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Master Thesis

Compensation of CMM geometrical errors using Laser Tracer – the pilot experiment at a CMM manufacturer

Supervisors

Prof. Giovanni Bracco

Ing. Emanuele Barini

Candidate

Benedetto Lombardi

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Abstract

Market requires products with increasingly high levels of accuracy, therefore it arises from the quality department the need to measure them with more performing Coordinate Measuring Machines (CMMs). These machines commit errors in carrying out the measurements, because of micro-irregularities of their structure and geometry. Therefore, after the production of a CMM, a procedure called geometrical compensation is carried out: it consists in measuring such imperfections and transforming them into a Compensation Map to be downloaded into the CMM controller. In order to maintain a high-performance level, an accurate error model is necessary to appropriately compensate the data acquired by the machine.

The availability of novel technologies also impacted the process of CMM compensation. Among them, the Laser Tracer (LT) enabled to improve the process, by reducing the overall time necessary for map estimation without negative effects on the uncertainty of the measurements.

The main goal of the thesis is to study the feasibility of integrating the LT technology into a compensation process. To this purpose, use cases have been provided by the Grugliasco plant of Hexagon Metrology. The technology has been applied on different machine families, including a horizontal-arm. The outcome of this new approach has been compared with the actual method used in the plant, both online and offline through a Matlab simulator appropriately developed. Promising results have been found.

Acknowledgements

This thesis represents the end of a long chapter of my life. I would like to dedicate a few words to thank all the people who have supported and helped me during this period.

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To my family. I wish to express my deepest gratitude to my parents for their unwavering guidance and their ability to listen to me. You have always been by my side, even when I decided to move a thousand kilometers away to complete my course of study. My siblings, Vincenzo and Francesca, also deserve special acknowledgement for encouraging me every day.

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Benedetto Lombardi

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1 Introduction

Metrology has always been recognized as a fundamental tool in sciences and engineering technologies. This discipline can be defined as the science of measurement. The International Vocabulary of Basic and General Terms in Metrology defines measurement as the "process of experimentally obtaining information about the magnitude of a quantity". The importance of a measurement process can be understood through a quote from Lord Kelvin. In 1883, he said:

"*I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is meagre and of unsatisfactory kind: it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the stage of science, whatever the matter they be.*"

The main function of metrology is to obtain reliable information. In a manufacturing process, such information consists in getting knowledge of some parameters of manufacturing products. Metrology represents certainly a cost in terms of time and money; however, it is necessary to improve the quality of the products. In a world where customers demand increasingly high levels of accuracy, manufacturers must measure their production output with appropriate tools. It is important that such devices used to measure have small measurement uncertainty in order to obtain accurate measurements.

1.1 Coordinate Measuring Machines

In industrial environment, the measurement activity is required to verify the dimensional and geometrical tolerances of the products. A Coordinate Measuring Machine (CMM) is one of the instruments that can be used to fulfil this task. According to ISO 10360-1, it is defined CMM "a measuring system with the means to move a probing system and the capability to determine spatial coordinates on a workpiece surface". This system can be represented as a set of three bodies that move linearly, to generate the three orthogonal axes of the machine reference system. Using a CMM has some advantages, such as the possibility of automating the measurement process and the reduction of the measurement time and costs.

Every CMM consists of some fundamental systems, each one with different functions:

- machine system;
- probing system;
- software system;
- control system.

The machine system moves the probing system in the CMM measurement volume, according to a triad of Cartesian axes (X, Y, Z). It usually consists of a base, carriages for motion and reading scales. The base is the part of the machine leaning on the floor and it supports the carriages, the scales and the probing system. Therefore, the weight of the CMM components and the presence of the workpiece must be considered during the sizing of the base, in order to avoid any variations in the machine geometrical structure. Moreover, it is necessary to minimize the deformations of the base, especially when it is used as a guide for the movement of the carriages. For all these reasons, the base is generally made of granite, a material that guarantees high stability as well as significant mechanical properties, such as stiffness, wear resistance and hardness. The carriages are defined as rigid bodies, which can move along three orthogonal directions. A rigid body is nondeformable and its position in a Cartesian space can be determined by six coordinates, three of which are linear while the others are angular. In almost all the CMM types, air bearings are used to support the carriages. The reading scales are the last constituent element of the machine system. They are displacement transducers, applied to the carriages, that allow to identify the positions of the carriages along their single direction of movement.

The probing system produces the command signal for the reading of the scales: when the stylus tip touches the workpiece, the CMM memorizes the contact point coordinates. Then the software system uses its calculation algorithms to determine the dimensional and geometrical characteristics of the piece, by analysing the previously acquired coordinates.

The control system consists of the devices necessary for power, such as motors and gear trains, and control, such as the interface between the software commands and the CMM control unit.

1.2 Types of CMMs

CMM manufacturers adopted different configurations of machines. The most common structures for CMMs are the following:

- fixed table cantilever;
- moving bridge;
- moving ram horizontal-arm;
- gantry.

A more detailed description is in the following sections.

1.2.1 Fixed table cantilever CMM

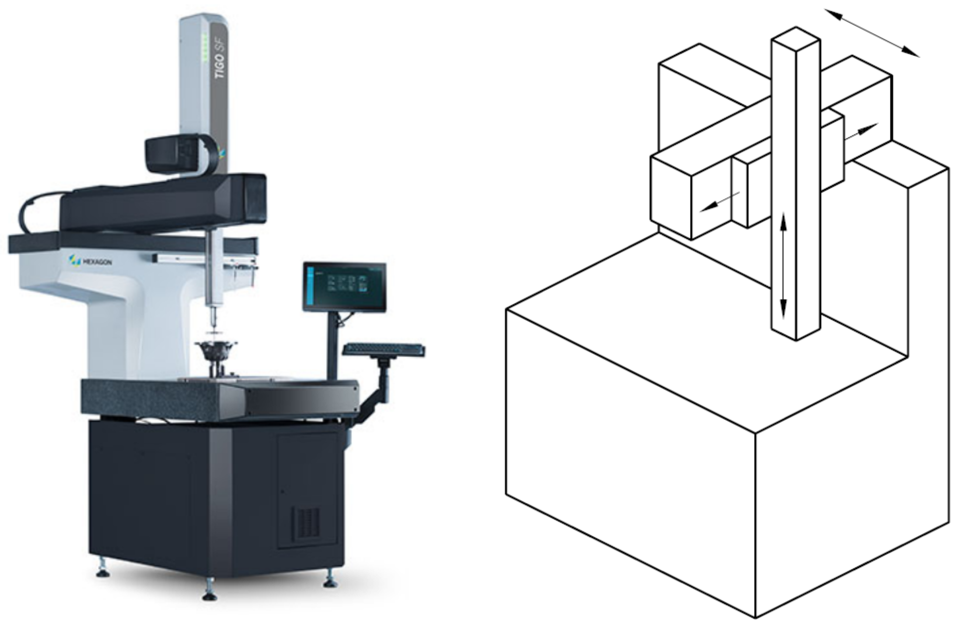


Figure 1: Tigo SF - Fixed table cantilever CMM

According to ISO 10360-1, “this is a CMM employing three components moving along guideways perpendicular to one another, with the probing system attached to the first component, which is carried on, and moves vertically in relation to, the second. The combined assembly of the first and second components moves horizontally relative to the third. The third component is supported at one end only, cantilever fashion, and moves horizontally relative to the machine base, on which the workpiece is supported.”

The big advantage of this CMM structure is that three sides of the machine are free, therefore the piece can easily enter the measurement volume. In addition, with this machine it is possible to measure pieces of larger dimensions than the table. This design is suitable for small machines.

This CMM is used to measure small components that require the maximum accuracy. This is one of the first CMM types used in the manufacturing industry. In Figure 2, the use case of 3B FLUID POWER S.r.l. in Novellara (Italy) is presented. It is possible to see an automatic cell for the production and testing of hydraulic components. In such cell, the fixed table cantilever CMM ensures that the manufactured products leave the production environment only if they reach a high quality standard.

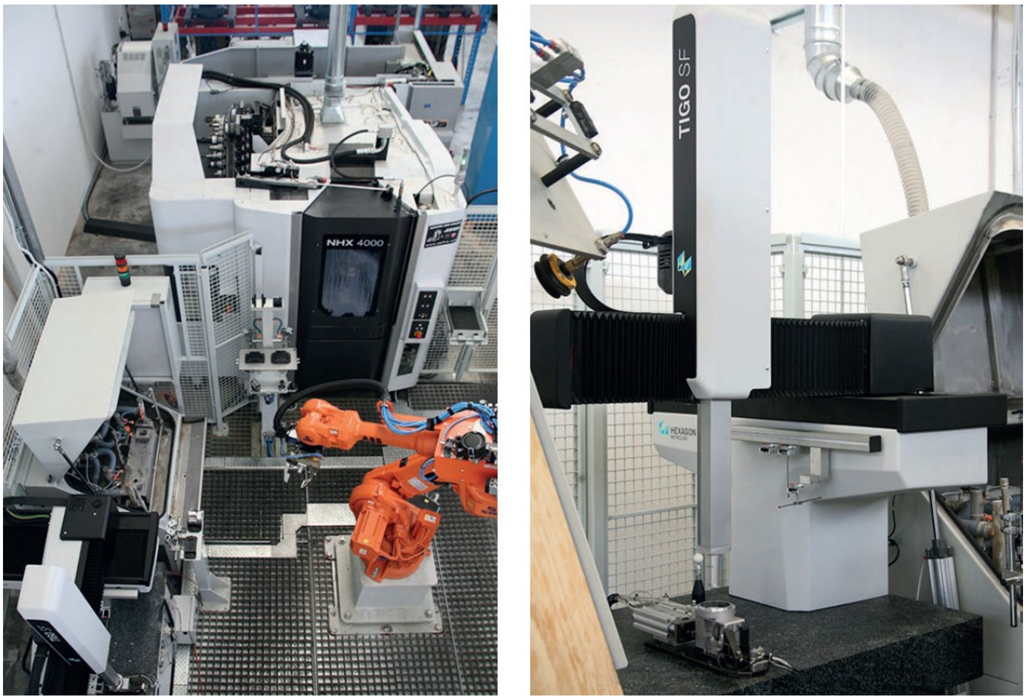


Figure 2: Application of a fixed table cantilever CMM

1.2.2 Moving bridge CMM

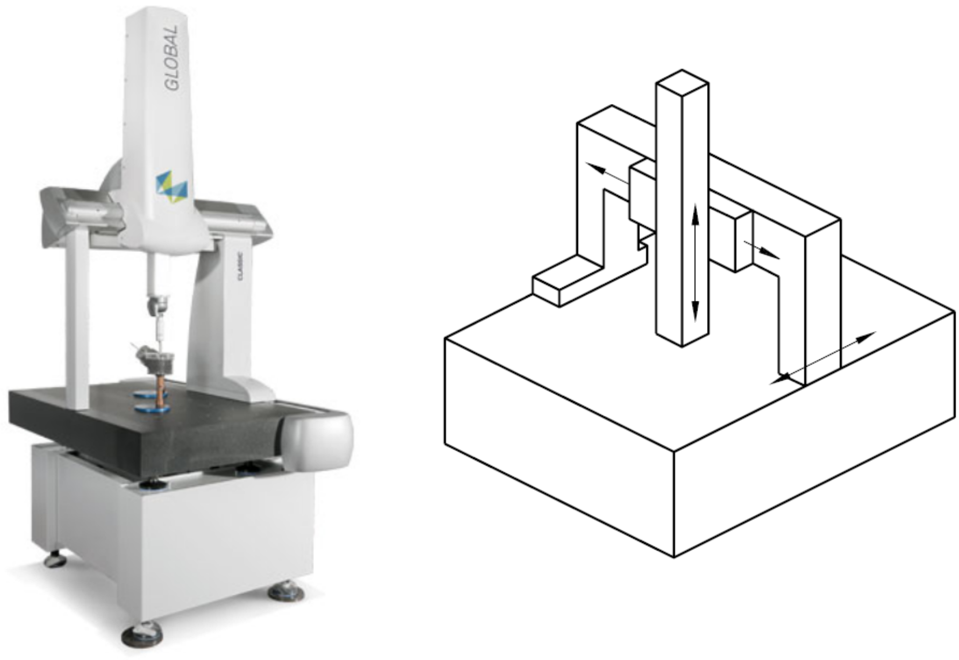


Figure 3: Global Classic - Moving bridge CMM

According to ISO 10360-1, “this is a CMM employing three components moving along guideways perpendicular to one another, with the probing system attached to the first component, which is carried on, and moves vertically in relation to, the second. The combined assembly of the first and second components moves horizontally relative to the third. The third component is supported on two legs which descend on opposite sides of the machine base, and moves horizontally relative to the base, on which the workpiece is supported.”

This structure is the most common, also thanks to the very low bending of the beam, which guarantees a higher accuracy level than the Cantilever type. By moving the bridge towards one side of the machine, a wide area on the table is cleared and it can be used to place the pieces in the measurement volume without any difficulty. Another advantage of this CMM regards the fact that bigger machines can be obtained from the same structure, by increasing only the size of the table along the third axis. Nevertheless, if the machine is too big the operator will have problems when moving manually the probing system because of the high inertia of the bridge.

This CMM is used to measure medium size components that require high accuracy. In Figure 4, the use case of Voith Turbo in Monaco (Germany) is shown. Such company produces components for buses, trucks and other vehicles. The CMM technology is adopted to verify that the geometry of such components respect the CAD designs. The measurements of the pieces are performed in a metrological room, separate from the production environment, in order to minimize disturbances from the outside.

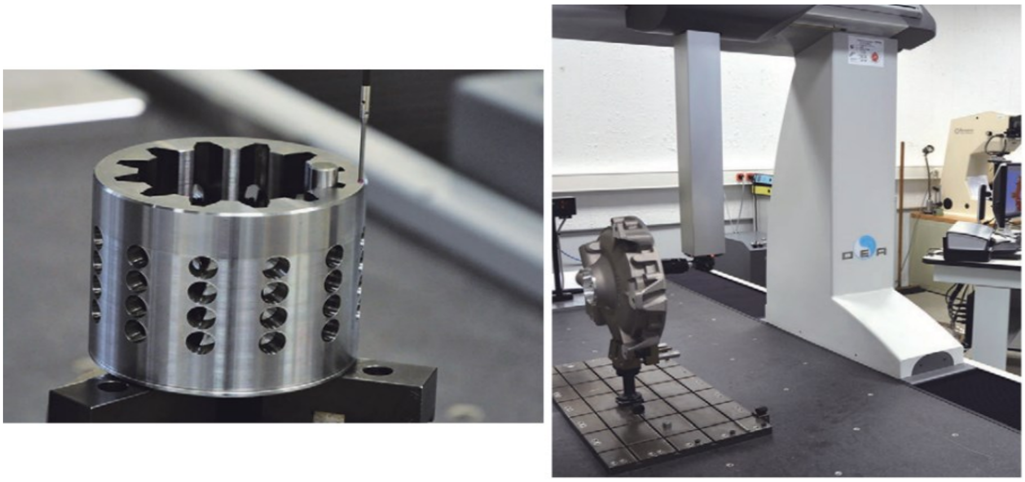


Figure 4: Application of a moving bridge CMM

1.2.3 Moving ram horizontal-arm CMM

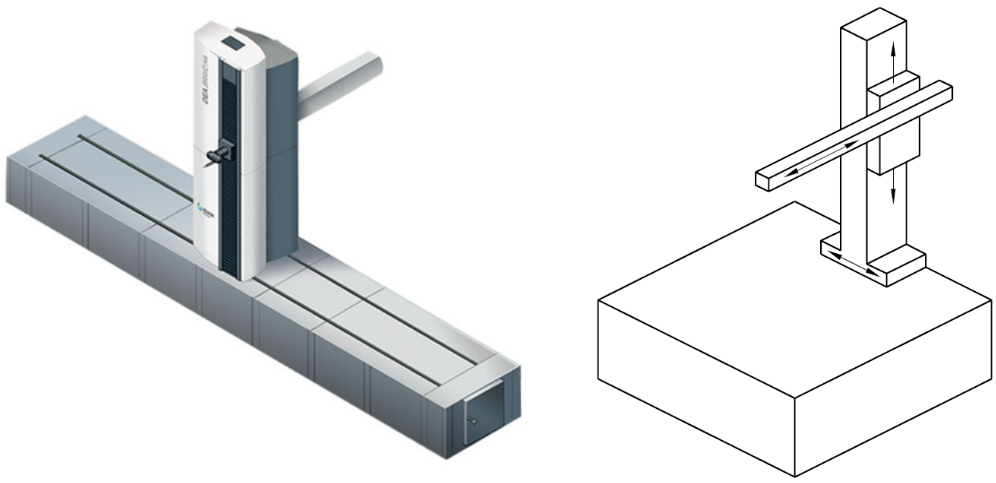


Figure 5: DEA Bravo HA - Moving ram horizontal-arm CMM

According to ISO 10360-1, “this is a CMM employing three components moving along guideways perpendicular to one another, with the probing system attached to the first component, which is carried on, and moves horizontally in relation to, the second. The combined assembly of the first and second components moves vertically relative to the third. The third component moves horizontally relative to the machine base, on which the workpiece is mounted."

This structure usually is less expensive than the previous ones, because the moving parts of the machine are more compact and easier to design. Besides, the horizontal-arm type is generally used to measure parts a lot bigger than the CMM itself. This is also due to the fact that this machine cannot reach a high accuracy level, which is required from the specs of small pieces, because of the high bending of the horizontal-arm.

This CMM is used to measure large components, which require low accuracy. Horizontal-arm machines are mostly used in automotive field. In Figure 6, a double arm machine is used to measure components at Italdesign Giugiaro in Torino (Italy).

Figure 6: Application of horizontal-arm machines

1.2.4 Gantry CMM

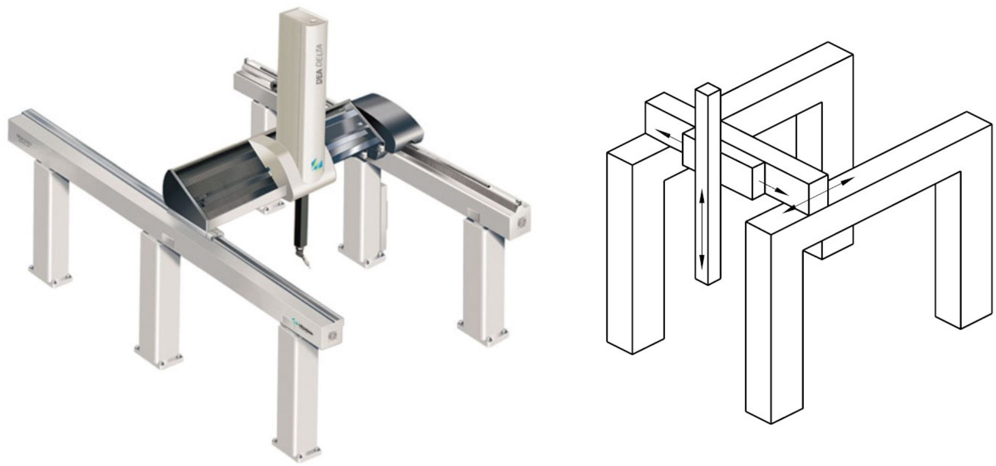


Figure 7: DEA Delta SLANT - Gantry CMM

According to ISO 10360-1, “this is a CMM employing three components moving along guideways perpendicular to one another, with the probing system attached to the first component, which is carried on, and moves vertically in relation to, the second. The combined assembly of the first and second components moves horizontally relative to the third. The third component moves horizontally on two guide rails raised on either side above the machine base on which the workpiece is supported.”

This structure usually is used for big machines, where the operator can work also into the measurement volume. A specific motor controls each axis of the CMM, because the moving parts are very heavy. In the Gantry CMMs, the base coincides with the foundation floor.

This CMM is used to measure large components that require high accuracy. For instance, one of the factories that adopt gantry machines is the ATR of Colonnella in Teramo (Italy), where these CMMs are used to measure hi-tech products, such as professional race bicycles or luxury car components. In Figure 8, the geometry of the chassis of a Lamborghini is verified using a Gantry machine.

Figure 8: Application of a Gantry machine

1.3 Geometrical Compensation

Hypothetically, the three carriages of the CMMs should have a rectilinear movement without rotations along the three Cartesian axes of a reference system. Therefore, it is necessary to have three couples of perfectly rectilinear guides located in three orthogonal directions. This behaviour is obviously ideal, because the guides have geometrical imperfections deriving from the mechanical processing operations. Besides, the elasticity of the machine structure produces deformations due to the displacement of the mass of the carriages. As a result, the CMMs commit errors in carrying out the measurements: when the carriages move to place the measurement centre in a given nominal position (X, Y, Z), the actual position assumed by the measurement centre ($X+E_X$, $Y+E_Y$, $Z+E_Z$) is different from the nominal one. E_X, E_Y and E_Z are the three deviations from the ideal behaviour and they are called geometrical errors. Therefore, it is important to create a kinematic model of the structural errors for describing the real behaviour of a CMM.

After the determination of the geometrical errors, they must be removed from the measurement returned by the machine, thus obtaining a more precise measurement. This procedure is called geometrical compensation.

1.4 Structure of the Thesis

This thesis is composed of three main parts.

The first part includes the first two chapters. After a brief introduction to the science of metrology, chapter 1 presents a general overview of Coordinate Measuring Machines (CMMs), starting with their fundamental systems. Then, different configurations of CMMs are described, highlighting their applications in factory. Finally, an introduction to geometrical compensation is presented. Chapter 2 analyses in detail the error model used for compensating a CMM and the traditional method of compensation actually performed in Hexagon Metrology. Therefore, the standard used for the acceptance of a machine is explained.

The second part is focused on the description of the new method of compensation proposed by the supplier Etalon. Particularly, chapter 3 introduces the tools necessary for this new approach of compensation, both hardware and software. In chapter 4, the Etalon procedure is discussed: at the beginning, there is a brief explanation of how to connect all the tools; therefore, all the steps necessary for estimating the compensation map are examined. Finally, the process of verifying the estimated map using the laser tracer is explained.

