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UCRL-II372

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CONSTRUCTION AND CALIBRATION OF
THE SCANNING AND MEASURING PROJECTOR

Berkeley, California

UCRL-11372
UC-37 Instruments
TID-4500 (28th Ed.)

UNIVERSITY OF CALIFORNIA
Lawrence Radiation Laboratory
Berkeley, California
AEC Contract No. W-7405-eng-48

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April 22, 1964

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ABSTRACT

The Scanning and Measuring Projector is a data-reduction system that digitizes coordinates of particle tracks in bubble-chamber film, and processes them through an on-line digital computer program to provide information about the nature of the particles in a form useful to the physicist.

The report gives a detailed account of the construction and calibration of the hardware associated with the SMP. Frequent reference is made to a complementary report (UCRL-11154), which gives a general description of the entire system including the digital-computer programs.

The complete system digitizes with a positional accuracy of about 3×10^{-5} in a projected field of 50×70 cm.

1. INTRODUCTION

The purpose of this report is to give a detailed account of the design, construction, and performance testing of the SMP hardware--in particular, of those aspects which are not self-evident from the existing mechanical and electrical drawings. Frequent reference is made to a complementary report (Ref. 1), which describes the basic philosophy of the SMP and the integration of a group of machines with an on-line digital computer to produce a complete bubble-chamber film-analysis system.

An SMP consists of three quite distinct parts, which can be constructed and tested almost independently. These are the measuring machine (consisting of a measuring table, a detecting head, and associated power supplies and electronic logic), the typewriter table, and the projector. Since the projector may assume different forms according to such things as format, required magnification, and number of views of the film being measured by each user, it is not described in detail. Instead, complete specifications of the image it must produce are given (Sec. 5); these should enable a prospective SMP user to design a projector that will work successfully with the existing measuring table.

2. THE MEASURING MACHINE: DESCRIPTION

2.1 Measuring Table

2.1.1 General description

The measuring table is a lighttight box 20 cm deep, mounted as rigidly as possible relative to the projector. Its lower surface is raised 63 cm from floor level to clear the operator's knees; its upper surface consists of a stationary skirt (on which the operator can rest his elbows) surrounding a movable white scanning surface. In the center of this surface is the detecting head; the remainder consists of two sets of flexible curtains that roll away at the edges of the table to allow the detecting head to be moved freely by the operator's hand anywhere in the measuring area. The scanning surface measures 58 by 72 cm, the skirt adding a further 7 cm all round.

The table contains the bench-mark plate, the detecting head and light collector, and the X- and Y-motion rails that support the detecting head. The function of all these parts is fully described in Sec. II of Ref. 1; certain mechanical tolerances mentioned below critically affect the accuracy of the measuring machine.

First of all, the Y-motion rails must be bolted into the welded box of the table. The box itself is supported by a welded steel frame bolted to the concrete floor; eight screws allow it to be jacked up and down relative to this frame. These screws must be adjusted to make the horizontal surfaces of the Y rails level to within 0.005-in. along their length; to ensure the rails are also parallel within a similar tolerance, and to prevent their warping, it may be necessary to loosen and shim one or both of them.

The X carriage rolls on the horizontal surfaces of the Y rails, being supported at three points. In addition, three more rollers (one of them spring loaded) maintain it at right angles to vertical surfaces machined on one of the Y rails. The spring tension must be strong enough for the operator not to overcome it even if he accelerates the detecting head smartly in Y when it is at the opposite end of the X carriage.

Next, the horizontal surfaces of the X carriage should be checked parallel and level to within 0.002 in. along its length, after it is mounted on the Y rails. The X and Y rails should, of course, be accurately at right angles; this can best be checked by reference to the grid on the bench-mark plate. The plate should be aligned parallel to the Y rails by moving the shadow of the X carriage up a column of bench-mark holes; then the X carriage can be checked by putting in a detecting head and running the shadow cast by some part of it along a row of holes. The rectangularity should be accurate to within about one hole diameter (about 0.020 in.) along the length of the X carriage; this corresponds to an error in the measured periscope angle of about one third of a least count.

The detecting head is itself spring loaded against one vertical surface of the X carriage; check that the spring tension cannot be overcome in normal motion. Finally, check that the top surface of the detecting head (assumed to be at right angles to the axis of rotation of the periscope) is level, and that its rock in a horizontal plane is less than 0.001 to 0.002 in. at one corner.

The bench-mark plate should lie on its supporting frame so that it is within 1/32 in. of parallel to the horizontal plane in which the detecting head moves; the vital thing is, of course, to ensure that the lower periscope mirror can never touch it. Final alignment of the bench-mark grid parallel to the Y axis is best made when the coarse scalers are set up (see Sec. 4.1.1).

The stiffness of the frame should be such that a sideways force of 10 lb applied at the end of the table causes a deflection of about 0.002 in. After final assembly of table, with curtains fitted, the total friction for Y motion is typically 5 oz, for X motion 6 oz.

2.1.2 Punching of the curtains

The curtains are now made of Mylar sheet, darkened with a blue dye and painted white on the top (scanning) surface. (They are no longer aluminized, partly because great opacity is not necessary and partly because later batches of the aluminized material showed a tendency to peel.)

The edges are perforated with rectangular holes about 5 mm long and 0.6 mm wide. The coarse digitizing system (see Sec. 2.4.1) counts the holes as the curtains move, to give an approximate indication of the coordinates of the center of the detecting-head aperture. The actual pitch of the holes is somewhat less than 1/8 cm; it is not an even fraction of a centimeter because the light arriving from the projector is slightly divergent, so that the pitch must be corrected for the optical distance between the planes of the curtains and of the bench-mark plate, according to the formula

$$p = 1/8 \left(1 - \frac{h+r}{l} \right),$$

where p = pitch,
h = vertical distance from curtains to bench-mark plate,
r = periscope radius,
l = projection distance from objective to bench-mark plate.

The curtains are punched by use of an automatic copying machine. A photographically reproduced grating about 1 in. wide, and rather longer than the distance to be punched, is taped to the curtain. (The correct pitch is easily obtained by photographic reduction of a truly metric grating.) The grating has alternating dark and light bars of equal width. The curtain is slowly drawn along by an electric motor rotating a rubber tire at a few rpm, while the edge of the curtain passes under an electrically triggered pneumatic punch operating under a pressure of about 50 lb/in.² A lamp-and-photodiode assembly generates a pulse each time a dark bar on the grating passes between them; this pulse is amplified, squared, and used to trigger the punch. Thus, as the curtain is inched along, holes are punched in it at exactly

the same pitch as that of the master. It takes about 8 minutes to punch all the digitizing holes in a curtain. The finished track must be carefully inspected for regularity of pitch--it is convenient to lay the master over the copy--though sideways wandering of the holes up to about 1 mm is acceptable.

After the curtain has been cut to its final size, a single hole is punched near the middle of the opposite edge. This is the "reset" hole; its function is described in Sec. 2.4.1.

2.2. Detecting Head

The rotating part of this assembly consists of the periscope, a magnetic-drum digitizer, and the rotor of an 1800-rpm synchronous motor. These rotate on two precision-grade ball bearings, whose central support is hollow to allow light from the projected image to reach the inside mirror of the periscope. The moving parts are enclosed inside a square housing that contains the stator of the motor, a magnetic-reading head, and a small microswitch (the "record button"). The housing is itself supported on ball bearings acting as rollers to allow it to slide along the X-carriage rail. The detecting-head assembly is the only mechanical part of the SMP that require special skill and tools to build and test. Those parts of its construction and maintenance which require more than normal machine shop practice are described below.

