Tactile coordinate metrology for ultra-precision measurement of optics: results and intercomparison

M. Baas[1*], I. Widdershoven[1] and H.A.M. Spaan[1]

[1] Esp 201, 5633AD Eindhoven, The Netherlands

**corresponding author (email: baas@ibspe.com)*

ABSTRACT:

This paper presents the achieved measured results of the Isara 400 3D Coordinate Measuring Machine. Verification measurements of a flat mirror measurement have shown traceable measurement errors as low as 11 nm. Round robin measurements in a European Metrology Research Program show good comparable results within a variety of measurement machines.

Keywords: Metrology, Nanotechnology, Coordinate Measuring machine (CMM), Accuracy, Comparison

1 Introduction

Coordinate Measuring Machines (CMMs) are widely used for 3D metrology of parts in science and industry. The Isara 400 3D coordinate measuring machine, developed by IBS Precision Engineering, advances coordinate metrology into ultra-precision accuracy, offering a flexible solution for full 3D measurement of a wide range of (large scale) products, with a measuring uncertainty at nanometer level. The Isara 400 3D CMM offers a theoretical measuring uncertainty of 57 nm (2σ) in 1D and 109 nm (2σ) in full 3D over a measuring volume of 400 x 400 x 100 mm, which is unprecedented in its field. The design, realization and calibration of the Isara 400 were presented at the 2011 ISMTII [1]. Since then, extensive research has continued for various measurement applications; the measuring capabilities of this machine have been successfully applied in several demanding measurement tasks [2].

Figure 1 shows an overview of the complete machine. Three plane mirror laser interferometers are applied as measuring systems for the machine axes. The interferometers each measure against the sides of a monolithic Zerodur mirror table, on which the work piece is mounted. These interferometers are mounted in a single body metrology frame, which also holds the probe system. The laser beams are aligned to the probe tip and their mutual alignment does not change during movement of the axes, thus fulfilling the Abbe principle in 3D within the complete measuring volume. As a result, straightness errors and rotations of the three translation stages will have no first order influence on the measurement result and the measurement uncertainty is independent of the measurement length.

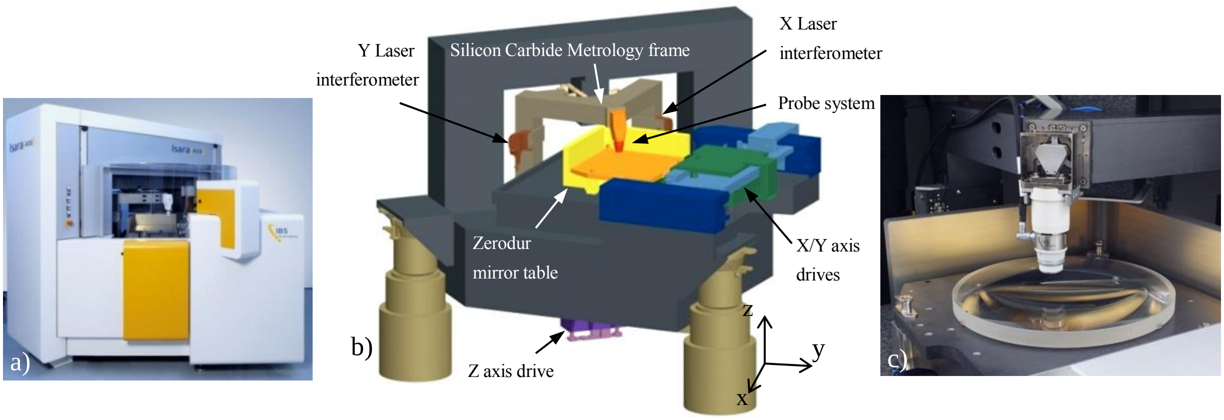

Fig. 1: a) Photograph of the Isara 400 3D CMM; b) 3D design concept; c) photograph of a product measurement.

In the following sections several comparison measurements are discussed. First a comparison of a flat mirror compared to optical calibration by the PTB, next two round robin artefacts used in a European Metrology Research Program.

2 Verification of machine accuracy: flatness measurement

The calibration procedure of the Isara 400, consisting of an accurate correction for flatness and out-of-squareness errors of the mirror table, is described in [1]. In order to verify the accuracy of the calibrated measuring machine, various reference artefacts are measured. One artefact which is used is an Ø150 mm Zerodur flat mirror. The flatness of this mirror was measured at Germany's national metrology institute, the Physkalisch-Technische Bundesanstalt (PTB), using Fizeau interferometry, which is directly traceable to the international standards.

