Design of the Science-Fold Mirrors for the Gemini Telescopes

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ABSTRACT

As a part of the Acquisition and Guidance Unit for the Gemini project a light-weight, 50cm flat mirror has been designed at the Fraunhofer Institute for Applied Optics and Precision Mechanics in Jena as a subcontractor of the Carl Zeiss Jena company. A light-weight design of the mirror and its mount was essential since the total mass of the whole assembly including the positioning system was limited to 50 kg while interferometric quality of the mirror surface was required for arbitrary orientation. The overall surface error was below 54 nm r.m.s. while 27 nm was achieved in the central part. The mirror was fabricated from low-expansion glass ceramics to avoid thermally induced deformations. By milling pockets into its rear surface the mass of the mirror was reduced by 70%. The mirror is mounted cinematically via six solid-state hinges to three steel levers. The levers are connected to the mount frame at their centers via ball-and-sphere joints. This arrangement determines the position of the mirror uniquely while it allows for the thermal expansion of the mount frame. The position of the mirror as well as its tilt around an axis perpendicular to the optical one may be controlled a precision of 20μm and 3 arcsec, respectively. The tilt axis is driven directly by two high-torque motors. To avoid an excessive power consumption of the motors the torque of the mirror had to be compensated for by a counterweight mechanism. The mirror may be deployed into the optical path using spindle driven linear rails.

Keywords: light-weight mirror, glass ceramics, cinematic mount, Gemini-project

1. INTRODUCTION

As part of the eight-meter GEMINI-telescopes a controllable, flat mirror with 50 centimeter diameter, the so-called "Science Fold Mirror", has been developed at the Fraunhofer Institute for Applied Optics and Precision Mechanics in Jena as a subcontractor of the Carl Zeiss Jena company. Located inside the Acquisition and Guidance Unit (AGU) of the telescope the mirror directs light from the main optical path as well as from calibration sources to the scientific instruments attached to the different ports of the instrument support structure (ISS). A scheme of the AGU is given in figure 1. The Science Fold Mirror is located on the second level.

The function of the mirror requires it to be tilted about its horizontal as well as vertical axes with an accuracy of 3 seconds of arc. Furthermore the mirror has to be positioned in and retracted from the optical path using linear slides. Its position should be maintained with an accuracy of 20 μm. These tolerances have to be guaranteed for arbitrary orientation of the telescope and different temperatures.

Since the mirror is located behind the adaptive optics module stringent requirements on the surface flatness had to be fulfilled. A r.m.s. surface quality better than λ/20 in any central 100 mm patch or λ/5 over the whole mirror should be maintained.

In *Optical Design, Materials, Fabrication, and Maintenance*, Philippe Dierickx, Editor,
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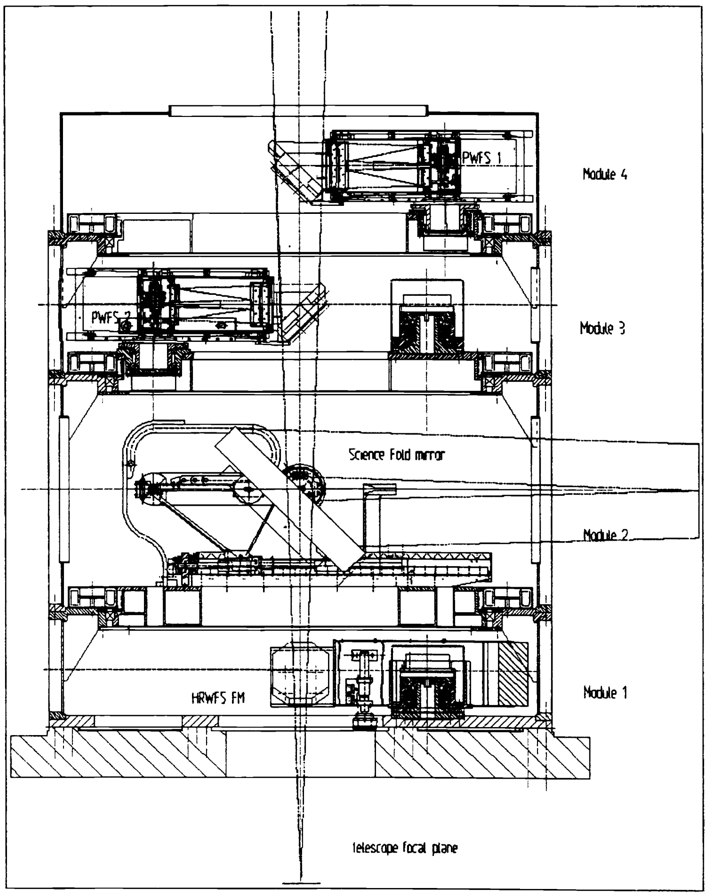