The third part of the thesis reports another activity carried out in parallel to compensation with the laser tracer, called offline compensation. The two approaches used are described in chapter 5.

Two case studies are discussed. In chapter 6, the process of compensation and verification of a horizontal-arm machine is analysed, adopting the following scheme: first, the online activity performed on the machine is described; therefore, the offline compensation activity is explained; finally, the results of both the procedures are reported. In chapter 7, the geometry verification of a gantry machine is presented.

Finally, the conclusions of the work of thesis are discussed.

2 Scientific Background

2.1 Error Model

Even in the best possible processing conditions, the mechanical parts of a measuring machine have geometric imperfections that must be detected and corrected in order to eliminate their effects on the measurement results. The error model has an important role in this process.

The error model is generic for every CMM, but it must be adapted to each machine through the determination of the model parameters.

2.1.1 Rigid Body Model

It is called “rigid body” a body that cannot be deformed, therefore the mutual distance between any two points of the body does not change over time and space. The carriages of the CMMs can be considered as rigid bodies.

A rigid body has 6 degrees of freedom in the space; therefore, six coordinates can uniquely determine the position of a carriage in the machine reference system. It is necessary to have 18 simple constraints to determine the position of the three carriages of a CMM for every position of the probing system. As a matter of fact, the kinematic model of a CMM is based on 18 mathematical functions that describe the unwanted displacements of the carriages during their movement, due to the imperfections in the geometry of the guides. In some cases, it is also possible to have 21 parameters in the model, by separating the contribution of the squareness errors.

The model is based on the following hypotheses:

- the structure of the CMM and the carriages are rigid bodies;
- the 18 kinematic functions are influenced only by the position of the carriage to which they are referred, therefore the movement of one carriage does not affect the others;
- the probing system does not introduce errors, so its contribution is not present in the model, however it is considered separately;

- the thermal state of the machine does not introduce errors, because the thermal effects and the structural deformations due to these gradients have a specific different model;
- the residual error, which represents the non-modelled parts, is small in comparison to the systematic error that is in the model.

The CMM errors of the rigid body model are illustrated in Figure 9. They can be divided as follows:

- 9 translation errors (L_{XX}, L_{XY}, L_{XZ}, L_{YX}, L_{YY}, L_{YZ}, L_{ZX}, L_{ZY}, L_{ZZ});
- 9 rotation errors (R_{XX}, R_{XY}, R_{XZ}, R_{YX}, R_{YY}, R_{YZ}, R_{ZX}, R_{ZY}, R_{ZZ});
- 3 squareness errors (Q_{XY}, Q_{ZX}, Q_{ZY}).

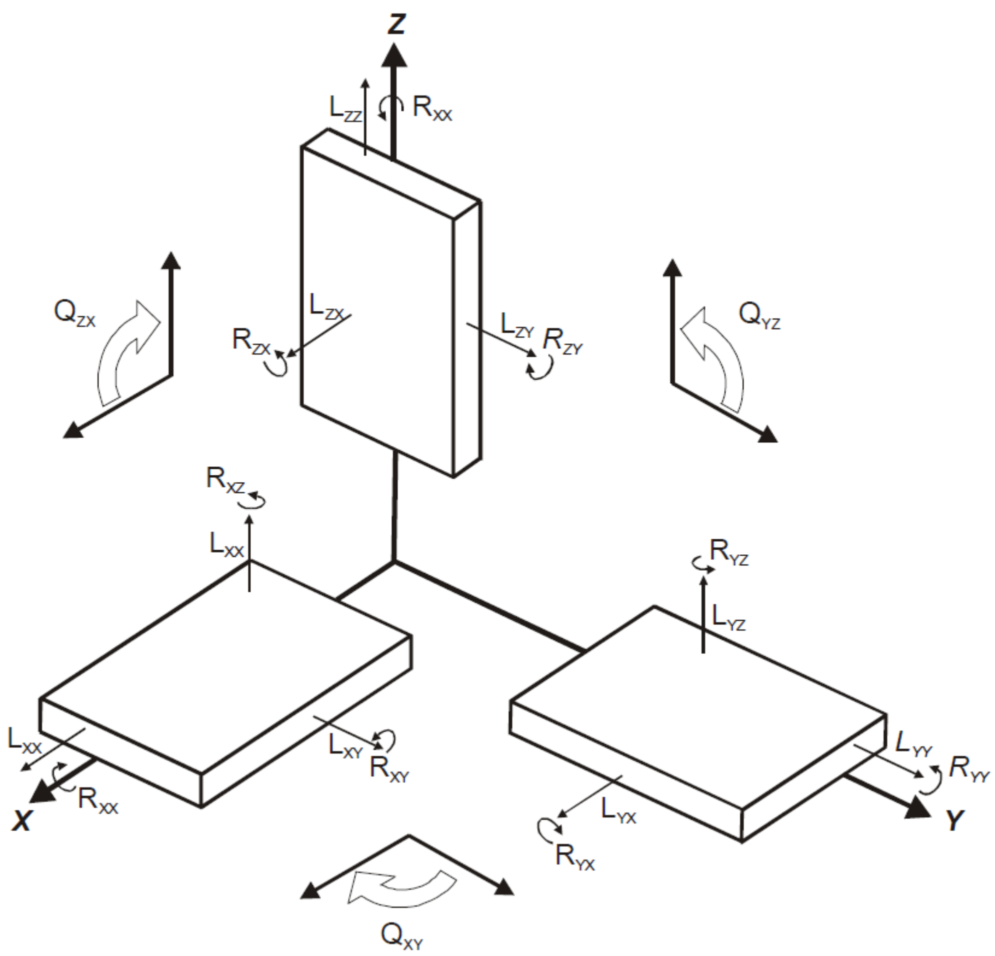


Figure 9: Rigid Body errors

The impact of such components on the CMM measurement errors can be written mathematically, as in the following matrix equation:

$$E = k \cdot M$$

With:

- $E = [E_X, E_Y, E_Z]$, measurement error of the machine;
- $k = [k_1, k_2]$, vector containing 21 geometric error components;
- $M = [M_1, M_2]^T$, weighted matrix that distributes each element of the k-vector on the three components of error.

The following equations show all the components of the k vector and the M matrix. Note that both the vector and the matrix have been divided into two parts for a better visualization of each component.

$$k_1 = [Q_{ZY}, Q_{ZX}, Q_{XY}, L_{YX}, L_{YY}, L_{YZ}, R_{YX}, R_{YY}, R_{YZ}]$$

$$k_2 = [L_{XX}, L_{XY}, L_{XZ}, R_{XX}, R_{XY}, R_{XZ}, L_{ZX}, L_{ZY}, L_{ZZ}, R_{ZX}, R_{ZY}, R_{ZZ}]$$

$$M_1 = \begin{bmatrix} -Z & 0 & -Y & 1 & 0 & 0 & 0 & Z + T_Z & -T_Y \\ -Z & 0 & 0 & 0 & 1 & 0 & -Z - T_Z & 0 & X + T_X \\ 0 & 0 & 0 & 0 & 0 & 1 & T_Y & 0 & -X - T_X \end{bmatrix}$$

$$M_2 = \begin{bmatrix} 1 & 0 & 0 & 0 & Z + T_Z & -T_Y & 1 & 0 & 0 & 0 & T_Z & -T_Y \\ 0 & 1 & 0 & -Z - T_Z & 0 & T_X & 0 & 1 & 0 & -T_Z & 0 & T_X \\ 0 & 0 & 1 & T_Y & -T_X & 0 & 0 & 0 & 1 & T_Y & -T_X & 0 \end{bmatrix}$$

T_X, T_Y and T_Z are the probe offsets, which are calculated from a reference point. Instead, X, Y and Z are the coordinates of the machine without considering the offsets. Such coordinates become the reference point for the calculation of the probe offsets.

More details concerning the measurement errors are explained in the following sections.

2.1.1.1 Translation errors

These errors analyse the undesired translation of each carriage along the three directions during its movement along the sliding axis of the carriage. They can be divided into straightness and linearity errors. Straightness errors point out the displacement due to the movement along the two directions perpendicular to the sliding axis of the carriage under observation. Linearity errors, also called positioning errors, are caused by the non-linearity of the used displacement transducers. In particular, the CMMs are equipped with optical lines, which can return an incorrect value of the carriage position along its sliding axis. The linearity errors can have very different values even when different positions of the same axis are considered.

2.1.1.2 Rotation errors

These errors describe the unwanted rotation of each carriage around the three axes during its movement along the sliding axis of the carriage itself. They are usually called roll, yaw and pitch. The roll error points out the rotations around the sliding axis of the carriage. The yaw error identifies the rotation around the axis perpendicular to the sliding plane of the carriage. In the end, the pitch error specifies the rotation around the axis perpendicular to the sliding axis of the carriage and lying on the sliding plane itself.

2.1.1.3 Squareness errors

These errors are the result of constraining mutually the positions of several rigid bodies. The guides necessary for the movement of the carriages should be perfectly orthogonal to each other; however, this ideal condition is not easy to satisfy.

Two axes can be defined in quadrature if they are orthogonal to each other. When the angle between them is different from 90° there is a squareness error.

2.1.2 Deflection Model

The rigid body model is not always enough to describe accurately the behaviour of a CMM. There are other causes of error, also due to the movement of the carriages, which need a specific design to be considered. The most relevant causes are the static and dynamic deformations of the structure, due to the fact that nothing really behaves like a rigid body.

2.2 Compensation Method

The traditional compensation method can be defined as a direct method. It means that each error is obtained by measuring it individually and can be added to the error compensation map.

2.2.1 Tools

The tools used for compensating the CMMs with the traditional method are the following:

- laser source;
- laser beam compensator;
- interferometers;
- reflectors;
- electronic levels;
- software for data processing.

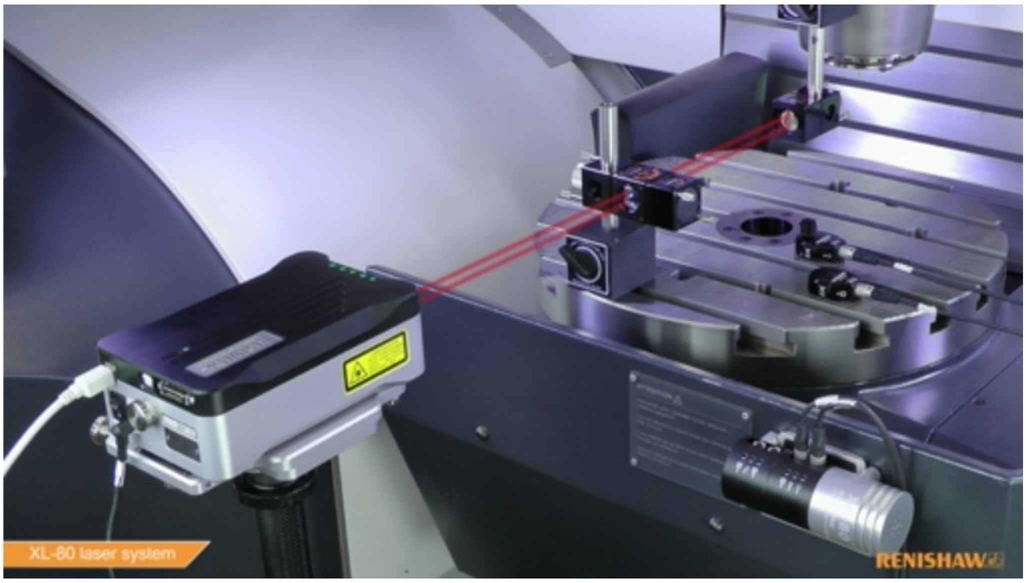


Figure 10: Renishaw tools for traditional compensation of a CMM

In Figure 10, it is possible to see an example of linear measurement with the traditional method. The laser source produces a stable beam. Its accuracy is due to the beam compensator (in the right lower part of the figure), which can measure air temperature, air pressure and relative humidity; then, the compensator modifies the nominal value of the laser wavelength, to give a true value. The outcome of this process is the removal of any measurement errors due to changes in environmental conditions.

2.2.2 Process

The compensation process consists in taking over every error parameter one by one. All the steps necessary for acquiring the parameters and including them in the compensation map after the connection of the machine to all its systems are explained in the following. Some errors must be detected using the laser, while others are spotted adopting electronic levels. The first procedure follows:

- place the laser in a convenient position in relation to the movement that the CMM will have to do;
- mount the reflector at the end of the ram of the CMM;
- place the interferometer between the laser source and the reflector;
- activate the measurement from the compensation software;

- at the end of the measurement, some differences will be detected between the nominal distances of the machine from the laser and the actual ones; such difference is the wanted error.

The interferometer plays a very important role in the process: it splits a single light beam into two identical rays, both covering different paths, and then brings them together to produce interference. Such interference is used to measure distances.

The electronic levels are used in the following way:

- place one level on the ram of the machine;
- place the second level on the base of the machine;
- activate the measurement from the compensation software;
- at the end of the measurement, some differences will be detected between the level on the ram and the one on the base; from this difference, the error is calculated.

After the detection of all the geometrical errors one by one, they are inserted in the compensation map and downloaded into the CMM controller.

2.2.3 Verification

After the estimation of the compensation map, the next step consists in testing its goodness. Therefore, the International Organization for Standardization (ISO) provided the norm ISO 10360, from the title "Geometrical Product Specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM)". The standard is divided in 12 parts, each one with a specific purpose. The parts of the standard useful for the goal of this thesis are the first two:

- the ISO 10360-1 establishes a vocabulary for CMMs and their acceptance and reverification tests;
- the ISO 10360-2 specifies the acceptance tests for verifying the performance of a CMM used for measuring linear dimensions as stated by the manufacturer and defines the reverification tests that enable the user to reverify periodically the performance of the CMM.

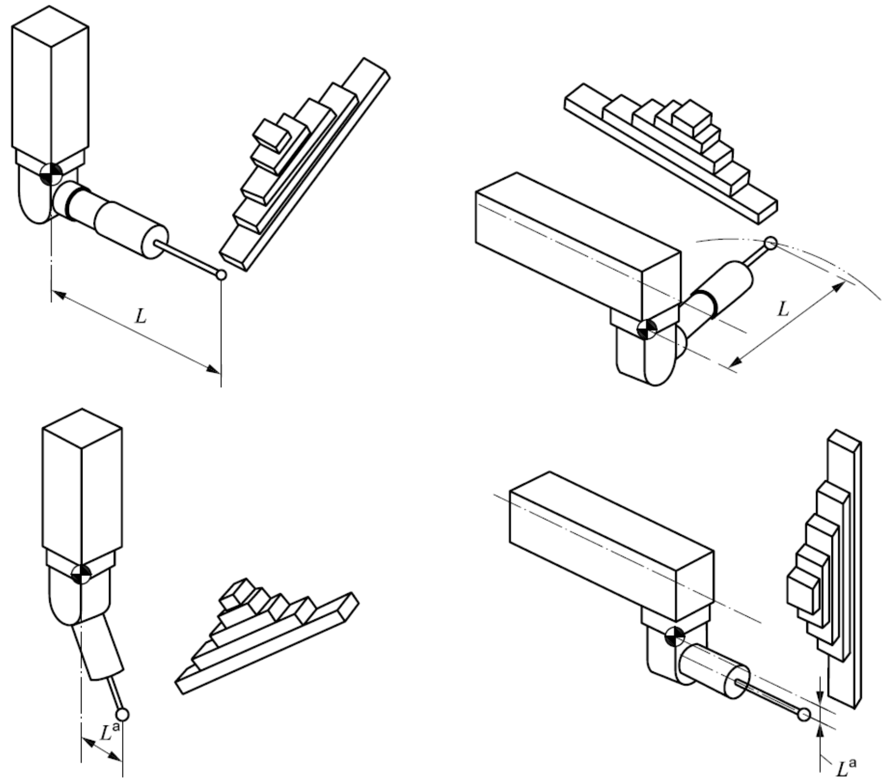
In the following section, the part 2 of the standard is discussed.

2.2.3.1 Acceptance Tests (ISO 10360-2)

The ISO 10360-2 is the standard used for the acceptance of a machine.

First, the standard explains some terms and definitions, which are necessary to understand the entire process of CMM verification.

It is defined ram axis stylus tip offset the "distance (orthogonal to the ram axis) between the stylus tip and a reference point". The manufacturer defines such reference point, which is usually in or near the probing system. In Figure 11, it is possible to see some examples of ram axis stylus tip offset, identified by the letter L, in the case of an articulated probing system.



a $L \approx 0$.

Figure 11: Examples of ram axis stylus tip offset

The length measurement error (E_L) is the “error of indication when measuring a calibrated test length using a CMM with a ram axis stylus tip offset of L, using a single probing point at each end of the calibrated test length”. The default values of L specified in ISO 10360-2 are L=0 mm and L=150 mm.

The repeatability range of the length measurement error (R_0) is the “range (largest minus smallest) of three repeated length measurement errors measured by a CMM with zero ram axis stylus tip offset”.

It is defined maximum permissible error of length measurement ($E_{L,MPE}$) the “extreme value of the length measurement error, E_L, permitted by specifications”. In the same way, the maximum permissible limit of the repeatability range ($R_{0,MPL}$) is the “extreme value of the repeatability range of the length measurement error, R_0, permitted by specifications”.

After the comprehension of the terminology adopted, the acceptance tests are discussed.

“Acceptance tests are executed according to the manufacturer’s specifications and procedures. The principle of the assessment method is to use a calibrated test length, traceable to the metre, to establish whether the CMM is capable of measuring within the stated maximum permissible error of length measurement for a CMM with a specified ram axis stylus tip offset (both 0 and 150), $E_{0,MPE}$ and $E_{150,MPE}$, and within the stated maximum permissible limit for the repeatability range, $R_{0,MPL}$.

The assessment shall be performed by comparison of the indicated values of five different calibrated test lengths, each measured three times, relative to their calibrated values. The longest calibrated test length for each position shall be at least 66% of the maximum travel of the CMM along a measurement line through the calibrated test length.”

In the standard it is also specified how the measurement must be performed. The procedure includes at least seven measurement positions, distributed as follows: “four of the seven positions shall be the space diagonals, while the remaining three positions are parallel to each of the CMM axes.” These seven positions are measured with zero ram axis stylus tip offset (E_0). “For CMMs with a high aspect ratio between the lengths of the axes, it is recommended that the manufacturer and the user, upon mutual agreement, add two additional measurement positions. A high aspect ratio CMM occurs when the length of the longest axis is at least three times the length of the intermediate axis. The recommended positions, each consisting of five calibrated test lengths, each measured three times, are the two corner-to-corner diagonals in a plane perpendicular to the longest axis.” These two positions are measured with ram axis stylus tip offset 150 mm (E_{150}).

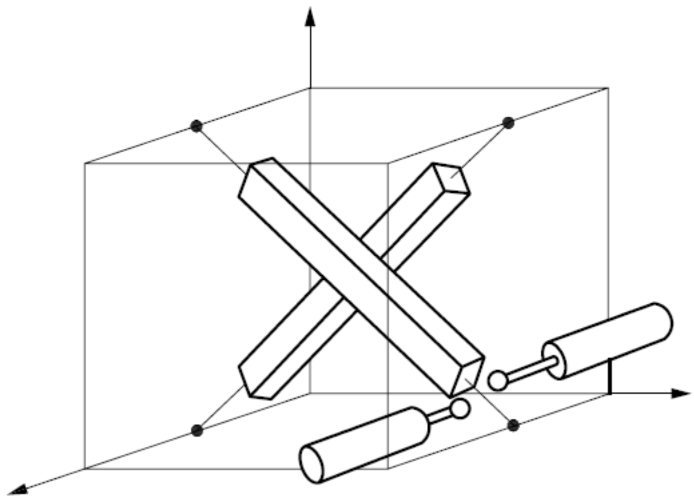


Figure 12: Example showing two of the four possible calibrated test length positions, and two of the possible probe orientations for the E_{150} test procedure

“The performance of the CMM used for measuring linear dimensions is verified if all the following conditions are verified:

- the length measurement errors measured with zero ram axis stylus tip offset (E_0) are within the maximum permissible error of length measurement ($E_{0,MPE}$);
- the repeatability range of the length measurement error (R_0) is within the maximum permissible limit of the repeatability range ($R_{0,MPL}$);
- the length measurement errors measured with ram axis stylus tip offset 150 mm (E_{150}) are within the maximum permissible error of length measurement ($E_{150,MPE}$).

For CMMs that are not intended for use with a ram axis stylus tip offset or CMMs not capable of being used with a ram axis stylus tip offset of any length L, verification of the length measurement error (E_L) is not required.”

2.2.3.2 Interpretation of the Results

After carrying out a measurement, it is necessary to calculate the length measurement error E_L, as the difference between the indicated measured distance and the calibrated one. Therefore, such error is plotted in a graph as a function of the measured length, as shown in Figure 13.

