Machine Tool 3D Volumetric Positioning Error Measurement Under Various Thermal Conditions

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ABSTRACT

To manufacture good quality or accurate parts, the measurement and compensation of three dimensional volumetric positioning errors of a machine tool are very important. Using a conventional laser interferometer to measure the straightness and squareness errors is very difficult and time consuming. Recently, Optodyne has developed a laser vector technique for the measurement of 3D volumetric positioning errors, including 3 linear displacement errors, 6 straightness errors and 3 squareness errors in a very short time. Using this laser vector technique combine with the data obtained from a set of thermocouples placed at key locations of the machine tool structure, the relations between the machine temperature distribution and the 3D positioning errors can be measured and modeled. The results can be used to compensate the 3D volumetric positioning errors under various thermal conditions.

Reported here are the definition of the 3D volumetric positioning errors; the basic theory and description of the laser vector technique; the temperature sensors and the laser vector technique measurement results obtained on a vertical CNC machining center under different spindle load, machine temperature and environmental temperature.

Keywords: Positioning Accuracy, Thermal effect, Squareness & Straightness, laser measurement, and compensation.

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1. Introduction

Twenty years ago, the largest machine tool positioning errors are lead screw pitch error and thermal expansion error. Now, most of the above errors have been reduced by better ball-screw or linear encoder and pitch error compensation. Hence, the largest machine tool positioning errors become squareness errors and straightness errors. Furthermore, due to the machine temperature changes with the environment, heating of the lead screw, high speed machining, cutting force and coolant, etc., it is important to calibrate and compensate the 3 dimensional volumetric positioning errors at various machine temperatures.

Using conventional laser interferometers to measure the straightness and squareness errors are very difficult with complex optics, expensive equipment and time consuming. To solve this difficulty, Optodyne has developed a new laser vector measurement technique[1, 2, 3] for the measurement of straightness and squareness errors. The setup and operation is simple. It can measure the volumetric errors in 2 hours for a machine working volume of 1 cubic meter. Using the measured volumetric positioning errors, a lookup correction table can be generated for the controller to compensate the machine positioning errors volumetrically[4]. Furthermore, several volumetric positioning error tables can be generated at various machine temperatures to compensate the errors caused by material thermal growth and achieving higher accuracy on a repeatable machine. To achieve this, it is important to understand the 3D positioning errors caused by machine structure and thermal distortion.

A method is developed for the compensation of 3D volumetric positioning errors of a CNC machine under various thermal conditions, and various environmental temperatures. The key to this method is quickly measuring the 3D volumetric positioning errors at various thermal conditions then generate several error compensation tables. When the thermal condition changed, a different error compensation table or interpolation between two tables, is generated to compensate the machine error.

2. Definition of the 3D volumetric positioning errors

For a 3-axis machine, there are 6 errors per axis or a total of 18 errors plus 3 squareness errors. These 21 rigid body errors [3, 5] can be expressed as the following.
Linear displacement errors: Dx(x), Dy(y), and Dz(z)
Vertical straightness errors: Dy(x), Dx(y), and Dx(z)
Horizontal straightness errors: Dz(x), Dz(y), and Dy(z)
Roll angular errors: Ax(x), Ay(y), and Az(z)
Pitch angular errors: Ay(x),Ax(y), and Ax(z)
Yaw angular errors: Az(x), Az(y), and Ay(z)
Squareness errors: Øxy, Øyz, Øzx,
where, D is the linear error, subscript is the error direction and the position coordinate is inside the parenthesis, A is the angular error, subscript is the axis of rotation and the position coordinate is inside the parenthesis.

The angular errors are pitch, yaw and roll errors. For most machines, the angular errors are related to the straightness errors. The effect of angular errors on the positioning accuracy is the angular error times the Abbe offset. In many cases the straightness error measurement already included the errors caused by the angular errors times an Abbe offset. For some CMM, the controllers have the capability of compensating the angular errors. But it is very difficult for CNC to compensate the angular errors separately.

