# Nanometer level freeform surface measurements with the NANOMEFOS non-contact measurement machine

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## ABSTRACT

Applying aspherical and freeform optics in high-end optical systems can improve system performance while decreasing the system mass, size and number of required components. The NANOMEFOS measurement machine is capable of universal non-contact and fast measurement of aspherical and freeform optics up to ∅500 mm, with an uncertainty of 30 nm (2σ). In this machine, the surface is placed on a continuously rotating air bearing spindle, while a specially developed optical probe is positioned over it by a motion system. A separate metrology system measures the probe and product position relative to a metrology frame.

The prototype realization, including custom electronics and software, has been completed. The noise level at standstill is 0.88 nm rms. A reference flat was measured with 13 µm and 0.73 mm tilt. Both measurements show an rms flatness of about 8 nm rms, which correspond to the NMi measurement. A hemisphere has also been measured up to 50° slope, and placed 0.2 mm eccentric on the spindle. These measurements reproduce to about 5 nm rms. Calibration and software are currently being improved and the machine is applied in TNO aspherical and freeform optics production.

**Keywords:** NANOMEFOS, asphere, freeform, optics, measurement, metrology, non-contact

## 1. INTRODUCTION

The performance of high-precision optical systems using spherical optics is limited by aberrations. By applying aspherical and freeform optics, the geometrical aberrations can be reduced or eliminated while at the same time also reducing the required number of components, the size and the weight of the system [1]. Their application requires new techniques for optical designing, manufacturing and measuring. New local polishing and fast- and slow-tool-servo diamond turning techniques enable creation of high-precision freeform surfaces. Suitable metrology (high accuracy, universal, non-contact, large measurement volume and short measurement time) is key in the manufacturing and application of these surfaces, but not yet commercially available. In collaboration with Technische Universiteit Eindhoven (TU/e) and the Netherlands Metrology institute (NMi VSL), TNO therefore developed the NANOMEFOS measurement machine [2]. This measurement machine has recently been completed, which now also completes the aspherical and freeform optics manufacturing value chain at TNO (Fig. 1).

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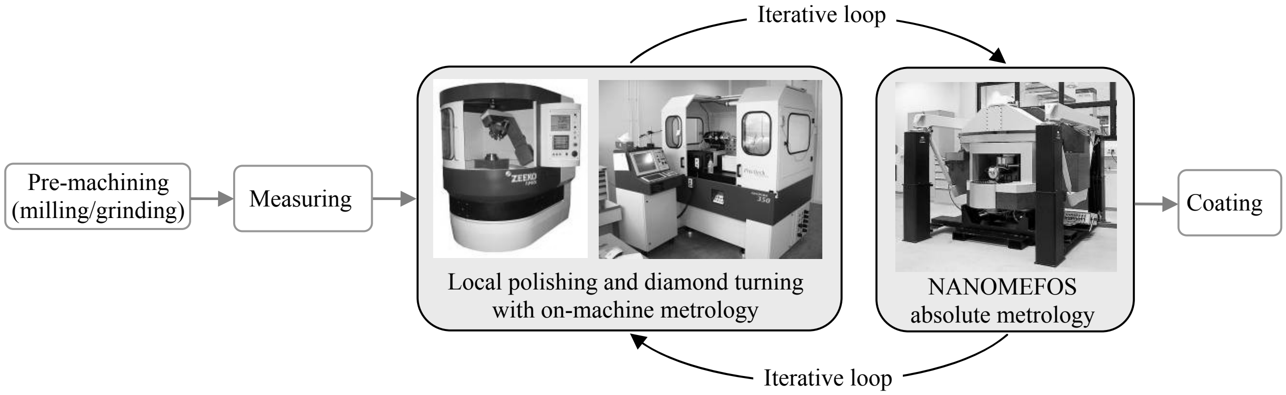


Fig. 1. TNO aspherical and freeform optics manufacturing value chain

In this paper, the design and realization of a new metrology instrument is described, and validation test results are shown. This measurement machine is capable of universal, non-contact and fast measurement of freeform optics up to ∅500 mm, with an uncertainty of 30 nm (2σ).

# 2. CONCEPT

A cylindrical scanning setup with an optical distance probe has been designed (Fig. 2). This concept is non-contact, universal and fast. With a probe with 5 mm range, circular tracks on freeform surfaces can be measured rapidly with minimal dynamics. By applying a metrology frame relative to which the position of the probe and the product are measured, most stage errors are eliminated from the metrology loop. Because the probe is oriented perpendicular to the aspherical best-fit of the surface, the sensitivity to tangential errors is reduced. This allows for the metrology system to be 2D.

