LaserTRACER™ – Highest Measuring Accuracy for Machine Tool Error Compensation

Volumetric Accuracy of Machine Tools

The geometric accuracy of machine tools is highly important for the quality of the manufactured products. Especially in flexible manufacturing, for which a zero defect production is required starting from the first part produced, a reliable geometry in the total working volume is indispensable. Furthermore, users increasingly demand geometric control in the manufacturing process, rather than in the measurement room. To achieve this, better calibration and inspection processes of machine tools are important.

Causes of Geometric Errors

Geometric errors in the working volume result from the overlapping errors of the single axes. The DIN/ISO 230-1 standard describes these errors and provides a terminology (see box). The errors of a single axis has 6 components: The position error in the direction of the axis movement, two straightness errors perpendicular to the direction of movement, and three rotary movements: pitch, roll, and yaw. These components are shown in **Fig. 1** using the x-axis in a machining center as an example. These movements also occur in the other axes; in addition there are constant squareness errors between the axes.

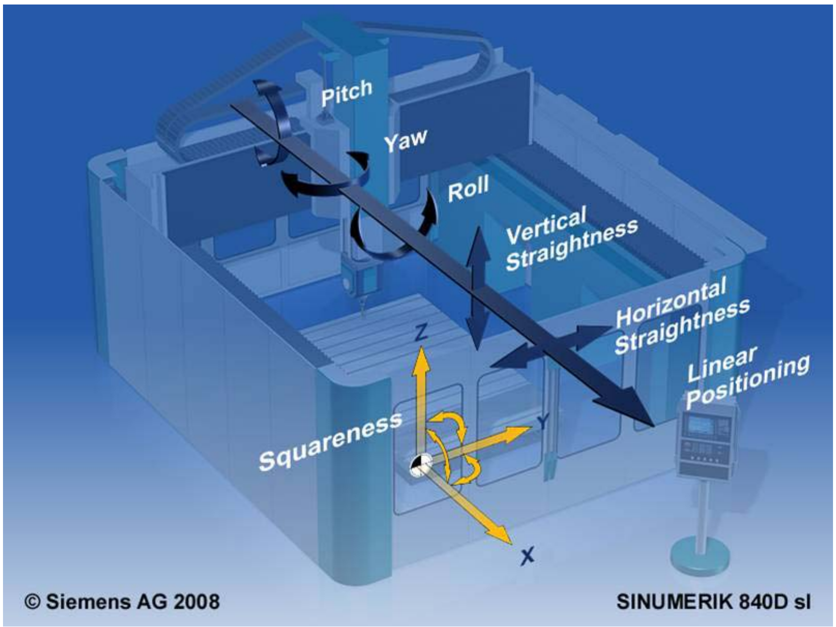


Fig. 1: Error components of a linear axis

How to Achieve Volumetric Accuracy

A considerable part of the cost of modern machine tools results from their mechanical precision requirements. Close geometric tolerances affect the assembly and commissioning, add costs and require long throughput times. In spite of best efforts, noticeable errors can be found in the finally assembled machine. This is where numeric compensation starts: If the errors are known, an increasing number of advanced controllers can correct the nominal positions in the controller. In this way, such errors no longer have an effect on the geometry of the manufactured part [1]. While the compensation of linear errors has long been state-of-the art, the total volumetric compensation of machine tools has been rather unusual so far. However, this is changing due to new possibilities of control and measurement technologies.

Since 2008 a total volumetric compensation under the designation *Volumetric Compensation System (VCS)* is being offered by Siemens for the controller Sinumerik 840 D sl. Heidenhain started offering a similar option designated *KinematicsComp* for the controller iTNC 530 in 2009. In July of the same year Fanuc released Spatial Error Compensation (SEC). These options allow for increasing the accuracy of machining centers if the volumetric errors were initially determined using suitable measuring technology. With the LaserTRACER and the software TRAC-CAL, Etalon AG offers an efficient and high-precision measurement system for volumetric calibration.

