The need of AO in Future Space Optical Instruments

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Abstract

For space optical instrumentation light-weight design is very important. For example, an areal density of less than 10 kg/m^2 is requested for the primary mirror of the 8 m NASA NGST. Similar requirements hold for the future ESA IRSI telescope. Present light-weight space telescopes (without active/adaptive optics) are off from this goal by a factor of 10. Mass reduction by such a scale inevitably makes large telescopes „floppy“. The means to correct for this floppiness are either to use active structures or adaptive optics or both.

In the first part of this paper we present the wavefront errors which we expect to occur when floppy telescopes are exposed to space environment, i.e. wavefront distortions by deformations of the mirror due to gravity release and periodic temperature changes in space orbits, and by the stress and strain of the mounting.

In the second part we present our approach towards correcting the wavefront errors by a micromachined silicon deformable mirror. Results obtained with a 25 mm diameter mirror are presented. A 50 mm mirror with effective 35 mm diameter is strived for, which then shall be operated in a closed loop configuration with a Shack-Hartmann sensor at a later stage.

1. Introduction

A compilation of optical space telescopes - already in orbit and under development - shows a rather simple dependence between diameter D and mass M of lightweighted primary mirrors: M increases with the 2.7th power of D (see Fig.1- a similar dependence was also found by Miller[1] and Yoder[2].).

$$M = c * D^{2.7} \qquad (1)$$

The constant c is a function of the specific stiffness E/ρ of the mirror material (E is the elastic modulus and ρ the density) and of the surface quality requirement Δy (WFE-rms). In our representation we find the following rule of thumb for weight estimation of standard lightweighted mirrors:

$$M = 2700 * \frac{\rho}{E} D^{2.7} \quad \text{for a WFE-rms of } \Delta y \approx 20 \text{ nm} \qquad (2)$$

or

$$M = \frac{1.2 * 10^4}{\sqrt{\Delta y}} \frac{\rho}{E} D^{2.7} \qquad (3)$$

with M in [kg], D in [m], E in [GPa], ρ in [g/cm3], and Δy in [nm].
Large optical telescopes in space ask for lighter primary mirrors than the existing ones. So, for instance, the New Generation Space Telescope (NGST) has a scheduled weight of 500 kg for a 8 m diameter primary. This figure is off from the present technology status by a factor of 10.

To cope with weight constraints in space, ultralight mirror technologies must be developed which no longer are based on inherently stable structures. Mirrors and structures will become "floppy"; active or adaptive measures for wavefront correction will be inevitable for diffraction limited operation.

