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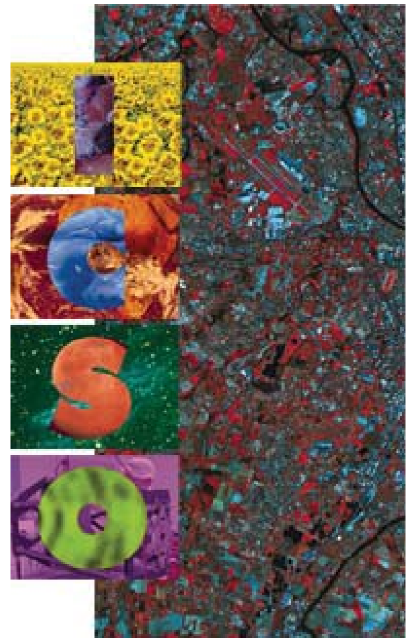

# *MEMS deformable mirror for wavefront correction of large telescopes*

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# MEMS DEFORMABLE MIRROR FOR WAVE-FRONT CORRECTION OF LARGE TELESCOPES

**Sigmund MANHART** *(1)*, **Gleb VDOVIN** *(2)*, **Neil COLLINGS** *(3)*,
**Zoran SODNIK** *(4)*, **Susanne NIKOLOV** *(1)*, **Werner HUPFER** *(1)*.

*(1) Astrium GmbH, 81663 München (Germany)*
*(2) TU Delft, Electronic Instruments, Delft (The Netherlands)*
*(3) Institut de Microtechnique, Univ. Neuchatel (Switzerland)*
*(4) European Space Agency, Noordwijk (The Netherlands)*

## 1 - ABSTRACT

*A 50 mm diameter membrane mirror was designed and manufactured at TU Delft. It is made from bulk silicon by micromachining - a technology primarily used for micro-electro-mechanical systems (MEMS). The mirror unit is equipped with 39 actuator electrodes and can be electrostatically deformed to correct wavefront errors in optical imaging systems.*
*Performance tests on the deformable mirror were carried out at Astrium GmbH using a breadboard setup with a wavefront sensor and a closed-loop control system. It was found that the deformable membrane mirror is well suited for correction of low order wavefront errors as they must be expected in lightweighted space telescopes.*
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## 2 - MIRROR DESIGN

The membrane micromachined deformable mirror (MMDM) is fabricated using the technology of bulk micromachining in silicon. The mirror reflective surface is formed by a thin composite nitride/polysilicon membrane, approximately 10 µm thick, coated with a reflective layer of gold. The membrane can be locally deflected by applying voltages to the underlying electrodes which are separated from the membrane by a gap of about 200 µm.

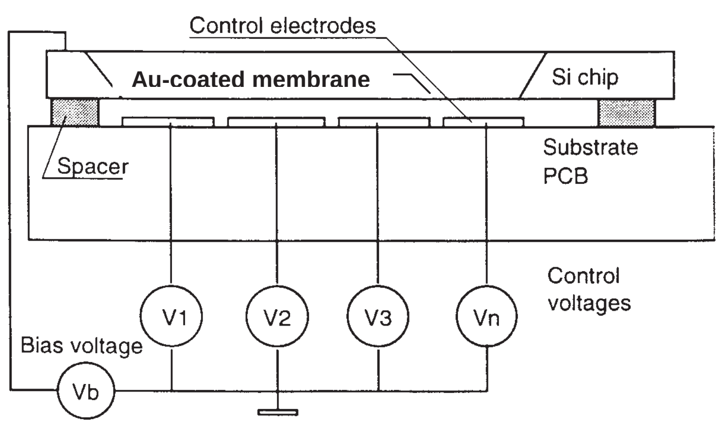



Fig. 1: Electrostatically deformable membrane mirror (schematically)

Since the membrane can only be pulled towards the electrodes, a bias must be applied to all electrodes to allow the bi-directional control. This causes a parabolic mirror offset, i.e. there is a certain radius of curvature (ROC) in zero position. In our case the ROC is 27 m at the nominal bias of 205 V. In this case the actuator voltages can be varied between 0 and 290 V providing equal stroke in both the “positive” and “negative” directions. Since the mirror deflection is proportional to the square of the voltage applied, the bias voltage should be set 1.41 times (square root of 2) lower than the maximum applicable voltage.

