Deflectometry based Surface Analyzer

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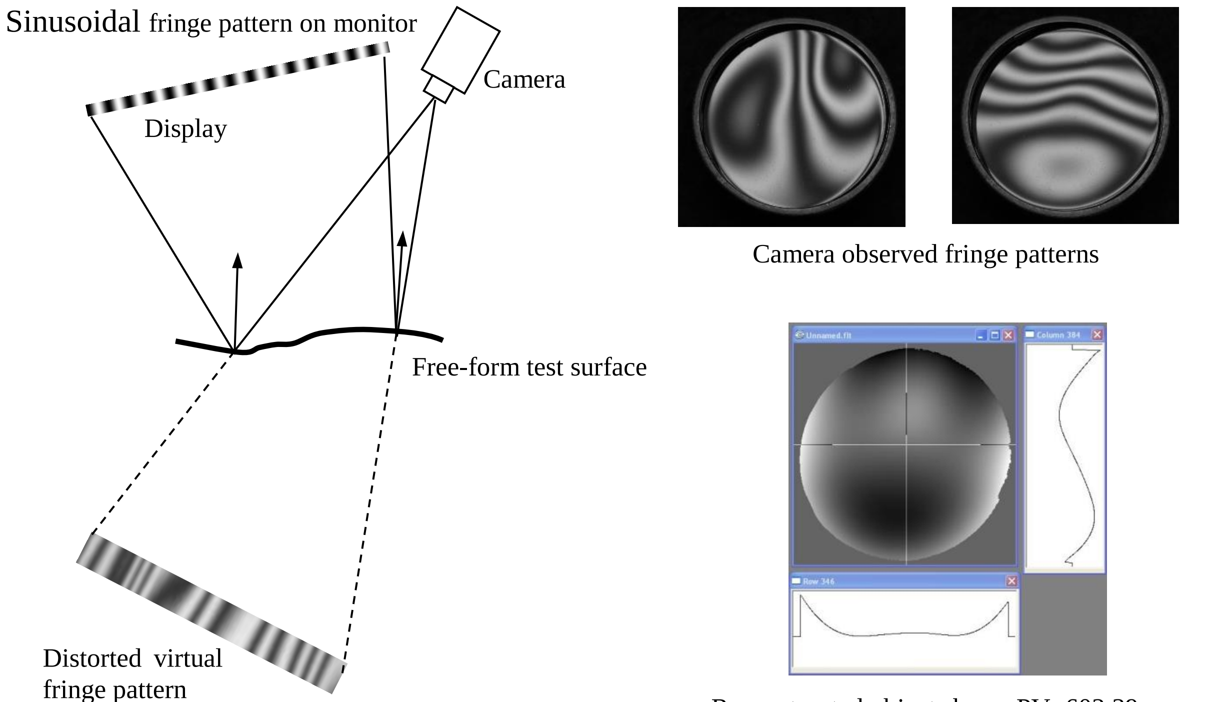
Content

1 Introduction

The deflectometry system, or sometimes called as fringe reflection technique (FRT), is a highly sensitive, incoherent optical full-field gradient measurement technique for free-form specular surfaces of any material, such as aspherical lenses, polished metal & glass mirrors, automotive and aircraft lacquers, liquid surface, etc. It utilises the deformation and displacement of a regular fringe pattern after reflection from a test surface to infer the surface slopes and reconstructs the 3D shape of the object.



Camera observed fringe patterns

Reconstructed object shape. PV~602.39µm

Figure 1: Measurement Principle.

As shown in Figure 1, the deflectometry measuring system consists of a TFT display and a high resolution CCD camera. A straight sinusoidal fringe pattern generated by the computer is displayed on the monitor during measurement, and the camera acquires the fringe image reflected by the surface of the measured object. Any irregularities on the object give rise to a distortion of the observed fringes, which can be evaluated quantitatively with very low uncertainty by virtue of the phase-shifting technique.

2 Advantage of the Technique

Ordinary optical non-contact three-dimensional measurement techniques, such as fringe projection, laser triangulation, etc., are ineffective for smooth surfaces. The deflectometry makes full use of the reflection of light by the measured object, which not only makes it possible to measure smooth surfaces, but also improves the measurement accuracy to the level of coherent optical measurements.
Deflectometry is a surprisingly simple & reliable technique for white-light fringe analysis that is evolving from a defect-testing technique towards being useful in industrial metrology applications, including those as yet restricted to the domain of interferometry. The low costed deflectometry system has the similar measurement accuracy to the interferometer, but only uses an incoherent light source. The system does not require sophisticated mechanical scanning devices (such as scanning white light interferometer), it can be directly used to measure irregular free-form surfaces compared to general interferometers that can only

measure planar and spherical objects. Thanks to VEW's newly developed camera and system calibration techniques, high-precision curvature and three-dimensional coordinate distribution can be obtained. Compared with other ultra-high-accuracy tactile 3D coordinate measuring instruments, deflectometry has the advantages of high speed and large data volume, and can acquire millions of data points in a short time.

3 Measurement Range, Resolution and Accuracy

By using different geometric parameters and hardware configurations, the lateral measurement range (coordinates X&Y) of the system covers from a few millimeters to about 500 millimeters depending on the radius of curvature (ROC) of the measured object. A plane surface being measured can not be larger than half of the screen size, but no such constraint exists in measuring of a concave surface. On the other hand, the measurable range of a convex surface will be much reduced when the ROC increasing. The measurement range varies with the curvature of the surface of the object. For surfaces with too large overall curvature, such as small diameter (<10mm) spheres, the camera will not see streaks on the display, which will reduce the measurement range.

The X&Y coordinates resolution is mainly dependent on the pixel number and the opening angle of the camera. For a general application, the lateral coordinate’s resolution is about 0.1mm.

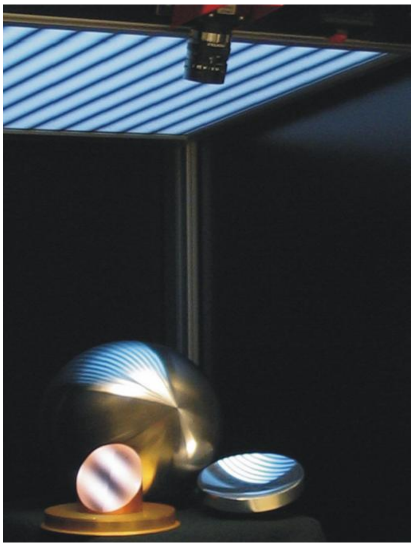


Figure 2: Measurement range of the deflectometry. The effective measurement range is where the fringe can be observed on the surface of the object. Therefore, the measurement range is different on the surface with different curvature (i.e. bending degree).

In the more interesting height direction (coordinate Z), another advantage of the deflectometry comes to bear here: its very high dynamic range. Whilst the height range of the surface amounts to almost ~10 mm, it is evident that surface imperfections of several nanometres can easily be resolved.

In the past, the industry’s interest has been focussed mainly on the detection of defects and ripples because of its nm range sensitivity. On the other hand, attempts to reconstruct the absolute surface shape from the gradient map have been plagued by systematic errors that accumulate to unacceptable uncertainties during data integration. Recently, thanks to improved measurement and evaluation techniques, the state of the art in absolute surface measurement has reached a level of maturity that allows its practical usage in precision optical manufacturing and qualification systems.

With the help of our optimized shape integration algorithm and system calibration technique, the accuracy of absolute shape measurement can archive to 50 nm in the 100x100 mm horizontal range for some surfaces, e.g. flat or trough mirrors. For an irregular free-form surface, the absolute measurement accuracy is typically better as 1 µm. Since the highest accuracy is not always required, it is a viable strategy to select the simplest approach that will comply with the specifications.