Fig. 1: Scheme of the Acquisition and Guidance Unit of the GEMINI telescopes (courtesy Carl Zeiss Jena[5]). The Science Fold Mirror is located on the second level (Module 2).

The total mass of the mirror, including mounts and deployment mechanism, was limited to 50 kg. For this reason a light weight design was critical.

2. DESIGN OF THE MIRROR

In a first step we performed semi-analytical calculations based on a polynomial fit to the deformation required by plate-bending theory[1]. The results were employed to optimize the mount design, in particular to find the number of support points necessary to fulfill the flatness requirements. The second goal was to determine their optimum position.

On the basis of these simulation results we decided to chose a 6-point cinematic mount. Simpler solutions like e.g. mounting the mirror at two points at its rim would have required a much too thick and hence too heavy mirror. The optimum mount points are located 60° from each other at 65% of the respective radius. These values agree reasonably with those given in the literature[2]. The deformations of this particular mirror geometry under gravity load perpendicular to its surface are depicted in figure 2.

The next step was the design of the lightweight structure. The goal was a maximum stiffness as well as compatibility with the existing technology. The mirror was made from glass ceramics to minimize thermal effects[3]. Light-weighting was achieved by machining pockets into the rear of a massive mirror blank.

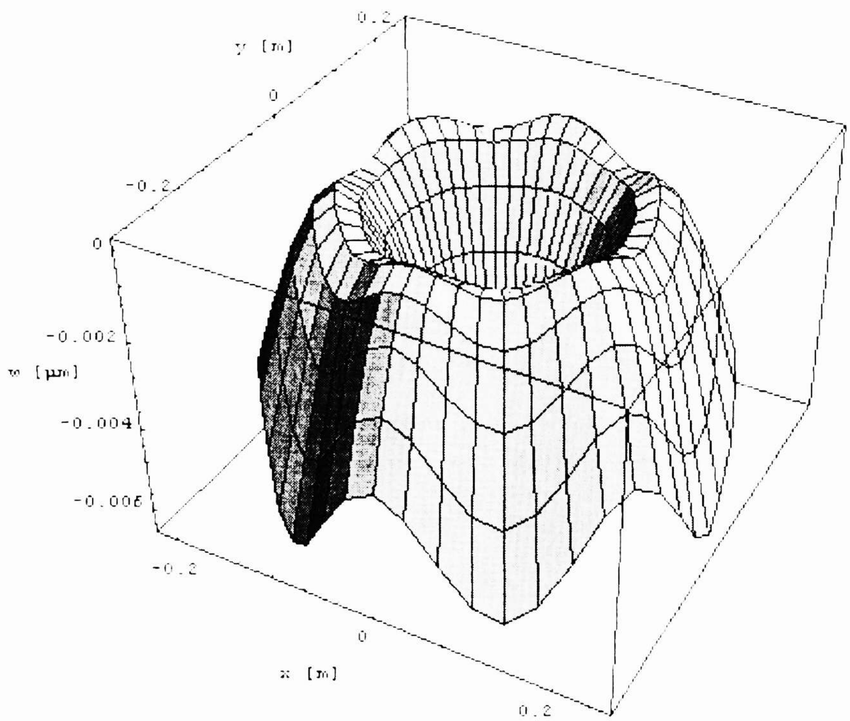

Fig. 2: Deformation of a massive, 80 mm thick glass ceramics mirror of 500 mm diameter under gravity load perpendicular to its surface.

