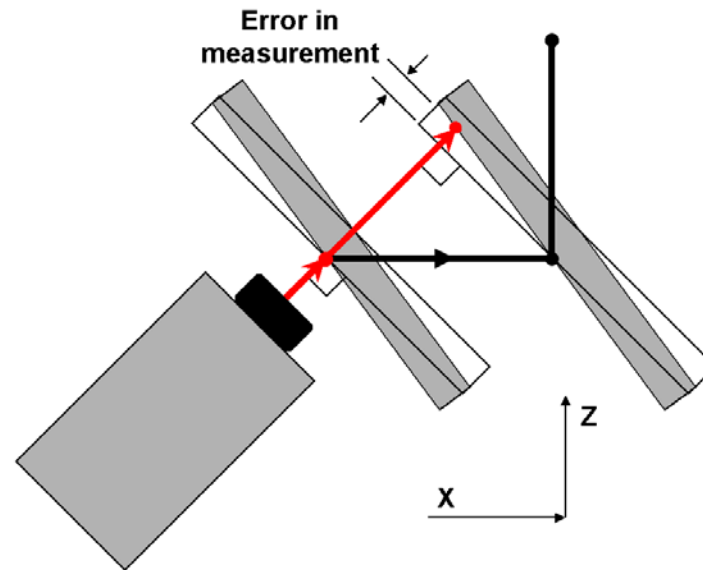


# Step diagonal tests - effect of mirror misalignment

- It has been proposed that, because this error is constant, it can be removed by software, e.g. by linear regression/slope removal, etc. However, there are two flaws in this approach.
- Firstly, the error will only be constant if the angle of the mirror doesn't change as it moves along the axis.
  - If the machine contains any pitch and yaw errors then the angle of the mirror will change.
  - Even small changes in mirror alignment of a few arcseconds will have a significant effect.
- Secondly, it isn't possible to determine whether the error in laser readings is caused by mirror misalignment or a genuine progressive linear over-travel or under-travel in the axis motion. The process of slope removal will remove the effects of both. **Thus eliminating one of the machine errors the system is claiming to measure.**

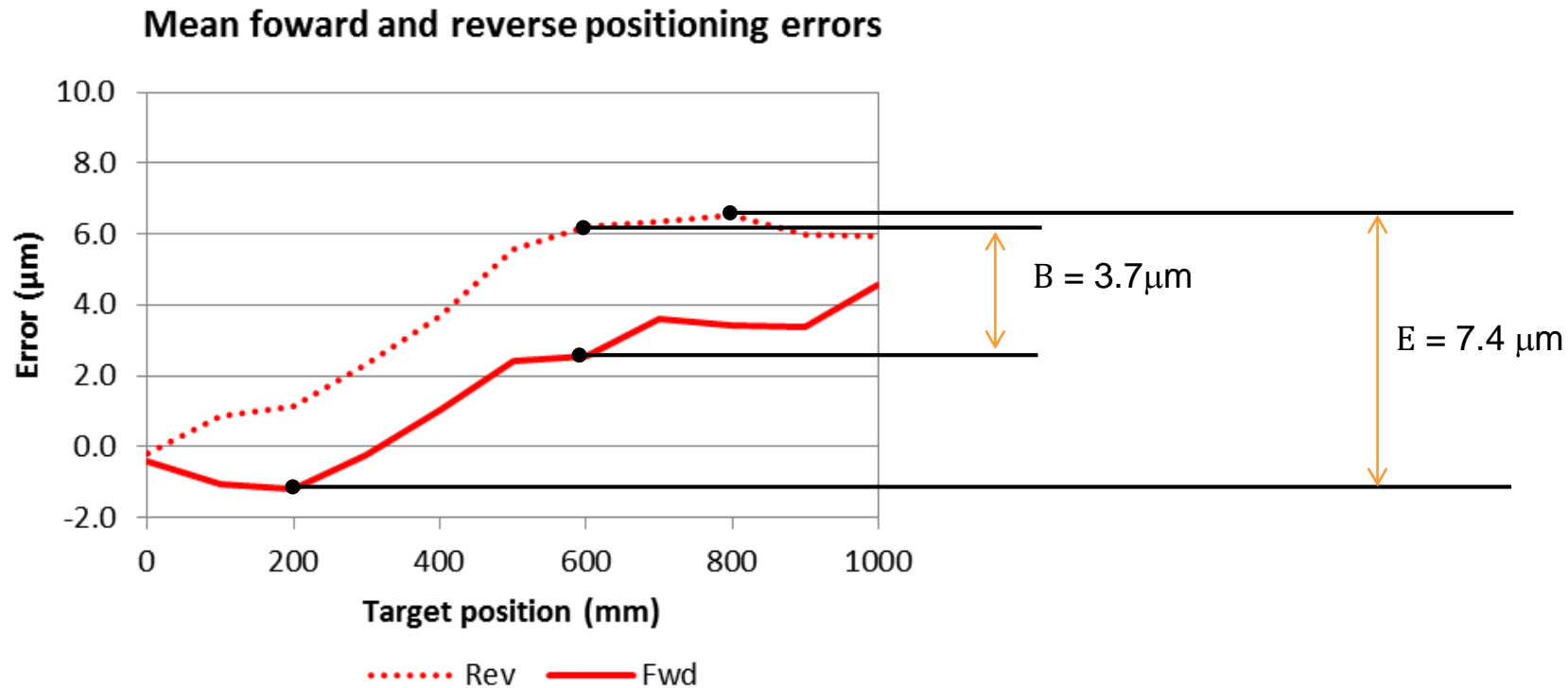
# Step diagonal tests - effect of mirror misalignment

