Publishable Summary for 15SIB01 FreeFORM
Reference algorithms and metrology on aspherical and freeform lenses

Overview

Aspheric and freeform surfaces are a class of optical elements with diverse and growing applications in photonics. Their use has grown considerably in the last few years because aspheres and freeform surfaces are superior to classical spherical optics but form metrology is a limiting factor. Thus, there was an urgent need to strengthen and harmonise the metrology for optical surfaces.This project focused on the development of i) reference algorithms to analyse form, ii) reference standards and iii) improved facilities for aspherical and freeform optical elements traceable to the SI metre definition with an uncertainty below 30 nm. The outcomes of this project will result in progress in the photonics research and industry sectors.

Need

In Europe, the photonics industry employs more than 2 million people and this is expected to double by 2020. Aspheres and freeform surfaces have diverse and growing applications in imaging systems (e.g. medical, safety, automotive, energy and defence applications), astronomy, lithography and synchrotron techniques. Due to their degrees of freedom, optical systems that use aspheres (e.g. cameras, satellites, medical devices, vision systems, smartphones and synchrotrons) tend to have fewer optical elements, which means lower production costs and weight, and higher imaging quality.

Within the EMRP project IND10, an uncertainty below 100 nm was achieved for aspheres and, in some selected samples, an uncertainty of 50 nm could even be obtained. Nevertheless, for high quality optical surfaces metrology, optics manufacturers and manufacturers of optics metrology instruments or polishing machines required improved metrological capabilities and high-accuracy traceability chains at NMIs/DIs. To guarantee this for asphere and freeform, it was necessary to develop reference least squares (L_2) and Min-Max (L_∞) algorithms enabling the robust analysis of measurements data and to develop suitable reference optical standards made of thermo-invariant materials.

Form metrology for optical aspheres and freeforms below 30 nm uncertainty level was considered a critical need for research institutes and industry. This need to develop accurate form metrology for asphere and freeform optics was strongly emphasised during ongoing discussions conducted at the High Level Expert Meetings and workshops of the Competence Centre for Ultra-Precise Surface Manufacturing (CC UPOB).

Objectives

The overall objective of this project was to build a traceability chain with an uncertainty below the 30 nm level. The specific objectives of this project were to:

1. **Develop robust reference least-squares (L_2) and Min-Max (L_∞) minimisation algorithms** including the generation of reference data (softgauges) and recommendation on the reference mathematical model for aspheres and freeforms optical elements. The algorithms will allow asphere and freeform evaluation to sub-nanometre accuracy.
2. **Develop advanced techniques for data analysis** (alignment/registration techniques, stitching algorithms, data fusion, interpolation methods and improved filtering methods) to support the experiments. To apply the algorithms to measurement datasets provided by the partners. To estimate the uncertainty of the reconstruction results with respect to the Guide to the Expression of Uncertainty in Measurement (GUM) and apply it for the determination of the uncertainty of measurement for the calibration of aspheres and freeform lenses.
3. **Design, manufacture and characterise innovative aspherical and freeform optical reference elements**, made of thermo-invariant materials to develop a reference calibration chain at European NMIs, and to facilitate the transfer of traceability between NMIs, standardisation organizations, research

laboratories and end users. The target uncertainty for the radius measurements of the thermo-invariant asphere and freeform materials is less than 100 nm.

4. **Improve measurement capabilities of NMIs and DIs on aspherical and freeform standards** for high-level areal and single point scanning reference measurement systems, achieving an uncertainty of less than 30 nm. This will involve the improvement of reference metrology instruments ensuring tactile and/or optical measurements such as ultra-high precision single point and optical imaging instruments.
5. **Develop a strategy for the long-term operation of the capability developed** including the take up of the technology and measurement infrastructure developed by the project. Two case studies on the application of the developed reference fitting algorithms and on the improvement of the metrology chain for innovative 3D printed precision freeform optics will be performed.

Progress beyond the state of the art

Robust reference algorithms and softgauges

To realise a reference metrology chain for aspheres and freeforms, robust and deterministic reference algorithms should be developed, which include the calculation uncertainty at the sub-nanometre level. Existing approaches did not offer the determinism required to guarantee a calculation uncertainty at the sub-nanometre level. Furthermore, several reference softgauges, also not existing at the start of the project, were developed to ensure the traceability of the developed algorithms for asphere and freeform analyses at NMIs.

