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1 Executive Summary

Introduction

The absolute form measurement of optical components – ranging from flat surfaces to aspheres and free form surfaces - was significantly improved by this project. This strengthens Europe's position in the global photonics market and leads to better optical components and systems which can be manufactured with less energy and waste.

The Problem

Optics and the optical industry are among Europe's strengths, but optical surfaces can only be manufactured as well as they can be measured. Thus, while advanced techniques for polishing optics enable removal of material from surfaces at the nanometre level is possible, it is not productive if the deviation to the design form cannot be determined exactly enough. This is even more challenging for the new aspherical elements with complex forms used in modern optical systems. A surface that is a modified sphere and still has rotational symmetry is typically denominated as an "asphere". Even if the rotational symmetry is lost, the surface is described as a "free form surface", but often "asphere" is also used for both categories.

Aspheres are found in almost every optical system from intraocular lenses used to treat cataracts, glasses, cell phone cameras, consumer and high-end cameras, to astronomical and photolithographic systems for computer chip production.

European manufactures of high-quality optics and metrology systems urgently needed more accurate form measurement, down to a few tens of nanometres, and improved asphere standards traced back to the National Metrology Institutes (NMIs). For the high-accuracy instruments existing at NMIs, in industry and institutes, absolute accuracy estimations, cross checks and comparisons are necessary. These also need to be supported by suitable reference surfaces. Improvements and new developments of high-accuracy measuring instruments foster these capabilities.

The Solution

As a basis for all form metrology, flatness metrology with single nanometre uncertainty has been improved with respect to lateral resolution (improved to 0.1 mm and below). A new setup for capacitive measurement of flatness has been realised at CMI, which offers an expendable flatness metrology solution for small and medium sized companies with nanometre uncertainty.

For asphere metrology, the innovative Tilted-Wave Interferometer (TWI), with very high flexibility, was realised as a metrological prototype for the first time. In parallel, high-accuracy point-wise scanning instruments (e.g. coordinate measuring machines, CMMs), with tactile or optical probing, were investigated and a traceable single-point form measurement accuracy of <50 nm for aspherical optical surfaces using tactile and optical single-sensor scanning methods was realised for the first time.

Thus, completely different physical probing principles were combined and compared in the project, which has led to a better understanding of the effects. The systems were analysed by simulations and task specific uncertainty estimations, and cross checked by comparisons, for which special metrological reference surfaces were developed. Data analysis of the large amount of information was also improved by the development of sophisticated algorithms.

Impact

Higher resolution in flatness metrology enables the improvement of ultra-precise mirrors, e.g. used as references or in synchrotron applications, while the capacitive method brings accuracy to industry in a very cost-efficient way.

From the asphere metrology results, the impact is widespread:

- Optics metrology instrumentation manufacturers are able to trace back their form measuring systems, analyse the accuracy and provide their customers with reliable information.

- Optics manufacturers can produce higher quality surfaces and systems and avoid unnecessary feedback loops and wasted energy and material.
- NMIs can offer new and improved calibration capabilities.
- The position of Europe's optics and optics metrology manufacturers is fostered and employment is increased.

The metrology manufacturer Mahr is bringing a commercial version of the TWI to market and several customers have already expressed their interest in such an instrument. Thus, the developments of the project will be available to a broad group of customers.

2 Project context, rationale and objectives

2.1 Context

Europe has a strong position in the global photonics market. In 2008, Europe shared more than 20 % of the worldwide production volume in the photonics industry, equating to 55 billion Euros from the global photonics market. In Europe, more than 5000 companies, most of them small and medium-sized enterprises (SMEs), with about 290000 employees involved in photonics. The core sectors are lighting, production technology, medical technology, defence photonics and optical components and systems; with shares of the global photonics market ranging from 25 % to 45 % (cf. Photonics21 Strategic Research Agenda, Second edition 2010, European Technology Platform Photonics21, VDI Technologiezentrum, http://www.photonics21.org/).

A range of new photonic technologies and applications requires optical elements such as lenses or mirrors with challenging specifications. For many decades spherical elements have dominated optical systems, pushed by the success of pioneers like Ernst Abbe, Carl Zeiss and Otto Schott. These elements can be accurately produced, with low form deviations, by the polishing techniques available.

Today, there is an increased use of aspherical and freeform optics which allow smaller, lightweight and higher quality optical devices. While the mass production of aspheres used in consumer products (e.g. low cost digital cameras) has already been shifted to East Asian countries, high-end aspheres and freeform surfaces are still developed and manufactured in Europe. These optical elements are used in medical laser systems, such as ophthalmologic and endoscopic systems, lithography optics, multi-media projectors, car head-up displays, LED lightning, astronomical telescopes and optical microscopes, as well as in synchrotron facilities. A key issue for these optical elements is the surface quality, and especially the surface form which is crucial for optical functionality. For flatness measurements, lateral resolution is the main challenge; and for curved surfaces, the form measurement accuracy generally needs improvement.