With a membrane diameter of 50 mm this device presently is the largest one manufactured in MEMS technology. It has the following important advantages over bimorph and continuous faceplate deformable mirrors:

- Relatively simple configuration.
- The actuator capacitance is low in comparison to both bimorph and continuous faceplate mirrors, leading to less power consumption - the total power consumption of a 39-channel MMDM driven with a frequency of 1 kHz does not exceed 20 W. Using the mirror at low frequencies rates can reduce the power consumption to less than 1 W.
- The whole assembly is relatively lightweight - 138 g for mirror, mount and actuators as shown in Fig. 2.
- Membrane mirrors are well suited for correction of low-order aberrations such as defocus, coma, astigmatism etc. Unlike with piston and continuous-faceplate mirrors, membrane mirrors achieve good correction with a relatively small number of control electrodes.

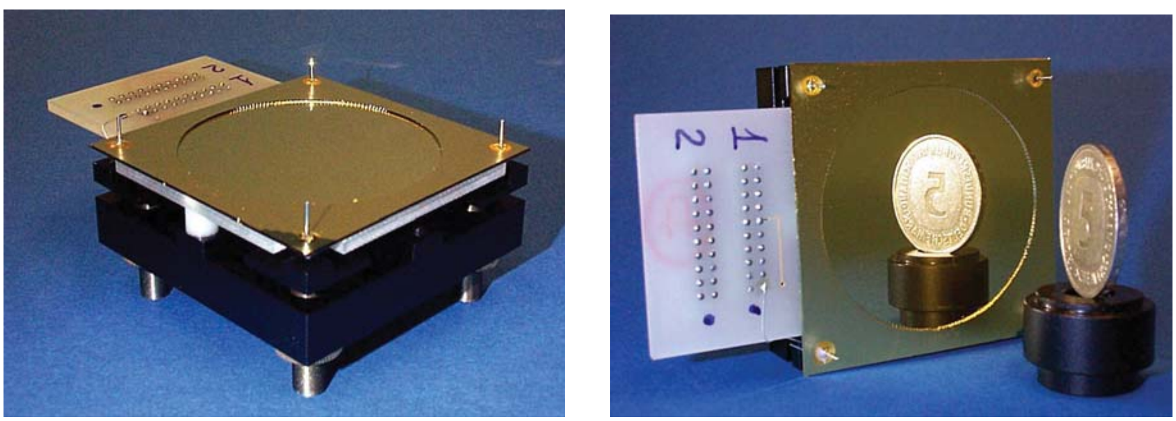


Fig. 2: Mirror-electrode assembly of the 50-mm MMDM

The electrode structure below the mirror membrane is shown in Fig. 3. There are 33 inner electrodes for correction of external wavefront errors within an effective diameter of 35 mm. Six outer electrodes are used exclusively for correction of the membrane deformation from mounting stress.

