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Authors
Alston-Garnjost, Margaret.
Davis, J.W.
Dauber, P.M.
et al.

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M. Alston-Garnjost

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A LARGE GRANITE MEASURING MICROSCOPE*

Margaret Alston-Garnjost, J. W. Davis,
P. M. Dauber,† and R. G. Smits

Lawrence Radiation Laboratory, University of California
Berkeley, California 94720

June 1971

We have constructed a stage and measuring microscope servocontrolled by a PDP-8 computer. The travel of the stage is 0.5×0.5 m (x, y) and the travel of the microscope objective is 7.5 cm (z). The measuring accuracy is 1 μm in the x-y plane and 5 μm along the z axis.

INTRODUCTION

In high energy and cosmic ray physics the determination of the momentum of a charged particle by magnetic deflection requires accurate position measurements of the intersection of the particle path with a detector plane. Spark chambers in current use, with both optical and digital readouts, have resolution in the range of 0.05 mm to several mm. Resolutions of ≈ 0.1 mm or better have been achieved only with wide gap chambers and high quality optics. Spatial resolution of the order of 1 μm is, however, achievable with nuclear track emulsions. The use of emulsions in magnetic spectrographs is made practical for large scale applications by using spark chambers to locate the tracks.[1] In order to realize position resolution in the μm range for large emulsion plates (>> 10 cm dimensions), it is also necessary to have a measuring microscope and stage with exceptional accuracy, range of motion, and controllability.

We have developed a stage and measuring microscope with better than 1 μm measuring accuracy and 0.5×0.5 m travel. The stage is servocontrolled via a PDP-8 computer; input and output of data are by magnetic tape. Readout of the stage position is achieved by use of laser interferometers on two axes, and the stage can be directed to a point within a fraction of 1 μm by means of the fringe counts. The extraordinary travel of the stage was achieved by air-bearing suspension of the massive (400 kg), movable, granite superstage on a 4000-kg polished-granite base with granite ways straight to 0.5 sec of arc. A microscope mounted on this base permits scanning and measurement either by transmitted or by reflected light. The image is relayed optically to the operator console. Control and adjustment functions, including horizontal stage motion, vertical microscope motion, adjustment of illumination, etc., are by remote control from this console. The stage is enclosed in an aluminum box to maintain constant temperature. Temperature, humidity, and barometric pressure are sensed via the computer and used for corrections in the conversion from fringe count to distance.

Although the measuring stage described here was built for applications to emulsion plates, there are a great many other possible applications both in and out of particle physics. For example, the stage could be used to calibrate any planar, high-resolution, particle-detection device. A number of such devices have been proposed[2] which operate in real time—a great advantage over emulsions in most experiments. Just to suggest the range of possible applications, we mention at this point the possibilities of using the stage to measure precision grids, to scan and to measure astronomical plates, to rule very large diffraction gratings, and to layout patterns for semiconductor devices of (relatively) enormous size. It will be seen below that the mechanical and optical construction of the stage and microscope, as well as the way in which the control electronics are organized, permit great flexibility of operation.

The organization of the rest of this paper is as follows: Sections I and II, respectively, describe the mechanical and optical parts of the system. Section III describes the electronics, including the computer and interface, and outlines the main features of the operation of the complete system. Section IV presents the results of our tests of the measurement capabilities of the instrument. Finally, Section V gives a brief description of the unique features of the machine, a summary of some measurements, and possible future applications.

I. MECHANICAL

The stage and microscope are built on a 4000 kg granite-block base (see Figs. 1 and 2). A steel bridge across the base holds the microscope lens turret over the object being measured. The object is carried over the granite base by the moving superstage. A periscope and lens system relays the microscope image along the bridge, down to the operator's eye level, and along a tube to the operator's eyepiece. The operator sits at a console and remotely controls the stage and microscope, which are enclosed in an aluminum box for thermal stability.

A. Stage and Base

The granite stage and base were made by Fox Instrument Company of Hayward, California. The stage motions are 0.5 m × 0.5 m and are designed to have a reproducibility of 1 μm in the stage plane (x and y axes). To the stage and base, we added a microscope system with 7.5 cm focal travel and 5 μm focal depth reproducability. These dimensions were chosen to reach the center of a one-meter/diam emulsion-coated glass plate.

The granite base has a 1.6 × 1.6 m square top surface, polished flat to 2.5 μm. The base is 0.6 m thick to assure that the top surface will remain flat with varying loads on its surface. Granite is used because it is inexpensive in the bulk required, will accept a good polish, has lower thermal expansion ($7 \times 10^{-6}/°C$) than most metals, and is very hard (Rockwell C-60-80). A 25-cm-diam hole through the granite provides space for the substage illumination system. The granite base lies on three 20-cm cubical wood blocks that rest on 1-cm-thick rubber (Iso mode) pads to decouple building vibrations.

B. Movable Parts of the Stage

The moving superstage is also made of granite and is 1 m square × 20 cm thick with a 66-cm-square cutout through it for the substage illumination system. The superstage weighs about 400 kg and can carry a 75-kg object to be measured. The superstage floats over the base on four self-leveling air-bearing feet. Each foot has a pneumatic gaging system which modulates the air pressure to maintain a constant 2.5-μm air film thickness independent of load.