Whilst the manufacturing of optical surfaces has steadily improved and nowadays advanced techniques allow the removal of material from surfaces at the nanometre level, this capability cannot be exploited for the production of improved optics and the development of novel applications. This is because the measurement of the surface topography and surface form produced is still not possible with the required accuracy of a few tens of nanometres for strongly curved surfaces. This problem has to be addressed now, because intense research activities in the field of optical metrology are in progress all over the world, putting Europe's current leading position in high-end optics and metrology system production at risk. For example, at the international '4th High Level Expert Meeting' 2010 of the Competence Centre for Ultra Precise Surface Manufacturing (UPOB) on "asphere metrology", the urgent industrial need for more accurate form measurement and improved asphere standards traced back to the NMIs was strongly emphasised.

2.2 Rationale and Objectives

The general project aim was to improve measurement capabilities for a broad spectrum of "optical surfaces" reaching from flat surfaces to aspheres. These have very particular properties as they are polished and consequently very smooth; and the surfaces may be flat, spherical, aspherical, or even a free-form type.

Flatness metrology

Flat surfaces are used as mirrors, or as reference surfaces in a variety of applications, e.g. for Fizeau interferometers, used in the optical industry and precision engineering for measuring the shape of an optical surface, or as representations of Cartesian coordinate systems in high-accuracy CMMs used in a wide variety of manufacturing processes. Two specific needs of industry with respect to ultra-precise reference surfaces were identified: the reduction of uncertainty and lateral resolution.

Additionally, the development of a highly cost-efficient flatness measuring system based on a capacitive technique was identified as an objective to enable SMEs to build affordable flatness metrology systems with nanometre resolution.

The specific scientific and technical objectives for flatness metrology were:

- To achieve measurement uncertainties of 1 nm (peak-to-valley) or 0.25 nm root mean square (rms) for nearly flat surfaces (peak-to-valley less than 1 µm).
- To develop a new technique of flat surface measurements based on capacitive distance-sensors with an uncertainty of 10 nm or better.
- To attain at least a 10-fold improvement (to less than 0.1 mm) in the lateral resolution in flatness measurements.

Optical imaging metrology for curved surfaces

Aspheres are the driving force of innovation in all optical systems today. In asphere metrology, the reduction of uncertainty is necessary for optics manufacturers and also for traceability for manufacturers of metrology equipment. To overcome the present limits of measurement systems, the scope of the project was to investigate and compare measuring instruments based on very different physical principles and realised in very different setups. From these comparisons, errors of particular measuring systems could be identified and corrected, leading to a reduction in measurement uncertainty.

A prominent physical technique in optics measurement is interferometry and it is often applied to flatness and sphericity measurements. In these applications, light travels from the interferometer to the surface under test and back again on a common path. Measuring and analysing the surface form accurately is relatively straightforward for flat surfaces and spherical forms. For aspheres and free-from components it is more complicated. The task of developing, applying and analysing such an asphere interferometer with the full knowledge of all hard- and software components was therefore an objective within this project.

The specific scientific and technical objective for the optical imaging metrology for curved surfaces was:

- To realise a sub-aperture tilted-wave interferometer for absolute form measurement of aspheres and freeform surfaces (diameter up to 200 mm), with uncertainties of a few 10 nm, and to produce the capability to measure specimens with maximum slope angles of 10° and a lateral resolution down to 10 µm.

Tactile and optical single point metrology for curved surfaces

In addition to interferometry, various single point scanning techniques are used as an alternative to assess the form of optical components at NMIs and in industry. They range from different realisations of the highest accuracy tactile CMMs to optical point sensors scanned by linear stages, or even a highest accuracy rotary stage. Full field interferometry and scanning form metrology have different strengths and weaknesses, but do complement each other. For example by full field interferometry, the whole surface is measured with low lateral resolution, while for tactile scanning only the scan lines will be assessed, but along these lines the lateral resolution can be high. The different techniques can yield different results and comparisons between them can provide information about the sources of errors. For example dust particles have little influence on full field interferometric measurements, but can have a large effect on tactile measurements.

The specific scientific and technical objectives for the tactile and optical single point metrology for curved surfaces were:

- To demonstrate an improved form measurement accuracy of <50 nm for optical surfaces using tactile and optical single-sensor scanning methods by investigating error influences using virtual CMM modelling (task-dependent for complex form parameters) with local slope angles of at least 50° for tactile- and 15° for optical-measurements.
- To realise tactile measurements for absolute form measurements of optical aspheres and freeform surfaces (diameter 1 mm to 80 mm, maximum slope angles of 90°) with uncertainties of a few 10 nm.

Data analysis

The different metrology principles were to be compared in the project by the use of selected surfaces; and for this, two comparisons were included (one with flat surfaces, a large asphere and a smaller asphere, the other with an asphere selected according to the experiences made in the first comparison).

For improvement of the measuring instruments, virtual modelling and simulation experiments, as close to the real machines as possible, was needed in order to assess the uncertainties of these complex instruments. By doing this, it would be possible to calculate task specific uncertainties to optimise the measurement uncertainty of the instruments.

Form measuring instrumentation generates large volumes of data, in the range of millions of individual data points. While the growth in computational capabilities has developed in the last few years and decades, to have the potential to analyse this data, to reconstruct surface topography, derive topographic parameters and the associated uncertainties, accurate and validated algorithms and software needed to be developed

Additionally, for highly accurate intercomparisons between instruments at the NMI and industrial level, data evaluation procedures are essential to make the quantitative comparison of surface topographies measured with different instruments possible, considering specimen properties (form, waviness) and instrument properties (lateral resolution, data grid, uncertainty).