2.2.1 Motor

The motor is a hysteresis-start, synchronous-run machine. The rotor consists of a cylindrical stack of iron laminations; the stator is wound with 0.008 in.-diam wire in 24 slots to produce a four-pole field rotating at 1800 rpm when delta-connected to three-phase 60-cycle ac. When the motor is started, the only torque is that supplied by this field forcing the iron in the rotor through its B-H loop, so the line-to-line supply voltage is raised to about 12 volts for 30 seconds. Once the rotor reaches synchronous speed the torque is larger, being caused by attraction between the rotating field of the stator and the poles formed by residual magnetism in the rotor; a motor with bearings in good condition will run at 6 volts rms or less. Failure of the detecting-head motor to come up to speed, or to stay synchronized, has usually been found to be due to

(a) The magnetic head touching the drum, or a dirt particle jammed in the gap (the drum becomes noticeably stiff to the touch).

(b) Failure of the bearings (due to foreign matter in the races, too much end thrust, or no lubrication).

(c) Rotor-stator gap more than 0.005 in., or vertically misaligned by more than 0.050 in.

(d) One or more turns in the stator winding short-circuited to ground, or one phase entirely missing from the supply voltage.

If a drum, forced up to speed by applying two or three times normal voltages, takes 30 seconds or longer to come to rest after switching off but still will not stay synchronized at a reasonable voltage, the trouble is most probably electrical—(c) or (d) above.

2.2.2 Magnetic-drum digitizers

The drum is of aluminum, about 10 cm in diameter and 2 cm deep. After its initial machining, it is mounted on ball bearings on a special mandrel for its final grinding and a light sandblast. The magnetic emulsion is then applied, allowed to harden, and itself ground by means of liquid coolant to within 0.0005 in. of the metal surface. This process, including the preparation of the iron-epoxy emulsion, has been described in detail in Ref. 2. After the drum has been completed the rotor laminations are cemented on, and the assembly is mounted on new bearings in its housing. The read/write head is placed in the housing and secured with four screws; shim stock is inserted under the flanges to give the correct clearance between the head and the emulsion surface. This clearance, which varies according to the run-out of the finished drum, is checked with a small piece of shim stock as a feeler gauge and should average between 0.5 and 1.0 mils. Run-out should be less than 0.3 mil. It is important that the clearance be checked at the bottom of the gap as well as at the top, to ensure that the ground surfaces of the head and the drum are parallel.

The recording made in the magnetic emulsion is of the non-return-to-zero (NRZ) type; areas of emulsion are alternately saturated north and south by a writing current of ± 60 mA in the same head that will be used for reading. Four tracks are written and read by four separate heads stacked axially in the same block. The angular spacing of the north/south transitions on the two inside tracks is made to vary inversely with the rate of change of the sine and of the cosine functions, respectively. When the drum is being read at speed, these transitions appear as voltage pulses and are counted in reversible scalers, which thus keep a running count of the sine and cosine functions. The outer two tracks contain the "quadrant" information, to determine when the scalers should reverse direction and to apply the correct algebraic sign to X_D and Y_D .

2.2.3 Calibration of the drum recorder

A specially built copying machine records the drums. It consists of a wheel about 12 in. in diameter, coupled via a torsionally rigid metal bellows to the drum and turned slowly by hand. A grating of 154 accurately spaced parallel dark lines covers exactly one half of the wheel; the other half is clear. Four photoelectric reading stations respond to the lines; outputs from two (mounted on one diameter) are combined to give a slow squarewave corresponding to the sine function; the other two are mounted on a diameter exactly 90° from the first, and these produce the cosine function. Flip-flops,

set and reset by the first pulses seen at each of the four stations, give the quadrant information (it will be noticed that they give it exactly half a least count late.) Currents corresponding to the sine, cosine, and quadrant waveforms are fed into the magnetic heads, so that all four tracks are recorded simultaneously as the wheel is turned around once.

The accuracy of the recording machine depends mainly on the angular positioning of the reading stations around the wheel, and the mounting of the grating lines relative to the center of the wheel. (Slop in bearings of wheel and drum, and irregularity in the grating itself, do not appear to cause appreciable error.)

To set up the reading stations, the lights and photocells are first adjusted to give symmetrical waveforms after passing through a squaring circuit; the radial position of each station is then checked on a Beckman counter set to count the number of lines seen during a complete wheel revolution. Since each line should be seen twice, this count should be $154 \times 2 = 308$. This corresponds to the optical length of the standard periscope, which $\frac{308}{128}$ cm -- Sec. 2.2.3.

Next, a transit theodolite reading to within 1 minute of arc is coupled to the wheel, and a sight taken--on a fixed mark 30 ft or so distant--when the first dark line is seen by the photodiode at each of the four reading stations. Three of the stations must be moved tangentially until the four sights are 90° apart within a minute of arc.

To check the accuracy with which the grating is centered, four more sights are taken. The CRT is again used to look for the first dark bar at each station, but with the wheel rotating in the opposite direction. Subtraction of each of these sights from the corresponding sight in the first set gives four small angles, which should all be equal to each other, and be one least count (9 minutes) in magnitude-- the inequality indicates the distance the grating was mounted off center.

A new drum recorder was completed in February 1964. The final checks mentioned above yielded these figures:

<u>Station</u>	<u>Counterclockwise sight</u>	<u>Clockwise sight</u>	<u>Count</u>
N	N $37^\circ 03'$	N' $216^\circ 55'$	308
S	S $217^\circ 04'$	S' $36^\circ 54'$	308
E	E $307^\circ 05'$	E' $126^\circ 56'$	308
W	W $127^\circ 04'$	W' $306^\circ 55'$	308

The differences N-N', S-S', etc., may indicate that the grating was mounted slightly too near the center of the wheel, but by less than 20 microns (one half minute at the rim). The differences N-E, N'-E', E-S, E'-S', etc., indicate that the four stations were within ± 1 minute of cardinal points. These errors can be considered acceptably small.

Evidence that the drum recorder had been knocked out of adjustment and needed realignment would be either an incorrect count from any station or a bad "crossover" (see Sec. 2.2.4) seen on drums after being recorded. Before making the smallest mechanical realignment, it must be checked that the squared outputs of the reading station photodiodes are symmetrical to within 10%.

2.2.4 Recording process

First of all, the drum should be brought up to synchronous speed (the periscope need not be mounted inside it). It should remain at this speed when the supply voltage is reduced to 6 volts. Next, any drum that is not virgin must be erased. While the drum is spinning, switch on a bulk eraser about 12 in. distant from the drum. Slowly bring it up until it touches the housing where the wall is thinnest, leave it there a few seconds, and slowly withdraw it before switching off. (The eddy current loading on the drum may cause it to slow down--if so, restart the motor.) Check that the residue of the old recording is less than 2-mV peak-to-peak on all four heads, using a differential preamp and the CRT sweep synchronized to line. If any apparent residue larger than this is visible, switch off the motor. If the residue remains stationary on the CRT while the motor slows, it is due to stray pick-up and can be ignored; if it moves it must be on the drum, so make further passes with the eraser until the residue disappears.

With the periscope and both leads to the housing removed, clamp the housing into the drum recorder. Rotate the drum until it is within a degree or so of the 0° mark on the coupler, then lightly clamp the coupler to the drum with adhesive tape. (This should ensure that 0° on the magnetic recording is close enough to the periscope axis for it to be compensated for by the electrical delay in the SMP--see Sec. 2.4.3.) Switch on the recorder electronics, and rotate the wheel at least once counterclockwise to set up the correct initial conditions in the quadrant flip-flops. Plug the recording cable into the magnetic head. While slowly rotating the wheel counterclockwise, turn up the recording current gradually from zero to maximum. Leaving it at maximum, rotate the wheel about five times, and keep turning while gradually lowering it to zero. Stop the wheel, unplug the two current driver boards in the electronics (to avoid accidental erasure), and switch off the electronics. Gently separate the drum from the coupler, unclamp the housing, and plug in the motor lead. Switch on the motor and synchronize the CRT to line to check the finished recording.