GPS Principles for the Machine Tool – With Sub-micrometer Accuracy

The method for completely recording geometric machine errors described in the following is based on a unique measuring instrument, the LaserTRACER. The LaserTRACER was developed by Etalon AG in cooperation with the Physikalisch-Technische Bundesanstalt (PTB) in Germany and the National Physical Laboratory (NPL) in Great Britain. The LaserTRACER's core component is a laser interferometer with nanometer-level resolution that automatically follows a reflector continuously measuring the distance to it. A patented principle ensures that the errors of the tracking horizontal and vertical rotary axes do not affect the distance measurements. This allows spatial distance measurements up to a radius of 15 meters with unrivalled accuracy and speed!

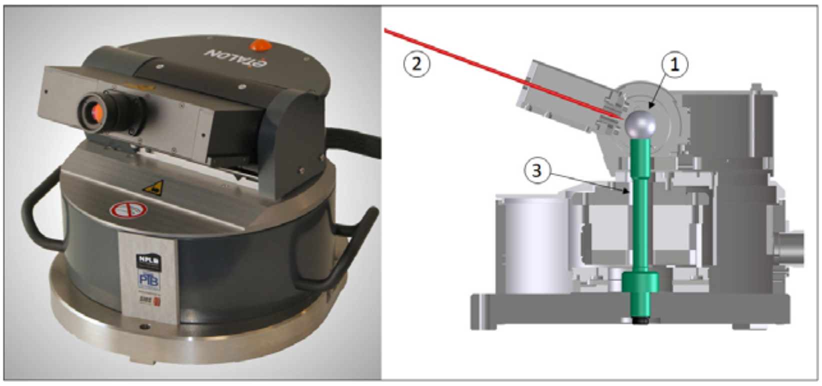


Fig. 2: LaserTRACER principle

(1) A precision sphere serves as the optical reference for all distance measurements
(2) Measuring beam of the laser interferometer
(3) Mechanically decoupled pillar for the reference sphere

Conventional laser trackers, which are also equipped with a self-tracking laser interferometer, differ mainly by lower accuracy and larger physical size. The LaserTRACER by ETALON is considerably more compact and thus can be used on smaller machines. The small size is due to the fact that the laser tube is located outside the instrument and the beam is led through a fiber optic cable. This design provides the additional benefit that there is no additional heat source in the measuring instrument, which leads to an increase in accuracy. The LaserTRACER intentionally does not use directional information since the beam direction, as inherent to the functional principle, has a potentially high degree of uncertainty due to air turbulence, thermal gradients and unavoidable errors of the angular encoders. The order of magnitude of these angular errors is represented in the

American standard ANSI/ASME B89.4.19: Through temperature gradients in the air alone, the error may amount to 100 µm over a distance of 10 meters! Reaching a sufficient accuracy for the calibration of machine tools on the basis of the angle information, therefore, is possible only in cases with very low requirements.

Unlike other devices, when calibrating measuring machines and machine tools with the LaserTRACER, the spatial information is exclusively determined by measuring the distance to various reference points – analogous to a Global Positioning System (GPS). This principle is also called multilateration and allows outstanding accuracy. In Table 1, the Etalon system is compared with the GPS system.

	Global Positioning System (GPS)	**Etalon System**
Measuring distance	Approx. 20,000 km	**0.2 m – 15 m**
Reference points	Satellites	**Reference sphere LaserTRACER**
Receiver	GPS receiver	**CatEye reflector**
Measuring signal	Microwave	**Laser light**
Absolute accuracy	10 - 50 m	**0.2 µm – 5 µm**

Table 1: Comparison between Global Positioning System (GPS) and the Etalon system

In contrast to the GPS system in which at least 3 - 4 satellites are located at the same time, the single LaserTRACER is placed in at least 3 positions in succession. As a result of the high resolution and high-precision optical components, it is possible to determine spatial displacements with accuracy in the sub-micrometer range.

Fields of Application of the Etalon system

The Etalon system is used for the calibration of measuring machines and machine tools of almost any size. **Fig. 3** shows three application examples.