Therefore, in this project an ultra-precise min-max fitting algortihtm with low level of calculation uncertainty was developed and validated on generated sauftgauges. This agorithm is dedicated to the analysis of the form of aspheric and freeform surfaces, described with a complex mathematical model. The developed Hybrid Trust Region (HTR) algorithm consists performs either trust region step, line search step or curve search step according to the specific situation faced at each iteration. This algorithm was validated using a set of reference datasets (softgauges) with previously known peak-to-Valley (*PV)* values, generated in this project. The main idea is to state optimality conditions and then derive datasets for which optimality conditions are automatically met. The developed reference HTR and softgauges are available at LNE.

Techniques for data analysis

To combine measurements made by different instruments, robust algorithms for stitching, interpolation and filtering of outliers will be developed. The investigation of such approaches creates the capability of using ultra-high precision Coordinate Measurement Machines (CMMs) with limited working range for scanning/probing of large asphere and freeform surfaces, which will go further beyond the state-of-the-art.
Thus, the measurement data sets from different sensors are transformed in the same coordinate system by a developed coarse and fine registration methods based on curvature calculation. A Gaussian Process (GP) model was built based on each of the two transformed data sets, followed by the maximum likelihood data fusion. This resulted in better mean and uncertainty than either of the two measurement data sets. Finally, the developed min-max fitting algorithm was used for assessment of the minimum zone. Those algorithms are available at LNE and ENS-Cachan.

Reference standards (aspheres and freeforms)

Innovative reference surfaces from thermo-invariant materials were realised by the partners of the project in close collaboration with the stakeholder committee. Surface forms suitable for new traceability routes were investigated and their designs were optimised for ease of manufacturability. This led to suitable and affordable reference surfaces for different types of aspheres and freeforms that will be useful to enhance the traceability of metrology instrumentation manufacturers and optics manufacturers to below 30 nm, especially for aspherical and freeform surfaces with small ampltiudes (few micrometres). For strongly curved surfaces, the 30 nm level could not yet be proven.

High accuracy reference measurement systems

The measurement uncertainty for form measurements was reduced to about 30 nm for aspheres and freeform surfaces with dimensions between 10 mm and 200 mm and small amplitudes (few micrometres). Measurement uncertainty was improved for the case of optical asphere and freeform surfaces with bigger amplitudes (some hundreds of micrometres). This was achieved by improvements of specific measurement instruments (ISARA400, UA3P, CSI, ultra-high precision multi sensor profilometer, ultra-high precision profilometer, F25, etc.) and statistical methods for the calibration of measurement devices, where appropriate.

Results

Robust reference least squares (L_2) and Min-Max (L_∞) fitting algorithms

Minimum zone, defined as the least value of peak to valley (PV), is widely used to assess form error. Least squares method (L2) is often used to determine Minimum zone but the resulting value is usually overestimated. Then, L2 is replaced by L∞ norm because it gives a more accurate value of the minimum zone (MZ) since it directly minimizes PV. Using L∞ norm results in a non-smooth optimization problem and consequently its resolution becomes more challenging compared to L2.

Min-max fitting methods for accurate metrology of aspheres and freeform, in particular the Hybrid Trust Region algorithm (HTR), were developed at LNE in collaboration with ENS Cachan, FU and GEOMNIA. To assess the performance of the introduced method, this was compared to an available min-max fitting algorithm based on a smoothing technique: exponential penalty function (EPF). The comparison was conducted on reference data and data gathered from measurements of a real optical surfaces. Results show superiority of HTR over EPF in both returned PV values and execution time.
Furthermore, several reference datasets were generated with a non-vertex solution and published on the project website for reuse. Reference data with non-vertex solutions are very important for testing algorithms in dimensional metrology.

Techniques for data analysis

Advanced techniques for data analysis including alignment/registration techniques, stitching algorithms, data fusion, interpolation methods, etc. were developed and validated on reference data.

The measurement data sets from different sensors were transformed in the same coordinate system by coarse and fine registration methods. Then, a Gaussian Process (GP) model was built based on each of the two transformed data sets, followed by the maximum likelihood data fusion. The fused result showed better mean and uncertainty than either of the two measurement data sets. Finally, a fitting algorithm was applied on the fused data for assessment of the minimum zone. It could be seen that registration, data fusion and fitting were the key methods.