The specific scientific and technical objectives for the data analysis were:

- To realise algorithms and software to reconstruct surface topography and derive topography parameters and associated uncertainties from a large number (some 10^5 to 10^6) of individual data points, taking into account instrument parameters and uncertainties.
- To realise procedures to make possible quantitative comparison of surface topographies measured with different instruments considering specimen properties (form, waviness) and instrument properties (lateral resolution, data grid, uncertainty).

Reference standards

Reference standard surfaces were also urgently needed to transfer traceability in asphere metrology to different measuring machines and ultimately from NMIs to manufactures and users. The properties of reference surfaces, expressed in the design function, had to be appropriate for the detection of errors of the measuring machines.

The specific scientific and technical objective for the reference standards was:

- To develop standards (including aspheres) applicable for calibration and characterisation of surface form measuring instruments for optical surfaces.

3 Research results

3.1 Flatness metrology

3.1.1 Measurement uncertainty improvements for nearly flat surfaces

High accuracy flatness metrology is possible with small angle deflectometry. In this method, the light from an autocollimator is directed to the surface under test by a pentaprism (or corresponding mirror combination), which always deflects the light by 90° (independent of small tilts of the pentaprism during movement). The prism is then scanned along sections of the surface under test (Figure 1). The uncertainty obtained using this technique is below that reached by other techniques (e.g. Fizeau interferometry).

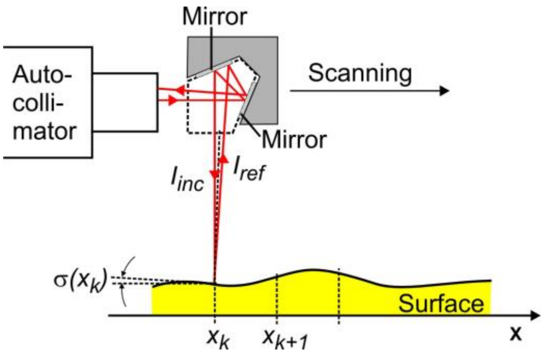

Figure 1: Scanning principle for highest accuracy flatness measurement

Uncertainty estimations for different specimen sizes were performed and for the deflectometer, an uncertainty of 0.25 nm (rms, k=1) resulted for a scan length of 120 mm. For larger scan lengths, this value increased. A comparison of PTB's deflectometer with the deflectometer used at the Helmholtz-Zentrum Berlin supported the uncertainty estimation because the deviations of both systems in a comparison showed a deviation of less than 0.5 nm for a scan length of 500 mm [30].

Thus, the objective to achieve measurement uncertainties of 1 nm (peak-to-valley), or 0.25 nm rms for nearly flat surfaces (peak-to-valley less than 1 µm) was obtained.

3.1.2 A new technique of flat surface measurements, with improved uncertainty, based on capacitive distance-sensors

At CMI, a highly cost-efficient capacitive flatness measuring system was realised [16] (Figure 2). This system enabled SMEs to build up an affordable flatness metrology system with nanometre resolution. The basic principle was that the surface to be measured was scanned in lines and compared to a well-known (calibrated) reference surface. This was realised within the project by a capacitive difference generator scanning both surfaces. For this purpose, the specimens (and the reference) had to be coated, but the costs of the complete system were moderate compared to interferometers.

An uncertainty estimation of the system gave a value of 2.7 nm (k=1). The system was also compared to a deflectometric one and the results agreed well within 10 nm. This confirmed the ability to achieve nanometre accuracy with capacitive distance-sensors in flatness measurements of conductive targets; and the optical flat referencing can also be used for testing high-accuracy motion systems.

Thus, the objective to develop a new technique of flat surface measurements based on capacitive distance-sensors with an uncertainty of 10 nm or better was achieved.

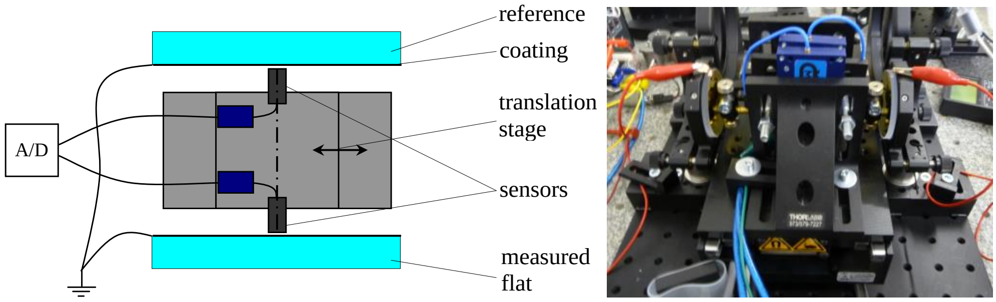

Figure 2: Capacitive measuring system for flat specimen realised in the project

3.1.3 An improvement in the lateral resolution in flatness measurements

A core component of small angle deflectometric flatness measuring systems is the autocollimator. For this reason, the calibration of autocollimators was developed further. The major error influences on the angle response of autocollimators, with respect to changes in their measuring conditions (e.g. path length of the measuring beam) which are used in deflectometric profilometers, were modelled by ray tracing and the results were compared to experimental data. A refereed publication [2] was published and the deflectometric profilometers could be traced back to the primary angle standard WMT 220 of PTB for the SI unit 'radian' through a precise calibration.