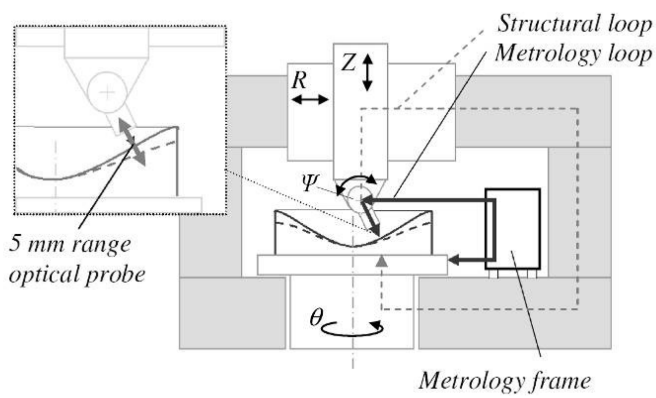


Fig. 2. Cylindrical machine concept with long range optical probe and separate short metrology loop

# 3. MACHINE DESIGN

## 3.1 Overview

The machine design can be split into three main parts: the motion system, the metrology system and the non-contact probe. Custom electronics have been developed for machine control and data-acquisition. The realized machine is shown in Fig. 3.

Fig. 3. NANOMEFOS non-contact measurement machine for freeform optics

### 3.2 Motion system

The motion system positions the probe relative to the product in 4 degrees of freedom (Fig. 4). The product is mounted on an air bearing spindle (θ), and the probe is positioned over it in radial (r), vertical (z) and inclination (ψ) direction by the R-stage, Z-stage and Ψ-axis, respectively. The motion system provides a sub-micrometer repeatable plane of motion to the probe. The Z-stage is hereto aligned to a vertical plane of the granite base using three air bearings, to obtain a parallel bearing stage configuration.

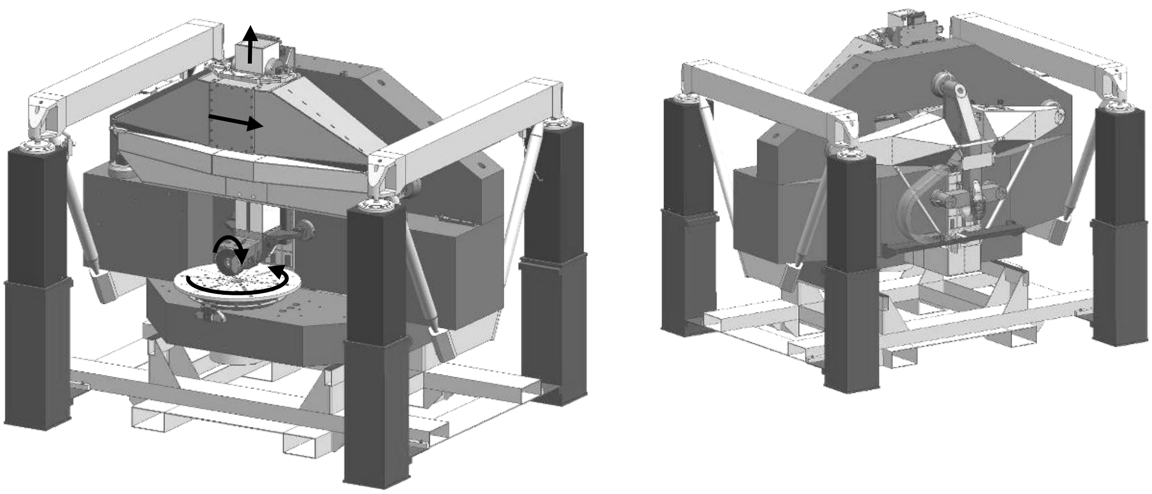

Fig. 4. Motion system design

To minimize distortions and hysteresis, the stages have separate position and preload frames. Direct drive motors and high resolution optical scales and encoders are used for positioning. Mechanical brakes are applied while measuring a track, to minimize power dissipation and to exclude encoder, amplifier and EMC noise. The motors, brakes and weight compensation are aligned to the centers of gravity of the R and Z-stage. Stabilizing controllers have been designed based on frequency response measurements.

### 3.3 Metrology system

The metrology system (Fig. 5) measures the position of the probe relative to the product in the six critical directions in the plane of motion of the probe (the measurement plane). By focusing a vertical and horizontal interferometer (1 and 2) onto the Ψ-axis rotor (3), the displacement of the probe (4) is measured relative to the reference mirrors (5 and 6) on the upper metrology frame. Due to the reduced sensitivity in tangential direction at the probe tip, the Abbe criterion is still satisfied.

