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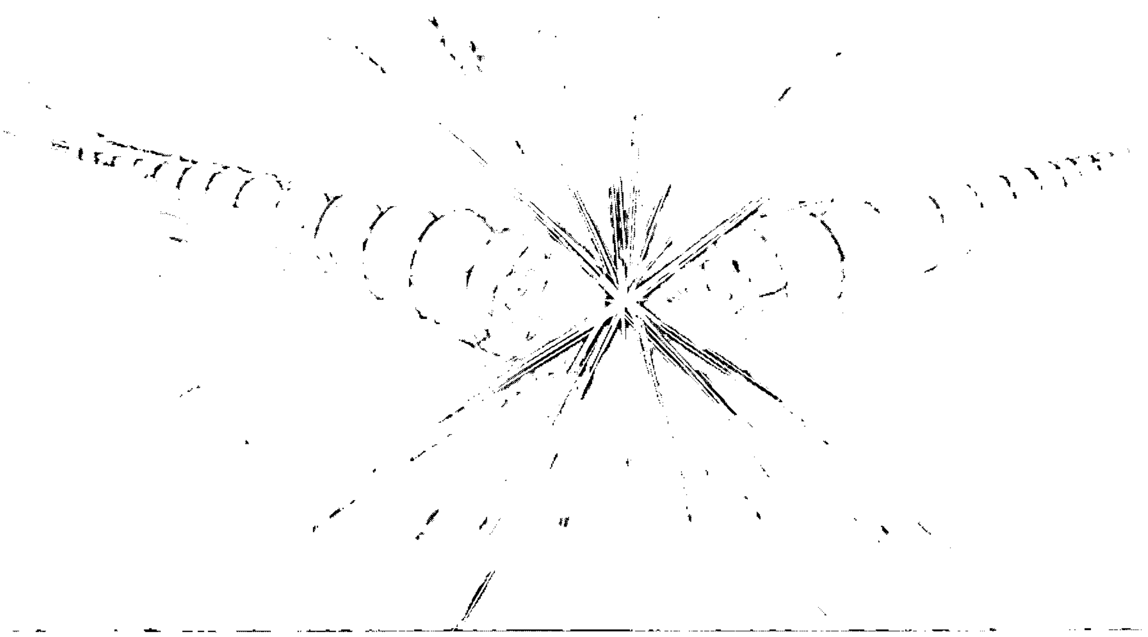

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The program for providing water cooled metal optics for the Advanced Light Source at Berkeley is reviewed with respect to fabrication and metrology of the surfaces. Materials choices, surface figure and smoothness specifications, and metrology systems for measuring the plated metal surfaces are discussed. Results from prototype mirrors and grating blanks will be presented, which show exceptionally low microroughness and mid-period error.

We will briefly describe our improved version of the Long Trace Profiler, and its importance to our metrology program. We have completely redesigned the mechanical, optical and computational parts of the profiler system with the cooperation of Peter Takacs of Brookhaven, Continental Optical, and Baker Manufacturing. Most important is that one of our profilers is in use at the vendor to allow testing during fabrication. Metrology from the first water cooled mirror for an ALS beamline is presented as an example. This 15" long Glidcop™ mirror is coated with electroless nickel from Acteron Corporation in Redwood City CA. The pre-plating processing and grinding and polishing were done by Tucson Optical. We will show significantly better surface microroughness on electroless nickel, over large areas, than has been reported previously.

Introduction

The optical components for the Advanced Light Source (ALS) present new challenges to both the designers and fabricators of mirrors and gratings. Maintaining the high brightness of the ALS source through the beamline to the experiment requires that the surfaces be better than previously obtainable, and be able to handle considerable heat loads from the wiggler and undulator sources of the ALS. We describe here the developments in optical fabrication and metrology that are necessary to make these optics.

Background

Historically, optical development has taken a secondary position in priority, since the primary goal of each synchrotron source construction project has been to get the accelerator working. Often the optical components have not even preserved the brightness and flux from first and second generation sources. This happened for several reasons. Beamline designers, unfamiliar with fabrication methods, often specified aspheric shapes that could not be made to the required tolerances, guaranteeing failure. Manufacturers sometimes mistakenly assumed that their fabrication and testing methods could be extended to make the optics. In most cases the necessary optical metrology to decide whether the optics were suitable did not exist either at the fabricator or at the user facility. Largely as a result of these problems (and the need for higher resolving powers) vacuum ultraviolet (VUV) monochromator beamlines have evolved toward the use of spherical optics which are, in general, easier to fabricate. The considerable astigmatism of focusing grazing incidence mirrors, which also helped drive the need for aspheres, is eliminated by the use of separate tangential and sagittal focal points.[1] Spherical surfaces can stay in continuous contact with the polishing lap, and can be moved randomly in two equivalent degrees of freedom during polishing. This tends to preserve good microroughness, and at the same time give good control over figure. Other techniques do not achieve the same accuracies. For example, the figure of a mirror may be quite accurately set by numerical grinding of the surface shape into the substrate. In the case of an asphere, however, the polishing tool cannot contact the entire surface at the same time; and the surface must be "zone polished" with a flexible lap. This process naturally introduces figure errors of the same order as the size of the lap. Even though the overall figure is preserved within some computer controlled limit, the optical surface undulates at spatial wavelengths in the intermediate range which is often critical to the performance of the optic in the soft X-ray region.

