LARGE MIRROR FIGURING AND TESTING*

K. BECKSTETTE, M. KÜCHEL, and E. HEYNACHER

Carl Zeiss O-Labor, Oberkochen, F.R.G.

(Received 8 February, 1989)

Abstract. We describe a method for figuring and testing large aspheric mirrors using a rectangular, flexible lap (the so-called 'Membrane Tool') and a vibration stabilized interferometer. The rear side of the lap is covered with computer controlled dynamic pressure actuators which determine the amount of material to be removed for surface error correction. This method has been developed in the laboratory and tested to some extent by figuring the *f*/2.2 primary of the 3.6 m ESO–NTT. We describe the ongoing developments and the manufacturing plan for 8 m-class mirrors.

1. Introduction

Many large telescope projects with 8 m-class primaries are under discussion or even have been started during the last years. One example is the *f*/2.0, 7.5 m diameter primary of the JNLT to which this meeting is devoted. In order to keep telescopes reasonably compact, these mirrors will have focal ratios between 1 and 2, considerably faster than any existing astronomical telescope. They present a serious technological challenge, because of their size, accuracy requirements and their asphericity.

The difficulty of polishing increases with asphericity, as the natural tendency of the polishing process is to produce spherical surfaces. The asphericity, the deviation of the surface from the closest sphere, increases dramatically with faster focal ratios: i.e.,

$$dz \approx D(D/F)^3 .$$

The absolute value of dz depends on the fit parameter for the reference sphere. Table I lists asphericities for various mirrors, including the *f*/1.0, 500 mm diameter mirror currently being polished as part of the membrane tool process (MTP) development for the SOFIA *f*/1.0, 3 m primary.

TABLE I

Typical asphericities

Telescope	Focal ratio	Diameter (m)	dz (μm)	Relative factor
JNLT	2.0	7.5	580	2.7
VLT	1.8	8.2	870	4.2
NTT	2.2	3.6	210	1.0
SOFIA	1.0	3.0	1860	8.9
Test	1.0	0.5	310	1.5

* Paper presented at the Symposium on the JNLT and Related Engineering Developments, Tokyo, November 29–December 2, 1988.

Astrophysics and Space Science **160**: 207–214, 1989.

The table shows that even the small $f/1.0$ test mirror has a higher asphericity than the fastest large astronomical mirror polished to date, the ESO–NTT primary.

Testing has always been an essential tool to the optician. For the new class of large telescope mirrors, testing problems arise due to the long focal length, asking for insensitivity of the test method to air turbulences and vibrations. The huge size requires higher lateral resolution to detect high-frequency errors.

2. Traditional Techniques for Making Fast Aspheres

The traditional process of making large aspheric mirrors for astronomical telescopes makes use of the fact that it is easily possible to polish spherical mirrors to very high precision with simple equipment. By use of this first step of lapping (or loose abrasive grinding) and polishing the best fitting sphere, has the big advantage, that a nearly perfect rotational symmetric workpiece is the starting pont for the aspheric figuring process.

Based on this symmetry, the iterative aspherisation process with medium size tools can be carried out relatively fast. The remaining non-rotational symmetric errors cause the use of smaller and smaller laps measuring $\frac{1}{100}$ or less of the mirror area and are the reason for time-consuming local fine correction. Additionally these small tools tend to produce zones and ripples appearing on smaller and smaller spatial scales. The whole process depends heavily on measuring the actual surface shape after every correction step. Logical evolutions of this traditional technique are:

– *Large area compensated tools*: A large tool (approximately workpiece dimension) is moved across the mirror. Due to different tangential and sagittal radii, only small amplitude motions are allowed. Local corrections are then performed by area weighted pitch trimming (petal tool). Of course trimming has often to be changed according to the actual surface profile. Therefore, tedious and time-consuming work is necessary acquiring, in addition, a high degree of experience.

– *The computer-controlled polisher* (*CCP*), a system which is well known in literature and has been used successfully for small to moderate-size optics (Jones, 1982). Here a very small lap with small polishing strokes is guided on its patch across the work. The removal pattern is realized by dwelling more or less on a spot depending on whether it is high or low. Good results concerning acute edges and the development of r.m.s.-values were reported.