An intermediate stage also rides on the base and carries granite ways with air bearings to prevent rotation of the superstage. The straightness of these ways is an important factor in this measuring machine because the position of the superstage is found by measuring the y position of the intermediate stage relative to the base and the x position of the superstage relative to the intermediate stage.

X and y motions of the superstage are accomplished by friction drive between steel rollers connected to the servomotors and steel pushrods connected to the stage. The absence of gear teeth permits motions of less than 1 µm without significant hysteresis, yet speeds up to 5 cm/sec can be achieved. Manual operator control of x and y is by means of a ball-type control; the top cm of a 10-cm-diam ball ("bocce ball") projects above the console. The operator rolls the ball in the direction he wants the stage to move. The ball floats in an air bearing and two pickoff wheels resolve its motion into orthogonal components. Servomotors drive the stage so that there is a close correspondence between bocce ball motion and image motion as seen in the microscope.

C. Interferometers

X and y positions are determined by two Michaelson interferometers using a single laser light source (see Fig. 3a). The interferometers were made by Union Carbide Corporation.[3] Their essential features are shown in Fig. 3b. The laser (Spectra Physics 119) has automatic cavity tuning to produce a stable single-frequency light beam.

The laser light is focused into a narrow, parallel beam of about 1.5 mm diameter. A beam splitter is used to send part of the light to each interferometer. In each interferometer, the beam is split again–one part goes to a fixed cube-corner reflector and the other part passes through the beam splitter to the moving cube-corner.[4] Each cube-corner reflector displaces the returning beam 6 mm from the outgoing beam. This displacement allows the same beam splitter to be used both to recombine and then to split the returning beams between the two photodetectors (photo-field-effect-transistors or photo-FET's).

A special absorptive aluminum coating on the front surface of the beam splitter produces a 90° phase shift between the light intensities at the two photo-FETS. Thus there are no spatial fringes. The light intensity at each photo-FET goes alternately light and dark as the stage moves. The peaks in the sine wave output of each photo-FET correspond to the stage position at which the combined beams are in phase. The second photo-FET in each interferometer is necessary to determine the <u>direction</u> of stage motion.

The advantages of this system are:

a. maximum brightness of light on the phototransistors because of small beam size;

b. no field adjustment of phase necessary because the relative phase is determined by the special absorptive coating on the beam splitter;

c. beam easily aligned parallel with axis of stage motion;

d. lack of spatial fringes means that an object passing through the beam may prevent counting but does not inject any stray counts; and

e. there is no disruption of the laser automatic cavity tuning by returning light.

D. Microscope Bridge

The bridge is made of two hollow steel box beams ≈ 25 cm apart, separated by a steel web. The design objective was to minimize the mass-to-rigidity ratio to raise the resonant frequency above 60 Hz in three axes. The uniform thickness of the steel promotes uniform temperature stabilization, and the symmetrical support balances thermal expansions about the objective lens.

E. Z-Axis Stage, Drive, and Readout

The stage which holds the microscope lens turret utilizes a set of ball-bearing ways to provide 7.5 cm vertical (focus) travel. This z-axis stage is positioned by means of a precision lead screw of 1 mm pitch, directly coupled to a dc servomotor and tachometer. An optical encoder produces readout in microns. Manual z-axis or focus control is by means of a pickup system similar to that used for x and y, except that a wheel is used instead of a bocce ball.

II. OPTICAL

Two illumination system are provided: one within the stage base for viewing transparent objects and one at the objective lens turret for viewing opaque objects by reflected light. When the selected objective lens is properly positioned, an image of the object is formed in space at the first focus within the microscope body (Fig. 1). The intersection of the crosshairs attached inside the microscope body defines the measuring point at the first focus.

Light passing through the first-focus image is collected by the relay lens and imaged with a magnification of about 2X at a second focus at the operator's eyepiece.

The operator's eyepiece is a Bausch and Lomb binocular microscope body in a coarse focus mount for critical focusing on the crosshairs. Various eyepieces can be used but 10X seems most satisfactory. Thus, a 32X objective and a 10X eyepiece yield a magnification of $32 \times 2 \times 10 = 640$.

A. Illumination

The substage illuminator utilizes a Tiyoda incandescent bulb in a suction-cooled housing to draw the heat away. One of five filters may be selected from a color wheel; the 0.7 N.A. Bausch and Lomb condenser lens may be focused and moved in the x or y direction; and the condensing lens aperture may be adjusted--all by remote control from the operator's console.

The Bausch and Lomb vertical illuminator (also suction cooled) utilizes a beam splitter for directing light out of the objective lens onto an opaque object. The illuminator requires no adjustments because it travels with the objective lens.

B. Relay System

The relay lens is an 18-in. focal length, f-4.5 Dallmeyer Serrac in a traveling mount. Since the cross hair at the first focus moves ≈ 7.5 cm (with the z-axis travel) and the operator's eyepiece is stationary, it is necessary to move the relay lens to keep the crosshair image sharp at the second focus. The relay lens moves in a cart by means of a screw of 22 threads per inch. This screw is driven at the same angular velocity as the z-axis screw. The relay lens, therefore, moves 25.4/22 times as far as the z-axis stage. The draw tube is preset, as well as the relative phase of the two screws, so the crosshairs stay in focus throughout the entire z-axis travel.