FEM calculations (see fig. 3) were used to optimize the shape of the pockets as well as to verify the results of the semi-analytical calculations. The favorite design has both triangular and quadrilateral pockets while competing honeycomb structure was found to be slightly less stiff. The resulting deformations for the chosen design under gravity load are depicted in figure 3. The deformation pattern is similar to the analytical results. However the maximum deformation amounts to 28 nm instead of 7 nm for the massive plate. This loss of stiffness is due to the fact that most of the rear surface of the mirror blank had to be removed in the milling process.

During light-weighting the mass of the mirror was reduced to approximately one third. The remaining material thickness both in the front plane and the cell walls was limited by the milling technology rather than by stiffness considerations. The light-weight structure of the uncoated mirror blank is demonstrated in fig. 4.

Wavefront measurements[4] for 9 patches with 100 mm diameter each were performed at Zeiss. The corresponding results for the strap-mounted mirror are given in Table 1:

Location from center [mm]	75	75	75	75	180	180	180	180	0
Subpupil Nr.	1	2	3	4	5	6	7	8	9
r.m.s. wavefront error [nm]	9.5	8.4	7.0	6.4	8.8	9.1	15.2	11.9	6.4
p.-v. wavefront error [nm]	55.0	53.0	38.7	35.3	60	63.9	80.9	62.2	49.1

Note: patches 6 and 8 are located above a mount point

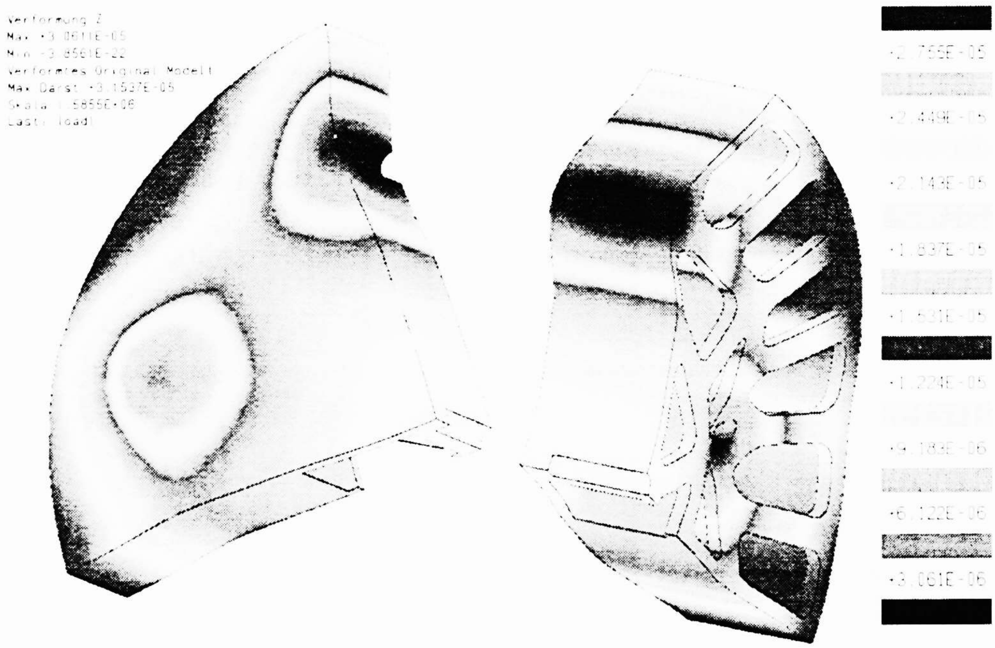

Fig. 3: FEM calculation of the deformation of the mirror under gravity load perpendicular to its surface. The maximum deformation is 28 nm at the rim). Because of the symmetry of the mirror only one quarter had to be calculated.

