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A METHOD TO ANALYSE THE SURFACE SLOPE QUALITY OF OPTICAL MIRRORS

by

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ABSTRACT

A method to diagnose the surface errors existing on planar mirrors was developed and tested. The reflective method developed represents a departure from the interferometric techniques frequently employed in optical component testing. The constructed instrument was completely automated. The operation of the instrument was calibrated and tested. The instrument's consistency was verified with a repeatability test. The performance of the insrument was comparatively tested against two different test methods.

The calibration revealed the instrument was able to resolve 1μrad changes in the surface slope on a planar mirror. The other tests indicated the instrument was operating consistently with results comparable, but not identical, to the other test methods.

The method can be upgraded to surpass and rival various interferometric methods being used today. In addition, the method can be modified to include the testing of lenses and curved mirror surfaces.

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I. INTRODUCTION

The optical sciences have experienced a period of invigorating growth and discovery following the advent of the laser. Many new developments have already been applied in numerous technical areas and figure to be utilized, to a greater degree, in the future. Such growth has created a greater demand for precision testing of optical surfaces.

The purpose of this investigation was two-fold. The central point was to choose or devise an optical method which is able to detect the surface errors existing on a planar mirrored surface. Once the method was established, a support system was to be designed and implemented. The support system was intended to make the model instrument completely automated.

The optical method chosen is unique among the test methods commonly practiced today. Most methods rely on the interference of light waves to diagnose the surface quality of the test element. The reflective method developed in this investigation utilizes the directional change of the light wave accompaning reflection off a surface incongruity. The distortions in the surface were quantified by measuring the beam deflection corresponding to a surface

distortion.

The purpose of the investigation was of an applied nature. The major theme was to construct an instrument able to resolve 1μrad changes in the surface-slope of a planar mirror. No attempts were made to establish standards(eg. the limting resolution of the method) or confirm theoretical hypotheses.

The text that follows is divided into three major divisions. A description of the instrument developed is presented. The results of various tests applied are illustrated and discussed. Finally, conclusions of the research and recomendations for future investigations are stated.

II. DESCRIPTION OF THE INSTRUMENT

A. Optical System

1) General Description

The optical system of the instrument is illustrated in figure one. The Helium-Neon laser is imaged onto a Reticon array(RA) off a facet of the polygonal test mirror(PTM). The Reticon array consists of 1024 light sensitive diode elements arranged linearly. The corner cube(CC) translates the beam across the facet and acts to compensate for any rotational errors that may exist in the translational mount(TM).

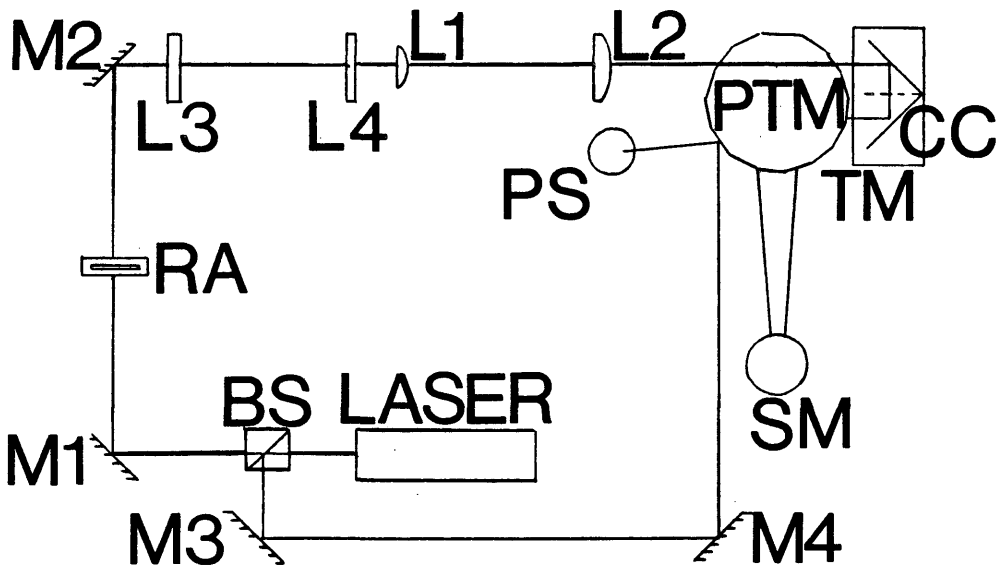

Figure 1. Optical System of the Instrument.

The cylindrical lenses L1 and L2 form a telescope. The telescope acts to amplify any off-axis deflection due to surface incongruities on the facet of the polygonal test mirror. The cylindrical lenses L3 and L4 correct for positioning errors of the image on the Reticon array due to the vertical offset of the facet planes(figure two). The mirrors M1 and M2 act to position the incident beam.

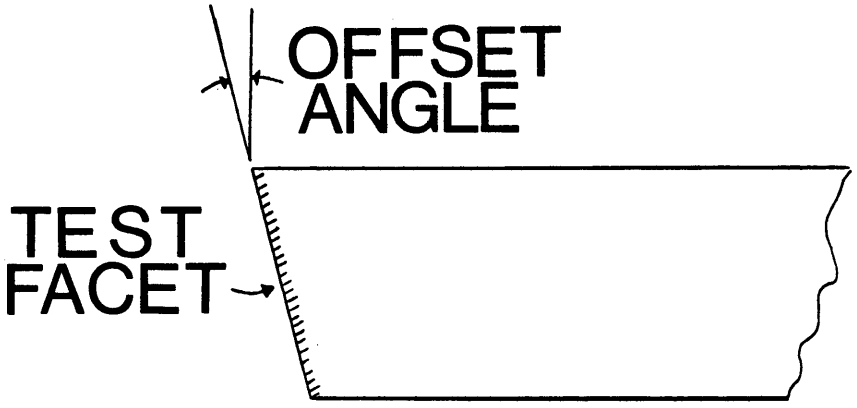

Figure 2. Vertical Offset of the Facet Planes.