The three mirrors used in the relay system and shown in Fig. 1 are all first-surface mirrors of $\lambda/4$ flatness.

C. Objective Lenses

Any of the common screw-mount objective lenses can be used with the microscope. In addition, there is provision for special vibrating objectives for track-finding in emulsion. Continuous use of oil immersion objectives requires an automatic oiler which has not yet been built.

III. ELECTRONICS AND OPERATION

The stage electronics and the PDP-8 operating program have several functions:

a. control the physical movement of the stage and microscope;

b. continuously monitor and record the stage and microscope positions;

c. monitor and record environmental conditions; and

d. establish communication between the operator, the computer, and the input and output magnetic and paper tapes.

A. Servo System

Mechanical drive to either axis of the granite stage is by a printed-circuit permanent magnet dc motor in combination with a similar motor used as a feedback tachometer. These motors are capable of instantaneous power exceeding 100 watts and are capable of accelerating the massive superstage to the maximum desired velocity of 5 cm per sec in less than 0.1 sec. Primary servodrive power is ac, channeled through a silicon-controlled-rectifier bridge such that positive half-cycles drive the servomotor in one direction and negative half-cycles drive it in the opposite direction. Limit switches in three echelons ensure against mechanical damage from servo overdrive. The first limit reduces the drive command signal, the second limit prohibits further drive in the offending direction but allows backout drive, and the third limit cuts off all drive power to the servomotor and requires manual reset.

The analog command signals into the servoamplifier chassis can originate either from the computer or from the operator via the x-y control (bocce) ball as shown in Fig. 4. In the first or "automatic" mode, the computer program controls the stage movement by providing digital commands to a digital-to-analog converter. The converted analog signal is one of the command signals to the servo chassis. In the second or "manual" mode, the operator generates the drive signal to the x-y axes of the machine by moving the bocce ball. The output signals are trains of phased square waves; phasing encodes the direction of ball rotation and pulse frequency encodes the speed of rotation. In the x-y ball control electronics, the phased square waves are converted into an analog voltage, which becomes the command input to the servo chassis.

B. Position Readout Electronics

The essential function of the interferometer electronics is the conversion of the 90° out-of-phase trains of sine waves from each pair of photo-FET's into binary scaler counts. The photo-FET signals are amplified and shaped into nearly square waves which go into the direction logic. The direction logic produces easily counted pulses in the ratio of four counts for each 2π of sine wave phase change or eight counts for each wavelength (0.6328 μm) of stage motion (since the reflected laser light path increments are twice the stage motion). Thus a least count in either the x or y counter represents stage motion of $\approx 1/12$ μm. The direction logic drives two (x and y) 24-bit scalers positive or negative; the stored binary count represents travel from the last zero count.

Considerable difficulties were encountered in satisfying the requirements of the system for high gain between 0 and ≈ 1 MHz counting frequencies. It was necessary to eliminate many potential sources of noise signals which could otherwise have resulted in false counts.

The signals from the z-axis encoder are converted to positive and negative counts in an 18-bit scaler. As mentioned above, the z least count is 1 μm. The x, y and z scalers are connected by separate interfaces to the PDP-8 computer, where the position count of each axis occupies two 12-bit words.

C. Environmental Servors

Several inherent difficulties in making precise measurements (to 1 part per million) over large distances are caused by environmental changes. The temperature of the component being measured may vary, changing its dimensions appreciably. For a Herculite glass plate the thermal expansion is 9.4 ppm per °C. A variation in temperature of 0.1°C will therefore change the size of a 1 meter object by 1 μm. Expansion is several times larger for some metals. Fluctuations in the temperature, pressure, and humidity of the air will change the wavelength of the laser light, so the number of interference fringes counted must be corrected. For temperature, the correction near 20°C is -0.94 ppm per °C; for pressure, the correction is -0.36 ppm per mm Hg; and for humidity, the correction is about +0.01 ppm per % relative humidity change.

It is clear that to control the environment to the required accuracy would be very difficult and costly. A better approach is to keep short-term fluctuations as small as possible, monitor the environmental conditions, and correct the measurements. The granite stage is

situated in an air-conditioned room; the temperature is controlled to within ± 1°C and the humidity to within ± 5% over long periods. The granite base slab, stage, and superstructure are enclosed in a draft-proof aluminum-sheet metal box with folding access doors. Several thermistors and a humidity sensor interfaced to the PDP-8 computer are placed inside the box to continuously monitor the temperature of the object being measured and the temperature and humidity of the air.

