Mach3 Z Axis Screw Mapping, version 1.2

By R. G. Sparber

There is a fundamental truth in machining: if the error is constant, it can be reduced.

A feature of Mach3 Computer Numerical Control software is Screw Mapping which is just what the doctor ordered for reducing my Z axis error.

Screw Mapping accepts data that describes the imperfections of a lead screw and attempts to cancel this error during machining operations.

Static testing shows a random error of +2 -4 thou as the quill moved from fully retracted to -3 inches down.

With Screw Mapping, this error was reduced to ± 0.5 thou.

You may have ball screws which have far smaller error than my feed mechanism. Screw Mapping can reduce your small error to an even smaller value.

Using Mach3's Screw Mapping feature was very difficult for me. There was very little written about it, none in the user's guide. I had to figure out a few procedures plus deal with a few bugs. Since development on Mach3 has ended, workarounds had to be devised. Thankfully, I received some key help from Scott Nichols on the Mach3 support desk.

[1] You are free to distribute this article but not to change it.

It has taken me a while[2], but I have finally reduced random error in my RF-30 mill drill to where I have a hope of getting an overall error of no more than ± 0.002 inches.

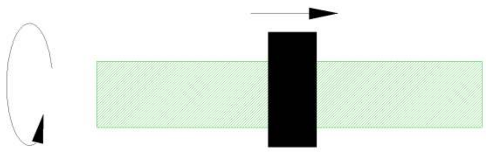
Since I am using my mill's original fine feed gears plus quill rack and pinion, there is a sizable error here.

I spent many days measuring over the full range of quill movement to convince myself that the error was ***stable*** to better than ± 0.001 inches.

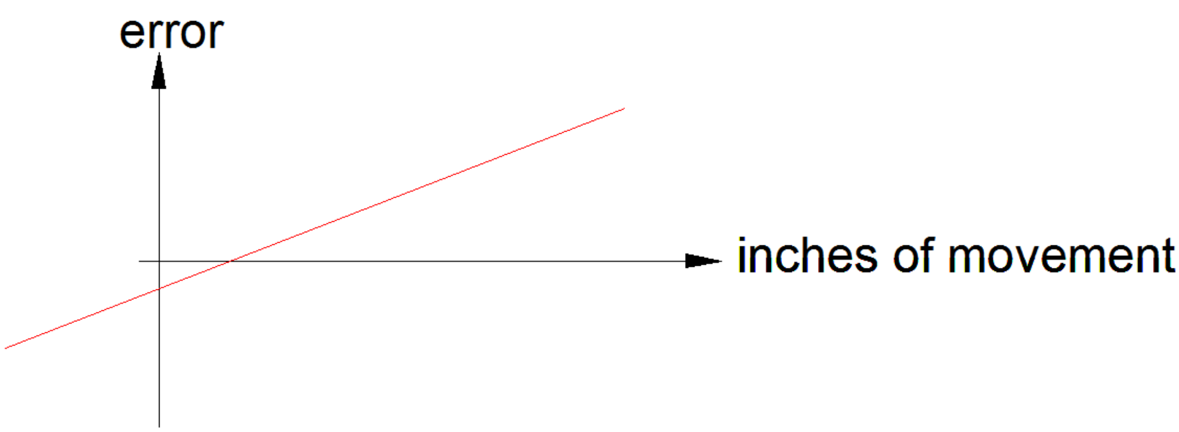
[2] See http://rick.sparber.org/ma.htm#13

Theory

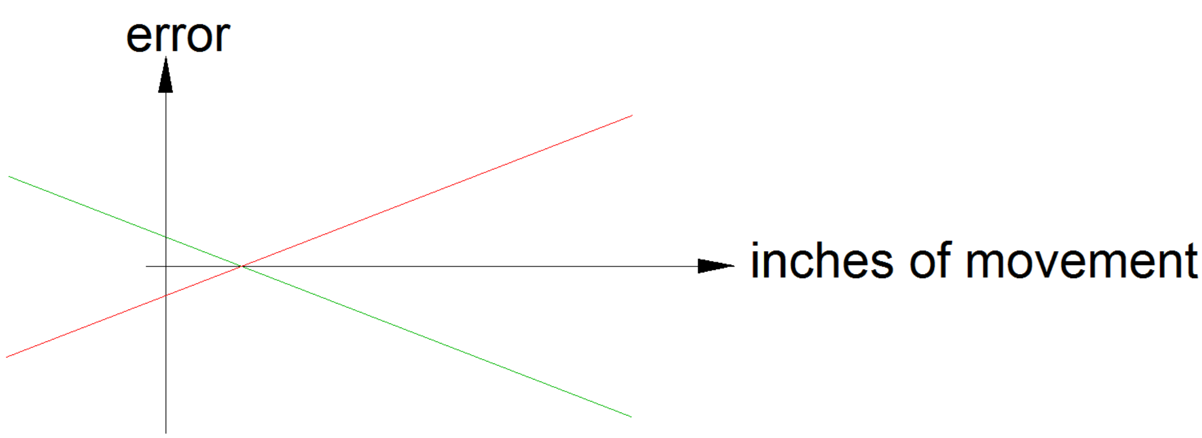
The concept of Screw Mapping isn't rocket surgery. Measure how the screw moves something and compare it to what you want. Then use this information to reduce the error.



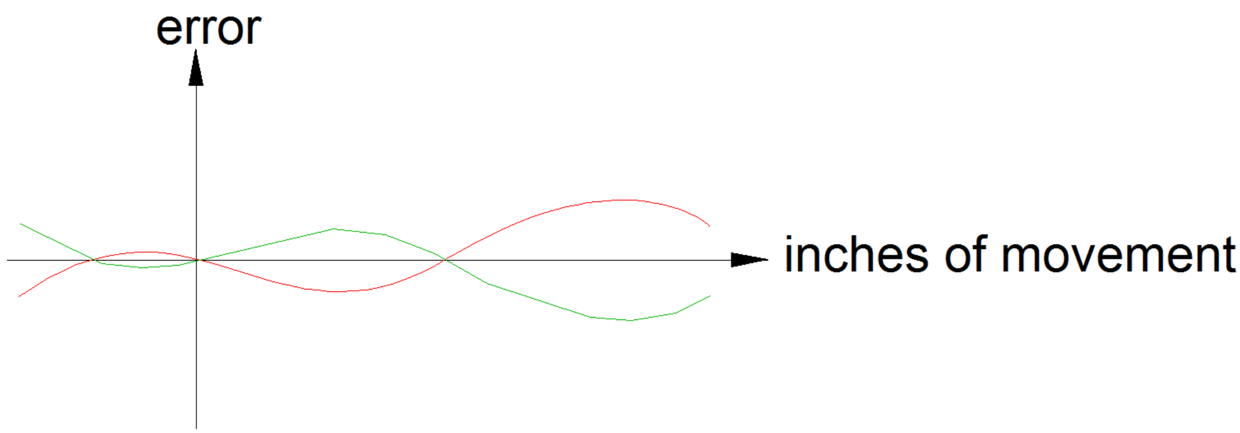
For example, say one revolution of a screw ideally moves the nut 1.0000 inches. But when you measured it, only 0.9975 inches was covered. The 0.0025 inches of error can be used to tell the software to turn the screw just enough more so the actual movement of the nut is 1.0000 inches.



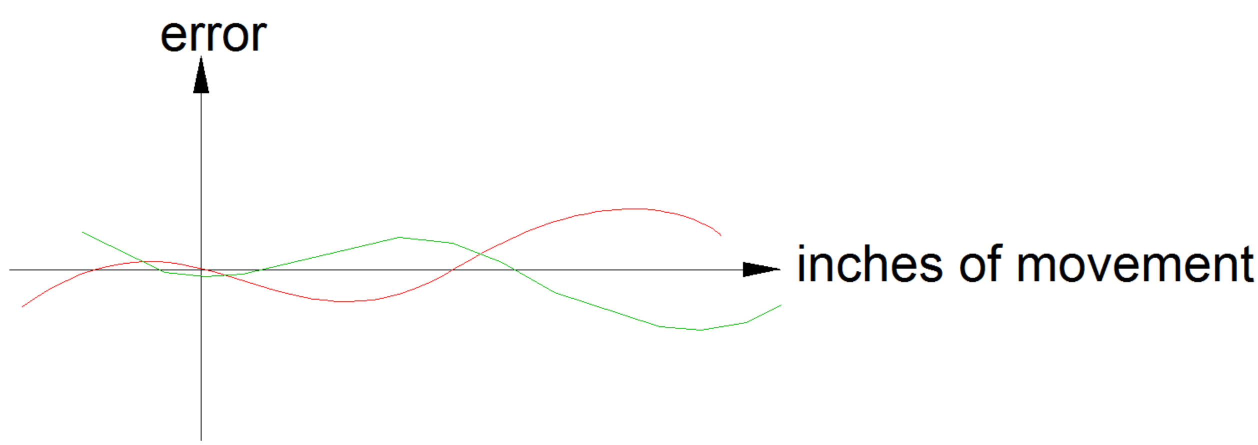
If the error is linear, then we only need to measure at the extremes of motion.



