
Available from: http://dx.doi.org/10.1016/S0263-2241(99)00030-5

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Design and error analysis of a surface reflector for a laser tracking measurement system

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Abstract
The aim of the research project described in this paper was to extend the operating range of the laser tracking measurement system by developing a surface reflector with improved measurement accuracy, calibration ability and longer reach than the existing device.

Two prototype surface reflectors were designed and manufactured. The new design extended the reach of the stylus and provided a mechanism enabling faster calibration with greater adjustment sensitivity. A calibration procedure was developed which was reasonably simple and effective, taking less than one hour to complete. With further developed it is considered that both the calibration time and the misalignment could be reduced. The calibrated surface reflectors were tested to determine the effect of misalignment on the systematic error and to compare the relative systematic error of the prototypes with that of an existing surface reflector.

Keywords: Coordinate measurement, dimensional inspection, laser tracking, surface reflector.

1 Introduction
Optical 3D coordinate measurement systems are used for dimensional inspection in the manufacturing industry. These systems are particularly suited to applications involving the measurement of large immovable objects because they are transportable, have large measurement volumes and can be used to obtain very accurate measurements. Inspection applications such as this are common in the large scale manufacturing industry, which includes aircraft and aerospace manufacturing, shipbuilding and automotive manufacturing. Optical 3D coordinate measurement systems have become increasingly automated due to the demand for higher levels of productivity in the manufacturing industry [1]. Consequently system set up and measurement times have been significantly reduced [1].

The optical 3D coordinate measurement systems include:

- Digital theodolite
- Digital photogrammetry
- Laser tracker

Digital theodolites involve a technology based on optical triangulation [1] incorporating between 2 and 16 theodolites [2]. The theodolite incorporates a telescope that is manually adjusted so that the sight is aligned to the target point. The
angular positions of the aligned telescope combined with the distance between theodolites are used to determine the coordinates of the measured point. It has been claimed that experienced operators can use the theodolite system to measure up to 5 coordinates per minute [3].

Digital photogrammetry uses optical triangulation techniques to obtain precise coordinate measurements from photographs. The procedure involves developing lines of sight from each camera location to the point of interest on the object [4]. The intersection of these pairs of lines of sight can then be triangulated to determine the 3D coordinate of the point on the object [4].

Digital photogrammetry systems [5] can be configured as either offline single-sensor systems (involving a series of sequentially acquired images) or multi-sensor real time systems [1]. Measurements obtained using the multi-sensor system can be obtained in real time, but are less accurate than those obtained with the single-sensor system which are produced in the order of minutes [6]. In some cases the accuracy achieved with digital photogrammetry is comparable to that of theodolite systems [7].

The laser tracking system is used to obtain coordinates by means of polar measurement [2]. This involves the measurement of two angles (zenith and azimuthal angles) using an encoder and a distance using an interferometer. Measurements can be obtained with the laser tracking system using a single observer and at a rate of up to 500 per second [2]. It has been claimed [3] that the manpower required when using the laser tracking system is in some applications only one third of that required when using the theodolite system.

When used in conjunction with certain hand held probes such as a corner cube, the accuracy of the laser tracking system is better than that achievable with digital photogrammetry systems [8], and sufficient to satisfy the stringent standards in the aircraft manufacturing industry [9]. Consequently there are measurement applications in the aircraft industry where the laser tracking system has replaced the theodolite system providing a significant saving in manpower.

Other hand held probes such as surface reflectors have been designed to enable the laser tracking system to be used in a wider range of applications, however they provide results that are significantly less accurate [9]. Consequently the aim of the research project described here was to develop a new surface reflector. The purpose of the new surface reflector was to enable the laser tracking system to be used for a wider range of applications. Increasing the range of applications in which the laser tracking system can replace the theodolite system reduces the requirement for manpower and as a result reduces manufacturing costs.

The development of the new prototype surface reflector involved design, manufacture, development of a calibration procedure, and testing. The new design incorporated a longer reach and a more flexible adjustment mechanism than the existing device. The new adjustment mechanism replaced the old system involving shims with screws and rings. The purpose of the calibration and testing phases of this project were to determine if the new adjustment mechanism could be calibrated in a shorter time and to a higher accuracy that the existing device. This involved an
investigation into the effect of surface reflector misalignment on the systematic error in measurements obtained using a laser tracking system.