D. Computer and Operating Program

The PDP-8 computer interfaced to the stage has a 4000-word core, (12 bits per word), a teletype with paper tape reader/punch, and two IBM-compatible magnetic tape units. Each of the interfaces namely the x, y, z, operator, environment, and magnetic tape interfaces are constructed of small printed-circuit cards in Nuclear Instrument Modules (NIM system). The input/output bus of the PDP-8 computer was bused across the rear of the NIM bin, thus allowing any interface to be plugged in any position in the NIM rack; providing, of course, that the specialized cables to each interface (e.g., servocontrols, limit switches, interferometer counter, etc.) were kept with each particular interface box as it was moved. This system was used primarily to allow ease of construction and maintenance. Operator/computer communication is established via a teletype and a pushbutton panel, both situated at the operator's console.

The PDP-8 is programmed for both calculations and control functions. All numerical calculations are performed in double-precision fixed-point arithmetic except for the calculations of distances between measured points, which require quadruple precision. The programming of the various control functions is modular so that several fun tions may be strung together to form any desired sequence. The functions which must be used while the operator is measuring a sequence of points are controlled by 10 pushbuttons at the operator's console. These include-record point (x, y, z,), delete point, advance through sequence, backspace, drive stage to next point in sequence, area scan, input data record, and output data record. The function of any button can be modified by software and may vary for different phases of the operation. More complicated functions and the setting up of sequences are initiated by typing two character mneumonics into the teletype. This procedure has led to a flexible system which has been very useful in debugging the machine and measurement procedures.

There are two basic modes of controlling the motions of the stage and microscope: either manually or under computer control. In general, large motions of the stage are made under computer control by inputting the approximate coordinates of the point to be measured from the teletype, paper tape, or magnetic tape, and by requesting the computer to drive the stage and microscope to the desired position. Small motions of the stage and fine focusing of the microscope onto a point to be measured are made manually by the operator by means of the bocce ball and focus wheel at the console. In addition, a pushbutton-initiated spiral scan is provided which can be used to find points or tracks within a few diameters outside the field of view of the microscope objective. Each spatial coordinate (x, y, z) is stored in binary counts in six consecutive core locations, two words for each coordinate. Up to 10 coordinate points can be stored at a time.

The computer samples the voltages from four thermistors and a humidity sensor within the aluminum box surrounding the stage via an analog multiplexer and digital voltmeter and converts these voltages

to temperatures and humidity. At present the atmospheric pressure is read from a mercury barometer and inputted manually at the teletype.

Data can be inputted or outputted at the teletype or from paper or magnetic tape. In the debugging phase of the machine, input/output of information has been almost exclusively from the teletype. In addition to a simple function which automatically prints the measured coordinate (x, y, z) in counts, functions exist which can be used by the operator to obtain the distance and δx, δy, δz between two measured points in counts, microns, or microinches. The operator can also use the teletype to sample the environmental conditions, zero the counters, enter indicative data, and carry on a limited dialogue with the computer.

IV. MEASUREMENTS WITH THE GRANITE STAGE

A. Quartz Bar

The first question to ask after building such a machine is: "How good is it?" To find the answer, we needed something to measure. We made a number of "fiducial-pins" shaped like right-circular cylinders (with axis vertical) and with an enlarged base in the form of a frustrum of a cone. The pins are $1\,{}^{1}/2$ mm diam and 2 mm high, and the base is 3 mm diam. The top surfaces of the pins are lapped and polished and scribed with an "X" of two intersecting 3 μm wide grooves.

To investigate the orthogonality of the x and y axes, we cemented two fiducial pins onto a rectangular-sectioned quartz bar at a separation of about 0.5 m. The bar was mounted on the superstage so that it could be rotated in the x-y plane. Measurements of the separation of the pins were made with the bar: (a) along the x axis, (b) along the y axis, (c) at 45° to the x axis and (d) at 135° to the x axis. From a comparison of (c) and (d), we checked the orthogonality of the ways, and by repeated measurements and adjustment of the intermediate stage guiding air bearings we reduced the variation in apparent bar length to less than 1 μm for any orientation of the bar.

B. Glass Disc

To determine the reproducibility and measuring accuracy of the system, we used one of the glass discs which would be coated with emulsion when used in an experiment. This series of measurements also checks the feasibility of measuring a large object with sufficient precision under real operating conditions.

The disc is 900 mm diam × 2.5 mm thick and has 21 fiducial pins cemented to it [Fig. 5(a)]. It is of such size that slightly more than one-quarter of it can be measured in one placement on the superstage. The pins are arranged so that nine pins can be measured in each quadrant; four of the nine are remeasurable during the measurement of the next adjacent quadrant. Furthermore, the nine pins nearest the center of the disc can be measured in one disc position, which we call the "fifth" quadrant. The center pin is common to all five quadrants.

The glass disc is pseudokinematically mounted on a fixture which permits centering of any one of the five regions to be measured on the superstage. The disc rests on a rotatable steel ring; a notch on the circumference of the disc is detented around a pair of ball bearings to fix a point. Another ball bearing at about 130° from the detent pair prevents rotation about the first point, and a spring at about 255° holds the disc against the three bearings. The ring rests on three ball joints mounted on air-bearing pads.