At the ALS we have chosen an integrated approach. In cooperation with industry we have developed the necessary optical metrology and placed it in the optical shop so that the optician can know the effect of his adjustment of the many variables of the grinding and polishing process. This has required the commitment of more personnel and funding that has been given before to optical development. Without this support, however, the optics for the ALS would not be available.

Materials

Before the initiation of this developmental program in 1989, the Mechanical Engineering staff of the ALS had selected what has turned out to be an excellent material for the construction of water cooled optics.[2] This material[3], Glidcop™, is an alumina dispersion strengthened OFHC copper alloy, containing approximately 0.15% alumina. Glidcop™ is readily machineable, allowing water cooling channels to be constructed as necessary to the heat load and footprint of the synchrotron radiation. Although the addition of the alumina creates a granular structure which complicates brazing and plating, (braze material tends to disappear into the surface) this is circumvented by only brazing to the OFHC skin of the material that is left on the outside of the bar of Glidcop™ by the extrusion process of manufacture. Custom extrusions are available so that water cooling geometry can be integrated into the fabrication process of the material. In the case of plating, an intermediate plated layer of pure copper serves to isolate the granular structure from the final plated layer that is to be polished. Significantly, the choice of material and the brazing process provide an optic that is stress free and stable. It is considerably better than aluminum 6061 T-6 which derives its properties from heat treating, and is therefore in a stressed condition. We have drilled and tapped holes within a few mm of a polished surface of a Glidcop™ mirror **after polishing** without any measurable effects on the figure of the surface. Glidcop™ mirrors have been installed in the beamline VI-1 spherical grating monochromator branchline at the Stanford Synchrotron Radiation Laboratory (SSRL), and at beamline X-1 at the National Synchrotron Light Source.

The second and critical material choice is that of what to polish as the optical surface of the Glidcop™. Before the start of the present developmental program electroless nickel was chosen as the top layer. This was logical as electroless nickel is hard (polishable), and is known to optical vendors. We have utilized three different companies to apply this layer in the course of our development. We have found that reproducible platings that can be superpolished routinely can only be obtained from a close collaboration with a vendor that specializes in optical platings and is committed to the best scientifically sound quality control.[4] We have found much of the conventional wisdom about electroless nickel plating for optics to produce sub-optimal results for the ALS optics. For example, many optics are polished to a high degree before the application of the nickel. We find that a certain degree of roughness before plating provides a better layer. In addition, the usual hard heat treatment of the nickel after plating can introduce recrystallization of the nickel out of the nickel and phosphorous mixture. We heat treat the nickel for increased hardness and densification, but do not cause any recrystallization.[5] In summary, the Glidcop™ blank is prefigured to the required shape, and left in a certain ground condition. A thin layer of pure copper is then plated to mask the granular structure of the alloy. Then the electroless nickel is plated with the proper phosphorous content. Finally, prior to lapping and superpolishing the nickel, a mild heat treatment is applied.

Polishing Methods

Since the figure, slope, and microroughness specifications for the mirrors and gratings for the ALS are very tight, we looked for the technique which had produced the best optical surfaces in the past. The method of continuous ring polishing has produced Fabry-Perot plates in the one two-hundredth wave class of flatness. What is particularly interesting about these plates for interferometers is that they must be smooth at all spatial wavelengths of surface error from microroughness to gross figure, or their performance degrades rapidly. The best of these optics have been made on continuous ring polishers. "Continuous" means that the part is always in intimate contact with the lap, and "ring" denotes the geometry of the lap. Such a machine is diagrammed in Figure 1. The lap rotates under the worked part which is in continuous contact with it. The shape of the lap is determined by the interaction of the lap with the large and heavy conditioning weight. The interaction of the optic being polished with the lap is just a perturbation. It was not widely realized that this method could be used for extremely high quality spherical parts. It has traditionally been used for making super accurate optical flats. To alter the curvature of the conditioning weight/lap combination the weight is moved either closer or farther away from the center of the ring. Partially funded with technology transfer funding[6], we have constructed a 48" diameter continuous ring polisher for the ALS water cooled metal optics for the first two undulator beamlines, U5 and U8. This machine will comfortably polish mirrors up to 15" long.