4 Requirements of Measuring Environment

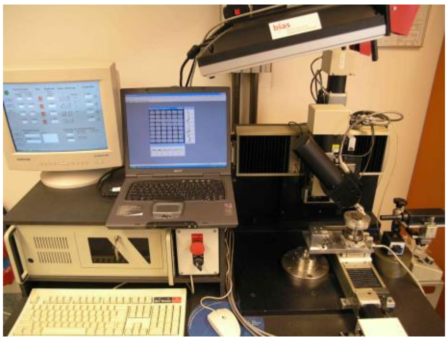
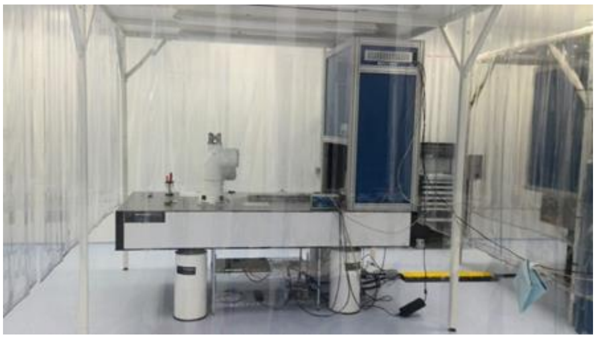
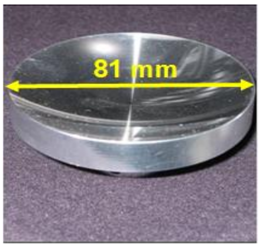



Figure 3: On-line deflectometry measurement systems. Left: mounted at polishing machine in open space. Right: mounted in a clean room for X-ray telescope mirror manufacture.

The deflectometry is a non-coherent optical measurement technique and has a low sensitivity to external mechanical vibration and other factors. It is robust enough to be mounted on the processing site, enabling an on-line measurement. A constant dark environment is generally required to facilitate the camera to obtain more accurate fringe images. However, there is no special requirement for a closed measurement space.

5 Requirements of Object Surface

The surface of the measured object must have a certain specular reflection characteristics. The resolution and precision of the measurement decrease with the decrease of the specular reflectance, and the measurement time also needs to be extended accordingly.



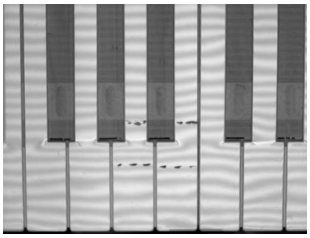
Diamond turned surface

Large aspherical mirror

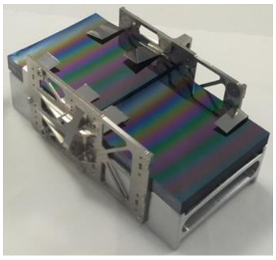
Glass or plastic lens

Liquid surface

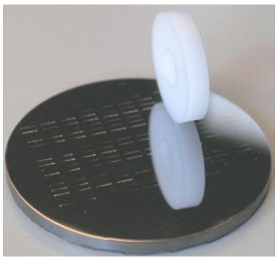
Measurable surface …



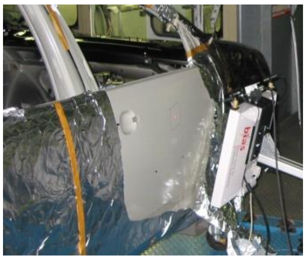
Wood & plastic surface



X-Ray mirror



Precision machining surface



Painted surface

Figure 4: Requirements of object surface.

6 Comparison with Interferometers & Tactile Profiler

We have compared a test object by using a VEW deflectometry system, a Zygo interferometer, and a Tencor P15 high-accuracy contact type coordinate measuring machine. Here the object is an approximately planar metal mirror (Al + MgF2).

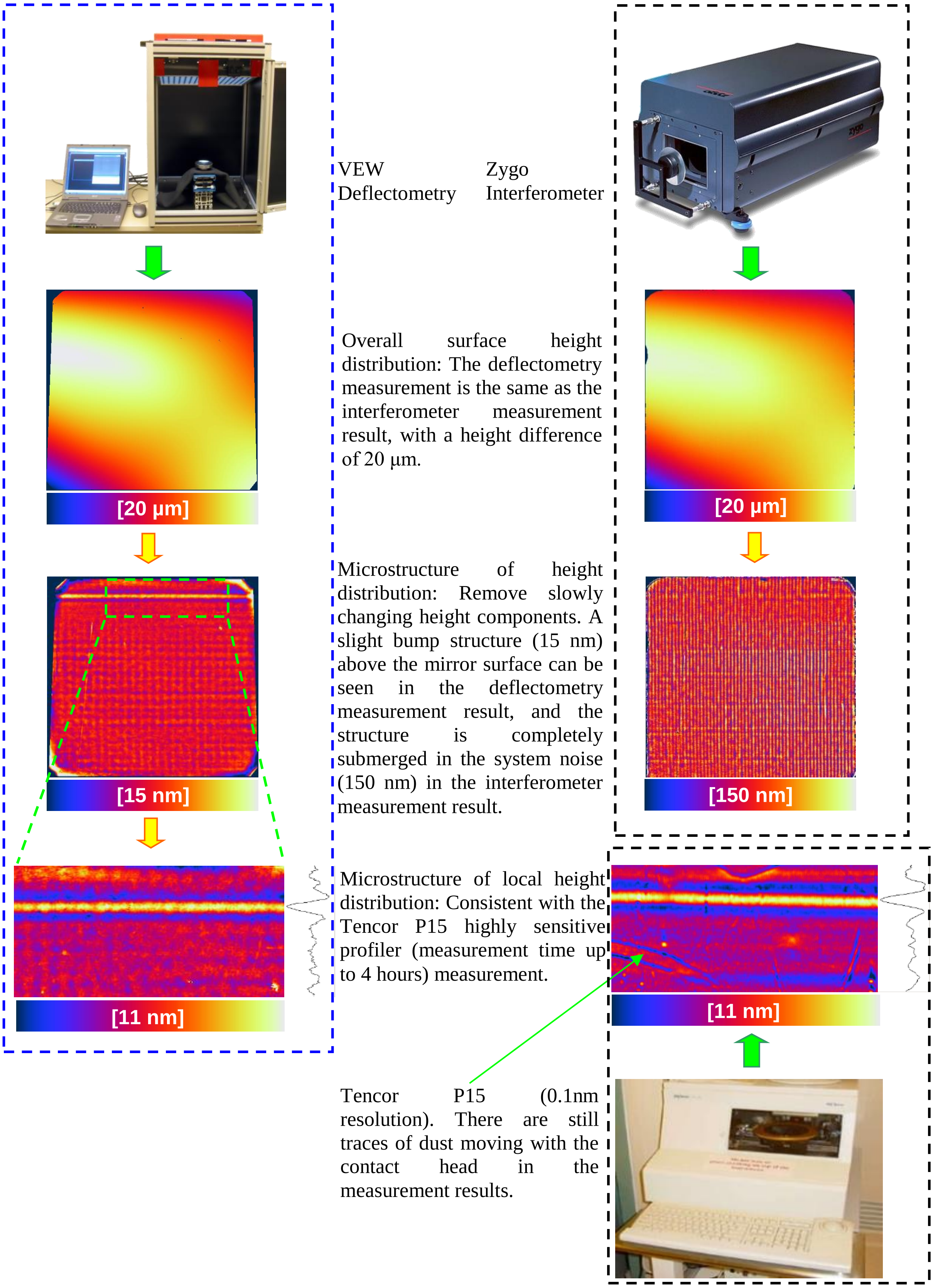


Figure 5: Comparison with Interferometers and highly sensitive profiler.