Conventional autocollimators use an aperture of several millimetres, but this limits the spatial resolution. For applications where a higher lateral resolution is needed, e.g. for synchrotron mirrors or flatness references, an alternative method was realised within the project. In this method, called Exact Autocollimation Deflectometric Scanning (EADS) [3], the tasks of scanning and angle detection were separated (Figure 3).

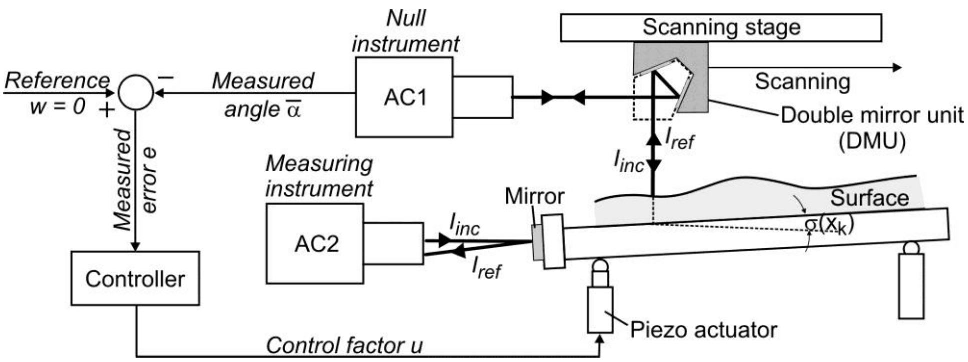

Figure 3: Exact autocollimation deflectometric scanning (EADS) procedure

Within the project, the EADS setup, shown in Figure 3, was practically realised with a small scanning beam. Measuring software was developed in LabVIEW and AC1 (Figure 3) was realised by a small aperture light beam. The aperture, typically placed close to the surface under test, could be reduced to 0.2 mm for a circular aperture and even down to 50 µm for a slit aperture [31]. Thus, the spatial resolution possible in deflectometric flatness measurements was largely increased beyond the state of the art.

Thus, the objective to attain at least a 10-fold improvement (to less than 0.1 mm) in the lateral resolution in flatness measurements was achieved.

3.2 Optical imaging metrology for curved surfaces

Developing, applying and analysing an asphere interferometer with the full knowledge of all hard- and software components was jointly realised in the project by PTB, Mahr and UST. The basic principle of the interferometer is called Tilted-Wave Interferometry because the specimen is illuminated by several wavefronts, which come from different point sources and result in differently tilted wavefronts (Figure 4). This principle was invented by UST. Mahr, as a metrology instrumentation manufacturer, will bring such an instrument to market. Mahr and UST had already cooperated on the development of the interferometer in a previous project, but the developments in this project have a new quality because PTB (NMI) was able to develop full and accurate knowledge of the system and estimate the uncertainty of the measurements. At PTB, a prototype of the TWI was set up (Figure 5) in cooperation with the partners and was optimised for uncertainty reduction. It has also been extended with an environment control system, including temperature sensors inside the instrument. Mahr will also bring a version suitable for industrial customers to the market (fast, optimised for user-friendliness, etc.), with a full understanding of its performance.