2 Laser Tracking System

The laser tracking system is made up of three components. They are:

- A computer to control the laser tracker, for data storage and manipulation
- The laser tracker unit
- The hand held retro-reflector

The laser tracker unit includes a laser source and associated optics to produce the laser beam, an interferometer for distance measurement and a position-sensing device, which measures change in position of the target. The head of the tracker unit which emits the laser beam can rotate in two directions, horizontally and vertically (elevation) so that the tracker can follow the target. The reflected laser beam is also received in the head of the tracker unit.

The retro-reflector is an optical device, which returns a collimated beam of laser light in the direction from which it came. The type of retro-reflector used during this project was the corner cube.

The corner cube is spherical in shape with three mutually orthogonal mirrors mounted internally. The purpose of the mirror system is to reflect the laser beam in a direction parallel to the incident direction. If the laser beam strikes the centre of the mirrors of the corner cube then the reflected beam will travel back along the same path as the incident beam. However, if the laser beam strikes the mirrors off the centre location then the reflected beam will travel in a direction parallel, but offset to the incident beam.

The tracker head emits a laser beam, which strikes the mirrors of the corner cube and is reflected back to the tracker head. The tracker head uses a position-sensing device to determine the offset of the reflected beam. The offset is used to adjust the tracker head so as to eliminate the offset and to keep the tracker head pointing in the direction of the centre of the corner cube.

Measurements taken with the corner cube are measured to the centre of its sphere [9]. Consequently there is an offset equal to the radius of the sphere between the measured value and the location of the point being measured. Other disadvantages with the corner cube are that it cannot be used to measure in holes or in steps.

A variety of measurement techniques are available with the laser tracking system. The results presented in this report were obtained using the stationary point measurement technique [9]. The parameters of the stationary point measurement are the rate and period of sampling. The system automatically calculates the average value and standard deviation of the measurements obtained during the period of sampling. Provided the standard deviation is within a predefined limit the measurement is accepted. In this case 300 measurements were recorded during a period of 3 seconds and the predefined limit of the standard deviation was $\pm 50 \mu m$. 
The location of the corner cube is determined in polar coordinates, which involves a radial distance and two angles. The two angles are determined by the angles of the tracker head at the time of measurement. The distance is determined using an interferometer which uses the incident and reflected laser beams to produce a fringe pattern. The number of fringes is counted to determine the distance between the corner cube centre and the laser tracker reference point.

3 The surface reflector

The surface reflector is a device designed for the measurement of surface features that are difficult to access using the corner cube [9]. Typically such features include; holes with a diameter less than the diameter of the corner cube and the inner joint in a right angle joint.

The surface reflector is a commercially available device. An example of a surface reflector is schematically represented in Figure 1.

![Figure 1 – Schematic representation of the existing surface reflector](image)

The corner cube is mounted on the surface reflector in a cradle. In the case of the existing surface reflector the cradle consists of three supports. The corner cube is held against the supports by a magnet.

The surface reflector can be fitted with either a pointed tip or a spherical tip. The pointed tip is used to obtain measurements without an offset. The spherical tip is used to obtain measurements with an offset equal to the radius of the spherical tip.

The reach of the surface reflector is defined as the distance from the base of the reflecting mirror to either the tip of the pointed stylus or the centre of the spherical stylus. The reach of a surface reflector determines among other factors the maximum depth of measurement. Other factors include the relative location of the measurement position with respect to the laser tracker head and the geometry of the surface in the region of the measurement location.

The principle of operation of the surface reflector requires that the corner cube and the stylus be accurately located with respect to each other and the reflecting mirror. It is
required that the corner cube and stylus are located on the same axis, which is orientated perpendicular to the plane of the mirror. By locating the corner cube and stylus at equal distances either side of the reflecting mirror, a laser beam directed at the stylus would be reflected into the corner cube by the mirror. The laser beam incident on the corner cube would then be reflected back to the laser tracker via the reflecting mirror. Provided these components are accurately positioned in this way, then the measured location of the corner cube is equal to the location of the stylus. Any misalignment in the positioning of these components will result in an error in the measurement.

The surface reflector can be calibrated to minimise any misalignment. Calibration of the surface reflector involves adjusting the cradle in which the corner cube is mounted. In the case of the existing surface reflector, the cradle is mounted on shims. By changing the thickness of the shims, the position of the cradle and hence the corner cube are also adjusted. This procedure requires approximately eight hours and the manufacturer-specified accuracy of the existing device is only \( \pm 200 \mu m \) [9]. This is unacceptable for many aircraft manufacturing applications [9].