7 Developed Measurement Systems

In order to obtain the best measurement results, we always design the deflectometry system for the user's requirements. For objects with different size and curvature, the suitable measurement setup may be different. Here we only show some examples.

7.1. Desk-top type

Figure 6: Desk-top type A.

Main features of desk-top type A:

- Field of view: 110×80 mm;
- Closed measurement space;
- Two laser pointers for object positioning;
- Controlled with external computer.

Figure 7: Desk-top type B.

Main features of desk-top type B:

- Field of view: 110×80 mm;
- Closed measurement space with rotary sliding door;
- Two laser pointers for object positioning;
- Build-in control monitor.

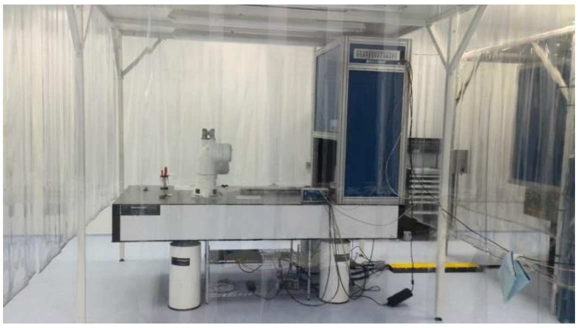


Figure 8: Desk-top type C. It is mounted in a clean room for X-ray telescope mirror manufacture.

Main features of desk-top type C:

- Field of view: 135×115 mm;
- Half-closed measurement space for object moving by robot;
- High-resolution medicine grey-value display,
- High precision confocal sensor for object positioning;
- Using high precision hexapod for object movement;
- Controlled with external computer.

7.2. Mobile type

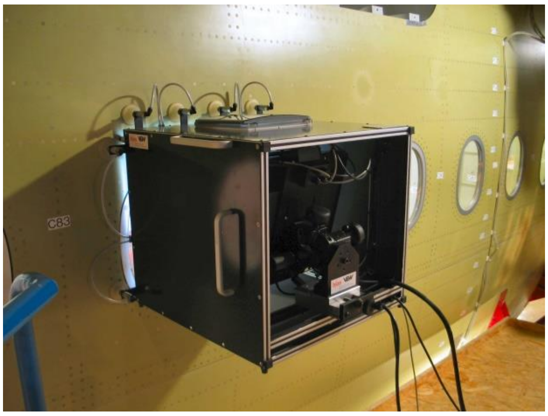


Figure 9: Mobile type A. It can be fixed onto the testing object, e.g. aircraft surface, by vacuum.

Main features of mobile type A:

- Field of view: 120×100 mm;
- Closed measurement space;
- Two laser pointers for object positioning;
- Vacuum adsorption system;
- Controlled with external computer.

Figure 10: Mobile type B. It can be fixed onto the testing surface by vacuum.

Main features of mobile type B:

- Field of view: 80×60 mm;
- Suitable for planar surface measurement: e.g. lacquer coating;
- Measure defect, scratch, orange peel, waviness;
- Closed measurement space;
- Vacuum adsorption system;
- Build-in computer and control monitor.

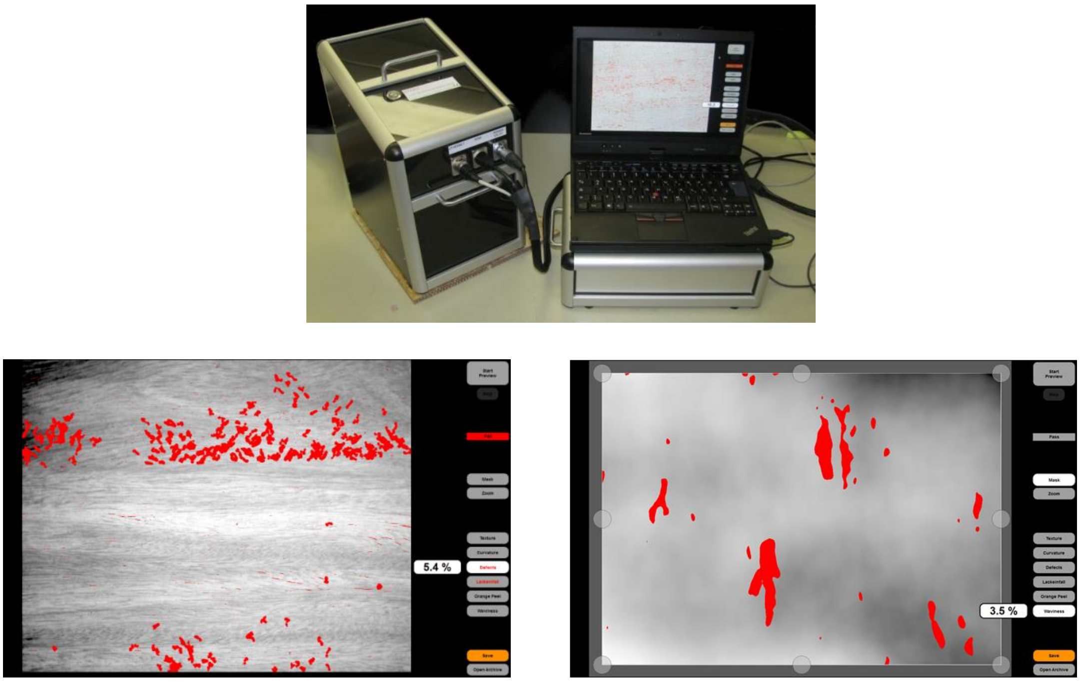


Figure 11: Mobile type C. It can be fixed onto the testing surface by vacuum.

Main features of mobile type C:

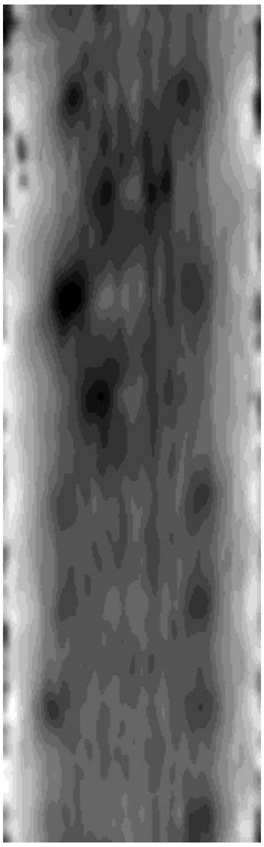
- Field of view: 75×55 mm;
- Suitable for planar surface measurement: e.g. lacquer coating;
- Measure defect, scratch, orange peel, waviness;
- Closed measurement space;
- Vacuum adsorption system;
- Controlled with external computer.

7.3. Floor-standing type

Measurement site

Solar condenser

Height map: an overall parabolic shape.



Microstructure oft he height map: irregular waviness.

Figure 12: Floor-standing type A. The system has been used to measure solar condensers.