This mirror is measured on the Isara 400 CMM; using the "Triskelion A-250" tactile probe system, a grid of 4400 measurement points was measured on the mirror surface (see figure 2).

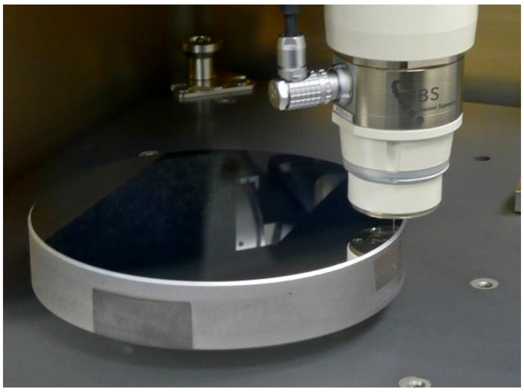

Fig. 2: Measurement of the Ø150 mm Zerodur flat mirror in the Isara 400 CMM

The measurement data from the Isara 400 CMM is compared to the interferometric measurement from the PTB, Figure 3 shows a comparison of the measurement results.

The difference between the Isara 400 measurement and the PTB calibration is determined by subtraction. The residual of this subtraction is shown as a surface plot and also as a histogram, which clearly shows the distribution of the residual. It is found that 95.5% of the data points match to less than 11 nm with the PTB calibration.

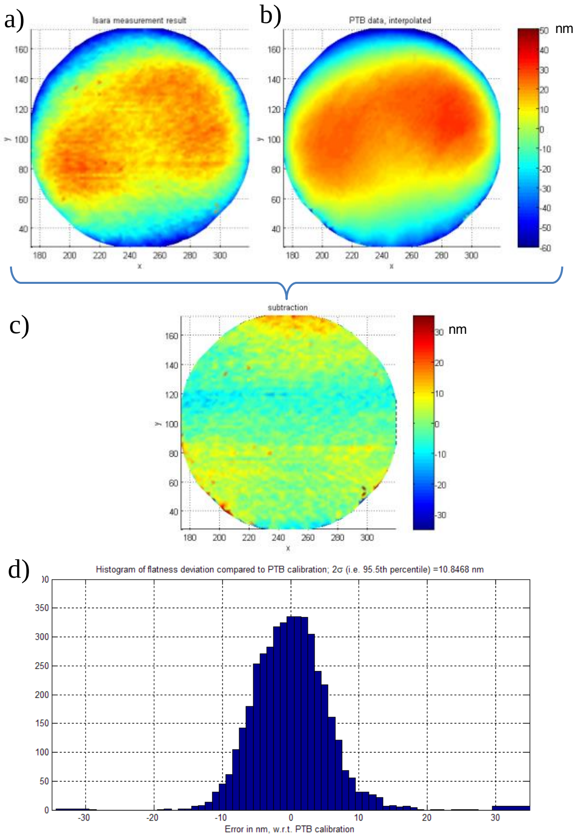

Fig. 3: a) Flatness measurement result from Isara 400; b) PTB calibration; c) Comparison; d) histogram of comparison.

In addition to point measurements, it is also possible to perform tactile scanning measurements, using the same Triskelion probe. During the scan, the deflection of the probe is used as feedback to maintain contact with the work piece; no prior knowledge of the surface is required. Figure 4 shows the result of such scanning measurements across the center of the flat mirror (measurement time 4 minutes, 600.000 data points in profile). The graph shows the form error along this line, for two scan measurements superimposed on the PTB calibration data. Again, this result indicates that the Isara 400 is capable of matching the optical calibration measurements to approximately 10 nm.

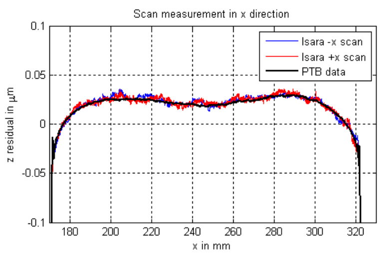

Fig. 4 Result of tactile scanning measurement across center of flat mirror

3 Measurement of aspheric lens for the Very Large Telescope

The European Metrology Research Program (EMRP) IND10 “Optical and tactile metrology for absolute form characterization” is a joint research projects which aims to improve the form metrology which is urgently needed for modern optical surface production. This project brings together experts from optical metrology as well as from coordinate metrology.