Metrology

The fundamental theorem of optical fabrication is that **one can only make an optic as good as one can measure it.** In the past, the types of metrology that were available determined the quality of the available optics. Typically the shape was generated by a conventional optical generator or numerically controlled grinder, and either custom test plates, or star, or Foucoult tests were employed. These methods often did not produce optics with arc second slope tolerances. Those shops with interferometric testing capability, even the computerized phase measuring variety, soon found that toroids, ellipsoids and shallow spheres could not be accurately and easily tested interferometrically. For example, testing a shallow sphere interferometrically requires the generation of a spherical wave of similar curvature. This requires a long focal length lens, and one has only succeeded in transforming the problem into one of accurately measuring the long focal length lens. If one chooses to test the long radius sphere with a plane wave, typically the number and density of interference fringes that are created swamps any detector or analysis scheme. After extensive study of the problem, we decided to improve and build two Takacs style long trace profilers (LTP).[7,8,9] These LTPs solve the metrology problem for long grazing incidence optics for synchrotron radiation. Even though they only measure the surface in one direction, two things ameliorate this limitation. First, grazing incidence optics in general do not need to be as good in the sagittal direction due to the well known "forgiveness factor." Second, properly polished optics tend to be as good in the sagittal direction as the tangential so that the tangential measurement suffices. Figure 2 outlines our model of the LTP. Our LTPs were assembled from subsystems manufactured by Continental Optical of Hauppauge, N.Y. in cooperation with Peter Takacs of Brookhaven National Lab (BNL), and Baker Manufacturing of Evansville, Wisconsin. Systems integration and software were done at LBL and Tucson Optical Research Corp. [10,11] A custom air bearing stage moves along an approximately one meter long ceramic beam. This carriage holds a laser diode and optical components which relay pairs of laser beams to the surface under test (SUT) and the reference. mirror (REF). The system is an optical lever which measures the slope of the surface. Height profiles are obtained by integration of the slope data.

A critical improvement is the reference mirror system which corrects for any changes in the laser diode's pointing direction, and any changes in pitch of the carriage as it scans the SUT. Since the distance to the reference mirror changes during a scan, and the distance to the SUT does not, the two beams do not follow exactly the same path through the optical system. The reference subtraction thus has a systematic error which is not removed. We are fabricating a new lens system which will reduce this error dramatically. In addition we can remove remaining systematic errors by calibration against an interferometric angle encoder or reference optical flat, as we will show in figure 6.

Specifications and Results

Since the optical surface is ideally specified by the tolerable deviations from true shape at all spatial frequencies, we specify the surface in two ways. For microroughness measurements, from spatial wavelengths of 5 microns to 5 mm on the surface we use a microprofiler that is a combination of an interferometer, microscope, and a computer. Our model is a WYKO NCP-1000, but other companies manufacture comparable instruments.[12] Generally electroless nickel, and all metals for that matter, had not been polished to extremely good microroughnesses. P. Z. Takacs of BNL, who also has a microprofiler similar to the one at LBL, has measured many metal mirrors, and found that the best one had only 10 Angstroms RMS roughness. This just is satisfactory for synchrotron applications, and most metal mirrors were not this smooth in his experience. Figure 3 shows a Micromap microprofiler scan of the electroless nickel plated U8-M1 mirror for the ALS. This is the only ALS optic completed through polishing. The RMS roughness of 2 Angstroms is typical of this 15" long mirror surface. We have scans showing smaller RMS roughnesses on this part, but they were not representative.[13] What we would like to stress is that this order of smoothness can be routinely obtained. As a result, the mirror designer can begin to consider electroless nickel as a polishing layer for substrates other than copper. Silicon carbide, for example, takes roughly twice as long to polish as the nickel, which doubles the finishing costs. The material costs for plated nickel are also lower that those for CVD silicon carbide. Properly applied and finished, the nickel layer can be only one or two mils thick. Thicker layers of CVD CVD silicon carbide, deposited at a considerably higher temperature than the nickel, are subject to considerably more internal stresses.