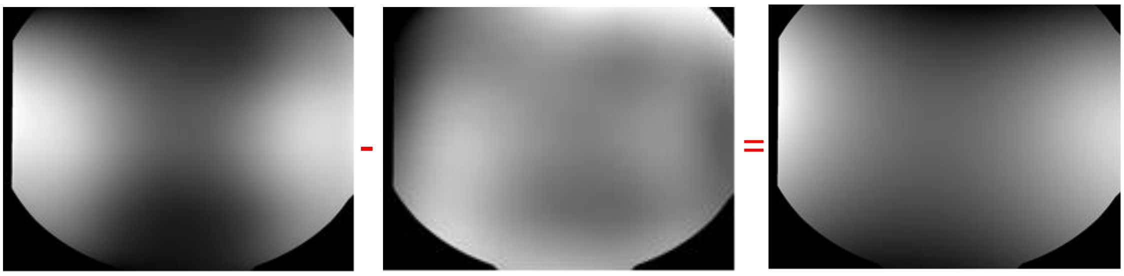
Main features of floor-standing type A:

- Half-closed measurement space;
- Two laser pointers for object positioning;
- Controlled with external computer.

8 Application Examples

8.1. Measurement of flat mirror (glass)

a) Object of the flat mirror. ∅ = 6 inch



b) Reconstructed shape which measured with vacuum pressure. PV~ 183nm

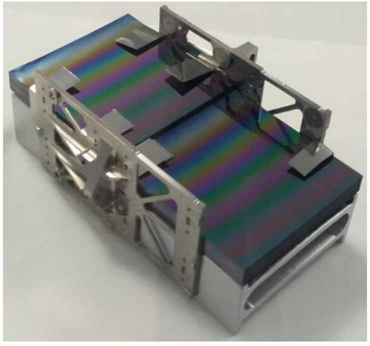
c) Reconstructed shape which measured without vacuum pressure, PV~ 140nm

d) = b) – c). PV~ 267nm

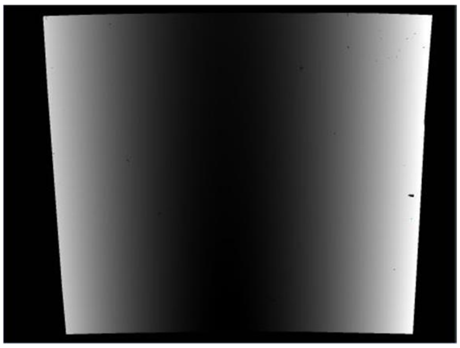
Figure 13: Measurement of flat glass mirror with the desk-top type C.

In this application, we chose a thick plane mirror (∅ = 6 inch) as the measured object. In order to keep the object stable during the measurement, we apply a negative vacuum pressure behind the object. From the measurement results, it is found that although the plane mirror is thick (~28mm) the negative pressure behind it significantly changes the surface topography of the plane mirror. Such deformations (more than 200nm) will have a big impact in the manufacture of precision optical components.

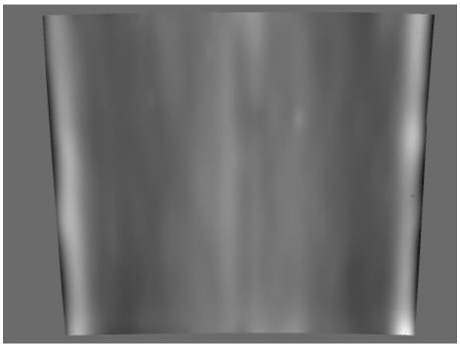
8.2. Measurement of X-ray telescope mirror



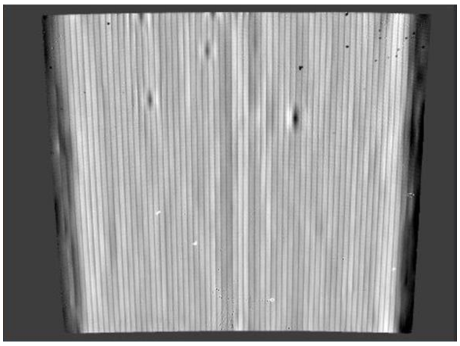
a) Object of X-ray mirror



b) Reconstructed shape. PV~830.1µm



c) Remaining microstructure of shape after best cone fit. PV~8.166 nm

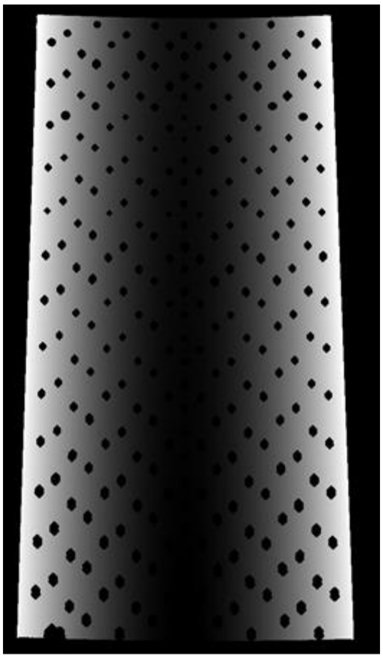


d) Averaged curvature map of the surface

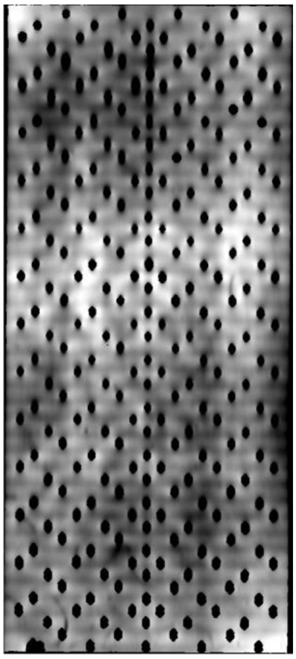
Figure 14: Measurement of X-ray telescope mirror with the desk-top type C.

In this application, we have measured an X-ray mirror which has an off-axis conical surface. The reconstructed shape is shown in Figure 14b). After a best cone fitting, the remaining shape is shown in Figure 14c). It can be seen in the figure that there is a pronounced bulge on the left and right sides of the mirror and some irregular stripe structure are visible in the middle. Differentiating the measured gradient data we can get the curvature distribution of the mirror surface, see 14d). Here we can clearly see the grating-like pattern caused by the special designed structures on the backside of the mirror. Some small spot defects can also be clearly observed both in Figure 14c) and 14d).

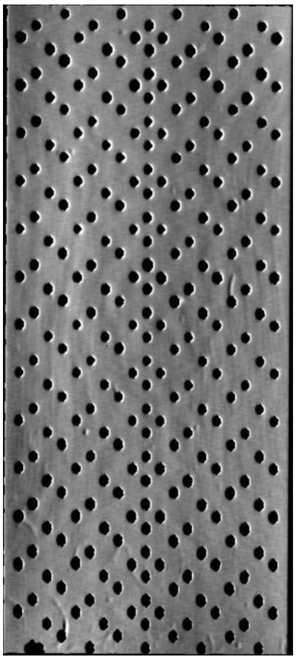
8.3. Measurement of mandrel (metal)



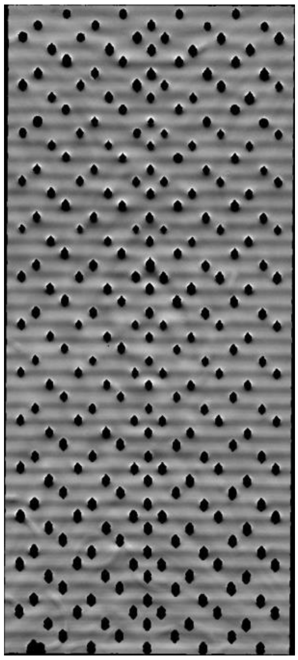
a) Reconstructed shape. PV~1051 µm



b) Remaining microstructure of shape after best cone fit. PV~114 nm, RMS ~15.72 nm



c) Remaining gradient map in X direction after 2nd polynomial fitting. PV~180 µRad, RMS ~34.18µRad



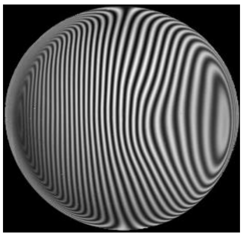
d) Remaining gradient map in Y direction after 2nd polynomial fitting. PV~80 µRad, RMS ~8.37µRad

Figure 15: Measurement of metal mandrel with the desk-top type C.