When it is desired to change the disc position between quadrants 1, 2, 3, and 4 (QI, QII, QIII, QIV), an air hose is connected to the air pads, and the ring is rotated, guided by a circular track. The track is mounted on a surface-ground steel plate which has two positions on the superstage. One position is with the disc center at the corner of the measuring area of the superstage for QI, QII, QIII, and QIV. The other position centers the disc on the measuring area for the overlap position, QV. The motion between these two positions is also assisted by air-bearing pads.

We measured the nine pins in one quadrant and made a repeat measurement on the center pin to get 10 measurements. This sequence was repeated 10 times to give 100 measurements in this quadrant. The disc was then repositioned so that the next quadrant could be measured and so on, giving a total of 500 measurements for all five quadrants. The atmospheric conditions (temperature, pressure, and humidity) and the temperature of the glass disc were continuously monitored and the readings were outputted for each series of 10 measurements.

The measurements were corrected for variations in laser wavelength and for thermal expansion of the glass disc. The wavelength correction was always small. The correction for the glass expansion (9.4 ppm/°C) was quite small for all the measurements within one quadrant because the short time temperature variation was typically ±0.1°C. However, uncorrected lengths between pins as measured on different days changed as much as several microns since the temperature varied about ±1°C.

Figures 5(b), 5(c), and 5(d), show the distribution of the corrected position minus the average position of any pin relative to the center pin when measured in one quadrant (i.e., without repositioning the disc on the superstage). As shown in the figures, the reproducibility in x and y is better than ±0.5 μm; in z it is better than ±5 μm. This probably represents the setting error on the fiducial marks rather than any limitation of the measuring engine.

We then compared the distances between the average positions of pairs of pins as measured on different quadrants. The results show variations of about ±1 μm. These variations are probably caused by: (1) the small nonorthogonality of the ways, which could be removed by correcting the x and y measurement; (2) thermal effects in the glass disc, since it is difficult to stabilize the temperature and monitor it with sufficient accuracy; and (3) mechanical distortion of the disc when it is reoriented on the superstage between quadrant measurements.

We have made a complete remeasurement of the glass disc and compared the distances between pairs of points with those obtained in the original measurement. Variations of less than 2 μm in the lengths are observed, but the disc is systematically larger in one measurement than in the other. This may be due to inaccurate measurement of the temperature of the disc caused by small changes in the thermistor calibration.

From these measurements we conclude that our measuring machine is capable of better than ±1 μm precision in the x-y plane for 0.5 m of travel in both x and y. The main limitation is in stabilizing and monitoring the temperature of the object being measured. In z we find deviations of less than 5 μm in a travel of 7.5 cm. The limitation in this case is the difficulty of setting on a point simply by focusing the microscope objective.

V. APPLICATIONS

The measuring stage described in this paper was designed primarily to measure particle tracks in large emulsion-coated glass plates, although it has never been used for this purpose. However, the instrument has several unique features which make it useful for other applications.

1. High accuracy of positioning and readout;
2. large distance of travel; and
3. on-line computer which provides easy control of the stage and microscope, and communication with input-output devices including a human operator.

We have used the machine for the measurement of grids, photographs such as spark-chamber film, and other objects. These measurements were carried out with a minimum of modification to the system.

Measurements more sophisticated than simple coordinate recording would require additional hardware. Possible examples are densitometers, flying spot digitizers, or other pattern recognition devices which could be mounted on the existing microscope bridge and interfaced to the computer. With suitable modifications, the measuring stage could be converted into a computer-controlled ruling engine for making very large diffraction gratings or precision grids.

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[†] Present address: Danish Space Research Institute, Lundtoftevej 7, 2800 Lyngby, Denmark

[1] For discussions of the method, see M. I. Daion and V. Volynskii, JETP 37, 906 (1959), Soviet Phys. JETP 10, 648 (1960); L. W. Alvarez and W. E. Humphrey, "Proposal for High Altitude Particle Physics Experiment," UCBSSL No. 192 (1964); M. I. Daion, V. B. Eliseev, and M. A. Kazaryan, JETP 50, 376 (1966), Soviet Phys. JETP 23, 250 (1966); and P. M. Dauber, L. H. Smith, and M. A. Wahlig, Nucl. Instr. Methods 84, 199 (1970).

[2] For example see S. E. Derenzo, D. B. Smith, R. G. Smits, H. Zaklad, L. W. Alvarez, and R. A. Muller, "Recent Developments in High-Resolution Noble Liquid Detectors," UCRL-20118 (1970) and National Accelerator Laboratory Summer Study Report SS-181 (Batavia, Ill., July 1970).

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FIGURE CAPTIONS

FIG. 1. Diagram showing the main features of the stage, microscope and operator's console. The stage is enclosed in a temperature control box. Most adjustments are made by remote control from the operator's console.

FIG. 2. Photograph showing the granite stage base, intermediate stage, and the superstage with a rotating mounting plate designed to carry 0.9-m-diam emulsion plates. The condenser lens of the substage illuminator and the microscope objective lens are visible at the center of the picture. Several of the air bearings and limit switches, the z-axis drive, and the relay and image shifter are also visible, as well as one of the authors (RS).

