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Development of Prototype Stylus Profilometry for Large Optics Testing

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The authors discuss a prototype stylus profilometer designed to measure large optics. It consists of a low contact force type probe system, laser reference system, interferometric distance measurement system, and horizontal driving system. The probe contacts the surface ; the height and the horizontal distances of the measurement points are measured by the interferometer. The freely propagated laser beam provides the reference line during the measurement. The developed stylus profilometry shows only ±60 nm of P-V error for the 157 mm diameter spherical mirror.

OCIS codes : 120.0120, 120.3930, 120.3940, 120.4640, 120.6650.

I. INTRODUCTION

All modern large telescopes are reflectors with aspheric surfaces. However, aspherics are not easy to make or to test. While a spherical mirror can be polished with tools of the same radius of curvature, an aspheric surface should be polished with tools of various diameters and radii of curvature according to the polished zonal area of the surface. It takes much time to make, compared to the same diameter of spherical mirror. Testing an aspheric is even more problematic. The most commonly used testing method for a spherical mirror, interferometry, would fail in testing even a mild aspheric mirror since it would generate too many fringes to analyse in the resulting interferogram. Using null correctors is one of the most frequent methods to reduce the fringe number without losing the measurement accuracy. However, this method sometimes leads to the wrong result. One significant example of those errors occurred at the testing of the primary of the Hubble Space Telescope (HST) [1]. It was tested with a reflective null corrector consisting of a field lens and two spherical mirrors. However, using an incorrect null corrector led to the form error of the primary mirror, which demanded the launch of space shuttle Endeavor in December 1993 to correct it. The secondary mirrors for large telescopes are often convex, highly aspheric, and large (up to 1.7 m in diameter). Since the incident beams become divergent on reflection from the convex surface, to test the secondary mirror is sometimes more difficult than to test the primary one, even though the size of the secondary mirror is smaller than that of the primary one. In conclusion, when constructing large telescopes, the difficulty in testing aspherics increases the cost and risk of telescope projects.

In this situation, stylus profilometry can be a very effective candidate for wide application since it has many advantages. For example, since the stylus directly contacts the surface to be tested and measures the height, it does not require making null correctors. Thus the testing cost is reduced and a source of error is eliminated. And it does not require precise alignment for the measurement. Furthermore, it can measure a spheric as well as an aspheric, a rough surface as well as a smooth surface, and a convex surface as easily as a concave surface. Last but not least, it can measure a special shape such as a saddle, which cannot be measured by null testing.

However, the conventional stylus profilometry is also known to have several drawbacks. For example, since the stylus contacts the surface directly and moves under gravitational force, it can damage the surface. Also, the geometrical shape and size of the tip may distort the profile of the surface. Furthermore, when a rough surface is scanned with a low contact force established, the frequency spectrum of the vertical motion of the stylus can overlap the resonance frequencies of the stylus structure and cause erroneous readings of the surface profile. And in some cases, a two-dimensional profile cannot reveal the whole picture of the sample. Finally, conventional stylus profilometry has a relatively short height measurement range (a few millimetres), compared to the height variation of large surfaces for astronomical telescopes.

However, the damage to the surface can be reduced by decreasing the contact force. Also, the effects of the shape and the size of the stylus on the profile measured has been investigated by several authors [2–5]. Furthermore, the general polishing process gives the point symmetry in the shape of the mirror, which enables a dimensional measurement to reveal the features the sample. Unfortunately, stylus profilometry for large optics testing for astronomy is rare in the world. Hence, Optical Science Laboratory (OSL) in University College London (UCL) initiated a long-term project in 1992, to develop stylus profilometry for measuring large optics very accurately.

In this paper, the authors describe the target principles of the stylus profilometry developed in OSL and some measurement results.

II. DESCRIPTION OF SPLOT (STYLUS PROFILOMETRY FOR LARGE OPTICS TESTING)

1. Requirements for SPLOT

SPLOT was designed to measure the form of large aspheric optics. We took the secondary mirror of the Gemini telescope as a case study. The values for the main parameters are shown in Table 1 [6].

From those values, requirements are derived as shown in Table 2.