Correction of this error is a straight line. Pick any point along the horizontal axis and you can find a point on the red line, our error, and a point of opposite value on the green line, our correction. Adding the error and correction together will always equal zero error.



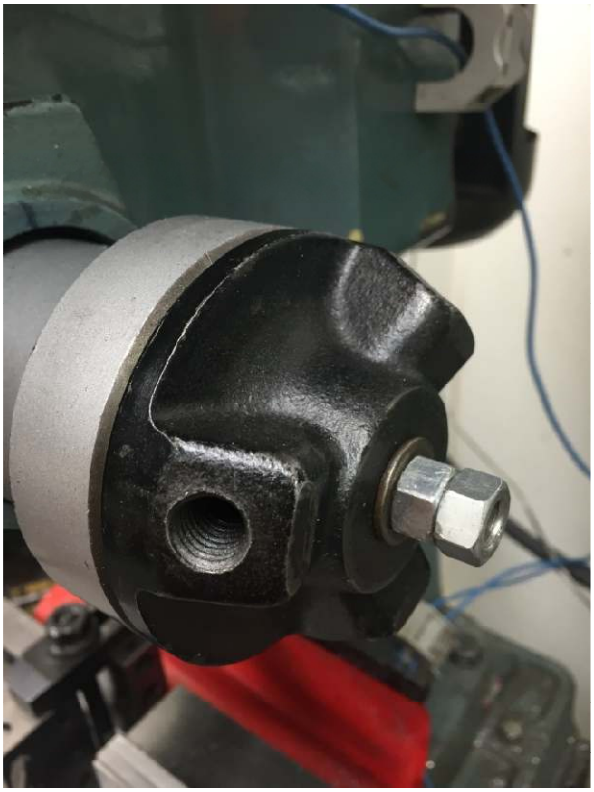
If the error is almost linear over a small range, then we can stitch together a series of line segments that approximately follow the actual error. You pick the acceptable residual error and that will set the number of line segments needed.



The red line is the error associated with our screw. The green line is a model stored in the computer that is designed to cancel this error. If the two lines are not perfectly aligned along the horizontal axis, the scheme falls apart.

It is essential that the start of the screw matches the start of the correction data. This is done by defining a physical location called "Home". With Home physically and logically aligned, the best possible error reduction occurs.

I raise up my quill until this 0.7000 inch tall spacer block does not fit in this gap. Then I lower the quill 0.0001 inches per step until it just slides in place. The quill is then at Home. By lowering the quill until I reach Home, backlash is avoided. All subsequent measurements were taken by lowering the quill down on spacer blocks.

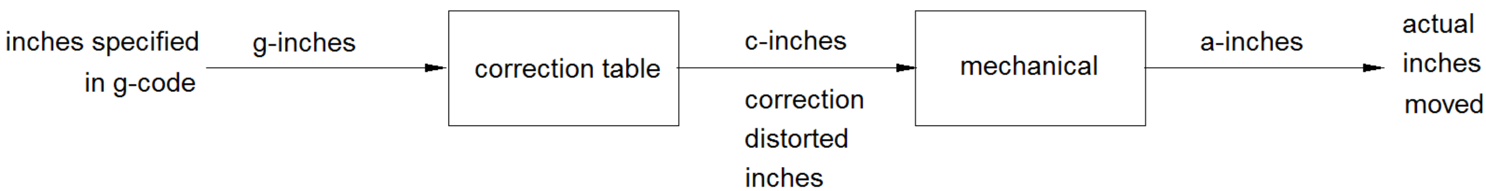


Paul Thompson noticed there was a flaw in my plan. Not only must the quill be set to Home, the gear train from drive motor to pinion gear must not change relative position. Variation in these gears contribute to error.

If the clutch was loosened, the quill would no longer be properly aligned with the data set. I have removed the knob that lets me easily disengage the clutch and replaced it with a length of threaded rod. Then I double nutted the end to prevent accidental loosening.

The Error Correction Process

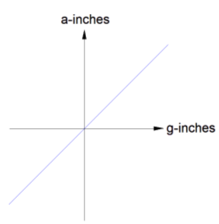
So far we have talked about how error is reduced by looking at graphs. Now let's talk about the process of transforming a g-code specified distance into an actual movement.



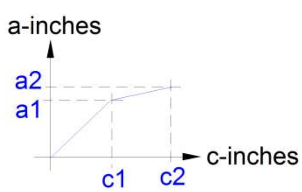
I can write "Z -0.250". This directs Mach3 to move the quill to -0.250 inches below the current point defined as zero. I give this number the units of "g-inches".

Mach3 feeds g-inches into a correction table containing our screw mapping data. The output is our correction distorted inches, call it "c-inches".

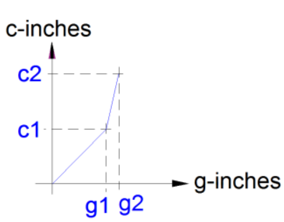
The c-inches are fed into our mechanical system. If the correction table entry is right, then the actual movement, in "a-inches", will exactly match the distance specified in the g-code.



Graphing this relationship, we have a straight line at a 45° angle. If I have 1.000 g-inches, I expect to get 1.000 a-inches.

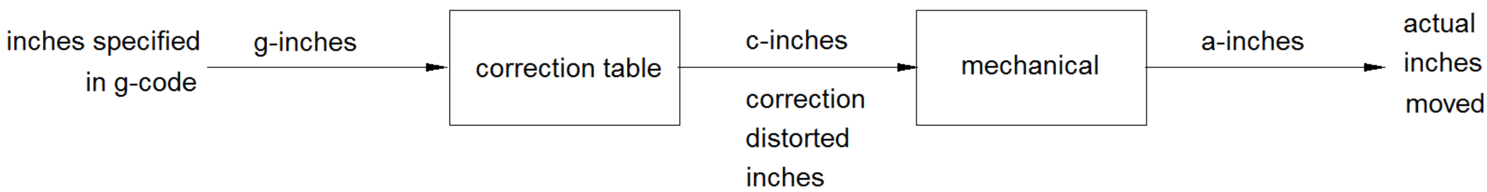


Here is one possible behavior for my mechanical system. From zero to **c1** c-inches, I have one mapping. From **c1** to **c2** there is a different mapping. If I input **c2** c-inches, I will get a quill movement of **a2** a-inches.

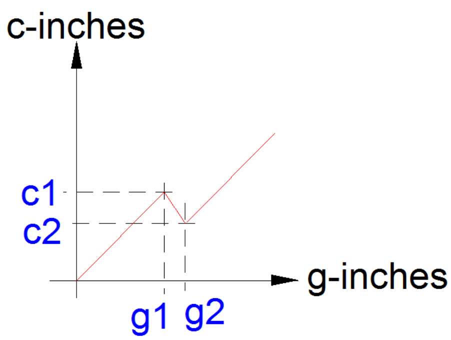


By carefully measuring the actual behavior of my mechanical system, I can create my compensation table. If I input **g2** g-inches, I will get out **c2** c-inches.

Putting it all together, say I specified **g2** g-inches. This goes into my table and out comes **c2** c-inches. Value **c2** is *larger* than **g2**. Then **c2** is fed into my mechanical system which moves **a2** a-inches. Value **a2** is *smaller* than **c2**. This is one case where two wrongs make a right. Movement **a2** a-inches exactly equals **g2** g-inches.



Now for a little mind bending. It is reasonable to assume that as I increase my c-inch values, my mechanical system will cause an increase in a-inches. The increase may be a complicated function but should at least go in the right direction. It is hard to image a leadscrew that would move in one direction as you turn it and then change directions as you continue to turn. No such limitations exist for our correction table.



I can easily construct this correction table. Starting at 0 g-inches, I output 0 c-inches. As I move from 0 to **g1** g-inches, the output goes from 0 to **c1** c-inches. This is no different than in the last example. But as I continue to increase my input and go from **g1** to **g2**, my output *decreases*. This forces my mechanical system to reverse direction. My quill moves in the opposite direction as I go from **g1** to **g2**. Then when I pass **g2**, the direction flips again. Further increases in g-inches causes an increase in c-inches. At each c-inch reversal in direction, backlash compensation kicks in.

Consider what happens as I slew from 0 to beyond **g2** g-inches. I smoothly move from 0 to **g1** g-inches and output 0 to **c1** c-inches. Then there is a whole lot of gear slamming as the motor changes direction and then changes back. As I move beyond **g2**, all is quiet again. In my system, this little bit of excitement causes lost steps. In other words, a-inches no longer equal g-inches. I must re-establish my zero point and start all over. But if I do not fix the correction table, the problem will repeat.