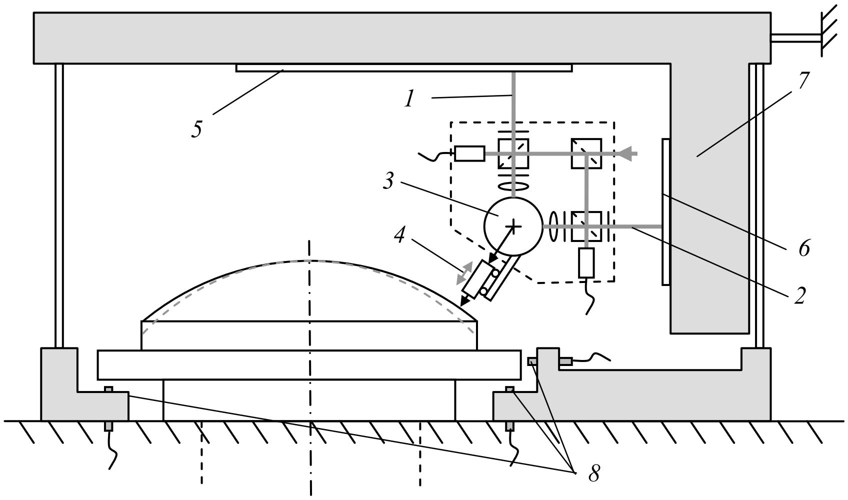


Fig. 5. Metrology system concept

Silicon Carbide is the material of choice for the upper metrology frame (7), due to its excellent thermal and mechanical properties. Mechanical and thermal analysis of this frame shows nanometer-level stabilities under the expected thermal loads. Capacitive probes (8) measure the spindle error motion. Simulations of the multi-probe method show capabilities of in process separation of the spindle reference edge profile and the spindle error motion with sub-nanometer uncertainty.

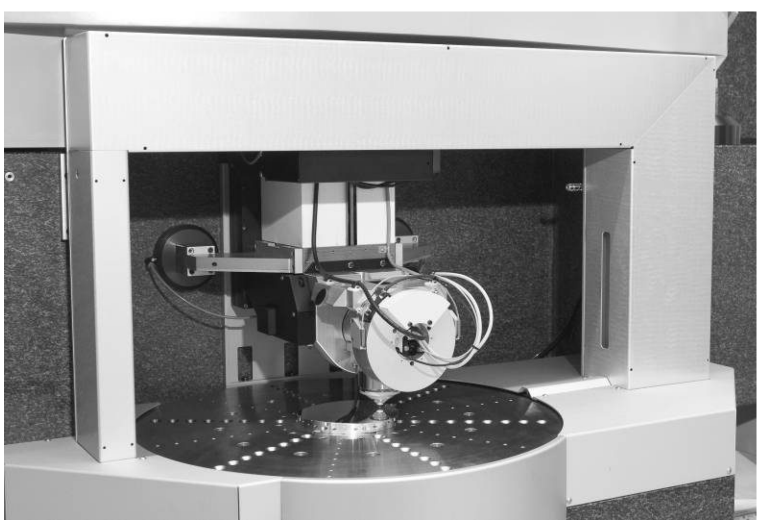

Fig. 6. The metrology system

Experiments show motion amplitudes in the order of 15 nm PV over 0.1 s, which is compensated to 0.6 nm rms by the metrology system. Over 15 minutes, 80 nm of drift in the most critical in *z*-direction is compensated to 2.3 nm rms. In the tangential *r*-direction, the stability is 8.2 nm rms over 15 minutes, just as in the out-of-plane *y*-direction. This drift can be compensated for in the measurement procedure, as will be demonstrated in section 4.3.

### 3.4 Non-contact probe

The non-contact probe measures the distance between the Ψ-axis rotor and the surface under test (Fig. 7). A dual stage design is applied, which has 5 mm range, nanometer resolution and 5° uni-directional acceptance angle [3]. This enables the R and Z-stage and Ψ-axis to be stationary during the measurement of a circular track on a freeform surface. The design consists of a compact integration of the differential confocal method [4] with an interferometer. The focusing objective is positioned by a flexure guidance with a voice coil actuator. A PSD in the loop monitors the position in the aperture of the beam reflected by the surface, to enable compensation of the inclination dependent error that is inherent to the use of an optical probe. A novel calibration method has been designed to calibrate the tilt dependency, of which the results are applied in section 4.5. A motion controller finds the surface and keeps the objective focused onto it with some tens of nanometers servo error.