3. Special Problems for 8 m-Class Mirrors

The traditional method can be pushed to make somewhat larger or faster mirrors but the difficulty increases rapidly with increasing asphericity. The major problems for the conventional methods are:

– *Material removal*: Comparing for example a 3.5 m, $f/3.7$ mirror to a 7.5 m, $f/2.0$ mirror, the volume of the material to be removed by polishing when starting the aspherisation from the sphere, increases by nearly two orders of magnitude. Even if the relative diameter for the tool used would be the same, the aspherisation process would last ten times longer.

– *Tool handling and preparation*: For the manufacturing of 3.5 m mirrors, laps of 3.5 m diameter have been used. It seems not possible to handle and prepare 8 m diameter laps in a reasonable time and with appropriate safety.

– *Local error correction*: Starting with aspericities of less than 50 μm, the traditional techniques could rely on producing the aspheric deformation by polishing and on saving the rotational symmetry during the aspherisation process. Increasing the deviation by more than an order of magnitude and keeping into account, that more flexible laps have to be used, would also increase the remaining non-rotational symmetric errors by more than a factor of 10! This means that the iterative method of local fine correction with small tools would be very time consuming and perhaps will not converge at all.

These considerations led us to the conclusion that a method for making large fast primaries should fulfill the following requirements:

– generation of the asphere by diamond wheel grinding;

– process designed to remove relative large errors of the grinding step on the aspheric surface; i.e., a lapping not a polishing process!

– large tool area for volume removal;

– to be used for figuring and fine correction without modification;

– relative stiff tool to prevent ripple production;

– fast tool preparation;

– fast and environment insensitive metrology useful during lapping and polishing.

The following chapters contain a detailed discussion of two main components for successfully polishing a large mirror, starting from the diamond wheel ground state: the tool and the metrology.

4. The Membrane Tool Process

The fundamental assumption of all removal predicting theories is given by Preston's law (Preston, 1927) which states that the wear per unit time is proportional to relative velocity and tool pressure. The basic idea in our process of membrane polishing is to split the polishing process into its relevant parts, i.e., relative motion and local pressure (Figure 1).

The tool consists of two major parts: a relative thin membrane which carries the polishing pitch and performs the relative motion between tool and workpiece and a set of actuators at the tool's rear side which apply the necessary removal pressure. This pressure is dynamically controlled by a computer. This lap works in principle like an arrangement of many small size laps, used, i.e., on the CCP, working in parallel. The actual removal of each *subtool* is controlled by the pressure applied through the actuator in contrast to the dwell time approach of the CCP. The membrane is designed flexible enough to accommodate the desired variations in curvature of the asphere and stiff enough to provide a smooth print-through function for the actuators.

There are some important advantages in this membrane tool approach compared to the discussed techniques:

– The tool can actively remove errors with low and medium spatial scales. The

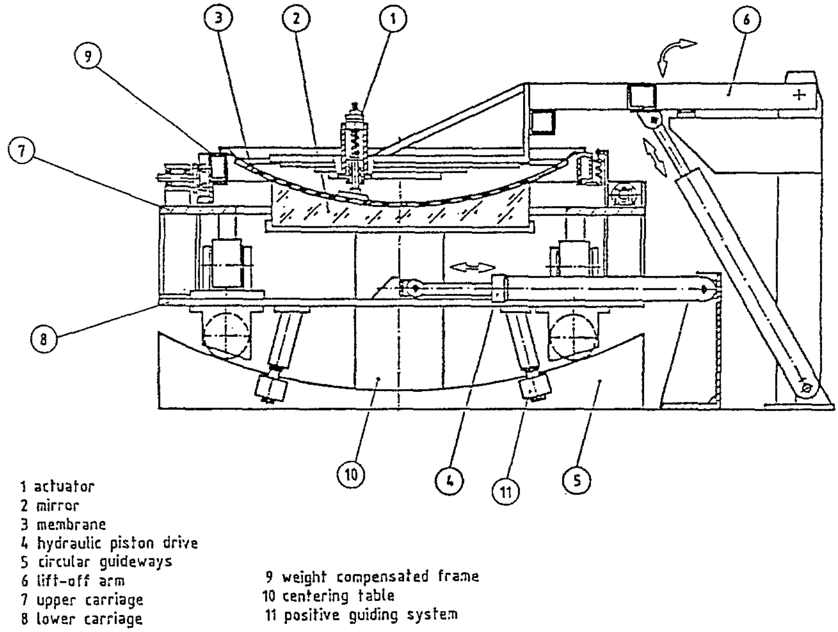

Fig. 1. Principle of the membrane polisher.

smallest spatial scale error which can actively be reduced is only determined by the actuator size.