The two outer tracks are easy to check; they must each show four "quadrant spikes" (per revolution) at least 20 mV high, and no spikes greater than 2 mV in between. The inner (count) tracks must be quite conscientiously examined--see Fig. 1. First, display a whole revolution. The envelope of the pulses should appear smooth, without sudden modulations (these may indicate missing areas of emulsion or too-rapid increase or decrease in recording current). It should show a smooth variation in amplitude, from lowest to highest recorded pulse rate, of less than 3:1. Larger variations may indicate excessive run-out of the drum surface; these can be distinguished since they will come at the same time (same angular position) on different

tracks. Second, use the delayed sweep to work through the entire revolution in detail. In particular, check the "crossovers" (two on each count track, formed where the output from, say, the E station on the recorder is joined to that from the W station). Due to errors of a few minutes of arc in positioning the stations (see Sec. 2.2.3), the two pulses astride the crossover point may be slightly too large or too small. For a recording to be read correctly by the SMP, the worst pair of pulses at the crossover should have a voltage of at least 20-mV peak-to-peak, as shown in Fig. 1. Worse errors at the crossover can be rectified only by realigning the drum recorder with a transit theodolite--see Sec. 2.2.3. Finally, check the low-frequency region and make sure there are no spurious pulses there of amplitude more than 10% of the signal pulses. The low-frequency pulses, especially if large, may show a tendency to ring at the resonant frequency of the reading head. This usually does not matter, but can be eliminated if serious by increasing somewhat the air gap between the head and the emulsion after the recording has been made.

If it is necessary to change the gap after a drum assembly has been recorded, loosen and shim one flange at a time on the magnetic head. This is to prevent any sideways or tilting movement of the head, which could affect the accuracy of the digitizing.

2.2.5 Periscope

At present the mirrors of the periscope are of glass about 1/16 in. thick, aluminized on the front surface, and then cemented into a black anodized aluminum body. One mirror is referenced to its front surface, so its thickness is immaterial; the other is referenced to its back surface, so the thickness of glass used must be selected to suit the length of the periscope as measured between the two reference surfaces. Both epoxy cement and Eastman 910 cement have been used to secure the glass; in either case it is essential to make the film as thin as possible, to minimize angular movement and warping of the mirrors as the cement hardens. If epoxy is used, the metal should be warmed before and during application to make the cement fully fluid; it is probably better than 910 since its shrinkage on drying seems to be smaller.

The completed periscope should be such that a light ray falling through the aperture on any part of the entry mirror is displaced along the periscope axis by 2.406 ± 0.001 cm. (For factors governing choice of periscope radius versus bench-mark spacing, see Ref. 3.) At present, the displacement of a single ray entering near the center of the mirrors is checked with the simple apparatus of Fig. 2. In this jig, an illuminated target is placed in about the same plane, relative to the periscope, as that in which the bench-mark plate will be mounted. The periscope (mounted in the drum, on its own bearings) is slowly rotated until the image of the target in the viewing microscope is deflected as far as possible in one direction. The target is then moved into alignment with the microscope cross-hair, and the micrometer is read. Next, the target is moved about two periscope lengths, and the periscope is rotated about 180° to deflect the image as much as possible in the other direction. Again the target is moved up to the cross

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Fig. 1. Typical count track.

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Fig. 2. Jig for testing periscope.

hair and a second micrometer reading taken. Subtraction of the two readings gives twice the optical length of the periscope, for the pencil of rays centered on one particular point on the mirrors. If the length is within ± 0.01 cm of 2.406 cm, it may be corrected by shimming one end of the periscope, tilting it up to reduce effective length, down to increase it.

Even if the test above is made accurately, the effective length at other parts of the mirrors may be different if they are not exactly parallel to each other. To check this, two tests can be made. The first test, made at present, is to hold the periscope up to view a very distant edge through the two mirrors (Fig. 3). If the mirrors are perfectly parallel, the image of the edge will remain in line with the true edge no matter where, or at what angle, the image falls onto the final mirror. (If the edge chosen is less than ≈ 100 yards away, the displacement of the image along the periscope axis becomes visible; this merely complicates the test.) If the mirrors are not parallel in a certain direction, the image is offset by a small amount relative to the true edge. To make a quantitative test, compare this offset with an object of known height at the same distance as the edge being viewed. The mirrors should be parallel to within 1 to 2 minutes of arc (corresponding to 10 to 20- μ error, on the bench-mark plate, caused by misalignment in the entry mirror 3.5 cm distant). The offset would then appear to be about 2 feet in an edge 1 mile away.

A test providing a more direct measurement of the error caused by either curved or nonparallel mirrors would be to alter the micrometer jig of Fig. 2, so as to allow the detecting head to be moved laterally by 1 cm in each direction, while keeping it in the same horizontal plane. The microscope objective should be stopped down to about $1/4$ cm diameter so that the pencil passing through the periscope would always be smaller than $1/4$ cm. Then, after making the initial measurement of periscope length with the central pencil, the whole detecting head could be moved sideways so that the target is viewed through various parts of the mirrors. Any shift of the image in the microscope eyepiece would be obvious, and could also be measured by seeing how far the micrometer screw had to be moved to bring the image back to the cross hair.

Finally, it is important that the periscope mirrors and top glass should be free of scratches and be kept absolutely as clean as possible. This is because both mirrors are practically in the focal plane of the projector; shadows cast onto the bench-mark plate by things such as scratches and particles of lint are dense enough to be digitized. The effect is that even when the periscope is in a clear area of film, there is a background of digitized points which quite readily cause failure of the filtering program to locate weakly ionized tracks. In the present location of SMP's in Building 46 at Berkeley, the dust problem is so bad that the inside of the measuring tables is kept slightly pressurized with air drawn through a filter by a fan mounted in the table. Also, a very thin glass plate sealing the bottom end of the periscope has recently been fitted; first impressions are that this has greatly reduced the problem. Should the mirrors still get dirty, a $1/8$ in. camel-hair brush and plenty of alcohol will remove the dust film without damaging the reflective coating; the lower mirror can be cleaned without removing the periscope from the drum.

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Fig. 3. Test for parallelism of periscope mirrors.

2.3 Power-Supplies Rack

A double 6-foot rack houses the power supplies and the electronic logic for the entire measuring machine. The left-hand rack contains chassis whose functions are described below.

2.3.1 Breaker panel

This contains several circuit breakers to control both the incoming line supply (208 V three-phase ac) and various single-phase outlets (e. g., utility sockets, vacuum pump, film-control unit in projector).

2.3.2 Contactor panel

This contains three-phase heavy-duty relays that apply power to chassis 5, 6, and 7 below, as demanded by the controller in chassis 4.

2.3.3 Meter-relay chassis

This chassis contains eight meter relays that indicate incoming line voltage, projector-lamp voltage and current (on View 2), voltage applied to the drum motor, and dc voltage and current being drawn from chassis 6 below, to supply all the transistor logic boards. These meters also shut off power to chassis 5, 6, and 7 if any of the measured parameters goes outside preset limits during operation of the machine.

2.3.4 Power-control chassis

This houses a timer and a quantity of relay logic to turn on and off the electronics according to a fixed sequence. Normal turn-on consists of the following: Momentary pressure of the "on" button starts all cooling-air fans in the SMP, which after gathering speed, operate air-flow switches (generally one per fan). These switches are connected in series with an interlock chain consisting of links on each of the modular-regulator boards powering the transistor-logic bins and microswitches on the hinging modular-regulator bins. Closure of the last switch after correct insertion of the regulator boards permits the contactors in panel 2 to energize the drum-motor power supply (5), the transistor-logic power supply (7), and projector-lamp supply (6), the latter also being interlocked with the projector-lamp cooling-air switch. At the same time that power is applied to chassis 7, a timer is started. When this times out (in about 3 seconds) a further interlock chain is tested, consisting of the meter relays (chassis 3) and relay contacts on three boards which detect conditions of too high or too low voltage at the outputs of the modular regulators. If this chain is closed when the timer times out, it indicates that the transistors in the logic circuits are all receiving the correct supply voltages, and power is allowed to remain on.