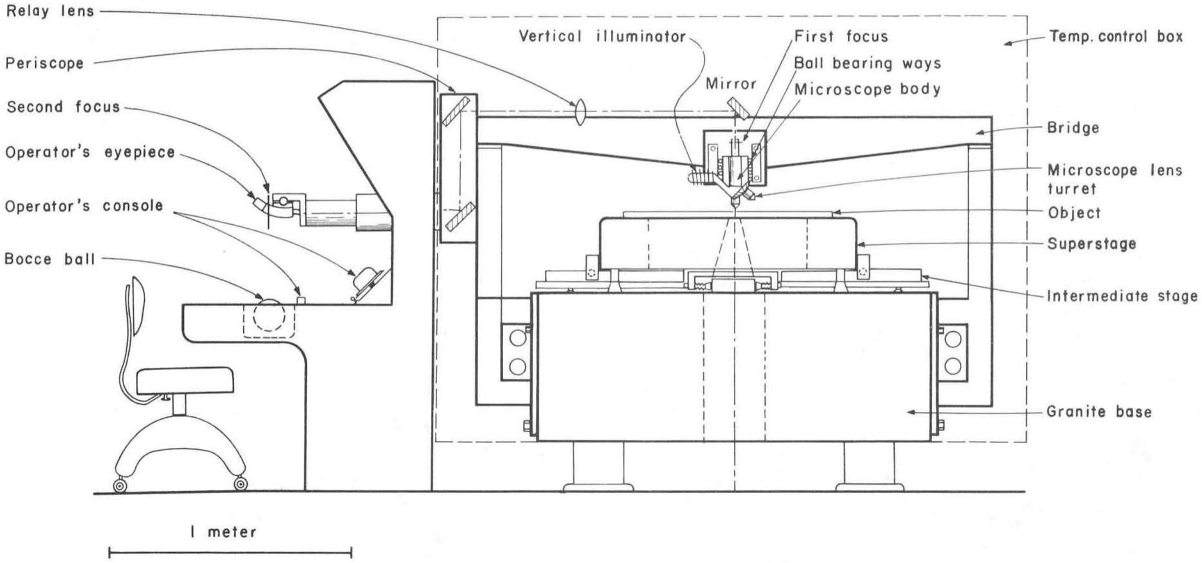
FIG. 3. (a) Plan view of the stage. The y interferometer is fixed on the stage base, but the x interferometer moves in the y direction with the intermediate stage. The laser light path to each interferometer and moving cube corner reflector is shown.

FIG. 3. (b) Light path within an interferometer. The beam splitter coating is on glass. The interference patterns detected by the two photo FET's are 90° out of phase because of the characteristics of the beam-splitter coating.

FIG. 4. Block diagram of x stage axis and associated electronics. Analog signals to the servoamplifier can originate either from the computer or from the x-y control (bocce) ball. The two phase signals from the interferometer photo-FET's are converted by the direction logic into positive or negative counts.

FIG. 5. (a) Diagram of the glass disc showing the positions of the pins. Pins 1 through 9 are measured in disc position I(QI); 1 and 7 through 14 in QII; 1 and 12 through 19 in QIII; 1 through 4 and 17 through 21 in QIV; and pins 15, 17, 20, 2, 1, 12, 10, 7, and 5 in QV. The x-y axes for all five disc positions are shown.

(b), (c), (d) Deviations of measured points from their average position relative to pin 1 in x, y, and z, respectively, after corrections have been made (see text).