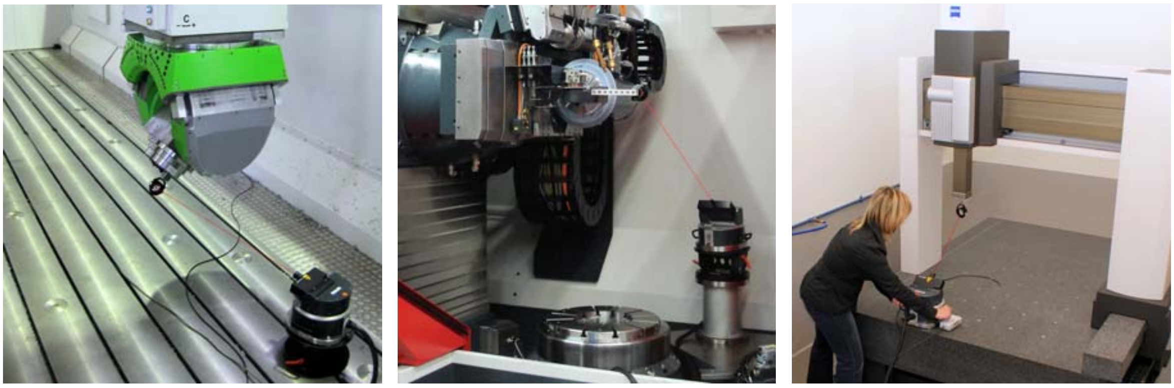


Fig. 3: Application of the LaserTRACER at (1) a large portal machine, (2) a grinding machine, (3) a coordinate measuring machine

The system is used by manufacturers of coordinate measuring machines like *Carl Zeiss IMT GmbH* and *Optical Gaging Products Inc*. *(OGP)*, where it is used for calibrating measuring instruments of maximum precision. Machine tool manufacturers in the high-end area such as *Gebrüder Heller Maschinenfabrik GmbH* or *Röders GmbH* rely on Etalon technology.

Calibration procedure

To completely calibrate a measuring machine or a machine tool, the LaserTRACER first is placed in one corner of the machine table and the reflector is clamped in the spindle. Then, the laser beam is roughly aimed at the reflector using a joystick. When close enough the beam will automatically engage. From that point onward the measuring beam automatically tracks the reflector within the machine volume. NC programs generated by the TRAC-CAL Software are executed on the machine. They move the machine in a three-dimensional grid with pauses of 1-2 seconds at pre-determined positions. A fully automatic measuring sequence usually lasts between 10 and 20 minutes. After the first sequence, the instrument is repositioned and the procedure is repeated. All in all the LaserTRACER is manually repositioned 3 to 5 times, but a fine alignment is never required! After all positions have been measured, the TRAC-CAL software calculates the parametric errors of all axes based on changes in displacement measurement of the interferometer signal within seconds. The total calibration of a medium-size machine takes about 1-3 hours. TRAC-CAL provides the volumetric compensation data for most controller and machine types. In addition, the errors are represented in a detailed measuring report and thus can be used for the detailed machine analysis as well.