If the chain is open, the controller goes into a "reset" condition, which cuts off power and lights a yellow lamp behind the reset button. The commonest cause of the chain being open is a short-circuited current-regulator board; this breaks the circuit by causing either the positive or negative 26-volt supply to deliver excessive current, which trips the corresponding

meter relay. To help in diagnosis, any of the meter relays remain latched in the position causing the fault until the reset button is pressed. Pressing it starts the timer, applies power, and causes the interlock chain to be tested again.

The 3-second limit for applying power under fault conditions is, of course, too long to save a bad logic board, but is short enough not to damage the large transistors and Zener diodes in the regulator modules, even under considerable overload.

The supplies to chassis 5 and 6 can be operated manually, independent of the interlocks and controller, by putting their switches to the "test" position.

2.3.5 Drum-motor supply

A Variac controls the supply of three-phase 60-cycle ac in the range 0 to 20 volts to the drum motor. In addition, two timers (used redundantly) automatically provide about twice the running voltage for about 30 seconds after switch-on, to allow the motor to reach synchronous speed (see Sec. 2.2.1).

2.3.6 Projector-lamp supply

This chassis supplies full-wave rectified dc to the three projector lamps. A separate relay switches each lamp either to full power (105 volts, adjustable by a Variac) or to a sustaining voltage of about 20 volts, obtained from a fixed tap on the Variac. Each lamp draws current from a separate phase. The relays can be energized either by manual-control switches at the operator's right hand, or by the computer servicing the SMP, via flip-flops and a transistor-driver board in the typewriter electronics.

2.3.7 Unregulated-dc-power supply

This supplies the dc power required by the transistor-logic boards. A three-phase transformer has two independent output star windings, each rated at about 26 volts rms at 20 amperes. Taps are available for fine setting of the output voltage (and hence, the raw voltage applied to the modular regulators). Each of these outputs is passed to a three-phase full-wave semiconductor rectifier; one produces -26 volts dc, the other +26 volts dc; both are capable of supplying 25 amperes. These raw voltages are not filtered but are passed directly to the individual voltage regulators in each electronics bin, where the constant-current board eliminates the 360-cycle ripple as well as line-voltage variations. The outputs of this supply are monitored on the meter-relay panel (Sec. 2.3.3).

2.4. Measurements Electronics

The digitizing process for the SMP is fully described in Sec. III of Ref. 1; a summary of the electronics involved is in Sec. V of the same reference. The descriptions below are intended to amplify that summary; they are based on the current design (SMP's 5 through 10) and reference is made to the drawings for those machines. Earlier machines (SMP's 1

through 4) are different in minor respects.

2.4.1 Coarse digitizers

This part of the SMP measures the approximate position of the center of rotation of the periscope, relative to the bench-mark plate, with an accuracy of about 1 mm. Its function is to enable the computer to associate the "delta" measurement (X_D, Y_D) of a certain bubble with the correct bench-mark hole; it follows that malfunction of the coarse digitizers can misplace the bubble only by an integral number of centimeters.

Rectangular holes are punched in the edges of the X and Y curtains with a pitch of rather less than $1/8$ cm (for reasons governing choice of pitch, see Sec. 2.1.1 above). The edges run in slits in a Teflon-block assembly; two miniature lamps are mounted on one side of the curtain and two photodiodes detect their light after it passes through collimating slits about 250 microns wide, spaced by $6-1/4$ pitches. As the slits are very liable to become clogged with dirt, they are now sealed and separated from the curtain by 10-mil microscope slide glass. It is also possible for the dirt to collect in the lamp holes. The rounded ends of the lamp bulbs are deliberately allowed to project slightly out of the block, to make them self-cleaning as the curtain passes over them.

This arrangement gives direction information and a least count of $1/32$ cm, because of the extra quarter-pitch separation of the slits. The photodiode output is about $10 \mu A$ for 7 volts: this is fed to a two-stage dc amplifier (LRL electronics engineering drawing number 8V 6482) having a shunt feedback resistor of $500 k\Omega$ to give an output swing of 5 volts. The zero-volt crossings are detected and formed into $1-\mu sec$ pulses by a bistable comparator (8V 6142); the pulses pass through Ferranti-type direction logic (9V 2473) into a 12 bit-reversible scaler (9V 2454).

The scaler is of the parallel-carry, trailing-edge type. It is conventional except that to decrease the number of transistors in the carry path (and hence the delay in carrying, for a given transistor type), the carry pulse is inverted between successive stages. When transistors of 5 Mc/sec alpha cutoff frequency were used, the carry time was measured to be $0.045 \mu sec$ per bit.

The scaler is reset by the output of a further photodiode-lamp assembly which responds to a single hole punched centrally in the opposite edge of the curtain. Gates controlled by the direction flip-flop of the scaler allow the leading edge of the photodiode pulse to reset the scaler when the count is increasing, and the trailing edge when it is decreasing; thus the same edge of the hole causes the reset in either direction of motion. Instead of adjusting the physical position of the reset photodiode, the correct relation between the bench-mark holes and the scaler is obtained by changing the bits which are turned on or off by the reset pulse, as described in Sec. 4.1.1.

The contents of each coarse scaler are temporarily stored en route to the computer in a register. The scaler is strobed into the register by the "enter coarse" pulse generated by the control logic (see Sec. 2.4.4) at the beginning of each enabled drum revolution. The same type of board, 9V 1772,

is used for both scaler and register, one bit on each board, with an indicator lamp. The register is connected to the input-data lines of the computer for the duration of the "present coarse" pulse, also generated by the control logic as commanded by the computer via several levels of multiplexing.

2.4.2 Fine ("delta") digitizers

The method of recording the functions $r \sin \theta$ and $r \cos \theta$ on the magnetic drum which carries the periscope is described above (see Secs. 2.2.2, 2.2.3, and 2.2.4). Two of the four reading heads give a train of pulses whose amplitude is in the range 20 to 200 millivolts peak-to-peak; these are the count channels. Each head is connected to a special board (8V 4722) which contains an amplifier to raise the signal to about 10 volts, a phase splitter which passes positive pulses to one output and negative pulses to the other, a dc restoring circuit which sets the dc level of the peaks of the pulses to -6 volts, and finally a diode clipper which cuts off the base of the pulses above 0 volts. This produces a train of sharply defined negative-going 6-volt pulses of uniform height, even though the input waveform varies rather drastically in amplitude, as shown in Fig. 1. The board used to amplify the two quadrant channels is the same except that in this case dc restoration is not suitable, and an external link in the logic wiring is used to cut out the dc restoring capacitor, replacing it with a Zener-diode level shifter.

The count pulses are squared and differentiated (9V 2463) ready for passing to the delta scalars. Provision is made for the delay (if necessary) of either the X_D or the Y_D count pulses by a maximum of just under two least counts, relative to the quadrant waveforms, though it appears that recent recordings are better aligned as between sine and cosine channels and so the one-shots used to give this delay can be removed.

The quadrant waveforms reverse each delta scaler at the appropriate pair of cardinal points, and reset it to zero at the other pair. As with the coarse scalars, the resets pulses should, in principle, be necessary only when first switching on, but they are allowed to occur all the time, thereby eliminating the possibility of cumulative error in the scalars.

The delta scalars are identical with the coarse scalars, except that with the former only 10 bits are used. In fact, the tenth (4-cm) bit should never be on, and is wired to act only as a convenient indication of failure in the reset or direction circuits. A register is associated with each delta scaler, as with the coarse scalars, but with the delta scalars an additional bit in each register is supplied by the quadrant waveform and indicates algebraic sign. The scaler contents are transferred to the register by the "enter delta" pulse, and the register connected to the computer by the "present delta" pulse (see Sec. 2.4.4).

It is shown in the Appendix that it is not worthwhile to inhibit the "enter delta" pulse while the scalars are carrying, since the probability of entering a garbled word is less than 1 in 180.

2.4.3 Video channel

A photomultiplier tube (type 6199) is carried beneath the bench-mark plate in such a way as to pick up any light able to pass through the periscope aperture and a bench-mark hole. The photocurrent for a typical periscope revolution is shown relative to the motion of a typical image across the bench-mark plate in Fig. 4. It consists of an irregularly spaced series of light "pedestals," some of which contain dips corresponding to the eclipse of bench-mark holes by dark bubbles. The function of the video channel (9V 2764) is to generate the "enter delta" pulse which causes the value of X_D and Y_D at the "height" of such an eclipse to be stored in the delta registers.