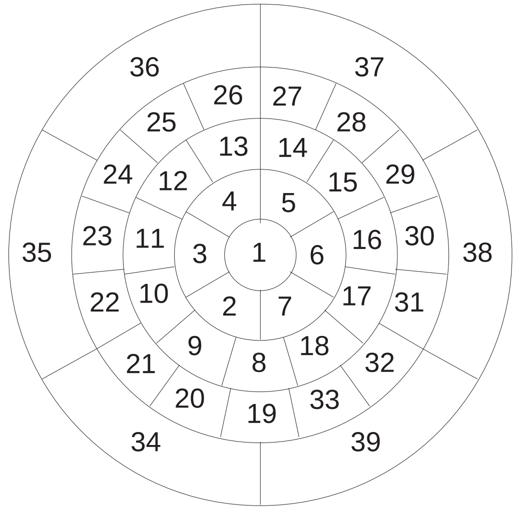


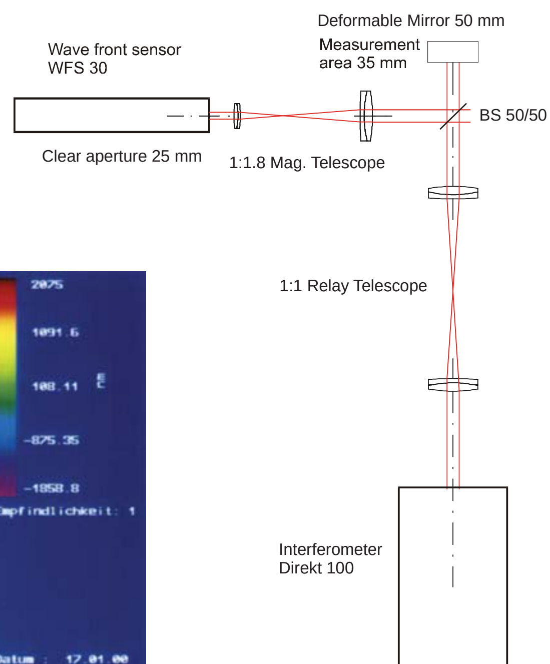

Fig. 3: Electrode structure of the MMDM

## 3 - MMDM PRETEST

### 3.1 - Test setup

The test setup of Fig. 4 was used for optical inspection of the unbiased and the biased MMDM. The Shack-Hartmann wavefront sensor (WFS 30 with 132 subapertures) and the Zeiss Direct 100 interferometer were operated simultaneously. The WFS 30 was connected to a PC to control the MMDM in closed loop. The Direct 100 interferometer was used to monitor the residual surface errors of the membrane mirror.

Fig. 4: Test setup for MMDM surface quality measurements



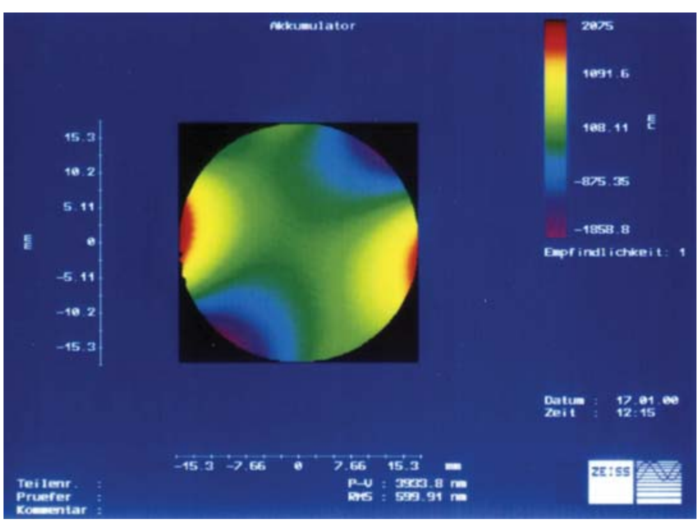



Fig. 5: Interferogramme of the unbiased mirror against a flat reference

### 3.2 - Unbiased MMDM

Fig. 5 shows the interferogramme of the unbiased mirror against a flat reference.

The wavefront error in the reflective mode amounts to 3934 nm pv (peak-to-valley), or 560 nm rms (root-mean-square) over the effective aperture of 35 mm; the main error being fourfold. This error is almost exclusively due to the mounting stress from the 4 fixations of the 0.5 mm silicon wafer.

### 3.3 - Biased MMDM

Fig. 6 shows the interferogramme of the mirror with the nominal bias voltage of 205 V applied to all electrodes. A spherical mirror of 20 m ROC was taken as reference.

The wavefront error after subtraction of defocus is 3067 nm pv, 458 nm rms over the 35 mm effective aperture. This is approximately the same as for the unbiased mirror, showing that no additional errors are introduced by the bias voltage.