For the measurement here, the 3D volumetric errors are 3 linear displacement errors, 6 straightness errors and 3 squareness errors. The error in each axis direction can be expressed as:

$$Dx(x,y,z) = Dx(x) + Dx(y) + Dx(z)$$
$$Dy(x,y,z) = Dy(x) + Dy(y) + Dy(z) + \text{Ø}xy*x/X$$
$$Dz(x,y,z) = Dz(x) + Dz(y) + Dz(z) + \text{Ø}yz*y/Y + \text{Ø}zx*x/X$$

The 3D volumetric error Dv can be defined as the maximum error in the volume,

$$Dv = SQRT[Max\{Dx(x,y,z)* Dx(x,y,z) + Dy(x,y,z)* Dy(x,y,z) + Dz(x,y,z)* Dz(x,y,z)\}]$$

3. Laser vector measurement technique

The laser vector measurement technique is developed by Optodyne for the measurement of volumetric positioning errors of a machine tool. Similar to the ASME B5.54 and ISO230-6 standards [6, 7] body diagonal displacement measurement, the laser beam is pointing in the body diagonal direction. However, instead of move x, y, and z-axis together along the body diagonal direction, stop and collect data, now move x only, stop and collect data, then move y only, stop and collect data, then move z only, stop and collect data, and so on until the opposite corner is reached. Hence, 3 times more data can be collected. For 4 body diagonal measurement, a total of 12 sets of data can be collected and the volumetric positioning errors determined. The measurement time is short, the equipment is compact, and the setup and alignment is simple [2,3].

Because of the large lateral displacement in the vector measurement technique, a laser interferometer with single aperture and a flat mirror as target is needed. It is noted that with a flat mirror as target, the movement parallel to the mirror do not displace the laser beam and do not change the distance from the source so the measurement is not influenced.

The laser measurement system used is a Laser Doppler Displacement Meter (LDDM), OPTODYNE model MCV-500 with SD-500 sequential step diagonal measurement accessory. The laser was mounted on the machine bed and used a steering mirror to align the laser beam parallel to the body diagonal. The 75×100mm flat mirror was mounted on the spindle with the surface perpendicular to the laser beam as shown in Fig. 1. The machine was programmed to move the spindle starting from one corner to the opposite corner. The Air temperature and pressure were measured to compensate the changes in speed of light and the machine temperature was measured to compensate the machine thermal expansion.

After the laser beam was aligned to the body diagonal direction and the flat-mirror perpendicular to the beam direction, the measurement data were automatically collected by the Windows LDDM software at every machine stop or at each single axis of movement. The measured error data can be analyzed by the LDDM software, by clicking on *4-diagonal* on the analysis section and loading the four collected diagonal data files. The errors for all three axes, including 3 displacement errors, 6 straightness errors and 3 squareness errors, were automatically calculated.

4. CNC machine and temperature sensors

The measurements were performed on a vertical machining center, MCFV5050LN, in Prague, Czech Republic [8] as shown in Fig. 2. The machine is equipped with linear motor drives, a cross bed with two driven axes X, Y and a vertically oriented spindle (Z-axis) form the structure of the machine. The strokes of each axis are as follows X-axis 500mm, Y-axis 400mm, Z-axis 400mm.

Many temperature sensors were located at various locations, 10 sensors for the spindle, 3 sensors for the x-axis, 3 sensors for the y-axis, 3 sensors for the machine base and 1 sensor for the ambient temperature. A photograph of the spindle with 3 temperature sensors is shown in Fig. 3.

5. Test condition and measurement results

The vector measurements were performed on the machining center over a working volume of X = 500 mm, Y = 400 mm, and Z = 320 mm. There were 4 setups, one on each of the 4 body diagonal directions. These 4 directions are ppp (all x, y, and z are positive), npp (x is negative and y and z are positive), pnp (y is negative and x and z are positive), and nnp (x and y are negative and z is positive). Based on the measured sequential step diagonal data, the volumetric positioning errors, including 3 displacement errors, 6 straightness errors and 3 squareness errors were determined.