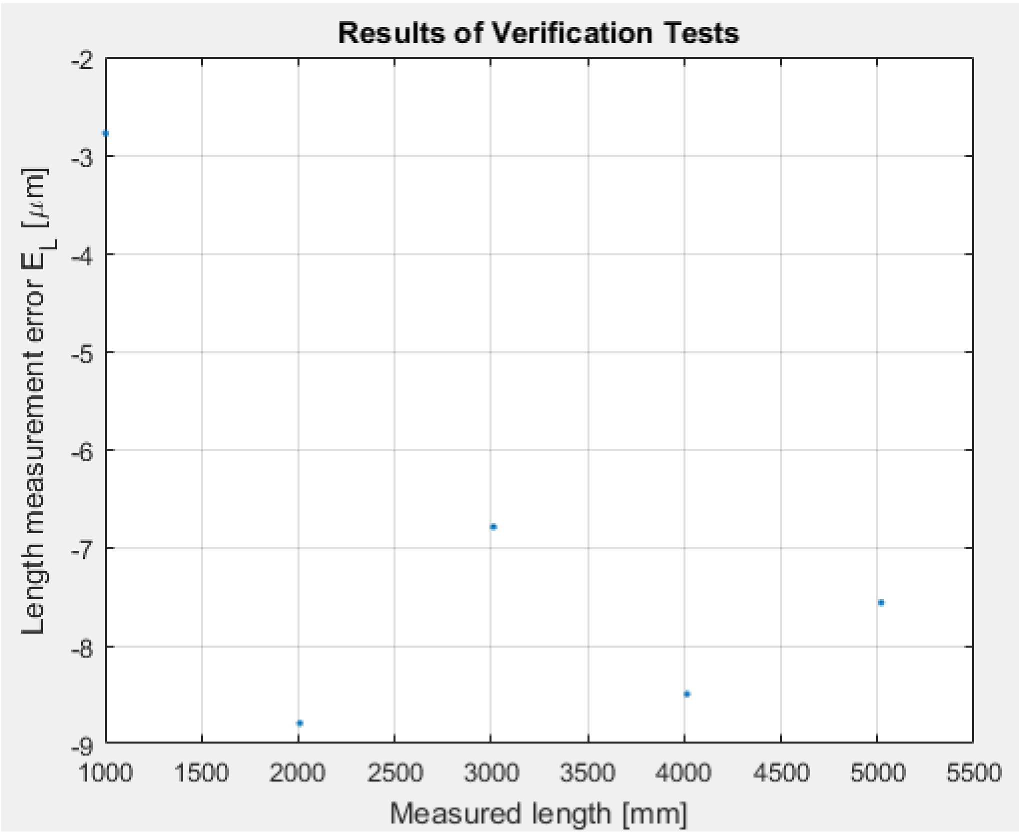


Figure 13: Length measurement errors plotted as a function of the measured length

In the previous graph, five blue points show that five length were measured along the line. However, this is not enough to understand if the CMM has carried out good or bad measurements. Therefore, the machine specifications are required in order to verify the geometry of the machine. Each machine has different specifications, which depend mostly on its geometry and mechanics. The specifications are usually reported in the technical data sheet of the machine. They usually follow a common pattern, visible in the following equations:

$$E_{0/150} = A + B \cdot \frac{L}{1000} \ [\mu m]$$

$$R_0 = A \ [\mu m]$$

A and B are coefficients whose value can vary according to the size of the machine and the temperature range in which the machine will work approximately. Instead, L is the measured length under observation. Therefore, the specifications have the shape of a straight line in the graph, which is symmetrical with respect to the abscissa axis. In Figure 14, it is possible to see the specifications plotted against the same measurement errors of Figure 13.

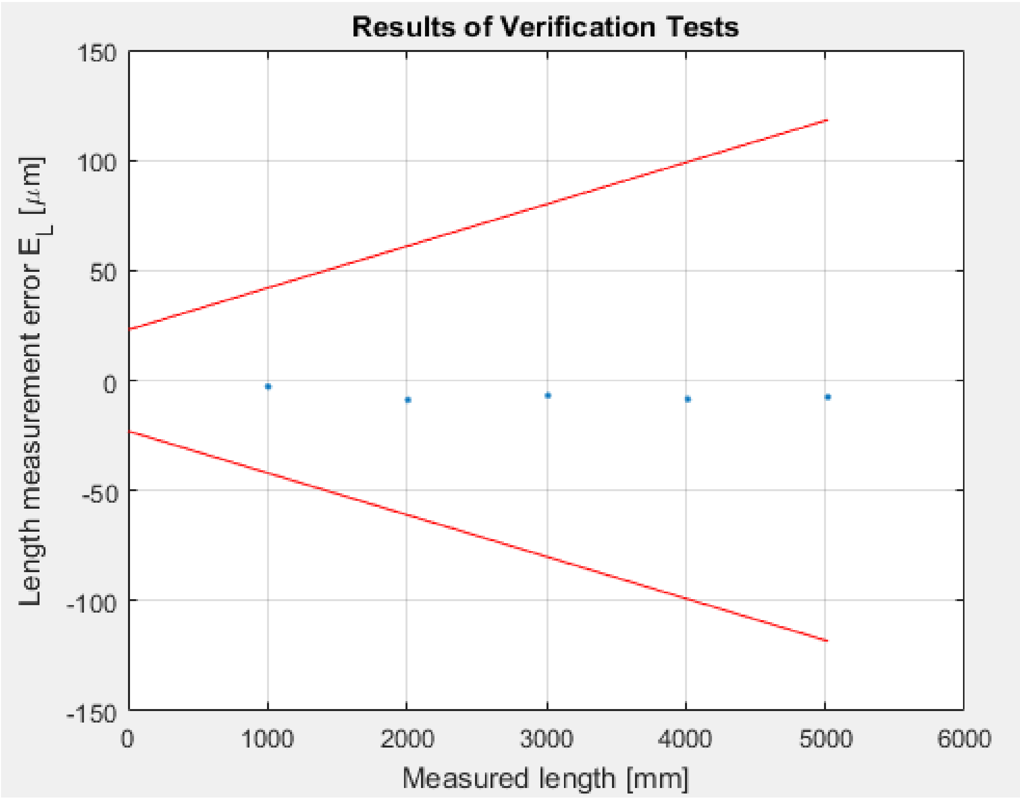


Figure 14: Specifications (red) plotted against the measurement errors (blue)

The measurement respects the specifications if all the measurement errors are within the two straight lines, as it happens in the previous graph.

In Figure 15, an example of bad measurement is reported. It is visible that the machine has measured with errors out of specification in three of the five measured length.

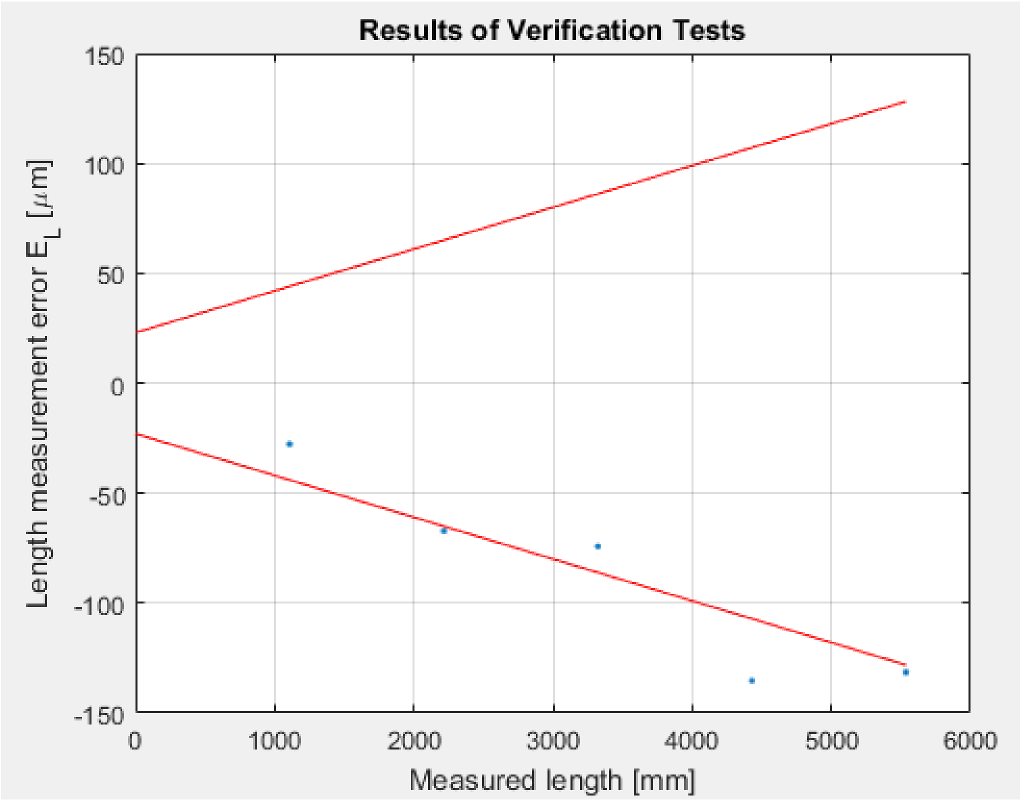


Figure 15: Example of bad measurement

3 Etalon tools

3.1 Hardware

The Etalon's equipment includes the following tools:

- Laser Tracer (LT);
- joystick to manually guide the laser beam;
- control unit;
- optical reflector;
- temperature sensor;
- air pressure and humidity sensor.

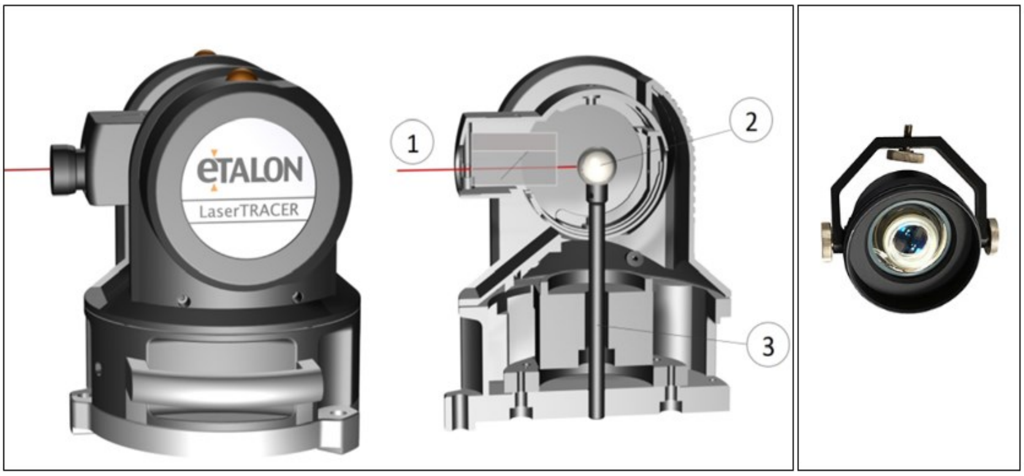


Figure 16: Etalon Laser Tracer (left) and optical reflector (right)

The LT is a self-tracking laser interferometer that can automatically track an optical reflector with high precision distance measurements. In Figure 16, it is visible what is integrated in the tracer: the measurement beam (1) hits a reference sphere (2), which is mounted on a stem made of a low thermal coefficient material (3). The beam has nanometric resolution, while the sphere is characterized by extremely small form errors, less than 50 nanometers.

The interferometer moves in a gimbal mount around the sphere. The only purpose for the sphere is to act like a reference for the interferometer. No external forces can modify the position of the sphere, since it does not have any mechanical function. The light beam is transmitted to the interferometer by a glass fibre, in order to reduce the weight of the LT and eliminate thermal influences.

The peculiarity of the optical reflector is its sophisticated design: two concentric mirrors guarantee a wide working angle, up to 120°.

The external control unit contains the laser source and the electronics for motor control and data processing.

The sensors measure air temperature, pressure and relative humidity and correct the laser measurement accordingly.

A general setup consists in placing the LT on the base of the machine or outside the CMM volume, while the reflector must be mounted at the end of the ram of the machine. Once the LT is locked-in to the reflector, the presence of the sphere ensures that the tracer can follow the machine during its movement. This is the main advantage of this technology, which distinguishes it from the Renishaw laser source. In Figure 17, taken from the paper by C. Schneider entitled "LASERTRACER – A NEW TYPE OF SELF TRACKING LASER INTERFEROMETER", an example of setup for a moving bridge CMM is reported. It is evident that the LT must be placed in three positions on the workpiece table. Besides, for each position, the reflector mounted at the end of the machine ram has different offsets with respect to the reference point of the machine head.

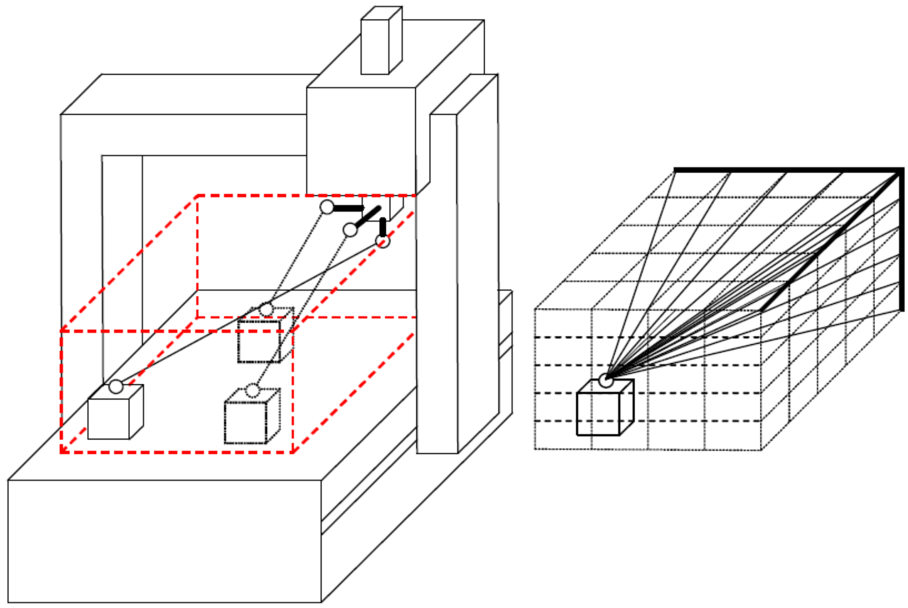


Figure 17: Example of setup for a moving bridge CMM

For each LT position, the CMM follows a path in the measurement volume. Some points are identified by a spatial grid in the volume. At each point, the machine stops and the interferometer acquires the distance associated to such point. Therefore, the error is calculated through the difference between the measured distance and the nominal one, which is obtained by the position of the reference point and the three coordinates of the CMM. The estimation of the error parameters is done through a best-fit calculation based on the kinematic model of the machine and the systematic errors.

3.2 Software

Etalon provided also two software, both used in combination with the LT system. The first one is called TRAC-CAL version 4.6 and it is used to determine all the systematic geometrical parameters in the compensation map. On the other hand, the second software, called TRAC-CHECK version 4.4, is used for the verification tests. The two software have similar interfaces.

4 Methodology for Compensation with Etalon

4.1 Lock-in process

The connection between the software and the LT is the first thing to manage. After that, it is necessary to lock-in the laser: this procedure is the same for both the software. The LT is defined locked-in if it is capable to follow the machine movement through a predefined path along the three axes. Once the user decides how the machine ram will have to move, he has to choose the inclination of the reflector as well as an opportune position for placing the LT. In order to take this decision, it is essential that the tracer is in a stable position and that does not interfere with the machine movement, avoiding any collisions. Then, the user can proceed to lock-in the LT by directing the laser beam towards the reflector, using its joystick. At this point, two alternative options are possible: the LT can be automatically locked-in if the laser beam has been perfectly centred, otherwise in most cases it is required to go through an intermediate phase. It is extremely difficult to direct manually the laser beam in the lock-in point; therefore, the LT has the capability to find the right point by itself: the user has to give as input only the distance between the centre of the laser source and the reflector. Such distance does not need to be very accurate; however, the LT uses this information to calculate a path where it can move in order to find the lock-in point. At the end of the lock-in process, the two lights on the top of the LT are turned on, as shown in Figure 18.

Figure 18: LT locked-in to the reflector

Occasionally, a phenomenon called beam brake may occur: the software can lose temporarily or permanently the signal arriving from the LT. If this happens while carrying out a measurement, the machine will immediately stop moving and the measurement is interrupted. The causes of beam brake may be various. One of them is the bad positioning of the LT: if it is placed in an unstable position or is not well fixed, the laser beam will not be steady during the measurement; therefore, it will miss the connection in some points. The same thing can happen if the laser beam is stable, but the reflector is not well pinned. Other plausible reasons for beam brake should not be user’s responsibility: the internal reference sphere of the LT may be dirty or perhaps the reflector may skip some points because of a manufacturing defect.

4.2 Compensation process

The main difference between the traditional method of compensation and the Etalon one is in the fact that the latter is an indirect method. In fact, the software can calculate the error parameters only after the successful conclusion of all the measurements.

A benefit deriving from the compensation with the LT system is the possibility to choose the way of performing the measurements between the “static” and “on-the-fly” mode. The substantial difference between the two modes is in the data acquisition. In fact, with the static mode, acquisition is governed by space: the user chooses the step after which the machine must stop. Therefore, acquisition of the point coordinates begins when the CMM stops. Once the acquisition is complete, the CMM will move to the next point and so on until the end of the measurement. On the contrary, with the on-the-fly mode, acquisition is governed by time: the user can choose the frequency of data acquisition and the CMM moves without ever stopping until the measurement ends. This way of proceeding allows to acquire thousands of points, which will be filtered in the post-processing phase in order to calculate the error parameters. The traditional method of compensation adopts static measurements, while for the Etalon method it has been used the on-the-fly mode.

The TRAC-CAL software is used to perform the compensation of the CMM. Its interface is structured in such a way as to guide the user in each step of the procedure. Once the software is open, its screen appears as in the following Figure 19. The red circles in the lower right part of the figure indicate that the LT system is not connected.

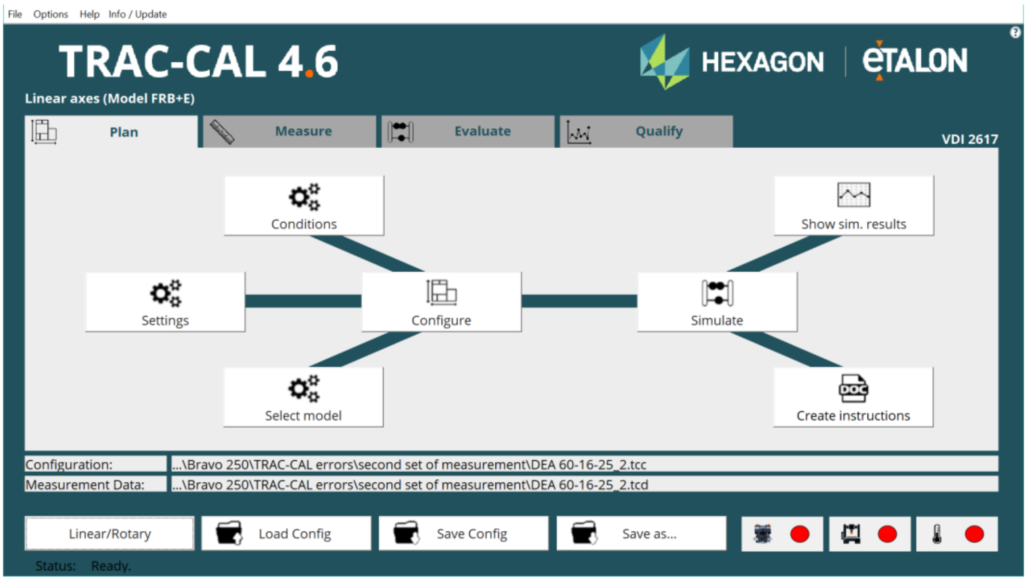


Figure 19: TRAC-CAL software interface

The first thing to do is to connect TRAC-CAL with the laser and the machine controller: it can be done with the "Connections" command, which is in the "Measure" section. When the LT is connected, the software warns the user, as shown in the following Figure 20.

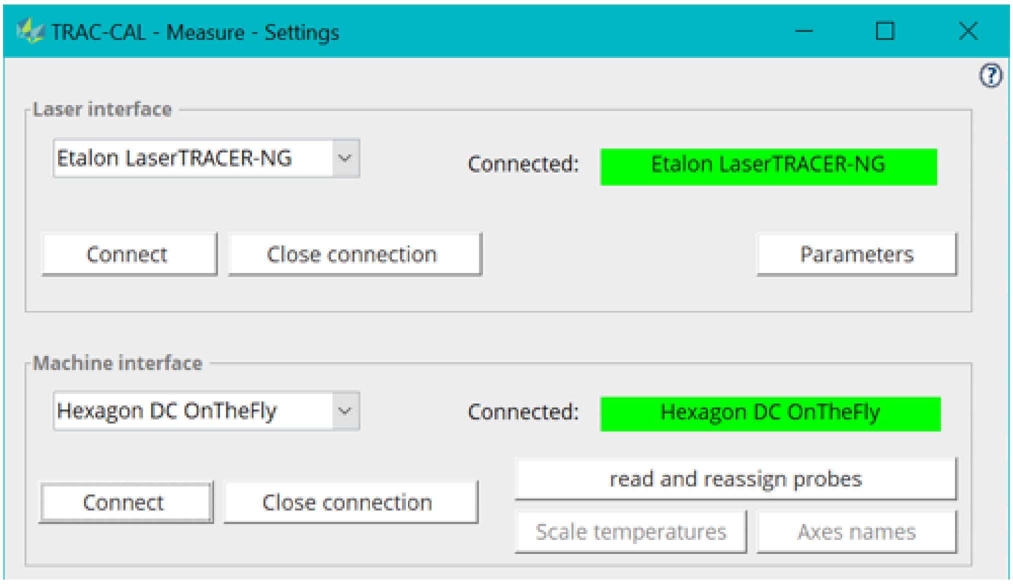


Figure 20: Laser and Machine connected to the software

A screen opens automatically, requesting the insertion of the probe that will be used in the measurements, with its offsets, and the one that will be used as a reference. During the compensation phase, there usually is an empty map in the CMM controller. In this case, it is necessary to insert a probe called “RefProbe”, with zero offsets on each axis, as both the probe used for the measurements and the one taken as reference. This is possible because the offsets can be added later in TRAC-CAL. Another possibility for the compensation of a CMM is to start from a not completely empty map. If this is the case, it is no longer possible to insert the RefProbe as the probe used for the measurements, instead the software requests to select the appropriate probe with the right offsets before carrying out each measurement.

The wrist can change its pitch angle and the roll angle if it is mounted an indexable head at the end of the machine ram. It is important to keep in mind that each variation in the wrist inclination implies different offsets for the reflector.