– The tool does not rely on its own shape or the shape of the mirror to remove the low-frequency errors. This reduces mirror support problems during manufacturing and also opens the possibility to design a tool flexible enough to accommodate the variations in curvature of the asphere.

– As the tool covers (at least in one dimension, see below) the whole surface of the work it can apply bending moments at the edges of the *subtools* which prevents the inherent edge problems of small laps and the production of ripples.

– The tool area can easily be made large, producing a good volume removal to accommodate the large surface errors produced by diamond wheel grinding.

– To change the removal function from one iteration step to the other, no tool preparation time is needed. The metrology data can, after some mathematical modifications, directly be fed into the control computer.

– Producing a *hole* in the surface during fine correction with a small area lap can be a big problem, as the whole surface of the mirror has to be *set back* with the small lap, a very time-consuming and error prone process. That is why the optician and even the CCP tend to remove during one iteration step less material than predicted. The membrane tool, working all the time on the whole surface area overcomes this problem; the convergence factor can be increased.

Figure 2 shows a setup of this tool especially adapted to the configuration for manufacturing a large primary. The tool has a rectangular shape. The relative motion

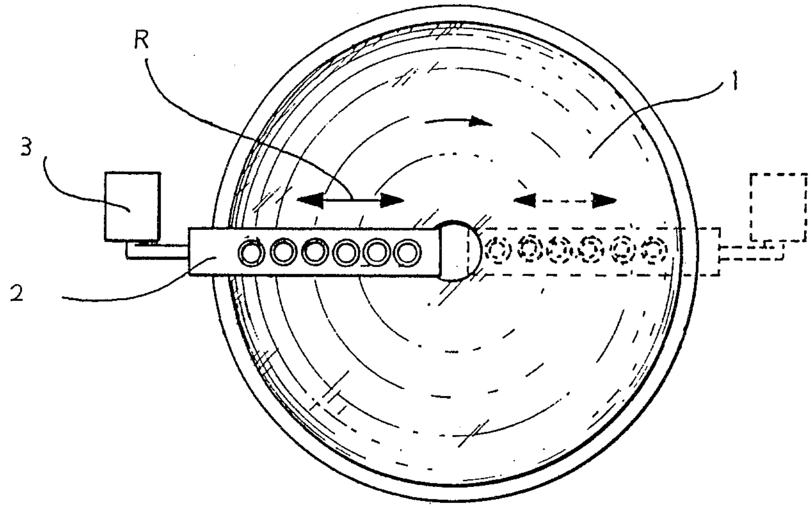

Fig. 2. Membrane Tool for rotational symmetric parts: (1) rotating mirror, (2) oscillating membrane tool, (3) tool drive.

between tool and mirror is performed by rotating the mirror and radially stroking the tool.

5. Testing as an Integral Tool

As figuring of large aspheres has and will be performed in an iterative approach where the results of metrology determine the next polishing step, testing has to be addressed as an integral part of the fabrication process. The convergence of the process is not only driven by the predictability of the tool removal but also by metrological accuracy. Two subsequent test results are used to predict the tool behaviour for the next polishing step. Thus high accuracy is required for a controlled and fast converging process. Metrology closes the feedback loop in a closed-loop controlled process.

Additionally, as discussed above, when starting from the diamond wheel ground asphere, the test method has to accept a rough surface with relative large errors. Regarding the large dimensions of the test tower, two additional requirements on metrology arise when manufacturing a large mirror:

- insensitivity against air turbulence;
- insensitivity against vibration.

All these different aspects were covered when lapping and polishing the ESO–NTT. So we report here the test methods used and discuss the enhancements required to manufacture a very large mirror.

5.1. IR-interferometry for the ESO–NTT primary

When figuring the ESO–NTT primary with lapping, IR-interferometry at a wavelength of 10.6 μm (CO_2) was used. In contrast to the manufacturing plan for an 8 m-class mirror where we will start from a CNC ground asphere, the NTT primary was figured with lapping, starting from the sphere. The figuring was performed in many cycles of measurement and lapping, until the final aspheric shape of the mirror was reached. Null lenses where used to adapt the plane wave from the Twyman–Green interferometer to the aspheric surface. The detector in the IR-interferometer was a pyro-electric vidicon. Taking into account the MTF of the vidicon, approximately 2000 points are resolved on the mirror. Phase-shifting interferometry is used to obtain a measurement precision despite the large wavelength of the used light. The interferometer was controlled by a micro-computer which also performs the on-line data analysis. The pointwise reproducibility of the measured mirror surface was approximately 250 nm, that is $\lambda/40$ for $\lambda = 10.6$ μm.