Detailed derivations of the above requirements can be found in the author's Ph.D. dissertation [7]

2. Basic Principle of SPLOT

Since the primary interest of SPLOT is the form measurement, it is not necessary to scan the surface with the stylus, as the conventional stylus profilometer does. Instead, a point-by-point measurement is the principle of the SPLOT. The stylus is lowered on the measured point and picked up after measuring the height and moved to another point for the next height measurement. This method also reduces the size of the data set for the large optics.

TABLE 1. Parameters for secondary mirror of the Gemini telescope.

Diameter	1.022 m
Conic constant	-1.612898±0.001
Radius of curvature	-4193.0685±5 mm

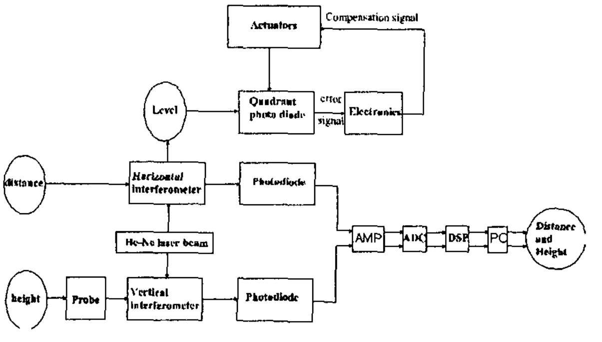

FIG. 1. The block diagram of the SPLOT.

Stylus profilometry has three main requirements: the measurement of vertical and horizontal displacement, and the provision of a reference of straightness with respect to which the vertical displacement is determined. This consists of a low-contact force type of probe system, a laser reference system, and an interferometric distance measuring system. Fig. 1 is the block diagram of the whole SPLOT, especially focused on the structure of the interferometric measurement system. The difference in optical path lengths of the split beams (reference and test beams) generates fringes. The moving distance can be calculated by multiplying the half wavelength by the fringe number generated during the motion. For higher resolution of the distance measurement, we need to interpolate between the fringes. For this, the interferometer generates quadrature signals ($=\lambda/4$ phase difference). These signals are converted to voltage in the photodiode, amplified, and digitized by the analogue to digital converter (ADC). The phase of the fringe and its direction are calculated and interpolated in the Digital Signal Processor (DSP). The Personal Computer (PC) collects the number of fringes from the DSP and converts them to the physical displacement length.

The height level of the vertical interferometer is maintained constant with respect to the reference laser beam by means of the feedback system. The horizontal interferometer and the beam splitter for generating the reference beam are on a separate Cervit pillar together, so that their heights with respect to the tabletop do not change according to the ambient temperature variation.

TABLE 2. Basic requirements for SPLOT.

Horizontal dynamic range	>1.022 m
Vertical dynamic range	>31 mm
Horizontal measurement accuracy	better than ±471 nm
Vertical measurement accuracy	better than ±57 nm

FIG. 2. The photograph of the SPLOT.

The light source for the vertical interferometer, horizontal interferometer, and the reference beam is a single frequency stabilized He-Ne laser. The beam emitted from the laser cavity is divided into two by a beam splitter, and coupled to two optical fibers. These transmit the laser beam to the vertical and horizontal interferometers. The laser beam for the reference system is derived from the horizontal interferometer by a beam splitter. Fig. 2 is a photograph of the SPLOT. In the next two sections, authors will briefly introduce the two main parts of the SPLOT, the probe system and the laser reference system.

3. Probe system

It is not exaggerating to say that the probe system is one of the most important parts of a stylus profilometer because it contacts the surface directly and measures the heights of the contacting point. Generally probe systems have two generic types of structure: a pivot (cantilever) system or a plunger system [8]. A pivot system has a simple structure; however, its arc motion requires a calibration or compensation process after the measurement. A plunger system has a relatively complicated structure for straight-line motion; however, it does not require any compensation process.

Fig. 3 is the schematic diagram of the probe system developed by the author. It is a hybrid type of probe system, combining the pivot and plunger types. The overall structure was the pivot type and the whole probe system moved vertically like the plunger type. That is, the whole probe system is moved down on the surface to be measured and its motion is stopped when the optical switch is triggered by a tilting motion of the probe arm after the probe tip contacts the surface. The software automatically detects the instant when the probe tip contacts the surface and records the height at that point. After measurement, the whole probe system is lifted up and moved to the next measurement position.