Before starting the measurements, it is important to create a measurement strategy that allows a correct evaluation of all the error parameters of the machine. In order to design a strong strategy for the machine under observation, some software commands need to be considered first:

- the "Settings" command allows to set the machine information, such as its volume, the type of laser used and the thermal expansion coefficients along the three machine axes;
- the "Conditions" command allows to select the uncertainties due to the laser used;
- the "Select model" command allows to select the model of the CMM under analysis.

After setting these first parameters, the measurement strategy can be performed using the "Configure" command: it is possible to create measurement configurations, while constantly having a feedback about the maximum uncertainties expected on the error parameters, which are calculated by means of a simulation. The creation of a measurement configuration consists of entering the position of the LT in the machine reference system, the probe offsets and the lines travelled by the reflector mounted on the ram of the machine. An example of measurement configuration is in the following Figure 21.

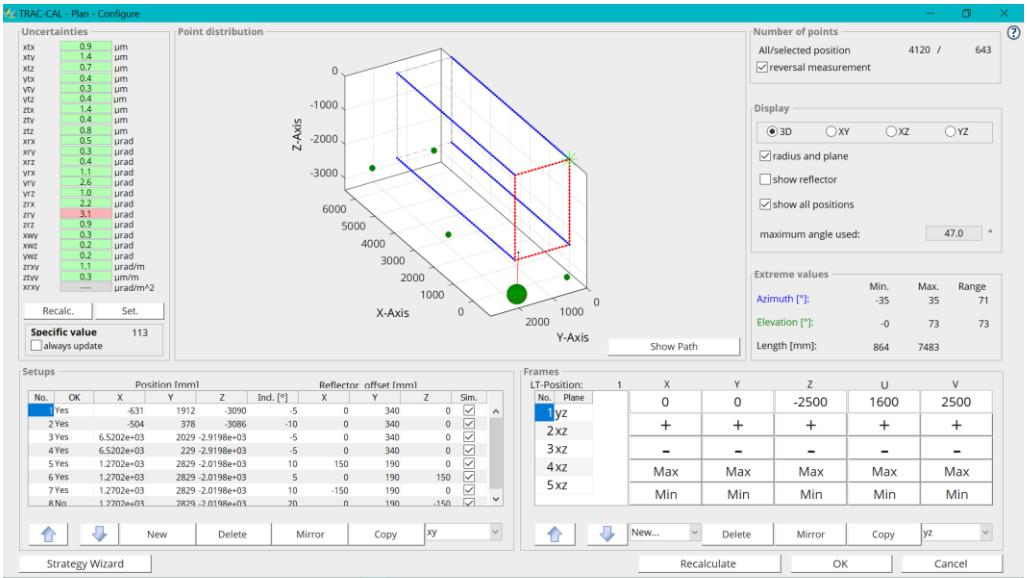


Figure 21: A measurement position in a configuration for CMM compensation

The creation of the measurement strategy can be also performed offline, i.e. without connecting the LT to the software; however, it is necessary to connect the LT before the execution of the measurements. The next step consists in carrying out the measurements, through the “Measure” section: it is possible to perform each position implemented in the strategy, by selecting it from a dropdown-list.

In the “Evaluate” section, it is possible to analyse the results of the performed measurements. In Figure 22, it is possible to identify all the commands useful for the estimation of the compensation map.

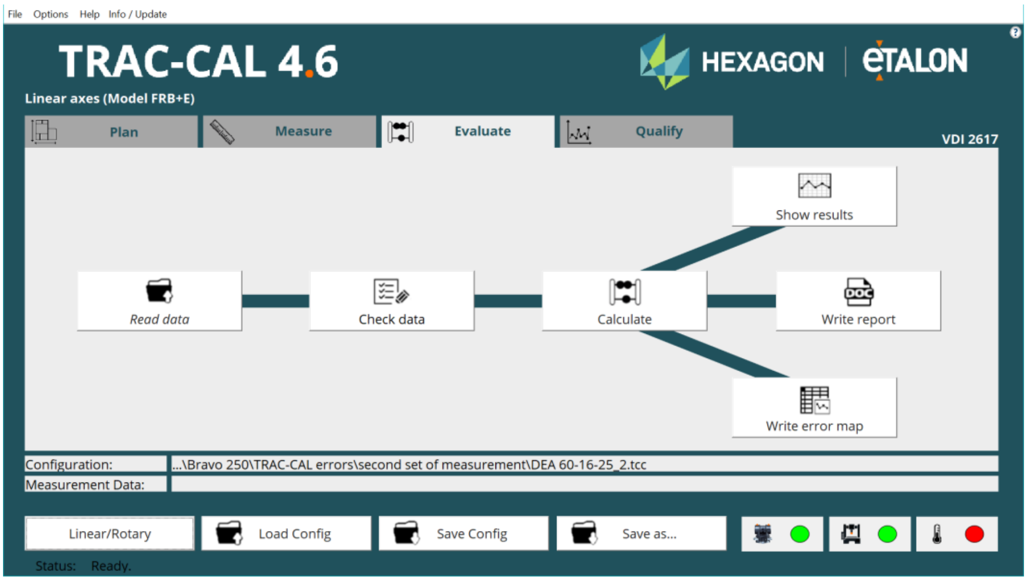


Figure 22: Evaluate section in TRAC-CAL software

The "Check data" command allows the user to examine all the measurements and select those useful for the calculation of the error parameters. The "Calculate" command is used to estimate these parameters. The last step of the compensation process consists in creating the compensation map, which can be done with the "Write error map" command.

4.3 Verification process

After the creation of the compensation map, it must be downloaded on the CMM controller. The verification process consists in carrying out some measurements with the TRAC-CHECK software, in order to verify the goodness of the error map created.

The interface of TRAC-CHECK is structured in such a way as to guide the user in each step of the procedure. In Figure 23, it is possible to see how the software screen appears once it is open.

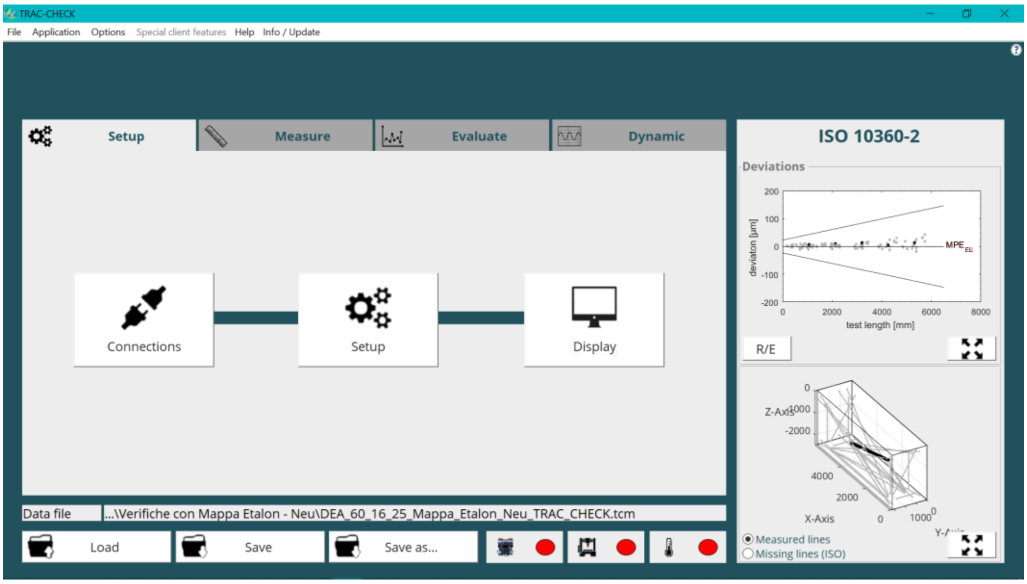


Figure 23: TRAC-CHECK software interface

The first thing to do is to connect TRAC-CHECK to the laser and the machine controller. When the LT is connected, a screen opens automatically, requesting the insertion of the probe that will be used in the measurements, with its offsets, and the one that will be used as a reference. Unlike the TRAC-CAL procedure, in this case, it is not possible to apply the right offsets in a second time; therefore, it is necessary to select the right probe offsets used in the measurements. On the other hand, the "RefProbe" can be used as the reference probe, as it happens with TRAC-CAL.

Then, through the "Setup" command, it is possible to input the characteristics of the machine, including the machine volume and tolerances. Other aspects to be entered are the specifications of the laser, such as the virtual expansion coefficient and the uncertainty. Finally, it is necessary to define the measurement strategy, i.e. how the machine will acquire the points, the number of points acquired per line, the number of repetitions for each measured length, the minimum distance that the machine must have from the centre of the laser source and the distance from the limits of the machine volume. In Figure 24, the highlighted measurement strategy is the one used for the acceptance tests of CMMs, according to ISO 10360-2.

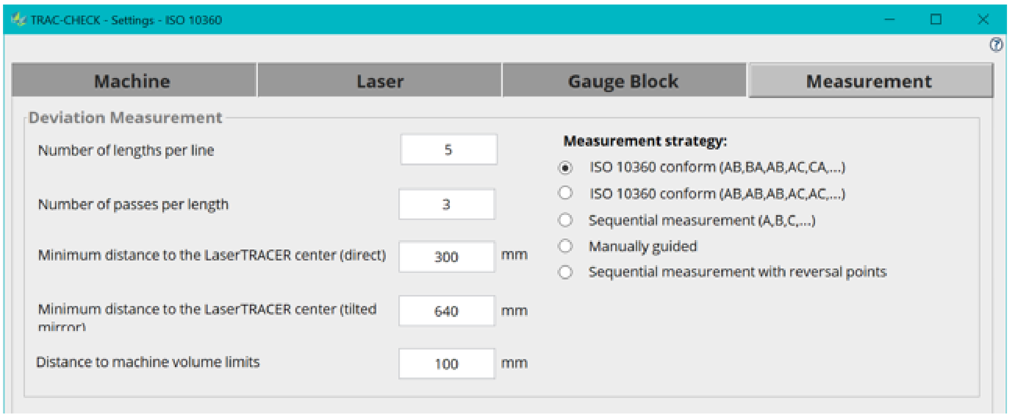


Figure 24: Typical measurement strategy, according to ISO 10360-2

After the setup phase, it is possible to choose how to display the measurement volume from the "View" command, by selecting the order of the kinematic chain and the orientation of the axes.

After completing this step, the actual measurement can start through the "Measure" command. To comply with ISO 10360 standards, it is necessary to carry out seven verification length measurements, divided as follows: three of them concern the measurement of the machine axes (X, Y and Z); the other four measurements correspond to the volumetric diagonals. In order to accomplish these measurements, it is therefore necessary to place the LT in at least four points, located next to the corners of the base of the volume. From each position, it is possible to measure the three lines along the axes (X, Y and Z); moreover, the diagonals of the XY, XZ and YZ planes can be measured, with the further addition of the volumetric diagonal (XYZ) described by the machine, starting from the position where the LT is located. In Figure 25, it is possible to see all the measurable lines from one LT position within the volume of the machine.

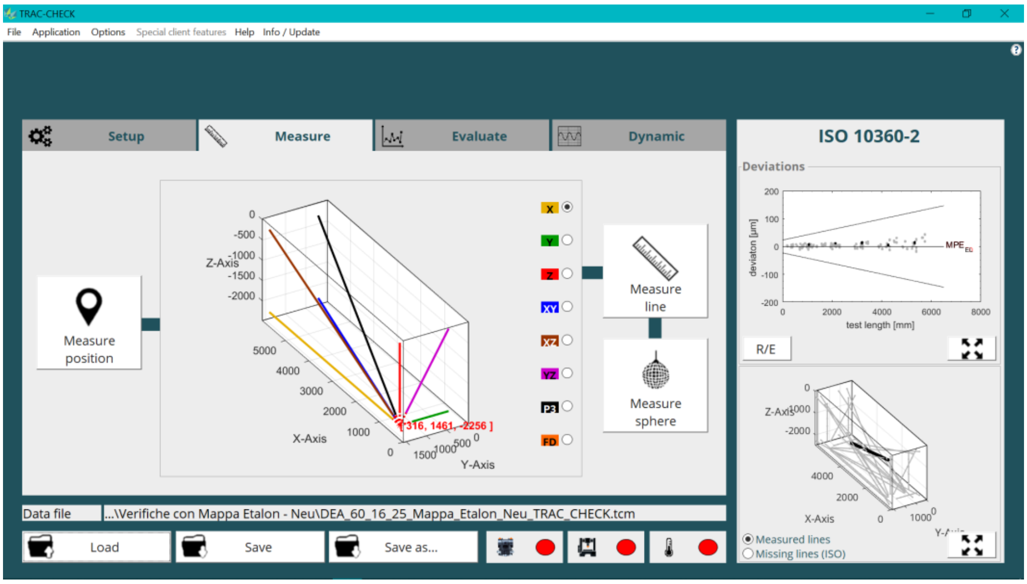


Figure 25: Measure section in TRAC-CHECK software

The measurement procedure is divided into the following steps:

- place the laser in a corner of the volume;
- tilt the reflector mounted on the machine so as to avoid the beam brake, i.e. the loss of signal;
- lock-in the laser to the reflector;
- measure the position of the laser inside the volume using the "Measure position" command;
- select the lines to be measured, press the "Measure line" command and start the measurement.

The machine will start moving and will perform the assigned measurements.

At the end of the measurements, it is possible to view the results in the "Evaluate" section, where the measured lines can be modified or removed; it is also possible to apply some residual correction values to the compensation map and create a report with all the measurements.

In the Etalon TRAC-CHECK report, each colour has a direct correspondence with a specific direction of measurement, as reported in Figure 26.

COLOUR	LINE
YELLOW	X-axis
GREEN	Y-axis
RED	Z-axis
BLUE	XY-diagonal
BROWN	XZ-diagonal
PURPLE	YZ-diagonal
BLACK	XYZ-diagonal

Figure 26: Explanation of colours in TRAC-CHECK

5 Offline Compensation

5.1 Goal

Offline compensation is an important activity, because working online on a machine takes a long time; moreover, it is not always possible to have CMMs available for testing. This type of compensation consists in the measurement of raw data on the CMM, obtained with measurements of some lines without having a compensation map on the controller. Therefore, different compensation maps can be applied offline on the same set of points, using an appropriately developed Matlab simulator. The first thing to develop for offline compensation is a Matlab function to read the files in *.txt format coming from TRAC-CHECK, in order to import the measured coordinates; therefore, it is possible to manipulate these coordinates to calculate residual errors and plot the results.

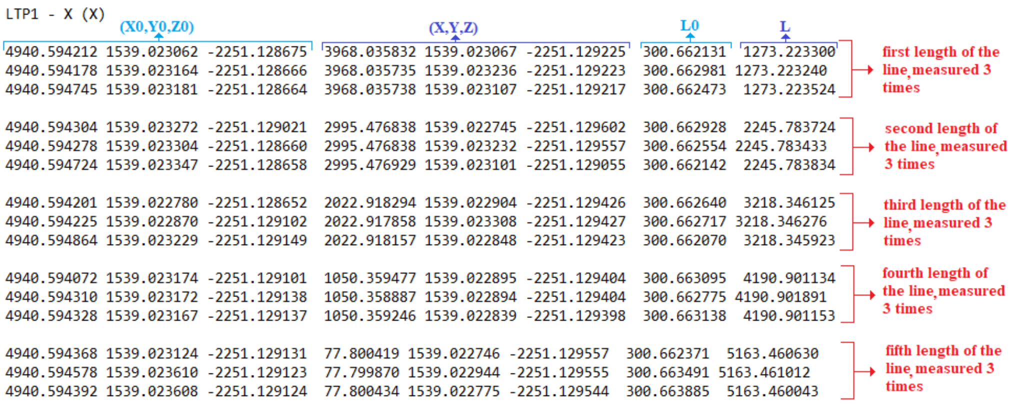
The main goal of offline compensation is to compare the capability of different maps in compensating the error starting from the same set of points. In particular, the Etalon compensation map obtained by TRAC-CAL must be compared with the Legacy map, obtained with the traditional method. Two different approaches have been used, described below:

1. perform some verification lines with TRAC-CHECK with an empty compensation map on the controller, in order to collect raw coordinates; then, these coordinates are compensated through Matlab by using different maps;
2. collect a series of coordinates with TRAC-CHECK with a map running on the machine; then, these coordinates are "uncompensated" through Matlab: the compensation error is removed from each of the measured points using the same compensation map that was on board during the measurements, thus obtaining a series of raw points. Finally, these points are compensated by using different maps.

More details about the two approaches are provided in the following paragraphs. However, in the first place it is important to understand how to calculate the compensation residuals.

5.2 Residual errors calculation

A typical TRAC-CHECK *.txt file reports one measured length in each row. The first three columns of the row are the coordinates of the starting point of the line (X_0,Y_0,Z_0). The next three columns are the coordinates of the end point of the line (X,Y,Z). Then, the next two numbers are the distances between the laser source and the starting point of the line (L_0) and between the laser source and the end point of the measured length (L). Every length is measured three times in order to study the machine repeatability. An example is in the following Figure 27.



LTP1 - X (X)

4940.594212	1539.023062	-2251.128675	3968.035832	1539.023067	-2251.129225	300.662131	1273.223300
4940.594178	1539.023164	-2251.128666	3968.035735	1539.023236	-2251.129223	300.662981	1273.223240
4940.594745	1539.023181	-2251.128664	3968.035738	1539.023107	-2251.129217	300.662473	1273.223524
4940.594304	1539.023272	-2251.129021	2995.476838	1539.022745	-2251.129602	300.662928	2245.783724
4940.594278	1539.023304	-2251.128660	2995.476838	1539.023232	-2251.129557	300.662554	2245.783433
4940.594724	1539.023347	-2251.128658	2995.476929	1539.023101	-2251.129055	300.662142	2245.783834
4940.594201	1539.022780	-2251.128652	2022.918294	1539.022904	-2251.129426	300.662640	3218.346125
4940.594225	1539.022870	-2251.129102	2022.917858	1539.023308	-2251.129427	300.662717	3218.346276
4940.594864	1539.023229	-2251.129149	2022.918157	1539.022848	-2251.129423	300.662070	3218.345923
4940.594072	1539.023174	-2251.129101	1050.359477	1539.022895	-2251.129404	300.663095	4190.901134
4940.594310	1539.023172	-2251.129138	1050.358887	1539.022894	-2251.129404	300.662775	4190.901891
4940.594328	1539.023167	-2251.129137	1050.359246	1539.022839	-2251.129398	300.663138	4190.901153
4940.594368	1539.023124	-2251.129131	77.800419	1539.022746	-2251.129557	300.662371	5163.460630
4940.594578	1539.023610	-2251.129123	77.799870	1539.022944	-2251.129555	300.663491	5163.461012
4940.594392	1539.023608	-2251.129124	77.800434	1539.022775	-2251.129544	300.663885	5163.460043

Figure 27: Example of TRAC-CHECK *.txt file

In order to have just one compensation residual per measured length, it is necessary to find the average value of each data among the three repetitions. Then, the deviations are calculated through the following equations:

$$dist_{CMM} = \sqrt{(X - X_0)^2 + (Y - Y_0)^2 + (Z - Z_0)^2}$$

$$dist_{laser} = L - L_0$$

$$deviation = dist_{CMM} - dist_{laser}$$

$dist_{CMM}$ is the distance between the start and end point of the line, read by the machine coordinates; instead, $dist_{laser}$ is the distance between the same two points, read by the LT. The difference between the two distances is the residual error, also called deviation.

5.3 First approach

The procedure adopted for the first approach of offline compensation with Matlab is the following:

- obtain coordinates (X,Y,Z) from TRAC-CHECK, measuring some lines while having an empty map on the controller;
- compensate these coordinates offline $(X,Y,Z)_{comp}$, by using one of the compensation maps at disposal, as shown in the following Figure 28;

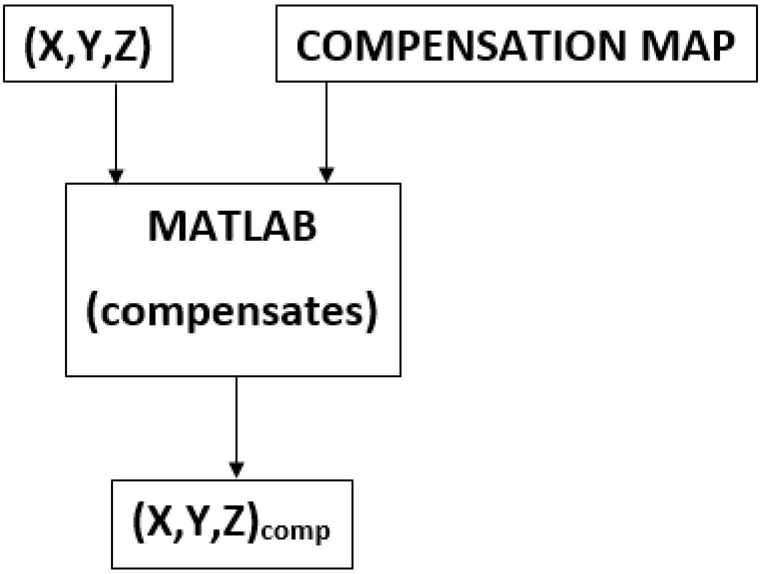


Figure 28: Offline compensation procedure without map running in the controller

- calculate the deviation, i.e. the compensation residuals, with the new compensated coordinates;
- plot the results against the machine specs.

To validate the whole offline compensation process, the calculated deviations must be compared with the online results, obtained by measuring the same lines while having in the controller the same compensation map used to compensate offline.

5.4 Second approach

The procedure adopted for the second approach of offline compensation with Matlab is the following:

- a set of points (X,Y,Z) on different lines is measured with TRAC-CHECK having one compensation map (for instance the Etalon one) running on the controller;
- the measured points are uncompensated to obtain new points $(X,Y,Z)_{non-comp}$. The same compensation map that was on the controller during the measurement (the Etalon map in this example) must be used;
- the uncompensated points are then compensated offline with different compensation maps. The deviations are plotted on the same graph to compare the maps and to see the differences.