In an attempt to improve the achievable calibration accuracy and reduce the time required for calibration, two prototype surface reflectors were manufactured which incorporated a redesigned adjustment mechanism.

The new design eliminated the need for shims and incorporates three pairs of screws. The pairs of screws are used to adjust the position of the cradle along each of the three orthogonal axes. Two of the pairs are grub screws and the other pair are ring screws. The adjustment mechanism is represented schematically in Figure 2.

![Figure 2](https://via.placeholder.com/150)

**Figure 2** – Schematic representation of the adjustment mechanism used in the prototype surface reflectors. Only the part of the surface reflector housing the adjustment mechanism is shown.

Other significant design improvements incorporated into the prototype surface reflectors include a rigidly supported stylus and an increased reach. The stylus support involves slotting the stylus into a collet and fastening it with a nut. The rigidly supported stylus arrangement is less susceptible to wear and movement resulting in a more accurate surface reflector.
The reach of the first and the second surface reflector prototypes was increased from 21.3mm to 50.5mm and 51.5mm respectively. The improved reach enables the surface reflector to be used for a wider range of applications. The first prototype surface reflector incorporated these features and is presented in Figure 3.

![Figure 3 – The first prototype surface reflector](image)

There is a geometrical relationship between the reach, the length of the mirror and the angle at which the surface reflector can be tilted away from the emitted laser beam. As a consequence of increasing the reach of the prototype the length of the mirror had to be increased. This ensured that the prototype could be tilted away from the emitted laser beam by an amount equivalent to that achievable with the existing surface reflector.

After testing the first prototype it was found that the changes incorporated into the new design improved the calibration speed and could be used to achieve equivalent calibration accuracy. It was also found that the long thick mirror limited the angle at which the first prototype could be tilted away from the emitted laser beam.

A second prototype surface reflector with further improvement was designed and manufactured. The areas of improvement included

- Finer pitch threads on adjustment screws for increased adjustment sensitivity
- Smaller thinner mirror to increase reach and angular range at which the prototype could be tilted away from the emitted laser beam. The thickness of the mirror was reduced to 3mm while maintaining a flatness of 0.25 of the 633nm wavelength of the emitted laser beam. Obtaining this degree of flatness on a 3mm thick mirror was difficult to achieve in practise.
- Fully adjustable handle for ease of operation
- Increased extension of the stylus from the collet to improve access to narrow cavities
- Manufacturing the device from titanium, a more thermally stable material than aluminium
The second prototype is presented in Figure 4.

![Image of the second prototype surface reflector](image1.png)

Figure 4 – The second prototype surface reflector

4 Surface reflector calibration

The purpose of calibrating the surface reflector is to accurately position the corner cube with respect to the mirror plane and the stylus. The desired location of the corner cube is at a distance from the mirror plane that is equal and opposite to that of the stylus, and on an axis that is perpendicular to the mirror plane, which passes through the stylus.

In order to calibrate the surface reflector a procedure was developed and a jig was designed and manufactured. The purpose of the calibration jig is to locate the surface reflector relative to the reference point and to align the coordinate system of the laser tracking system so that it coincides with the adjustment rings and screws. The calibration jig is shown in Figure 5.

![Image of the calibration jig with surface reflector mounted](image2.png)

Figure 5 – The calibration jig with surface reflector mounted

The procedure involved measuring a reference point with the corner cube, which is known to be more accurate than the surface reflector. The surface reflector is mounted on the jig, which is positioned over the reference point. The jig is positioned so that the surface reflector is in position to obtain a measurement of the reference point. The laser tracking system coordinate axes are then aligned so that each axis is parallel to each adjustment axis. The reference measurement is then subtracted from the current measurement and the result is displayed in real time on the laser tracking system monitor. The results displayed are presented in terms of a misalignment in
each axis. The surface reflector is calibrated by adjusting the rings and screws in order to reduce these misalignments in each axis.

At the completion of the calibration process, the magnitude of the remaining misalignment in each adjustment axis was recorded. The results are presented in Tables 1 and 2 of Appendix 1.

5 Systematic error and misalignment

The value of the quantity under investigation is known as the measurand, \( Y \). In this application which involves position measurement, the value of the measurand cannot be completely known. In this case, the result of a measurement is only an estimate of the measurand. The complete description of a measurement includes the estimate of the measurand, \( y \), and a quantitative statement of its uncertainty, \( u \) [10].