Within this EMRP project, extensive intercomparison measurements on optical artefacts have been performed. One such artefact is an Ø380 mm aspheric lens. The lens was developed for the Very Large Telescope (VLT) in Chile as part of an instrument for projecting artificial stars to compensate for atmosphere turbulence and has been manufactured by the Dutch research organisation TNO. Such lenses are manufactured in an iterative loop of measurement and re-polishing to obtain an end product with less than 25 nm RMS form deviation [5]. This particular lens was rejected in an early stage of production and will therefore show higher form deviation.

Due to the dimensions and accuracy requirements of this lens, it is challenging to measure using conventional measuring techniques. Within the EMRP project, the intercomparison was limited to the Isara 400 CMM and the NANOMEFOS [6], a non-contact measuring machine specifically design for measurement of aspheres and freeform optics.

To measure the lens on the Isara 400, the CAD model of the lens is imported in the CMM software. A few points are measured manually and a (coarse) alignment is determined. Next an automated measurement grid is defined and measured (see Figure 5) and the new best fit alignment is evaluated. The final measurement of this large lens was performed using a point-to-point grid measurement of 4800 points.

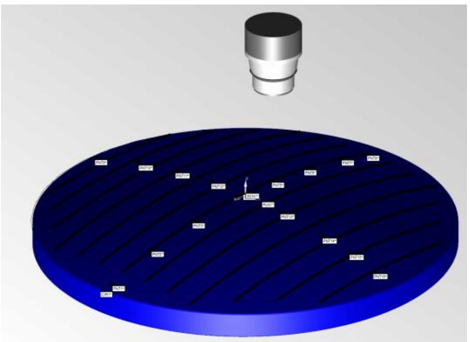

Fig. 5: Measurement setup of the Ø380 mm Optical Tube Assembly (OTA) lens in the Isara 400 3D CMM

The best fit with respect to the theoretically prescribed asphere is obtained using the aspheric formula (Eq. 1). Best fit alignment with respect to x_0, y_0, z_0, ψ and θ is determined.

$$\frac{}{{}_{0}\cdot\left(\sqrt{\left(\frac{{}^{2}.(K\ \ 1)}{}\right)}+1\right)} \qquad (1)$$

Table 2 below shows the parameters for this lens, indicating that it is an ellipsoid, as the conical constant is between -1 and 0.

Table 1: Parameters of the VLT Asphere

Lens Type	Glass
Clear Aperture	300 mm
Radius	637.38 mm
Conical constant	-0.4776

Figure 6 shows the form error of the asphere as measured with the Isara 400 CMM. This measurement was executed twice and the differences between measurement 1 and 2 are shown on the right hand side. On the bottom right a histogram shows that the repeatability of these two measurements is less than 13 nm (2σ).

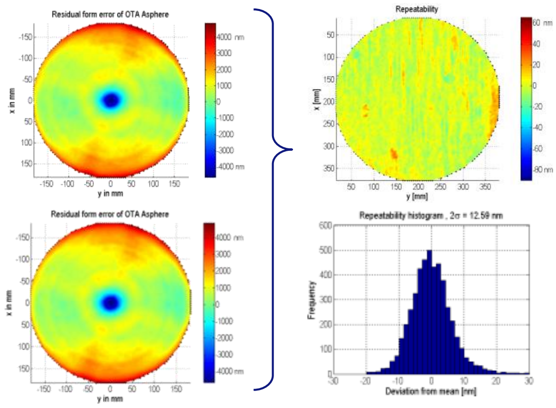

Fig. 6: Repeatability of the measurement, 2 measurement results (left), residual after comparison (right). The histogram shows that the measurement repeats within 13 nm (k=2).

Figure 7 shows the measurement done by TNO using the NANOMEFOS machine on the left and the measurement result obtained from IBS Precision Engineering’s Isara 400 CMM on the right, using the same color scales and plotting styles. Good comparability between these different measurement methods can be observed.

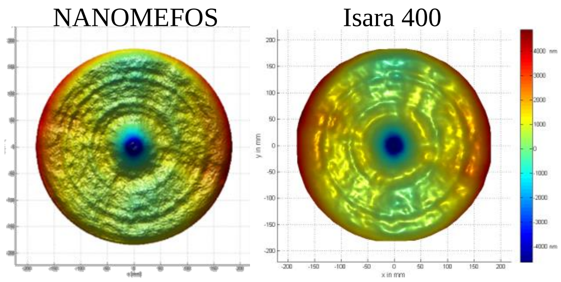

Fig. 7: Measurement results of TNO using the NANOMEFOS (left) and IBS using the Isara 400 CMM (right)

Peak-to-Valley values and RMS form error of the two measurements are listed in table 3 and it can be seen that RMS values match within 30 nm.