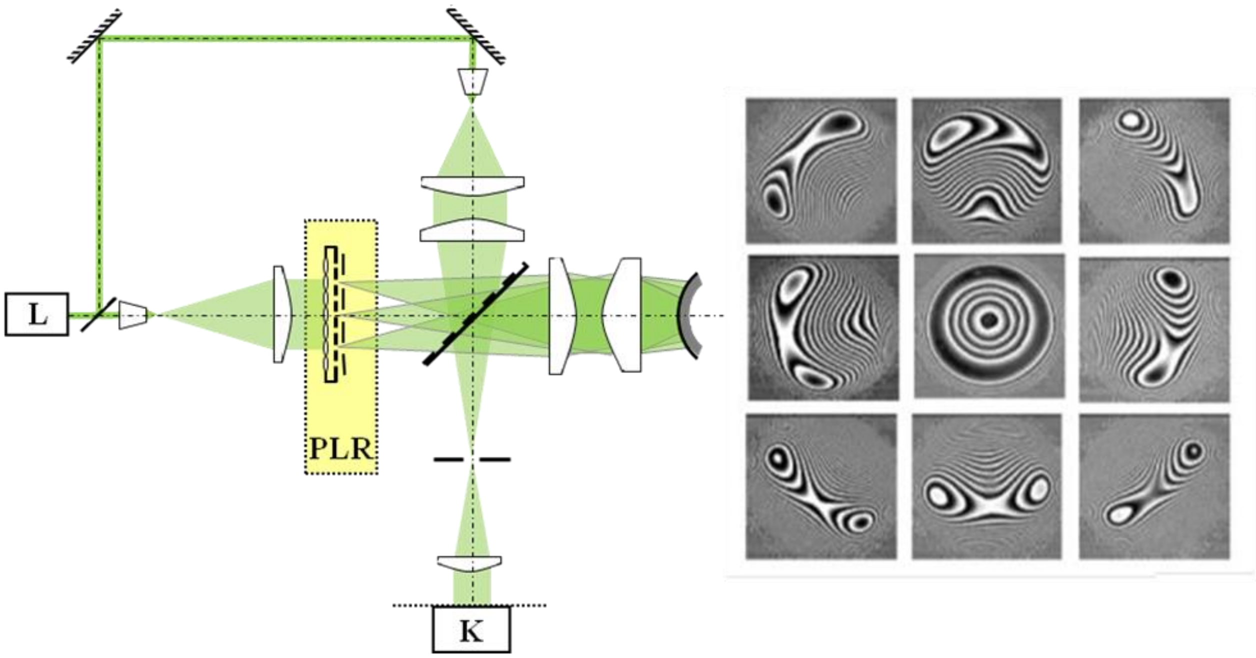

Figure 4: Principle of the TWI and resulting interferograms for different point sources when measuring a specimen

For the instrument at PTB, stitching procedures were developed and analysed to cover a large range of specimens. The uncertainty estimation for the instrument resulted in a value of only several 10 nm.

The objective to realise a sub-aperture tilted-wave interferometer for absolute form measurement of aspheres and freeform surfaces (diameter up to 200 mm), with uncertainties of a few 10 nm, and to produce the capability to measure specimens with maximum slope angles of 10° and a lateral resolution down to 10 µm was achieved, but the developed stitching capability necessary for diameters larger than 45 mm could not be tested experimentally because the movement system of the instrument is still equipped with a preliminary stage system (Figure 5).

Figure 5: The TWI prototype at PTB

3.3 Tactile and optical single point metrology for curved surfaces

As explained in Section 2.2 Rational and Objectives, to overcome the present limits, the scope of the project was to investigate and compare measuring instruments based on very different physical principles and realised in very different setups. The optical imaging interferometer, presented in the previous chapter, and the various single point measuring principles described below complement each other.

3.3.1 Improved form measurement accuracy for optical surfaces using tactile and optical single-sensor scanning methods and virtual CMM modelling

The ultra-high precision single point form measuring machines of the NMIs (LNE, VSL, SMD and METAS) and the industrial partners (TNO and IBSPE)) were improved in accuracy by investigating, and consequently reducing or eliminating, error influences [21].

These machines are equipped with tactile or optical single point scanning probes often with subnanometric resolution. Since their probing errors can be characterised separately from the machine geometric errors, their behaviour was investigated indecently. The results obtained revealed that the probes do not present similar types of behaviours, but are highly repeatable. The information was used to compensate for the probe errors and improve their measuring capabilities. Additionally improvements were made in compensating geometric errors, specifically flatness and straightness errors.

Task specific uncertainty modules, based on numerical modelling, were developed and implemented for the measuring instruments at VSL, METAS and TNO (Figure 6). With this tool, not only the uncertainty for a specific specimen could be estimated, but moreover, an uncertainty could be associated to each parameter of the asphere.

For these measuring machines, using tactile and optical single-sensor scanning respectively, an improvement of the single-point form measurement accuracy to <50 nm for optical surfaces was demonstrated as an example and validated by a comparison.

Thus, the objective to demonstrate an improved form measurement accuracy of <50 nm for optical surfaces using tactile and optical single-sensor scanning methods by investigating error influences using virtual CMM modelling (task-dependent for complex form parameters) with local slope angles of at least 50° for tactile- and 15° for optical-measurements was achieved.

Figure 6: Photo of the Zeiss F25 at VSL, the Isara 400 at IBSPE, the METAS microCMM and the optical NANOMEFOS system

3.3.2 Realisation of tactile measurements for absolute form measurements of optical aspheres and freeform surfaces and improved uncertainties

The investigation of probe surface interactions for tactile probing revealed several critical parameters that influence the onset of plastic deformation: mechanical properties of the materials, mass of the probing system, probing speed and the elastic constant of the suspension. For ultra-precise systems (e.g. Zeiss F25), the static probing force is below the onset of plastic deformation for most of the materials of optical surfaces.

Dynamic forces play a more important role and the requirements were that the mass of the probe, the probing/impact speed and the elastic constant of the suspension should be kept as small as possible. This was within the possibilities of the machines used in the consortium. For soft materials care should be taken to set the probing/impact speed low enough.

At CMI an experimental setup for the measurement of probing deformations with a resolution of 10 nm was designed and assembled enabling further investigation of the mechanical effects.

The objective to realise tactile measurements for absolute form measurements of optical aspheres and freeform surfaces (diameter 1 mm to 80 mm, maximum slope angles of 90°) with uncertainties of a few 10 nm was achieved. Exact numbers for the uncertainty, of course, depended on the specimen characteristics.

3.4 Data analysis

3.4.1 Least square (L_2) algorithms and software to reconstruct surface topography and derive parameters

Different measuring instruments, i.e. the imaging and the single-sensor optical and tactile systems, deliver topographical data that differ due to differences of the lateral resolution and the measurement grid of the systems; and the amount of data can be as high as 10^6 individual data points. Detailed knowledge of the implications of these effects on measured topography data was developed within the project.