The planned use of narrow slits (10 microns) to achieve high resolving powers in the spherical grating monochromators in beamlines U5 and U8, and the distances of a few meters between optical elements drive the RMS slope tolerances for the ALS optics. The error budget allows only 0.5 to 1.0 microradians RMS slope error for the vertically focusing mirrors and gratings. We have achieved this level of accuracy from our LTP systems when we remove the reference nonlinearity from the data, as mentioned above in the section on the metrology. The ALS U8-M1 15" long water cooled mirror was completed before the profiler was operational at Tucson Optical Research (TORC). In figure 4 we show the LTP height profile of this mirror. A best fit sphere of 300 meters has been removed from the data, so that we see the residual deviations from that sphere. As it is horizontally focusing in the beamline, and is more loosely toleranced than the other mirrors, we chose to fabricate it first. The height profile is exceptionally smooth, as is to be expected from the continuous polishing process. The "winged pattern" can theoretically consist of figure errors in the mirror plus our non-linearity problem. We are confidant that the mirror is at least this good, and is within specification. It is also good example of what has traditionally happened to optics before long trace profilometry. The optician could only look at one third of the aperture of the mirror at a time with his conventional metrology. Hence, over any third, the profile is quite good. The optician could not get this mirror any better in figure without a method like the LTP to view the entire surface in one measurement. If we remove the slowly varying shape from the mirror's profile and plot the residual slopes, we see in figure 5 a very satisfying better than 1.0 microradian RMS mid-period error for this mirror.

As a post-LTP result we present figure 6. This figure shows the residual slope error from a 7 inch long water cooled nickel plated grating blank now being manufactured at TORC for beamline VI-1 at SSRL, after removal of a best fit sphere of 54.62 meters. In this case we scanned a precision flat with the LTP just after scanning the grating blank with the LTP. The reference signal was subtracted from both measurements, and then the scan of the flat was subtracted from the scan of the grating blank in order to remove any systematic errors in the subtraction of the reference beams in the two cases. The slope error is 1.0 microradians RMS, or one-fifth arc second. This is approaching the random noise error limits for our LTP machines in their present configuration, and we will likely need to address air turbulence and thermal effects to proceed to better measurements. These two effects should be the final limitations to LTP performance once the lens system is improved, and any remaining non-equivalences between reference and sample beams are calibrated out.

Cylindrical and Toroidal Mirrors

Particularly in the case of bending magnet beamlines, where the horizontal fan of radiation is much wider than that from undulators, optical flats and spheres do not satisfy all of the requirements for beamline optics. In order to extend the benefits of continuous polishing to toroidal and cylindrical surfaces TORC has designed proprietary fixturing which makes the two orthogonal polishing motions more equivalent in the case of generating a cylinder. We present in figure 7 the residual slope errors from a 700 mm long nickel plated cylinder of 50.8 mm sagittal radius. A tangential best fit radius of several kilometers has been removed from the data. Our optical non-linearity in the profiler has not been subtracted from this data. This mirror was manufactured with the profiler operational. Its maximum residual RMS slope error is 4 microradians (less than one arc second). We believe that this is considerably better than existing cylindrical mirrors.

We are in the process of manufacturing a toroidal mirror for beamline VI-1 at SSRL by bending the mirror to a convex shape during polishing. After the cylinder is finished the mirror will then assume a toroidal shape after relaxation. We expect to achieve this level of optical quality on the toroid also.

Diffraction Gratings

Experiments are in progress with grating manufacturers to place square wave profile grooves directly into the nickel layer.[14] We feel that the holographic generation of the grooves will afford superior stray light, and that this, and the possibility of higher order suppression offset the possible lower efficiency of a square wave grating profile. We have received a blazed grating from Hyperfine, Inc of Boulder Colorado ruled on a water cooled nickel blank that has greater that 30% efficiency in the VUV; and shows excellent groove profile, as demonstrated by good higher order efficiency up to and including fourth order.[15] Gratings like this one, intended to be used sometimes in higher order should be ruled.

Summary and Conclusion

We have reviewed the status of the developmental program for optics for the ALS. The use of metrology, particularly long trace profilometry in the optical shop is critical to successful fabrication of the optics. Electroless nickel has been shown to be a good choice for the polishable surface, without a penalty in surface roughness as in the past. Slope errors on nickel coated copper alloy substrates with internal water cooling channels are approaching the one microradian RMS level, and the extension of our optical fabrication philosophy to cylindrical and toroidal surfaces is proceeding well.

This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Sciences Division of the U.S. Department of Energy, under Contract No. DE-AC03-76SF00098.