For each measurement day, Step 1, the linear displacement errors were measured with 2 laser systems aligned parallel to the x-axis, then y-axis then z-axis. Three bidirectional runs were performed in approximately 1 hour. Step 2, using the laser vector technique, the 4 body diagonal displacement errors were measured. For rapid measurement, 2 laser systems were used and each aligned to a different body diagonal direction as shown in Fig. 4. Three bidirectional runs were performed on 4 body diagonals in approximately 2 hours. Step 3, the x, y, z axes were moved and the spindle rotated to heat up the machine for approximately 30 minutes. Step 4, same as step 2, except only 2 bidirectional runs were performed on 2 body diagonal directions, npp and pnp, in approximately 30 minutes. Before taken data, repeat step 3 to heat up the machine 30 minutes and repeat the same 4 times. Step 5, repeat the measurement in step 2 for approximately 2 hours. The temperature sensors were continuously recorded at 2 minutes interval over the whole measurement period.

For each measurement day, the measurement performed were the same, except the step 2, the x, y, and z axes were moved at different feed rates, the spindle was rotated at different rpm, and the environment were set at different temperatures.

A typical day #8 data are shown here. In the step 2 the x, y, and z axes were moved at a feed rate of 10m/minute for 30 minutes. The data collected in the morning were plotted in the Figs. 5, 6 and 7. For x-axis, the linear displacement errors, vertical straightness and horizontal straightness were plotted in Fig. 5. The maximum vertical straightness error (deviation in the y-direction) is -0.009 mm; the maximum horizontal straightness error (deviation in the z-direction) is -0.011 mm; and the maximum displacement error is -0.008 mm.

For Y-axis, as shown in Fig. 6, the maximum vertical straightness error (deviation in the x-direction) is -0.0025 mm; the maximum horizontal straightness (deviation in the z-direction) is 0.0005 mm/-0.0005 mm; and the maximum displacement error is -0.0071 mm. For Z-axis, as shown in Fig. 7, the maximum vertical straightness error (deviation in the x-direction) is -0.003 mm; the maximum horizontal straightness error (deviation in the y-direction) is -0.015 mm; and the maximum displacement error is -0.005 mm.

Due to the x, y, z axes movement and the spindle rotation, the machine temperatures measured were increased continuously above the ambient. The measured temperature distribution and rate of increase were different for different feed rate and spindle rotation speed. A plot of measured temperature vs. time in Day #8 is shown in Fig. 8.

It is noted that the data collected in the evening after the machine bed and the spindle were heated up, the changes in the straightness were relatively small, except the squareness errors. The data collected in the morning showed that the measured squareness errors were XY = 37.26 arcsec, YZ = -16.6 arcsec and ZX = 21.7 arcsec at the initial condition. The data collected in the evening after the rapid XYZ movement, the measured squareness errors were changed to XY = 36.7 arcsec, YZ = -33.71 arcsec and ZX = 14.18 arcsec. A plot of the squareness errors vs. the machine temperatures is shown in Fig. 9. It is noted that the maximum changes of squareness errors in the XY = 0.56 arcsec, in YZ= 17.11 arcsec, and ZX= 7.56 arcsec. As expected, the largest change in squareness error in the YZ-plane is due to the sag of the spindle mount. Based on the relations between the squareness errors and the machine temperature, the squareness errors can be compensated at various machine loading conditions.

6. Summary and conclusion

Using the vector method, volumetric errors of a machining center can be measured in a short time. Measurements were performed at various machine temperatures under simulated working conditions to understand how the volumetric errors change under different machine temperatures and distributions. Based on these measurements, it is possible to generate a few volumetric compensation tables at a few machine temperatures. Using the interpolation strategy, a volumetric error compensation table can be generated to compensate the machine errors at various machine temperatures.

In conclusion, the preliminary data showed that the straightness errors were not sensitive to the machine temperature changes. However, large changes in squareness errors occurred due to the changes in machine temperatures. Hence the proposed 3D volumetric error compensation strategy, using the vector method to measure the volumetric positioning errors at various machine temperatures and working conditions to generate several compensation tables at different temperatures should work very well. More detailed measurement results, modeling and analysis will be presented in Svoboda's Ph.D. thesis to be published later.

References

[1] C. Wang, "Laser Vector measurement Technique for the determination and compensation of volumetric positioning errors. Part I: Basic theory, Review of Scientific Instruments, Vol. 71, No 10, pp 3933-3937, 2000.

[2] O. Svoboda, "Volumetric positioning accuracy of a vertical machining center equipped with linear motor drives (evaluated by the laser vector method)", Proceedings of the LAMDAMAP 2003 Conference, Huddersfield, England, July 2-4, 2003.