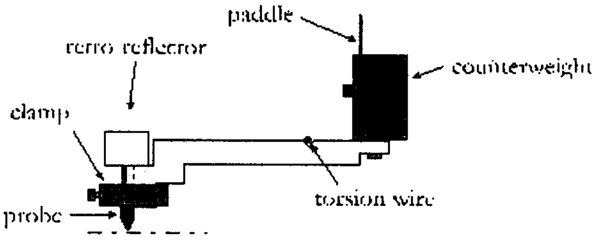

FIG. 3. The schematic diagram of probe system.

The retro-reflector on the probe tip is the moving arm of the vertical interferometer, so that movement of the probe system is detected by the interferometer. The torsion wire is used as a pivot. The amount of torsion applied can control the contact force. In principle, it has negligible static friction, so that a very low contact force can be achieved. However, due to the thickness of the wire, the authors at most achieved about 70 mg of contact force. More investigations on the torsion wire will result in much lower contact force. The tip is a commercial spherical ruby tip of 1 mm±0.5μm in diameter and of ±0.25μm in roundness, supplied by Taylor Hobson Pneumo. Fig. 4 is the repeatability test with the probe system developed and some strong drift trend during the repeatability test. The boxed points the represent test and the solid line represents the drift test. The measurement resolution was set to 20 nm. For the repeatability test, the probe system was lifted 300 μm from the surface and moved down on the same position of the surface, to measure the height. The interval of each measurement was nearly constant (30 seconds). For the drift test, the probe system is stationary in the air and the height is recorded during the same amount of time as the repeatability measurement just after the repeatability test is finished. As shown in the figure, both

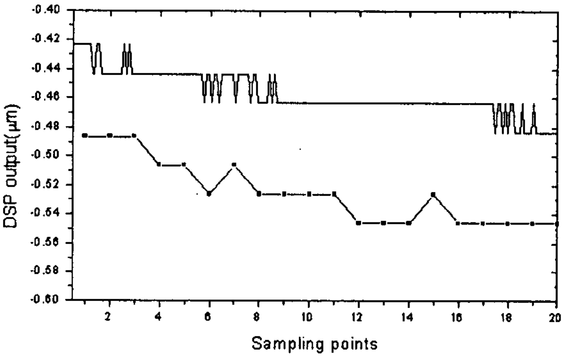

FIG. 4. The repeatability test on the flat surface (square points) and the drifting measurement (solid line).

curves followed the same trend. If the drifting trend were removed from the original repeatability test, 1σ of the repeatability could be reduced to 10 nm. This leads us to believe that the drifting trend in the repeatability test is not from any dynamical motion, but from the change of the environmental conditions.

4. Laser reference system

Since the height is measured with respect to the reference surface, errors in the reference propagate into errors in the height measurement. Therefore, the reference system is a very critical part for high precision profilometry. The transducer of the probe system displacement must move along a reference line so that the output represents only the stylus movement on the surface being scanned. There are two conventional ways of generating a reference line: a skid and a separate reference surface (absolute reference surface). Their pros and cons are well explained by Whitehouse [9]. Especially, using the reference surface, one of the most widely used methods in the precision measurement, has difficulties in the installation of a large optical flat with very little distortion as well as in cost.

Fig. 5 shows the schematic diagram of the reference system of SPLOT. SPLOT used the laser beam, which propagates freely in the air, as a reference line. Because the narrow intense laser beam follows a straight path (at least in a vacuum), it provides a ready means for the reference line. The quadrant diode which senses the position of the reference beam is located in a Cervit holder that is cemented to the horizontal flexure frame. The cube beam splitters in the vertical interferometer for measuring the sample height are cemented to the Cervit holder. Since the retro- reflector on the top of the stylus tip is a part of the vertical interferometer, there is a direct and tight metrology loop between stylus tip and reference of straightness. The flexure system uses a pair of flexing leaves, which constrain motion vertically and horizontally. Since it has negligible static friction, or hysteresis, it is suitable for extremely high precision positioning. The positional offsets recorded by the quadrant diode are nulled by the hybrid actuator, using a servo loop implemented in hardware. The vertical interferometer then correctly measures stylus height with respect to the laser reference beam. This system experimentally showed less than 10 nm accuracy in the positional recovery for the 0.7 μm of disturbance (this amount of disturbance was common in the stable laboratory situation).