- It might be thought that by reversing the axis movement sequence it could be possible to separate the errors caused by mirror misalignment from any linear travel errors in the axis.
- Unfortunately this is not the case. In both instances the laser records additional (i.e. over-travel) movement in the X axis, even though the movement sequence has been reversed and the laser beam has travelled onto the opposite side of the mirror.



# Step diagonal tests - regular diagonal results

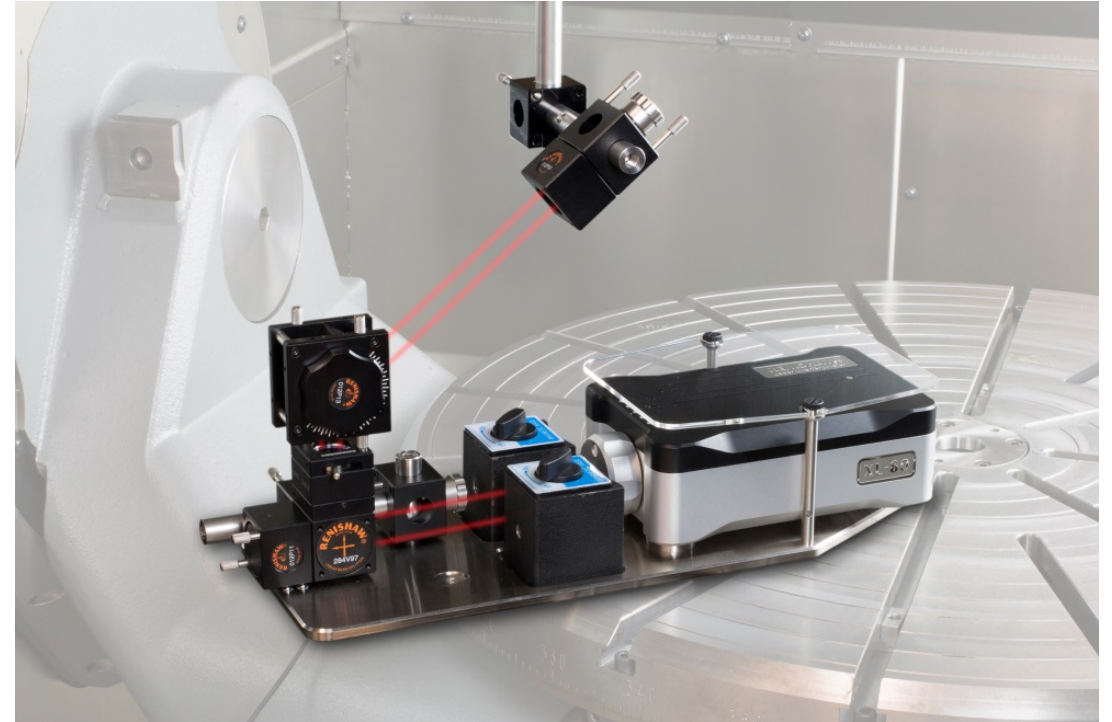
- Although the step diagonal technique cannot reliably measure the linear positioning errors in an axis, it can provide systematic error in diagonal positioning and reversal error results, in accordance with the B5.54 and ISO 230-6 standards.