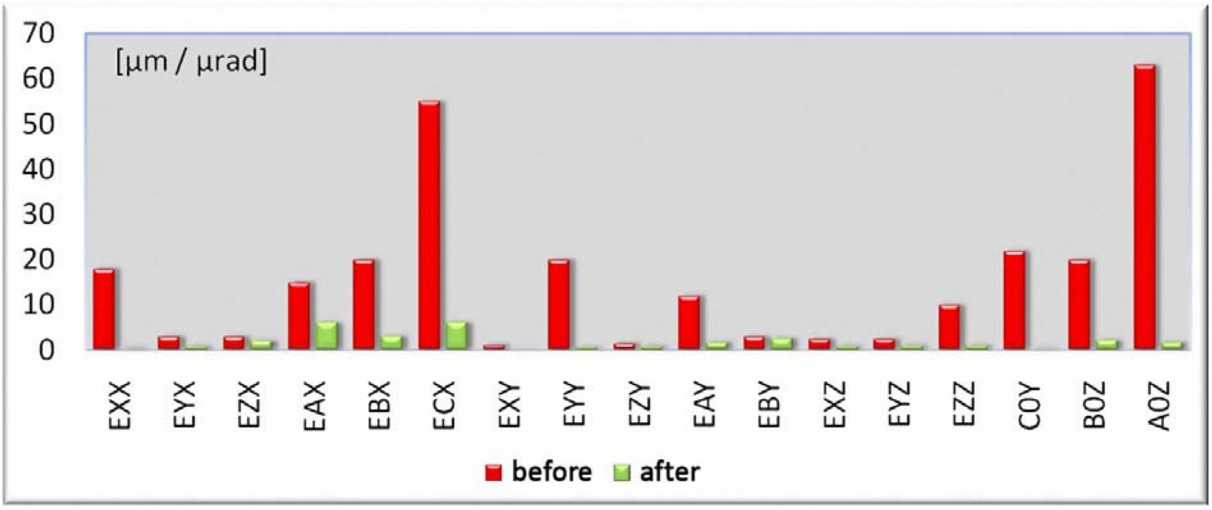
A further development of this method is the on-the-fly measurement, which is now available from Etalon AG. With this version, pausing the machine at each measuring point during the program flow is not necessary. Measurements are continuously performed during the machine movement. This allows a distinctly higher sampling rate during the machine geometry recording. The method has already been used for coordinate measuring machines, offering the advantages that

very short-wave geometry errors of the machine can be detected,

total calibration time can be reduced.

Efficiency of the Compensation

The data determined by the Etalon system can be directly used for the compensation of systematic errors. Depending on the controller, copying a single file is sufficient in most cases. Most manufacturers of coordinate measuring machines have used so-called volumetric full error correction for many years. Etalon has demonstrated in many different applications that volumetric compensation is able to offer a clear increase in accuracy for machining centers as well. The reduction of geometric errors is shown in Fig. 4 using the example of a “corrected” vertical and horizontal machining center. The single errors are designated according to ISO 230-1. The designation according to ISO 230-1 is also given in the box below.



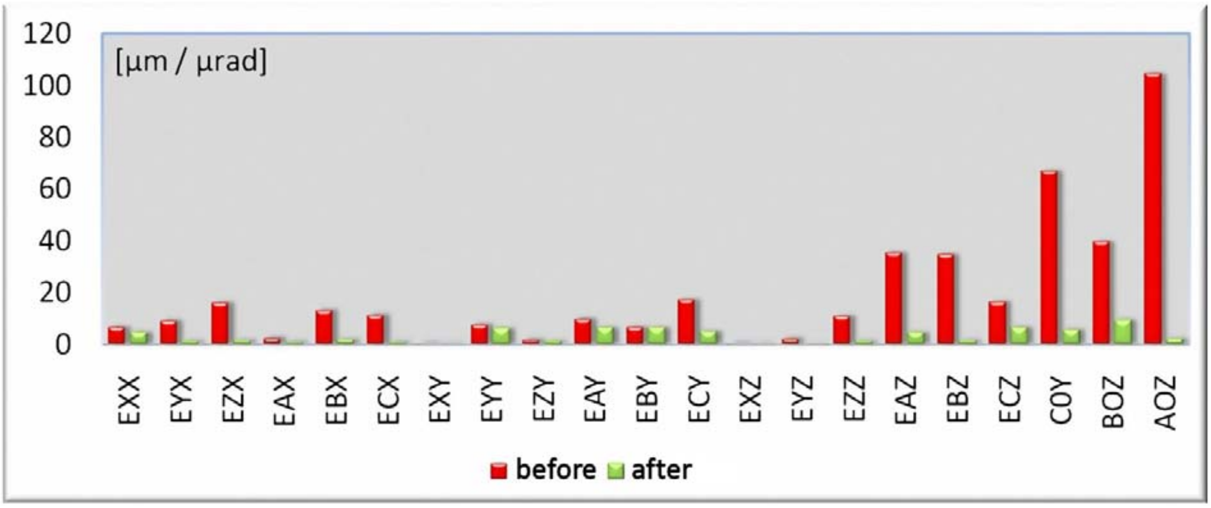


Fig. 4: Reduction of systematic errors through volumetric compensation for a vertical and a horizontal machining center

