OPTICAL SHOP TESTING OF LIQUID MIRRORS

E. F. Borra, M. Beauchemin, R. Arsenault, R. Lalande
Physics Department, Laval University
Quebec G1K 7P4 - Canada

ABSTRACT - Borra (1982) has argued that it is scientifically useful and technically feasible to build very large optical telescopes (diameters over 15 meters) having as primary mirror a rotating container filled with mercury. We report here the results of various optical tests on prototype liquid mirrors. The results are very encouraging and seem to indicate that large liquid mirrors are feasible.

I. INTRODUCTION

In a recent publication Borra (1982) has argued that it should be possible to build very large optical telescopes, in the 30-meter diameter class, if we use as primary mirror a rotating container filled with mercury. The instrument proposed is strictly a zenith transit telescope as it cannot be tilted. This is, however, not a major limitation as alternative tracking techniques are available. For imagery, it is possible to use the electro-optical tracking technique described by McGraw, Angel and Sargent (1980). For spectroscopy, one can track the end of an optical fiber and pipe the light to a spectrograph on the ground (e.g. see Weedman 1984). These techniques are now possible thanks to modern technology and, in particular, the advent of fast computers, mass storage media (magnetic and optical disks), CCD detectors and fiber optics. The use of these techniques makes it thus possible to overcome the main limitation of the liquid mirror.

The scientific case for a large zenith instrument is also very strong. The sort of extragalactic research discussed by Oke (1984) in this colloquium could be carried out with a large liquid mirror telescope. If we want, for example, to study the evolution of galaxies or the clustering properties of galaxies at large redshift, the part of the sky one observes is not important. This is particularly true for cosmological observations and a very large liquid mirror telescope promises to be the ultimate cosmological instrument.

The liquid mirror concept, its practical considerations and the scien-

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tific case for such an instrument are fully discussed by Borra (1982).

We are now in the final stages of a feasibility study to determine whether, in practice, it is possible to generate an optical quality surface on a rotating liquid. This paper gives a progress report of the project.

II. PRESENT STATUS OF THE EXPERIMENT

We have built, spun and extensively tested a 1-m diameter f- 1.6 mirror. We have built and spun a 1.65-m diameter f-0.89 mirror. (Figure 1).

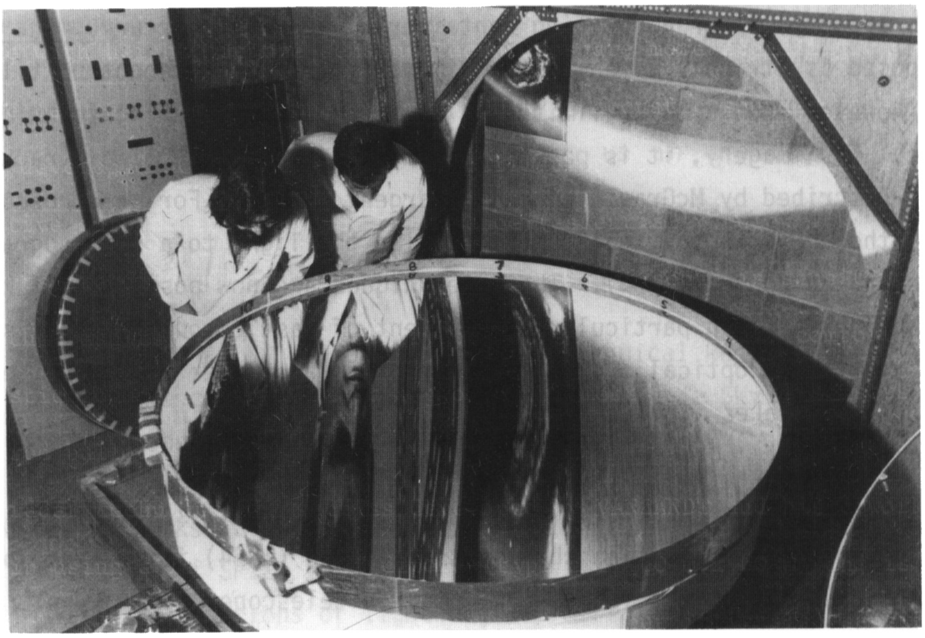

Figure 1

Liquid mirror having a diameter of 1.65 meter and 1.5 meters focal length.