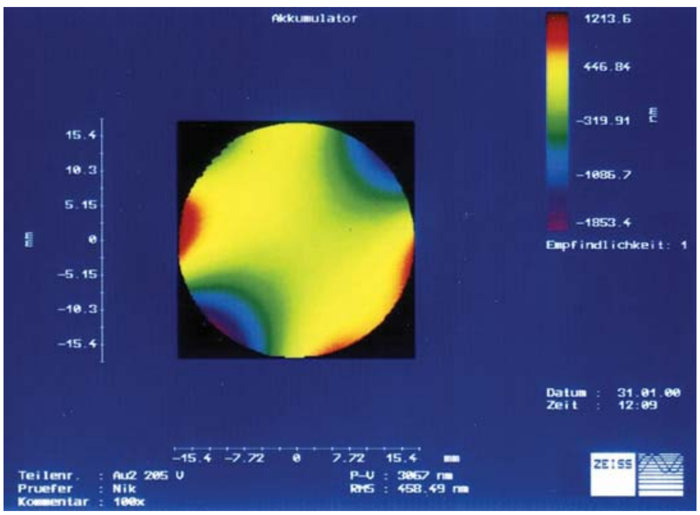



Fig. 6: Mirror with 205 V on all electrodes

### 3.4 - Self-correction via outer electrodes

The 6 outer electrodes were individually biased to partly correct for the stress induced mirror deformation; all inner electrodes were kept at the nominal bias voltage of 205 V.

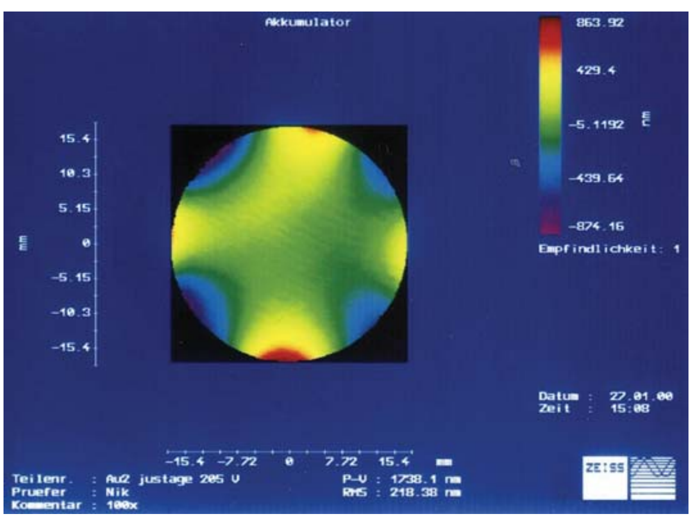



Fig. 7: Mirror with 205 V on the inner electrodes and different voltages on the outer electrodes

The remaining wavefront errors after self-correction are 1738 nm pv and 218 nm rms. This corresponds to 0.34 $\lambda$ rms in optical reflection and 0.17 $\lambda$ rms mechanical surface deformation ($\lambda$ = 633 nm).

| MMDM operation mode | Wavefront error [pv] | Wavefront error [rms] |
|---|---|---|
| unbiased | 3934 nm | 560 nm |
| nominally biased | 3067 nm | 458 nm |
| self-correction via outer electrodes | 1738 nm | 218 nm |