XBL704-2645

Fig. 1

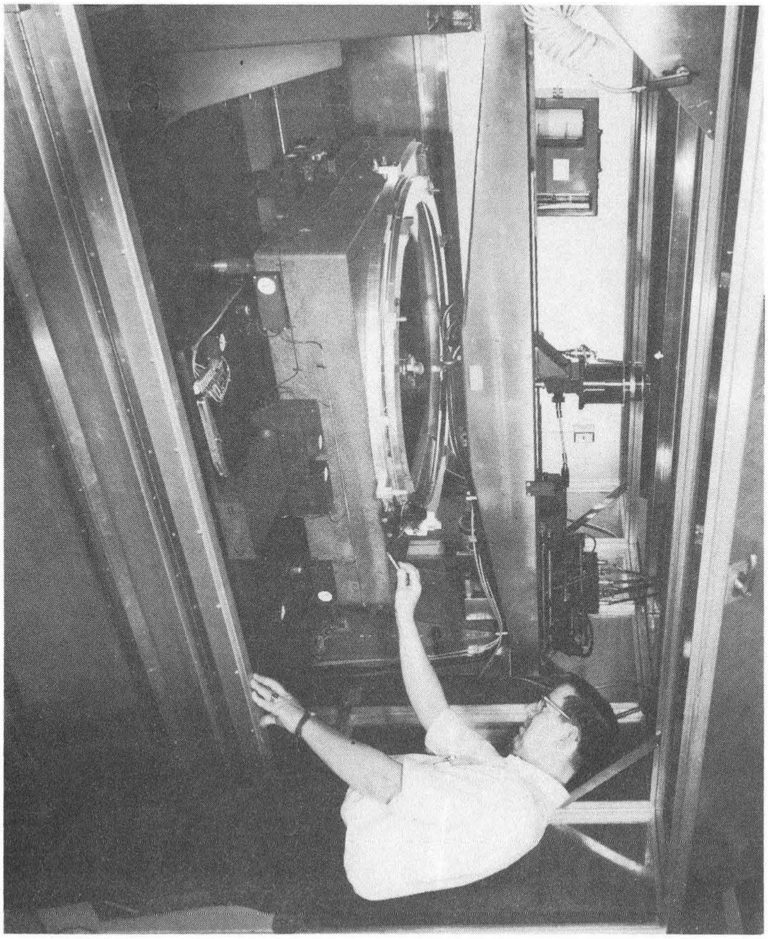
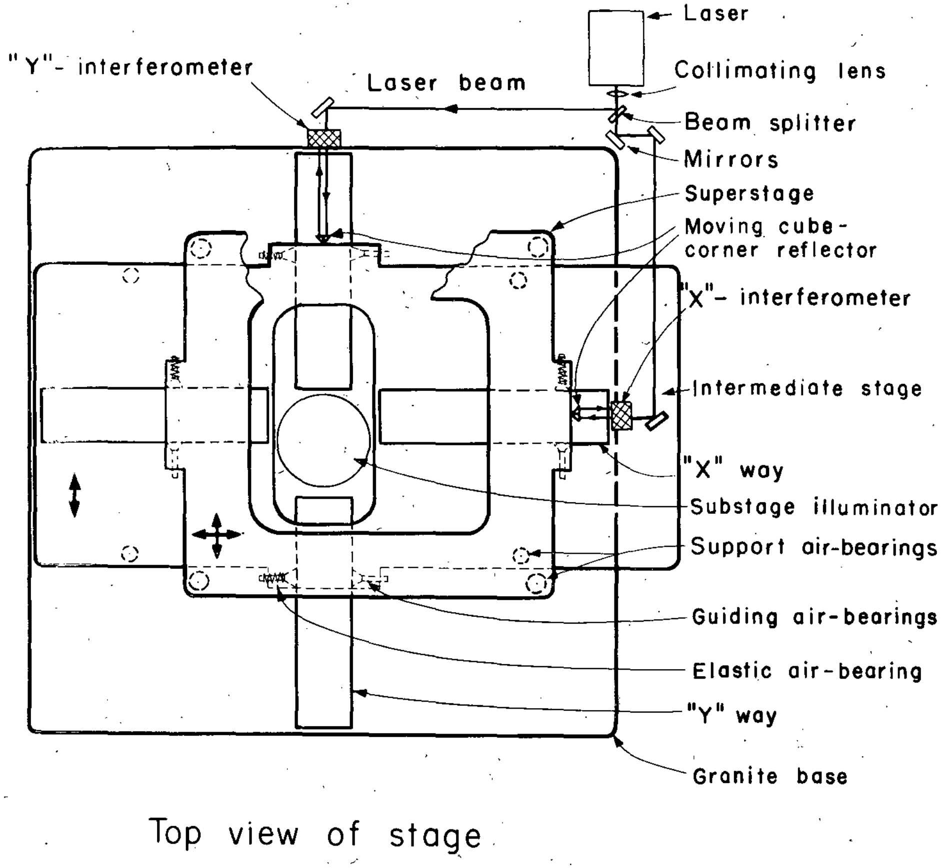