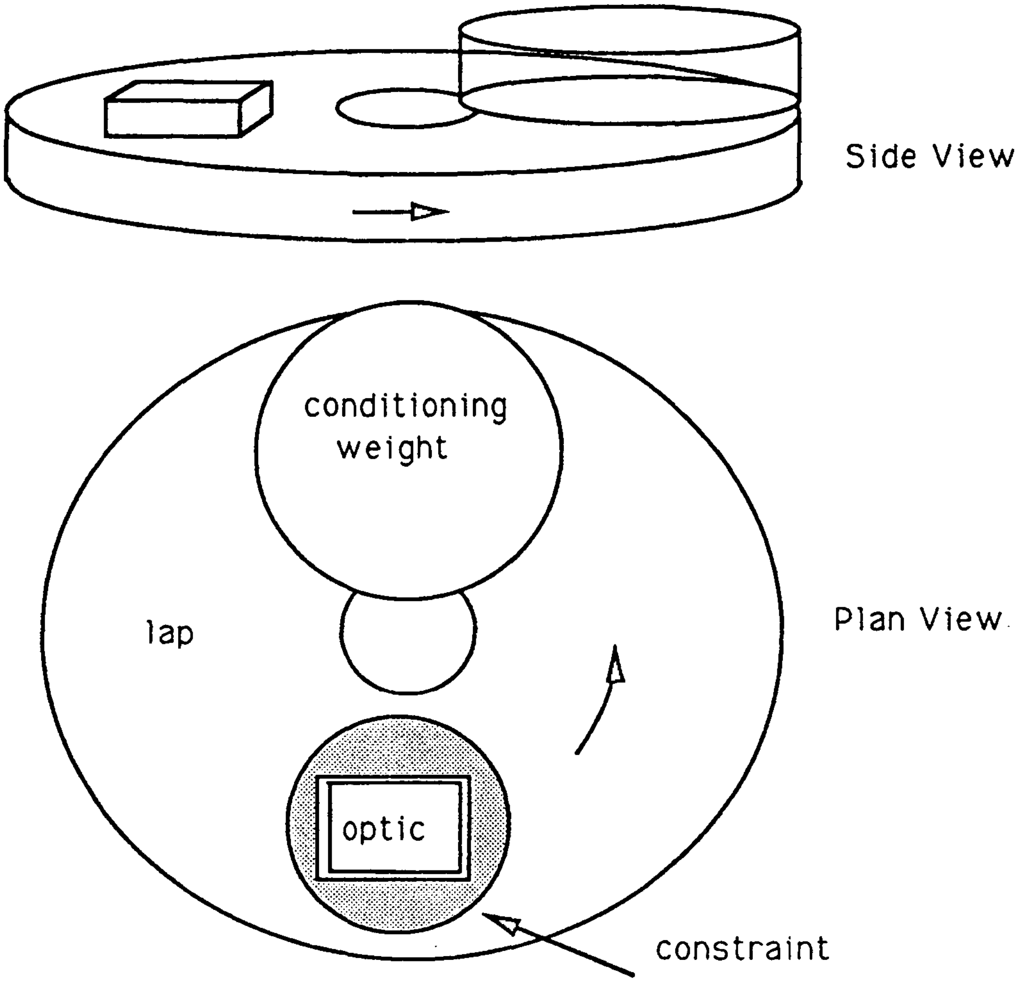

FIG. 1 The continuous ring polisher in two views, showing those parts essential to understanding the advantages of this polishing method.

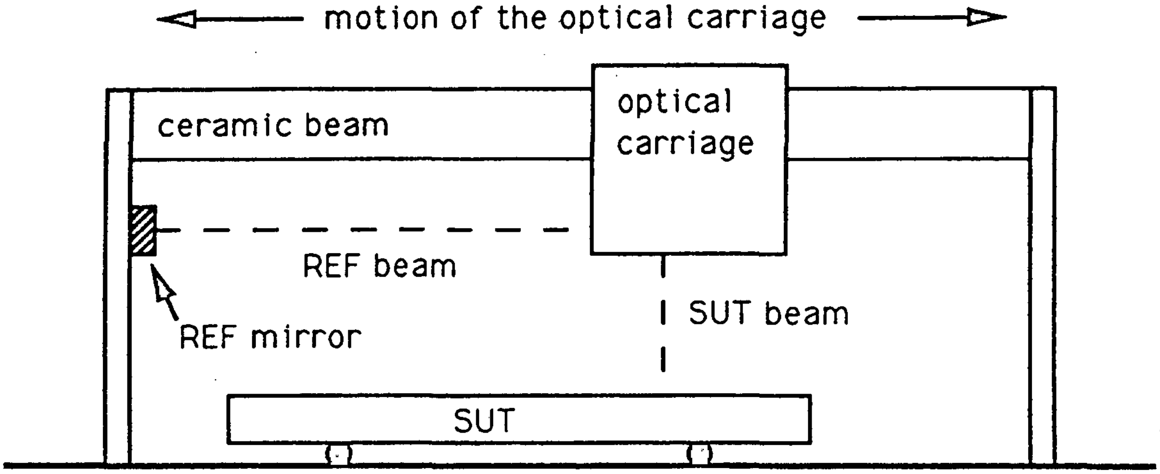

FIG. 2 Two of these one meter Long Trace Profilers (LTP) have been constructed. One is at Lawrence Berkeley Lab. (LBL), and the other is at Tucson Optical Research Corp (TORC).

