Compensation Map Increments

Table of Contents

Purpose

This article is written as a guide for the choice of compensation map increments used on coordinate measuring machines. Selecting a suitable increment is important since a step size that is too large or too small will result in a loss of machine accuracy.

Often the actual compensation map increment is selected based on secondary reasons (i.e. matches the increment of a step gauge or is simply a round number). In some cases map increments are selected with the believe that using a very small increment will improve the performance of the CMM. Most calibrators only have one opportunity to fully map a machine so comparative tests where the map increment is adjusted are never performed.

Description

The compensation map is a description of the machine errors from a perfect orthogonal axis system. For machines that are 'perfect' no compensation map is required but these machines are nearly impossible to manufacture so some sort of compensation is usually applied to try and make the machine behave as though it was mechanically perfect.

The compensation map increment is the distance between measurement sample points of a compensation map. Measurements are performed between the full range of the axis at the compensation map increment for all parameters.

The description of the machine errors contained in a compensation map are standardized to roll, pitch, yaw, horizontal straightness, vertical straightness, and scale error for each axis. Additional layers of correction can be added to the basic compensation data which could be hysteresis compensation, parametric compensation, dual scale compensation, or a variety of other systems that are usually machine and manufacturer specific.

The machine errors recorded in a compensation map are relative values to a reference or zero position. The recorded errors at the reference point do not need to be zero nor does this point in the volume need to be at XYZ coordinate zero.

Maximum Map Increment

The maximum map increment represents the largest step size that can be used and provides enough information in order to have suitable error correction or meet machine accuracy expectations.

This upper limit was tested by simulation. Using a spreadsheet a typical machine error curve was created then compared with samples taken at two, three, five, and seven point increments along the range. The formula for the error shape is:

$$err = 0.002\,x + 0.0000135\,x^2 - 0.00001125\,x^3$$

Where:

err = calculated error at position x in millimeters
x = position along axis in meters

This expression was randomly chosen which provided a resulting shape and magnitude this is typical of angular errors from a CMM. The angular data is used for this calculation as it is the most sensitive and typically the largest. For some machines errors up to 100 um/m over the length of the axis is not out of the ordinary.

A curved shape is typical for most measurement errors observed on machines. The final shape of a machine axis is the result of any number of factors related to manufacturing or stresses from assembly. These components will never have short increment changes but instead have gradual curves and twists over the entire length.

The following shows a graphical representation of the simulated machine error and the resulting interpolation from two, three, five, and seven point samples along the length of the data.