These tools were necessary for comparing the measurements on selected aspherical and freeform optical reference elements made from thermo-invariant materials, which were carried out on improved reference instruments. An additional method for data interpolation was also developed which is based on moving least squares with 2D polynomial of degree 2 or 4.

Innovative aspherical and freeform reference elements

Six innovative aspherical and freeform optical reference standards made of thermo-invariant material were designed in this project. Existing manufacturing processes (Single Point Diamond Turning (SPDT) and Magneto-Rheological Finishing (MRF)) were discussed and used depending on the geometrical specifications of each artefact and its material. Three Zerodur material standards were manufactured by Thales Agx in collaboration with LNE and three Invar material standards were manufactured by IPP in collaboration with PTB. For some artefacts, the first prototypes were manufactured from conventional material to test the manufacturing process in advance, while other artefacts could directly be manufactured using thermo-invariant material. Furthermore, one classical asphere has been provided by Asphericon. Measurements were made with different instruments available in the consortium and the final calibration was conducted with improved tactile and optical reference measurement instruments (white light interferometry, radius measurement bench, CMMs and standard interferometry). The appropriate instruments for calibration were chosen depending on the design of the MRS. The thermo-invariant standards are available at the participating NMIs to overcome the current lack of traceable measurement tools and methods for reliability assessment of aspheres and freeforms.

Measurement capabilities of NMIs/DIs on aspherical and freeform standards

There are several ultra-high precision measuring machines at NMIs, universities and industries that allow the measurement of flat surfaces with accuracies at the nanometre level. These instruments are equipped with optical or tactile probes with accuracies at the same level. To reach a low measurement uncertainty asphere and freeform optical surfaces, the traceability of these machines has been investigated and improved. It included the optimisation of the probing systems, the calibration procedures (adaption of physical model parameters and of Zernike representation of wavefronts), the alignment of the artefact along the vertical axis, etc. Furthermore, innovative coatings were developed for optical artefacts to increase the slope range of measurement technologies based on coherent and incoherent optical sensors from 10° to more than 20°.

UNOTT developed software and coating based solutions for increasing the slope range of coherence scanning interferometry and confocal microscopy. A new method has been developed for calibrating the 3D transfer function of coherence scanning interferometry (CSI) and it was demonstrated that ITF (Instrument transfer function) can be estimated from the 3D transfer function by measuring a micro-scale sphere. An innovative coating technique for overcoming the slope limit of an optical measuring instrument has been developed. Using the so-called fluorophore-aided scattering microscopy, we have shown that the surface topography with slope angle of 57.4° can be easily measured using a 0.4 NA (Numerical Aperture) objective (which has a conventional slope limitation of around 20°).

After testing of the preliminary version of the multi sensor freeform measurement device, VTT has built and tested the final version of the device. IPP has equipped the multi-wavelength interferometer linear and rotary optical encoders and developed sub-aperture stitching software package to measure larger surfaces. PTB and USTUTT have adapted simulation tools for tilted-wave interferometer (TWI) measurements and used different test cases for comparing their simulations. They have also simulated effects of surface misalignments and positioning in tilted-wave interferometer measurements to reduce measurement uncertainty. To implement the optimal strategy for decreasing uncertainty due to positioning errors, a white light interferometer was integrated into an experimental setup at USTUTT to measure the absolute distance between the last surface of the objective and the surface under test (during measurement and model calibration). Furthermore, PTB has investigated and tested a new surface reconstruction method and USTUTT has investigated new concepts for the calibration of the TWI model. AIST has used a random ball technique to determine the probe tip diameter of the high accuracy reference measurement system (UA3P) with high accuracy. A measurement uncertainty about ~ 30 nm was reached for optical asphere and freeform surfaces with small amplitude (few micrometres), but further work should be done to be able to characterise optical asphere and freeform surfaces with bigger amplitudes (some hundreds of micrometres) at the same level of uncertainty.

The calibration of the radii of the two-radii freeform as well as of the toroidal surfaces was done at PTB using the new radius measurement bench. For this purpose, the improvement of the radius measurement bench and its validation was performed in close cooperation with USTUTT.

Impact

A stakeholder committee was established which includes five members. The stakeholder committee signed a Non-Disclosure Agreement, and has been invited to attend the progress meeting and to provide assistance and recommendation to the project partners. The members of the stakeholder committee had access to the project website's member area. The stakeholder committee ensured that the results and expertise are relevant to users of asphere and freeform optical elements.