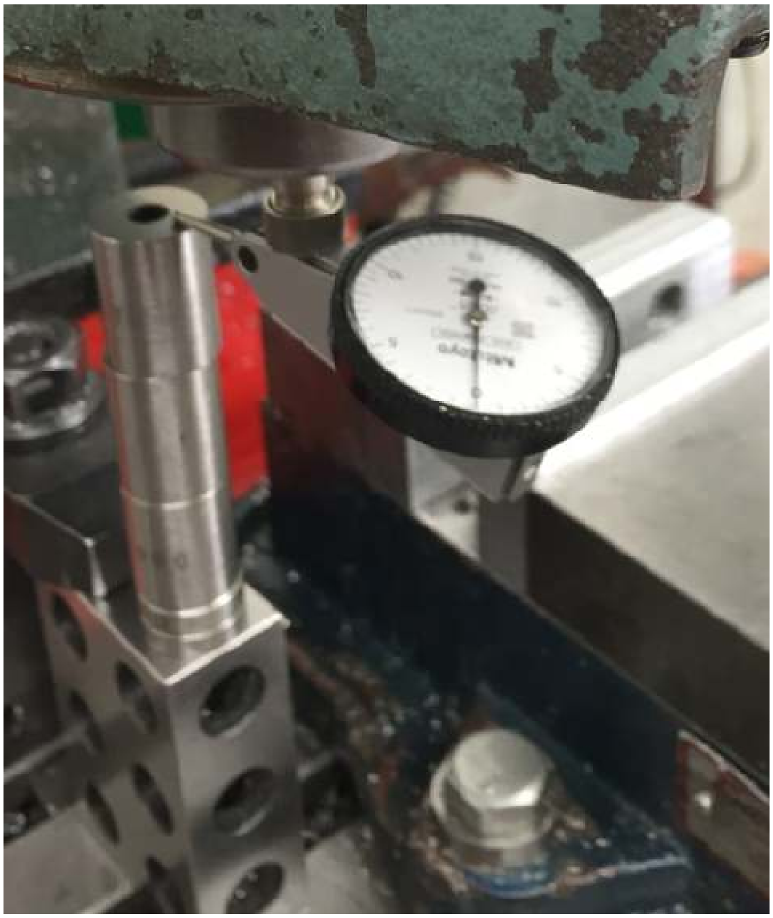
The length of the backwards segment doesn't matter. Even a 0.0001 inch back step will cause motor direction reversals and possible loss of steps.

If you enter a correction point and later want to change it, there is a risk that you will not be at exactly the same g-inch point. If the new point causes a change in direction for c-inches, you may lose accuracy.

Adding correction points away from the existing ones should present little risk of causing a direction reversal.

Preparation

Before I started to look seriously at Screw Mapping, I had to verify my error was repeatable. It took me weeks to find and minimize all sources. I will leave that side trip for another article.



Two instruments are essential for setting up Screw Mapping.

You must have a means of detecting when you are contacting a reference surface. A finger Dial Test Indicator (DTI) that reads ± 15 thou is my choice. It has minimum error when reading zero. The larger the deviation from 0, the more error creeps into the reading[3]. I can easily see a movement of 0.0001 inches.

You must also have known distances. I own a spacer block set from Enco[4] that is accurate to ± 0.0001 inches.

Together, these instruments can show me a change in position of better than ± 0.0002 inches. The data used by the software is limited to the nearest 0.001 inches. In my measurements and calculations, I will carry four places to the right of the decimal and round to three before giving it to Mach3.

[3] See http://rick.sparber.org/Articles/DTI/DTI.htm
[4] Model #630-4050

Repeatability
Recall that the cornerstone of minimizing error is having repeatability. Using my DTI and stack of spacers, I moved the quill up and down five times and recorded the position of the DTI's needle. In all cases I lowered the quill down onto the surface of the spacer to avoid backlash.

My first round of data was at Home. Each of the five data points was within 0.00005 inches of zero. This error is about half the thickness of the DTI's needle.

Next I tested at one inch extension of the quill. The first data point was at -0.0007 inches and the remaining three were at zero.

At an extension of two inches, the first data point was at -0.0004 inches and the remaining three were at zero.

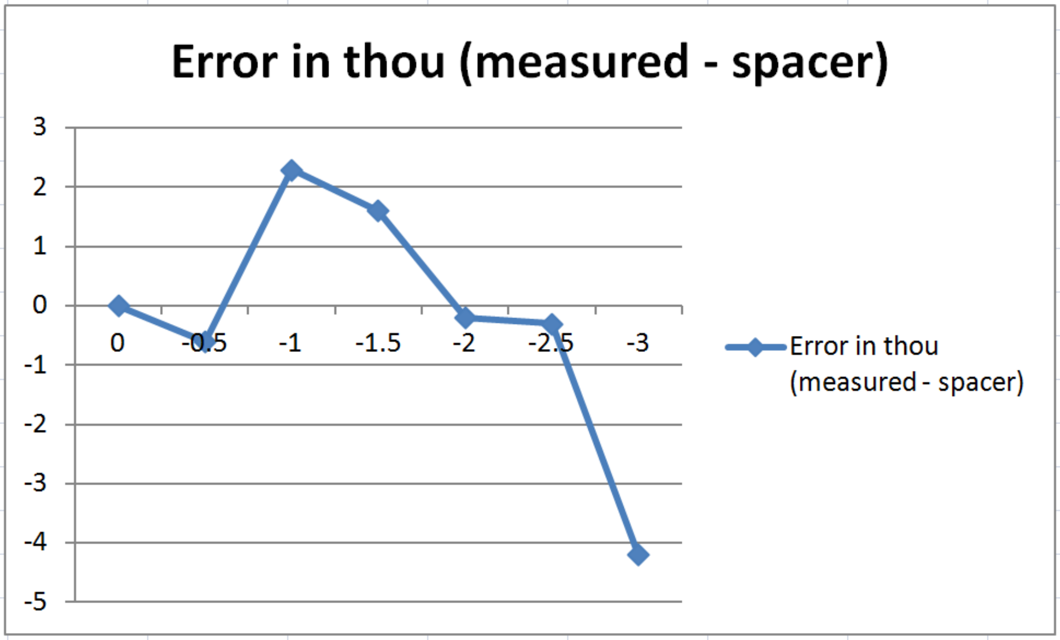
At an extension of three inches, all four data points were at - 0.0003 inches.

At four inches, all data points were zero.

Bottom line: I have repeatable error at these four quill positions. It is likely but not proven that I have repeatability from zero to four inches.

Although the quill will extend down four inches, I would not run an end mill out there. At least for now, I will concentrate on zero to three inches.

Error



Here is a typical error run. I set zero at Home so there is no error there. When I lower the quill down to -0.5000 inches, my error is -0.6 thou. Moving down another 0.5000 inches gets me an error of +2.3 thou.

Note that data only exists at the squares. The lines are linear extrapolations of the data. Could I be jumping right over large spikes in error? Sure. We might need to reduce the change in quill movement between each data point. Only experience can tell.

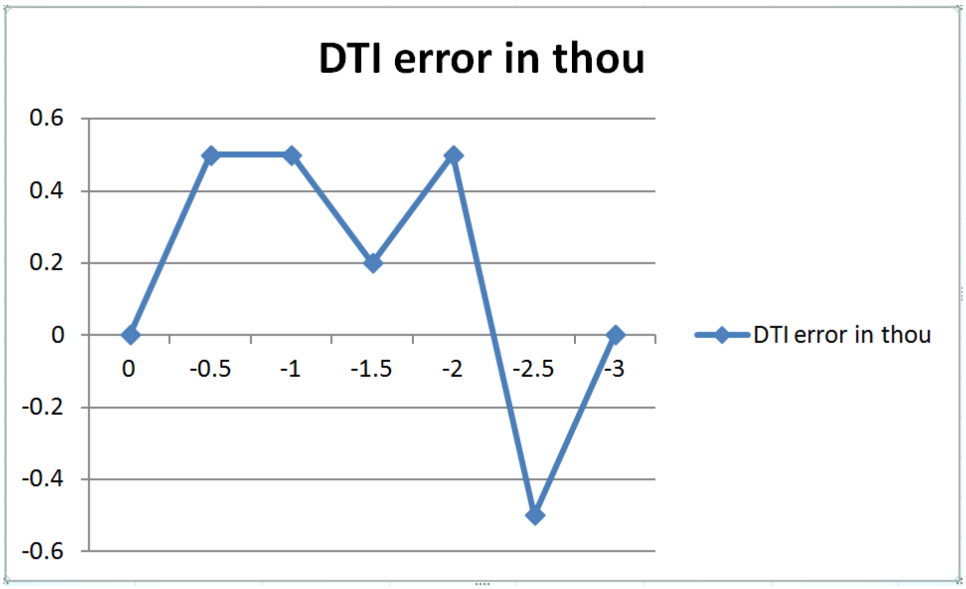
To better see how well linear extrapolation works, say we did not take a measurement at -0.5000 inches. The error is zero at 0 inches and 2.3 thou at -1.000 inches. Since -0.5000 inches is half way between them, the linear extrapolation of these two data points tells me the error is also half way: 1.15 thou.