Table 2: Measurement results OTA lens

Measurement	PV-value	RMS-value
TNO (NANOMEFOS)	9673 nm	1021 nm
IBS (Isara 400)	9523 nm	1052 nm

4 Small polymer lens measurement

Another artefact which is part of the comparison measurements within the EMRP project is a small polymer coated lens, which has been made available by Anteryon. This lens is measured by several partners in the project, including IBS on the Isara 400 CMM, The Dutch metrology institute VSL on a Zeiss F25 [10,11], the Swiss metrology institute METAS, using a small interferometer based microCMM [7,8] and the Institut fur Technische Optik (ITO) of the University of Stuttgart, Germany using a Tilted-Wave-Interferometer (TWI) [9]. Figure 8 shows the polymer lens on the left and the measurement setup in the Isara 400 CMM on the right. Table 4 lists the details of the polymer lens.

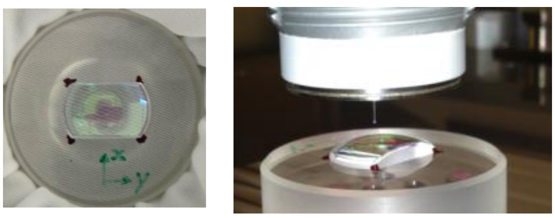

Fig. 8: Polymer lens (left) and measurement setup on the Isara 400 (right).

Table 3: Details of the Polymer lens artefact

Lens Type	Polymer Coated Asphere
Clear Aperture	11.74 mm
Radius	1e20 mm
Aspheric constants	α2,4,6,8,10≠0

Figure 9 shows the form error as measured on the Isara 400 CMM; the clear aperture is indicated by the dashed circle. This area is re-measured using a fine grid spacing of 0.2 mm.

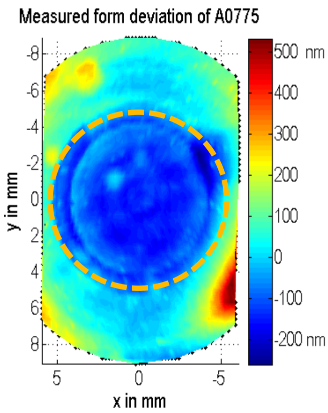

Fig. 9: Measurement result of the full lens, showing the clear aperture

The results of IBS (Isara 400 CMM), VSL (Zeiss F25), METAS (microCMM) and ITO (TWI) are shown in figure 10. This data was evaluated by the Physikalisch-Technische Bundesanstalt (PTB), to ensure uniform data processing. The data points are shown as squares, indicating the grid spacing; finer grid spacing results in more data points thus smaller squares in the plot. Some plots show small white areas, which are removed data points (for example outliers due to contamination).

It can be observed that for every measurement method, different grid spacing is used, due to the nature of the measurement. The optical interferometry based measurement from ITO receives pixel information, while the tactile methods of IBS and VSL use physical point measurements. The METAS machine has used scanning lines over the surface and therefore has a smaller grid spacing in y-direction compared to the x-direction. Nonetheless, good similarity in measurement results was obtained between these four measuring systems; the results are summarized in table 5, which lists the PV-values and RMS form error for every measurement.

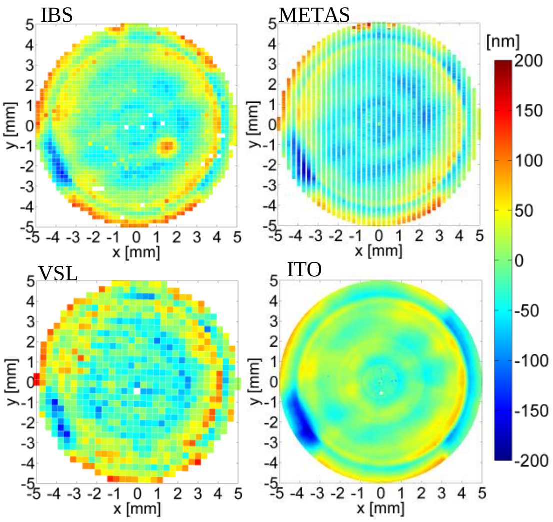

Fig. 10: Form error results of the polymer coated aspheric lens within a Ø10 mm aperture.