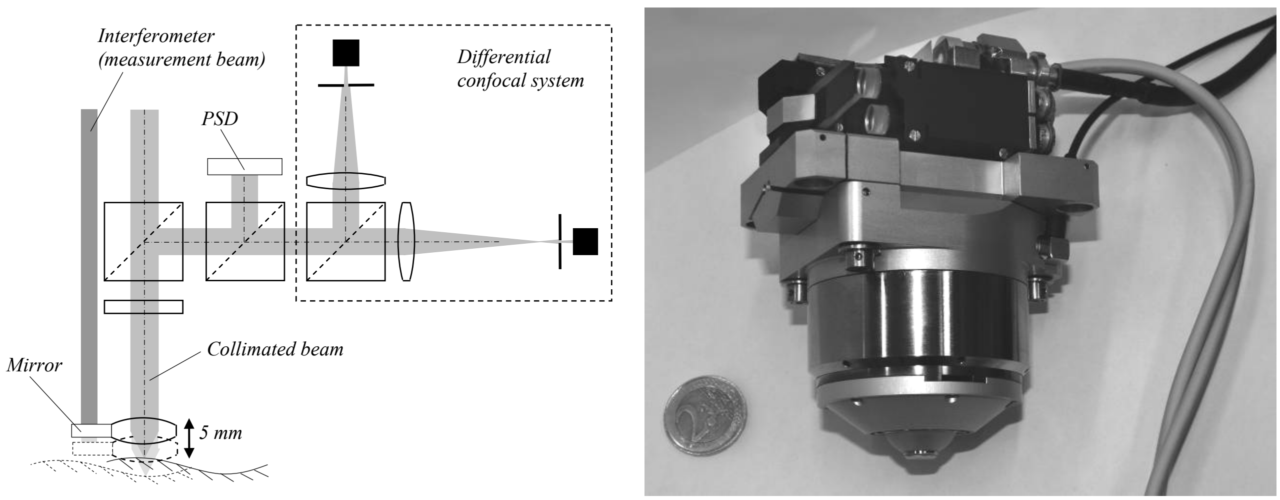


Fig. 7. Non-contact probe with 5 mm range, 5° uni-directional acceptance angle and sub-nanometer resolution

The differential confocal method has been modeled, tested and optimized. The range of the system realized is 4 μm and the noise level is 0.17 nm rms. The repeatability over the full range is 4.1 nm rms. A PSD is added for compensation of the inclination dependent error. Preliminary measurement results show a tilt dependency of about 550 nm at 5°, which may be compensated to nanometer level uncertainty. In interferometer and FES control, a bandwidth of respectively 900 and 1600 Hz is possible. A switching controller has been designed that is capable of automated searching and locking on to a surface under test.

### 3.5 Electronics and Software

The electronics and software are designed to safely operate the 5 axes of the machine and to acquire the signals of all measurement channels. The electronics cabinet contains a real-time processor with many in and outputs, control units for all 5 axes, a safety control unit, a probe laser unit and an interferometry interface. The software consists of three main elements: the trajectory planning, the machine control and the data processing. This software is currently being extended to enable universal automated measurement and data-processing, and interfacing with the manufacturing machines.

# 4. VALIDATION MEASUREMENTS

The prototype realization, including custom electronics and software, has been completed. To validate the machine performance, several experiments have been conducted. First, the basic noise level at standstill will be shown. Next, a λ/20 reference flat is measured with 13 μm and 0.73 mm tilt. The probe inclination dependency has recently been calibrated, of which the results are applied here. A hemisphere has also been measured to determine the repeatability for surfaces for which all machine axes are to be actuated.

## 4.1 Noise level at standstill

To test the stability, the probe is focused onto a stationary test surface (Fig. 8, left). The metrology loop measures the probe position relative to the product, and the probe measures the distance to the product. The difference should be zero. Fig. 8 (right) shows the measurement signals of the two parts of the loop. The difference is shown to be 0.9 nm rms over 0.1 s in the lower graph.

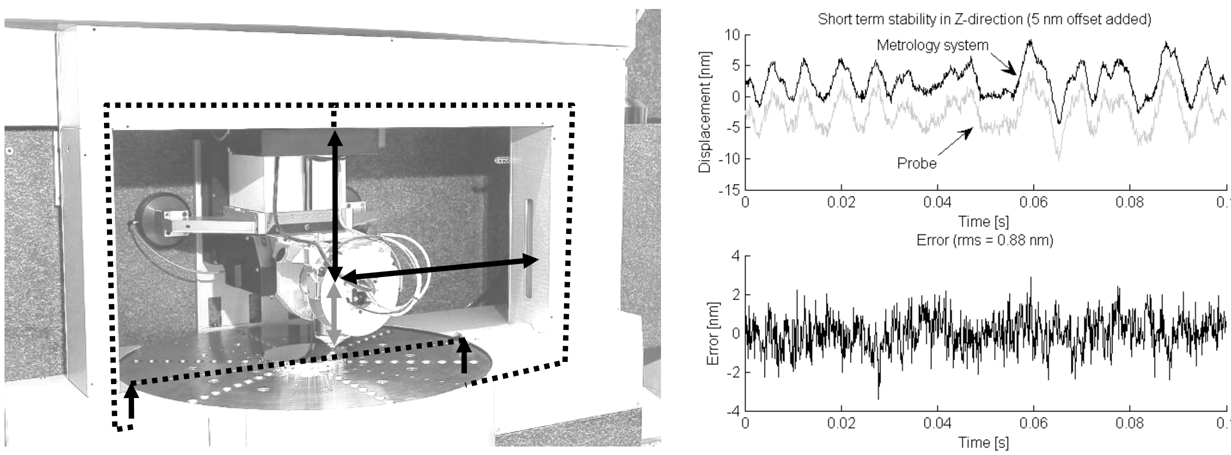


Fig. 8. Metrology loop stability

## 4.2 Reference flat

A ∅100 mm λ/20 reference flat has been measured on the Fizeau interferometer of NMi VSL to be about 44 nm PV and 7.1 nm rms (see Fig. 9). This flat will be measured with little and large tilt, to determine the repeatability and the flatness.