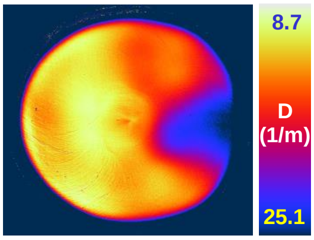
The mandrel is a tool for the X-ray telescope mirror manufacture. It has an off-axis conical surface. The measurement results show that the mandrel is indeed a conical surface. At one end the radius of curvature (ROC) is 276.877mm, at the other end the ROC is 277.568mm. We also found regular ripples on the surface, as shown in Figure 15b). The PV range of these ripple structures is very small (~114nm) and mainly distributed in the direction of Y. The gradient maps in X & Y clearly show this effect. These structures maybe produced during the manufacture of the mandrel.

8.4. Measurement of free-form eye-glass lenses

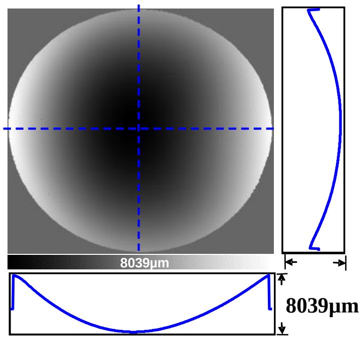
Eye-glass object



Observed fringe

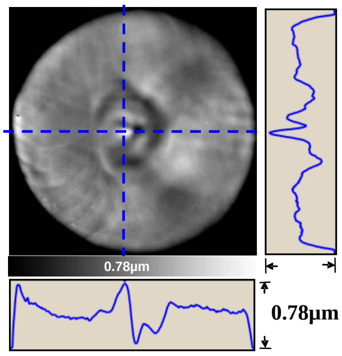


Measured curvature

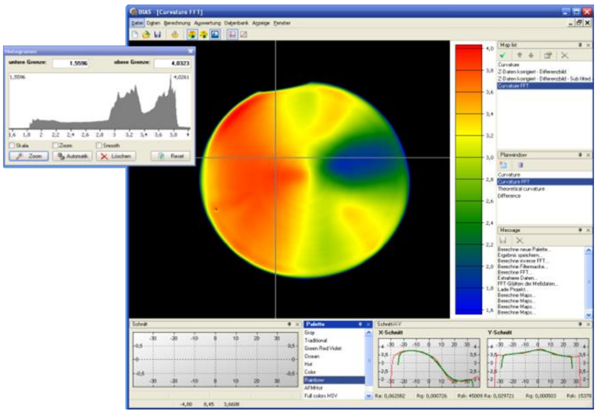


Measured shape

Remove the low-frequency structure



Micro-structure of shape

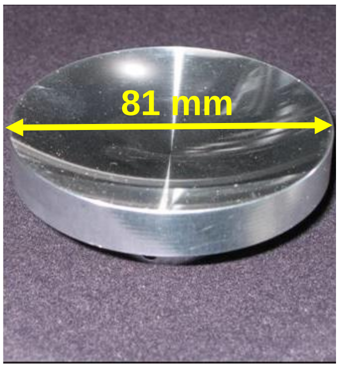


The output data format could be binary, ASCII, STL, etc. User can do the data analysis by their own software.

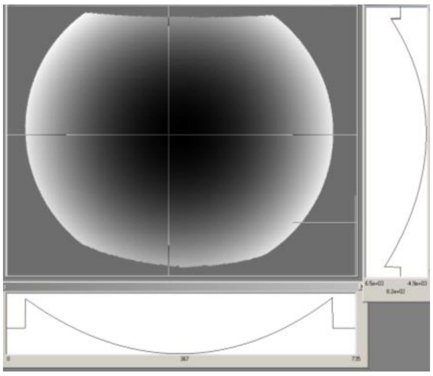
Figure 16: Measurement of free-form eye-glass lens with the desk-top type B.

In the manufacturing process of the eye-glass lens, people must accurately control the surface topography to obtain the designed diopter and other requirements. In Figure 16, the absolute shape and the microstructures of top-surface of the eye-glass are exactly measured. From the output curvature map, we found that the lens' diopter varies gradually in different place. In the center part of the surface there are some arc structures which should be the remaining trace of the surface polishing.

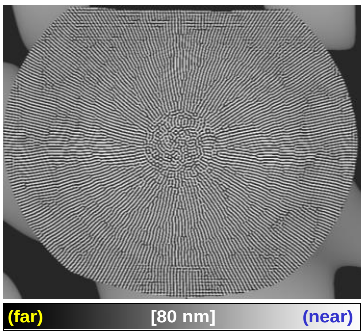
8.5. Spherical lens mold (Aluminum, diamond turned)



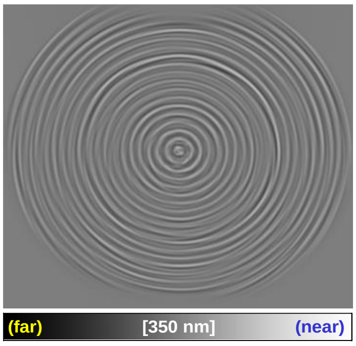
a) Mold object



b) Height map (PV~ 11.8mm)



c) Microstructure in tangential direction



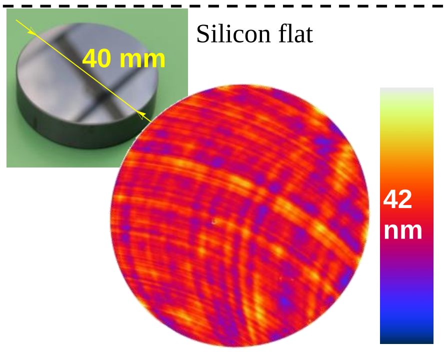
d) Microstructure in radial direction

Figure 17: Measurement of a diamond turned spherical lens mold with the desk-top type A.

In this application we measured a diamond turned spherical lens mold. The dynamic range of the object in the height direction is very large (nearly 12mm), as shown in Figure 17b). After removing the low-frequency shape component, we found a lot of interesting structures in both tangential and radial directions, as shown in Figure 17c) and 17d), respectively. The chatter information from the high speed milling is presented in the microstructure in the tangential directions, while in the radial direction the circled tool traces are clearly visible.