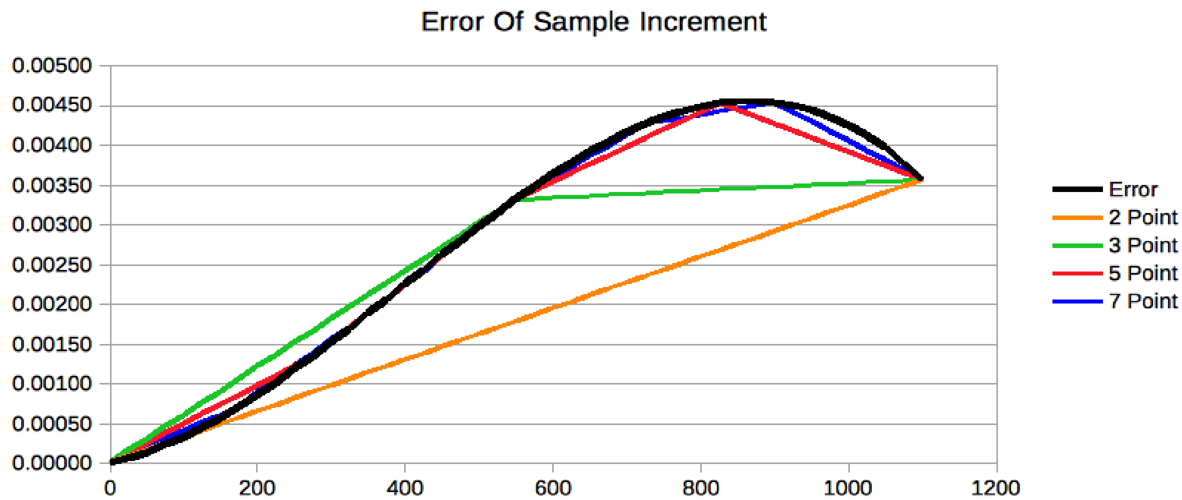


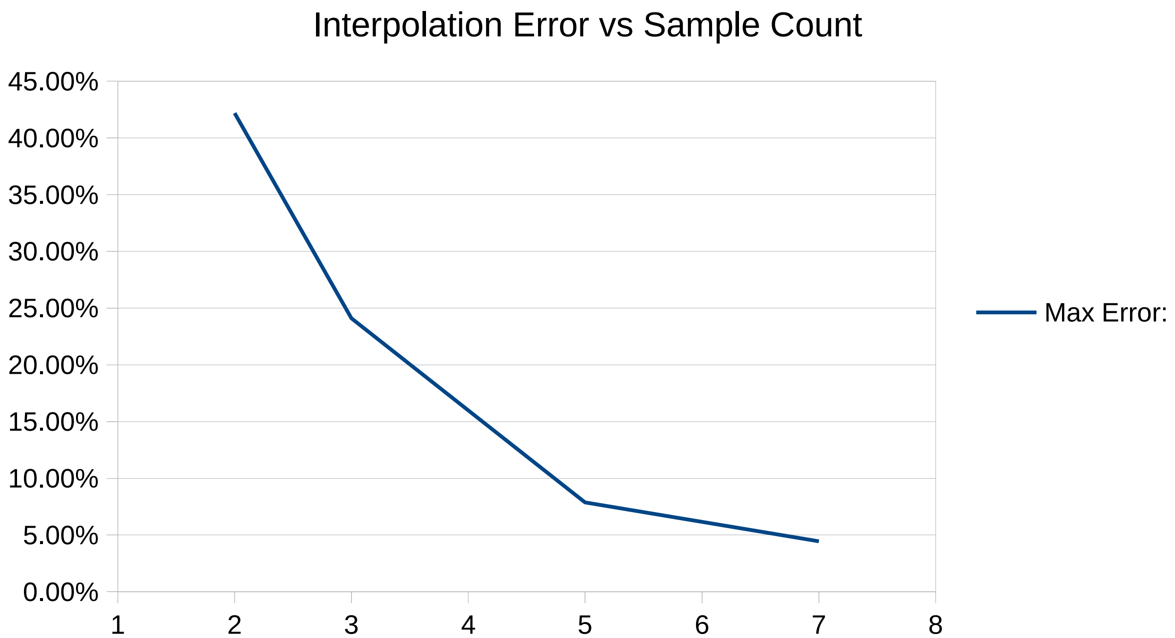
Illustration 1: Comparison of simulated error with various increment samples

Based on the data generated in the spreadsheet for a measurement error of 1100 mm in length the following was observed:

Number of Samples	Increment	Error (percentage of maximum input error)
2	1100 mm	42.2%
3	550 mm	24.1%
5	275 mm	7.9 %
7	157 mm	4.5 %
Approach Infinity	Approach zero mm	0.0%

The error value was calculated as the difference from the original input shape and the interpolated result using only the samples points. When using only two points (line drawn between first and last point of the axis data) the difference between the real shape and the interpolated shape can be quite high. The value is reported as a percentage of the difference between the interpolated shape to the real shape compared to the magnitude of the error from the real shape.

Although not unexpected the more samples used along the data axis range the better the results.



llustration 2: Comparison of interpolation error to number of samples along length of axis

An interesting observation is with the five point sample of the error along the axis range the residual error was less than 10% or the original input error. The shape of the input error has an impact on these results therefore a shape was chosen that is somewhat typical for a CMM axis parameter.

Based on this a typical axis should have a no less than seven samples along an axis. This gives a reduction of machine error by approximately 95% from the original error. By extrapolating these results ten sample points along a machine axis should represent most typical machine errors with an accuracy of approximately 99%.

Minimum Map Increment

The minimum map increment represents the smallest compensation map step that should be used where using a value smaller than this is actually detrimental to the accuracy of the machine. In theory as the map increment decrease the results should improve but in practice this is never true.

The lower limit for the compensation map increment is based on the amount of noise in the actual measurement. Noise is a general term and can be from a variety of sources including the equipment, machine, and environment. Vibration from the environment often contributes to non stable results that frequently require filtering by the equipment to produce a stable value. The machine will have mechanical repeatability problems which can often be seen by performing bi-directional measurement tests. Some measurements performed are at the resolution of the equipment used which contributes to measurement noise.