# Step diagonal tests - regular diagonal results

- However, the method has some disadvantages compared with using a regular linear laser interferometer and retro-reflector, as shown on right.
  - The system is harder to align accurately to the machine diagonal.
  - Any misalignment of the laser beam to the machine diagonal can combine with misalignment of the mirror to cause small measurement errors. This problem does not occur when using a retro-reflector.
  - Secondly, the step diagonal test takes longer because of the more complex part programming and additional target positions required. This makes the test more prone to environmental fluctuations that may occur between the measurement of each diagonal.



# Step diagonal tests - error compensation

- The step diagonal method does not give reliable linear positioning accuracy data for the machine's axes.
- However, the technique can give reliable diagonal displacement accuracy results in accordance with B5.54 and ISO 230-6.
- It is therefore possible to estimate the body diagonal lengths and squareness errors between machine axes and to carry out a compensation to improve the diagonal test results.
- If the body diagonals are different lengths then machine squareness can be adjusted, or compensated using the cross axis compensation parameters, until all four body diagonals are the same length (although they may all still be too long or short).
- Once this is done, then it is possible to apply a **single**, simple scale correction to the travels of all three linear axes to ensure that the body diagonal lengths are also corrected.
- This will improve the B5.54 and ISO 230-6 test results.

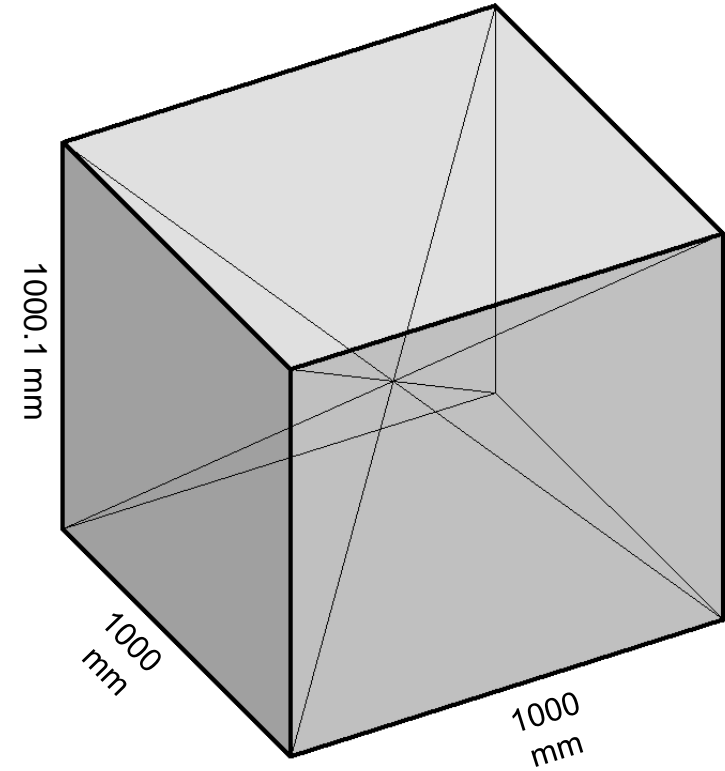
# Step diagonal tests - error compensation

Although the diagonal test results have been improved, is it true that the machine's positioning accuracy must have been improved too?

- **Not necessarily**
- Unfortunately, the combined weaknesses of the step diagonal method and ISO 230-6 or B5.54 diagonal tests, used in isolation, mean that the machine performance may actually have been degraded.
- This is because;
  - The step diagonal method does not give reliable linear positioning accuracy data for the machine's axes (as discussed earlier).
  - The ISO 230-6 and B5.54 diagonal test results cannot detect the presence of complementary linear positioning errors in two or more axes. This is described in more detail in the Renishaw presentation entitled "Laser diagonal tests".
- This is best illustrated by the example on the following slide.

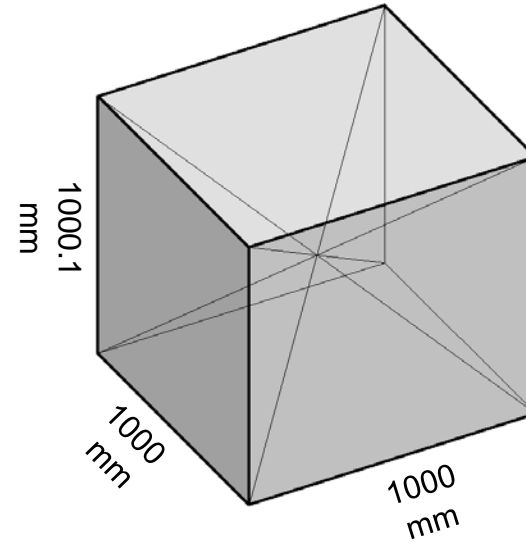
# Step diagonal tests - error compensation example