8.6. Measurement of milled / polished surface

Silicon flat



Height map

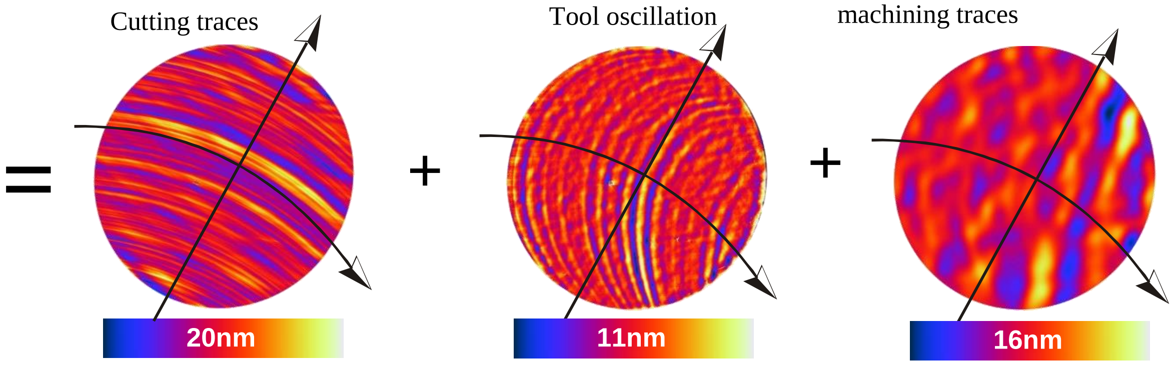
Diamond milled silicon flat mirror

The surface height map can be separated into different compositions: 1) Cutting trace by guidance vibration, 2) Tool oscillation by cutting force change at border entrance, 3) Remaining non-systematic machining traces

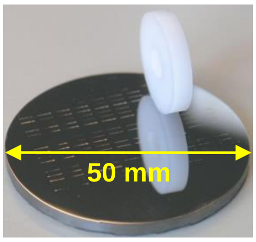
Cutting traces

Tool oscillation

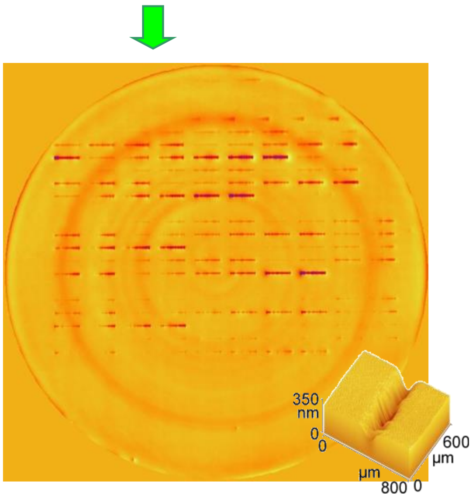
Remaining non-systematic machining traces



Polishing wear

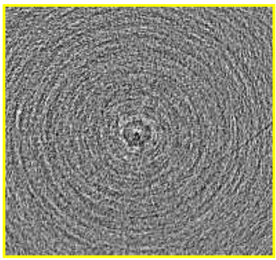


Object and polishing tool

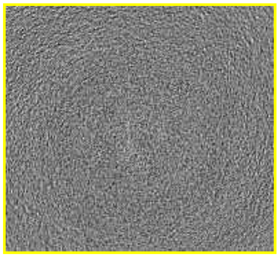


Measure the shape of polished surface and the volume of cut-out footprint. It is consistent with the WLI measurement.

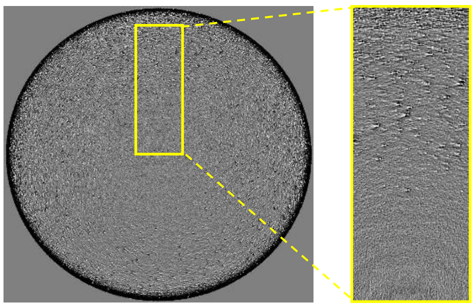
Eye-glass polishing



Curvature map after a short-time polishing.



Curvature map after a long-time polishing.



The number of holes increases towards larger radii where the cutting speed is too high.

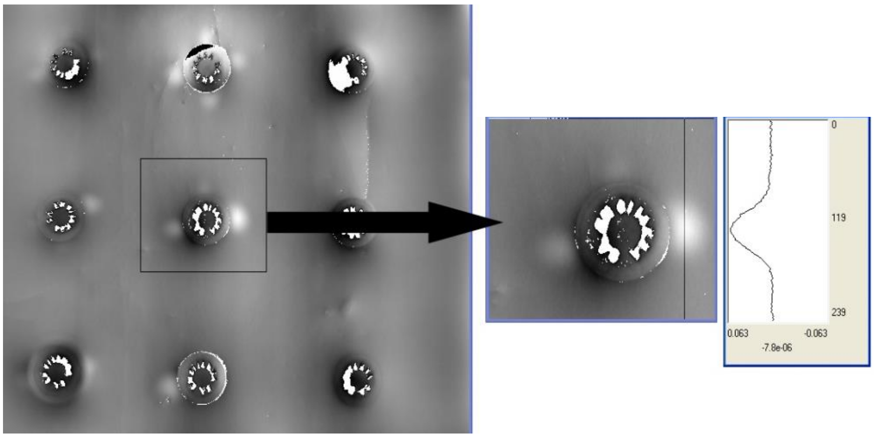
Figure 18: Measurement of milled / polished surface.

8.7. Measurement of rivet holes on aircraft surface


Surface cleaning


Adjust instrument position


Measuring



This is the result of a measurement of the deformation around the rivet hole of an aircraft. Asymmetrical deformations can be seen in some places, with a range of about 50 µm.

Figure 19: Measurement of aircraft surface with the mobile type A.

The aircraft manufacturing company had already used the deflectometry system to measure the deformation around the rivet hole. Instead of directly measuring the internal flaws of the rivets, the system judges the fit of the rivets and the aircraft materials through the deformation around the rivet holes in the outer surface of the aircraft. The deformation around the rivet hole should be uniform in the normal situation. This is measured at the aircraft fatigue test site. By comparing measurements from every few months, the safety of rivets and materials can be evaluated.

8.8. Lacquer surface – frequency separation

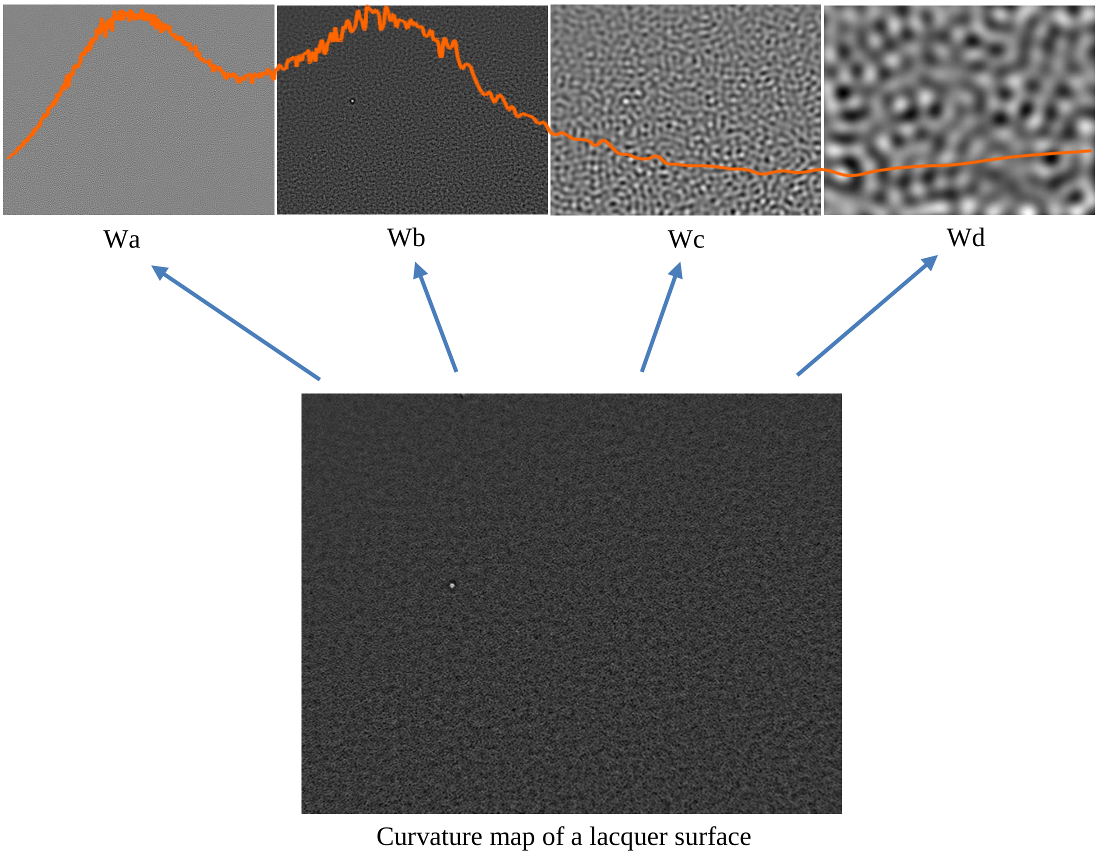


Figure 20: Measurement of lacquer surface.