IR-interferometry is insensitive to air turbulences and vibrations. An enhancement of the existing setup would be to use a CCD with a higher resolution than the pyro-electric vidicon. Data for a *closed-loop* control of the membrane tool is available in the analysis computer.

5.2. VIS-INTERFEROMETRY FOR THE ESO–NTT PRIMARY

By use of a phase-shifting interferometer equipped with a high-resolution CCD-camera, working at He–Ne wavelength of 632.8 nm, the influence of air turbulence in the test tower can be reduced to harmless level by averaging data sets. Thus the speed of the individual measurement becomes important. For the 8 m-class mirrors the same simple and cheap approach can be used. But it has to be kept in mind, that the test tower length will grow by approximately a factor of 2 and that the air volume will increase by nearly a factor of 10! If the air turbulence effects are proportional to the air volume the number of the individual measurements has to be 100 times higher. For the manufacturing of a very large mirror, measurement speed will be increased by more than this factor.

Polishing the ESO–NTT primary, vibrations of the test tower are compensated by a 3-axis stabilization of the interferometer. The axial motion and the tilt of the mirror with respect to the interferometer is measured and fed to a control loop which performs the active stabilization by tip-tilt controlling a mirror in the beam path (Figure 3). Thus frequencies up to 1000 Hz can be eliminated. This allows measurements during the day, with running machines, air conditioning, etc. The stabilization system also introduces the required phase shifts for the data acquisition under control of a microcomputer. This microcomputer later performs the calculations for the wavefront at all the data points on the mirror, at present approximately 40 000 points. When manufacturing a very large mirror, it will be possible to increase this number by a factor of 20. The surface of an 8 m mirror can be measured at a sampling spacing of 8 mm by 8 mm.

Important for the reproducibility of the measurement is the number of individual wavefronts to be averaged. A good compromise between measurements time (see above) and precision, about 50 individual wavefronts were averaged, leading to a local uncertainty of the surface shape of approximately 4 nm.

One great advantage of computerized interferometry is the fact that the measured wavefronts are directly available for all kinds of mathematical analysis. In the case of the ESO–NTT primary it was important to reach the best possible ‘intrinsic quality’,

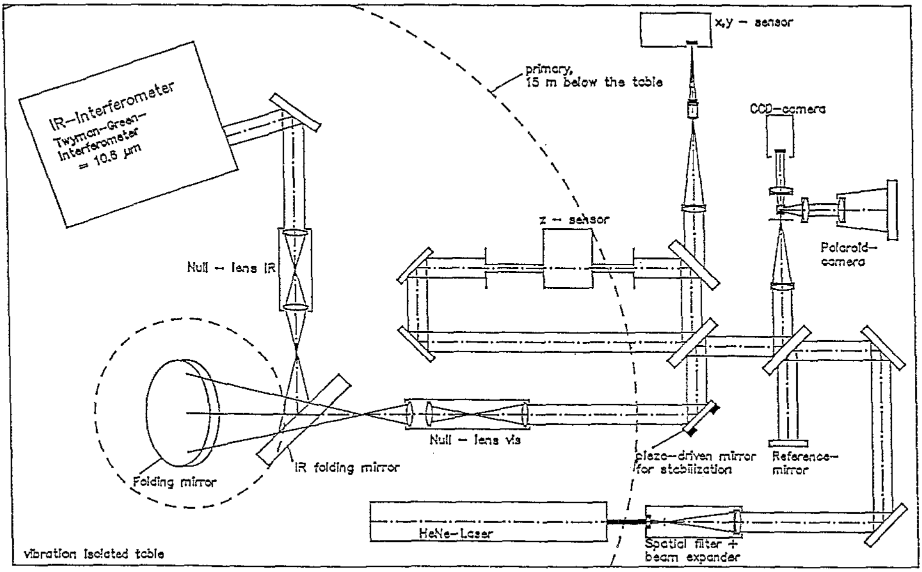

Fig. 3. Schematic of the vibration stabilized IR- and VIS-interferometer used for ESO–NTT.

which was defined through the geometric spot size E_{80} after the subtraction of various error terms from the wavefront. For analysis of the polishing process these error terms were routinely subtracted and the spot size calculated.