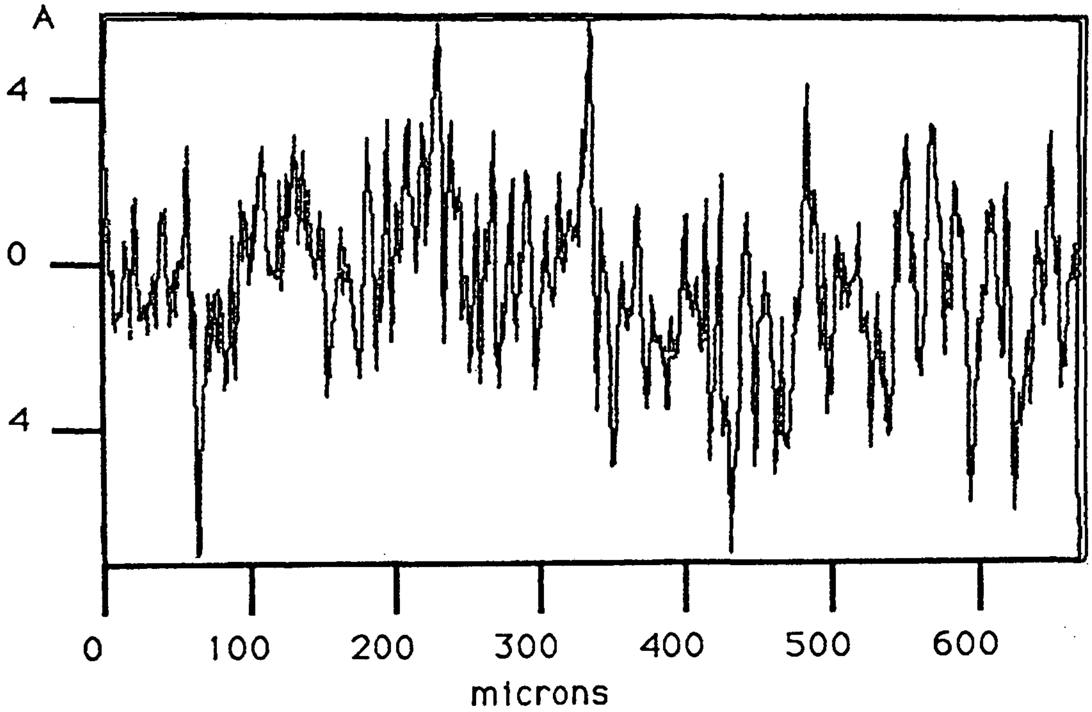

FIG. 3 A microprofiler scan of the ALS U8-M1 spherical nickel plated Glidcop™ mirror showing 2 Angstroms RMS microroughness.