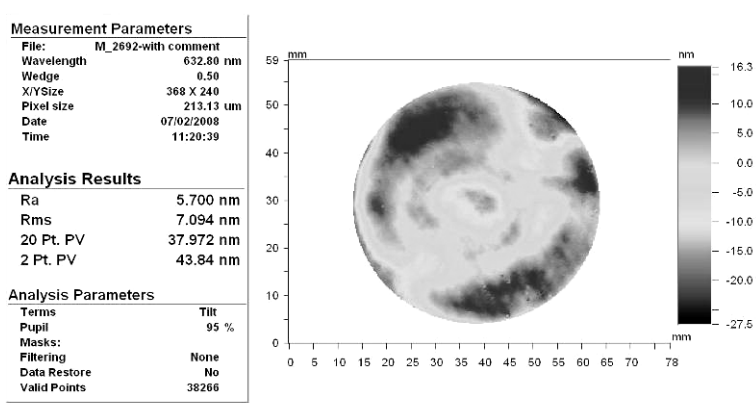


Fig. 9. NMi reference flat measurement result

### 4.3 Drift compensation

The measurement of all circular tracks takes about 6 minutes, so drift accumulates between measuring the outer and the inner track. Five circular tracks are measured in 5 s, and are averaged to obtain the circular profile at a certain radial position. Drift during measurement of such a profile is negligible. It is therefore assumed that each average circular profile is exact, but that the vertical position of the profile is offset by the drift.

For drift compensation, two radial scans (at standstill) at 0° and 90° are measured. The radial scans take only 4 s per scan, so the drift will be small here and four scans are averaged. The *z*-position of each circular profile at 0° and 90° is now compared with the radial scans at this position. The difference is the drift that occurred during the circular measurements. This difference is subtracted from the vertical position of each profile to obtain the drift compensated surface measurement.

This procedure is demonstrated by an example measurement of a 13 µm tilted flat. Fig. 10 (left, top) shows the radial height measurements at 0° and 90°. The bottom figures show the same profile with a linear fit removed, and the filtered average interpolated to the radial positions of the circular tracks. Some drift has occurred between the first and second series of scans, but the measured profile repeats well.

The profiles at 0° and 90° are quite different. These profiles consist of the flatness of the surface under test (different at 0° and 90°), and a common component of the flatness of the horizontal reference mirror.

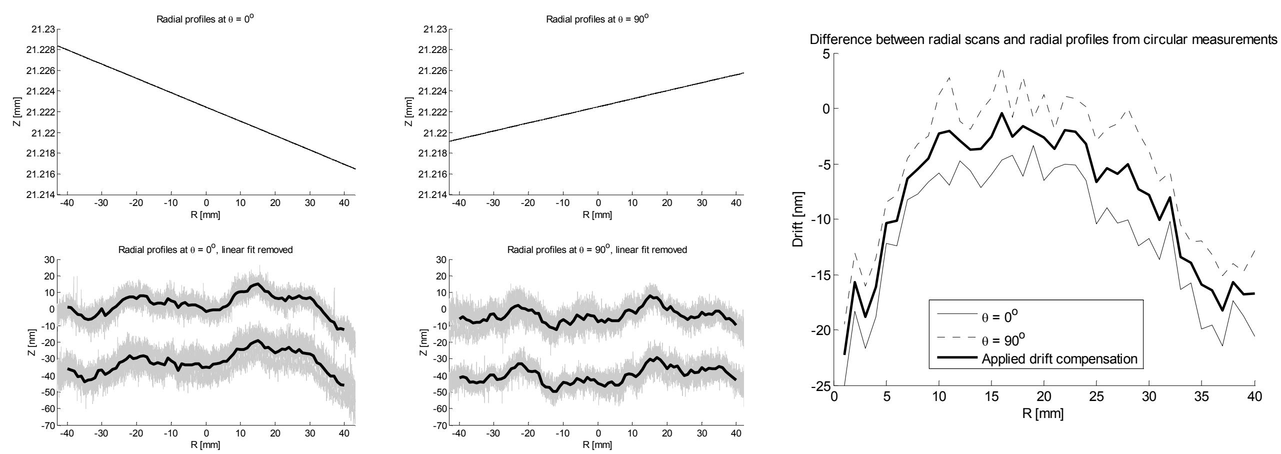


Fig. 10. Drift compensation by radial scans

The measured radial profiles from before and after the circular measurements are averaged, and compared to the outcome of the circular scans at 0° and 90°. The difference is shown in Fig 10, right. The difference between the profiles is very similar, and is averaged again to obtain the drift offset per circular track for the compensation. The result of this drift compensation on the repeatability of the surface measurements will be shown in the next sections.