Different algorithms (Limited memory-Broyden-Fletcher-Goldfarb-Shanno (L-BFGS), the Levenberg–Marquardt (LM) and one variant of the Iterative Closest Point (ICP)) were tested and validated with simulated data, with added noise and systematic errors. They were assessed based on their capacities to converge relatively fast to achieve a nanometric level of accuracy, to manage a large volume of data and to be robust to the position of the data with respect to the model. L-BFGS showed linear time complexity with respect to the number of points and ran faster than LM and largely faster than ICP. The results were published in [18].

Thus, the objective to realise least square (L_2) algorithms and software to reconstruct surface topography and derive topography parameters and associated uncertainties from a large number of individual data points (some 10^5 to 10^6), taking into account instrument parameters and uncertainties was achieved.

3.4.2 Realisation of procedures to make quantitative comparison of surface topographies measured with different instruments

It was also of major importance for the data analysis software to quantitatively compare data measured with different instruments and thus was necessary to validate the form measuring instruments (Figure 7). When the measurements are performed and the data recorded, the surface form should be evaluated by fitting the appropriate model to the measured data with nanometre accuracy.

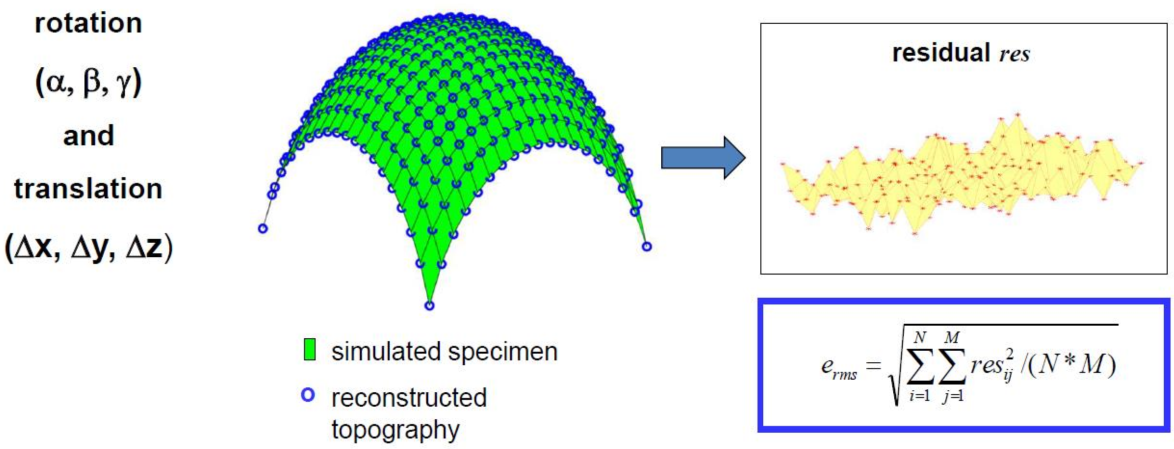

Figure 7: Schematic illustration of the fitting of a model to a measured topography (e is the quality parameter of the fit).

Two comparisons were performed during the lifetime of the project, and revealed differences between the instruments (Figure 8), after which the instruments were then checked and improved. A dominant effect, for example, is localised structures in the case of tactile instruments, which might be due to a pickup of some contamination by the measurement probe.

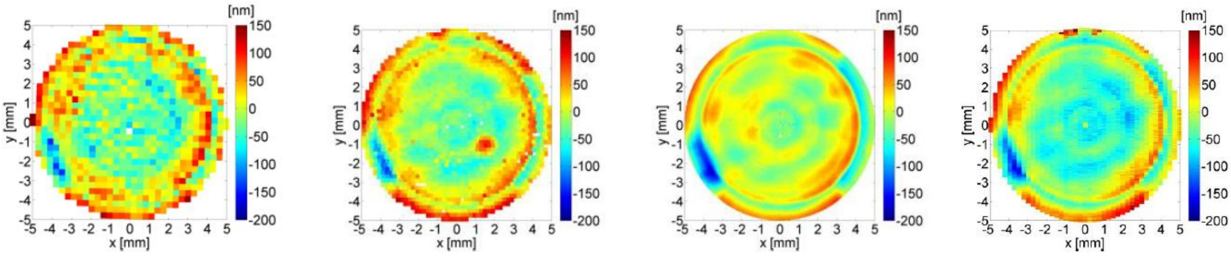

Figure 8: Examples of measurements (basic aspherical function subtracted) of some instruments with differently gridded data

Thus, the objective to realise procedures to make possible quantitative comparison of surface topographies measured with different instruments considering specimen properties (form, waviness) and instrument properties (lateral resolution, data grid, uncertainty) was achieved.

3.5 New artefacts and marker structures

Novel artefacts for transferring traceability in asphere metrology are the final link to industry. Whilst conventional aspheres, as applied in real optical systems, can be used, metrological aspheres, i.e. surfaces that do not necessarily make sense in real optical systems, but reveal properties that are suitable to detect particular errors, were developed within the project (Figures 9 & 10). They are of high importance for the calibration and characterisation of surface form measuring instruments for optical surfaces. A chirp structure helped identify the spatial resolution of the measuring instruments: i) for specimens with plateaus, their height can be measured with conventional interferometers; ii) specimens with additional Zernike contributions on the surface can be used to detect sensitivity to those particular contributions; and iii) multi-sphere specimens can be used to trace back to absolute radius measuring setups.