The estimate of the measurand can be expressed as the mean value of an infinite number of measurements of the quantity under investigation, carried out under repeatability conditions [10]. Any difference between the value of the measurand and the estimate of the measurand is equal to the systematic error, \( E \) [10]. A correction value, \( c \), can be added to the estimate of the measurand to compensate for the systematic error [10].

A quantitative statement of the uncertainty in the measurement of the measurand is expressed as an estimated standard deviation, \( s \) [10]. This standard deviation is known as the combined standard uncertainty, \( u_c \) [10], because it generally consists of a number of components.

In this application the quantity of interest is the systematic error which is expressed in terms of a length. The systematic error is used as an expression of the accuracy of the measurement results obtained under reproducibility conditions (where the changed condition was the measurement location).

A significant cause of systematic error in a surface reflector is the misalignment of the corner cube relative to the mirror plane and the stylus. It is the purpose of the calibration process to minimise the misalignment. As a consequence of the finite sensitivity of the adjustment mechanism, it is not possible to completely eliminate the misalignment.

The total misalignment is equal to the square root, of the sum of the square of the components of misalignment, \( m_x, m_y, m_z \), along each coordinate axis. Misalignment is evaluated using Equation 1.

\[
Misalignment = \sqrt{m_x^2 + m_y^2 + m_z^2} 
\]

Equation 1, has been evaluated for the prototype surface reflectors and the results are presented in Tables 1 and 2 of Appendix 1.
6 Surface reflector testing

The objective of the experimentation was to determine the systematic error of the surface reflector. The systematic error is defined as the difference between the value of the measurand and the value obtained, in this case using the surface reflector.

In this application the value of the measurand is not known and so an estimate of its value is used. The estimate of the value of the measurand is obtained using the corner cube, which is a more accurate measurement tool than the surface reflector. The combined uncertainty associated with measurements obtained using the corner cube have been found to vary from approximately 35 $\mu m$ [8] (involving compensation for atmospheric conditions) to 50 $\mu m$ [9] (involving typical measurement conditions). The combined uncertainty associated with measurements obtained using the existing surface reflector is approximately 200 $\mu m$ [9].

A systematic error and an uncertainty are associated with the above estimate, which contributes to the systematic error and the uncertainty of the surface reflector. This is considered to have an effect on the experimental results.

The experimental procedure used to determine the systematic error and the combined uncertainty (involving a Type A evaluation [10]) involved measuring 4 data points. The results of a data point measurement are the values of the $x$, $y$ and $z$ components of an orthogonal coordinate system. Each point was measured with the corner cube and a surface reflector using the left and right faces of the laser tracking system. The series of left and right face measurements of data points obtained using the corner cube are:

$x(i)_{cl}, y(i)_{cl}, z(i)_{cl}, \ldots \ldots \ldots x(i)_{cr}, y(i)_{cr}, z(i)_{cr}, \ldots \ldots$

The symbols $x$, $y$ and $z$ represent the components of the coordinate system measurements and $i$ represents the data point measured. The subscripts, $c$, $l$, and $r$ represent the corner cube, the left face and the right face of the laser tracking system.

The average value is determined between the left and right faces of each coordinate axis component of the corner cube, data point measurements.

\[
x(i)_c = \frac{x(i)_{cl} + x(i)_{cr}}{2} \quad \ldots (2)
\]

\[
y(i)_c = \frac{y(i)_{cl} + y(i)_{cr}}{2} \quad \ldots (3)
\]

\[
z(i)_c = \frac{z(i)_{cl} + z(i)_{cr}}{2} \quad \ldots (4)
\]

The series of left and right face measurements of the data points obtained using the surface reflector are:

$x(i)_{sl}, y(i)_{sl}, z(i)_{sl}, \ldots \ldots x(i)_{sr}, y(i)_{sr}, z(i)_{sr}, \ldots \ldots$
The undefined subscript, \( s \), represents a measurement obtained using the surface reflector.