### 4.4 Measurement of 13 µm tilted flat

To demonstrate machine performance, a 100 mm diameter Zerodur optical flat has been measured (Fig. 11). First, this flat has been measured with only 13 µm tilt. The spindle speed was 1 rev/s, which results in 250 mm/s scanning speed at the outer edge. Five revolutions were averaged per track, and the track spacing is 1 mm. The surface was measured three times, and each was compared with the average to determine the repeatability.

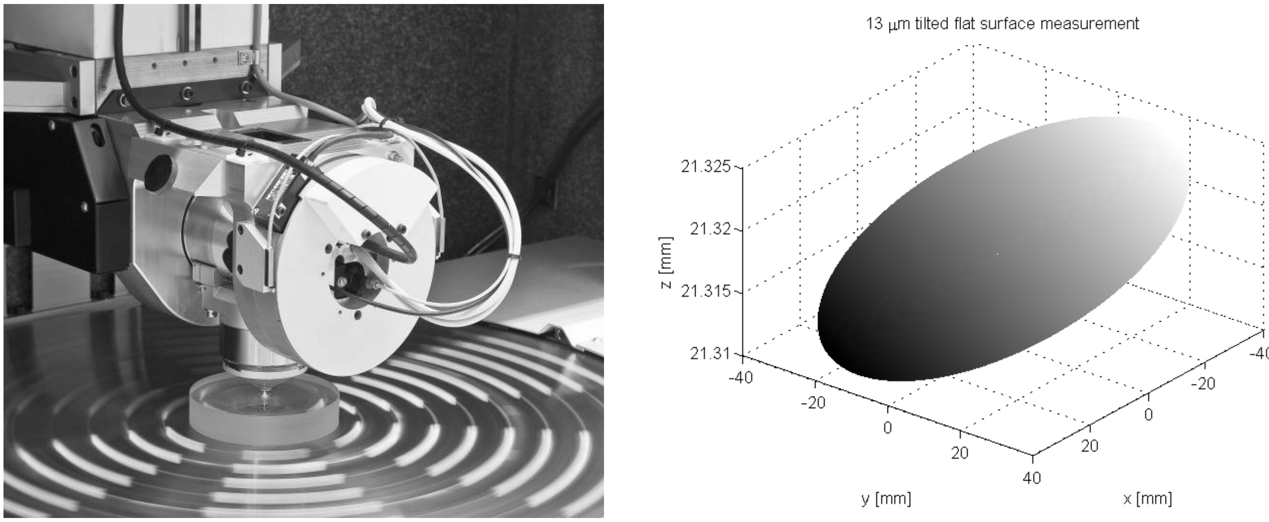


Fig. 11. Measurement of a tilted flat and measurement result

Radial scans with a stationary product are taken before and after each measurement to compensate for the drift that accumulates during the scanning of the circular tracks. Without drift compensation, the repeatability is 8-9 nm rms. When the drift compensation is applied, this improves to 2 nm rms (Fig. 12). The flatness of the surface was determined by NMi VSL to be 7 nm rms and 40 nm PV. The uncalibrated machine measures a flatness of 8-9 nm rms and 50 nm PV of the 13 µm tilted flat (Figure 4, right), which matches the NMi data well.