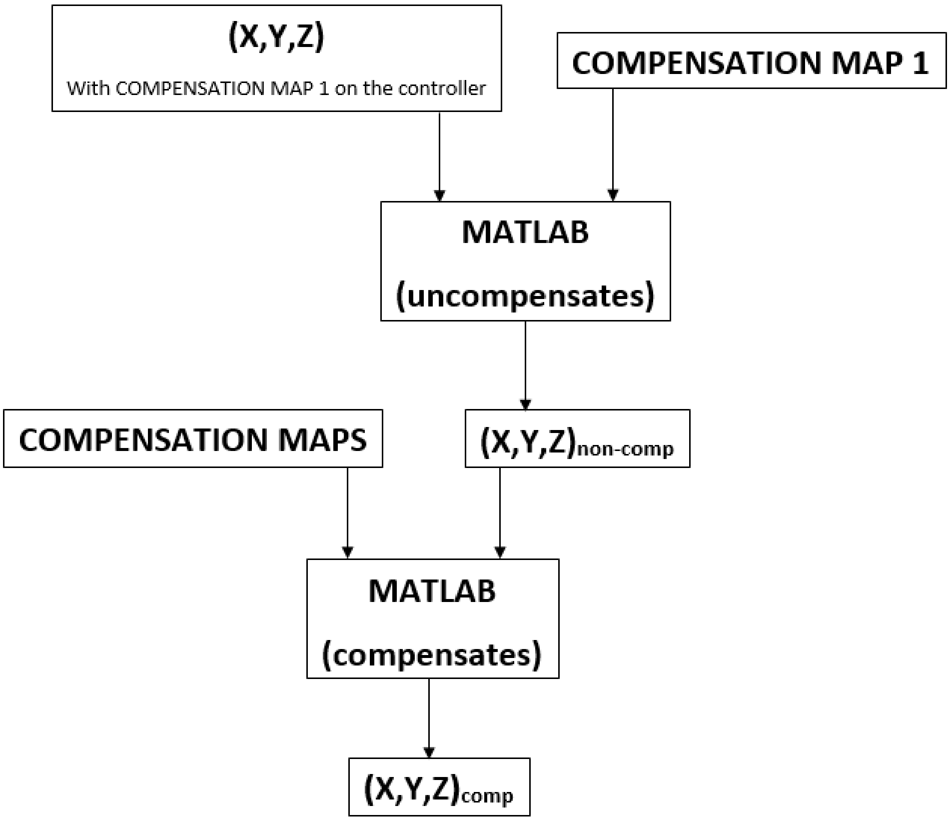


Figure 29: Offline compensation procedure with map running in the controller

6 Case study 1

6.1 Compensation and Verification of a Horizontal-Arm Machine

Hexagon Metrology has provided a horizontal-arm CMM, called BRAVO. It is a dynamic, accurate and robust system and can operate at high speeds. The open architecture of the system enables effective integration of the measurement cell in manufacturing environments, as it is visible in Figure 30. BRAVO machine can inspect several components in a single measurement cell and use a broad range of heads, extensions and sensors.

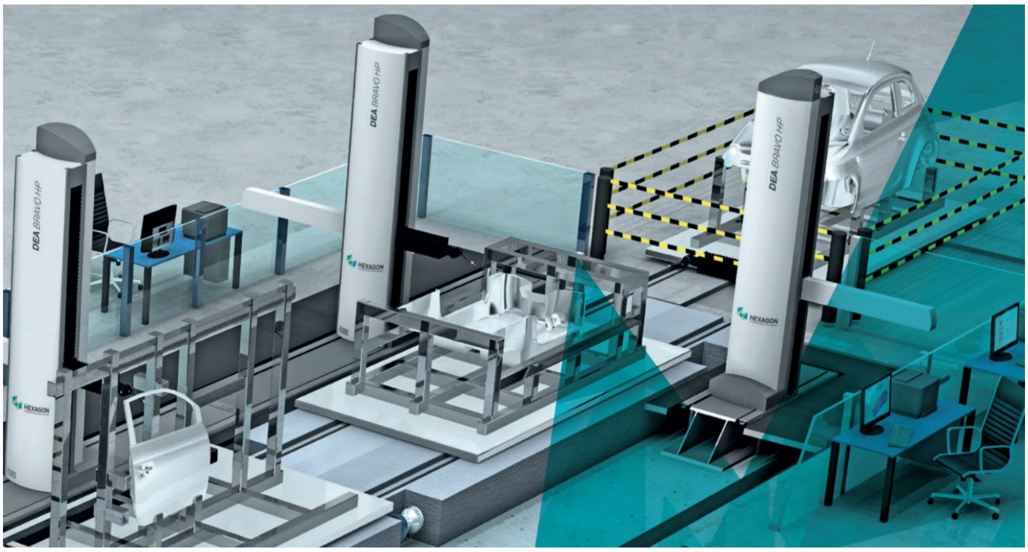


Figure 30: A series of BRAVO machines working in manufacturing environment

The measurement volume of the BRAVO machine used is 6000 x 1600 x 2500 [mm]. Its coordinate reference system is evident in the following Figure 31.

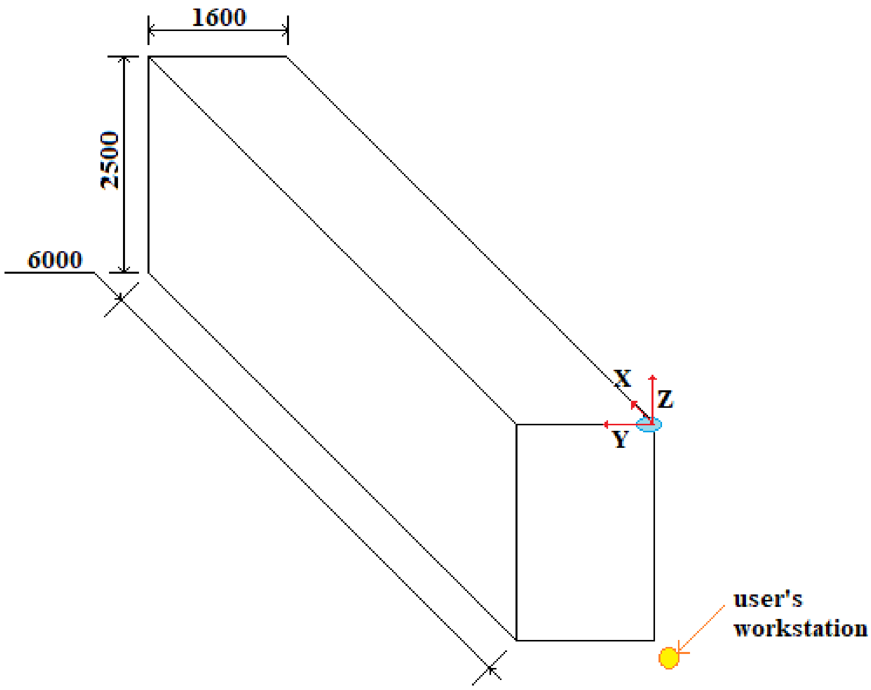


Figure 31: BRAVO measurement volume - coordinate reference system

In order to minimize the measurement errors in such a large machine, it is necessary to modify the rigid body model of error, by adding some parameters that take into account the deflections of the carriages during their movement. The traditional method of compensation used in Hexagon offers excellent results; however, the goal of this research and development project is to study the applicability of the LT technology to the legacy error model, in order to reduce the time of the whole compensation and verification process. Every manufacturer company of CMMs has its own model of error for each type of machines. A model to compensate the BRAVO machine was developed in the Etalon TRAC-CAL software: this model is very similar to the one currently used in Hexagon, so it is possible to perform a direct comparison between the two estimated maps. In the following paragraphs, there is a description of all the activities executed in the Grugliasco plant.

6.2 Online work

Online work on BRAVO machine is divided in two phases. First, the CMM is compensated with the traditional method. In this process, the so-called Legacy map is estimated through the detection of each error parameter one by one. Furthermore, some verification lines are measured to verify the goodness of the map, according to ISO 10360-2. As expected, the legacy map returns excellent results, with measurement errors that largely meet the specifications. Such results are reported in Figure 32.

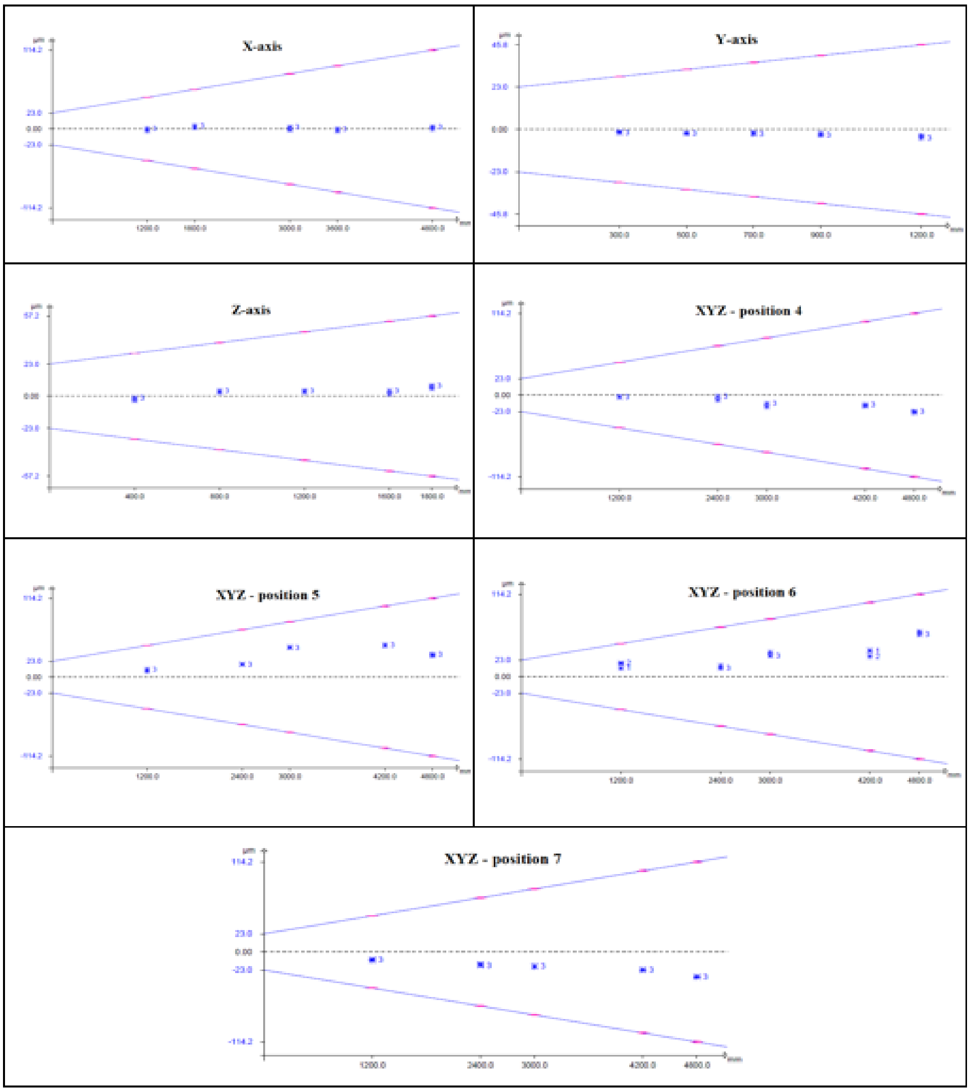


Figure 32: Acceptance tests of BRAVO performed with the traditional method and Legacy map in the CMM controller

The second step consists in the compensation of the same machine with the Etalon method. The measurement setup for this CMM requires the LT to be placed on the floor in several positions and on a tripod or pillar. The machine is equipped with an indexable wrist, which can modify its own inclination in order to hold the reflector in different positions with respect to the ram axis. The measurement volume of the machine should be completely clear to avoid any collisions during the measurements. The measurement strategy developed for BRAVO includes eight measurement runs in five different tracer positions. The first four positions require to have the LT in the four low corners of the measurement volume, on the floor. The angles of the indexable wrist must remain the same for all these positions. As for the latest measurements, the LT is fixed in one position, located on a pillar outside the measurement volume. The wrist must change its pitch angle and the roll angle in order to create the last four configurations.

Figure 33: Setup with the LT outside the measurement volume

Once all the measurements are performed, as described in paragraph 4.2 Compensation process, the Etalon software provides a legacy-like compensation map. At the beginning, the software was unable to create the error map: the cause was identified in an incorrect setting that was not compatible with the Hexagon map format.

A first check of the map format was performed to understand if the controller could correctly read the file generated by TRAC-CAL. To accomplish this task, it is necessary to download the map into the CMM controller. Thus, it is possible to manually drive the machine in some points of the volume and observe the geometric correction values that the controller applies to the coordinates: they should be different from zero and change when moving the ram from one point to another.

Then, TRAC-CHECK software was used to measure different lines in the machine volume with the Legacy compensation map activated in the controller, in order to verify the CMM geometry in accordance to ISO 10360-2. From each LT position, it is possible to measure up to seven lines, including the three axes of the machine (X, Y and Z), the three two-dimensional diagonals (XY, XZ and YZ) and the volumetric diagonal (XYZ).

After the confirmation of the good quality of the Legacy map, the next step is the verification of the Etalon map estimated with the LT. Several measurements were carried out, until the TRAC-CHECK results respected the machine specifications.

6.3 Offline work

Offline work on BRAVO starts with carrying out some measurements with TRAC-CHECK software: it is necessary to have an empty compensation map running in the controller in order to acquire raw data. The measurements are affected by all the errors of the machine, as shown in Figure 34: it is clear that almost all the measures do not comply with the specifications of the technical data sheet of the machine.

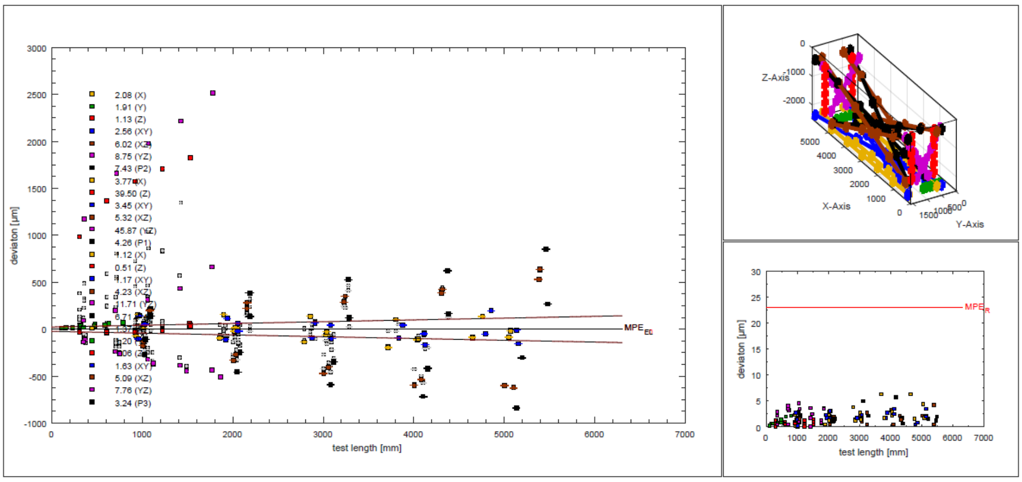


Figure 34: TRAC-CHECK results with an empty map in the CMM controller

Later, the two approaches described in chapter 5 Offline Compensation are performed.

6.4 Results

The quality of the Legacy map was tested also with the LT technology.

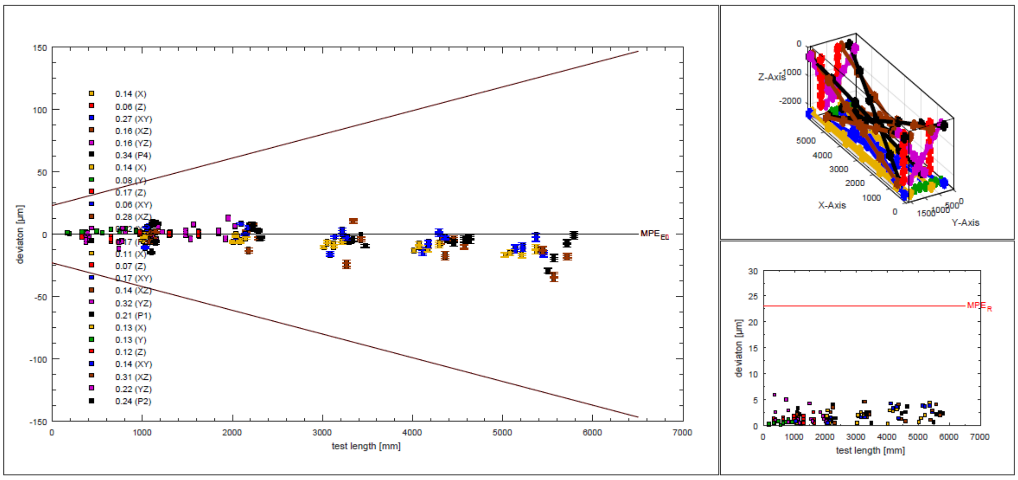


Figure 35: TRAC-CHECK results with the Legacy map in the CMM controller

The results are visible in the previous Figure 35. It is possible to see how all the measured lines have errors in specification, represented by the two red half-lines in the graph on the left. In particular, 26 lines were measured: in the upper right part of the figure, these lines are visible inside the measurement volume. Each line was measured three times to study the repeatability of the machine. The technique used for the measurements respects the ISO 10360-2; therefore, five lengths per line were measured, covering at least 66% of the total length of the line. This strategy was applied also for the measurements performed with the Etalon map activated in the CMM controller.

Three steps were necessary to obtain measurements under specification with the Etalon map. The first version of the Etalon map returned imperfect results, because the first error model implemented in the TRAC-CAL software had some discrepancies with the real behaviour of the CMM. Therefore, the measurements carried out with the first version of the Etalon map in the controller were not all under specification, as it is evident in Figure 36.

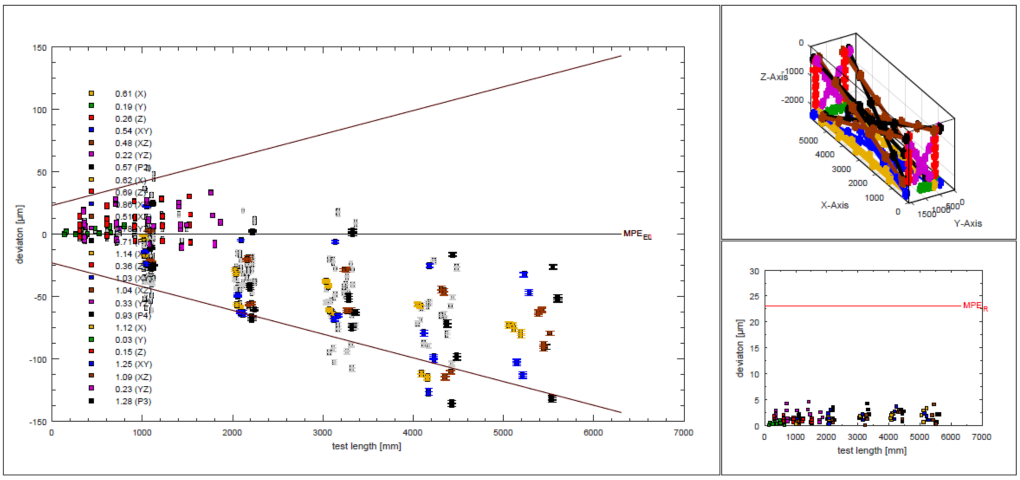


Figure 36: TRAC-CHECK results with the first version of the Etalon map in the CMM controller

Particularly, 24/390 measured lengths (6%) happened to be out of specification.

The second version of the Etalon map gave better results, shown in Figure 37: a different filter was applied to the on-the-fly measurements carried out with TRAC-CAL software.

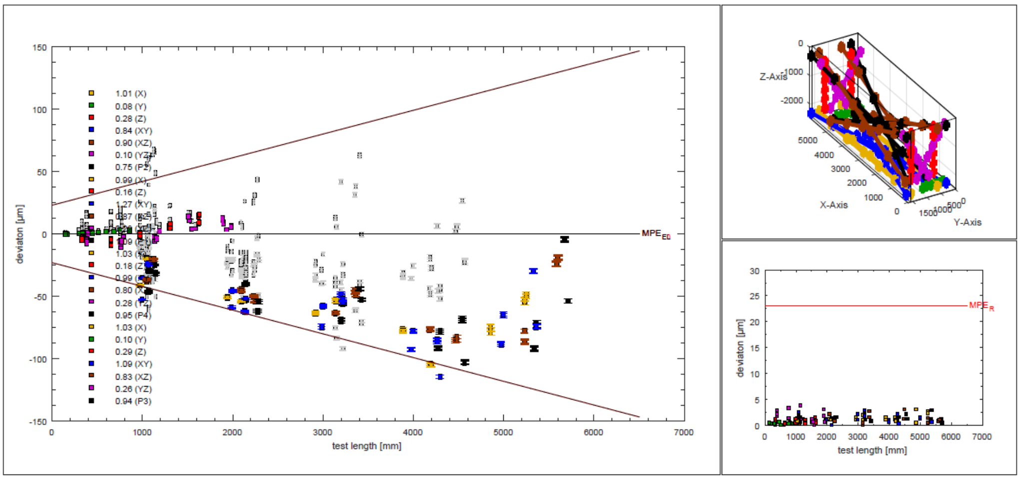


Figure 37: TRAC-CHECK results with the second version of the Etalon map in the CMM controller

In this case, the number of measured length out of specification is reduced to 14/390, corresponding to the 4%.