## 4 - WAVEFRONT CORRECTOR SETUP

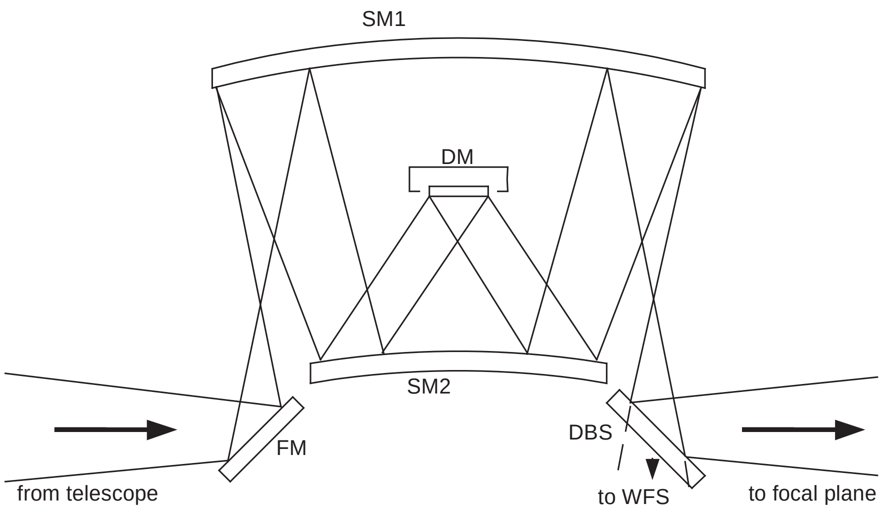



Fig. 8: Wavefront corrector with Offner design

The wavefront corrector (WFC) breadboard consists of an Offner type system with 2 spherical mirrors adjusted to the ROC of the deformable mirror (DM). It is a 1:1 optical relay system with a F/# = 16, a field size of +/-20 mm (0.04°) and a pupil diameter of 35 mm at the location of the DM. In principle, the WFC can be inserted into the focal plane of any optical telescope with appropriate parameters. The wavefront sensor WFS 30 is of the Shack-Hartmann type with 132 subapertures.

The actual test setup with WFC and auxiliary interferometer (Direct 100) is shown in Fig. 9. The light from an external telescope would travel along the path from BS1 via M1 and the Offner system into the focal plane assembly, here represented by the Direct 100 for wavefront analysis.

The operational wavelength is a HeNe beam generated by the Direct 100. It is reflected to the Offner system via the folding mirror M3, propagates through the Offner system and is backreflected by the dichroic mirror BS1. For addressing off-axis field points in the Offner system the collimator lens L4 is laterally shifted (together with the folding mirror M3).

The control wavelength of 830 nm is produced by a diode laser. It passes the dichroic mirror BS1, is reflected by folding mirror M4, travels via M1 and L3 to the WFC and transmits BS2 to reach the wavefront sensor WFS 30. M4 can be replaced by a wavefront disturber, i.e. a mechanically deformable mirror.