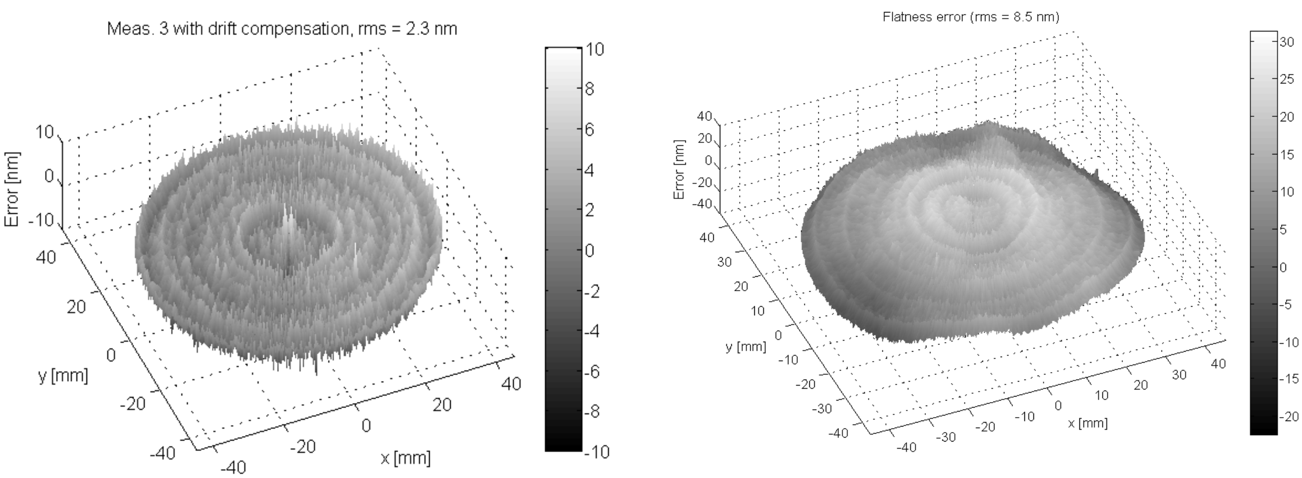


Fig. 12. 13 µm tilted flat typical repeatability and flatness measurement result

## 4.5 Measurement of 0.73 mm tilted flat

When measuring a tilted flat, the inclination dependency that is inherent to optical probes will cause measurement errors. At the centre, there is no height variation by definition, but due to this tilt dependency, an apparent height variation is measured. To compensate for this, a PSD is present in the probe, which monitors the position of the reflected beam in the aperture. By applying a novel calibration method [3], the tilt dependency was determined and compensated for. Fig. 13 (left) shows the measurement without the tilt compensation, with the clear discontinuity at the centre. Fig. 13 (right) shows the result with the tilt correction applied. The 7.5 nm rms of this measurement corresponds well to the NMi and

13 μm tilted flat. A quantitative comparison is still to be made. In these measurements, the parameters were equal to the previous section, and the probe captured the 0.73 mm departure from rotational symmetry in its range.

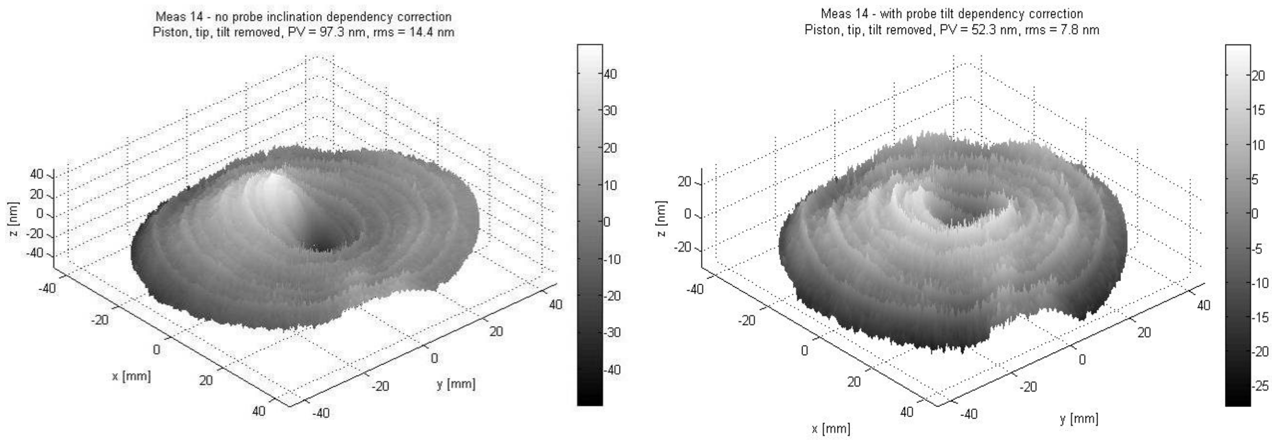


Fig. 13. 0.73 mm tilted flat measurement result before and after compensation of the probe tilt dependency

### 4.6 Repeatability of hemisphere

In the previous measurements, the Z-stage and $\psi$-axis were blocked. To determine the repeatability for surface that require actuation of all machine axes, a hemisphere was measured (Fig. 14). To enable this measurement, the machine control was upgraded for three axis movement, and the data-processing software was further automated and improved.