The consortium disseminated knowledge and results on the project's webpage, and through participation at international conferences, input to standardisation committees, organization of workshops and trainings as well as publications in peer reviewed and trade journals. 12 papers were already published in different peer-reviewed journals e.g. Journal of the European Optical Society, Precision Engeneering, Optics Express, Optics Letters; and 4 papers are drafted and submitted. Furthermore, partners have given 42 presentations at national and international conferences/workshops/interest group meetings in the area of freeform optical surfaces including e.g. EUSPEN, ASPEN/ASPE and Macroscale.

Impact on industrial and other user communities

This project aimed to improve the metrological capabilities within the optics area to support the industrial community. The reference least-squares and min-max fitting algorithms, and reference surfaces that have been developed in this project can be directly used by the user communities. These outputs will also improve the capabilities of the metrology machines used in the measurement of aspheres and freeform surfaces. All end users from the photonics industry will be able to harmonise their work on a high level.

The uptake of the results from this project will lead to the production of more accurate asphere and freeform surfaces in industry and research laboratories, which will exhibit higher and more advanced functionality and application. These advancements will enhance the traceability chain for all optical systems, such as consumer imaging systems, industrial imaging systems, lithography optics and many other high-end systems in astronomy and linear accelerators.To reach this aim, the outputs of the project were shared with Soleil (synchrotron), Essilor, DisgitalSurf, Mahr, Mitutoyo, Asphericon, Bruker and Thales-Agx by email and lateral visits. LNE and ENS Cachan developed reference algorithms for min-max fitting and generated several softgauges for the verification of commercial software. Discussions have been held between ENS Cachan and the companies DigitalSurf about the use of reference softgauges. Further discussions were conducted between LNE, PTB and NPL concerning the use of reference sauftgauges. Thales Agx is benefitting from the metrology developed in this project to improve their optics manufacturing process. Mahr collaborated with PTB and USTUTT for the improvement of the TWI technology. PTB measured the two radii artefact made of thermo-invariant material with the TWI and compared the sphericities in the spherical segments to the results of a Fizeau interferometer. These results are important for the traceability of TWI measurements. Furthermore, PTB and USTUTT developed and compared different simulation software for the TWI. UNOTT developed a new method for calibrating the 3D transfer function of coherence scanning interferometry. This technology can be used by Zygo, Alicona, etc. VTT developed a new multi-sensor profilometer for measuring large freeforms, which has already been used to measure samples from customers. Additionally, PTB, IPP and LNE developed metrological reference surfaces (MRS), made of thermo-invariant material, that are available for calibration services. Those MRS were used in themeasurement comparison between the partners of the project.

Furthermore, participants from several industrial companies and research centres attended the training on: optical metrological reference surfaces, accurate measuring aspheres with TWI and radius measurement which was organised by USTUTT and PTB. Results of the project were regularly presented at the High Level Expert Meeting (CC UPOB) which has members from industry and research institutes, as well as at theSpecial Interest Group Meeting: Structured & Freeform Surfaces SFS-EUSPEN annual meeting and the 1st International Workshop On Optical Freeform organised in Paris. About 100 particpants attended the SFS-EUSPEN and more 50 particapants arrented the 1st International Workshop On Optical Freeform.

Impact on the metrology and scientific communities

The significant improvement of the measurement capabilities will have immediate metrological impact through comparison measurements between NMIs. The artefacts used for the comparison have been selected after analysing the technical requirements suitable for the measuring instruments involved in the project. Furthermore, a test procedure, describing the measurement procedure, data acquisition and data handling has been prepared. For the effective comparison of the datasets, the data comparison software was developed. The evaluation methods and results of this round robin included three optical freeform surfaces made from a temperature-stable material, Super Invar. The freeforms had diameters of 40 mm, 50 mm and 100 mm and best-fit radii of 39.75 mm (convex), 40.9 mm (convex) and 423.5 mm (concave). The freeforms were measured by means of different optical (pointwise and areal) instruments as well as a tactile measuring instrument. For comparison, the bilateral pointwise differences between the available measurements were calculated. The root-mean-square values of these differences ranged from 15 nm to 110 nm (neglecting spherical contributions) and provided an insight into the status of typical freeform measurement capabilities for optical surfaces. The results of the inter-laboratory comparison measurements for three metrological reference surfaces have been submitted to a peer-reviewed journal. These international comparison measurements ensure that NMIs and recognised research laboratories benefit from the achieved results by strengthening their scientific knowledge of asphere and freeform metrology and unifying the international metrology methods for such surfaces.