The remainder of the optical apparatus is a feedback system. The feedback system aids in the positioning of the light on the Reticon array. The beamsplitter(BS) taps off a portion of the incident beam. The light is imaged onto the position sensor(PS) off a facet of the polygonal mirror. The mirrors M3 and M4 serve to position the beam on the mirror facet. A detailed theoretical calculation of the accuracy and range of the instrument follows.

2) Accuracy and Range Computation

The accuracy and range of the instrument can be calculated by modelling the instrument's optical system with the arrangement shown in figure three. Depicted from left to right are a facet of the polygonal mirror, lens 2, lens 1, and the Reticon array. The facet of the polygonal mirror makes an angle θ/2 with the optical axis of the system. A beam incident onto the facet that is coincident with the optical axis will be reflected at an angle of θ, again with respect to the optical axis.

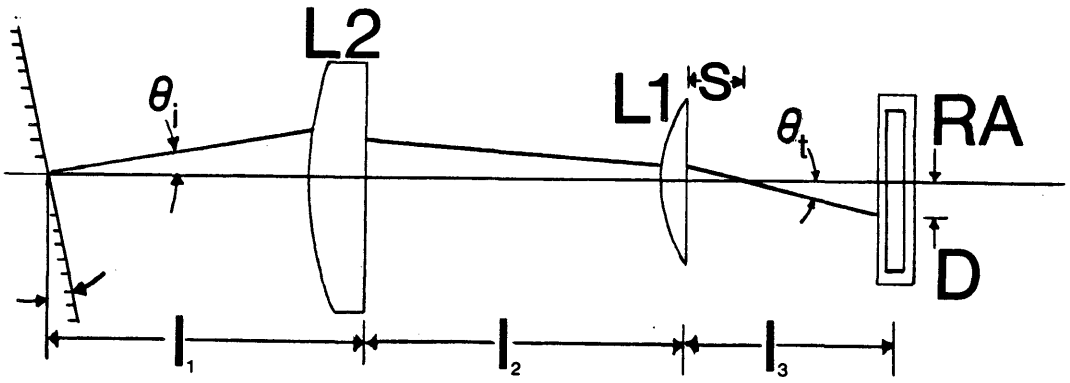

Figure 3. Model Telescope Optical System.

The lenses L1 and L2 act as a telescope and magnify the deflection due to the surface distortion in the mirror. The magnification of the telescope is given by,

$$M=-f_2/f_1=-\theta_t/\theta_i \qquad (1)$$

where f_1, and f_2 are the focal lengths of lenses 1 and 2, respectively.

The position at which the outgoing light ray passes the optical axis can be computed using simple Gaussian paraxial ray theory. The result is,

$$S'=(f_1/f_2^2)(f_2^2-f_1(l_1-f_2)) \qquad (2)$$

The number of diode elements the light ray is deflected from the optical axis can be found. The distance the ray is deflected along the Reticon array is given by,

$$D=-\theta_t(l_3-S'). \qquad (3)$$

The relationship between the focal lengths of lenses L1, and L2 and their separation is,

$$l_2=f_1+f_2. \qquad (4)$$

The expression for D can be synthesized using equations 1, 2, and 3,

$$D=\theta_i(f_2/f_1)(l_3-S'). \qquad (5)$$

Letting t be the spacing between successive diode elements, the number of diode elements the beam is deflected can be found,

$$N=D/t. \qquad (6)$$

The expression for the number of diode elements per radian shift in deflection angle is,

$$N/\theta_i=(f_2/f_1)(l_3-S')/t. \qquad (7)$$

This expression can be computed for the instrument constructed. The above variables were measured at,

f_1=43mm

f_2=217mm

l_1=570mm

l_2=250mm

l_3=625mm

t=.025 mm.

The value computed for the number of diode elements per μrad is,

N/θ_i=.120 diode elements/μrad in beam deflection.

This value compares very well with the experimentally measured value of .110 diode elements/μrad.

The range of the instrument can be determined. Assuming there are approximately 950, of the total 1024 diode elements, open for the peak of the intensity distribution to fall on, the range computes to 9.0 mrad. The large range indicates that larger telescope magnifications or a smaller array could be used.

3) Compensating Lens System

The action of the compensating lens system, lenses L3 and L4, can be modeled. The real system can be replaced by a model system shown in figure four. The analysis can be carried out using the thin lens equation for paraxial rays,

$$1/S_i+1/S_o=1/f. \qquad (1)$$

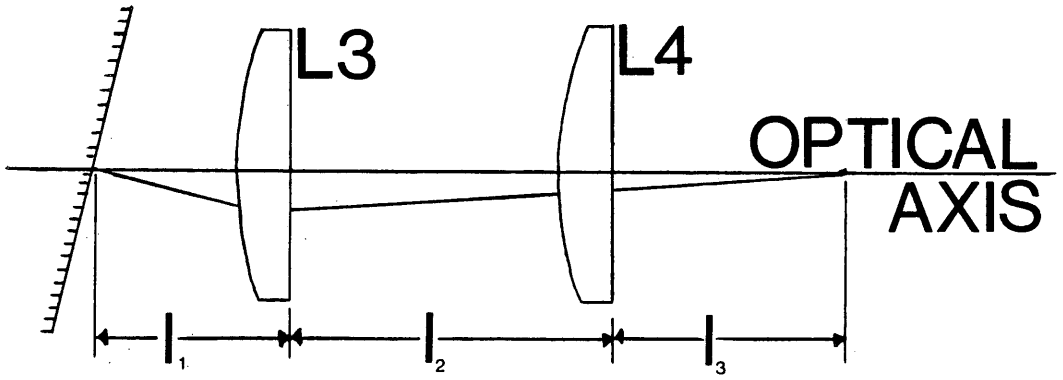

Figure 4. Compensating Lens Model System.