This last mirror has not been fully tested yet, we will test it soon. Although it is just as easy to make slower mirrors, we have little choice in our focal length because we are limited by the height of the basement room in which we are working. Unfortunately fast mirrors are very difficult to test; this limitation has been a major cause of problems and delays.

Originally Borra (1982) anticipated three main sources of problems.

1) The rotational axis of the turntable must be aligned with respect to the vertical.

This has never been a problem as this alignement is not critical. We align the axis with a commercially available spirit level. One of our early surprises was to see that it is actually possible to tilt the mirror by several aroseconds without destroying the figure seen by a knife-edge test.

2) The most serious question raised by Borra (1982) was the very high stability needed for the rotational velocity in order to have a stable focus.

If we want a focus stable enough to yield images smaller than 0.2 arseconds, it can be shown that the rotational velocity of the turntable must be stable to better than one part in a million. This is a very severe requirement for a mechanical system. In practice, this has been the easiest problem to solve as knife-edge tests showed, from the very beginning, that the focus was rock-steady. The solution to the stability of the rotational velocity was the one proposed by Borra (1982). We drive the turntable with a synchronous motor and a loose belt. The motor is coupled to the turntable directly via the belt. The belt does not transmit any vibrations to the mercury. The reason for using a synchronous electromotor is that it rotates at a speed that is controlled by the frequency of the sinusoidal voltage signal that feeds it. We use a frequency controlled AC power supply. It is very easy to stabilize the power supply to better than one part in a million. The synchronous motor assures us thus that the rotational velocity of the turntable is constant on time scales larger than a full turn of the motor. The short-term stability (time scales of the order of, or smaller than, a full turn of the motor) is controlled by the inertia of the turntable that rotates on an air lubricated bearing. Airbearings have a very low friction coefficient. It can be appreciated that a high inertia turntable rotating on a nearly frictionless bearing will rotate at a constant speed.

3) Vibrations coming from the bearing, the drive, the floor and the air.

This has been a minor problem as our mirrors, viewed with a knife-edge test, show, at the center, concentric ripples induced by vibrations coming through the floor. These ripples have a low amplitude and do not affect the imagery, as is shown in Figure 2. Also, we would like to emphasize that these vibrations are present uniquely because of the poor location of the laboratory we are working in. Out of convenience, we are working in the basement of the Physics Department. This building, like any building, shakes and vibrates (we have several large pumps and motors running next door). The vibrations in the room are severe enough that,when we moved into the room, we could hear two pieces of sheet metal vibrating against each other. On an isolated mountain top and with a properly built mounting base, vibrations should not be seen at all.

III. OPTICAL SHOP TESTING

We performed three optical tests, imagery of a resolution bar-test chart, knife-edge test and Hartmann test. All the tests discussed from here on, have been performed on the 1-m mirror. We always worked at the center of curvature of this mirror. Knife-edge tests show the typical signature of a parabola (Ojeda-Castenada 1978). Because this parabola is very fast (f-1.6), it is difficult to see its edges with the knife-edge test. This test has been mostly useful to look at the central part of the mirror. The knife-edge test shows that concentric ripples are present on the surface of the mirror. They are caused by vibrations coming from the floor. These ripples have a very low amplitude and they do not affect the imagery (Figure 2). As mentioned earlier, these vibrations are due to the very poor location of the laboratory.

We have photographed a bar-test resolution chart (USAF.1951). The photograph was obtained with a 35 mm camera at the center of curvature of the 1-m mirror. A parabola, used at its center of curvature suffers from spherical aberration; we had therefore to diaphragm the mirror down to about 0.4 meters. Actually, because of vignetting, the pupil was elliptical in shape, measuring about 0.4 m along the major axis and 0.2 m along the minor axis. A reproduction of the photograph is shown in Figure 2.