The photomultiplier anode is biased to -7 volts with a load of about 50 k Ω and passed in the measuring table through a double emitter-follower amplifier, which lowers the impedance to below 100 Ω without changing the signal voltage. With 1 kV on the tube and some 4 foot-candles on the table, this signal is about 5 volts for absolutely clear film, dropping to about 0.2 volt in the darkest regions where tracks can barely be discerned by eye. To ease the work of the center-finding circuit, this variation in signal of about 25 times is reduced by an automatic-gain-control (AGC) board (9V 2772) to about 20%.

This circuit is one in which the modulating element (a cadmium sulfide photocell whose resistance is ohmic, and varies from about 2 to 100 k Ω) is controlled by the actual voltage swing of the input light "pedestals," after the latter have been peak-detected and integrated. Such a circuit acts in sharp contrast to the more conventional type of AGC, in which a feedback signal controls the modulator in such a way as to reduce the difference between the detected output signal and a desired constant level. The disadvantage of the system used is that since there is no over-all feedback loop, the variation in output cannot be reduced to any desired extent (however non-linear the modulator) merely by raising loop gain; instead, the improvement obtained depends on how accurately the gain of the modulator can be made to vary with its control voltage--in effect, the requirement is for a good analog-division circuit. The combination of two matched CdS photocells and a miniature lamp lit by the output of a two-transistor amplifier performs as an analog divider with 10% accuracy maintained over a range of about 50:1 in input signal; such accuracy is more than enough for the AGC application. The major advantage of the system is that one is free to apply very powerful control to the modulator in only a few cycles of input signal--say 10 pedestals--since there can be no over-all loop instability.

Direct-current coupling is maintained from the photomultiplier anode through the AGC circuit up to the input of the center-finding circuit (9V 2764). At this point, the video-signal pedestals vary from about 4 to 5 volts; the height of track pulses varies only with the contrast of the film--and somewhat with low ionization-density, when bubbles may only partially eclipse bench-mark holes. In the center-finding circuits, the video signal is divided. One part (called the "reference" signal) passes through a simple amplifier. The other part passes through a lumped-constant delay line which has 150

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Fig. 4. Video channel waveforms.

sections and provides a total delay of about $180 \mu\text{secs}$ with very little distortion (but some attenuation) of the signal. A second amplifier restores this delayed signal to the same amplitude as the reference. It is easy to see (Fig. 4) that the time when the delayed signal crosses the reference signal is later than the true center of the track pulse by half the delay line value Δ , irrespective of the amplitude or duration of the track pulse so long as that part of the pulse below the level of the crossing point is assumed symmetrical.

Two bistable comparators A and B (8V 6142) have their input terminals attached to the reference and delayed signals. Each triggers when the voltage between its input terminals exceeds an accurately defined backlash v in either direction, giving an output pulse. The only difference between A and B is that B is connected via a fixed-voltage offset (equal to its backlash v), whereas A is connected direct. [For historical reasons, the offset applied to B is obtained by shifting the dc level of the reference signal by v volts, and a further offset applied to A exactly negates the first one.]

The effect is that comparator B is "cocked" by any track pulse able to exceed an effective threshold of twice v , and is "triggered" precisely at the crossing point (since its effective backlash in this direction has been reduced to zero by the offset voltage). Unfortunately, B may also trigger anywhere along the indeterminate "crossing" of the signals during the dark gap between pedestals, since this gap appears to it like an overlong track pulse.

The purpose of A is to generate an "accept" signal, with which the output pulses of B may be gated. It will be seen from line IV of Fig. 4 that this gate signal must be generated some time after the true crossing point; that is, when the signals have diverged by an amount equal to v . The transitions of comparator B are accordingly delayed by a oneshot, whose duration δ (line VII, Fig. 4) is related to the delay-line value Δ , since both are comparable to the duration of the longest acceptable track pulse. After the delay, the transition pulses of B are gated with the "accept" signal. The result is to get unequivocal rejection of any dark pulses longer than those desired, including automatically the gap between pedestals; the only price paid is the extra delay of the center strobe, which now emerges $(1/2 \Delta + \delta)$ μsec later than the true track center.

In order to read the correct X_D, Y_D from the delta scalers when the track-center strobe finally arrives, it is necessary to advance the periscope mechanically by an angle ϕ relative to the recording on the drum.*

* (For convenience, the periscope is advanced by rather more than ϕ , so that the final angular adjustment can be made electrically, by varying the oneshot time δ . This process is described in Sec. 4.2.3.)

For correct compensation,

$$\begin{aligned}\phi &= (1/2 \Delta + \delta) \frac{d\theta}{dt} \\ &= (1/2 \Delta + \delta) \omega\end{aligned}$$

where ω is the angular velocity of the periscope. Note that this equality holds exactly only for a constant ω ; in fact, the drum motor, like any other synchronous machine, varies from its synchronous speed by an estimated maximum of about 2%. The worst error thereby introduced in the timing of the center strobe is, therefore, 2% of $(1/2 \Delta + \delta)$ or about 5 μ secs, equivalent to about one quarter of a least count. This error is not systematic, of course, and its average value is much smaller than the worst case; its effect is similar to that of a little excess noise in the photomultiplier.

2.4.4 Control logic

The measurements electronics is controlled by the logic of 9V 2484. This consists of three sections:

1. One revolution permissive circuit
2. Extra coarse data circuit
3. Coarse/delta interlacing circuit (multiplexer).

Circuit 1 allows an "enabled periscope revolution" to occur when the operator has moved the detecting head enough to give two 1/4 cm transitions in the coarse scalars. These transitions may be either in X_C or in Y_C or one in each; the effect is to enable a revolution after a minimum movement of $1/4\sqrt{2}$ cm (at 45°) to a maximum movement of 1/2 cm (parallel to either axis). In addition, a revolution is enabled each time the "record" button is depressed by the operator. At the start of such a revolution, an "enter coarse" pulse is sent to the coarse registers and as a result a coarse word (X_C, Y_C) is later passed to the computer. As the revolution proceeds, any bubbles detected are digitized, their center strobes sent as "enter delta" pulses to the delta registers, and the resulting series of (X_D, Y_D) words passed to the computer--typically, about five of them. The computer associates each of these with the coarse word that preceded the series.

If the operator is moving the detecting head at a speed such that, at the end of a revolution, it has moved more than 1/8 cm from its position at the beginning, the last-detected bubbles might become associated with the wrong bench mark holes--thus initiating errors of 1 cm along one or the other axis in the digitized points.

Circuit 2 therefore is reset at the beginning of each enabled revolution and counts 1/16 cm transitions in either, or both, scalars as in 1. If it reaches a count of two before being reset, an additional coarse word is passed to the computer (and later delta words will, of course, be associated with this additional word since it is the most recent). This corresponds to a

speed of more than 4 cm/sec parallel to an axis ($4/\sqrt{2}$ cm/sec at 45°). It is possible for an operator to exceed 8 or conceivably 12 cm/sec; in these cases the circuit still supplies additional coarse words as required, so that the accuracy of digitizing remains unaffected. The density of points obtained on the track will, however, be reduced since the periscope is now moving in a continuous cycloidal path, which will cause fewer track intersections than the series of nearly perfect circles obtained at lower speed.