My direct measurement of the error at -0.5000 inches was -0.6 thou but my extrapolation from adjacent points predicted an error of 1.15 thou. Not very impressive. There is a lesson here: the larger the change in error, the larger the need for more data points.

It is likely that measuring between -1.0000 inches and -1.5000 inches would turn up an error close to 2 thou.

For now, I will limit myself to data only at 0.5000 inch multiples. Before I am done mapping my quill, a much larger data set will be generated. No change in theory, only a closer estimate of the error.

Screw Mapping Results

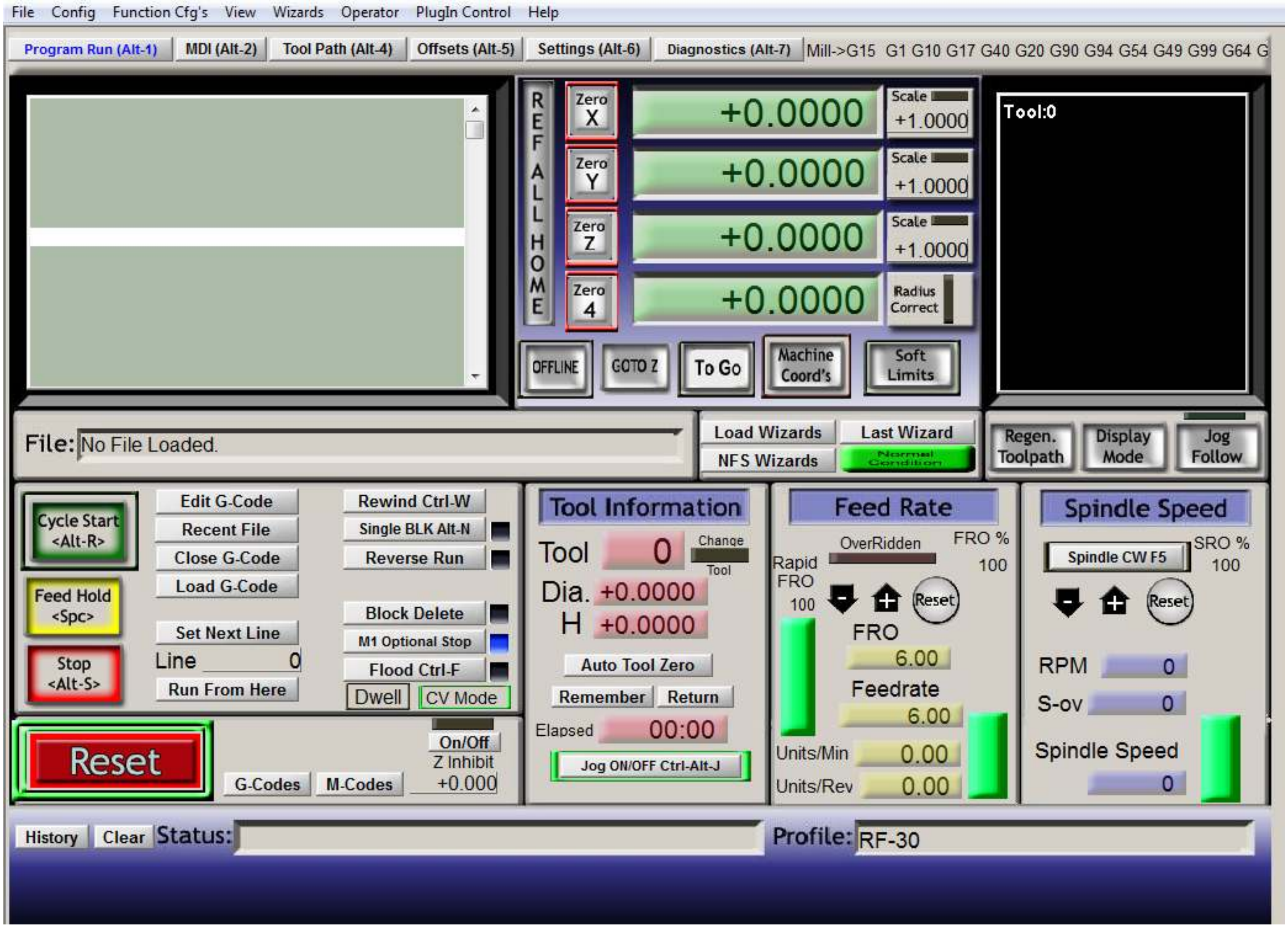


This data is surprising good although at first glance, it may seem to be all over the place.

The mapping software only accepts corrections to three places to the right of the decimal. This means that I must round my corrections to the nearest thou. That alone generates an uncertainty of ± 0.5 thou.

Before mapping, I had an error of +2.3 - 4.2 thou. After mapping, the error was ± 0.5 thou . This is an error reduction by a factor of 6.5. I know I will have to give some of this back when actually running the mill. But it sure feels great to see it all working here.

Mach3 Screw Mapping



Here is the Program Run screen of Mach3. I am running version 2.0 as noted on the startup screen[5]. If you are not running this version, some of the following may not apply.

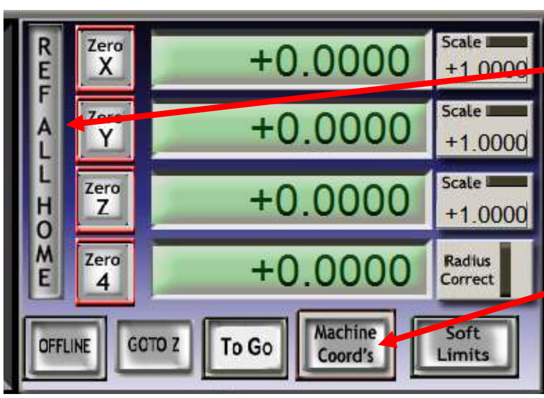
[5] If I go to the menu Help and click on About Mach3… I see Version R3.043.066.

No Place Like Home

All data measurements must be preceded by locking in Home.

I first physically go Home by using my 0.7000 inch spacer.

Then I zero my DTI at the top of my stack of spacers.



Only then can I tell Mach3 that I am Home. Press the REF ALL HOME button. This zeros both the Current Work Offset as seen here on the Digital Read Out (DRO) and also the Machine Coordinates.

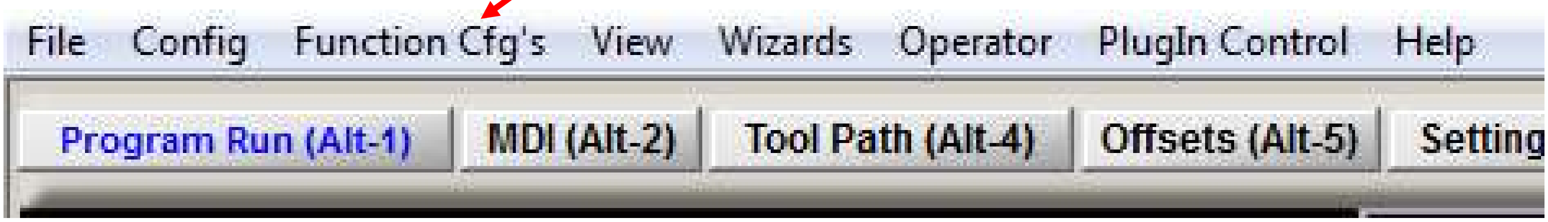
If in doubt about what was zeroed, press the Machine Coord's button and the display will toggle between these two sets of numbers.