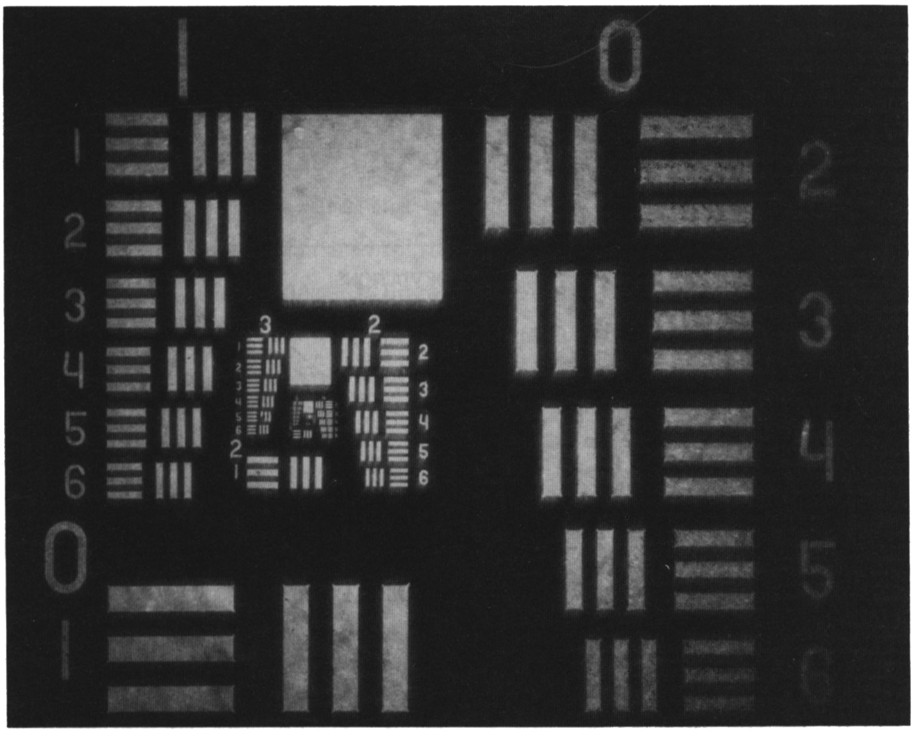

Figure 2

Photograph of a resolution bar-test chart enlarged about six times. Some resolution has been lost in the reproduction. Visual inspection of the original with a binocular microscope shows a resolution of 10 microns (1/2 arcseconds). The faint fuzz around the bars comes from spherical aberration (expected at the center of curvature of a parabola) and coma (off-axis imagery).

Some resolution is lost in the reproduction. Viewing the original picture with a binocular microscope, we can resolve bars as narrow as about 10 microns. This corresponds to about 1/2 arcseconds, close to the theoretical resolution for a mirror this size. Figure 2 shows some fuzz around the images. This is due to remaining spherical aberration. The fact that the fuzz is more important in one direction than the other comes from the fact that the pupil was elliptical.

Figure 3 shows the results of a Hartmann test.