Circuit 3 is a two-channel multiplexer which time-interlaces coarse and delta words passed to the computer. Its logic is identical with that used elsewhere in the system to interlace output from several SMP's and groups of SMP's, described in detail in Ref. 6. It has two demand inputs, connected to "enter coarse" and "enter delta" after gating with the record button. There are also two return wires ("present coarse" and "present delta") and an out (DRM) and return (RDM) pair to the next higher multiplexer. It has the capability of storing demands on its inputs, and passing them in turn to the next multiplexer (and eventually to the computer) even if they occur simultaneously. As soon as the computer is ready to receive the data, an RDM signal is passed down through the multiplexers to become a "present coarse" (or delta) at a certain SMP; this signal is terminated as soon as the computer acknowledges receipt of the word. In this way, an IBM 7040 computer is able to handle bubble digitizations as they occur in perhaps six or eight SMP's measuring simultaneously, without intermediate storage. (It is likely that for some computers having a different logical structure than the IBM 7000 series (eg. Elliott 503), it will be preferable to treat each SMP as a separate data channel. The effect of this would be to let the computer execute inter-SMP multiplexing instead, although coarse/delta multiplexing would probably still be best done inside the SMP.) The multiplexer is cleared and reset automatically before each track measurement by a 10- μ sec pulse derived from the front edge of the "enable SMP" signal (see Sec. 3). Also this signal must be present before any DRM demands are allowed into the computer from a given SMP.

2.4.5 Output circuits

Each bit in the coarse and delta registers, after passing through an AND gate controlled by the "present" line, goes through an OR structure to one of the 36 data lines into the direct data channel of the computer. Each data line is extended as a bus to every SMP in the system. All registers feed out to this bus via sections of inverter boards 8V 2542, on which the collector load resistor and catching diode have been removed. The effect is to make a multiple OR gate having two inputs (one coarse, one delta) at each SMP; machines which are switched off can present only zeroes to the data-line bus. This arrangement has the disadvantage that each inverter must charge the capacity of the entire bus as it branches to all the other machines; a better arrangement would be to use a resistor in series with the output of each of the inverters to define a current of 6 to 10 mA into the data bus, which could give an OR action into a receiver at the computer end of the bus. This would restrict the voltage swing to about 0.5 volt, eliminating the large capacitive current, but still giving rapid response. (A similar current-switching technique is already used for all the control signals in the SMP multiplexing system.)

3. TYPEWRITER TABLE AND ELECTRONICS

The typewriter used in the present SMP's is an IBM Selectric machine, fitted by Invac with photoelectric input and timing transducers and called the Invac TTR 200. More details on the Invac machine are given in the makers' manual(Ref. 4), and the method by which the typewriters communicate with the IBM 7040 sense lines is described in Ref. 5.

The TTR 200 uses mechanical encoding and decoding for all characters; machine functions are encoded by a diode matrix board fitted inside the typewriter, but must be decoded by the external electronics, a separate solenoid being fitted for each machine function. The SMP system uses carriage return, tabulate, space, and up and down shifts as output from the computer; the space function is the only one used operationally as input, but for convenience in testing the typewriter, provision is made for sending in the other functions also. (So far, the tabulate mechanism has not been found reliable on the Invac machine, although the makers hope to rectify this.) The codes used are a modified "tape BCD," using 6 bits.

The typewriter electronics (9V 3074, 3083) are contained underneath the typewriter table and provide the necessary timing control, buffer storage, and interface between the TTR-200 and six of the ten sense lines, which communicate with bits 12 through 17 of the 36-bit words in the computer. These six lines carry the character code in "core BCD"; the remaining four contain a source code designating which of up to 15 SMP's is concerned. In addition, the electronics detects and stores seven special codes which (in common with all unrecognizable codes) are printed as commas, and serve to switch views on the projector, to advance an "events measured" counter, and to set and reset the "enable SMP" flip-flop. This signal indicates that the computer is prepared to receive measurement data from a particular SMP, and its receipt by the control logic (Sec. 2.4.4) clears and resets the coarse/delta multiplexer and then permits "DRM" demands to proceed into the computer.

A character to be printed appears on the 10 sense lines from the computer, accompanied by an "SOR strobe" pulse. Receipt of this pulse along with the correct address code causes the character to be converted to tape BCD and stored in the input-output register, starting a print cycle. The code in the register is changed by another set of gates to the TTR-200 code, and applied to the six solenoids when permitted by a "data gate" signal generated by the timing disk on the typewriter's power shaft. This selects the appropriate character by tilting and rotating the print ball. A seventh solenoid operates a clutch which actually prints the selected character. The typewriter will print at 15 characters per second. This speed is possible partly because the data solenoids and selector bars for the new character can be set up while the previous one is being printed; the TTR-200 therefore gives its "completion" pulse before the previous character has been printed. This pulse terminates the write cycle, initiates an interrupt to the computer (the "DRT" demand), and replaces the code in the register with a special code (37)₈ which is seen by the computer as (77)₈. When the computer recognizes this code it places the next character for that typewriter onto the sense lines, thus starting the next print cycle.

Execution of a machine function sent by the computer is similar, except that an external decode matrix detects the function, energizing the correct function solenoid while inhibiting the print solenoid. In this case, the completion signal appears only when all movement has ended.

When the decode matrix recognizes a code that is neither a machine function nor a normal character, the register code is replaced by the code for a comma within about 1 μ sec; after this the comma is printed and the completion signal returned, as for any other character.

When the operator strikes a key to send a character into the computer, the TTR-200 gives a "strobe" signal. Ten msec after the start of this signal, the six photodiodes linked to the keyboard encoder are sampled, and the code--duly converted by gates to tape BCD--is read into the same input-output register. (In the case of a machine function, the code is actually generated by a diode matrix and combined on the same six lines.) The "completion" signal is given by the typewriter exactly as if the computer had printed the character, and for convenience it is again used as the "DRT" pulse, this time to notify the computer that the code struck by the operator is ready to be read from the register. As before, gates between the register and sense lines convert from "tape" to "core" BCD.

A special flip-flop is set by all DRT's emerging from the typewriter, and reset by the trailing edge of the subsequent RDT, which is caused by execution of a "store sense lines" instruction by the computer. As long as it remains set, the register contents are deliberately frozen, and in addition the keyboard lock solenoid is energized. The effect of this is that failure of multiplexers or computer to acknowledge receipt of any character from the register locks the keyboard physically, thus indicating to the operator that his last character was not accepted, as well as preserving the ignored character indefinitely in the register until an RDT is finally received. This feature applies to the 77 return signal also, and should eliminate the uncertainty experienced with the typewriters on older SMP's--which had no keyboard lock or input register--where it was impossible to tell whether a character had in fact been read into the computer, or not.

If necessary, the lock-up can always be overridden by pressing the space bar, which is not locked mechanically; the computer will again be interrupted, and the code presented will be the ignored character (or 77) frozen in the register, not the space function.

4. CHECKOUT AND CALIBRATION

Since SMP's are generally used on-line to a digital computer, the checkout procedure suggested below for a completed machine is divided into two parts: preliminary tests which should be done before connection to the computer, and final tests which are most conveniently done making use of the computer. Although no attempt has been made to economize on computer time used, it is possible to make an almost complete checkout by reading the data from registers and other indicators by hand.

4.1 Preliminary Tests without Computer

4.1.1 Coarse digitizers and bench-mark plate

To check out the coarse digitizer blocks, amplifiers, direction logic, and scalers it is best to have the measuring table assembled with both curtains attached to the detecting head. First set up all the lamps in the digitizer blocks to 1.1 volts, and remove the photodiodes from the blocks to make sure that all the slits are visibly clear of swarf and dirt, and that the protective glasses are in position (slightly recessed below the level of the Teflon blocks to minimize curtain wear). Measure the lamp voltage directly on the lamps, since the long flexible leads have enough resistance to make readings at the supply board unreliable. Check that the tips of the lamp bulbs protrude slightly from the block, to prevent accumulation of dirt in their mounting holes. While moving the curtains, connect a CRT to the photodiode amplifier outputs. Adjust the output level to get the voltage swinging symmetrically about ground. The amplitude should be at least 5 volts peak-to-peak. Larger swings will saturate the amplifier, but this is unimportant so long as the 0 volt crossings can be made symmetrical by means of the level control. (The subsequent squaring circuit operates on ± 0.5 volt only). Smaller swings almost always indicate a partially blocked light path; if it appears clear, the lamp voltage may be raised to 1.3 volts, but if the output signal is still too small, the block--or conceivably the amplifier--must be changed. The lamps are rated at 1.5 volts nominal, but under-running them extends their life indefinitely. After adjusting the lamp voltage, always recenter the output voltage swing by means of the level control. All four count channels and two reset channels are adjusted the same way.