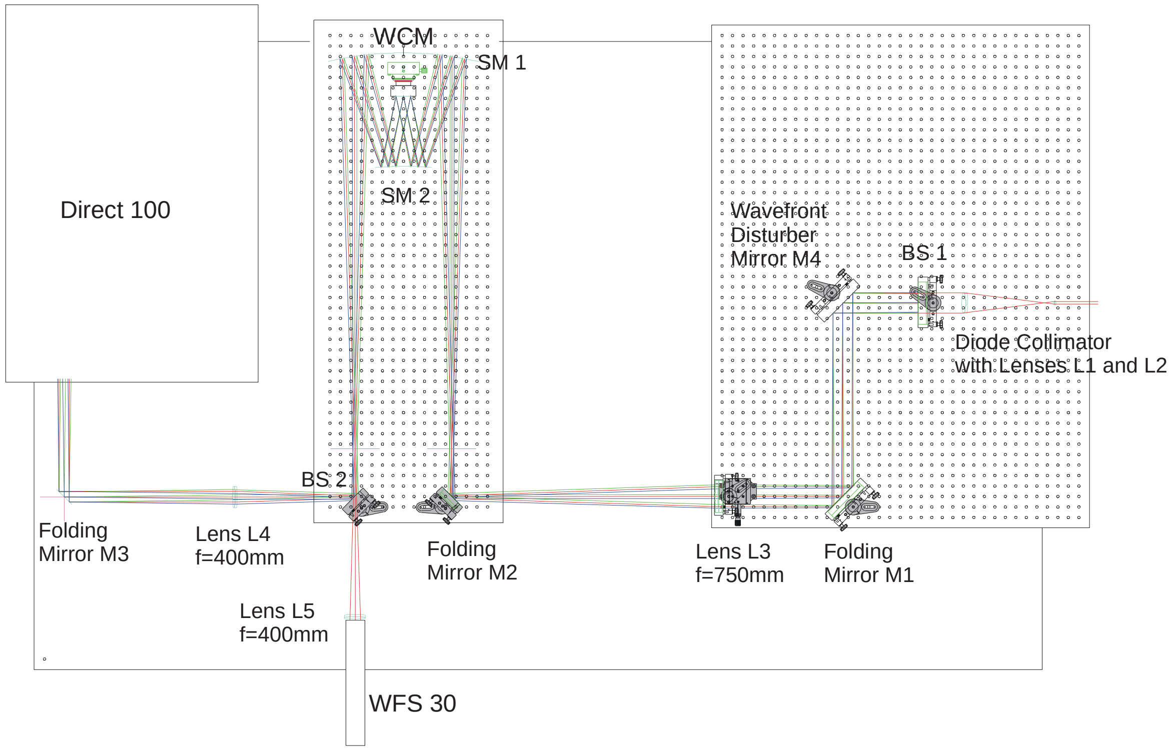



Fig. 9: Bread board test setup – schematically

In order to obtain the mechanical surface deformations of the MMDM the wavefront errors measured with Direct 100 have to be divided by 4 (interferogramme after double reflection) and the wavefront errors measured with the WFS 30 have to be divided by 2 (interferogramme after single reflection).

## 5 - BREADBOARD TEST RESULTS

### 5.1 - Maximum mirror deflections and correction depths for individual Zernikes

The maximum Zernike deflection was measured at the control wavelength 830 nm with the WFS 30. The individual Zernike´s were simulated by software and the MMDM was operated in closed-loop control to counteract the simulated disturbance. Maximum deflection was achieved when one or more of the actuators reached the maximum permissible voltage or zero voltage. Maximum deflection was measured for both cases, push- and pull-direction. Fig. 10 shows the maximum deflection (push and pull) for each Zernike coefficient.

It can be seen that for lower order aberrations such as tilt, focus, astigmatism and coma as well as trifold the mirror can be significantly deflected up to several wavelengths. The deflections are nearly symmetric for the push and pull directions. The higher order aberrations have lower deflections because the MMDM would need more actuators for correcting higher order aberrations. In Fig. 11 the rms aberrations are shown when the mirror shape is optimized in a closed-loop modal control for each maximum Zernike deflection.