- Consider a 1m x 1m x 1m machine which has perfect X and Y axes, but the Z axis over-travels by 100  $\mu\text{m}/\text{m}$ . All three axes are perfectly square to one another and contain no other errors.
- The diagonal results will show all four body diagonals are too long (each body diagonal is 1.732109 m long instead of 1.732051 m, an error of +58  $\mu\text{m}$ ).
- However, any calculations used to remove the errors due to mirror misalignment in the step diagonal method will also destroy any information about which of the machine's axes is responsible for the fault.
- The step diagonal technique will therefore fail to identify that the Z axis alone is responsible for the problem, thereby making correct linear compensation impossible.

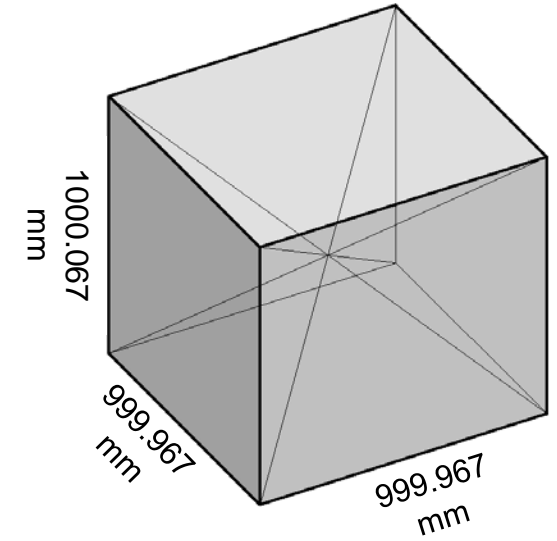


# Step diagonal tests - error compensation example

- It is possible to apply a single compensation value of  $-33 \mu\text{m}/\text{m}$  to all three axes to improve the B5.54 or ISO 230-6 diagonal test results.
- This will produce a good diagonal test result, **but it hasn't fixed the problem with the machine.**
- The Z axis is still left with a linear error of  $+66.7 \mu\text{m}/\text{m}$  and the X and Y axes (which were perfect), now have a linear error of  $-33.3 \mu\text{m}/\text{m}$ .
- **After compensation, the machine's accuracy in the X-Y plane has been seriously degraded, even though the B5.54 and ISO 230-6 body diagonal results indicate that the machine is now perfect.**



Before compensation



After compensation

# Conclusions

# Step diagonal tests - conclusions

- The sensitivity of the step diagonal method to mirror misalignment means that the method cannot be used, in isolation, to reliably determine the linear positioning errors in a machine. Such errors must be measured using conventional linear laser measurements taken parallel to the machine's axes.
- The step diagonal method can be used to give diagonal positioning performance results in accordance with B5.54 and ISO 230-6. But this is not as accurate, or convenient, as using a direct diagonal measurement using a conventional linear interferometer and retro-reflector (as described in B5.54 and ISO 230-6).
- The results from the step diagonal test, in isolation, should not be used for linear error compensation of a machine. Even though the B5.54 and ISO 230-6 results may show improvement, the machine's positioning accuracy may actually be worse.

# Further developments



# Further developments - Renishaw paper

- Following on from the original work at Renishaw, described earlier, there have been a number of developments.
- In 2003 Renishaw submitted a detailed technical paper covering this topic to the Journal of Precision Engineering, where it was independently reviewed and subsequently published<sup>3</sup>.
- The abstract of this paper states:
  - *This paper highlights the limitations in the results produced by diagonal-based measurements and by the more recently introduced vector or step diagonal methods. The purpose of this paper is to alert potential users of these methods to their limitations so that they can make informed decisions as to whether the reduction in calibration time they can provide outweighs the loss of accuracy and detail in the results. It also indicates some of the dangers in using laser diagonal data alone for the compensation of machine tool errors.*



# Further developments - NIST paper

- In 2005 J.A. Soons at NIST (National Institute of Standards and Technology, USA) performed a detailed theoretical analysis of the step diagonal test. The results of this work were presented at the Lamdamap 2005 Conference in the UK and published<sup>4</sup> in the proceedings. The abstract of this paper states:
  - *Our analysis confirms that setup errors in the alignment of the return mirror cause significant errors in the slope of the estimated positioning errors that cannot be detected from the (step-) diagonal measurements. Correction requires information on the slope of the positioning errors of two axes.*