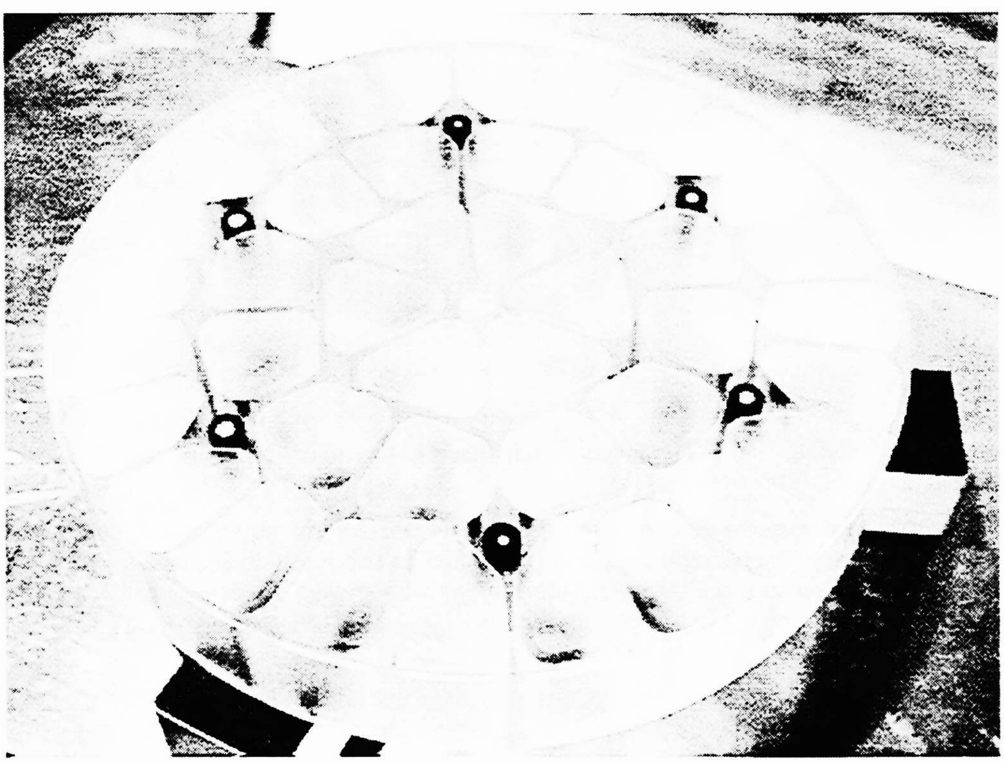

Fig. 4: The uncoated mirror blank. The pockets as well as the mount points are clearly visible through the front plate.

3. DESIGN OF THE MIRROR MOUNT

The mirror is mounted to a welded steel frame which connects the six mount point at the mirror with the tilt axis.

Solid state hinges are glued to the mirror at each mount point. They allow for the differing thermal expansion of the mirror and its mount structure as well as for deformations of the frame and for production tolerances. To avoid over-constraining of the mirror each pair of adjacent hinges is connected by a moveable beam, each of which interfaces to the mounting frame with a single ball-and-sphere joint.

The frame was optimized by FEM modeling for minimum deflection under gravity load while its mass had to be minimized. The resulting design is depicted in figure 5.