Box:

Systematic Guidance Errors According to ISO 230-1 (and VDI 2617):
EXX, EYY, EZZ (xtx, yty, ztz): Position errors of the linear axes
EYX, EZX (xty, xtz): Straightness errors of the x-axis
EXY, EZY (ytx, ytz): Straightness errors of the y-axis
EXZ, EYZ (ztx, zty): Straightness errors of the z-axis
EAX, EBX, ECX (xrx, xry, xrz): Rotation errors of the x-axis (pitch, yaw and roll)
EAY, EBY, ECY (yrx, yry, yrz): Rotation errors of the y-axis
EAZ, EBZ, ECZ (zrx, zry, zrz): Rotation errors of the z-axis
C0Y (xwy): Squareness between y-axis and z-axis
B0Z (xwz): Squareness between z-axis and x-axis
A0Z (ywz): Squareness between z-axis and y-axis

Machines with 4 or 5 Axes Benefiting from Etalon Technology

Many existing calibration routines provided by controller manufacturers are based on the measurement of reference spheres on the rotary axes with a probe clamped in the spindle. In this way, the orientations of the rotary axes in the machine system are determined. Since the movement of the linear axes serves as the reference for the calibration of the rotary axes, their errors directly influence the quality of the calibration. If the linear axes are compensated in the best possible way before the rotary axis calibration, the accuracy of the calibration is considerably increased. At the Control 2009 trade fair a software option for the LaserTRACER was introduced which supports the analysis of the rotary axes. As for the linear axes, it is now possible to determine all types of errors for rotary axes: axis position, angle position, wobbling, and radial and axial runout.

Testing of Measuring Machines and Machine Tools Conforming to Standards

The use of the LaserTRACER is not limited to the analytical recording of systematic machine errors. With TRAC-CHECK, Etalon additionally offers software for performing test measurements in accordance to ISO standards. This testing is required to quickly test machines at regular intervals for spatial accuracy conforming to standards. If the machine does not correspond to the specification, the compensation by TRAC-CAL is used. The efficiency of the compensation can be checked again with the standardized method.

The testing can be carried out according to IS0 230 - 2 / 4 / 6 (testing of machine tools) and ISO 10360 - 2 (testing of coordinate measuring machines). The measurement of spatial diagonals according to Sheet No. 6 of ISO 230 is especially reasonable since here the influences of several single axes are tested. The patented TRAC-CHECK method also satisfies this application. First the program determines the spatial position of the LaserTRACER. The ISO measuring lines are related to this position and will be used in the machine program. When such a program is started, the measuring beam is automatically aligned by its tracking mechanism so that no manual alignment is necessary. According to Sheet No. 4 of ISO 230 it is also possible to use the LaserTRACER for the circular test. Here, a given circle is performed by means of at least two linear axes. The form deviation includes several error effects of the machine and thus gives information on the quality of the movements. The application using the LaserTRACER is especially suitable for large machines since the measurement is possible for a radius of up to 12 meters.

Summary and Outlook

As far as measuring machines are concerned, volumetric compensation already has a successful track record. The fact that important controller manufacturers have integrated volumetric compensation will lead to a breakthrough for its application on machine tools. For this, Etalon offers highly efficient measuring technology for the machine manufacturer and the high-end user. The Etalon calibration system combines maximum accuracy, a very short measuring time and simple handling. The revolutionary measuring principle allows for measuring spatial errors with accuracy in the sub-micrometer range. By using the LaserTRACER for the calibration of rotary axes, its field of application is further extended; the complete calibration of a 4-axis or 5-axis machine with only one system is now possible.

[1] H. Schwenke, W. Knapp, H. Haitjema, A. Weckenmann, R. Schmitt, F. Delbressine; Seite 660-675, CIRP Annals Band 57/2, 2008.

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