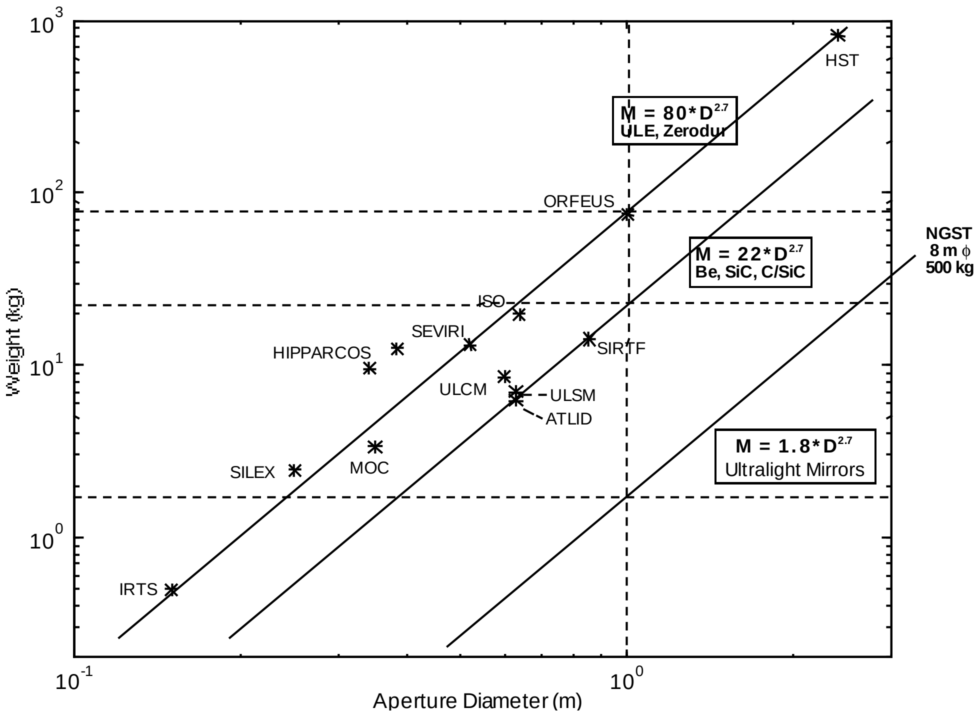

Fig.1: Weight-diameter dependence of space telescope primary mirrors

2. Ultralight Mirrors and Wavefront Errors

The three classes of ultralight mirrors are:

(a) thin meniscus

These are mirrors with a thickness-to-diameter ratio of 1:30 to 1:50, which are generally not structured. The thin meniscus must be supported to a rigid structure, which can be made from a favourable material (e.g. CFRP - carbon fiber reinforced plastic).

(b) ultralightweighted mirror

It consists of a very thin facesheet and a lightweighted support structure which is an integral constituent of the mirror. Both parts generally are of the same material to avoid distortions by thermal stress.

(c) segmented mirror

Segmented mirrors are composed of ultralight mirror elements. The avoidance of wavefront discontinuities at the segment edges is a demanding task with segmented mirrors.

The wavefront error sources with segmented mirrors are manifold. For simplicity, we restrict our discussion of mirror distortions to thin meniscus or ultralightweighted monolithic mirrors. The major wavefront distortions come from:

(1) manufacturing errors
(2) gravity release
(3) thermal effects & CTE (coefficient of thermal expansion) mismatch
(4) mounting stress & bimetallic bending

The type and magnitude of WFE which we expect from the distortions of a 3 m monolithic mirror and from the misalignment of the telescope structure are discussed in the following. The resulting rms-WFE and the corresponding Zenike coefficients are compiled in Table 1.

2.1 Manufacturing errors

With the aid of computer controlled polishing and ion surface figuring it is possible to obtain diffraction limited performance even with large mirrors. But the costs rise dramatically with diameters larger than 1 m. This is mainly due to the increasing effort for the handling and testing gear. Therefore, it seems reasonable to dispense the ultimate surface fit in favour of an adaptive correction method. The typical large optics manufacturing error is a low spatial frequency one which leads to a flattening at the outer edge and can roughly be described by

$$\Delta y = a_1 \cdot \sin^2(\pi \cdot r / D) \qquad (4)$$

where Δy is the deviation from the ideal mirror shape (parabolic or hyperbolic). For a D = 3 m diameter mirror we assume the amplitude of the deviation a_1 = 1 lambda (@ 550 nm).

2.2 Gravity release
A gravitational sag is expected in the support structure which shows in a radially symmetric deviation in the mirror surface. The deformation will be a parbolic distortion

$$\Delta y = a_2 \cdot (r / D)^2 \qquad (5)$$

Again we assume a deviation of 1 lamda over the surface, a_2 = 1 lambda (@ 550 nm).

2.3 Thermal effects
Thermal effect in ultralightweighted mirrors are small but a two-blade error due to the residual anistropy of the facesheet and support structure is most likely with thin meniscus mirrors. With ΔT = 20 K from the perfect alignment conditions and an anisotropy of ΔCTE = 10^{-8} we obtain a barrel-type deformation of $2.5\text{x}10^{-6}$ m.