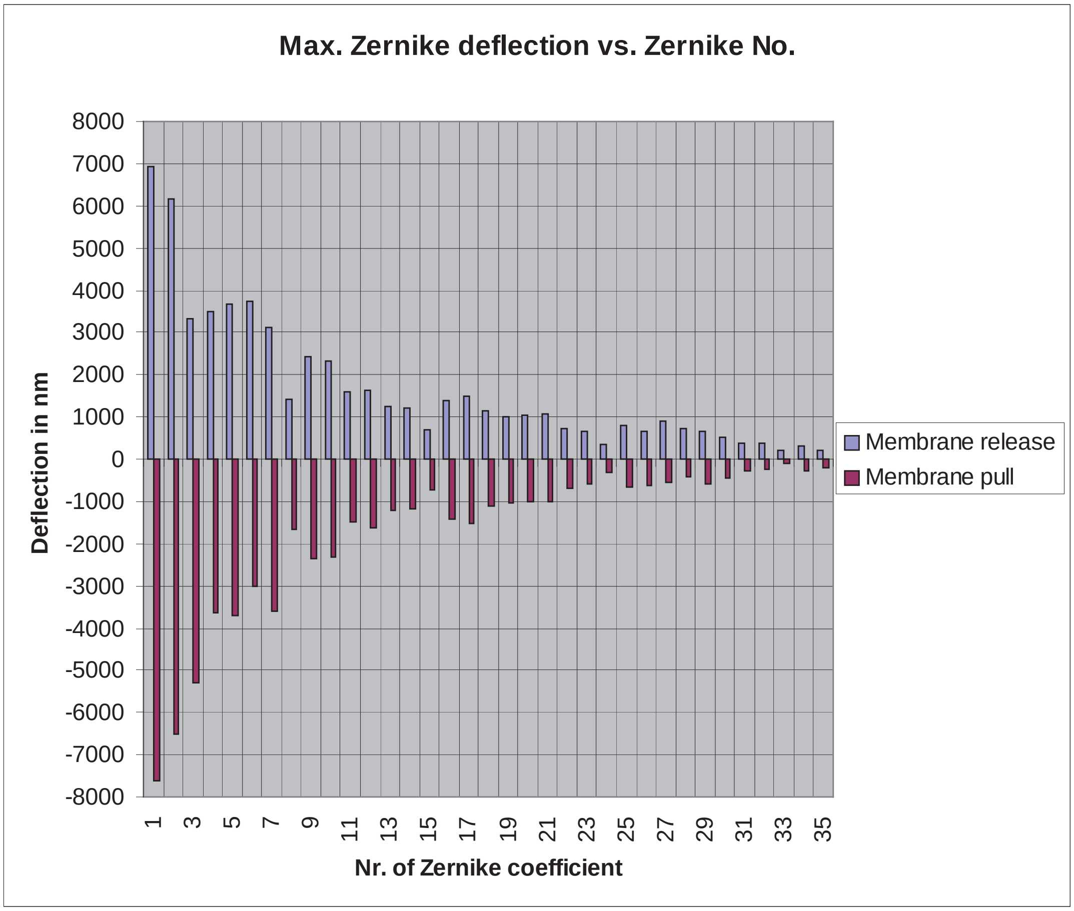



Fig. 10: Maximum mirror deflection for each Zernike coefficient

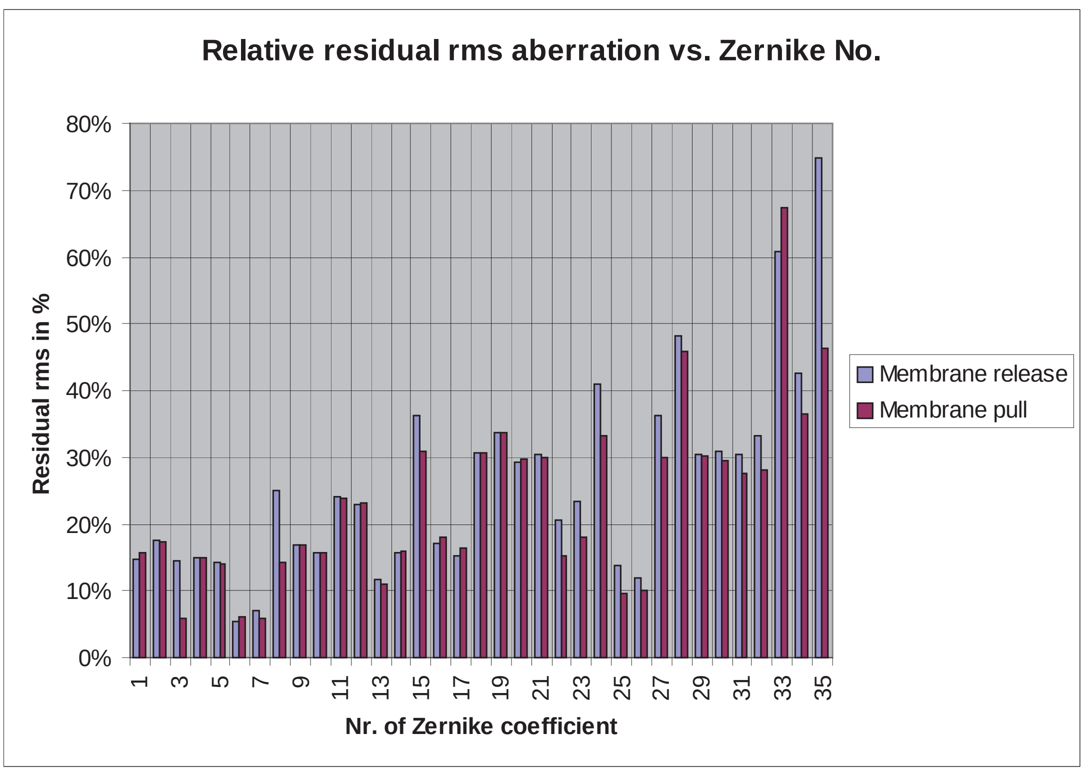


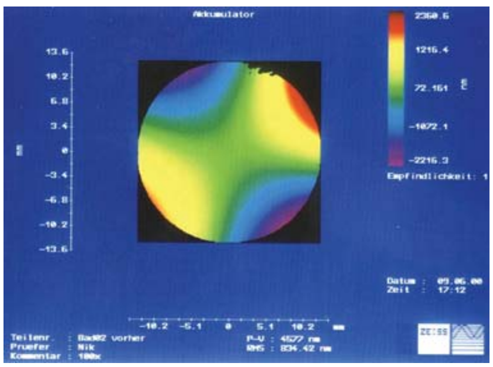

Fig. 11: Correction depth for each Zernike - w.r.t. to maximum mirror deflection

It can clearly be seen that low order wavefront errors can be corrected to approximately 5 - 15% of their original wavefront distortion. The majority of higher Zernikes is correctable to 10 - 40% of the original distortions.

### 5.2 - WFEs from a mechanically stressed mirror

In this test the correction capability for external wavefront errors was demonstrated. For this purpose, the mirror M4 is replaced by a thin surface mirror, which can be mechanically deformed in a special mirror mount and which allows the simulation of typical wavefront errors which must be expected in "floppy" telescopes. These are in particular: astigmatism, defocus, trifold and some higher order aberrations. One representative example for astigmatism with some trifold is shown in Fig. 12. The WFE´s are recorded before and after closed-loop correction.

The table below the interferogrammes shows the depth of correction in form of RMS wavefront quality and values of the main Zernike coefficients before and after correction.



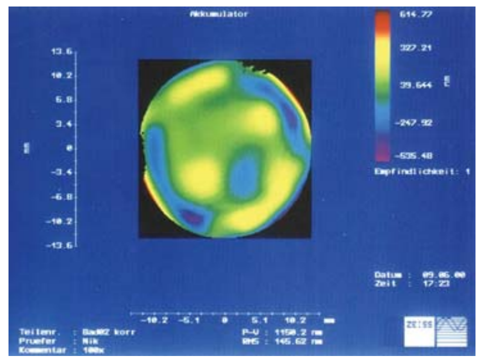




Fig. 12: Interferogramme of deformed mirror M4 before and after correction with WCM

| Direct 100, double pass | before correction | after correction |
|---|---|---|
| Wavefront quality rms | 834 nm | 146 nm |
| Zernike coeff. Asti. x / y | 788 nm / 1843 nm | -12 nm /-65 nm |
| Zernike coeff. Trifold | 29 nm / 308 nm | -41 nm / -3 nm |

The wavefront correction quality for externally generated wavefront errors is very good for first order aberrations such as astigmatism, defocus, trifold, etc. These aberrations can nearly be corrected to zero; the residual aberrations are of higher order.