The following analysis assumes that the focal lengths of the two lenses are equal, as was the case in the constructed instrument. The thin lens equation can be applied twice to determine l_3. The result is,

$$l_3=(1/f-(1/(l_2-(1/f-1/l_1)^{-1}))^{-1}. \quad (2)$$

The measured values for the parameters in equation 2 are,

$$f=470mm$$

$$l_1=800mm$$

$$l_2=230mm.$$

The computed value for l_3 using equation 2 and the measured values is,

$$l_3=31cm.$$

The measured distance for l_3 in the instrument is 33.5 cm. The discrepancy can be attributed to use of a paraxial ray theory and the spherical aberration of the lenses. The existence of spherical aberration was verified experimentally. The foci for paraxial rays and off-axis rays were found to be displaced from one another, as the result above indicates.

B. Instrument Support System

1) General Description

The optical system was supported by an IBM PC-XT working in conjunction with a Keithly Series 500 data acquisition system(DAS). The Keithly DAS was controlled by an IBM PC via Soft500 and Plus500 software. The interface between the support equipment and the optical system is depicted in figure five. System components that utilized Soft500 software were the Reticon array, the Sigma stepper motor, and the Quantrad position sensor. Only one element, the Newport actuator, was controlled with Plus500 software.

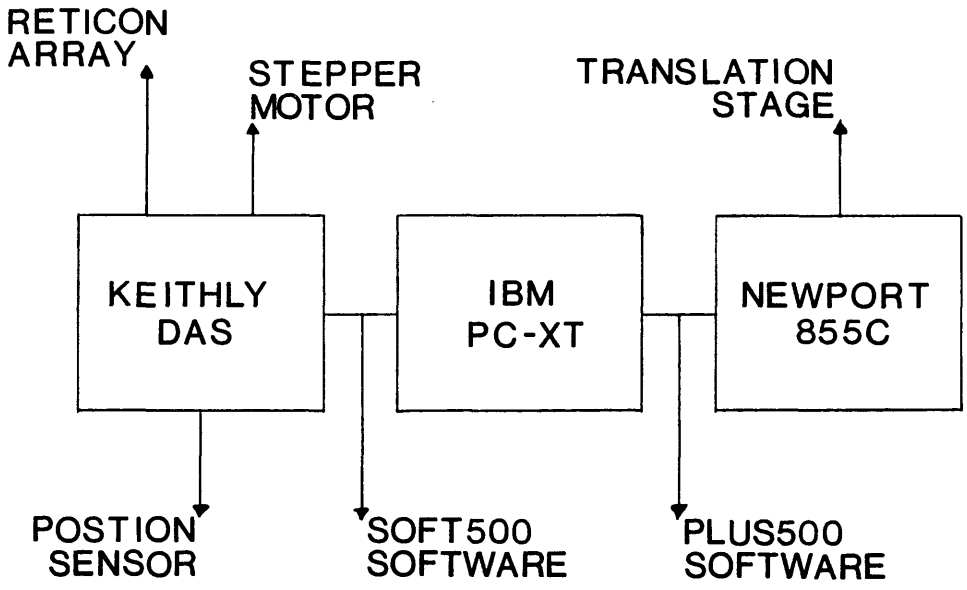

Figure 5. Block Diagram of the Instrument.

The Reticon array consists of 1024 photodiodes arranged in a linear order. Each diode element indicated the intensity of the light over the 25μm span of the element. The stepper motor(SM) rotates the mirror through a gear reduction box. The motor was linked to the reduction box with a rubber belt. The position sensor indicated the position of the beam in two orthogonal directions. In addition, the sensor read the intensity of the incident beam. The Newport actuator(motorized micrometer) and translational stage positioned the beam at the desired points along the length of the facet.

The instrument was fully automated. Once the polygonal mirror was fastened to the rotational drive, the instrument proceeded to analyze the entire mirror. The stepper motor positioned the polygonal mirror such that the first test facet imaged the light onto the Reticon array. The corner cube swept the light beam across the test facet in incremental steps. At each position on the test facet the DAS acquired the image on the Reticon array and then wrote the information onto the hard disk of the IBM PC. Once the test facet had been viewed, the polygonal mirror was rotated until the succeeding facet imaged the light onto the Reticon array. The feedback system aided in the positioning of the mirror during each rotational process.

The procedure continued until all fifteen facets of the polygonal mirror had been analyzed. The operating programs for the instrument are listed in the first Appendix.

2) Reticon Array Interface

Figure six illustrates the circuit used to interface the Keithly DAS and the Reticon array. The circuit operated in two modes; the acquisition and standby modes.