Finally, with the third and last version of the Etalon map, all the issues were solved: the most relevant was in the use of a different coordinate reference system for one of the bending errors implemented in the TRAC-

CAL software. In Figure 38, the results obtained with the last version of the compensation map are represented.

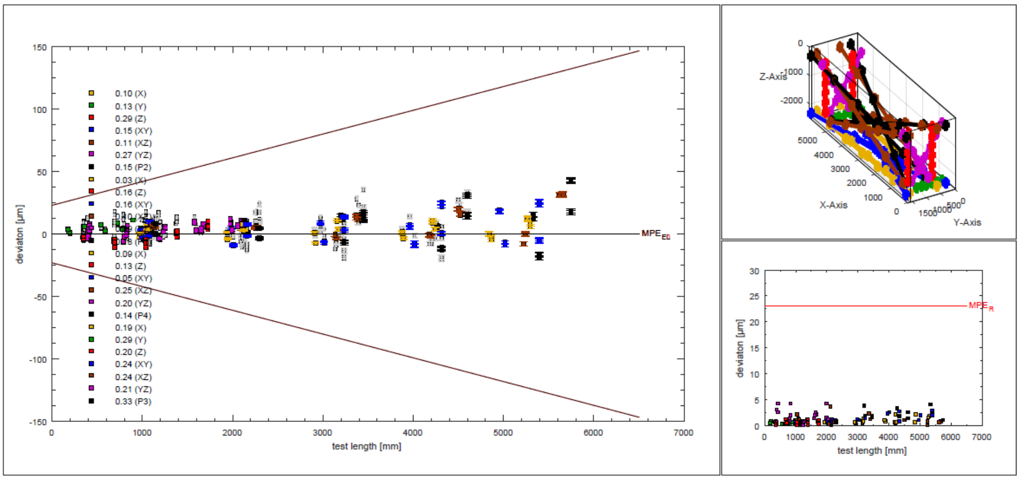


Figure 38: TRAC-CHECK results with the third version of the Etalon map in the CMM controller

It is possible to observe that each of the 390 measured lengths meets the specifications.

The results of the Etalon method on the BRAVO machine are very reliable and similar to those obtained by the traditional method. Therefore, the integration of the LT technology on a horizontal-arm machine is certainly both possible and profitable in terms of time necessary for the entire procedure. As a matter of fact, the legacy process requested for compensation and verification of a BRAVO machine is currently 5 days. On the contrary, the total time with the Etalon method on the horizontal-arm CMM can be estimated into 1 day for the machine compensation using TRAC-CAL and half a day for the machine verification using TRAC-CHECK.

A comparison between the two rigid body maps is performed using Matlab: the two models are very similar, as it is visible in Figure 39 and Figure 40. The main difference between the two compensation maps is in the bending errors.

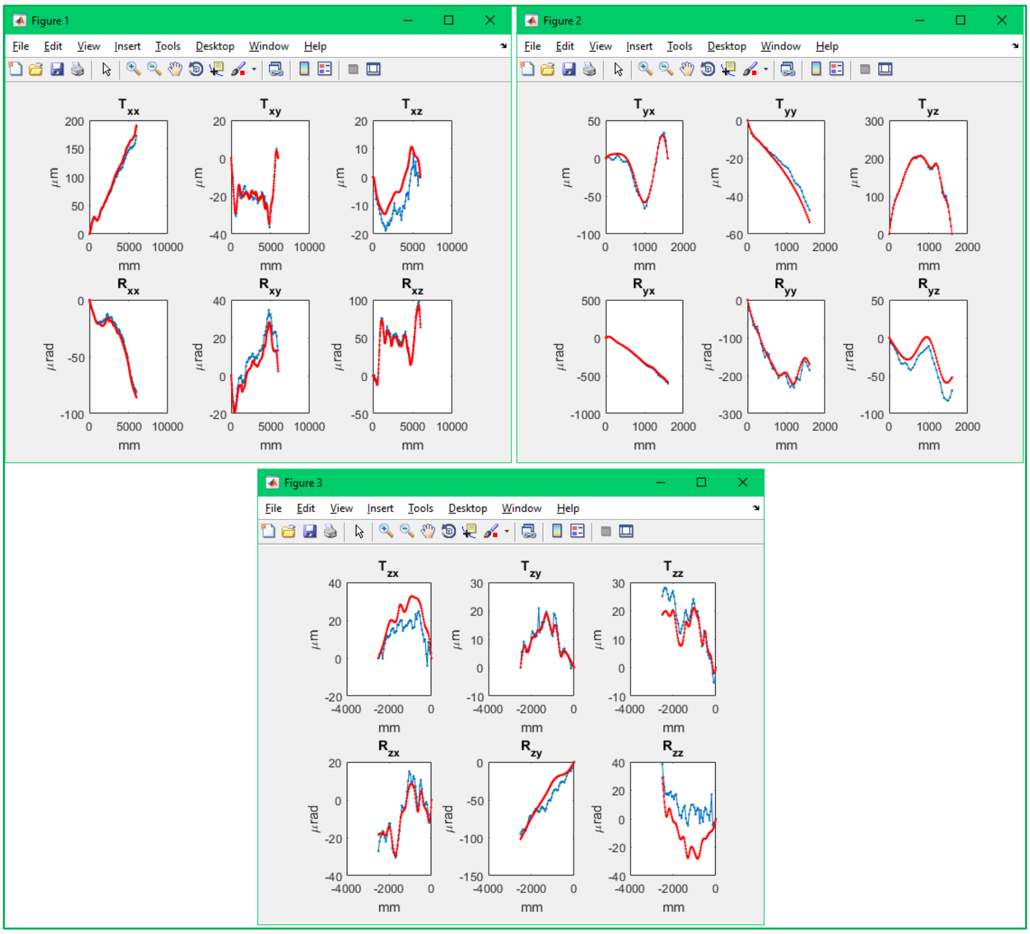


Figure 39: Comparison between Etalon (red) and Legacy (blue) rigid body error maps

	Q_{XY} [µrad]	Q_{ZX} [µrad]	Q_{ZY} [µrad]
Etalon	-10.9583	-631.0600	325.3800
Legacy	-18.8000	-634.1000	322.1000

Figure 40: Comparison between Etalon and Legacy squareness error maps

The first approach of offline compensation on BRAVO gave strange results in some cases, while with the second approach results were more repeatable and stable.

In the first approach of offline compensation, after obtaining some coordinates from TRAC-CHECK by measuring with an empty compensation map on the CMM controller, those coordinates are compensated offline using the final version of the Etalon map. Then, the calculated deviation is compared to the corresponding one obtained by measuring the set of points with the map running online. To reduce the deviation related to the environment, two consecutive measurements (without and with map) were performed reducing the time between the two at the minimum value. Nevertheless, the position of the LT was initialized at each measurement.

In Figure 41, it is evident that in some cases the results are very similar, while in other this does not happen.

A possible explanation could be the fact that the measurement volume occupied by the CMM is very large; therefore, when measuring raw data directly with the LT, the various errors can actually cause residuals in the order of the millimeter, which are difficult to compensate offline.

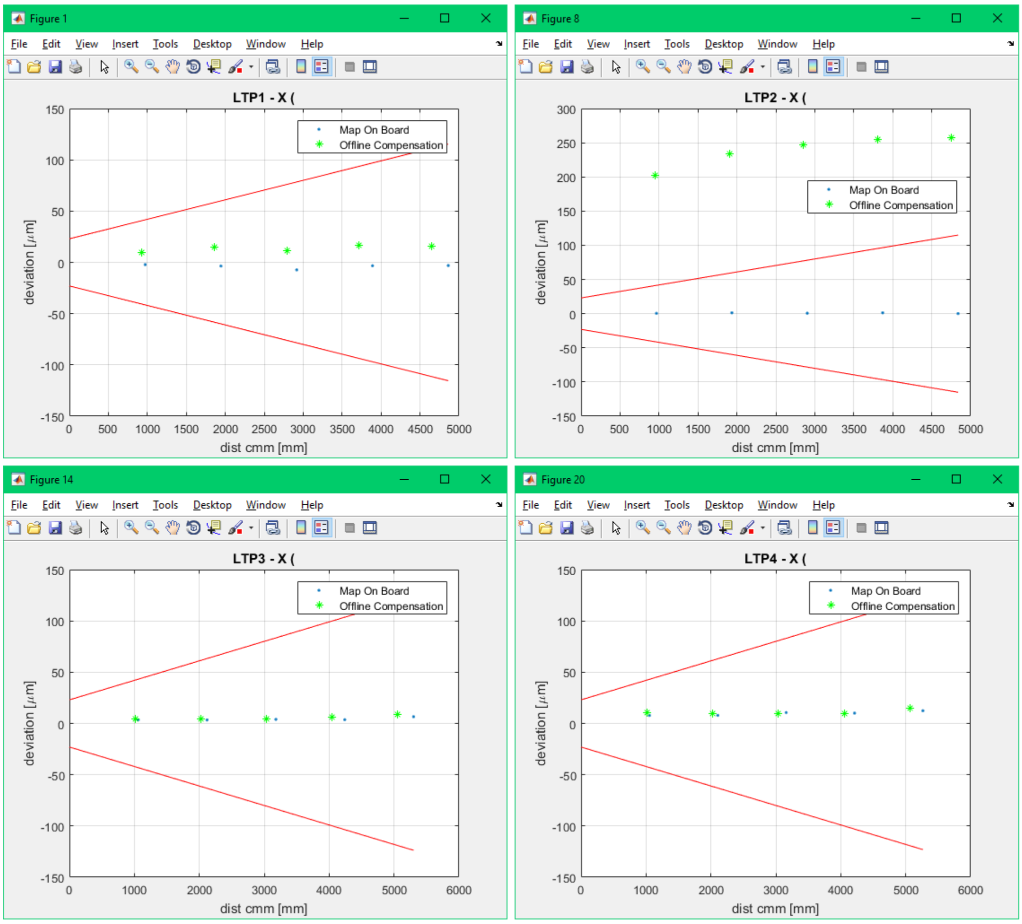


Figure 41: Comparison of X-axis measurements between online and offline compensation using the first approach

In Appendix 1, the entire comparison between the two processes is reported.

A possible workaround to the first approach consists in measuring some lines leaving the LT in one position. A first measurement was made with the second version of the Etalon map running on the controller and then without it. Before the measurement without map on the controller, the position of the LT was not measured through the TRAC-CHECK "Measure position" command, because it had not changed. Therefore, the first approach of offline compensation with these specific data worked for every line. An example is in Figure 42, where the online results (blue points) and the offline results (green points) coincide perfectly.

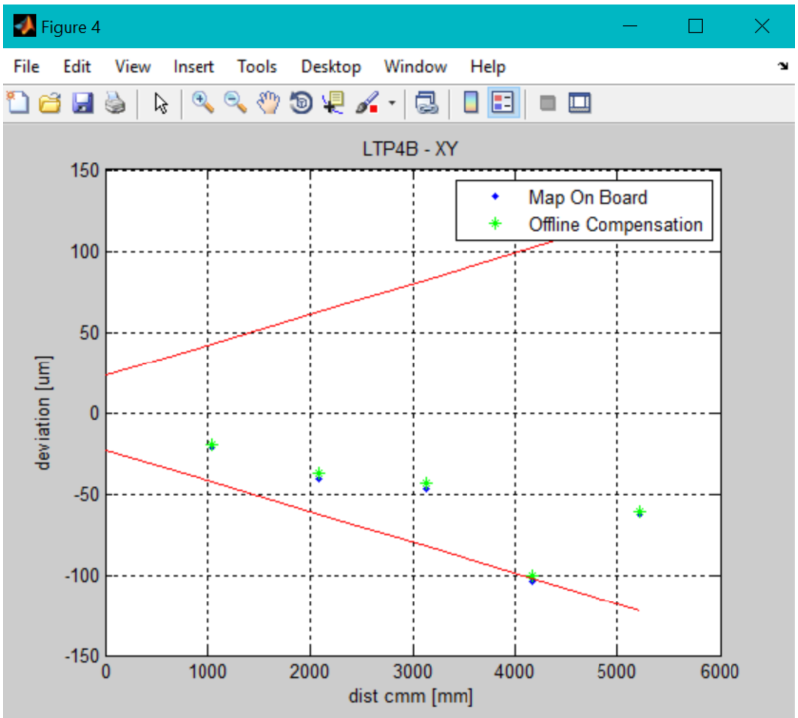


Figure 42: Offline vs online compensation

The second approach of offline compensation has the goal to bypass the issue found in the first approach. Since the machine moved very badly with an empty compensation map running in the controller, another way to obtain raw data was used. In particular, the error committed by the CMM was calculated from the TRAC-CHECK results carried out with the Legacy map in the controller. Therefore, the compensation error is subtracted from the measurement, thus obtaining raw data. This procedure is valid, even if it is not completely accurate: an error calculated on compensated coordinates is different from that obtained on raw data. However, the difference between them is in the order of the nanometer, negligible when compared with the micrometric deviations of the BRAVO CMM. Starting from raw data, it is possible to compare the capability of different maps to compensate offline the same set of coordinates. In Figure 43, there is an example of this second approach.

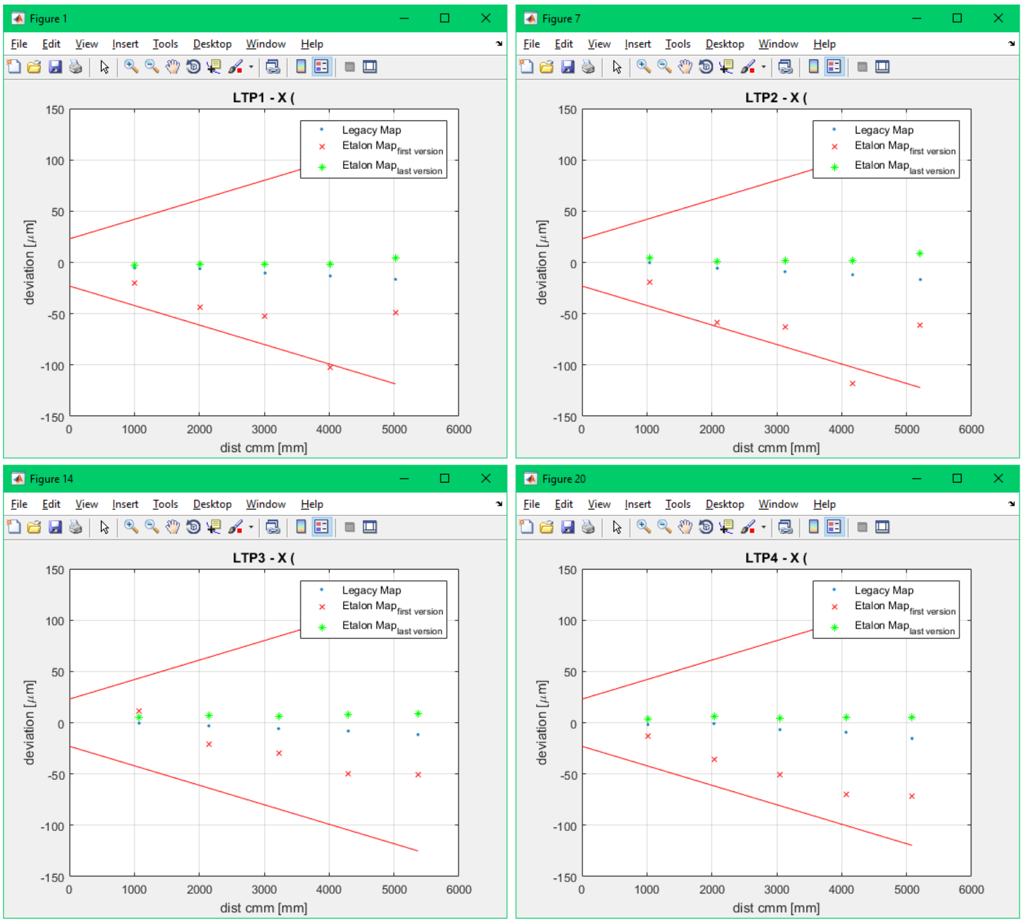


Figure 43: Comparison of X-axis measurements between online and offline compensation using the second approach

It is clear from the graphs of the X-axis measurements that both Legacy and the last version of Etalon map can successfully compensate the coordinates. Besides, it is confirmed that the first version of Etalon map has some issues, because it compensates worse than the last one.

Using this approach, it is possible to obtain a complete comparison of Legacy vs Etalon map on the full set of verification lines, as shown in Appendix 2.

7 Case study 2

7.1 Verification tests on a Gantry Machine

Hexagon metrology provided a Gantry machine in order to perform some functional tests with the LT technology. It is a CMM characterized by a flexible measurement system. It can mount a wide range of probe heads and can be used both in metrological rooms and in environments without air-conditioned systems.

The measurement volume of this CMM is 3000 x 5100 x 2000 [mm]. Its reference system is explained in the following Figure 44.

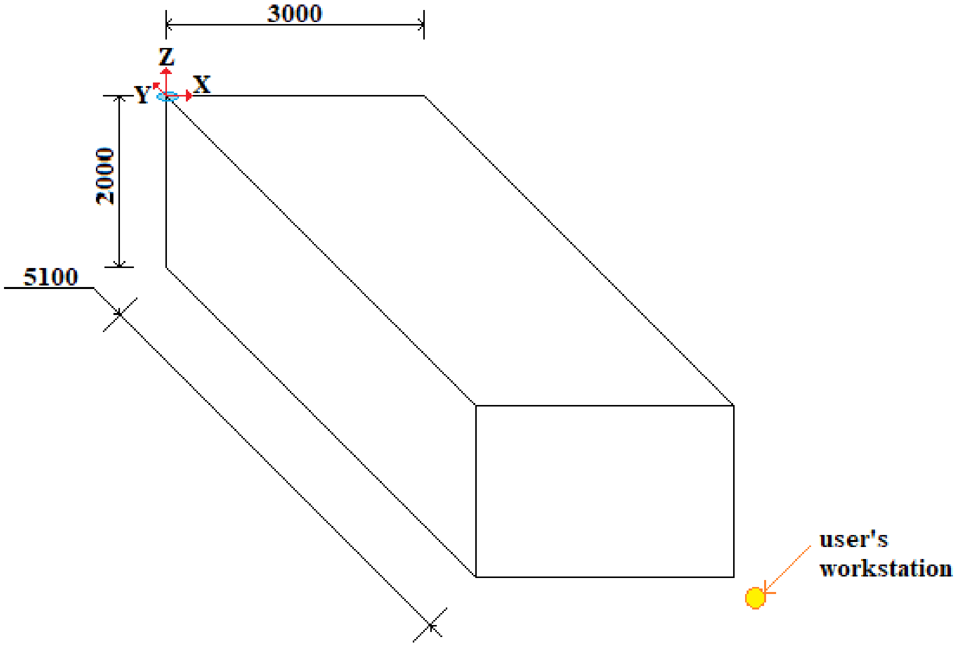


Figure 44: Gantry machine measurement volume – coordinate reference system

One of the peculiarities of this CMM is the double reading scale along the carriage of the Y-axis. The reading of the position along the Y-axis takes place according to a combination of the two readings, which depends on the proximity of the machine ram to the left or right scale.

Unfortunately, it was not possible to compensate the machine with the Etalon method, since the specific error model is not implemented in the TRAC-CAL software. Nevertheless, the LT system has been used to carry out several verification lines useful for the comprehension of some issues detected on the machine.

Numerous works were carried out on the machine before the geometry verifications with the LT. First, the Gantry machine was compensated with the traditional method. Therefore, acceptance tests were performed with Renishaw laser. Those results met the specifications of the machine. After these steps, some mechanical parts of the machine were replaced in order to analyse the effects of such parts on the CMM geometry. Therefore, the machine was compensated again with the traditional method. Finally, the verification lines were performed with the LT to speed up the process.

In the following paragraph, the results of the TRAC-CHECK activity are reported.

7.2 Results

The goal of this activity is to obtain many measurements that cover the entire measurement volume; therefore, the strategy adopted consists in measuring each line twice, forward and backward, acquiring 20 points per line. The LT is placed in six different positions within the measurement volume: four of them are the low corners of the volume, while the other two are respectively in the center of the Y-axis and in the center of the X-axis.

The results of all the measurements are reported in Figure 45.

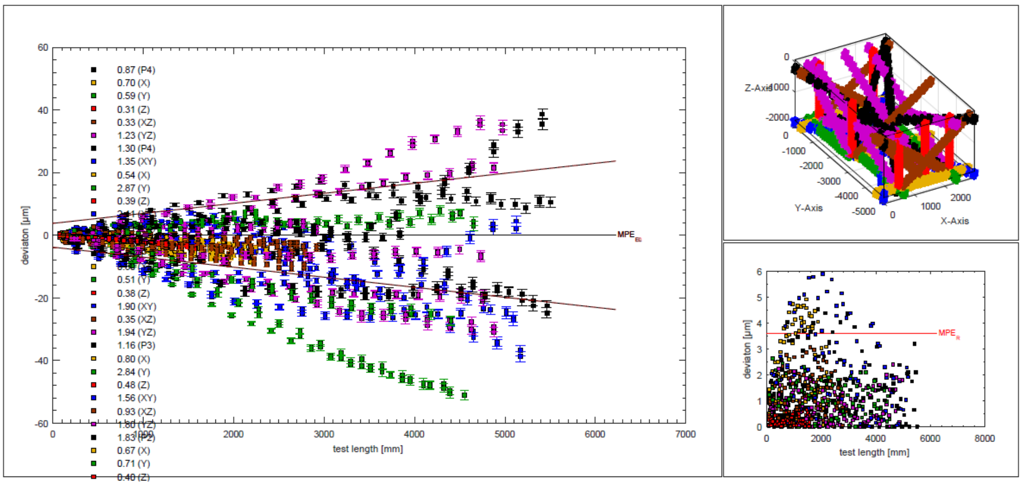


Figure 45: TRAC-CHECK results on Gantry machine

It is possible to see that some measured lengths do not meet the specifications of the machine. In particular, note that each measurement out of specification involves the Y-axis, such as the two-dimensional diagonals (XY and YZ) and the volumetric diagonal (XYZ). Instead, all the results concerning only the other two axes are in specification. Therefore, the analysis of Y-axis measurements is required. In Figure 46, a comparison among these measurements is performed. It is evident that the Y-axis measurements get worse passing from left to right of the measurement volume.