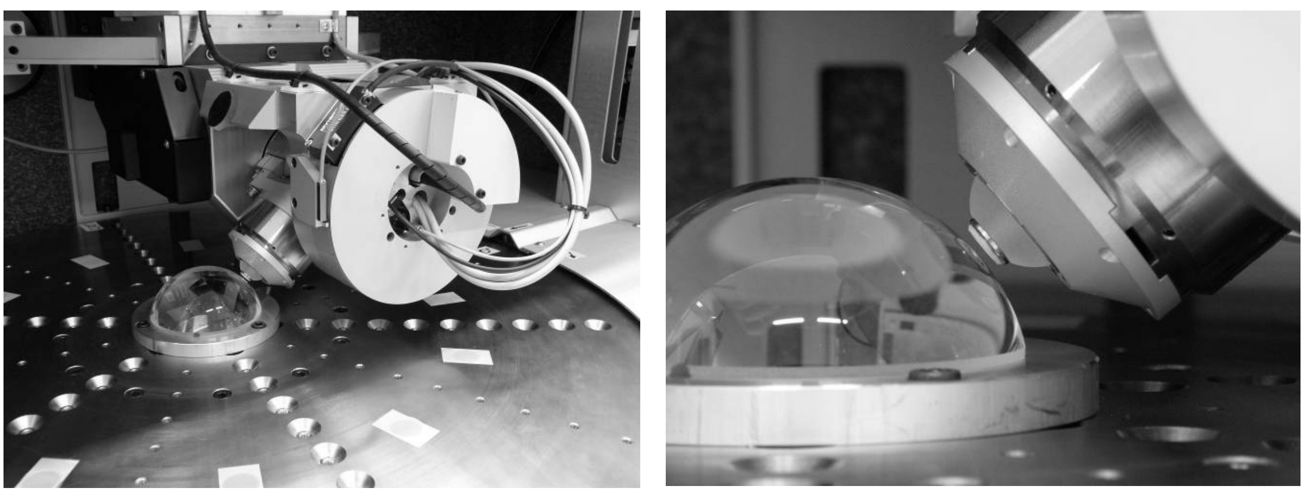

Fig. 14. Measurement of a hemisphere

The surface was measured with a track spacing of 1 mm, at 1 rev/s and radial scans were applied for drift compensation. The maximum slope is 50°, and the surface was placed 0.2 mm eccentric on the spindle. Fig. 15 shows the measured surface shape, and the typical repeatability figure. The average repeatability is about 5.8 nm rms. It is thought that an improved interpolation scheme will further improve this.

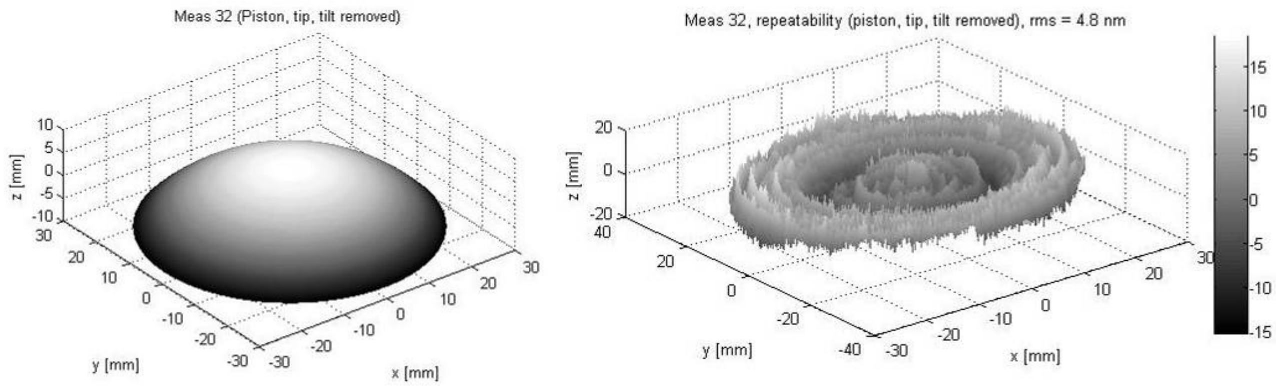


Fig. 15. Hemisphere measurement result and typical repeatability

## 5. ACHIEVABLE UNCERTAINTY ESTIMATION

Besides the probe tilt dependency, no calibration data has yet been applied. The repeatability is however above expectations, moreover considering there is still room for improvement. Together with NMi VSL, an estimate of the calibration uncertainty of each individual systematic error source was made. The main parameters are the surface diameter and the local surface slope (the departure from rotational symmetry). The original error budget still appears to be feasible. The estimated achievable uncertainty budget is shown in Fig. 16, with an expanded uncertainty ($2\sigma$) that is below 30 nm for rotationally symmetric aspheres, and may increase up to 55 nm for highly freeform surfaces. The gray area at the bottom is the surfaces for which the goal of 30 nm is met.

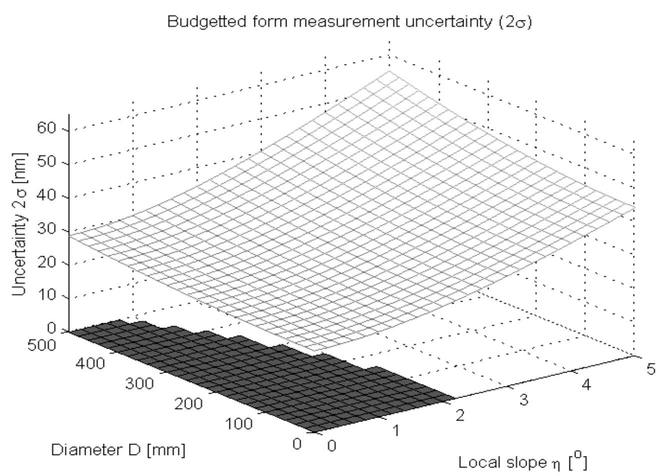


Fig. 16. Achievable measurement uncertainty estimate

## 6. CONCLUSION

A new non-contact measurement machine prototype for freeform optics has been developed. The characteristics desired for a high-end, single piece, freeform optics production environment (high accuracy, universal, non-contact, large measurement volume and short measurement time) have been incorporated into one instrument. The validation measurement results for tilted flat as well as curved surfaces exceed the expectations, especially since they are still virtually raw data. Calibrations and software improvements are currently in progress. The machine is being applied in several projects within the TNO optical workshop, with which the value chain for universal manufacturing of aspherical and freeform optics has been completed.

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