Next, use the CRT to add together the squared output of the two X count flip-flops. The square waves should be out of phase by 90° ($\pm 30^\circ$, say) for correct operation of the Ferranti-type reversible-scaler direction-logic; this condition shows up well after addition in the CRT as the stepped waveform of Fig. 5. The steps should be of roughly equal width. Check that for every pitch of the curtain all four pulses arrive at the input of the correct four-way OR gate in the direction logic (9V 2473) both when adding and subtracting. Check that the lamp on the direction flip-flop does not flicker when moving the carriage steadily either way, and finally observe whether the scaler lamps count up and down correctly, reading centimeters in binary code. Repeat the above for the other axis, and check that the reset indicator lamp "blinks" and sets the scaler to zero in both directions.

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Fig. 5. CRT display to check coarse digitizer phasing.

When both coarse scalers are working perfectly, the bench-mark plate should be aligned and the correct reset number wired into the scaler. To do this, first remove the X curtain. By use of the projector or other source of nearly vertical light, cast a shadow from some part of the X carriage onto one of the holes on the exposed part of the bench-mark plate. Run the carriage from top to bottom of the table, and check that the shadow precisely follows up the center of a column of holes. If not, realign the plate by using two of the lateral adjusting screws, until the column of holes appears perfectly parallel to the Y axis. This aligns the grid of bench-mark holes; rectangularity between the X carriage and Y rails should already have been checked (Sec. 2.1).

With the X curtain still removed, lay a 6-in. rule on top of the detecting-head housing, overhanging it on either side and with one edge against the center line scribed across the top surface. Move the carriage to reset the Y scaler, then, keeping within a few centimeters of the center of the table, move it in Y until the shadow of the edge of the rule cuts the center of a row of bench-mark holes. This aligns the center of the periscope accurately with the row of holes. Note the Y scaler reading. It should read an integral number of centimeters (say 35) plus one-half centimeter. (The reason for adding one-half cm is explained in Sec. III of Ref. 1.) Subtract the observed from the desired scaler reading. This is the amount to be added to the reset number; wire in the revised reset number, pass again through the reset point, and back to the same row of holes. Check that the scaler now reads the desired value ($\pm 1/32$ cm is quite accurate enough).

Repeat the above for the X scaler, after replacing the X curtain and removing the nearer (unperforated) Y curtain. Finally, replace this curtain and scribe the position of the two reset blocks on the frame, in case they have to be removed later.

4.1.2 Fine ("delta") digitizers

Using a differential millivolt preamp on the CRT, check that head signals, as described in detail in Sec. 2.2.4, are reaching the input of all four magnetic-head amplifiers. (Take great care not to short-circuit these inputs; doing this could possibly write a spurious pulse on the drum.) Next, use the CRT to add the two outputs of the head amplifier (described in Sec. 2.4.2). Check that each output is contributing alternate negative-going pulses. Increase the amplifier gain until the weakest section (generally the crossover point, see Sec. 2.2.4) is just amplified to a 5-volt pulse. Using the delayed sweep, examine the whole track, watching for missing sections and signs of recorded noise riding on the low-frequency regions. Check that the cross-coupled gates following the amplifier are squaring the signal correctly, and work through the subsequent logic in 9V 2463 up to the input of the scalers. Repeat for the other count channel and for the quadrant channels. Make sure that the waveforms on all four channels are in the correct places relative to 0 degrees, as shown on 9V 2463--if not, transpose the inputs to the magnetic-head amplifiers.

Next, use a strobe lamp triggered from the differentiated quadrant channels (available as the "enter delta" pulse when the delta test switch is

moved to its positions 0° , 90° , 180° , or 270°) to illuminate the mask of the periscope, which should be rotating counterclockwise. The masks should appear to stand still, pointing to E, N, W, and S respectively, as shown in Fig. 6. If it does not, the inputs to the magnetic-head amplifiers must be transposed.

Check that the count pulses arriving at the input of the scalers are quite clean and free from noise; also check the reset, add, and subtract lines at each scaler. The scalers should now be counting correctly--check that each stage is dividing by 2. When the test switch is moved to the cardinal points, the scaler counts, together with the sign bits, are strobed once per revolution into the registers, where they should appear frozen. The correct register contents are also shown in Fig. 6; one or other register should, of course, always contain (in binary) plus or minus the radius of the periscope, 2.406 cm. Steady errors as much as two least counts in these register readings, which appear consistently at two cardinal points, should be corrected as follows:

If the count is too large (in X_D , say) reduce the gain of the X_D sign (quadrant) channel--this delays the subtract/add reversal, relative to the count pulses, in the scaler.

If the count is too small, increase the gain of the X_D sign channel; or, if absolutely necessary, use the optional one-shots (described in Sec. 2.4.2) to delay the count.

Note that the X_D and Y_D register readings can be adjusted independently of each other.

Larger errors, in particular those indicated by the register count fluctuating by more than one least count on any test position, signify either noise pickup or a section of the count track being insufficiently amplified--look back at the output of the magnetic-head amplifiers.

When the registers contain the correct counts, use the CRT to add the "count" to the "sign" waveforms on each channel, picking up these signals immediately before they enter the scaler. Examine the transitions of the sign waveform on each channel, and make sure that neither one is nearly splitting a count pulse--again, use the gain of the sign-channel amplifier for fine adjustment of delay. A margin of 2μ seconds is adequate to ensure that the scaler will not attempt to add and subtract the same count pulse; a larger margin helps to minimize the effect of small changes in gain of the sign-channel amplifier.

4.1.3 Video channel

4.1.3.1 Light collector. With the CRT synchronized to line, look at the input to the AGC board; turn on the projector and high voltage and examine some typical groups of pedestals with the detecting head in various parts of the table. Their amplitude at this point should be between roughly 0.25 and 2 volts, and their flat tops should not vary in height by more than 30% during each revolution. In particular, there should be no obvious gaps in the revolution in which pedestals never appear, no matter where the detecting head is

Register contents:

X_D	$+r$	0	$-r$	0
Y_D	0	$+r$	0	$-r$

$r = 2.406$ cm (decimal)
 $= 10.0110100$ cm (binary)
 $= 2.320$ cm (octal)

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Fig. 6. Appearance of periscope mask under strobe light.

moved on the table. Such gaps indicate that the light collector is not directly underneath the detecting head, so that light from part of the periscope revolution is missing the edge of the collector lens. The light collector is best realigned while looking at the same display of pedestals; detach and peel back the far (perforated) Y curtain just enough to get access to the point where the cord moving the collector is clamped to the detecting-head bracket, then move the cord about a half inch to and fro until the gaps disappear.

If the height of the pedestals still varies cyclically in each revolution by more than 30% after the collector has been centered, the photomultiplier tube probably is responding unevenly over its cathode area and should be replaced. Ideally, photomultipliers used for the SMP should be selected for uniform cathode sensitivity. High sensitivity and low dark current are relatively unimportant since the light signal is quite large.

4.1.3.2 Automatic-gain control. Adjustment of the electronics in the video channel is extremely easy as long as its method of working is thoroughly understood (see Sec. 2.4.3).

First, with the high voltage on, but projector very dim, check the AGC board. The Pinlite lamp should appear dim. Using a CRT, check the dc output level. Adjust this level (using the single trimmer on the board) until it lies between +1 and +5 volts. Some residual "pedestal" waveforms and background noise will be visible, since the AGC gain will be at its maximum.