6. Development Steps Towards 8 m Diameter

The Membrane Tool Process is under ongoing development at Carl Zeiss. Starting with a setup of five linear arranged actuators over a five by five array, working on a plano surface, the membrane tool has been developed to an extent where good results have been shown on a 500 mm *f*/1 spherical mirror.

Two aspects of the Membrane Tool Process have been used, figuring the ESO–NTT 3.6 m *f*/2.2 primary:

- rectangular, non-rotating tools;
- computer controlled pressure actuator with dynamic pressure variation.

By use of these tools in cooperation with the above-mentioned metrology, it was possible to reach the final result of an 'intrinsic quality' $E^*_{80} = 0.096''$ with a complete computer controlled process. This intrinsic quality is the geometric spot size after subtraction of low-order Seidel terms: focus, decentering coma, third-order spherical aberration, third-order astigmatism, triangular coma, quadratic astigmatism.

A complete version of the Membrane Tool will be used during the mirror fabrication hardware study for the Stratospheric Observatory For Infrared Astronomy (SOFIA), a 3 m *f*/1 telescope to be flown on a Boeing 747. During this study which will be finished in mid-1989, a 500 mm *f*/1 Paraboloid with 50 mm thickness is manufactured, using the above discussed Membrane Tool Process.

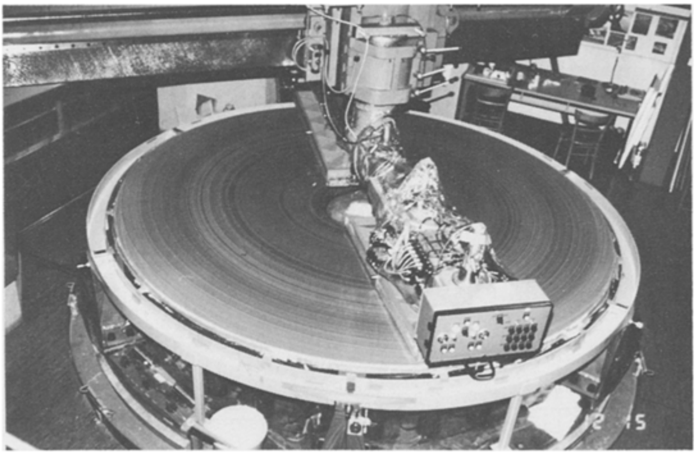

Fig. 4. Lapping the ESO–NTT primary with two rectangular tools.

7. Summary

Membrane Tool Polishing is a method especially designed to figure very large mirrors with low focal ratios in a short time. It has been extensively tested experimentally, principally verified polishing the ESO–NTT primary and will be fully developed for SOFIA. It shows a good convergence factor and produces superior optical quality. The estimated lead time for a 8 m-class mirror, starting from the aspheric ground surface is less than 2 years.

The measurement technology for manufacturing very large mirrors is available and tested. Further improvements with the trend towards shorter times for the data analysis and acquisition, more data points, and consequently towards a still higher precision are under an ongoing development.

References

Jones, R. A.: 1982, *Appl. Optics* **21**, 562.
Preston, F. W.: 1927, *J. Soc. Glass Techn.* **9**, 42.

WONG – Can the membrane lap handle non-axial-symmetrical or local error? And how?

BECKSTETTE – The membrane lap is designed to work on non-axial-symmetric errors. For these we used already a 500 mm full aperture size lap. Local errors can be handled by the computer-controlled actuator concept.

BECKERS – How fast an 8 m mirror can you polish with your membrane technique?

BECKSTETTE – We calculated the necessary membrane parameters for 8 m *f*/1.0 mirrors and also for non-symmetrical *f*/0.5–*f*/1.0 anamorphic mirrors. Both can be worked on without problems.

KODAIRA – How long a time will be needed for polishing and figuring of an 8 m-class mirror?

BECKSTETTE – Starting from a diamond-wheel ground surface of approximately 0.5 mm P/V, we expect approximately 1.5 years. It has to be tested, if this can be reduced to 1 year.