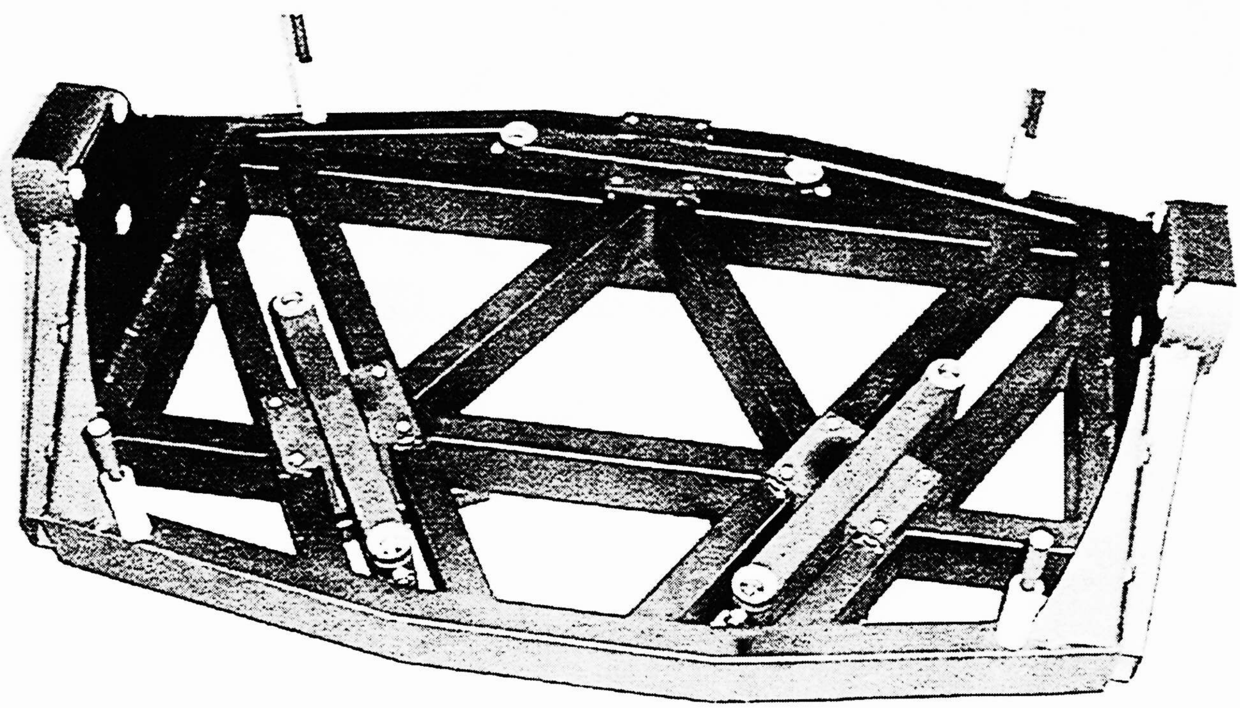

Fig. 5: Welded steel construction of the mounting frame. The levers which attach to the mount point are clearly visible. The tilt axis attaches to the left and right of the frame.

The tilt axis of the mirror is driven directly by one motor on each side. Additionally one side carries an angular encoder to control the mirror's tilt. The whole mirror assembly including the tilt axis is mounted on two linear slides, one on each side of the optical path. The spindle driven slides allow to place the mirror into the optical path with a precision below 10 µm. On the other hand the mirror may be retracted into a parking and maintenance position. Optical encoders are used for position control.

The remaining deformations under arbitrarily directed gravity load were calculated by FEM as well as checked experimentally. Because of the restrictions introduced by the given mass limit the remaining deformations exceeded the required tolerances. However, their influence as well as thermal effects could be included into the positioning software as a correction matrix.

The whole mirror assembly rests on a turntable which allows for a ±220° rotation about the optical axis of the telescope. This can be seen in the scheme of the complete AGU given in figure 1. The complete assembly of the Science Fold Mirror during integration is depicted in figure 6.

To avoid excessive power consumption of the motors when the mirror is holding its position, the torque about the tilt axis had to be compensated for mechanically. The mechanics used for torque compensation had to be installed behind the mirror because it may not obstruct the optical path. It consists of one counterweight lever on each side of the mirror. The connection between the tilt axis and the counterweights represents a critical part of the design. Because of the high precision requirements on the tilt angle any backlash or stick-slip effects had to be avoided. Furthermore the connection must be stiff enough to avoid interference with the control system. For these reasons we decided to choose a belt drive to connect the counterweights with the tilt axis.