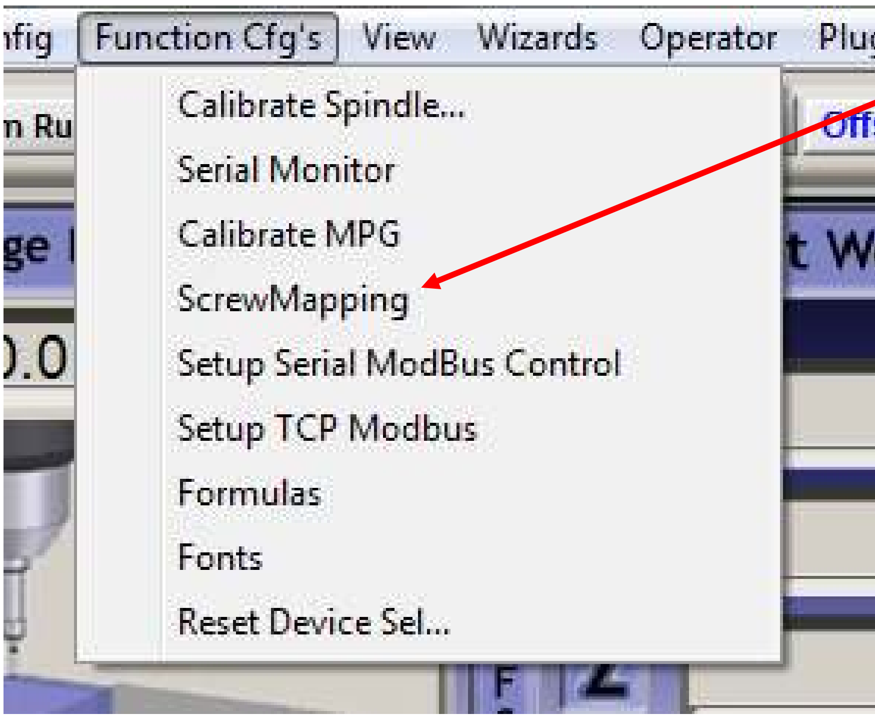
If you jog the quill such that the Z DRO reads ***greater*** than 0, you might hear the stepper motor shutter and then the quill moves to a value ***less*** than 0. I call this the "Alice In Wonderland Bug". You want to move up but you move down instead.

You may have the Z Axis Correction box checked. See page 18 for how to turn it off.

Running the Screw Mapping Feature

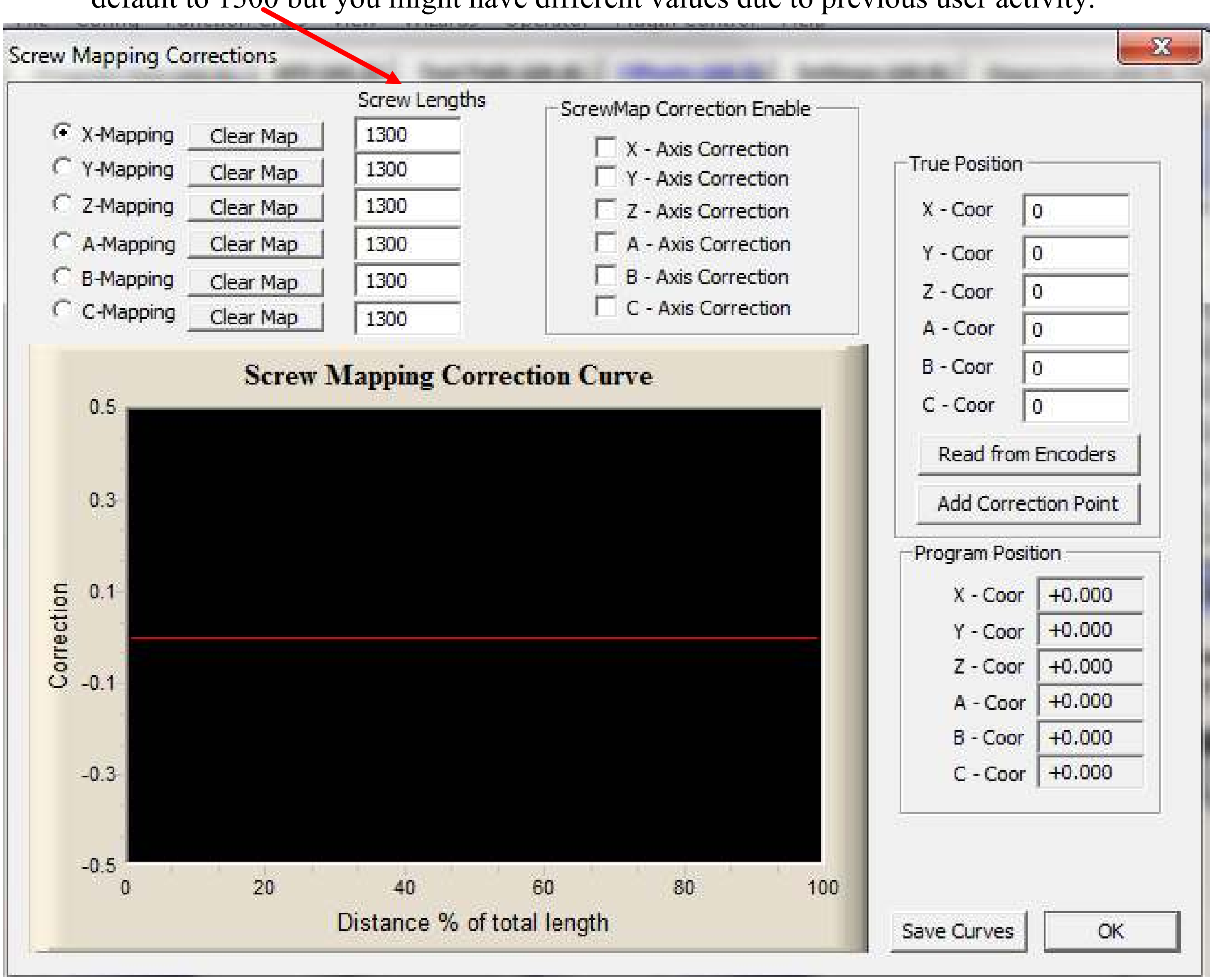
First select the Function Configurations menu.





Then select ScrewMapping from the drop down menu.

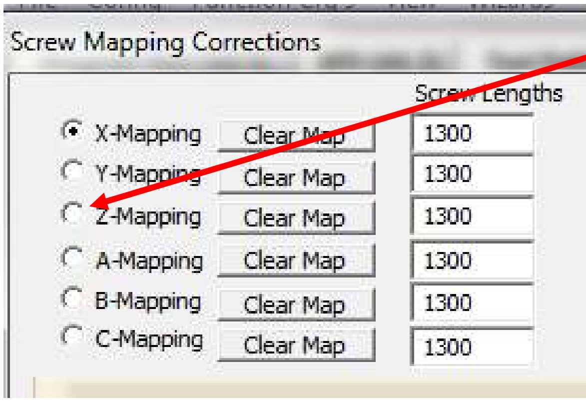
When you click on ScrewMapping, this screen should come up. Screw Lengths default to 1300 but you might have different values due to previous user activity.



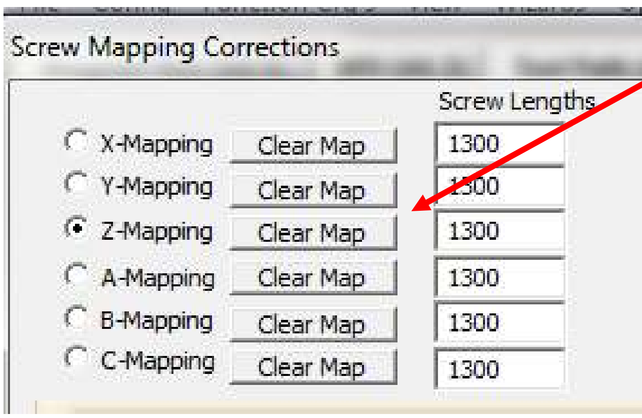
There are bugs in the ScrewMapping code. If you deviate from the following instructions, these bugs will plague you. In one case, your only option will be to press Clear Map and start all over again. Not pretty.

I have so far only performed Screw Mapping on the Z axis so that is what you will see below. At this point, I have no reason to believe that the X and Y axes will behave the same. As I gain experience with X and Y, I will amend this article.

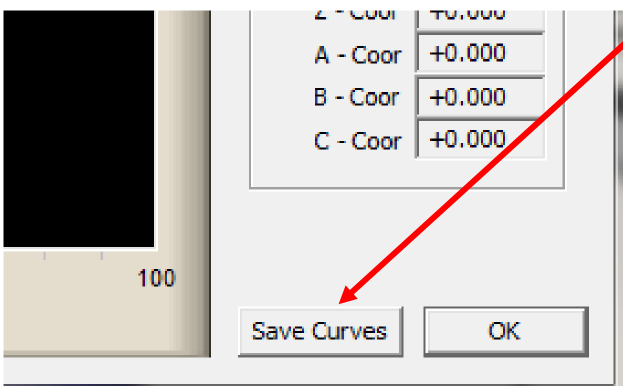
1. Set the quill to Home as shown on page 13.



2. Click on the circle in front of Z-Mapping. Failure to do this will cause all measurements to be put into the default error correction file associated with X-Mapping.