# Further developments - ASME B5.54 revisions

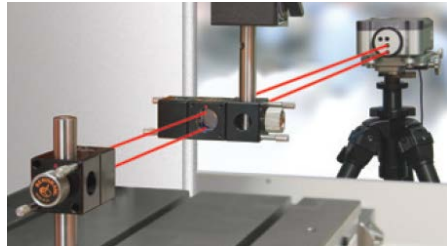
- In 2005 a new edition of ASME B5.54 was published. The new edition advises against using laser diagonal measurements, in isolation, to assess machine performance.
- In 1992 ASME B5.54 in section 5.9.2 stated:
  - *Volumetric Performance Using Laser Diagonal Displacement Measurements - The volumetric accuracy of a machine may be rapidly estimated by measuring the displacement accuracy of the machine along body diagonals*
- Section 7.7 of the new edition of ASME B5.54 2005 now includes a revised statement:
  - *Diagonal displacement tests are used to determine displacement accuracy of the machine along body or face diagonals. To obtain an estimate of the volumetric positioning capability of the machine, one has to combine the results of these tests with those of linear displacement tests” [i.e. parallel to the machine’s axes]*

# Further developments - ASME B5.54 revisions

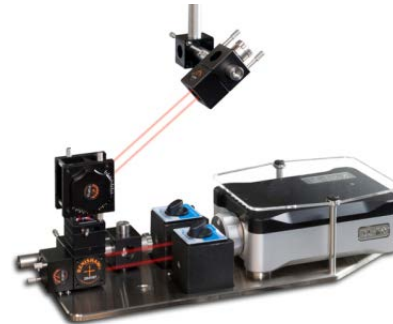
- ASME B5.54\* now also recommends a minimum test set for quickly estimating the performance of a three axis machine tool.
- **Recommended minimum test set**



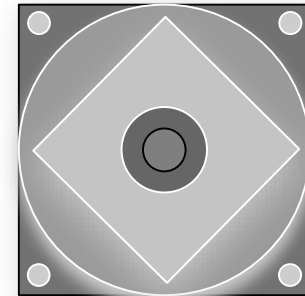
1. **Contouring performance test** using circular tests in 3 planes using, for example, a telescoping ballbar



2. **Linear positioning accuracy and repeatability test** of each axis, using, for example, a laser interferometer.



3. **Diagonal displacement tests** along 4 body diagonals using a laser interferometer.



4. **Precision contouring machining tests** including, for example, the classic "circle diamond square" test.

\* Refer to Appendix A3 of 2005 version

# Further developments - RCMT paper

- In 2006 a paper, by O. Svoboda of the Research Center for Manufacturing Technologies (RCMT) at the Czech Technical University in Prague, was published<sup>5</sup> in the Journal of Precision Engineering. The abstract of this paper states;
  - *This paper describes the results of a set of linear displacement accuracy measurements performed on two vertical CNC machining centers. The scope of this work is to verify or disprove some of the recently claimed limitations of the conventional diagonal measurement method and of the “laser vector” or “sequential diagonal” method. Basically, we tested the effect of a large linear error deliberately introduced into one of the machine tool’s axes. It is concluded that the laser vector method has not correctly identified this error and distributed the error into the remaining axes of the machine tool.*

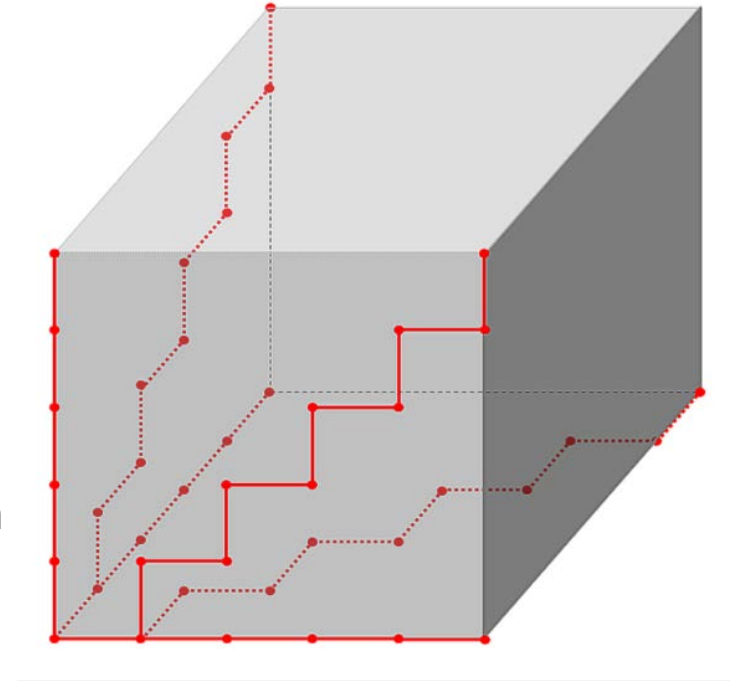
# Further developments - Kyoto University papers