The average value is determined between the left and right faces of each coordinate axis component of the surface reflector, data point measurements.

\[
x(i)_s = \frac{x(i)_l + x(i)_r}{2} \quad \ldots(5)
\]

\[
y(i)_s = \frac{y(i)_l + y(i)_r}{2} \quad \ldots(6)
\]

\[
z(i)_s = \frac{z(i)_l + z(i)_r}{2} \quad \ldots(7)
\]

The difference between the average value of the respective components of the corner cube and the surface reflector for each data point is equal to the components of systematic error, \( e_x, e_y \), and \( e_z \).

\[
e_x(i) = x(i)_c - x(i)_s \quad \ldots(8)
\]

\[
e_y(i) = y(i)_c - y(i)_s \quad \ldots(9)
\]

\[
e_z(i) = z(i)_c - z(i)_s \quad \ldots(10)
\]

The mean value of the components systematic error, \( \hat{e} \), for the 4 data points is determined.

\[
\hat{e}_x = \frac{1}{n} \sum_{i=1}^{n} e_x(i), \quad (where \ n = 4) \quad (11)
\]

\[
\hat{e}_y = \frac{1}{n} \sum_{i=1}^{n} e_y(i), \quad (where \ n = 4) \quad \ldots(12)
\]

\[
\hat{e}_z = \frac{1}{n} \sum_{i=1}^{n} e_z(i), \quad (where \ n = 4) \quad \ldots(13)
\]

The square root of the sum of the square of the mean value of the components of the systematic error is evaluated and is used as a quantitative expression of the standard error of the surface reflectors.

\[
\hat{e} = \sqrt{\hat{e}_x^2 + \hat{e}_y^2 + \hat{e}_z^2} \quad \ldots(14)
\]

The estimated standard deviation of the mean of the components of systematic error, \( s_x, s_y, s_z \), is determined.
\[ s_i = \sqrt{\frac{\sum_{i=1}^{n} (e_i - \hat{e})^2}{n(n-1)}}, \quad (\text{where } n = 4) \] \hfill (15)

\[ s_y = \sqrt{\frac{\sum_{i=1}^{n} (e_y - \hat{e})^2}{n(n-1)}}, \quad (\text{where } n = 4) \] \hfill (16)

\[ s_z = \sqrt{\frac{\sum_{i=1}^{n} (e_z - \hat{e})^2}{n(n-1)}}, \quad (\text{where } n = 4) \] \hfill (17)

The estimated standard deviation of the mean of the components of systematic error, \( s \), is determined and is used as a quantitative expression of the precision of the surface reflector.

\[ s = \sqrt{s_i^2 + s_y^2 + s_z^2} \] \hfill (18)

The combined uncertainty is equal to the standard deviation.

\[ u_c = s \] \hfill (19)

This procedure has been used to experimentally estimate the systematic error and the combined uncertainty for the first prototype, the second prototype and the existing surface reflector. The results are presented in the next section.

7 Discussion of the calibration and test results

The prototype surface reflectors were calibrated and the recorded components of misalignment were used to calculate the misalignment using Equation 1. The systematic error was also determined experimentally using the procedure described in Section 6. The calculated and experimentally determined systematic errors are presented in Figure 6.
Measurement sets 1, 2 and 3 involved the first prototype surface reflector (refer to Figure 6). Measurement sets 1 and 2 involved calibration using a CMM. The procedure utilised a trial and error method. This involved measuring the position of the corner cube relative to the mirror plane and stylus. The surface reflector was then adjusted to minimise the misalignment between the corner cube and the stylus. This procedure was repeated until the misalignment was reduced to the required magnitude.

In the case of the first measurement set the pointed tip stylus was used for calibration. The pointed tip was difficult to measure accurately and accordingly the misalignment could not be determined and a large systematic error resulted. The spherical tip was used for the calibration of the second measurement set which resulted in a reduction of the systematic error. The third measurement set involved the laser tracking system and the calibration procedure presented in Section 5, which further reduced the systematic error.

Measurement sets four and five involved the second prototype surface reflector. In both cases the calibration technique involved the laser tracking system and the procedure presented in Section 5.

In the first three measurement sets, the misalignment accounts for the majority of the systematic error (refer to Figure 6). For this reason it was considered that further significant reductions in misalignment would lead to significant reductions in systematic error.

In the last two measurement sets, the misalignment represents only a small fraction of the systematic error (refer to Figure 6). For this reason it was considered that further significant reductions in misalignment would lead to only minor reductions in systematic error. In this case sources other than misalignment not investigated during
the course of this work are considered to account for the majority of the systematic error.