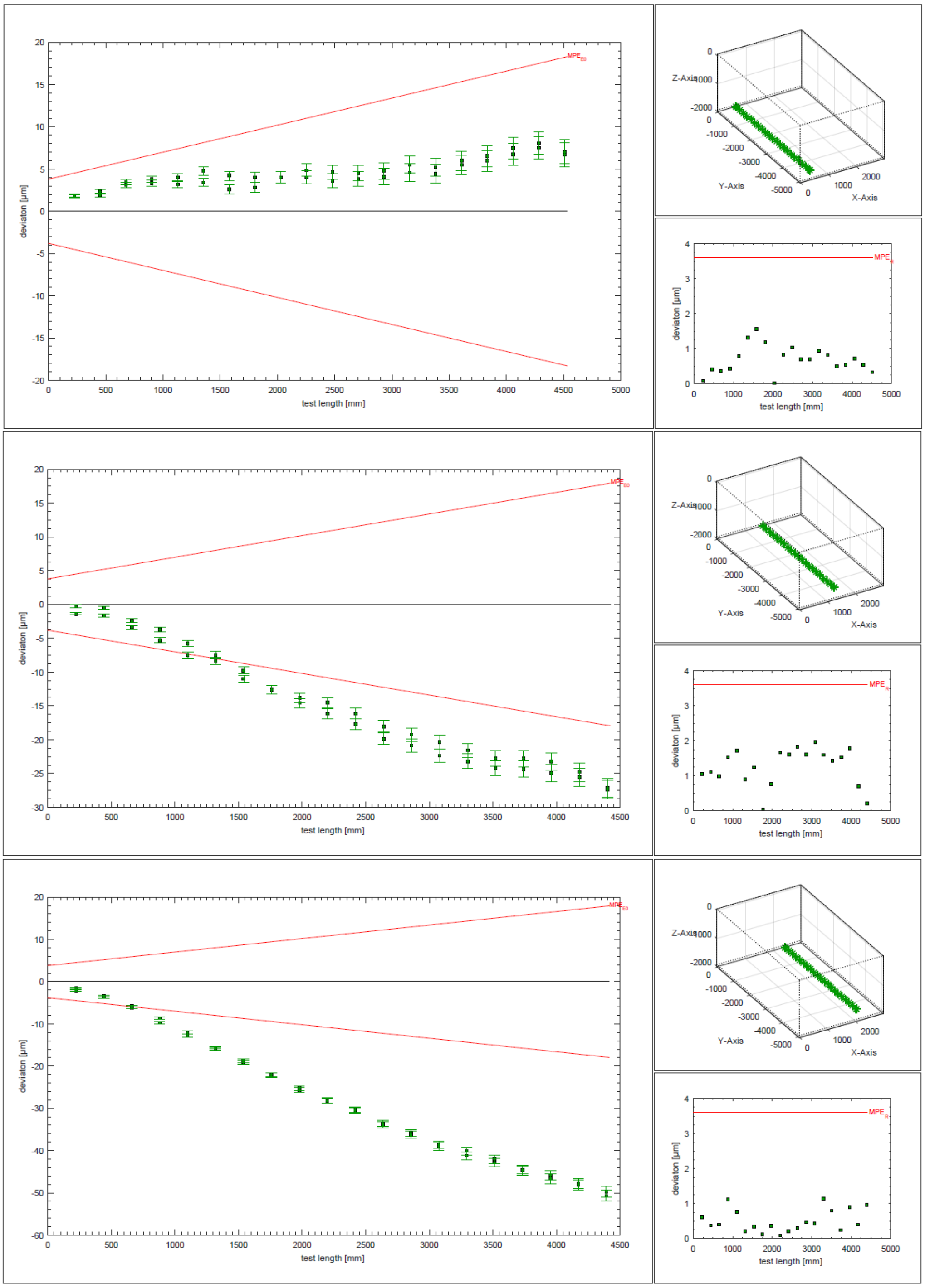


Figure 46: Comparison among Y-axis measurements

The use of LT technology to perform the measurements on the Gantry machine was fundamental: in fact, with the traditional method, it would not have been possible to obtain such a high number of lines measured in a short time.

8 Conclusions

The aim of the thesis was to study the feasibility of integrating the LT technology into a CMM compensation and verification process. To this purpose, the entire process was tested on a horizontal-arm machine (BRAVO) while only verification tests were performed on a gantry machine.

Two ways of proceeding were adopted on the BRAVO machine. The online work was necessary to carry out some data and verify the process directly on the machine. The offline work was useful to test the ability of different maps to compensate the same set of points. Therefore, a full comparison between the Etalon and the Legacy compensation maps was possible thanks to a Matlab simulator appropriately developed.

The results of the online work were very reliable. It was possible to obtain excellent results from the verification tests obtained with the last version of the Etalon map in the CMM controller. The main issue encountered in this activity concerned the kinematic model implemented in the TRAC-CAL software, which did not represent perfectly the real behaviour of the machine at first. After solving this problem, the TRAC-CHECK results were all in specification, such as those obtained with the legacy method. Therefore, the integration of the LT technology on a horizontal-arm machine is certainly both possible and profitable in terms of time necessary for the entire procedure. As a matter of fact, the legacy process requested for compensation and verification of a BRAVO machine is currently 5 days. On the contrary, the total time with the Etalon method on the horizontal-arm CMM can be estimated into 1 day for the machine compensation using TRAC-CAL and half a day for the machine verification using TRAC-CHECK.

The offline work gave strange results with the first approach, where it was not possible to compare the online and offline processes on the full set of measurements. An explanation to this issue is in the fact that the first approach was based on some TRAC-CHECK measurements carried out without a compensation map in the CMM controller. However, in a large machine like BRAVO, when measuring raw data, it is normal to have residual errors in the order of the millimeter, which are difficult to compensate offline.

The second approach of offline compensation was developed to bypass the issue found in the first one. It was possible to obtain a complete comparison of Legacy vs Etalon on the full set of verification lines with this approach.

About the activity on the gantry machine, several measurements were carried out with TRAC-CHECK. The goal was to obtain many measurements that cover the entire measurement volume. The use of LT technology to perform such measurements was fundamental: in fact, with the traditional method, it would not have been possible to obtain such a high number of lines measured in a short time.

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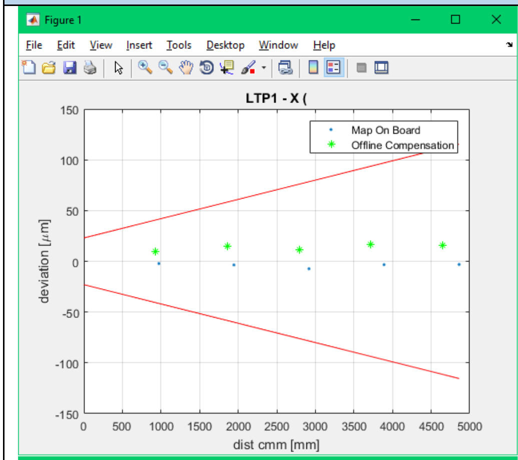
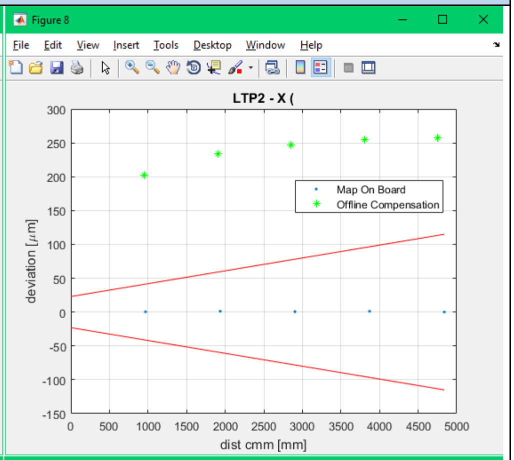
Appendices

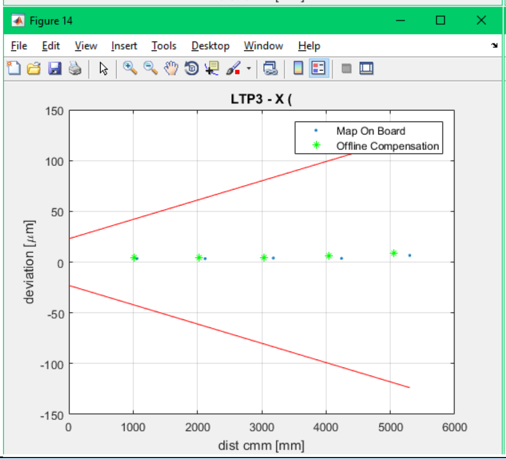
Appendix 1

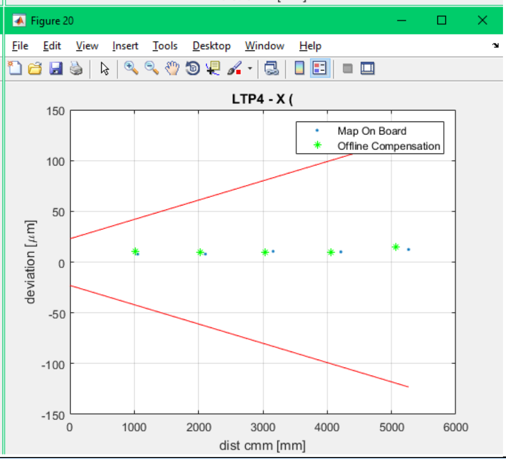
Full report of offline compensation: first approach