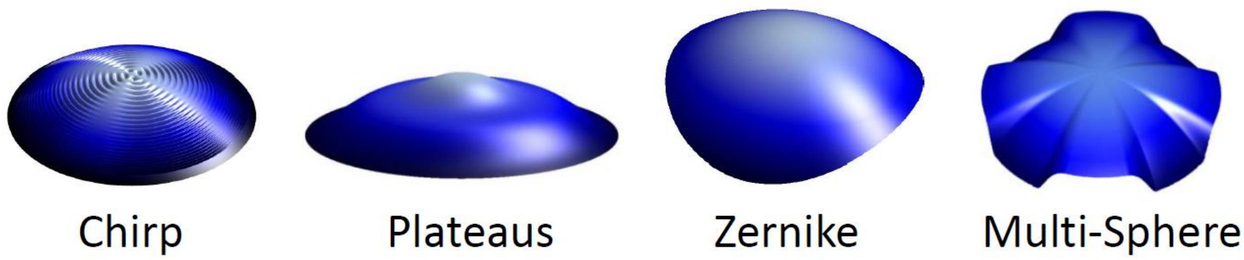

Figure 9: Examples of metrological aspheres with exaggerated additional contributions

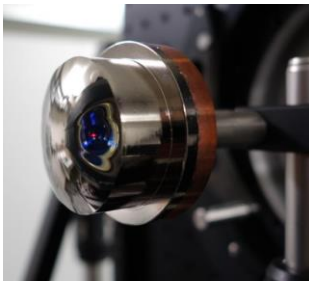

Figure 10: Photo of a multi-radii reference surface with a radius of 40 mm and 39.5 mm

If the form standards are not completely rotationally symmetric, they should have easily detectable structures for lateral positioning. Therefore, marker structures are important and were developed within the project by one of the external researchers associated with the project and TU-IL. The challenging task was to develop, produce and measure marker structures on curved optical surfaces, as shown in Figure 11. These markers enabled the referencing of the coordinate system from measured topography data with high precision.

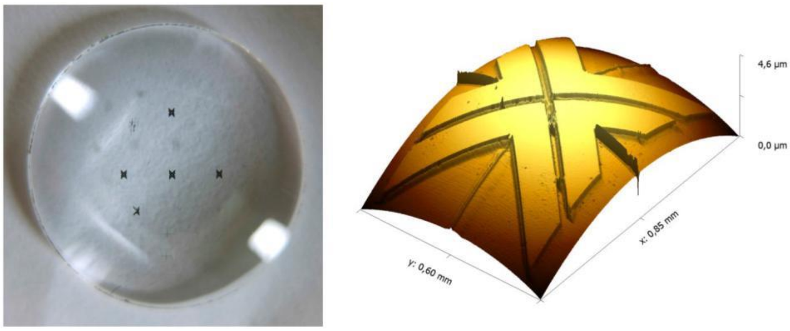

Figure 11: Spherical lens with markers (left) and measurement of a marker structure (right)

Thus, the objective to develop standards (including aspheres) applicable for calibration and characterisation of surface form measuring instruments for optical surfaces was achieved by generating some exemplary surface forms.

4 Actual and potential impact

4.1 Metrology achievements

The metrological capabilities for the form measurement of aspheres (and freeform surfaces) as used in optical systems have been improved significantly:

- Flatness metrology has been improved by further developing small angle deflectometric principles. Regarding uncertainty, the level of 1 nm peak to valley was reached and regarding resolution, a level below 0.1 µm was attained.
- An asphere interferometer was realised at a NMI with the knowledge of the complete system. Thus the uncertainty can now be completely understood and estimated.
- The highest accuracy optical and tactile single point scanning instruments at the NMIs, institutes and in industry have been improved and task specific uncertainty estimations have been realised.
- Some NMIs can now offer traceable calibration services for aspheres with fix or fitting parameters.
- An absolute uncertainty of the form measurement of less than 50 nm has been realised.
- Data analysis appropriate for aspheres was developed; and
- Reference surfaces suitable for reducing uncertainty and marker structures suitable for curved surfaces have been developed.

The results have been disseminated as described below.

4.2 Dissemination activities

4.2.1 Scientific publications

Within the project lifetime about 30 high impact publications in key journals were generated by cooperation between the partners. More are now in preparation and incorporate the significant scientific outputs of the project. A full list is provided in section 6 List of Publications.

4.2.2 Presentations

Presentations were given by the partners at various conferences throughout Europe (Germany, Netherlands, United Kingdom, Spain, France, Croatia, Austria and Hungary). Some examples are:

- German Society for Applied Optics
- IMEKO - International Measurement Confederation
- Topical Meeting - Structured and Freeform Surfaces at NPL
- Conference of the Dutch Society For Precision Engineering
- VDI - German Association of Engineers
- NanoScale conference
- SPIE Optical Metrology
- Fringe - International Workshop on Advanced Optical Imaging and Metrology
- European Society for Precision Engineering
- Synchrotron Radiation Instrumentation conference
- Metrology and Properties of Engineering Surfaces conference

A keynote presentation was given at the European Optical Society conference at the World of Photonics Congress 2013, titled “Testing for Fabrication and Assembly”.

Several presentations were also given outside Europe in the USA (American Society for Precision Engineering Conference, Optical Fabrication Conference), South Africa, and Taiwan/China (Conference on Metrology and Properties of Engineering Surface, Asian Precision Engineering Conference, International Symposium on Optoelectronic Technology and Application).