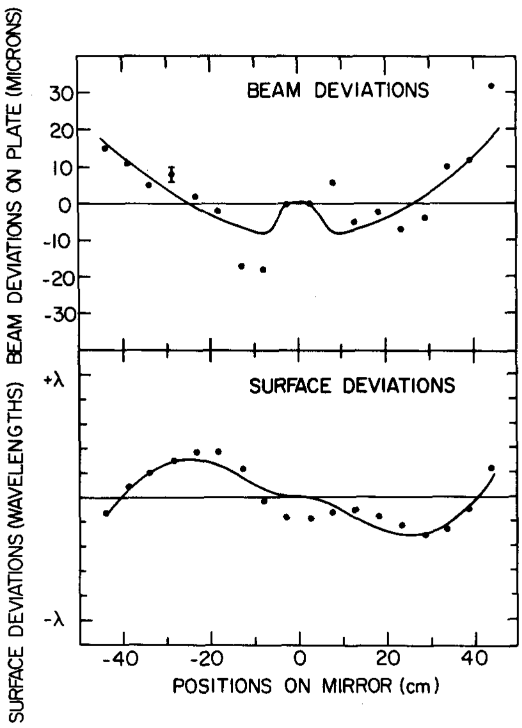

Figure 3

Results of Hartmann test (1-m f-1.65 mirror). See text for details.

The screen used is a linear screen. There is thus a single row of holes. We can rotate the screen at different azimuth angles. This particular test was made with the screen oriented in an East-West direction. The holes have half-inch diameter and are spaced two inches in between. We can see that nearly the entire diameter has been sampled. The last spots could not be measured because they fell right at the edges of the mirror. The full scale of the surface deviations in Fig. 3 is ± one wavelength (5,000 A). A small subdivision corresponds thus to 1/5 of a wave. The dots show our measurements. A perfect parabola would give a straight horizontal line. We can see what looks, at first sight, like a standing wave on the surface of the liquid, having a peak to peak amplitude of 0.7 waves. However, this is highly unlikely to be real. Consider that the exposure time of the Hartmann plate was 30 seconds and that the period of rotation of the mirror was 3.8 seconds; were the wave on the mirror, it would have to be a wave fixed in the reference frame of the laboratory. We ran computer simulations to see the effects that alignment uncertainties of the Hartmann test apparatus have on the surface deviations. The continuous line in Figure 3 is the result of a simulation in which we introduced a 0.5 mm misalignment in the Hartmann screen. This is about the error that we know we have in our system. Any alignment errors that we introduce in our system will give spurious surface deviations similar to the one seen in Figure 3. We can see that the simulation fits our data quite well. We believe therefore that the quality of the mirror is actually substantially better than seen in Figure 3 and is probably better than 0.1 waves. Notice that the measurement errors are not negligible. It is difficult to display the measurement errors in terms of surface deviations because surface deviations are obtained by integrating beam deviations (top portion of Fig. 3), which are the measured quantities. The errors in surface deviations are thus cumulative. To give an estimate of the errors, we display, in the top portion of Fig. 3, the errors (± one variance) associated with a measurement of the deviations. These are internal errors computed from the internal scatter coming from multiple measurements of the spots of the Hartmann plates.

IV. CONCLUSIONS

This work is not finished yet and this is a preliminary report. However, our testing is advanced enough that we can say with some confidence that, yes, it is possible to generate an optical quality surface on a rotating liquid. It is quite clear that the central part of the mirror is of optical quality and up to astronomical standards. This is shown by the knife-edge tests and by direct imagery. The Hartmann tests indicate that the ove-all shape of the mirror is parabolical within the tolerances necessary for astronomical work. A remaining question to answer concerns the quality of the surface, from diameters of 0.4 m to the edges, over regions smaller than the separation between two holes in the Hartmann screen (5 cm). The Hartmann test does not give us informations over regions that small and it is difficult to see the edges of such a fast parabola (f-1.6) with the knife-edge test. We will carry out a null test to view those regions as soon as we will have obtained the necessary null lenses. There is, however, some strong indications that these regions are also probably good. Notwithstanding the rapidly changing slopes near the edges, it is still possible to see the surface with the knife-edge and we do not see anything dramatic happening there.

We take this opportunity to answer some of the most frequently questions asked during private conversations at the meeting. The reflectivity of mercury is 80% in the visible rising to 90% at 13 microns. The metal itself is not toxic, although some salts are highly toxic. Mercury evaporates exceedingly slowly so that any ventilation will get rid of what little vapor there may be. Damping times against perturbations are short, of the order of a few seconds. Mercury gets dirty; however it is extremely easy to clean, so that, in practice, the reflectivity of a mercury mirror cleaned once a week will probably be better than that of an aluminum mirror cleaned once a year.