[3] G. Ren, J. Yang, G. Liotto, and C. Wang "Theoretical Derivations of 4 body Diagonal Displacement Errors in 4 Machine Configurations", Proceedings of the LAMDAMAP Conference, Cransfield, UK, June 27-30, 2005.

[4] O. Svoboda, P. Bach, G. Liotto, and C. Wang, "Volumetric Positioning Accuracy: Measurement, Compensation and Verification", Proceedings of the JUSFA 2004 Conference, Denver, CO, July 19-21, 2004.

[5] C. Wang, O. Svoboda, P. Bach, and G. Liotto "Definitions and correlations of 3D volumetric positioning errors of CNC machining centers," Proceedings of the IMTS 2004 Manufacturing Conference, Chicago, IL, September 8-10, 2004.

[6] Methods for Performance Evaluation of Computer Numerically Controlled Machining Centers, *An American National Standard*, ASME B5.54-1992 by the American Society of Mechanical Engineers, p69, 1992.

[7] ISO 230-6: 2002 "Test code for machine tools – Part 6: Determination of positioning accuracy on body and face diagonals (Diagonal displacement tests)", *an International Standard*, by International Standards Organization, 2002.

[8] O. Svoboda, "Comparative study of the volumetric positioning accuracy of CNC machining centers using the latest laser measurement technology", MATADOR Conference, Manchester, UK, July 6-8, 2004.

Figure captions

Fig. 1, The laser Vector measurement setup with a laser mounted on the bed and a flat-mirror mounted on the spindle. The laser beam is pointed in the body diagonal direction.

Fig. 2, A photo of the Vertical machining center MCFV5050LN.

Fig. 3, A photo of the spindle with temperature sensors.

Fig. 4, A photo of the machining center and the vector measurement setup. Two lasers are mounted on the machine bed and 2 flat mirrors are mounted on the spindle.

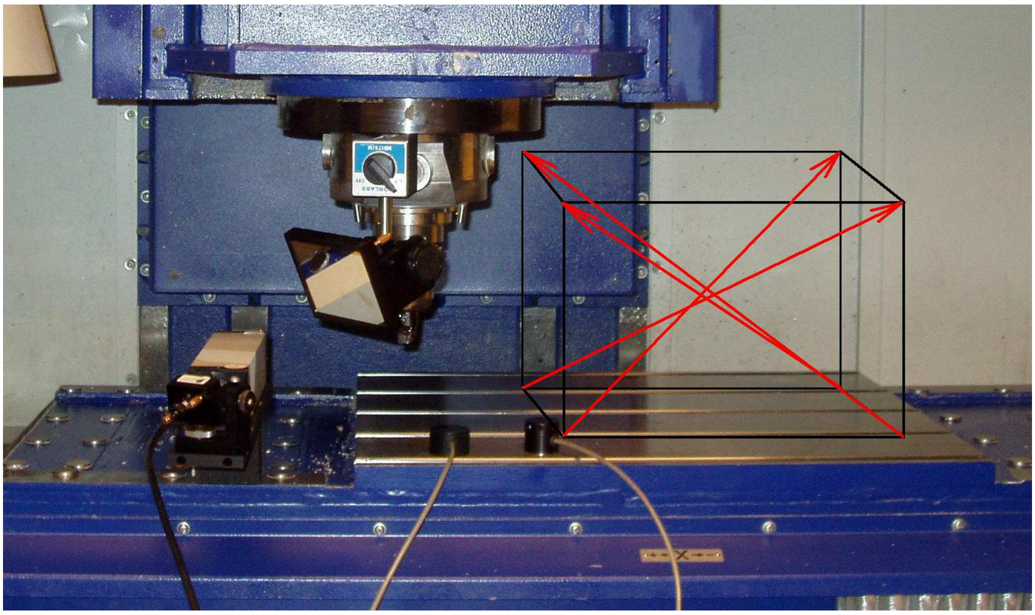
Fig. 4, Measured X-axis errors, LF, VF and HF are the displacement error, vertical straightness and Horizontal straightness, respectively.

Fig. 6, Measured Y-axis errors, LF, VF and HF are the displacement error, vertical straightness and Horizontal straightness, respectively.

Fig. 7, Measured Z-axis errors, LF, VF and HF are the displacement error, vertical straightness and Horizontal straightness, respectively.