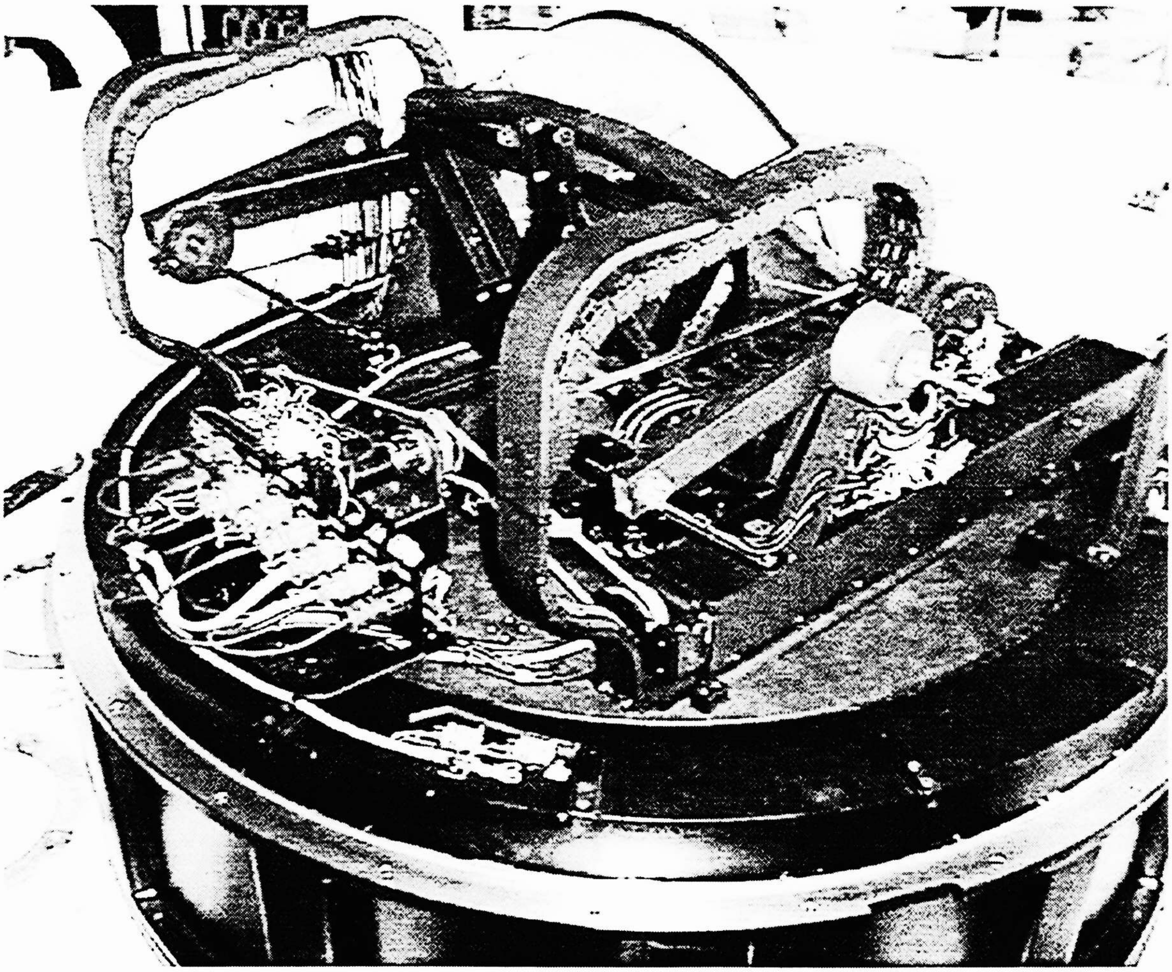

Fig. 6: The Science Fold Mirror for the first GEMINI telescope during assembly. The mirror depicted in the photograph is an aluminum dummy which was used for coarse adjustment. Note the levers for torque compensation which are located behind the mirror.

4. SUMMARY

In the present paper a light weight mirror assembly was presented which is used inside the Acquisition and Guidance Unit of the GEMINI telescopes. It allows for a positioning accuracy better than 3 seconds of arc in tilt and rotation as well as 20 μm for its radial position. The remaining surface errors complied with the required overall flatness of 54 nm r.m.s. and 27 nm r.m.s. central part, respectively.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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