Table 4: Intercomparison results for the Polymer lens measurement

Participant	PV-value	RMS-value
IBS (Isara 400)	270 nm	42 nm
METAS (microCMM)	419 nm	31 nm
VSL (Zeiss F25)	292 nm	46 nm
ITO (TWI)	286 nm	40 nm

5 Conclusions

The presented measurement applications and comparison of the ultra-precision coordinate metrology on the Isara 400 3D CMM demonstrate the capabilities of the machine. The Isara 400 offers a measurement uncertainty in the nanometer range, in a large measurement volume of 400 x 400 x 100 mm. Various measurement applications have been shown to illustrate versatility and measurement capabilities which is offered by this ultra-precision CMM. A flat mirror verification measurement showed traceable measurement errors as low as 11 nm.

The measurement of the Very Large Telescope asphere (Ø380 mm) requires almost the full measurement range of the Isara 400. The results are shown to be repeatable within 13 nm. Comparing the measured form deviation to a measurement by TNO on the NANOMEFOS machine, RMS values show good comparability within 30 nm, showing that both machines offer an innovative solution for the demanding measurement task.

A second comparison measurement of a polymer coated aspheric lens and was measured on a variety of measurement machines within the IND10 EMRP project. RMS form error values of the optical surface match to within 15 nm between the four measurement techniques applied in this intercomparison. Three partners have applied a tactile measurement using different types of ‘micro CMMs’, showing that this technology is mature and reliable for the measurement of high precision optics.

6 Acknowledgments

The work presented in this document is part of the European Metrology Research Program (EMRP): IND 10 “Optical and tactile metrology for absolute form characterization” which is jointly funded by the EMRP participating countries within EURAMET and the European Union. The authors would like to thank the participants for sharing their measurement data. Also we would like to thank TNO in particular, for providing the large aspheric lens for the comparison measurement.

Finally we want to give special thanks to Gernot Blobel of the PTB for his efforts to do the data analysis and comparison for the Polymer lens measurement.

7 References

[1] I. Widdershoven, R.L. Donker and H.A.M. Spaan, “Calibration of the Isara 400 ultra-precision CMM”, Proceedings of the 10th international symposium of measurement technology and intelligent instruments (ISMTII), June 2011

[2] I. Widdershoven, M. Baas and H. Spaan, “Ultra-precision 3D coordinate metrology results showing 10 nm accuracy”, Proceedings of the 11th international symposium of measurement technology and intelligent instruments (ISMTII), July 2013

[3] H. A. M. Spaan, R. L. Donker, and I. Widdershoven, “Isara 400: Development of an ultra-precision CMM for 3D measurement of large parts”, Proceedings of the ASPE spring topical conference, April 2009.

[4] I. Widdershoven, M. Baas, and H. Spaan, “Ultra-precision 3D coordinate metrology results showing 10 nm accuracy,” in The 11th international symposium of measurement technology and intelligent instruments, 2013, pp. 1–5.

[5] G. Gubbels, R. Henselmans, C. van Drunen, “Flexible manufacturing of large aspheres for VLT's Optical Tube Assemblies”, In the

Proceedings of Optical Manufactering and Testing IX volume 8126, (2011).

[6] R. Henselmans, “Non-contact measurement Machine for freefrom optics”, PhD Thesis, Technica; University of Eindhoven (2009).

[7] A. Küng, F. Meli, R. Thalmann, “Ultraprecision micro-CMM using a low force 3D touch probe”, Measurement Science and Technology, 18 (2007) 319-327.

[8] T.A.M. Ruijl, “Ultra Precision Coordinate Measuring Machine, Design, Calibration and Error Compensation”, PhD Thesis, Technische Universiteit Delft (2001).

[9] E. Garbusi, C. Pruss, and W. Osten, "Interferometer for precise and flexible asphere testing," Opt. Lett. 33, 2973-2975 (2008)

[10] M. Vermeulen, “High-Precision 3D-Coordinate Measuring Machine; Design and Prototype-Development”, Ph.D. thesis, Technical University of Eindhoven (1999).

[11] M.G.A. van Veghel, R.H. Bergmans and H.J. Nieuwenkamp, Proceedings of the Euspen international conference 2008, Zurich, Switzerland. P263, V2.