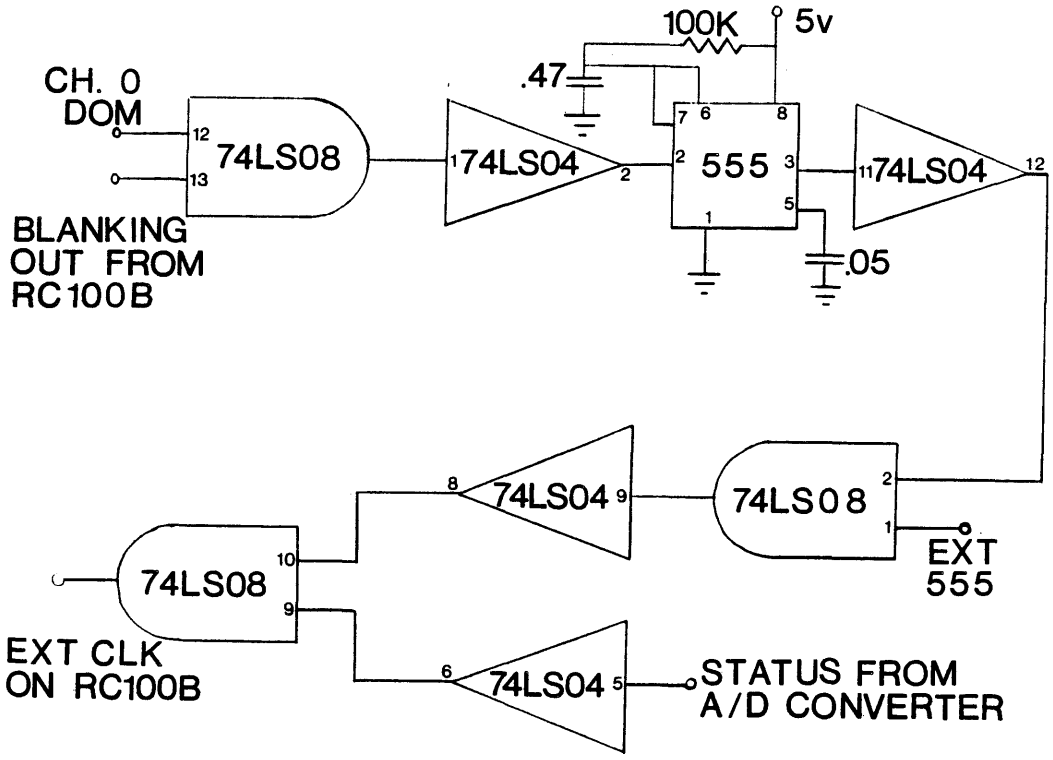

Figure 6. Reticon Array-Keithly Das Interface.

In the acquisition mode, the interface circuit connects the status signal of the A/D converter to the Ext Clk line

of the RC100B circuitry. When in the standby state the an external 555 clock is linked to the Ext Clk input.

The acquisition mode was initiated by bringing channel zero of the digital output module(DOM) in the Keithly DAS to a high state. The blanking out signal from the Reticon array indicated that the array was ready to relieve itself of the charge built up on its photodiodes. When both the blanking out and the DOM signals were high, the output of the and-gate went high and brought the output of the inverter low. The 555 timer acted as one a shot; when the input at pin 2 went low, the output at pin 3 went high into a monostable state. The succeeding inverter brought one of the and-gate inputs low, which turned off the external clock. Once the status signal from the A/D converter began, it passed through the remaining and-gate.

The standby state was typified by the DOM signal being in a low state. In this condition pin 3 of the 555 was low, which brought one input of the and-gate high and allowed the 555 external clock to pass through the gate. The status signal being in a low condition forced one input of the and gate high and allowed the 555 external clock to pass through the remaining and-gate.

One problem was encountered with the operation of the interface circuit. The transition from the 555 external clock to the status signal was not immediate. The delay allowed dark currents to charge the photodiodes appreciably. The problem was resolved by eliminating the first acqiusition containing the dark current noise from the analysis.

3) Stepper Motor Interface

The circuitry allowed for either manual or computer control of the stepper motor. The stepper motor was linked to the circiutry by a model 3025 Bipolar Chopper Stepper Motor Driver.

The stepper motor required three inputs. The inputs activated the motor, defined the direction of rotation, and stepped the motor. When under computer control, the three inputs were linked to channels 1, 2, and 3 of the DOM in the Keithly DAS. CW-CCW, enable and 555 timer circuits provided the necessary circuitry when operating in the manual state.

4) Feedback Position Sensor

The position sensor assisted in the automation of the instrument. the sensor was able to detect the position of an incident light beam in two independent directions. One dimension was used to position the light image off the polygonal mirror onto the Reticon Array. Although the other dimension wasn't directly used, it could have easily been calibrated to measure the vertical offset of each facet of the polygonal mirror. The sensor also had the additional ability to measure the intensity of the light incident on its surface. This feature was used to initiate homing procedures for positioning each facet of the polygonal test mirror.

The circuitry of the interface is illustrated in figures seven, eight and nine. The interface consisted of current-voltage, position sensing, and intensity circuits. The sensor contains four output pins which act as current sources. The current-voltage circuit, illustrated in figure seven, converts the current sources to voltage sources.

The detector was designed to indicate the position in either dimension by subtracting the voltages of pins 1 and 2, and pins 3 and 4. The position-sensing circuitry,

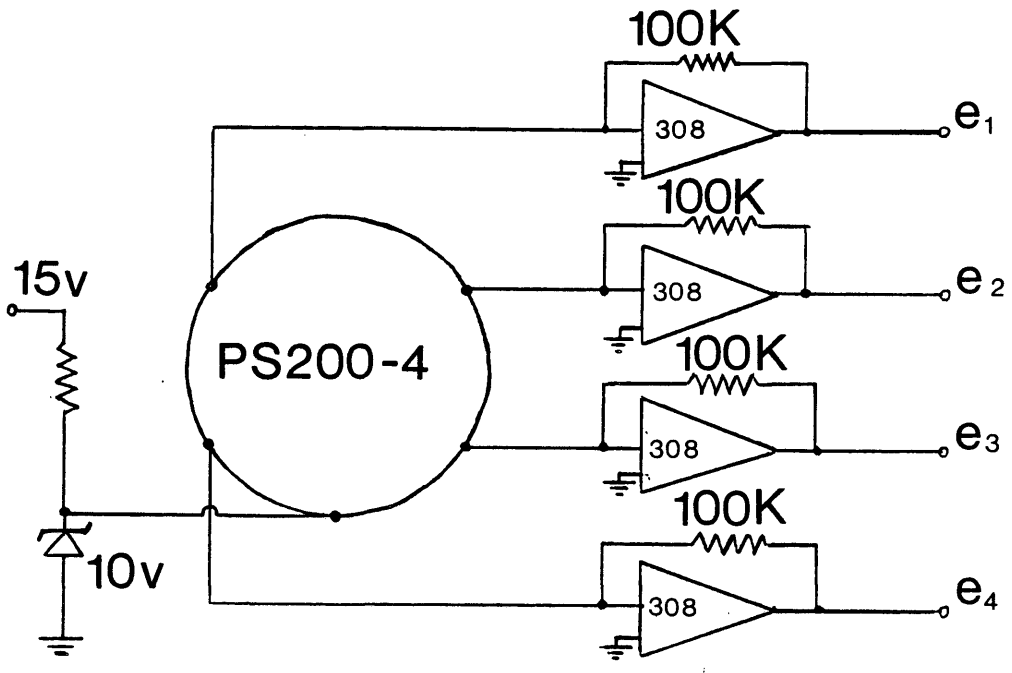

Figure 7. Current to Voltage Converter.