Finally, we wish to point out that making these mirrors has been very easy. What has been difficult and time consuming was setting up the testing facilities and testing these very fast mirrors. This project has been very cheap as well. No special funds were asked, the cost of the entire experiment being less than 10,000 dollars. This is, of course, quite relevant because this concept only makes sense if liquid mirrors can be made very large, very cheaply and very easily. Notice also that a transit telescope will have a cheaper frame and a cheaper observatory than a stearable telescope. As an illustration, Figure 4 shows an architect drawing of an observatory for a 6-m f-1 telescope. The cost of the structure (that uses a commercial grain silo) is about 30,000 dollars. One can appreciate the savings.

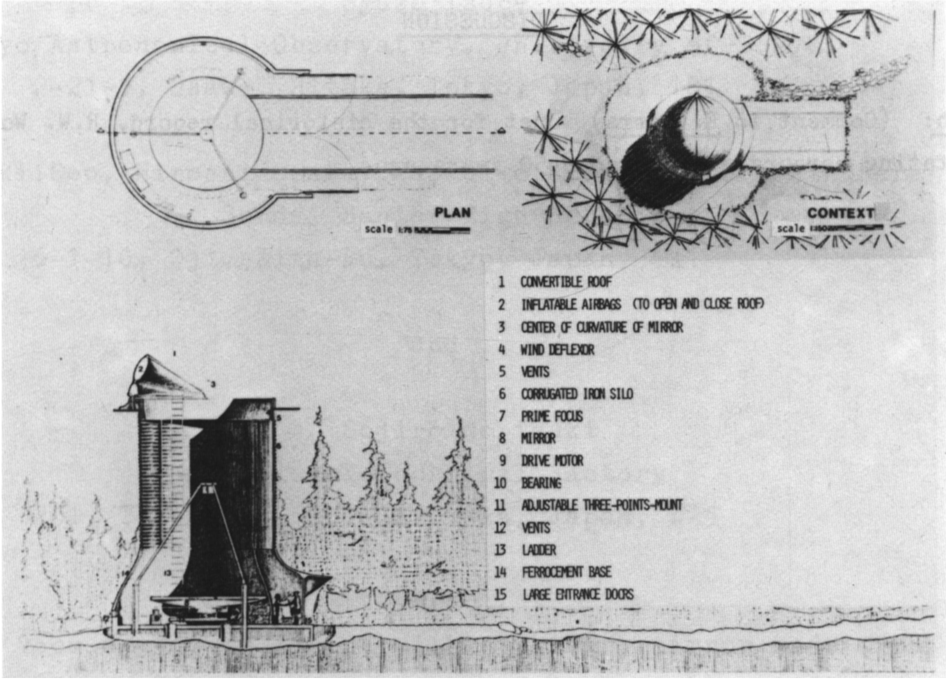

Figure 4

Architect plans of an observatory for a 6-meter diameter f-1 telescope.

A very large number of people have helped in this project by giving us either their time, advice or equipment, we wish to thank them all. This research has been supported by a Natural Sciences and Engineering Research Council of Canada operating grant to EFB.

REFERENCES

Borra, E. F., 1982, Journ. Roy. Astr. Soc. Canada, 76, 245.

McGraw, J. T., Angel, J. R. P. and Sargent, T. A., 1980, Proc. Soc. Phot. Instr. Eng., 264, 70.

Ojeda-Castaneda, J., 1978, in Optical Shop Testing, D. Malacara ed., John Wiley and Sons, p. 231.

Oke, J. B., 1984, (I. A. U. Colloquium 79).

Weedman, D., 1984, (I. A. U. Colloquium 79).

DISCUSSION

H. Smith: (Comment to E. Borra) Just for the historical record, R.W. Wood made some rotating mercury mirrors some 50 years ago.