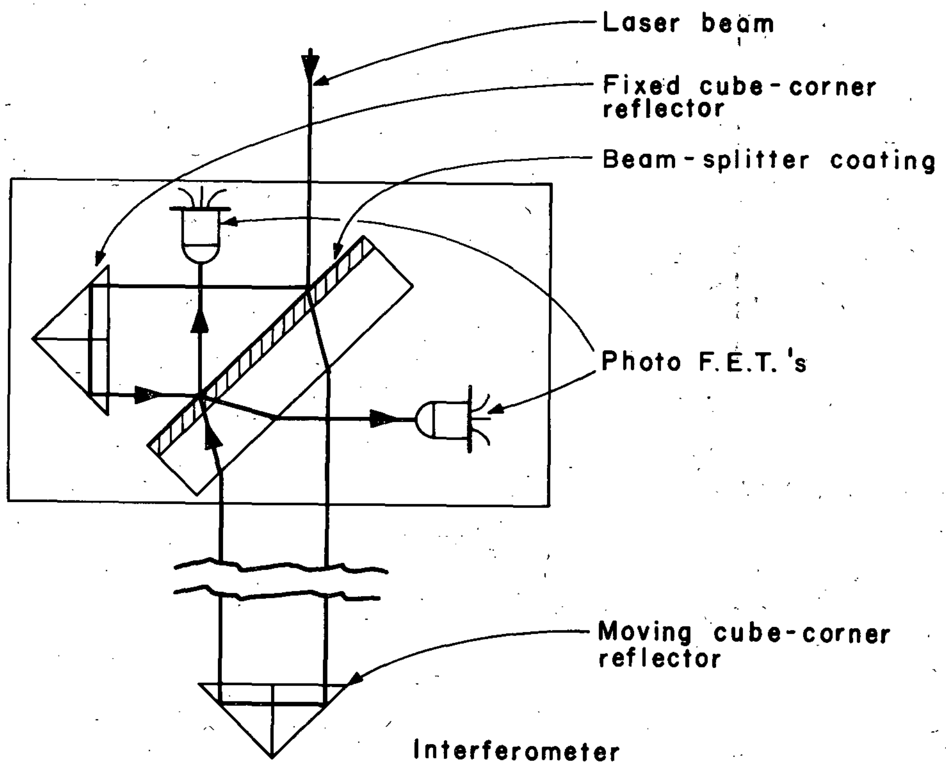
Fig. 2

CBB 703-1416



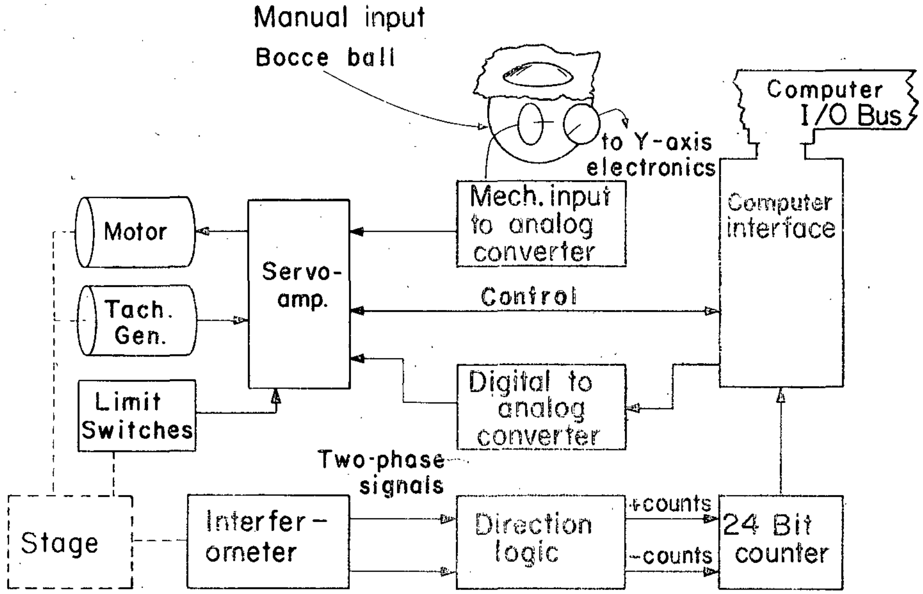
XBL 704-2646

Fig. 3a



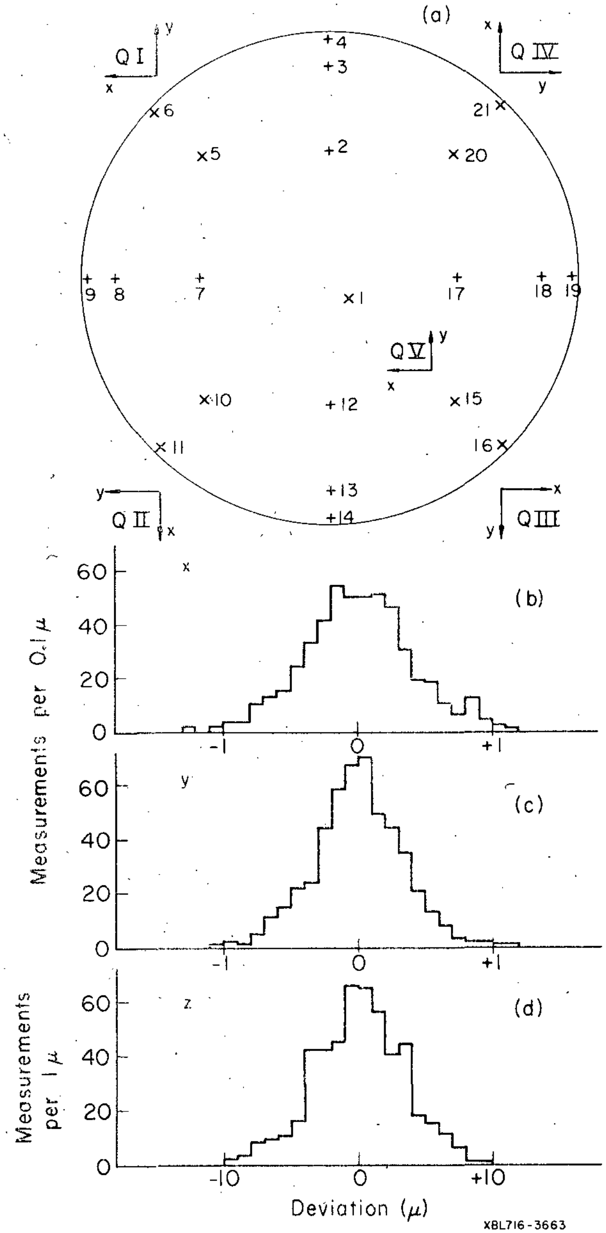
XBL 716-1075

Fig. 3b



XBL 716-1074

Fig. 4



XBL716-3663

Fig. 5

TECHNICAL INFORMATION DIVISION
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720