Also, at highly important international stakeholder meetings, seminars and High Level Expert Meetings of the competence centre for ultra-precise surface finishing CC-UPOB (http://www.upob.de) the status of the project was regularly reported, together with presentations of the results from the partners.

Altogether 62 talks, presentations and posters were presented by the partners.

4.2.3 Exhibitions and trade journal articles

Four trade journal articles were published to make the project known to a broader audience:

- “Flexible and Rapid Measurement - Asphere metrology with the tilted wave interferometer” in Optik & Photonik
- "Höhere Präzision bei der Formmessung von Asphären" in Photonik
- "The national metrology institute of the Netherlands" in Mikoniek
- “Systematische Messfehler bei der Formprüfung mittels Computer-generierter Hologramme“ in Photonik

And the project and its results were presented at several trade shows and company booth presentations at conferences:

- Optatec
- DGaO
- Laser Trade Show
- Dutch Precision Fair
- Micronora, France
- Euspen
- CC UPOB HLEM
- Business day at VSL

4.2.4 Stakeholder Engagement and Standards

All project participants have been in close contact with end users, both within CC UPOB and beyond. Other stakeholders included the synchrotron community, optics manufacturers, metrology instrumentation manufacturers and commercial end users. End user contacts are of particular interest for those project partners that are metrology manufacturers (confidential).

PTB and FhG were active in the DIN working group “measurement techniques for optics” and FhG in the DIN working group “Freeform Optics“. These are mirror committees of the corresponding ISO working groups and thus the link to the international standardisation committees was realised.

4.2.5 Workshops and training

Seven workshops and training modules were performed by the partners during the project, including:

- A workshop on asphere metrology organised together with CC UPOB and attended by almost 80 participants representing the international stakeholder community. A large number of stakeholder companies took part in the connected industry exhibition.
- Training for stakeholders was held at a day for end users, manufacturers and commercial metrology suppliers at VSL.
- Training on asphere metrology was held by UST

Training within the consortium was also performed, including:

- Training on probe-work piece interactions was undertaken by the Research Excellence Grant (REG) researcher at Xpress.
- Training on tilted-wave interferometry and interferometer was carried out by REG(Mahr).
- Training on asphere interferometry was done by REG(FhG).
- Training on results of the REG was performed by Mahr.

4.2.6 Patents

Applications for four patents have been submitted during the lifetime of the project for an asphere calibration surface, two dimensional topography estimation (in cooperation with EMRP JRP SIB08 ‘Traceability of sub-nm length measurements’), optimised TWI calculation and TWI calibration.

4.3 Examples of early impact

An example of an early impact is the contribution of Mahr as the manufacturer of an instrument based on TWI interferometry. The instrument which was manufactured within this project is a first prototype. Mahr performed a market study which found that worldwide over 100 companies exist that produce aspheric lenses made of glass, with a strongly growing trend. There will be a worldwide demand for very many interferometers based on the TWI principle. This interferometer will be the only one that is traced back in cooperation with an NMI and thus it will be a unique instrument on the market with a high importance for all manufacturers of optical surfaces.

FhG has contacted two SME enterprises and comprehensively informed them about the project results for consideration in their production and measurement process.

4.4 Potential impact

A surface that is a modified sphere and still has rotational symmetry is typically denominated as an “asphere”. Even if the rotational symmetry is lost, the surface is described as a “free form surface”, but often “asphere” is also used for both categories. Aspheres are found in almost every optical system from intraocular lenses used to treat cataracts, glasses, cell phone cameras, consumer and high-end cameras, to astronomical and photolithographic systems for computer chip production.

Optics and the optical industry are among Europe’s strengths, but optical surfaces can only be manufactured as well as they can be measured. Thus, while advanced techniques for polishing optics enable removal of material from surfaces at the nanometre level is possible, it is not productive if the deviation to the design form cannot be determined exactly enough; and this is even more challenging for the new aspherical elements with complex forms used in modern optical systems.

European manufactures of high-quality optics and metrology systems urgently need more accurate form measurement, down to a few tens of nanometres, and improved asphere standards traced back to the National Metrology Institutes (NMIs). For the high-accuracy instruments existing at NMIs, in industry and institutes, absolute accuracy estimations, cross checks and comparisons are necessary. Based on the results of this project, the metrology capabilities at NMIs for the form measurement of aspheres (and freeform surfaces) as used in optical systems have been significantly improved.

The possibility of the implementation of marker structures on optical surfaces will enable precise data comparison or data fusion of topography measurements stemming from various technologies. This will lead to the reduction of the uncertainty of measurement systems in general.

During the project, an intense exchange with the participants of the High Level Expert Meetings of the Competence Centre for ultra-precise surface manufacturing (CC-UPOB), which is a worldwide forum for asphere metrology, was established and will also in future be used for generating impact. The first measurement requests on aspherical surfaces from industrial customers are being processed by PTB.

Contact has also been made between project partners and metrology companies and asphere manufacturers across Europe; with one partner so far providing assistance to an optics manufacturer to estimate the uncertainty of measurements of their optical components.

5 Website address and contact details

JRP website address: http://www.ptb.de/emrp/ind10-home.htm

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