To get an idea of the amount of noise introduced consider that a machine axis likely has only gradual slopes and curves to the shape. By comparing the collected data to the smooth ideal shape an indication of the noise level can be determined.

Compensation Map Increments

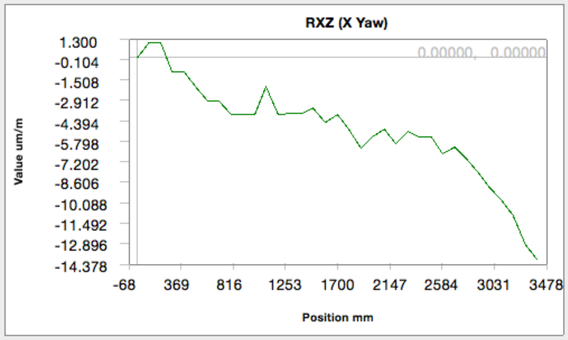


Illustration 3: Measurement of a parameter showing effects from sample noise

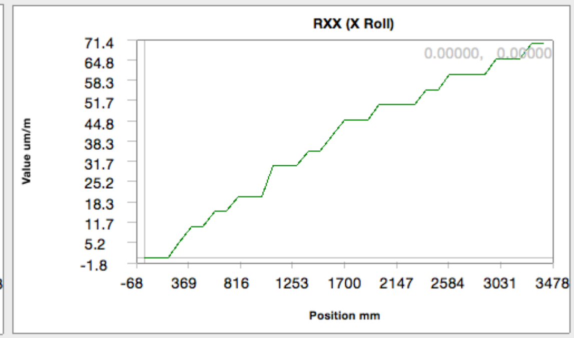


Illustration 4: Measurement of a parameter showing noise partly due to the instrument resolutio

In general the measurement noise is small in relation to the error that is measured. When the measurement step size becomes too small this noise begins to create a new type of short distance error. The end result is typically seen as large form error measurements on artifacts that are known to have a (nearly) perfect form.

Illustration 5 shows the effect of introducing a 0.001 mm random noise to a parameter measurement and the effect of this from different sample increment values.

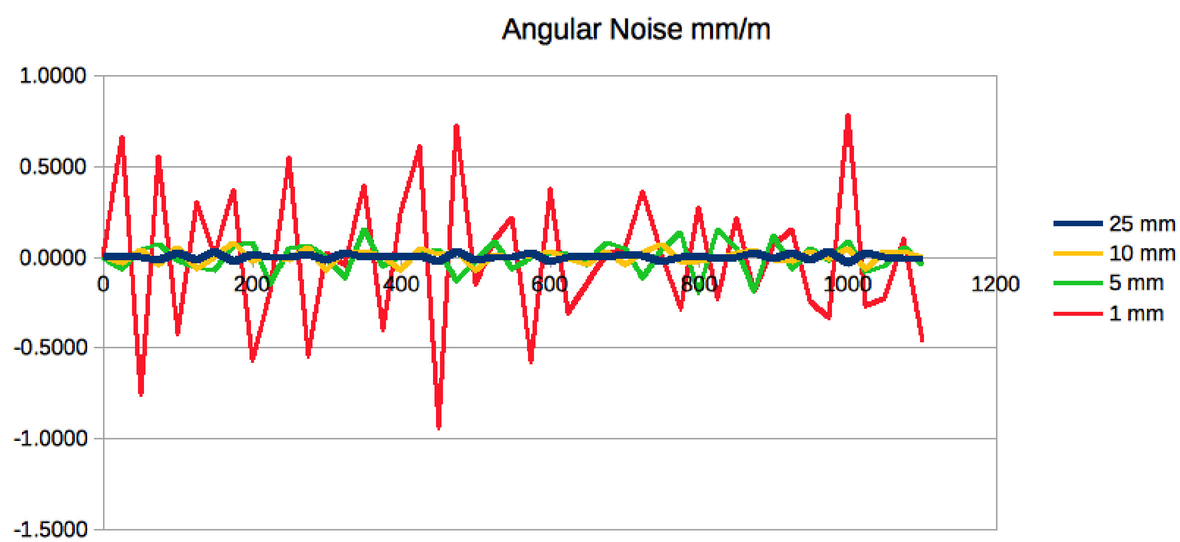


Illustration 5: Effective change in angular data between increments due to noise. Some results are approaching 1 mm/m of angular error with a 1 mm map increment.