3. If you are just starting the Screw Mapping process, click on Clear Map on the Z-Mapping line.

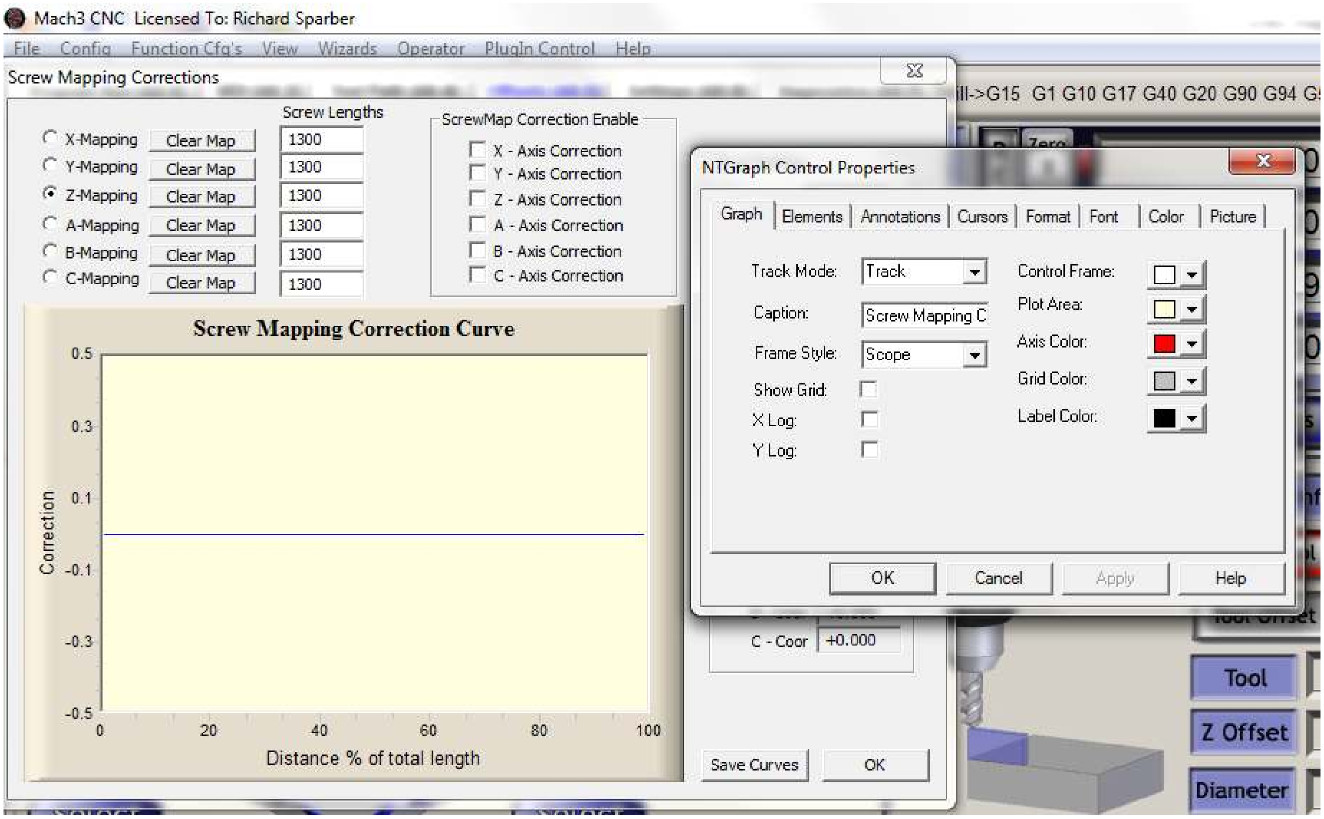


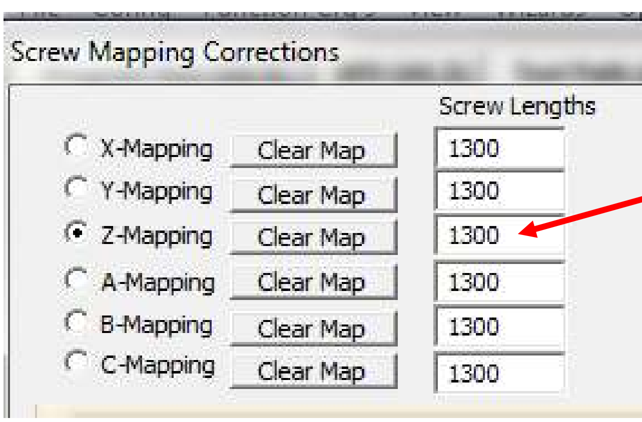
Then press Save Curve. This will erase all data from the Z axis correction file.

If you are unsure if the map has really been cleared, go to C:\Mach3 and then to your profile. Mine is RF-30 is go to C:\mach3\RF-30. Then go into the macros folder and fine the file curve2. Hover your cursor over the file name and it should indicate 36 bytes if empty.

Each correction point uses 16 bytes. So, for example, if the file contains 84 bytes, then after subtracting off the 36 byte overhead, we are left with 48 bytes. $\frac{48}{16} = 3$ correction points.

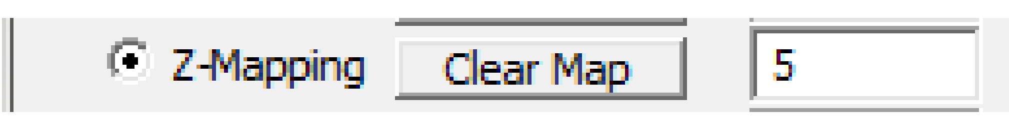
If you find the contrast between the curve and the background difficult to see, double click within the graph area. You will see a control box that lets you change colors. I changed the Plot Area to yellow. Click OK when done.



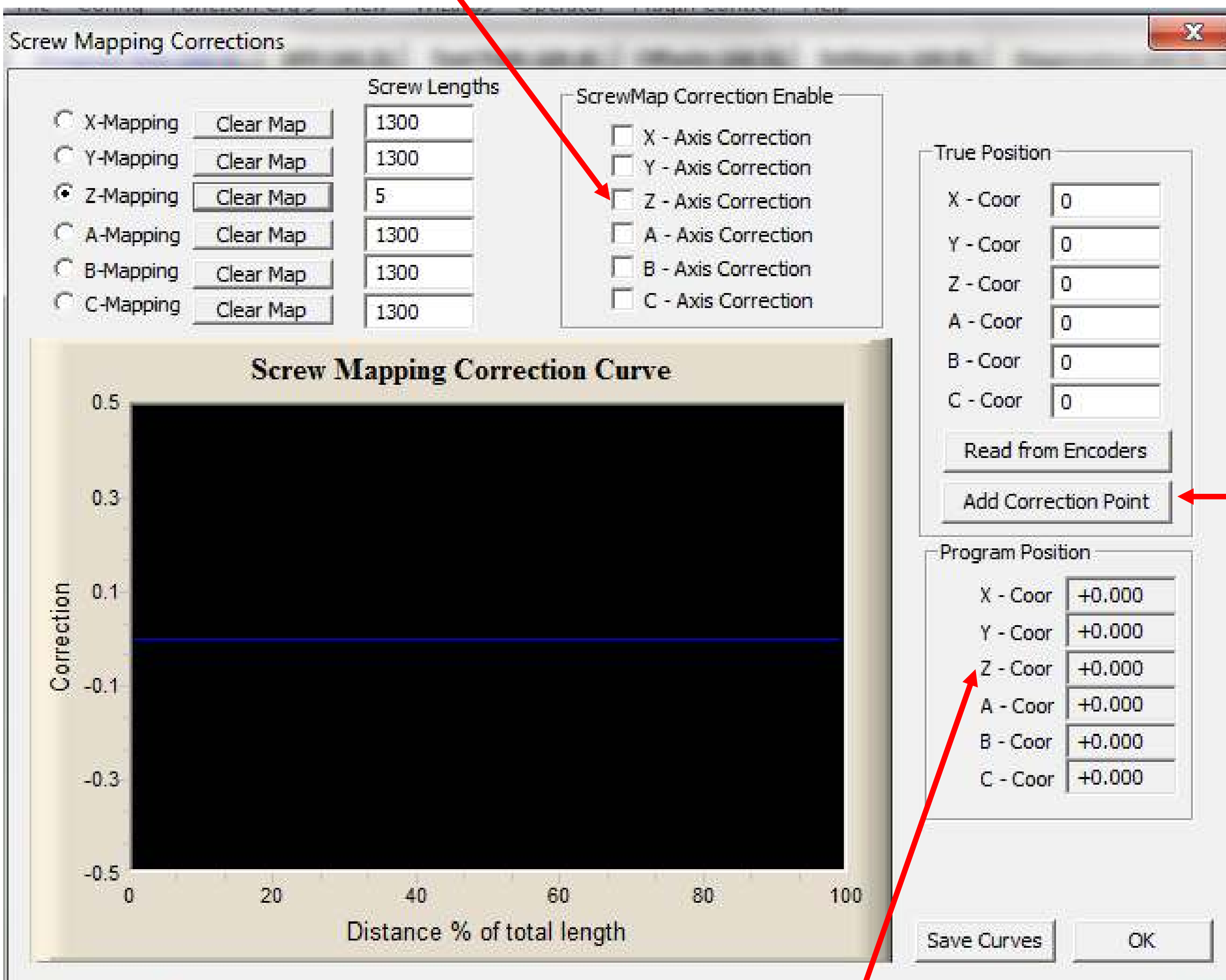


4. When you first set up Mach3, you had to tell it if you wanted to work in inches or mm. That choice comes into play as we set the Screw Length for the Z axis.