diagramed in figure eight, performed this with a unity gain differential amplifier. The positions, indicated by the sensing circuits, were connected to channels 3 and 4 of the AIM(Analog Input Module).

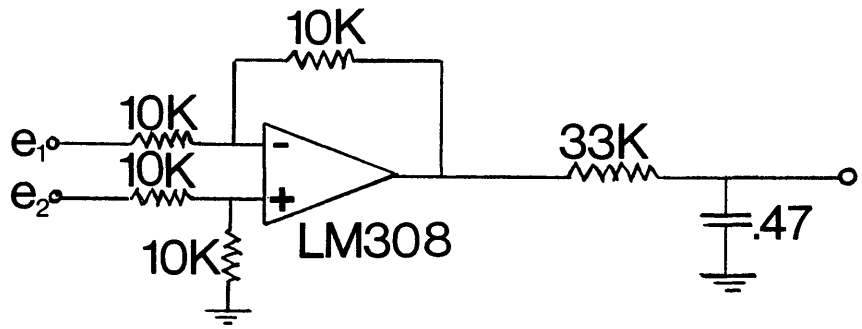

Figure 8. Unity Gain Differential Amplifier.

The intensity of the light incident on the detctor was measured by the circuit in figure nine. Each of the four outputs, e_1, e_2, e_3, and e_4, are summed by the summing amplifier to produce a signal proportional to the intensity of the light incident on the detector surface. The Keithly DAS read the intensity line via channel 5 of the AIM.

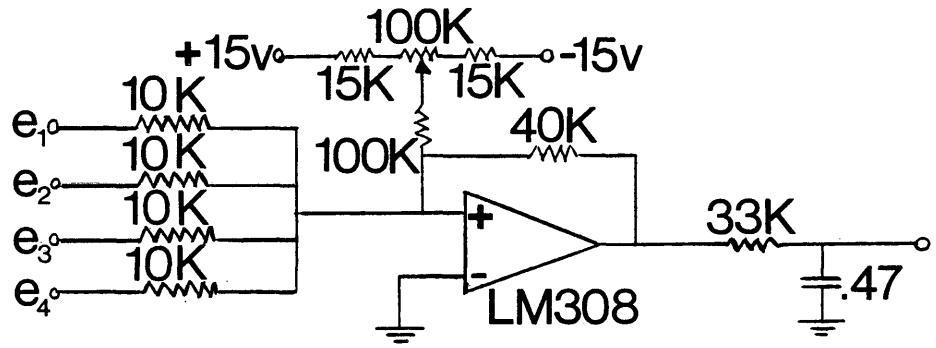

Figure 9. Summing Amplifier.

INSTRUMENT PERFORMANCE

A. Problems Encountered

Some problems were encountered while constructing the instrument. The major problems were interfacing the Reticon array to the Keithly DAS and eliminating external noise sources.

The Reticon array and the Keithly DAS both operate on their own timing clocks. It was necessary that the DAS and the Reticon array be timed synchronously when an acquisition was performed. The two systems were coordinated by the interface circuit diagrammed in figure six. When the DAS was ready to look at the array, the interface circuit turned off the external clock and substituted a clock signal from the DAS in its place. When the acquisition was complete, the array clock was reinstated.

The transition between the array clock and the DAS allowed dark noise currents to deposit charges on the diode elements of the Reticon array. The noise only affected the first acquisition(i.e. the first 1024 elements). This effect necessitated removing the first acquisition from the data analysis.

A second problem encountered was noise produced by air turbulence. Fluctuations in the position of the light image on the Reticon array corresponding to as many as 50μrad were common. The instrument was isolated from the outside environment with a large wooden box enclosure. Air movements were further reduced by shielding the optical path with cylindrical tissue tubes. The box and the tubes reduced the fluctuations to an acceptable level.

Another source of error in the instrument were laser fluctuations. The direction of the laser beam wandered due to thermal fluctuations in the cavity. The orientation of the mirrors were not rigidly fixed when thermal gradients exist in the mirror supports.

Although the laser fluctuations were not a problem, they could have been substantially reduced through the use of careful mirror mounts and a circular aperture. Mounts composed of materials possessing a low thermal conductivity and a high degree of homogeneity would diminish unwanted thermal drift. A circular aperture would further enhance the stability. The aperture has the property that when plane waves are normally incident upon it the diffracted field is insensitive, to first order, to changes in the direction of the source field. Thus, small fluctuations in

the direction of the incident laser light will be reduced to second order variations in the diffracted field.

B. Test Results

The operation of the instrument was checked with three tests. The accuracy of the instrument was measured with a calibration procedure. A pre-tested polygonal mirrror was inspected. The results are compared with the results of two tests administered at IBM in Boulder. Finally, the consistency of the instrument was examined with a repeatabilty test.

1) Calibration

The instrument's accuracy was calibrated with a test mirror of a known curvature. The test mirror consisted of a concave spherical surface with a radius of twenty meters. The mirror was placed in a position that a polygonal mirror facet would normally occupy. The beam was swept across the spherical mirror in increments corresponding to a 2μrad change in beam deflection. The results of the calibration test are graphically illusrated in figure ten.