- In 2009/10 two papers<sup>6,7</sup> were published in the Journal of Precision Engineering by the Micro Engineering Department of Kyoto University.
  - These papers confirm the conventional step diagonal method is subject to a significant estimation error caused by misalignment of the mirror and laser.
  - To overcome this they propose a new method which utilises additional linear measurement data taken parallel to the machine's linear axes.
  - It is claimed the new method can produce estimates of volumetric accuracy, and the linear, straightness and squareness errors of the X, Y and Z axes.
  - The method was tested successfully on a high precision machining centre.
  - However, it should be noted that an unresolved weakness remains. The latest paper<sup>7</sup> includes the following statement in the conclusion.

*... it is difficult to cancel the influence of angular errors using this formulation. Step diagonal measurements may deteriorate when the machine to be measured has significant angular errors.*

# Further developments - Korean papers

- In 2012 the Korean University of Science and Technology and Korean Institute of Machinery and Materials Technology 09/10 published a paper<sup>8</sup> in the International Journal of Machine Tools & Manufacture.
  - The paper shows a revised data capture method along the lines shown in red.
  - Setup is easier.
  - Results using a Renishaw fibre optic laser and plane mirror interferometer, **on a machine with negligible angular errors**, indicate that the method can provide results for linear, straightness and squareness errors in X,Y, Z axes.
  - Constant errors in the alignment of the mirror are removed mathematically.
  - The effects of any pitch and yaw errors in the axes are not identified.
  - Work by Renishaw indicates that even small angular errors in the machine's axes can make the straightness errors calculated by this method unreliable.



# Overall conclusion

- Step diagonal (vector) methods, used in isolation, cannot reliably determine the linear positioning errors in a machine.
- It is necessary to take additional, conventional, linear laser measurements, parallel to at least two of the machine's X, Y and Z axes, in order to determine the linear accuracies of all three.
- The requirement to take additional linear measurements lengthens the time taken to calibrate a machine, thereby reducing one of the key benefits claimed for the original step diagonal (vector) method.
- If these additional linear measurements are taken it is possible to produce results for linear, straightness and squareness of the machine's axes and for the volumetric accuracy.
  - **However the results for the straightness, squareness and volumetric accuracy will be degraded if the machine has angular errors.**
- Angular errors in the machine's axes have not been measured successfully using step diagonal methods.



# References

1. C. Wang, "Laser vector measurement technique for the determination and compensation of volumetric positioning errors, Part 1: Basic theory", Review of Scientific Instruments, Vol 71, No 10, October 2000
2. C. Wang, G.Liotto, "A laser non-contact measurement of static positioning and dynamic contouring accuracy of a CNC machine tool", Proceedings of the Measurement Science Conference, Los Angeles, January 24-25, 2002.
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4. J.A. Soons, "Analysis of the step-diagonal test", Proceedings of 7th Lamdamap Conference, pp. 126-137, 2005.
5. O. Svoboda, "Testing the diagonal measurement technique", Precision Engineering 30 (2006), pages 132-144.
6. S. Ibaraki, T. Hata, A. Matsubara , "A new formulation of laser step diagonal measurement – Two Dimensional Case", Precision Engineering, Vol 33, Issue 1, Jan 2009 pages 56-64.
7. S. Ibaraki, T. Hata, A new formulation of laser step diagonal measurement – Three dimensional case", Precision Engineering, Vol 34, Issue 3, Jul 2010, pages 516-525.
8. C.B. Bui, J. Hwang, C.H. Lee, C.H. Park "Three-face step-diagonal measurement method for the estimation of volumetric positioning errors in a 3D workspace", International Journal of Machine Tools & Manufacture 60 (2012) pages 40–43