2.4 Mounting stress (1) - three-blade error due to tripod mount
The tripod mounting of the mirror support structure gives rise to three-blade deformation of $2.5\text{x}10^{-6}$ m maximum.

2.5 Mounting stress (2) - high spatial frequency due to "print-throughs"
In general, the fixations of the thin meniscus to the support are arranged at regular intervals, and bumps may be imaged to the mirror surface with the periodicity of the fixations, coming from mounting stress and CTE mismatch. Typically such "print-throughs" are parabola shaped. However, the amplitudes of this high-frequency distortions can be made much smaller than the low-frequency distortions by chosing optimally matched materials for the fixations.

2.6 Longitudinal alignment error - from assembly inaccuracy and CTE of CFRP tripod
As a realistic example we assume a CFRP metering structure with an CTE = $2*10^{-7}$ and ΔT = 10 K which leads to a longitudinal displacement of 10 µm.

2.7 Lateral alignment error - from temperature gradient of CFRP tripod
A lateral displacement between primary and secondary will lead mainly to tilt, astigmatism and coma in the resulting output wavefront. In our D = 3 m optical model a lateral sift of 1 mm between primary and secondary mirror leads to the Zernikes as shown in Table 1.

Error Source	**rms**	**Z1**	**Z3**	**Z4**	**Z5**	**Z6**	**Z8**	**Z9**	**Z11**	**Z15**	**Z18**	**Z24**
Manufacturing	0.52		-0.929				0.418			-0.045		0.004
Gravity Release	0.55		-0.984				0.01					
Thermal Effects	3.68			-9.0		0.08			0.03			
Mounting Stress (1)	3.26							-9.0	0.03		0.023	
Longit. Alignment	0.14		0.241									
Lateral Alignment	0.67	-3.65			0.37	-1.81						
Angular Alignment	0.03	0.16			-0.02	0.08						
Sum of all Errors	5.015	-3.49	-1.67	-9.0	0.35	-1.65	0.428	-9.0	0.06	-0.045	0.023	0.004

Table 1: Zernike polynomial coefficients of analysed errors
(high-spatial frequency mounting stress not included)

2.8 Angular alignment error - from temperature gradient of CFRP tripod

A slight tilt due to temperature gradients on the tripod structure will again lead to tilt, astigmatism and coma in the resulting output wavefront. In our numerical example a Z1- coefficient of $5x10^{-6}$ m is assumed for tilt. Such a value would also correspond to a temperature gradient of 20 K across a 3 m primary mirror of CTE = $2x10^{-6}$ K^{-1}.

All the above error sources are practically independent from each other; therefore, they can be superposed by simple addition of the Zernikes. The resulting WFE is depicted in Fig. 2.

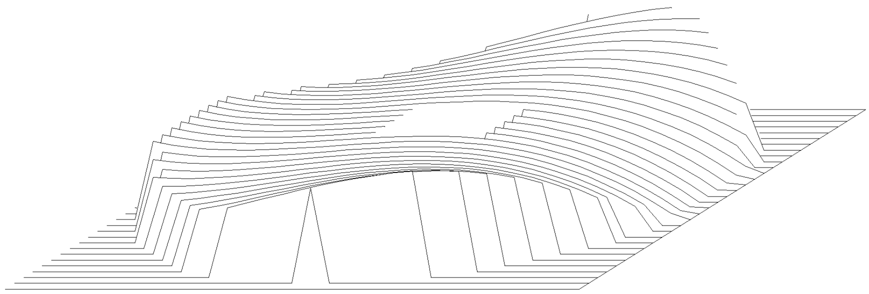

Fig. 2: Superposition of wavefront errors

3. Micromachined Membrane Deformable Mirror

In our optical model with a passive primary mirror it is the task of the adaptive optics to correct as far as possible all the above WFE contributions. Practically all WFEs are of low spatial frequency (except those from the cellular structured support for the thin facesheet), and are either static or slowly varying. Therefore, the most demanding requirement for ground observatories - fast sensing and speed of response - is not important in space. Besides optical quality, reliability and cost, the aspects of size, weight, power consumption and durability are by far more dominant in space. In particular, the following approach has to be followed:

<u>3.1 Basic design of a wavefront corrector</u>
Deformable mirrors should be small, light, consume low power and should be fabricated using inexpensive micromachining technologies. On the other hand, small deformable mirror will impose additional restrictions onto the instrument field of view and might complicate the instrument design, especially for primary diameter in excess of 2 meters. Deformable mirror with 30 to 50 mm aperture may be used with a primary of up to 3 m in diameter and allows for relatively inexpensive fabrication using micromachining technologies.

<u>3.2 Range of surface deformations</u>
Even if the wavefront tilts and translation due to thermal effects are excluded from the consideration as they can be corrected by simple re-alignment of the system, the expected wavefront deformation may have amplitudes of several micrometers for ultralight optics. To preserve a considerable field of view the wavefront deformations of the light-weight telescope must not be too large and the range of deformable mirror correction should not exceed significantly the value of 10 µm.

<u>3.3 Power consumption</u>
should be minimized and should not exceed 30 W under operational conditions.

<u>3.4 Speed of response</u>
is not very critical for thermal deformations, response time of the order of 1s is acceptable.

3.5 The number of actuators

The major wavefront errors analyzed in the previous section have low-order nature. In the case of ideal corrector with Zernike response functions, only 24 channels are needed to correct for all mentioned low-frequency aberrations. In practice, the number of degrees of freedom should be at least twice this number because of approximation errors.

3.6 Temperature range

The deformable mirror should be able to operate at room temperature and at cryogenic temperatures of the order of 30 to 70K.

4. Deformable Mirror Design Approach

In view of the above aspects the technology of micromachined membrane deformable mirrors (MMDM)[3] seems to be quite adequate for space application.

A micromachined mirror essentially consists of a thin flexible membrane of low-stress silicon nitride fabricated by isotropic etching into a bulk silicon die. The membrane is coated with a reflective material, preferably aluminium, gold is also possible. It can be locally deflected by applying voltages to electrostatic actuators. The actuator structure may be integrated on a silicon wafer together with the control electronics. The most economic way is a hybrid combination of the MMDM with a printed circuit board (PCB) which contains the actuator structures and the analog control electronics. The mirror schematic is shown in Fig. 3.

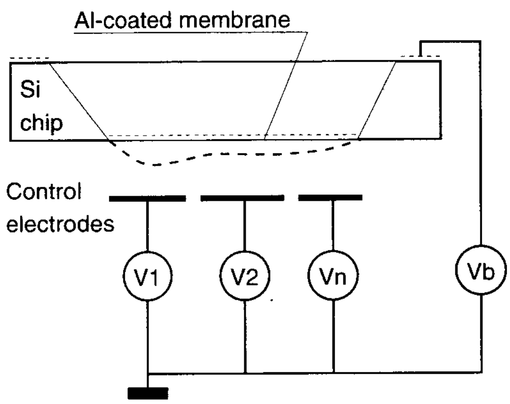

Fig. 3: Micromachined membrane mirror - schematic

Fig.4: 25 mm micromachined membrane mirror

Compact and lightweight metal-coated MMDMs provide a good correction quality for low-order aberrations, can work in a wide spectral range, consume less than 0.15 W per control channel and can be operated at low temperatures.

A fabricated prototype of 25 mm clear aperture which presently is being tested at TU Delft is shown in Fig. 4. Further work will be directed to the fabrication of membrane mirrors with larger diameters of the reflective membrane, up to 50 mm seem possible. A breadboard prototype of an adaptive optical system with an effective correction diameter of 35 mm will be assembled and tested in a following step that should satisfy the majority of the technical requirements listed in the previous section.

References

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