X axes

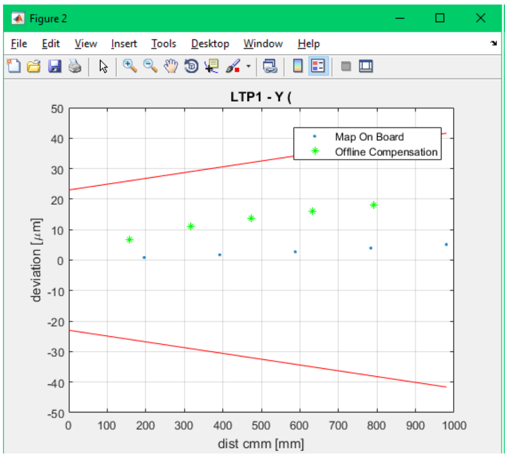


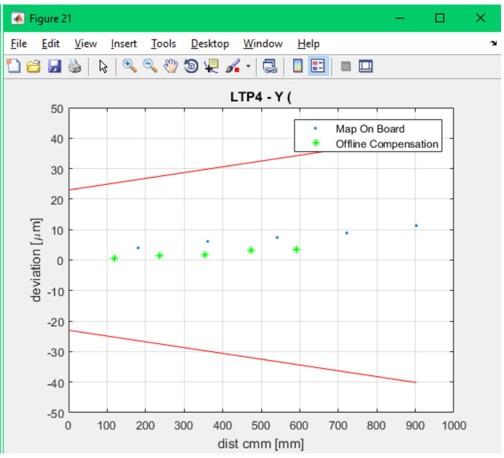




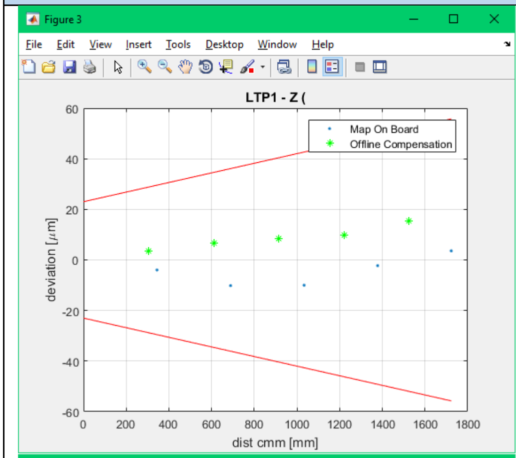


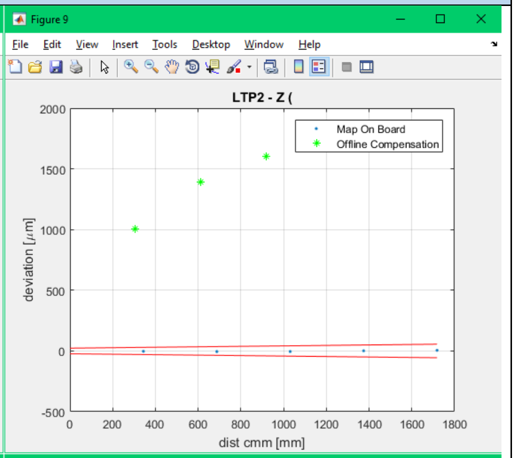
Y axes

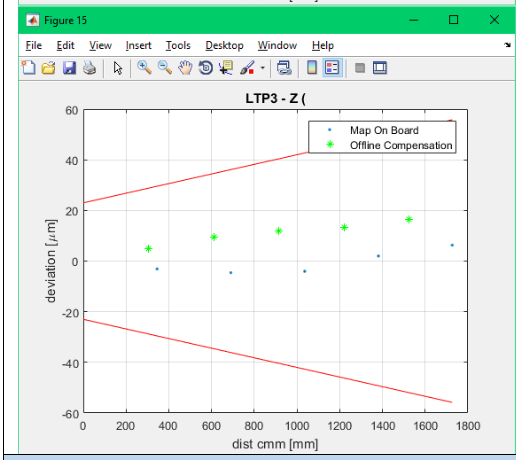


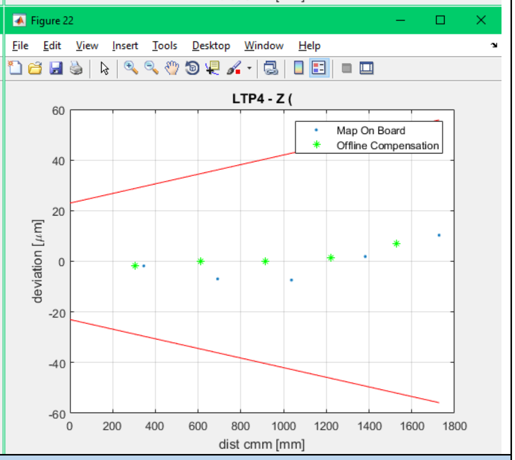


Z axes

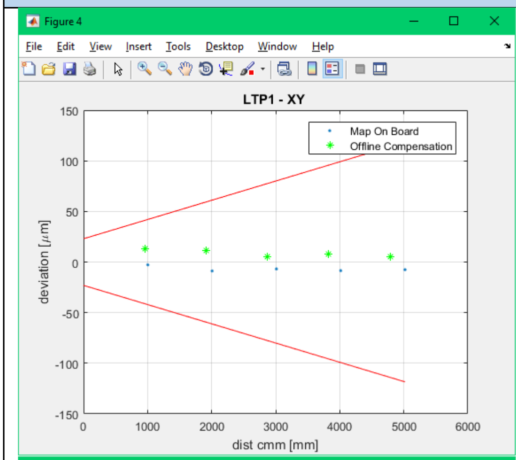


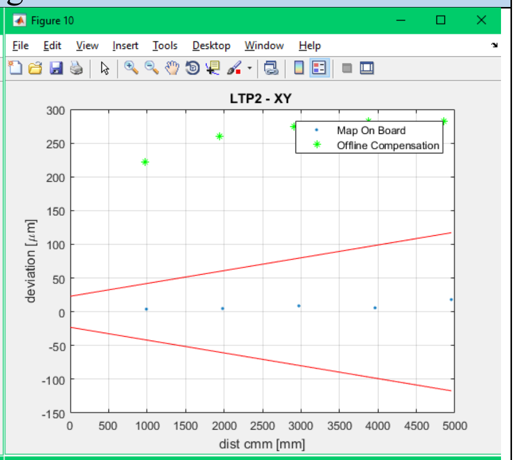


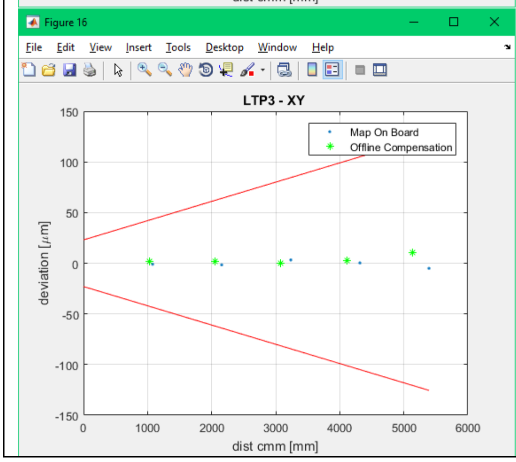


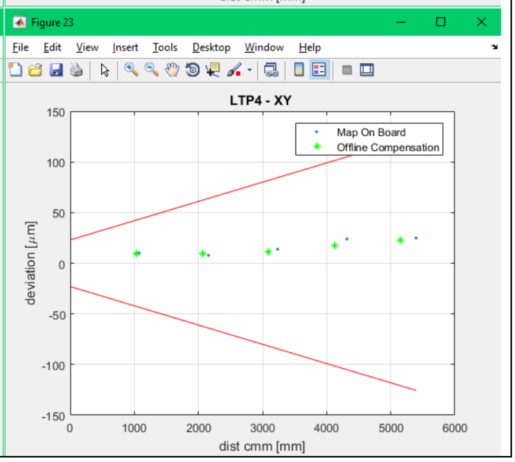


XY diagonals

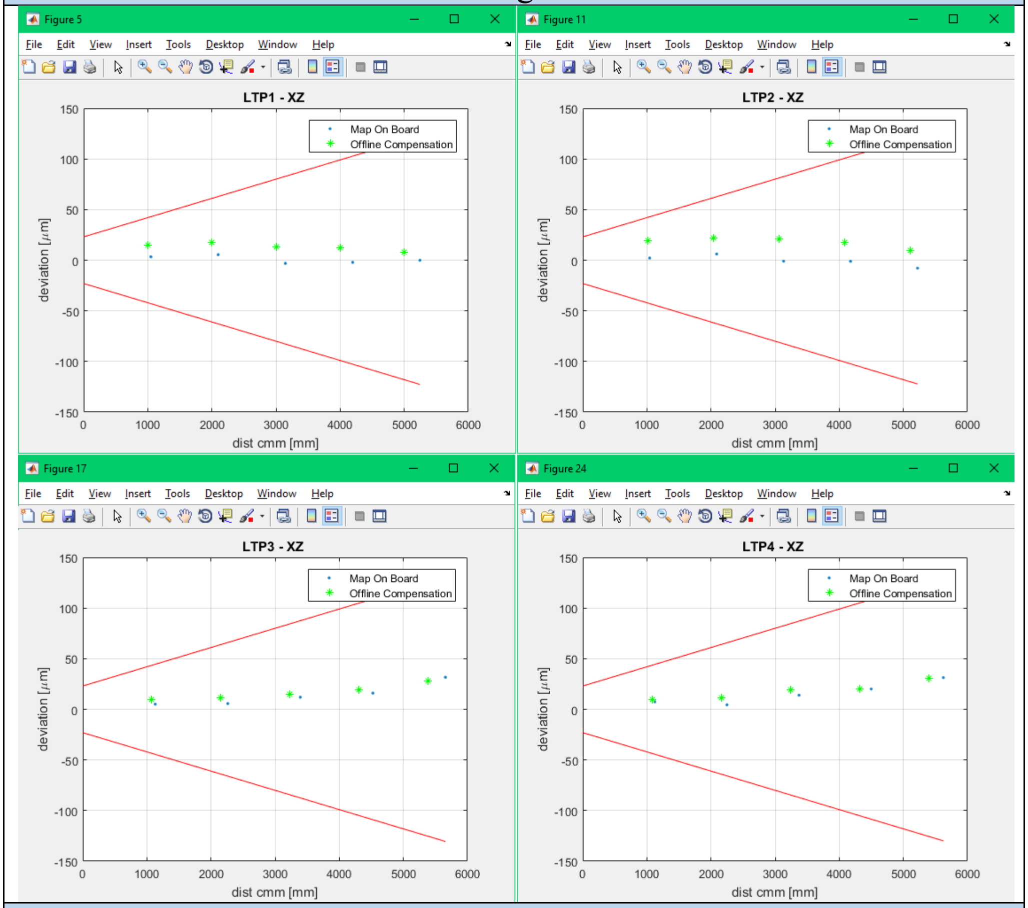




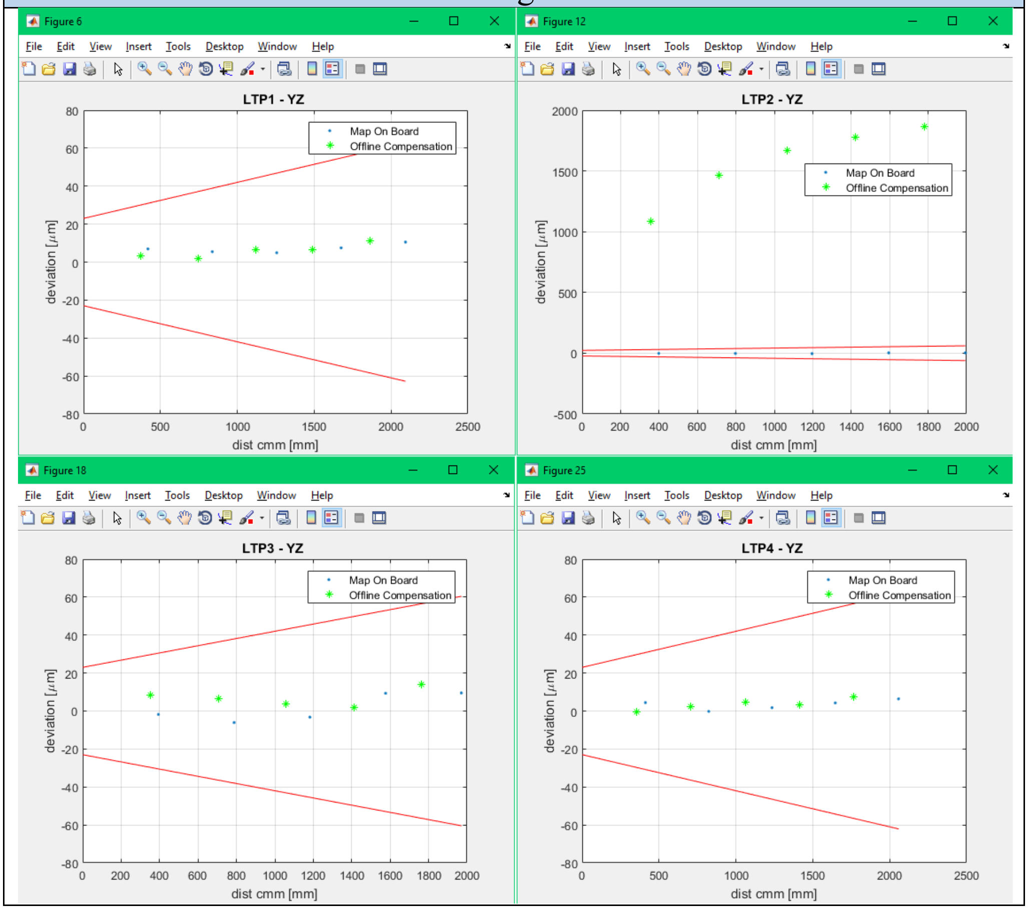




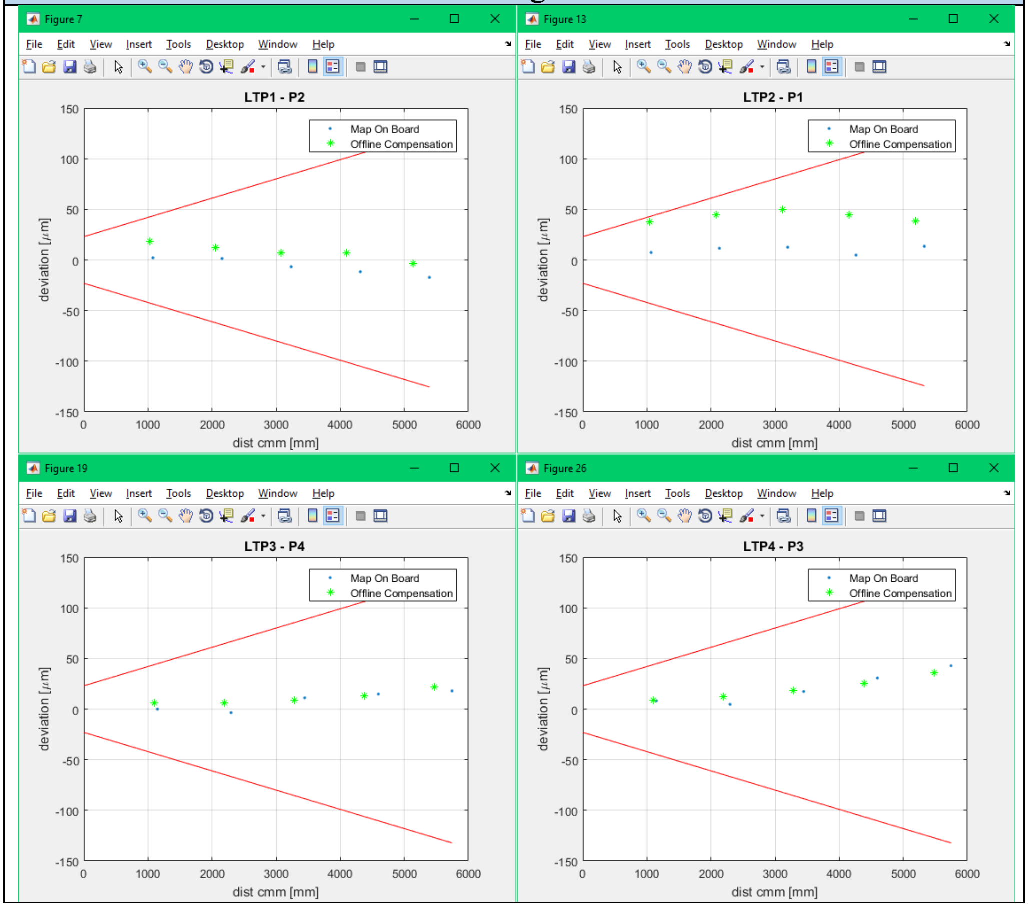
XZ diagonals



YZ diagonals



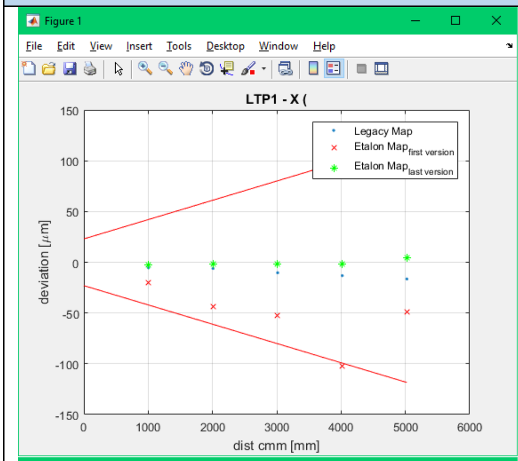
XYZ diagonals

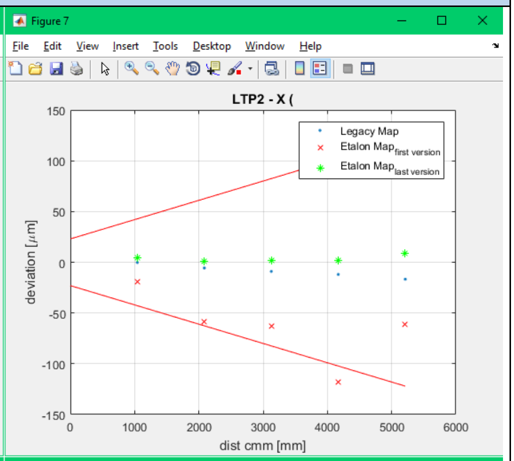


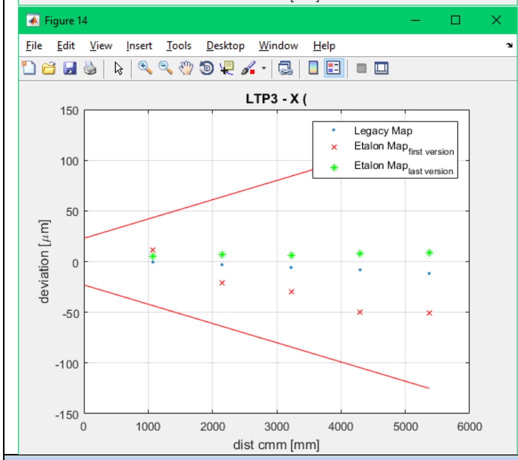
Appendix 2

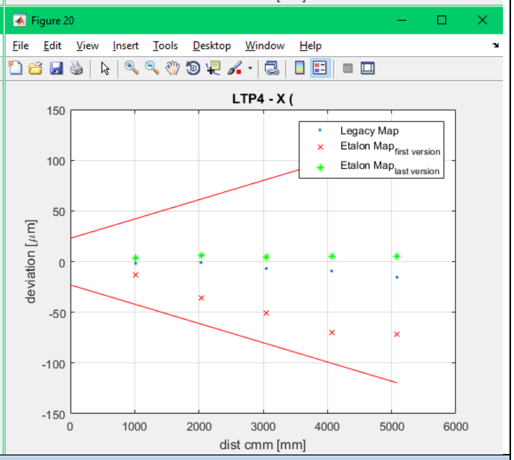
Full report of offline compensation: second approach

X axes

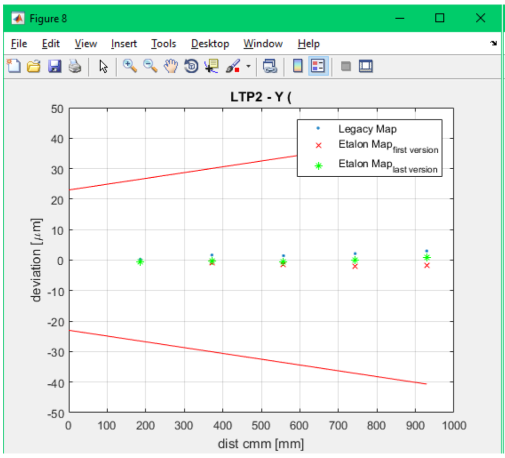


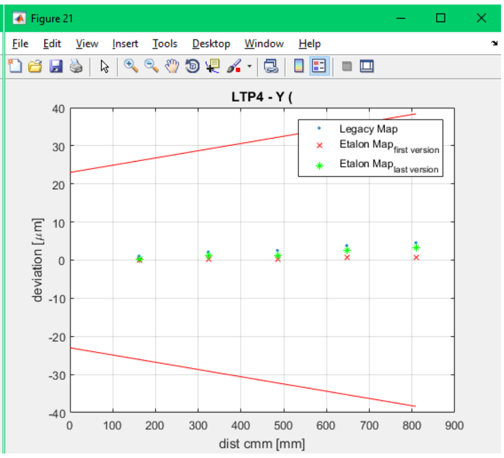




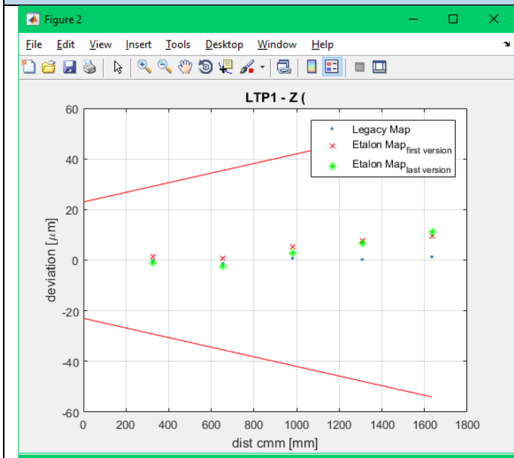


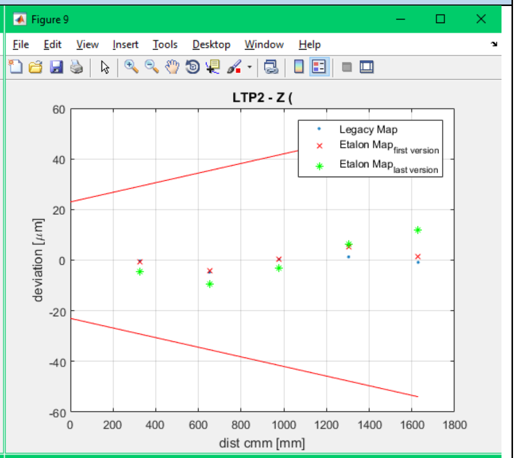
Y axes

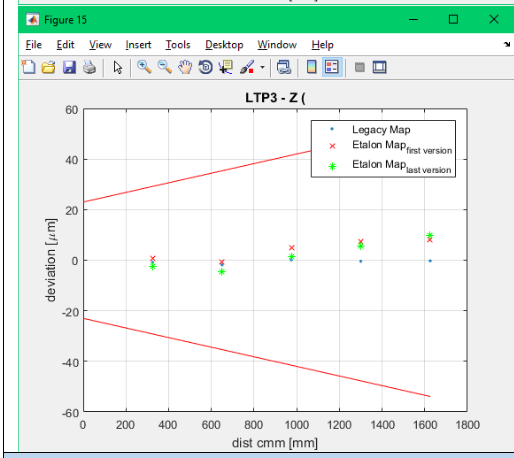


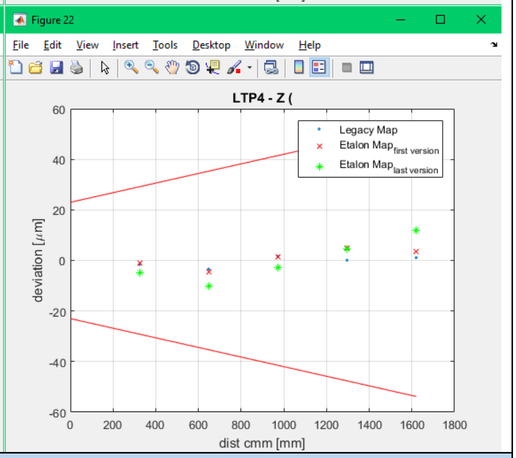


Z axes

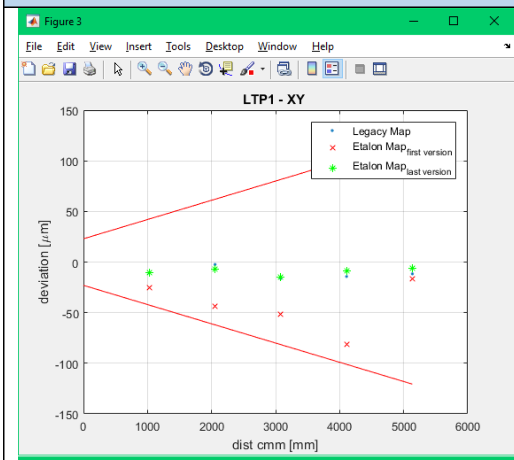


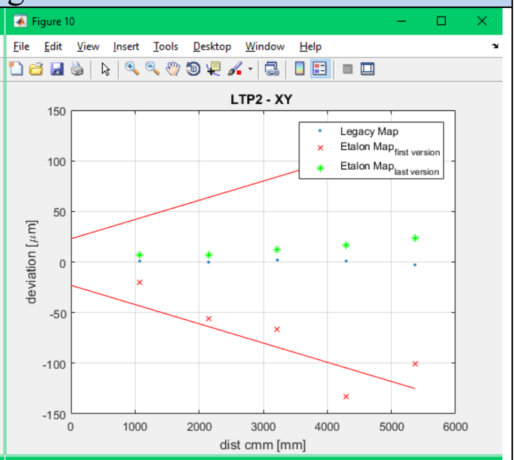


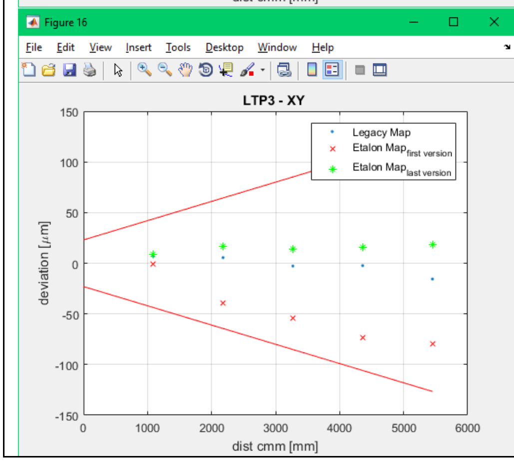


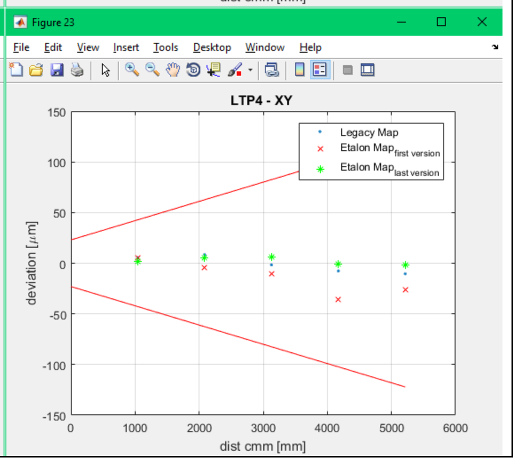


XY diagonals

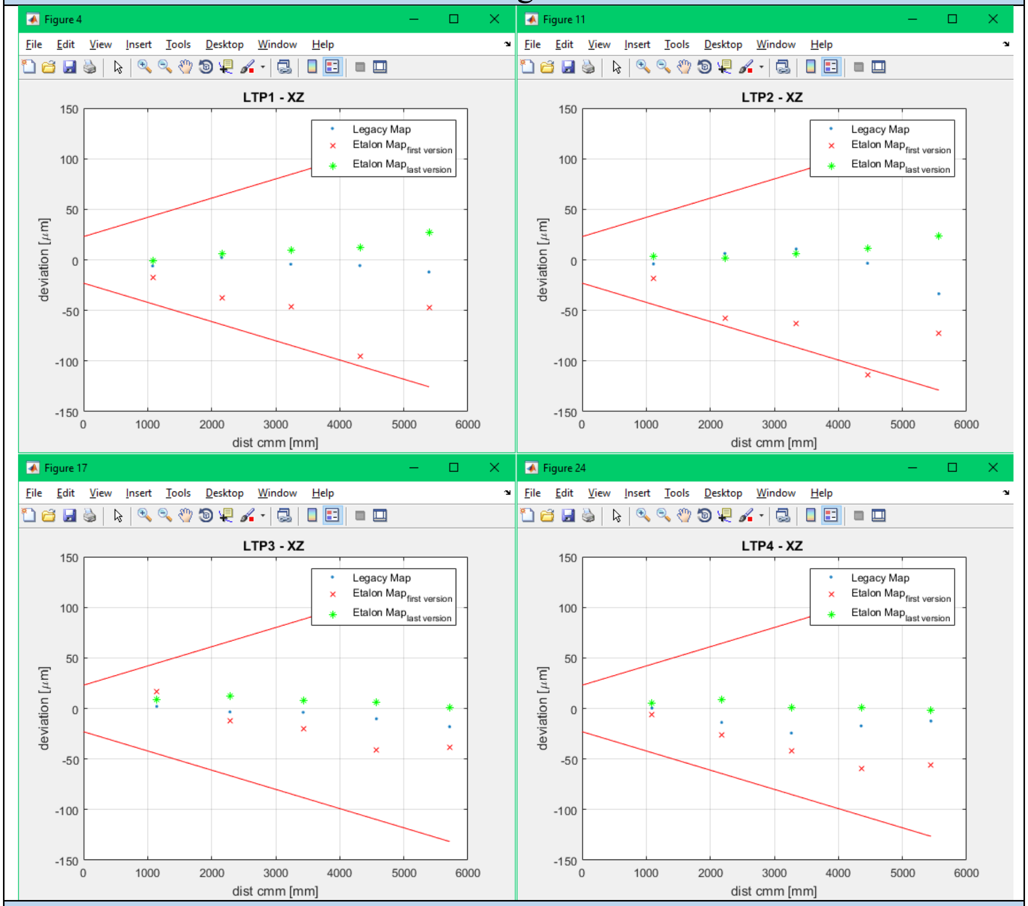




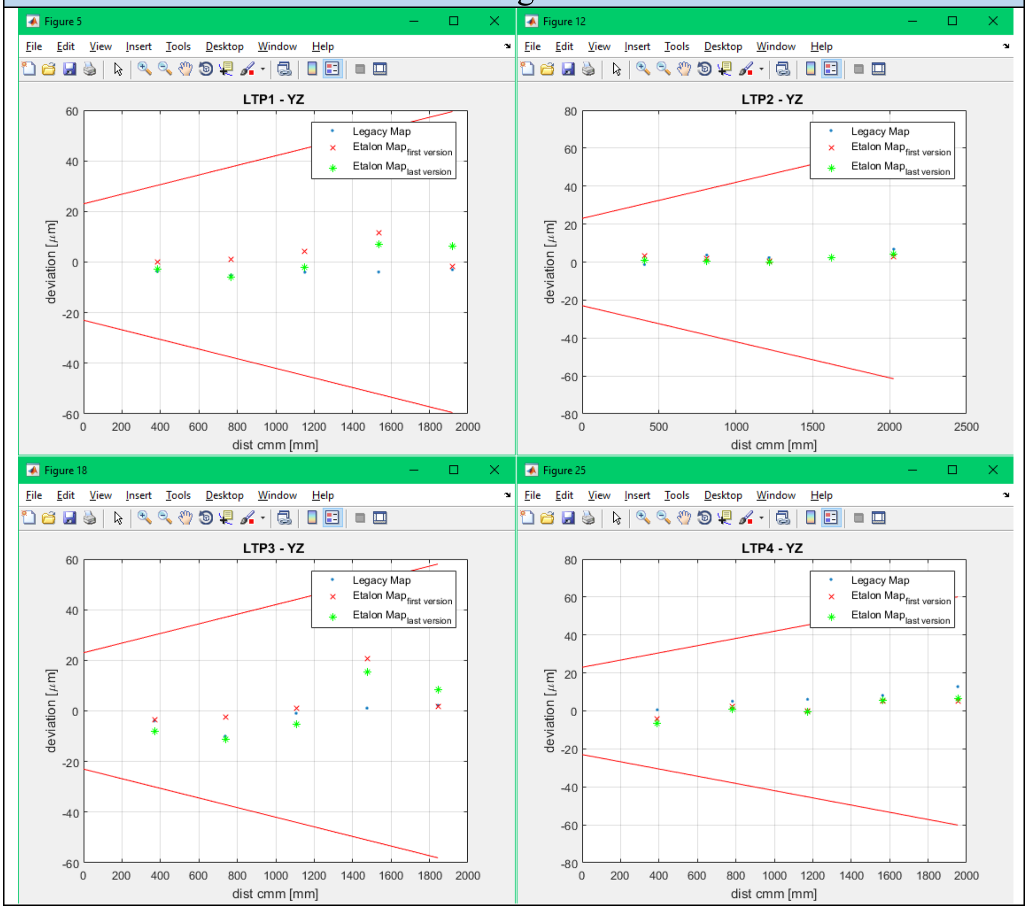




XZ diagonals



YZ diagonals



XYZ diagonals