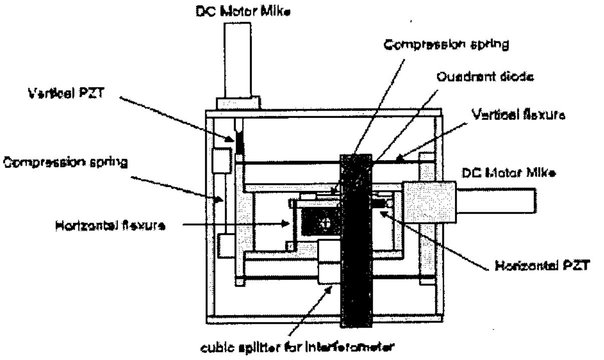

FIG. 5. The schematic diagram of laser reference system of SPLOT.

Fig. 6 shows the performance test of the reference system by comparing measurements of the same optical flat by WYKO phase shifting interferometer and the SPLOT. The sample was a 150 mm diameter and 25 mm thickness Zerodur flat. It had been polished to 400 nm p-v nominal flat, plus some subsequent polishing experiments on this surface. The resultant scan by SPLOT satisfactorily replicated the features of the surface observed by the WYKO 6000. The profile from the SPLOT showed the particular features of the polished surface. However, due to the sampling distance, the detailed description of the complex central part was simplified in this particular experiment. The p-v difference between SPLOT and WYKO 6000 results was ±0.2 μm, of which the main source was found to be systematic errors. More detailed descriptions of the reference system will be published soon.

III. MEASUREMENT OF CURVED SURFACE

1. Concept of differential height measurement

When measuring a curved surface, motional errors

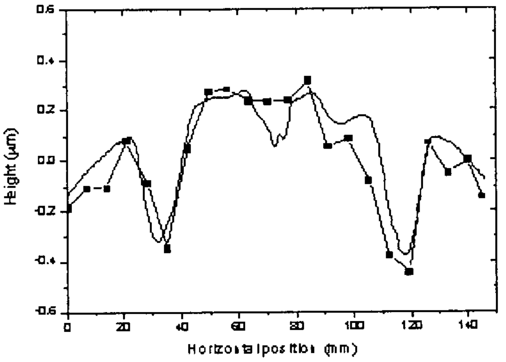

FIG. 6. Profile measurements of the sample flat with the reference system enabled. Square points are results by SPLOT and the solid line is the profile produced by the WYKO 6000.

(pitch, roll, yaw and displacements error) of the horizontal driving system and the probe guide system become distinctive. For very high accuracy measurement, these errors should be monitored and compensated. Unfortunately, SPLOT was found not to compensate the motional errors of the horizontal driving system completely.

In this situation, the absolute height measurements cannot give accurate profiles of the curved surface. However, there is one promising method to use SPLOT in measuring curved surfaces accurately without compensating such errors; it is the differential height measurement. It is to use the differential height of two surfaces: the target asphere and the best-fit sphere to this target. The procedure is as follows:

1. The wavefront error of the best-fit spherical surface is measured with interferometer: $W(x)$
2. The profile of the same spherical surface is measured with SPLOT (absolute height measurement) and its residual error from the ideal circle is obtained: $S(x)$
3. The measurement error of SPLOT is the difference between two profiles, or $E(x) = S(x) - W(x)$
4. The curved surface is measured with SPLOT: $T(x)$
5. The measurement error in $T(x)$ can be eliminated by the subtraction of the $E(x)$, or the final profile of the curved surface $F(x) = T(x) - E(x)$.

Since the deviation between two surfaces is very small (typically order of few tenth micrometers) compared to the deviation from flat, the measurement errors (systematic errors) of each measurement are similar and they can be eliminated by subtraction. In this way, an accurate measurement can be carried out without the reference system enabled.

However, in order to evaluate this method, two difficulties should be overcome in the preparation stage. It requires two surfaces (one the target aspheric and the other the best-fit sphere), and the target aspheric should be tested with another method such as null testing for comparison. Instead, a simpler method requiring only one sphere was developed to overcome this difficulty. The target sphere is measured two times in different conditions, one with no-tilt and the other with some tilt. The maximum deviation between no-tilt and tilted surface can be thought of the asphericity of the asphere. The systematic error in the measurement of the tilted surface can be mostly removed by the procedure explained above. Since the sphere can be easily characterised by interferometry, the evaluation of the measurement result is very easy. Also, since the deviation between two surfaces (no-tilt and tilt surface) is expressed as a linear line, any deviation from the linear line would be considered as the measurement error. This alternative way of evaluation can reveal the capability of SPLOT in measuring the curved surface without the reference system enabled.