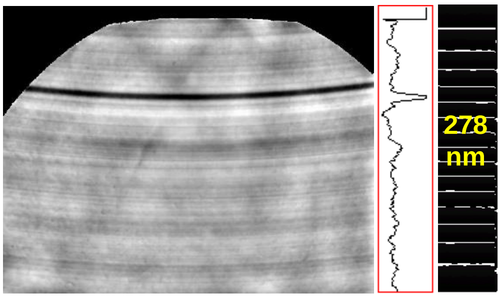
The lacquer surfaces, e.g. automobile, painted wood, etc., are very suited for quality control using deflectometry. The reflective properties of the surface are largely determined by the microstructure of the shape. Normally the microstructure will be separated into different scale ranges, for example, Wa (0.1~0.3mm), Wb (0.3~1.0mm), Wc (1.0~3.0mm), Wd (3.0~10.0mm), etc. The amplitude of height distribution in these ranges will indicate the reflective characters of the surface. Currently, the industry generally adopts one-dimensional photoelectric scanners to measure these parameters. By using deflectometry system, we get a two-dimensional distribution, e.g. curvature map, which can better describe the surface. As shown in Figure 20.
In the meantime, the deflectometry system can also be used to detect other surface features, like defect, scratches, orange-peel, waviness, etc.

8.9. Other Applications

- **Laser mirror (copper)**

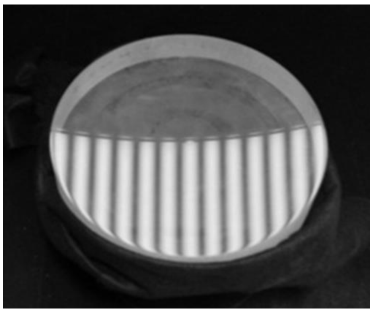
Laser mirror

Measurement fringe pattern

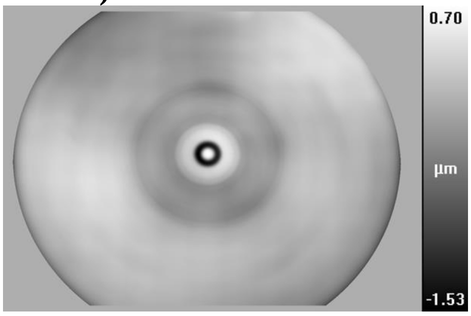


Here is the height map after removing a polynomial. A deep groove is visible.

- **Parabolic telescope mirror (glass, ∅ = 200 mm)**

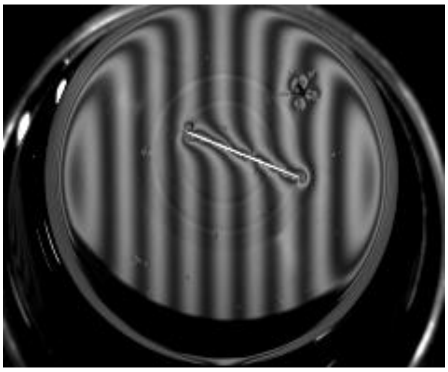


Parabolic mirror

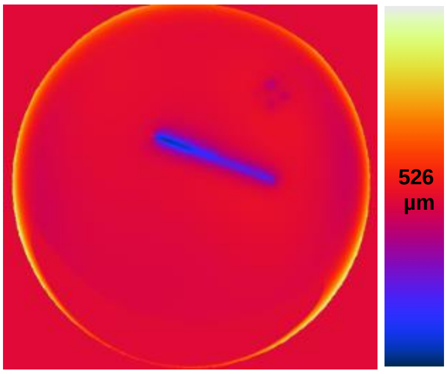


Paraboloid fit residual
f = 517.8 mm

- **Liquid surface**



Water surface deforms under the effect of surface tension. Here is a needle floating on the water.



The measured height map of the water surface

9 Development According to User Requirements

As mentioned earlier, the measurement volume of the deflectometry system depends on the curvature of the measured object. We always design the geometrical parameters of measurement system and choose the most reasonable hardware configuration based on the user provided information, such as lateral dimensions and curvature radius of the object, surface reflection characteristics, the desired coordinates resolution and measurement accuracy, etc. For this purpose, we have developed aided design software that can accurately simulate the behavior of the measurement system in the case of different measured objects. At the same time, it can also calculate possible measurement error distributions based on noise patterns, positioning errors and other parameters.
Figures 21~24 show the observed camera fringes reflected from different objects (plane, sphere, parabolic trough and hyperboloid) in an otherwise identical measurement set-up. With the simulation, the measurable range on different object surfaces is easy to check. By adjusting the system parameters, we can measure the surface of the object as large as possible. The simplest such adjustment is to change angles and distances between components, and if necessary, also use different kind of camera lens, CCD chips and the displays.

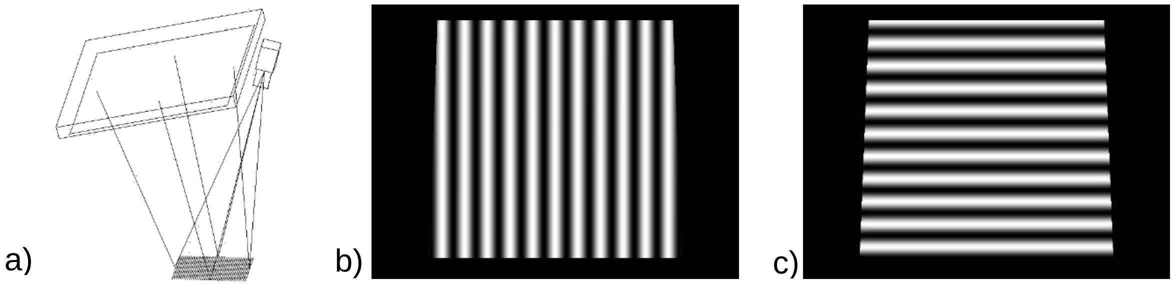


Figure 21: Simulated fringes reflected by a plane (size 160x160 mm2, located at the reference plane). a) Set-up; b) and c) simulated camera fringe images in direction x (straight and vertical on the monitor) and y (straight and horizontal on the monitor), respectively.