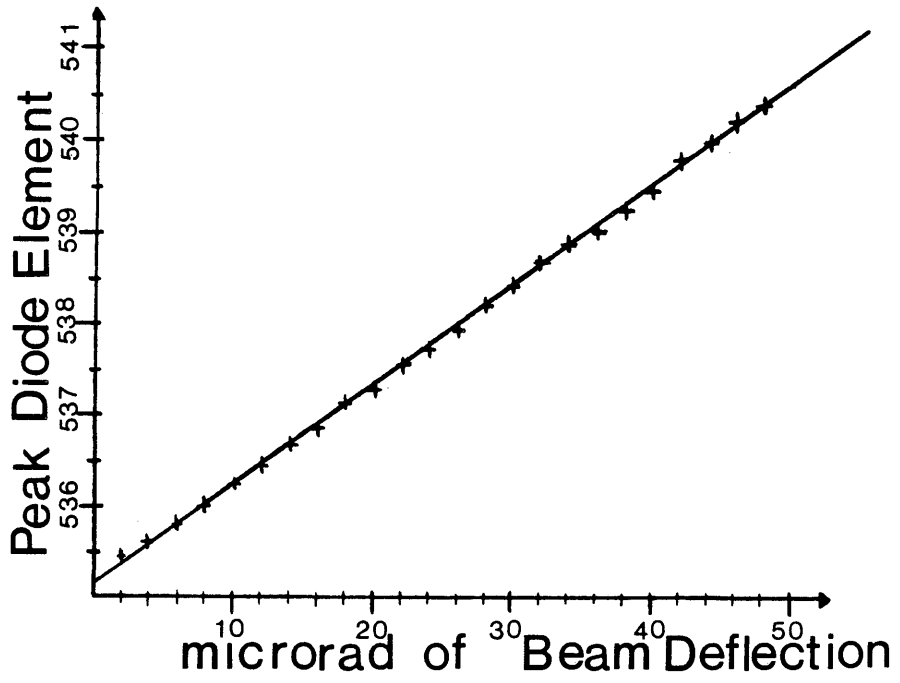

Figure 10. Calibration Results.

The graph depicted in figure ten displays the peak diode element of the intensity distribution, imaged onto the Reticon array, plotted against the net change in beam deflection angle, as measured from the initial scan point. The data was fit to a line with a least squares method. The value of the slope indicates the instrument is able to resolve 2μrad changes in the beam deflection angle. The numerical result for the slope is,

Slope=.11±.01 Diode Elements/μrad.

2) Comparative Tests

A pre-tested polygonal mirror was examined. The mirror, number Nachi-1, was pretested at IBM in Boulder with at least two different methods. The graphs, depicted on pages 23-24, are plots of the beam deflection error versus the position along the facet.

Generally, the results(the contours depicted with starred lines) are more supportive of method two(solid) than method one(dashed). The shapes of the contours are similar. The results, however, are not identical. The vertical scales on graphs 6, 8, and 12 are offset, indicating a possible discrepency in the reference point on those facets. Oftentimes similar features within one contour were translated relative to the corresponding features in another contour(eg. facet ten). It is difficult for any conclusions to be drawn which would explain these differences without a fuller understanding of the techniques used used in methods one and two.

The surface height resolution can be compared with other methods. The light incident on the test surface had a waist of approximately 5mm. With the 1μrad slope resolution, the instrument was actually resolving changes