2. Measurements

The sample sphere was a concave, 157 mm diameter, and 30 mm thickness made of BK7. When the curved surface was measured with SPLOT, two factors were compensated: the size of the probe tip and the wavelength of the laser. Due to the slope of the surface and the relatively large sag, these two factors became more significant than in the measurements on the nominal flat surface. The deviation of the height (Δy) due to the size of the probe tip (radius R) is given by [10],

$$\Delta y = R\left(\frac{1}{\cos\theta} - 1\right) \qquad (1)$$

where θ is the slope of the profile. The light wavelength depending on the environmental conditions is well formulated in *Tables of Physical and Chemical Constants* [11]. Fig. 7 illustrates a series of measurements on the sample sphere at zero slope after the compensation of the size of the probe tip and the wavelength of the laser. The measurements consist of 23 points at 7 mm intervals. The radius of the probe tip was 0.5 mm and the corrected wavelength of the He-Ne laser (λ_{vacuum}=0.63299142 μm) was 0.6328212 μm at 23.1°C and 1 atm (1013 mbar). The temperature variation was within ±0.1°C during the measurement. From this measurement, the sag of the nominal sphere was about 1.26 mm and the radius of curvature of the spherical mirror was about 2434.7 mm. The simple calculation showed that the maximum slope of this surface was about 0.032 rad at periphery.

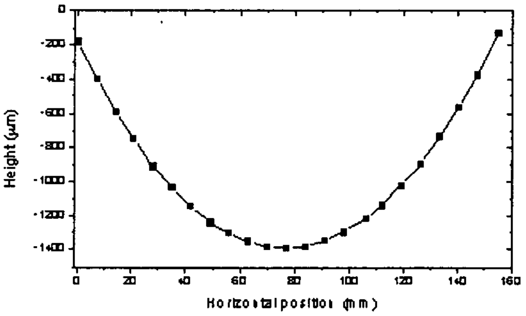

FIG. 7. Profile measurement of the sample sphere.

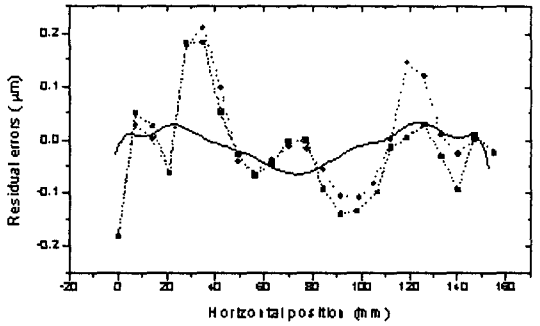

FIG. 8. Residual errors of the sample sphere, which were generated by subtraction of the best-fit sphere from the original data. Square and circle points are measurements on the no-tilt surface and tilted surface by SPLOT respectively. The solid line is the residual error produced by WYKO 6000.

Also, the same measurement was carried out on the sample sphere at the chosen inclination (1.1 mrad). Tilting the spherical mirror was performed by inserting a thin shim (thickness ~0.1 mm) under one side of the sample. The tilt depended on the length of the shim inserted under the sample. Each measurement was subtracted by its best-fit sphere, to generate the residual error of the surface. Fig. 8 shows the comparison of the residual errors of the same object according to the different situation. The square and circle points are related to residual errors of no-tilt and tilted surface measurements respectively. The solid line was the residual error along a centre line selected for the probe tip of SPLOT to trace measured by WYKO 6000. The only tilt and curvature errors were removed from the original wavefront error. The maximum difference between SPLOT and WYKO results was within ±0.2 μm.

The most remarkable feature appeared in the absolute height measurements is the periodic variation of the residuals around the solid line. The locations of the residuals were periodically changed approximately at every three-measurement-points (or 21 mm interval) with regard to the profile from the WYKO 6000. It is very unlikely that the main source of this periodic result comes from the motion errors of the horizontal driving system, as the size of its carriage is about ten times larger than that period. This short spatial wavelength of periodic errors is more likely to be generated by the motion errors of a small carriage such as the Grazier bearing in the probe guide system (12 mm in length). This kind of motion error was not visible in the flat measurement because the position of the probe system carriage was nearly the same on the probe guide system during the measurement.