Fig. 8, A plot of machine temperatures vs. time

Fig. 9, A plot of squareness errors, XY, YZ, and ZX, vs. the measured machine temperatures



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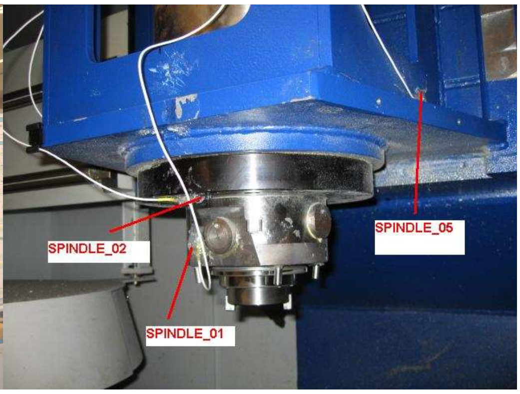
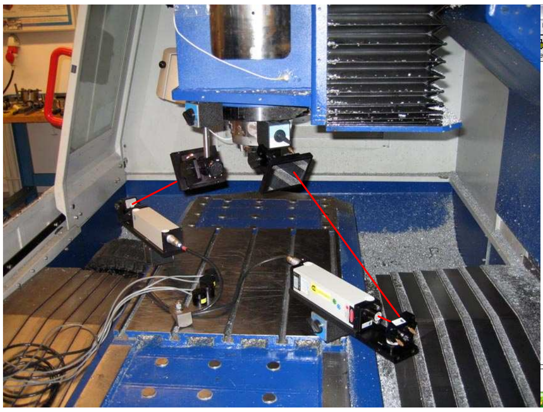


Fig. 3, A photo of the spindle with temperature sensors.



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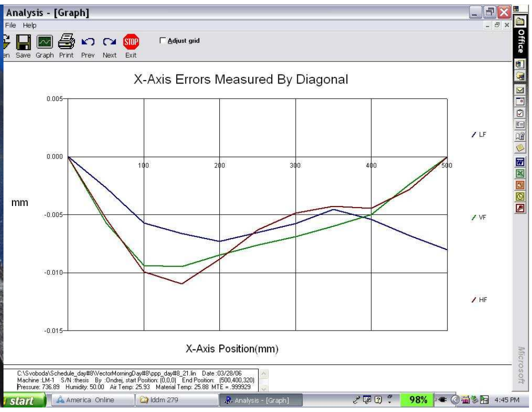

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Machine :LM-1    S/N :thesis    By  :Ondrej, start Position: (0,0,0)    End Position:   (500,400,320)
Pressure: 736.89    Humidity: 50.00    Air Temp: 25.93    Material Temp: 25.88  MTE = .999929
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Fig. 5, Measured X-axis errors, LF, VF and HF are the displacement error, vertical straightness and Horizontal straightness, respectively.

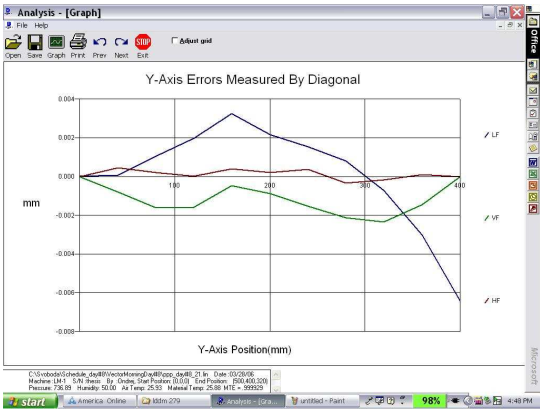

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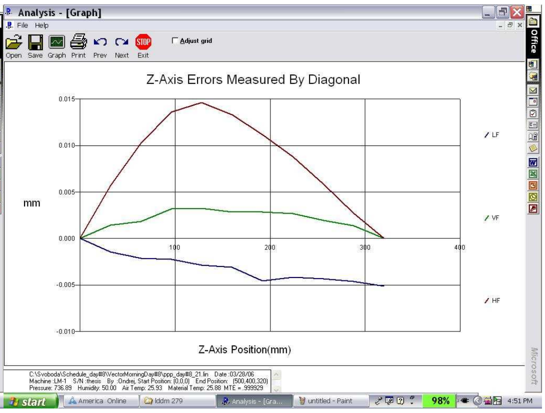
Fig. 6, Measured Y-axis errors, LF, VF and HF are the displacement error, vertical straightness and Horizontal straightness, respectively.