The magnitude of the misalignment achieved in the second prototype was significantly less than that achieved in the first prototype. The reason for the significant reduction in the misalignment was due to the improved adjustment sensitivity possible in the second prototype. The adjustment sensitivity, which depends on the pitch of the adjusting screws and rings was reduced from 1mm to 0.8mm from the first to the second prototype surface reflector.

The experimentally determined systematic errors obtained with the existing and the prototype surface reflector are presented graphically in Figure 7.

The systematic error obtained with the existing surface reflector remained relatively constant compared to that of the prototype surface reflectors, throughout the five measurement sets (refer to Figure 7). The existing surface reflector was not calibrated during the course of these tests.

The systematic error obtained with the first prototype in measurement sets 1 and 2 was larger than that obtained with the second prototype. This is primarily due to the calibration technique used, which involved a trial and error method and the CMM. The calibration technique resulted in a relatively large misalignment and systematic error in the prototype surface reflector.

The systematic error obtained with the prototype surface reflectors in measurement sets 3, 4 and 5 were less than that obtained with the existing surface reflector (refer to Figure 7). The reason for this was due to the improved calibration technique and adjustment sensitivity of the second prototype.
The experimentally determined systematic error is considered to be larger than the actual value, and is actually equal to the difference between a corner cube measurement and a surface reflector measurement. The systematic errors associated with the two measurements are combined resulting in a systematic error that is larger than the estimated systematic error of only the surface reflector.

In total there was only five attempts made on different occasions to calibrate the two prototype surface reflectors. Each attempt took between a half an hour and one hour. It is considered that with more practice, the time required for the calibration of the prototype surface reflectors could be reduced. It is also considered that further improvements in the calibration procedure or the adjustment mechanism would not necessarily lead to significant reductions in systematic error. This is because misalignment only represents a small percentage of the systematic error in the case of the second prototype surface reflector.

8 Conclusion

A new surface reflector was designed and prototypes were manufactured. The new design extended the reach of the stylus and provided a mechanism enabling faster calibration with greater adjustment sensitivity.

An improved calibration procedure was developed, which was reasonably simple and effective, taking less than one hour to complete. With further practice it is considered that both the calibration time and the misalignment could be reduced.

The calibrated surface reflectors were tested and evaluated. The purpose of the testing was to determine the degree to which the misalignment effected the systematic error and to compare the relative accuracy and precision of the prototype surface reflectors with that of the existing surface reflector.

The second prototype surface reflector has successfully satisfied the project objectives. The new design provides a longer reach extending the range in which it can be used. It can be calibrated to a higher degree of accuracy in a shorter period of time than the existing surface reflector and can also be used to obtain more accurate and precise measurements than the existing surface reflector.

9 Acknowledgments

The authors of this paper acknowledge the contribution of the Cooperative Research Centre for Intelligent Manufacturing Systems and Technologies for funding and overseeing this research in collaboration with the Industrial Research Institute at Swinburne University (IRIS). The authors also wish to thank Hawker de Haviland LTD for providing facilities and valuable industrial expertise during the design and testing stages of this project.

10 References


11 Appendix – Calibration and test results

<table>
<thead>
<tr>
<th>Measurement Set</th>
<th>Calibration method</th>
<th>Components of misalignment ($\mu m$)</th>
<th>Misalignment ($\mu m$)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>X</td>
<td>Y</td>
</tr>
<tr>
<td>1</td>
<td>CMM</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
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<td>CMM</td>
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<td>3</td>
<td>LTS</td>
<td>51</td>
<td>51</td>
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Table 1 – Calibration results, (components of misalignment and misalignment) for the first prototype surface reflector.

<table>
<thead>
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<th>Calibration method</th>
<th>Components of misalignment ($\mu m$)</th>
<th>Misalignment ($\mu m$)</th>
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<td>LTS</td>
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<td>13</td>
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Table 2 – Calibration results, (components of misalignment and misalignment) for the second prototype surface reflector.
<table>
<thead>
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<th>Measurement set</th>
<th>Systematic error (μm)</th>
<th>Combined uncertainty (μm)</th>
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<td>2</td>
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<td>3</td>
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Table 3 – Test results for the first prototype surface reflector.

<table>
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<th>Measurement set</th>
<th>Systematic error (μm)</th>
<th>Combined uncertainty (μm)</th>
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<tr>
<td>5</td>
<td>89</td>
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Table 4 – Test results for the Second prototype surface reflector.

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<th>Combined uncertainty (μm)</th>
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<tr>
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Table 5 – Test results for the existing surface reflector.