The minimum value is 5. Since I use inches, this is 5 inches. On the Curve display, 100% will now mean 5 inches.

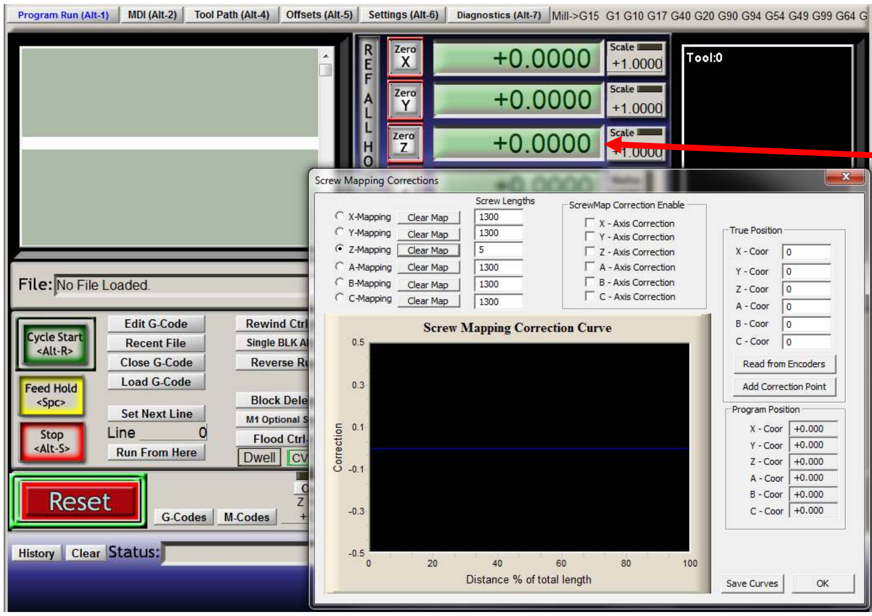


5. Verify that Z - Axis Correction is off.



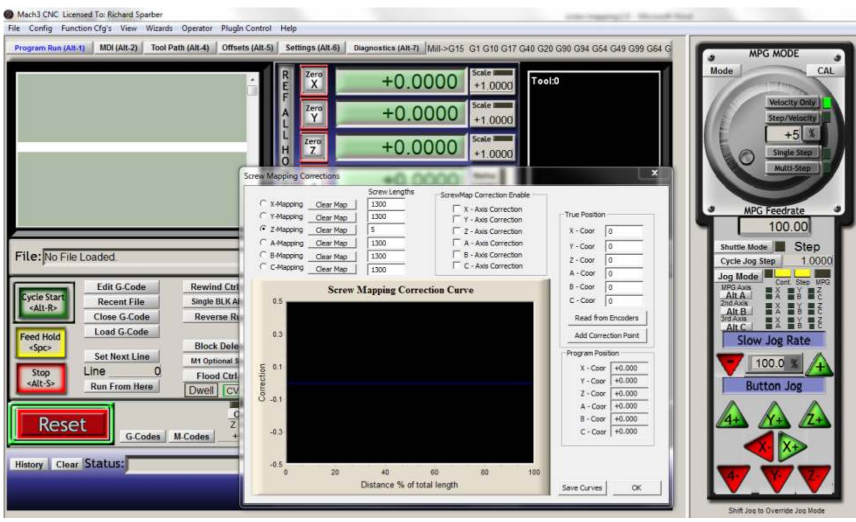
6. Verify you are really Home. Program Position, Z - Coor must be 0.000. If it is not, see page 13.

7. WARNING: We are now ready to start moving the quill and recording data. The quill is Home and the Program Position for the Z - Coordinate is 0. You might think it would be good to press the Add Correction Point button. ***Don't do it!*** That will trigger the second bug: The Z DRO window will show +1.#QNB. If you do accidently set a Correction Point while at Home, the only option is to press Clear Map and start all over again.

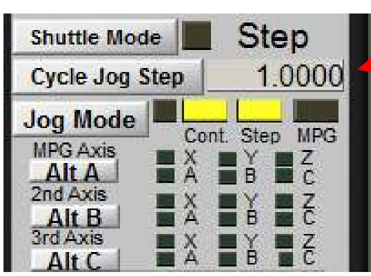


8. Move the Screw Mapping window over to the right and down so you can see the Z DRO window too.

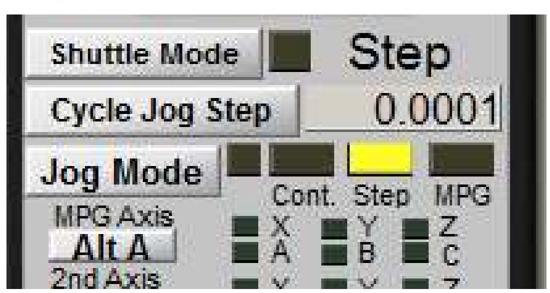
You will be moving between these windows as you enter data.



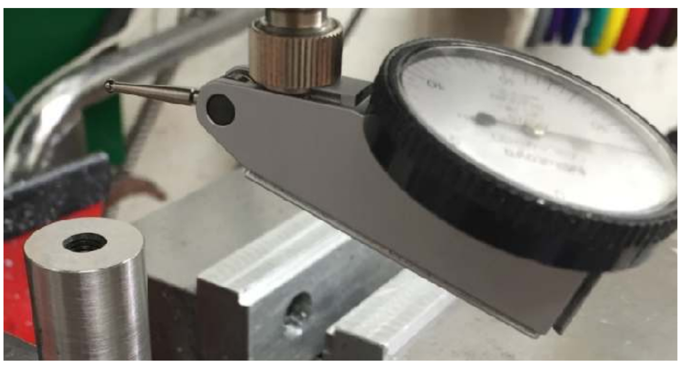
9. Move to the Program Run window and press Tab on your keyboard. The jog window should come up.



You can see here that the Step size is 1.000 [inch]. Press Cycle Jog Step until is show 0.0001. Then press Jog Mode until it shows only a yellow box above Step.



10. You are finally ready to actually input data. At the moment, I am at Home. My DTI is resting on top of my stack of spacer. The DTI has been zeroed and both the Machine Coordinates and my Z DRO read zero.

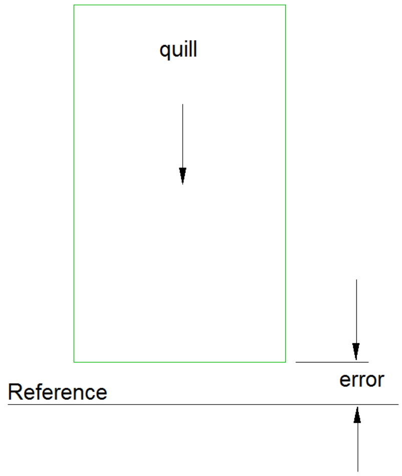


11. Remove the desired spacers in preparation for moving the quill down. Here you see a gap of 1.0000 inches.

12. If you tap the Page Down key on your keyboard, the quill should jog down 0.0001 inches. If you hold down the Shift key and then hold down the Page Down key, the quill will move down at maximum speed. It won't take you long to master the skill of quickly lowering the DTI's finger so it lands on the top of the spacer stack and with a few jogs, the needle will read zero.

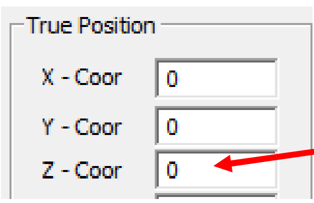
As the quill moves down, a white vertical line will move across the Curve window. If you do not see this line, review this procedure again. Something is wrong. Are you sure you have selected the Z axis for your data?

13. When the DTI reads exactly zero, read off the Z DRO value.



For example, I moved 1.000 inches down and the Z DRO read -0.9977. This means that I intended to move down 1.0000 inches but only moved -0.9977 inches; an error of 0.0023 inches.

But wait, we are about to receive another visit from the Alice In Wonderland bug. If you simple enter -0.9977 into the True Position, Z-Coor box, the resulting correction will cause an error twice as bad as no correction.