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Pressure: 736.89    Humidity: 50.00    Air Temp: 25.93    Material Temp: 25.88  MTE = .999929
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Fig. 7, Measured Z-axis errors, LF, VF and HF are the displacement error, vertical straightness and Horizontal straightness, respectively.

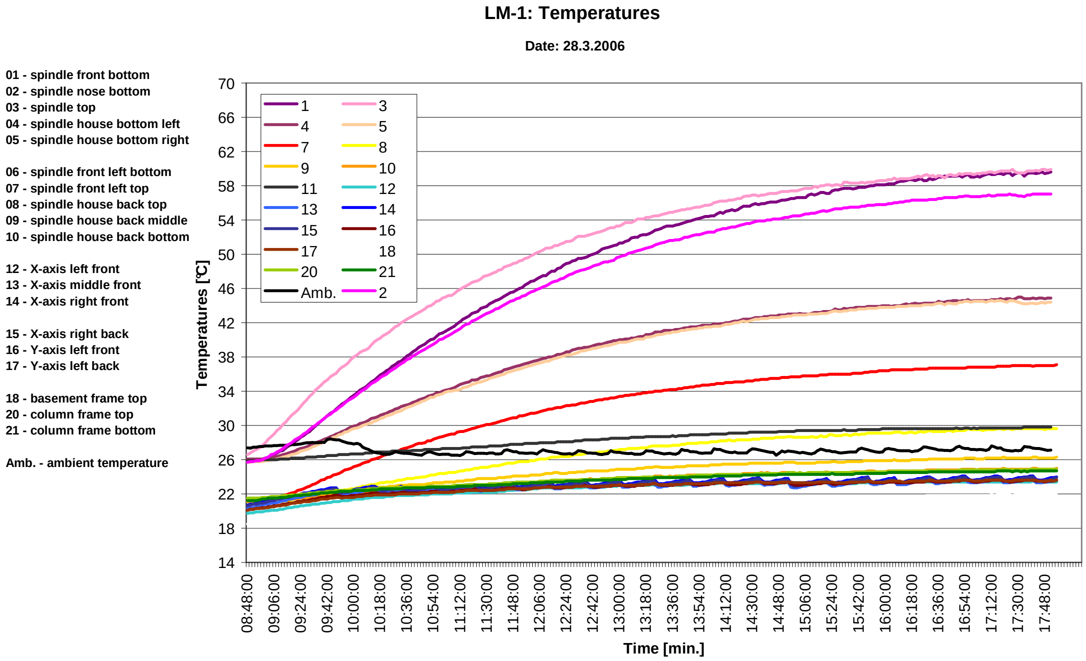

Fig. 8, A plot of the machines temperatures vs. the time.

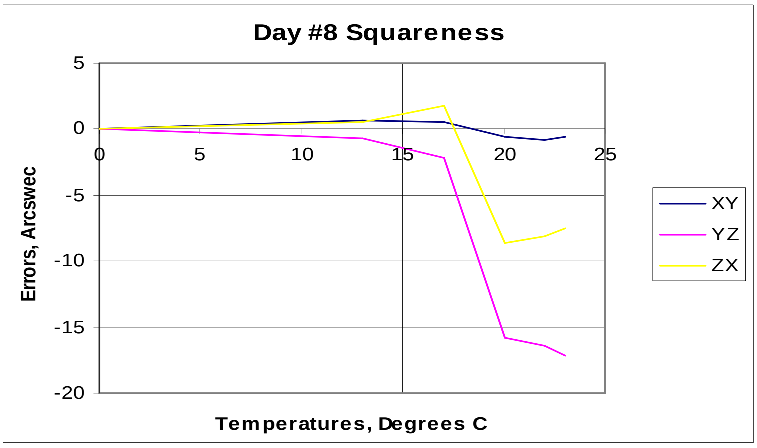

Fig. 9, A plot of changes in squareness errors, XY, YZ, and ZX, vs. the measured machine temperatures changes.