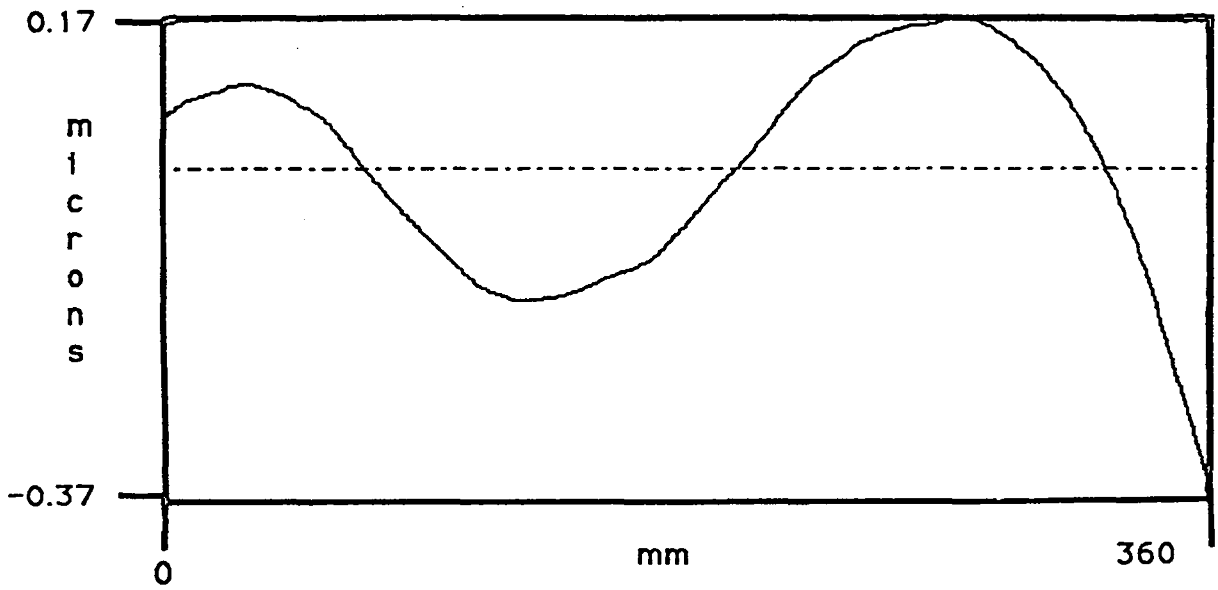

FIG. 4 A Long Trace Profiler Scan of ALS U8-M1 showing residual height variations after the subtraction of a best fit sphere. Much of the "winged" pattern is an optical non-linearity in the reference subtraction in the profiler, and not the mirror.

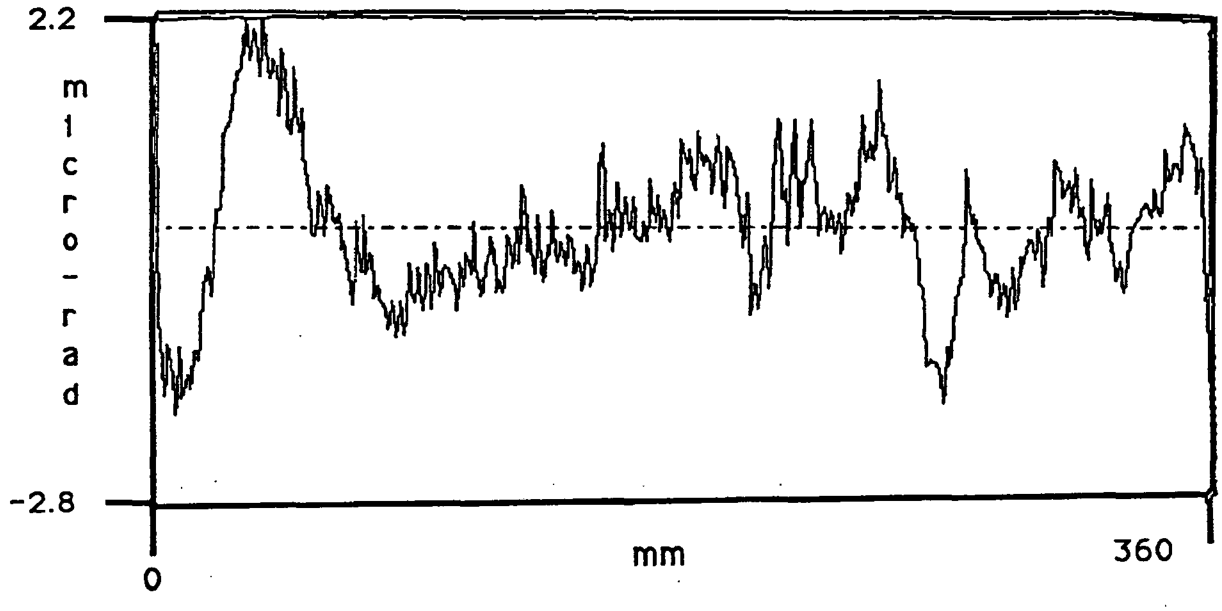

FIG. 5 The residual slope error of ALS U8-M1 after the "winged" shape has been removed from the data. Exceptionally good mid-period residuals are shown by the less than 1 microradian RMS slope error.