Instead, you will need to use this equation for the True Position:

$$\textbf{True Position Z Corr} = \mathbf{2} \times \textbf{Z DRO} - \textbf{Actual} \qquad (1)$$

Continuing the example from above, Z DRO was -0.9977 and Actual was -1.0000

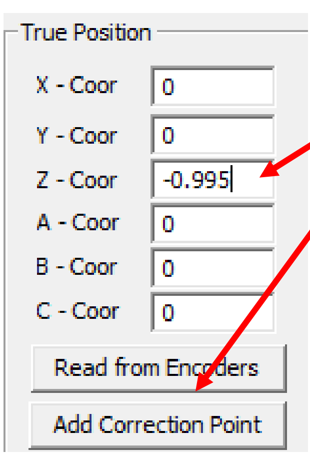
$$\textbf{True Position Z Corr} = \mathbf{2} \times (-\mathbf{0.9977}) - (-\mathbf{1.0000})$$

$$\textbf{True Position Z Corr} = -\mathbf{1.9954} + \mathbf{1.0000}$$

$$\textbf{True Position Z Corr} = -\mathbf{0.9954}$$

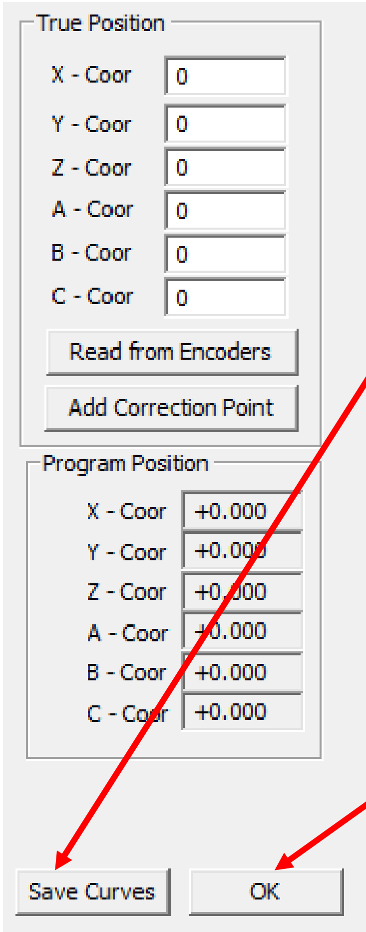
In other words, take the Z DRO value and add the error: -0.9977 + 0.0023.

Then round this value to three places to the right of the decimal: -0.995.



Enter this value into the True Position area within the Z-Corr box. Then press the Add Correction Point bar.

This may look way to complicated right now but after the first few data points it will be second nature.

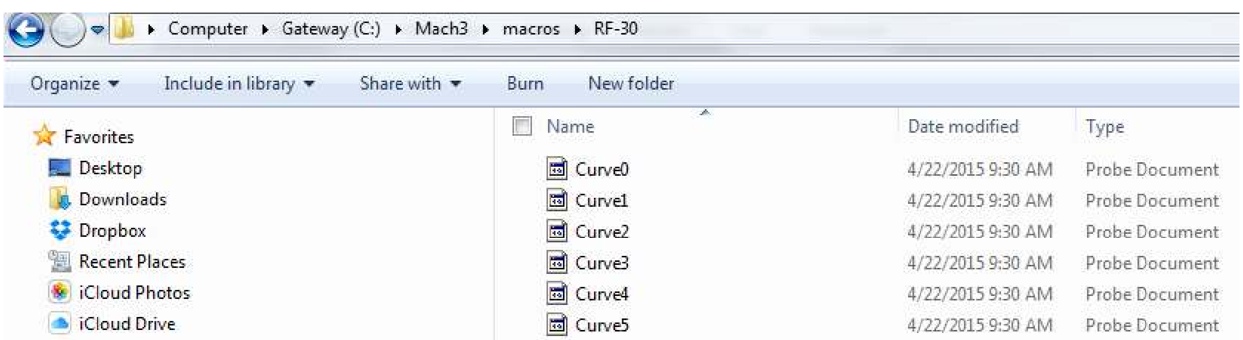


14. Repeat steps 11, 12 and 13 until all quill positions have been recorded. You ***may***[6] be able add more data points later. Be sure to Home first.

15. When done, press the Save Curves button.

Do not enable Screw Mapping yet. That will interfere with your efforts to move back to Home.

Then press OK to close the window.

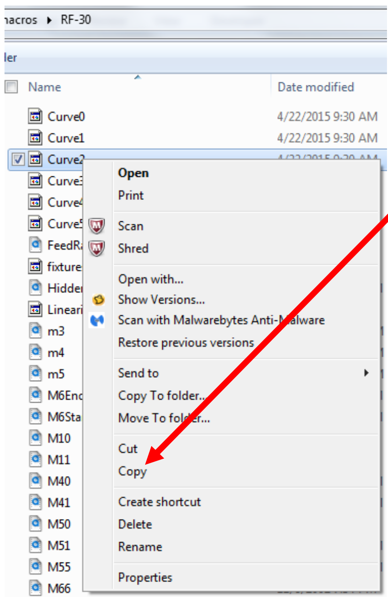


Having just put a lot of time into this data set, you may want to protect it. On the computer you run Mach3 on in your shop, you can follow the path C:\Mach3\macros and find the shortcut you defined for your machine. In my case, it is called RF-30. In there you will find the files Curve0 through Curve5. Curve0

[6] On one occasion I updated an existing data point and it caused violent stuttering of the drive motor and a large error. I assume this was because the software was trying to reconcile points that were close together along the Z axis but not that close in value. I have not been able to reproduce the failure.

is all data associated with X axis Screw Mapping. Curve 1 is for Y and Curve2 is for the Z axis.

If you park your cursor over each file name, it will tell you the number of bytes. An empty file will have 36 bytes. Curve2 after I calibrated every ½ inch had around 180 bytes. I suggest you look at the size of Curve0. If it is not 36 bytes, then at least some of your data ended up in the wrong file.



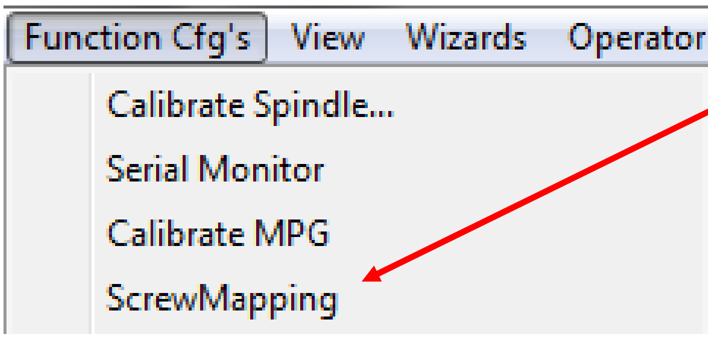
Click on Curve2 and then right click to bring down a menu that includes Copy.

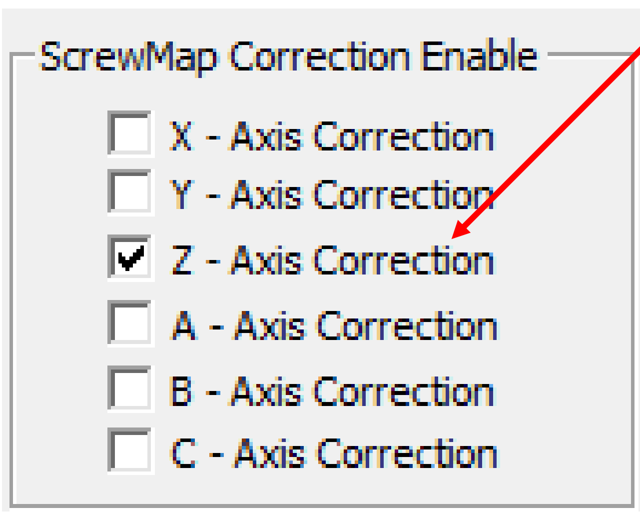
Click on Copy. Then create a folder called Backed Up Curves in some memorable location and open it. Hold down the Ctrl key and then press the V key to paste a copy of Curve2. Mach3 will continue to use the original copy and will make its own backup. This private copy is just belt and suspenders.

If the need arises, delete the working copy of Curve2 and paste in your backup copy.

Using Screw Mapping

1. Move the quill to Home as explained on page 13.
2. Go to the Function Cfg's menu and click on ScrewMapping





3. Within the Screw Mapping window, click the box in front of Z-Axis Correction.
4. Press the OK button.

When you use a g-code, this correction will be used. It will ***not*** be used when jogging.

Acknowledgments

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I welcome your comments and questions.

If you wish to be contacted each time I publish an article, email me with just "Article Alias" in the subject line.

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