The random noise is applied to an angular map parameter. The effect of this noise will vary depending on the distance the angular value is applied to. The further away from the reference axis with the noise the larger the effect will be. The generated values are calculated as the error at a distance of 1000 mm from the reference axis.

The simulated results are described in the following table.

Noise	Increment	Noise StdDev
0.001 mm/m	25 mm	0.0165

Compensation Map Increments

Noise	Increment	Noise StdDev
0.001 mm/m	10 mm	0.0402
0.001 mm/m	5 mm	0.0846
0.001 mm/m	1 mm	0.4024
0.001 mm/m	Approach zero mm	Infinity

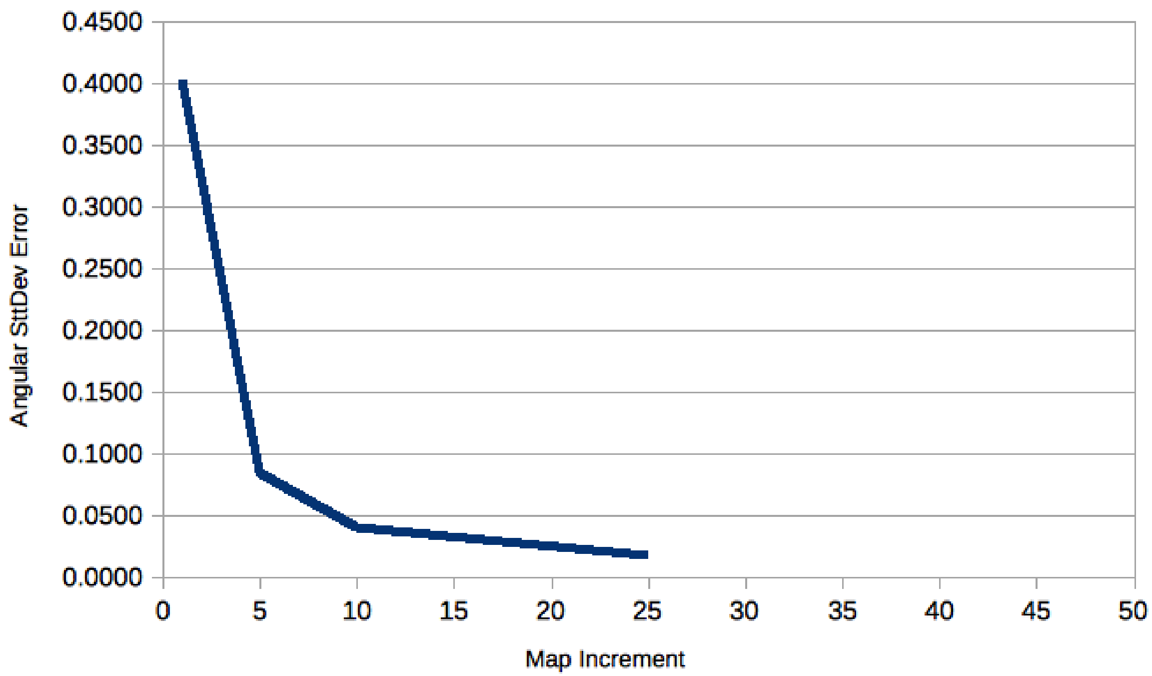


Illustration 6: Simple extrapolation for minimum map step

The following is an example of one particular machine which had a great deal of measurement noise. Since the belief that a smaller map increment is better there are many examples of this in the field.