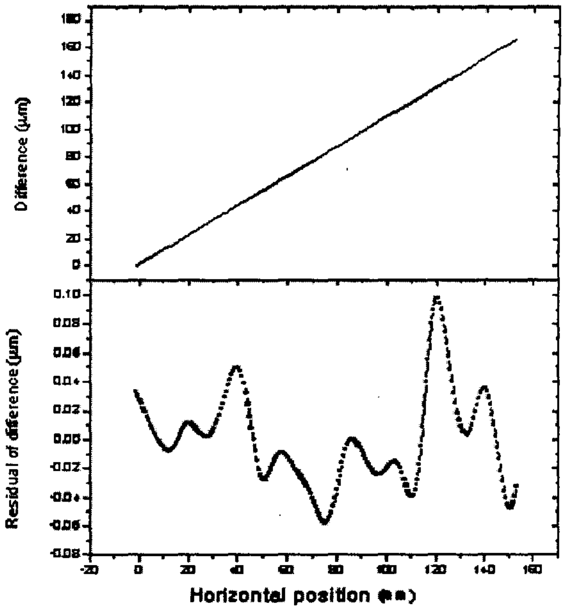

FIG. 9. Differences of best-fit curves of two measurements (upper) and residuals generated by the subtraction of the best-fit linear line from the differences (lower).

3. Accuracy of differential height measurement

It is necessary to subtract the two series of measurements (no-tilt and tilt), to remove the systematic errors included in the absolute height measurement. Unfortunately, the direct subtraction of original measurements was not possible, as the sampling positions were different at each measurement due to the low positional repeatability (but high measurement accuracy) of the horizontal drive system (< ±0.1 mm). Because of the slope of the surface, the maximum height variation from this low positional repeatability was about ±3.2 μm. To produce the significant difference of two sparse-sampled measurement sets, each set was curve-fitted and then differentiated. Each best-fit curve was obtained by two successive fitting processes: the circle fitting to the original data and the cubic spline interpolation to the residual errors of the circle fitting. The final best-fit curve is then the combination of the circle fitting and the cubic spline interpolation.

Fig. 9 illustrates the differences between two best-fit curves for no-tilt and tilted series of measurement sets (upper graph), and residuals from the linear fit (lower graph). From the upper graph, the maximum deviation between the two curves is about 170 μm, which effectively simulates the differential measurement of an asphere with 170 μm departure with respect to its best-fit spherical surface. From the lower graph, the P-V error of differences was about ±60 nm, except around 120 cm in the horizontal position. This error is 30% of P-V error by the absolute height measurement, which means that the systematic errors in the absolute height measurement can be effectively reduced by the differential height measurement method. This result indicates that an asphere with 170 μm departure from the best-fit sphere can be measured with the accuracy of ±60 nm. The differential height measurement is a highly promising method to measure aspherics with high accuracy.

The source of the exceptional area around 120 cm in the horizontal position is still in doubt. Repeated measurements on the same surface with similar conditions always showed the same problem in that position. Hence, it is not a random error. More investigation on this problem is on the way in OSL.

IV. CONCLUSION AND FUTURE WORK

The SPLOT developed for the accurate measurement of the large optics had two unique features; the low contact force type probe system and the laser reference system. Its measurement range was vertically 30 cm and horizontally more than 1 m. The repeatability of the probe system was less than 10 nm and the laser reference system was tracking with accuracy of less than 10 nm for less than 0.7 μm disturbance. However, the uncompensated motion errors of the horizontal driving system led to the measurement error of ±0.2 μm. To increase the measurement accuracy under this situation, the differential height measurement was developed and verified. As a result of this measurement, the measurement error was reduced ±60 nm. One of the next works is that the reference system should be modified to completely compensate the motion errors of the horizontal driving system to increase the measurement accuracy. Also, more investigation is necessary to reduce the contact force, so as not to damage the target surface. Then, this SPLOT can be a very promising instrument to measure large optics or verify the result of the interferometer.

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