Additionally, two case studies applying the project’s results have been investigated. One case study focused on the application of reference algorithms and reference softgauges and the other case study on 3D printed freeform optics. VTT planned the case study on 3D printed freeform optics with UEF. In this context, the possibilities and limitations that 3D-printing can offer to the manufacturing of freeform optics have been discussed.

The calibration capabilities at the NMI level have been significantly enhanced which will benefit the wider metrological and scientific communities by enabling NMIs and DIs to offer new and enhanced measurement services in asphere and freeform calibration.

A good practice guide was prepared to provide a definition and manufacturing process of reference thermo-invariant standards (aspherical and freeform optical surfaces) made of thermo-invariant materials. These reference standards can be calibrated using ultra-high precision measuring machines (accurate single point or imaging instruments) and the calibration traceability has been carefully established. In this guide, the calibration procedure of innovative reference thermo-invariant asphere as well as freeform optical standards, also called Metrological Reference Surfaces (MRS) is described.

At PTB, the new uncertainty value of the radius measurement for spherical sections has been reported to the quality manager and will be included in the next update of the measurement and calibration capabilities. At LNE, sauftgauges for freeform surface were uploaded onto the website of the project and they can be used for testing min-max fiting algorithms. Further sauftgagues for aspheres and freeforms can be generated for specific uses.

A patent application on "high accuracy radius measurement" was also submitted by PTB, which covers a radius uncertainty of 100 nm for typical (full aperture) spherical sections.

Impact on relevant standards

The consortium was active in International and European metrology activities. Partners participated at the TC-Length annual meetings held at VSL in October 2016 and at VTT-MIKES in October 2017. These partners have participated and presented the progress of the project in the TC-Length annual meeting that held at LNE in October 2018.

Several partners were involved in different standards organisations: ISO TC 172 "Optics and photonics": DIN NA 027-01-02 "Fachbereich Optik" and ISO TC 213 "Dimensional and geometrical product specifications and verification". ENS-Cachan actively participated at the French Experts meeting for ISO TC 213 (UNM 08) and at the ISO TC 213 activities (as committee member of WG 18 and WG 12). Furthermore, ENS-Cachan participated at the 42nd international meeting session of ISO/TC 213 and contributed to a new draft for ISO 18183-1: Geometrical product specifications (GPS) - Partitioning - Part1: Overview and Basic concepts. This draft will include the curvature-based approaches for fitting, registration and data fusion that will be developed in the project as the basis of new methods and algorithms for partitioning. LNE also participated in the French ISO TC 213 activities (as committee member of WG 15 and WG 16). PTB participated at the DIN committee NA 027-01 FB "Fachbereich Optik" in June 2017 which contributed to ISO TC 172 SC1.

Longer-term economic, social and environmental impacts

The manufacture of optical surfaces is an iterative process, based on measurements of the current shape of the specimen and subsequent shape correction. The improved measurement capabilities at NMIs/DIs allowed industries to achieve a more accurate measurement of the current shape of optical surfaces. As a direct consequence, the required number of iteration steps can be minimised, leading to a drastically reduced production time and cost per individual asphere and freeform optics.

The outcomes of this project led to improve the reliability, efficiency and speed of asphere and freeform surface production through the improved measurement and traceability capabilities of manufacturers. These improvements avoided waste parts and optimize the number of iteration steps needed for the manufacturing, leading to a reduced environmental impact. By using aspheres and freeform optics which achieve similar or usually better results than multiple large spherical optics, the consumption of material and energy is drastically reduced. Weight and size of optical systems is reduced too. Further improvement of optical components supported the miniaturization of optical systems and help to protect the environment, saving resources and energy.

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Internal Funded Partners: 1- LNE, France 2- CMI, Czech Republic 3- PTB, Germany 4- SMD, Belgium 5- TUBITAK, Turkey 6- VTT, Finland	External Funded Partners: 7- ENS-Cachan, France 8- IPP, Czech Republic 9- UEF, Finland 10- UNOTT, United Kingdom 11- USTUTT, Germany	Unfunded Partners: 12- AIST, Japan 13- FU, China 14- GEOMNIA, France 15- IBSPE, The Netherlands 16- POLYU, Hong Kong 17- Thales Agx, France 18- TRIOPTICS, Germany 19- UnB, Brazil
RMGs: -		