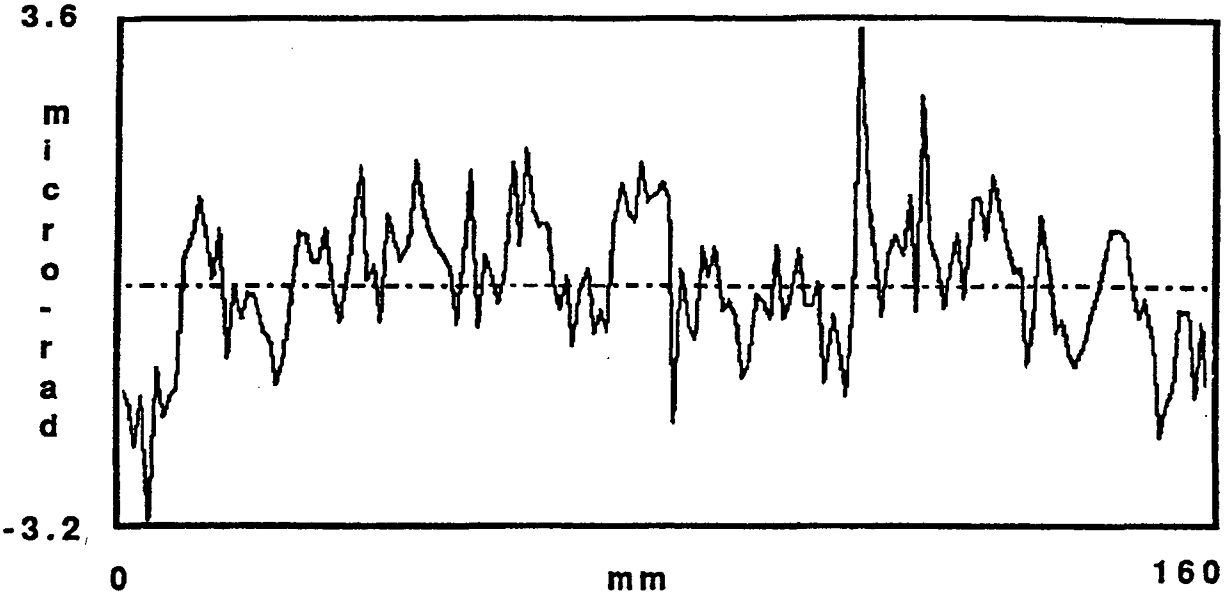

FIG. 6 The residual slope error of a 7 inch long nickel plated spherical grating blank. The slope error of 1.0 microradians RMS is due to the shape of the mirror and random errors in the measurement. A precision reference flat has been used to remove systematic errors in the reference beam subtraction.

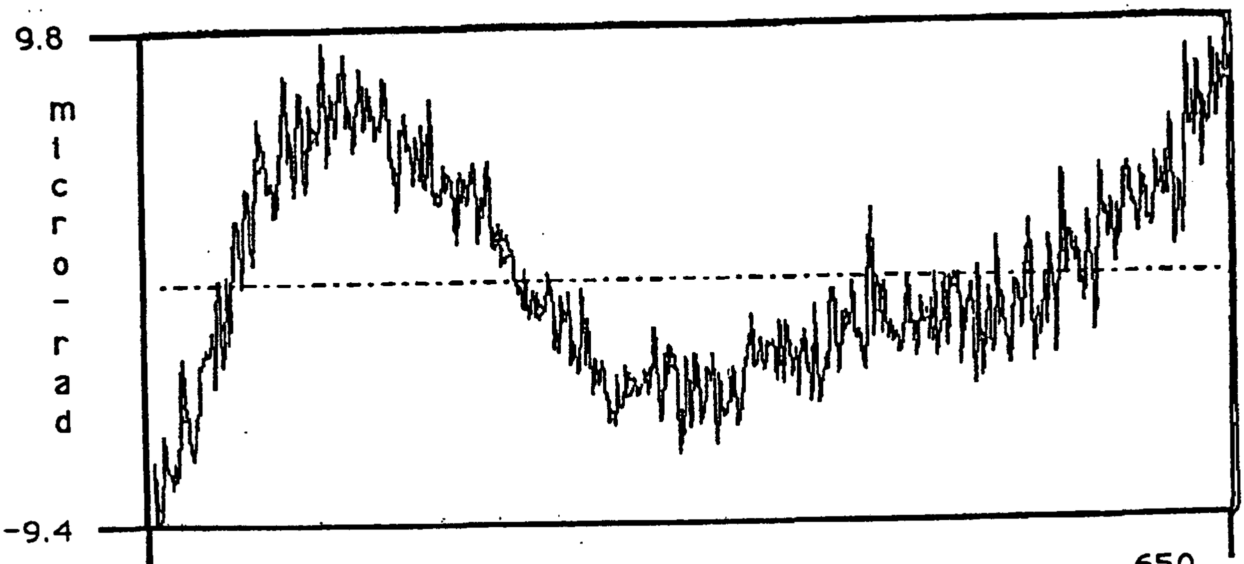

FIG. 7 The residual slope error of a 700 mm long nickel plated cylindrical mirror. The RMS slope error of 4 microradians is the sum of the profiler's optical non-linearity and the shape of the mirror.

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[6] These DOE technology transfer funds were obtained in collaboration with Malcolm Howells of LBL.

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[12] For example, Micromap, Tucson, AZ, or Zygo, Middlefield, CT.

[13] Since the Micromap instrument has a different spatial frequency response function than the WYKO, the 2 Angstroms RMS value would be a little higher on the NCP-1000.

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