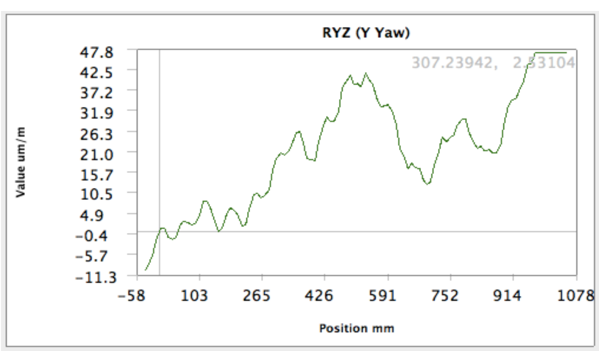


Illustration 7: Noisy angular data collected with small map increment

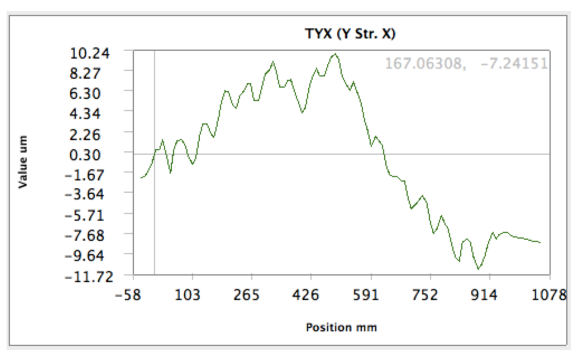


Illustration 8: Effect of noisy angular data on corresponding straightness measurement

Compensation Map Increments

The noise from the angular data had a direct impact on measurements of a step gauge (illustration 9) which under normal conditions would typically have an error bandwidth of no more than 0.001 mm for this particular model of machine.

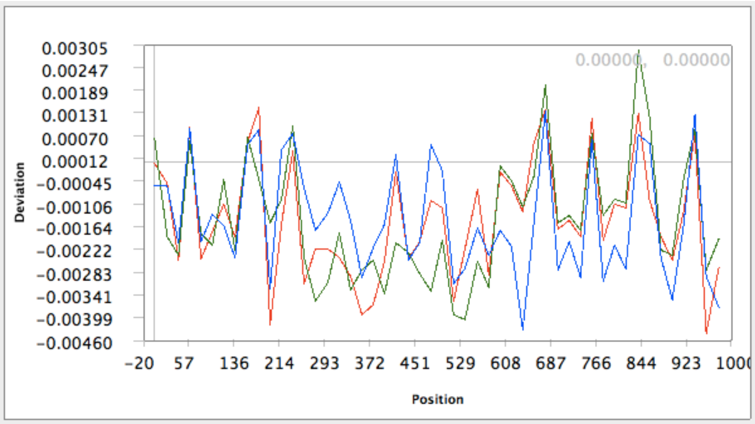


Illustration 9: Influence of noise on scale measurement performed using a step gauge.

There may be an advantage of having small map increments with filtering knowing that no one measurement may be entirely correct but there are sufficient measurements to better define the average shape through the data. It is not clear if this is actually an advantage over having better, less frequent, samples of the data through the volume. The extra measurements require additional time which is more likely to result in thermal drift of the data.

Based on this a typical axis map increment should be no less than 50 mm. For increments smaller than this some additional technique must be used to remove the measurement noise.

Opinions

Since there are many contributing factors it is necessary to judge each machine on a case by case basis. Some machines are very mechanically accurate and do not require too many map steps and other machines are simply too noisy to benefit from having many map steps.

It has been suggested that the map steps should be based on the dimensions of the air bearings (this has been stated many times by many people). Although this is likely fiction the dimensions of air bearings happen to be about the right size in most cases and grow proportionally with the size of the machine that if this was used it wouldn't be a problem.

Based on this and past observations the compensation map increment for any coordinate measuring machine should be in the range of 50 – 200 mm.   The smallest increment should be no less than 50 mm and the largest should be no greater than 200 mm provided this gives at least 10 sample points along the axis. The choice of 200 mm maximum (10 samples minimum) for the upper limit is done as this is a respectable distance. Machines with an axis of greater two meters will likely have additional errors and can benefit from the additional measurement samples.

Mechanically Accurate Machines

There have been many who argue both for and against mechanically accurate machines for a variety of reasons. As an argument supporting mechanically accurate machines these tests show that geometric compensation will produce significantly better results than a machine which was not designed to be mechanically accurate and only relying on geometric compensation.

Filtering Of Map Data

Filtering map data is generally considered to be a good idea particularly if the map increments are too small or measurement noise is too great. One problem that should be considered is the effect of over filtering. A filter with a cutoff of around 50 mm should be the starting point and increased if found to be insufficient.

As an option to filtering repeated measurements of an axis will produce naturally filtered results when all of the samples are averaged together. This can also be a good method to determine the amount of measurement noise.

One observation about filtering is that some vendors have adopted this process automatically. They produce compensation maps with very small increments containing heavily filtered data. These machines are likely not mapped using the very small increments but interpolated down to this very small increment.