## 6 - CONCLUSIONS, OUTLOOK

Large space optical systems need wavefront correction, because they are subject to distortions from manufacturing errors, thermal effects, mounting stress, and gravity release. Since the produced wavefront errors in general have low spatial frequencies and are slowly varying over time, classical bimorph correction techniques may be practicable. However, bimorph wavefront correctors suffer from severe drawbacks. The most important ones are:

(1) they are heavy and rather complex in construction

(2) they need high voltages

(3) only low spatial frequencies can be corrected

(4) the deflection (stroke) is rather small

The MEMS deformable mirror eliminates these drawbacks because it is very light, simple in construction, driven with low voltages and low power, and it provides reasonable deflections even at relatively high spatial frequencies.

A few constraints remain with the present technology of MEMS mirror fabrication:

(1) The thickness of the standard Silicon wafer is only 0.5 mm. This makes the mirror substrate very sensitive to stress and bending. It is very important to have a mount which is free of stress and which is thermally matched.

(2) A bias voltage must be applied to the membrane to allow "push-pull" operation. This means that the MMDM needs voltage in zero position and that the standby surface is curved. In case of voltage failure the element is no longer in its operational range.

(3) The long term stability of the membrane is not yet ascertained. This means that more experience is needed before this type of wavefront corrector can be envisaged for space projects.

The development and test results in this project have demonstrated that the MEMS technology is capable of producing high quality deformable mirrors up to the size of 50 mm clear aperture. The test have further shown that all first order wavefront distortion such as defocus, astigmatism, coma, trifold etc. can be corrected almost perfectly.