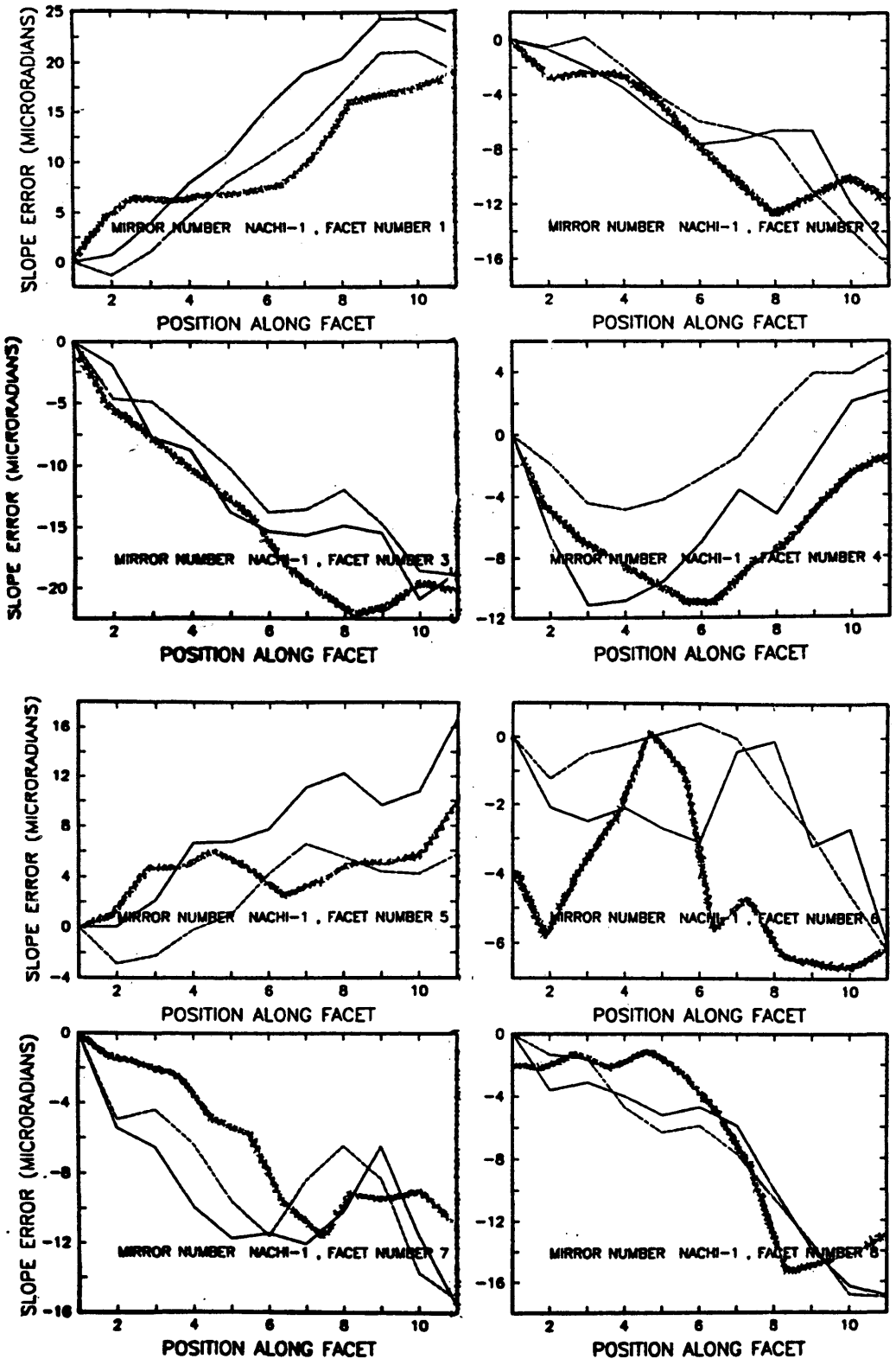

Figure 11. Test Results of Facets 1-8.

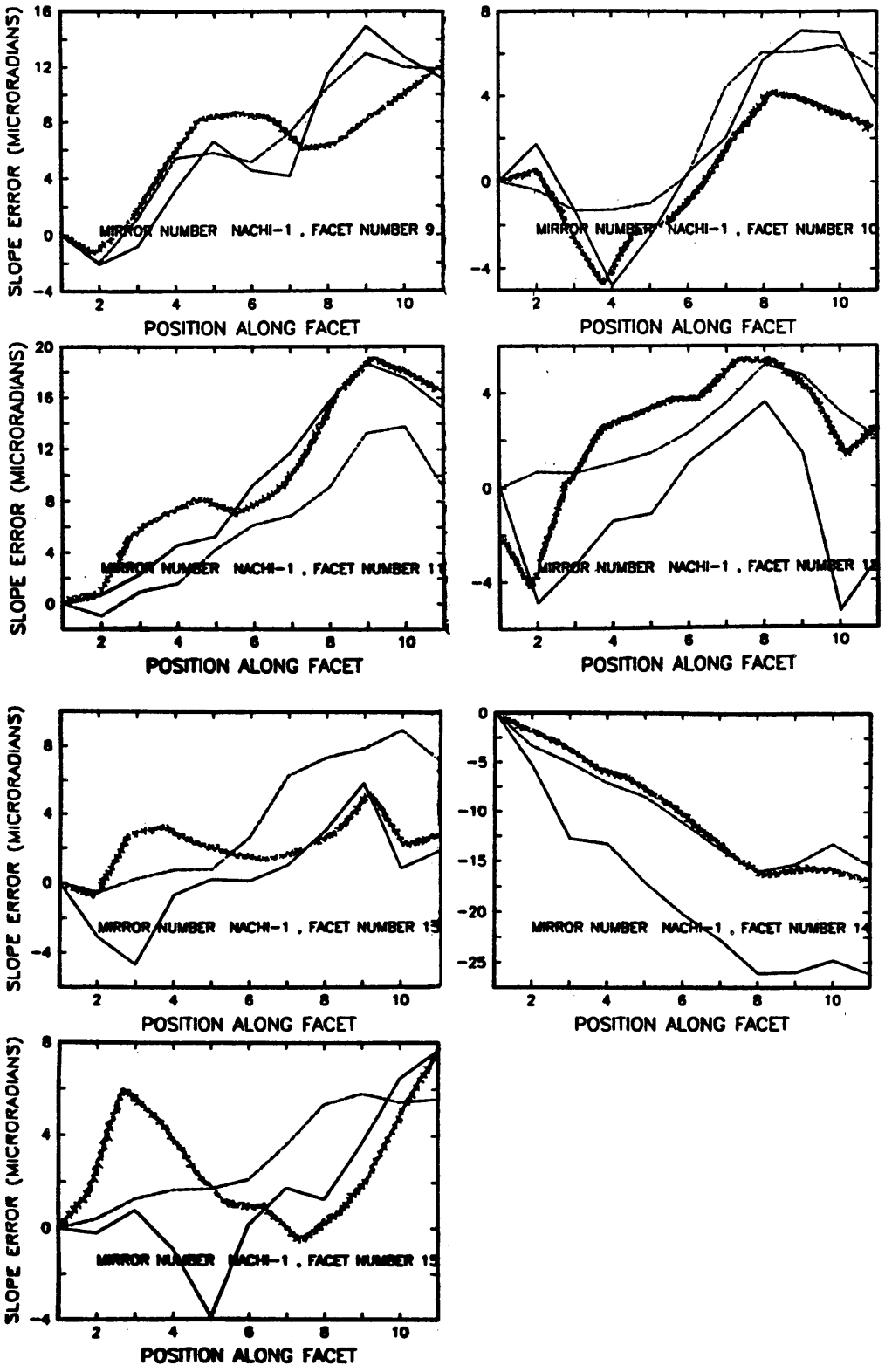

Figure 12. Test Results of Facets 9-15.

in the surface height corresponding to 50Å. Standard test methods practiced today offer comparable accuracy. A Tyman-Green interferometer can resolve changes of λ/100, or about 500Å in the visible. A stylus instrument can identify changes as small as 25Å. And finally, a double beam Fabry-Perot interferometer can resolve height changes of λ/500, or approximately 10Å.