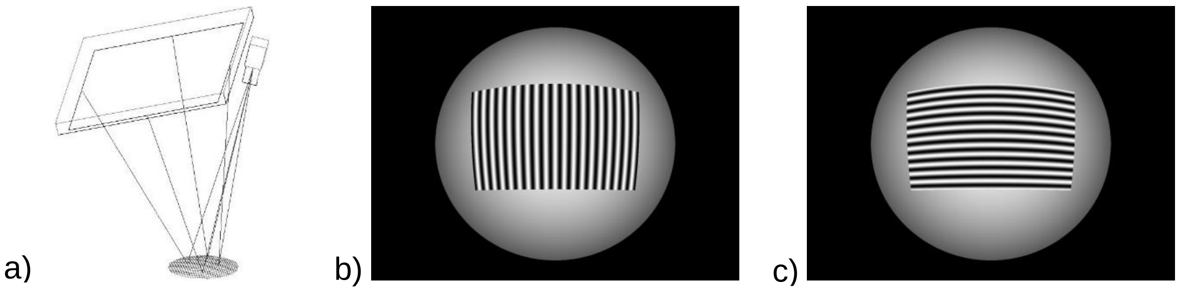


Figure 22: Simulated fringes reflected by a convex sphere (curvature radius R = 300 mm, ∅150mm). a) Set-up; b) and c) simulated camera fringe images in direction x and y, respectively.

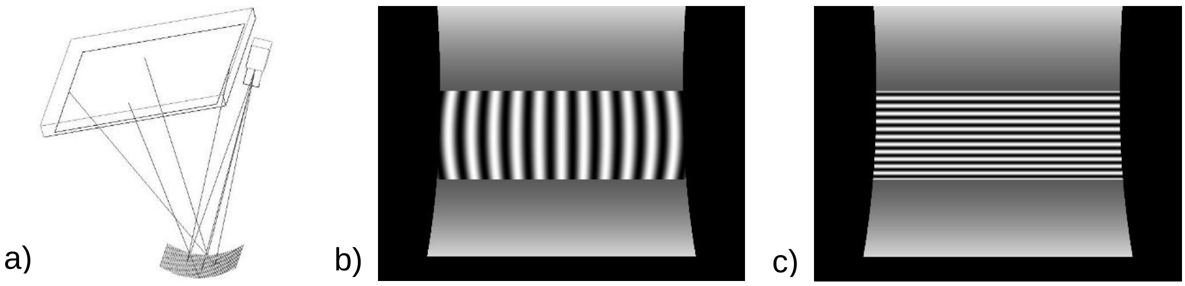


Figure 23: Simulated fringes reflected by a concave parabolic trough (focal length in y direction is 56.25 mm). a) Set-up; b) and c) simulated camera fringe images in direction x and y, respectively.

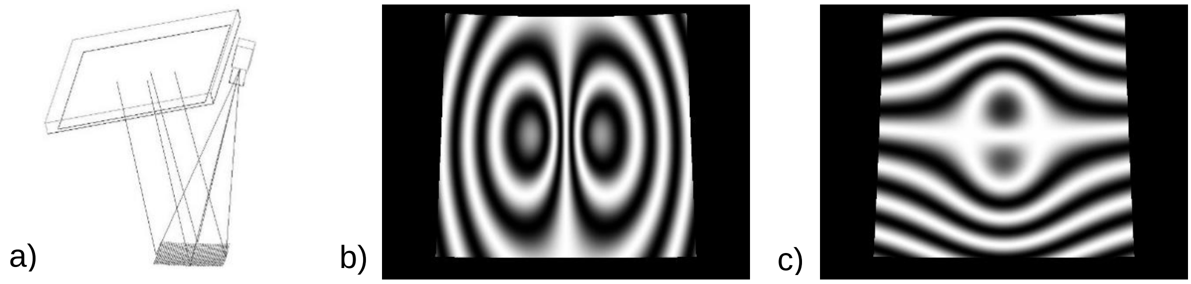
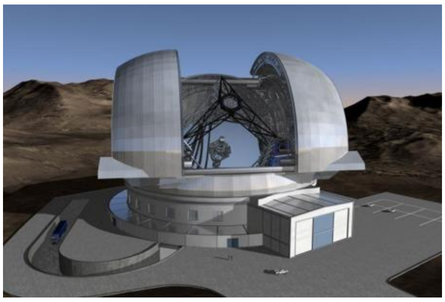
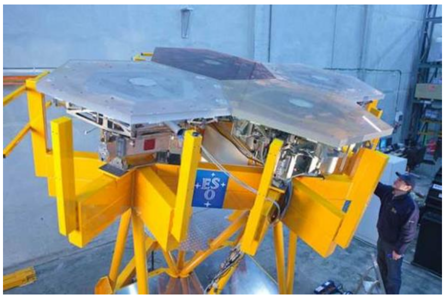


Figure 24: Simulated fringes reflected by a concave hyperboloid (described by x2/(400 mm2) + y2/(900 mm2) – z2/(9 mm2) = –1). a) Set-up; b) and c) simulated camera fringe images in direction x and y, respectively.

VEW had participated in the E-ELT project of European Southern Observatory (ESO).
The main mirror M1 of the telescope has a diameter of 39m, and each segment of M1 is a hexagonal glass mirror whose lateral size is round about 1420mm. VEW had proposed a deflectometry system to characterise deformations of E-ELT mirror segments. According to our simulation, the accuracy of the deformation measurement can achieve to 50~100nm.
The E-ELT telescope and our proposed deflectometry system are shown in Figure 25.
The E-ELT is a very large telescope, consisting of 798 mirror elements.
It is built in the Atacama desert.



The E-ELT telescope

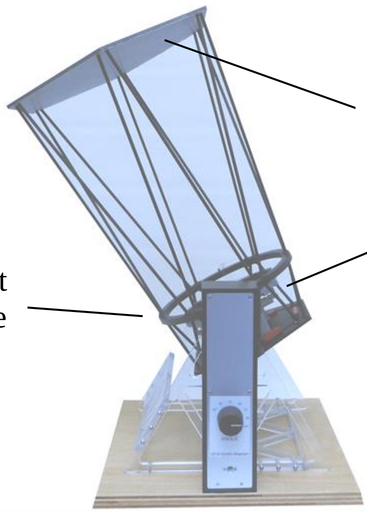


Mirror segment

Projection of the patterns with centrally arranged CCD camera

Mirror segment to be measured, mounted on piezo actuators

Ring with multiline-lasers that measure the exact distance to the projection surface



Model of the proposed deflectometry system

Over all dimension:
1:1 approx. 5m

Figure 25: The deflectometry system for deformation measurement of the mirror segment of the E-ELT telescope.

10 Technical Specifications

We take the desktop type B as an example.

Device size	**500×500×790mm**
Device weight	**~30kg**
CCD camera [1)]	**Network, USB or Fire-wire, 1392×1040 pixel**
TFT display [1)]	**Display port, DVI, 410×310mm, 1600×1200 pixel**
Measurement time	**1~600s (according to expected resolution settings)**
Lateral measurement range	**110×80mm**
Surface normal variable range	**~25º**
Lateral coordinate resolution	**80µm**
Height coordinate resolution [2)]	**~1nm**
Curvature resolution [2)]	**0.05/m (curvature radius 20m)**
Full field measurement accuracy [2)]	**Object positioning use laser pointer Plane: ~50nm Freeform surface: include an extra parabolic structure (PV~10µm) Object positioning use a high accuracy confocal sensor: Plane: ~50nm Freeform surface: 200 nm**
Local range accuracy (microstructure and waviness) [2)]	**~1nm**
Output Data	**Binary, ASCII, STL**
Measurement Software	***FringeProcessor* 6.8, include user SDK.**
Environment temperature	**0~30ºC**
Environment humidity	**0~80%**
Laser class [2)]	**Class 2**

Note:

1) Configurable according to user requirement.
2) The resolution and accuracy here are for surfaces with good specular reflection. If the surface has a certain degree of diffuse reflection, multiple reflections, etc., its specifications will decline accordingly.