3) Repeatability Test

The consistency of the instrument's performance was verified by testing its repeatability. Facet number four of the polygonal test mirror was analyzed. The facet was scanned ten times with twelve points per scan and each point consisting of ten samples. The first two scans were rejected. The remaining eight scans are illustrated in figure thirteen.

The curves demonstrate a remarkable likeness. The contour shapes are very similar. The offset, between the zeroes of the curves, is about 1μrad. The variation in the vertical range, from the left maximum to the central minimum, between the contours is less than .1μrad. The results indicate the instrument is operating faithfully.

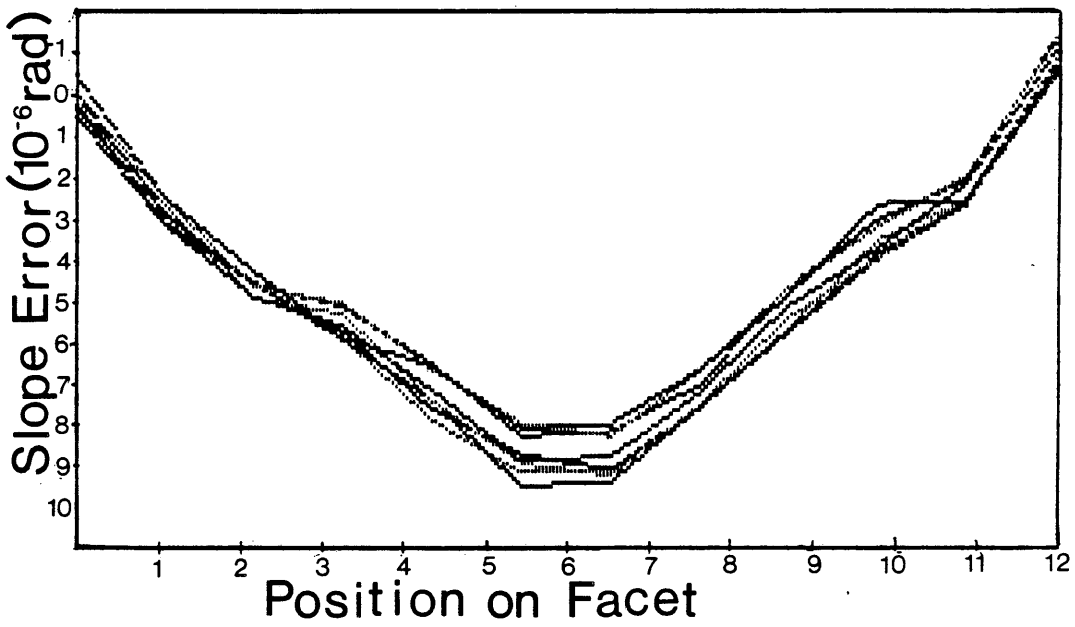

Figure 13. Repeatability Test Results.

CONCLUSIONS AND RECOMENDATIONS

A method has been developed that is able to analyse the surface-slope quality of optical mirrors. An automated instrument has been constructed that utilizes the method. Various tests indicate the instrument is operating consistently. In addition, the method can be improved and expanded to test a larger class of optical components.

The instrument was calibrated and tested. A known test mirror was used to calibrate the instrument. The results of the calibration are in accordance with a model of the optical system. The instrument was tested for its repeatabilty. The results indicate the instruments response is consistent. Finally, the method was tested against two commercial methods. The constructed instrument generated similar surface-slope contours with comparable ranges. The results of the calibration and tests demonstrate the instrument is able to resolve surface slope variations of 1μrad consistently.

The surface contuor resolution of the instrument described can be upgraded. The tests were conducted with a beam waist of approximately 5mm on the test surface. Subsequent laboratory experiments indicate the beam waist

can be reduced by approximately an order of magnitude. The attainble beam waists combined with the 1μrad surface-slope resolution indicate the method can be applied to detect changes in surface elevation as small as 10 angstroms or less. Such a resolution rivals and surpasses many interferometric methods in practice today.

A larger class of optical elements could be tested with a minor modification. Replacement of the test surface with the combination shown in figure fourteen would enable lenses or curved surfaces to be tested. The separation between the lens and the mirror can be adjusted such that the combination ideally acts as a planar mirror. Employing a standard element for one of the components the quality of the remaining component could be deduced. Deviations from the ideal response could be used to ascertain the quality of the unknown test component.

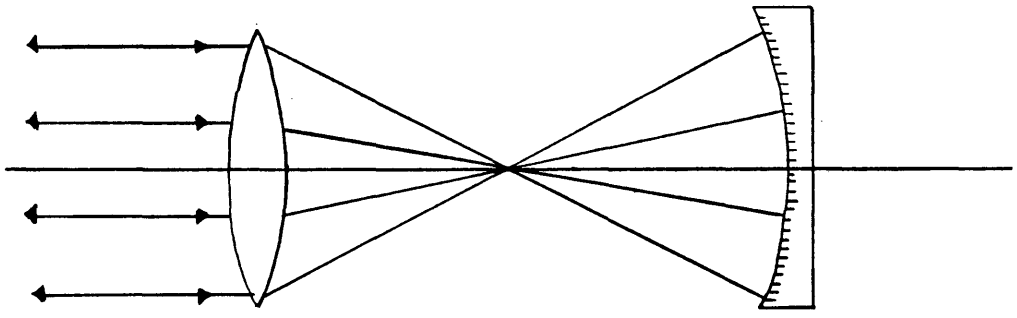

Figure 14. Mirror-Lens Combination.

The recent multitude of fundamental discoveries and developments in the optical sciences has created new demands on the testing of optical components. The design constraints of various optical components have forced component manufacturers to the perimeter of the established testing techniques. Improvements and minor modifications of the research described may prove to be a useful development for the field of optical component testing.

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