Next, set the projector to give about 4 foot-candles (8 to 10 divisions on the operator's light-level meter) on the table in a completely clear piece of film. This is taken as the maximum-expected light-level. Increase the high voltage at this level until the collector of the first transistor on the AGC board is seen to saturate on the tops of pedestals. (This point will coincide with maximum brightness of the Pinlite lamp, and therefore lowest resistance of the photocells.) The AGC board will then maintain the pedestal height within 20% while the projector intensity is reduced from 4 to about 0.2 ft-c. It may tend either to over- or undercompensate, within 20%, according to mismatch between the two photocells.

4.1.3.3 Center finder. There are two trimmers on the center-finder board, for setting the level of the "reference" and "reference minus one-quarter volt" signals, relative to that of the "delayed" signal. Using a voltmeter, set the difference between the "reference" and "delayed" signals to 0.35 volt $\pm$ 50 mV--that is, until it equals the designed backlash of the bi-stable comparator. The reference signal should be the more positive. This is the only adjustment necessary to ensure that the center-strobe pulse from the comparator occurs exactly $0.5 \Delta \mu\text{sec}$ later than the center of any track pulse (see Sec. 2.4.3).

Next, set the "reference minus one-quarter volt" signal level to within 50 mV of the "delayed" signal level; the important thing is to ensure that the "accept strobe" waveform appears as shown in Fig. 4, and that it remains low (to inhibit center strobes) between pedestals. Check that the loud-speaker crackles when tracks are entering the periscope, and is reasonably quiet in clear areas of film.

Finally, set the capacitor box on the azimuth calibration oneshot to $0.1\mu\text{F}$ and trim the associated timer board to give a delay of $100\mu\text{sec}$. Check that any other setting of the capacitor box (up to $0.250\mu\text{F}$) produces the corresponding delay. The video channel is now completely set up except for the computer run described in Sec. 4.2.3, which determines the final setting of the capacitor box.

4.1.4 Control logic

The first part of the control logic to be checked should be the one-revolution enabling circuit. A drum revolution should be enabled each time the carriage is moved 0.5 cm along either axis, or when the record button is first pressed. Check that at the beginning of each revolution the coarse scalars are accurately strobed into the registers, and that the delta registers change if any bubbles lie in the periscope aperture; check that the contents of the delta registers on a few bubbles are consistent with the periscope radius (i.e., $X_D^2 + Y_D^2 = r^2$). When the carriage is moving rapidly, additional "enter coarse" pulses should be generated (Sec. 2.4.4).

The coarse/delta multiplexer should normally be scanning between its two inputs (lamps equally bright). It should stop on the "coarse" light--if the "enable SMP" line is down--as soon as the record button is pressed. Check that raising the "enable SMP" line generates a $10\text{-}\mu\text{sec}$ reset pulse, which should start the scan again. Next, leaving the SMP enabled, connect the SMP to a higher multiplexer (or any other test device returning a positive RDM pulse at least $5\mu\text{sec}$ long, not less than $2\mu\text{sec}$ after receipt of a DRM).^{*} The multiplexer lamps should remain equally bright while servicing a stream of coarse and delta words, stopping only if the multiplexer is removed or the SMP disabled. An even more stringent test is to simultaneously connect the "enter delta" pulse to the coarse and delta demand inputs. In this condition, a CRT triggered by the incoming "enter delta" demand pulse should show both the "present delta" and "present coarse" pulses appearing shortly after every demand, their order being randomly exchanged according to the state of the scan at the instant the demand is received.

4.1.5 Output circuits

Having ensured that the "present" pulses are arriving at the gates controlling the output of the coarse and delta registers, the 36 data lines are best checked by using the computer (see Sec. 4.2.2).

4.1.6 Typewriter circuits

To check out the typewriter table, it is necessary to use either a completed multiplexer (which contains a typewriter-testing facility) or a pulser giving about one pulse/sec. In either case, the output sense lines (which carry data to be printed on the typewriter, and the address code) are held fixed with the code of the character to be tested on them. A convenient way to hold them fixed is to open-circuit the input of a line-receiver board (8V 1792);

^{*}All design details of the SMP multiplexing system are in Ref. 6.

any transistors plugged in then produce a "1" bit. Apply the pulser to the SOR strobe line, and check that the input code is correctly converted to tape BCD and entered into the register. Check that either the print trigger solenoid or the machine function gate is energized, that the correct character or function is executed, and that as soon as the completion signal is given, a DRT pulse is generated. This should force the register contents to $(37)_8$, and the return character $(77)_8$ is passed to the computer. Next, check that unrecognizable codes are printed as commas, and that those used to set and reset view-control flip-flops are in fact doing so.

Pressing a character or function key should put the correct code (in tape BCD) into the register. Check the register lock-up circuit (see Sec. 3) and notice that if a multiplexer is not connected, only the first-struck key enters its code into the register; the keyboard lock should then prevent further keys from being hit or any other code from reaching the register until an RDT is received and terminated to acknowledge receipt of the original character.

Finally, the "loop typewriter" test position on the multiplexer can be used to check that a DRT pulse is returned to it for every character printed.

4.2 Final Tests Coupled to Computer

The descriptions below refer to use of an IBM 7040 with certain test programs current at the time of writing. It is hoped that the procedure will be considerably simplified by more elaborate diagnostic programs now being written.

The typewriter of a new SMP must be checked out completely before anything else, since all programs depend on it for communication with the computer.

4.2.1 Typewriter test

As soon as it is loaded, the program of this name prints out a complete alphabet and all machine functions (including case shifts) simultaneously on all typewriters connected into the system at that time. Any failures (e.g., receipt of a return signal other than 77, or one carrying the wrong source code) result in specific program stops; the accumulator of the computer, visible at the console, always contains the last-received typewriter character, which will generally be the one responsible for the stop, thus making diagnosis very simple.

After the initial output message has been finished, the program waits for input messages of up to 200 characters, which may be typed in on any typewriter, alone or simultaneously with others, and which are then stored in core. Input messages must end with a dialogue comply $(53)_8$; the message should then reappear from core and be printed out exactly as typed in, including all machine functions. If any errors are printed, pressing the sense switch having the same number as the source code of the suspect typewriter again initiates print out of the input message, this time on the on-line printer; in this way it is obvious whether the error occurred during the input or the output process. (The on-line printer merely spaces for all machine functions.)

4.2.2 Transmission of coarse and delta data

A simple program called SPECIAL RAID "enables" all SMP's, and then stores measurement data words in core (not processing them in any way) from one SMP at a time. When the measurement comply button is pressed, the measurement words are printed out in the same order as they were received on the typewriter of the same SMP, with 12 octal digits comprising each 36-bit word.

This provides a rapid and complete check of all the data lines, since both the coarse registers can be set to a known combination of ones and zeroes simply by moving the detecting head and pressing the record button. If bubbles are projected into the periscope, pressing of the record button once results in a coarse word followed by a series of delta words. The coarse words should begin with a 4 label, and the delta words with a 2 label. If required, known words can also be set into the delta registers by use of the cardinal-point test switch (see Sec. 4.1.2). Finally, a few centimeters of track should be measured, and the sequence of coarse and delta words checked, thus verifying the operation of the one-revolution enabling circuit (see Sec. 4.1.4).

4.2.3 Calibration of periscope azimuth

A program called PT 109 can be used either to write on tape or print on the SMP typewriter the reconstructed coordinates of bubbles digitized by any SMP. The important difference between the program and SPECIAL RAID is that with PT 109, X_C and Y_C are combined with X_D and Y_D to arrive at the true decimal coordinates (in centimeters) of digitized bubbles, and each set of bubble coordinates is followed by those of the bench mark it eclipsed. In order to print on the typewriter, code 2 must be set into the final octal digit on the console (after the cards have started to load); code 1 makes it write on tape.

Lay a straight wire shadow about 0.5 mm wide on the table. Set the detecting head to read an integral number of centimeters, plus 0.5 cm, in the X scaler. Position the shadow to fall close to the center of the periscope aperture; run the carriage up and down in Y and align the shadow until it appears parallel to the Y axis. Press the record button once and strike T on the typewriter; the X coordinates of the points obtained should be within 1 mm of an exact number of cm. If so, press the record button and move about 5 cm down the wire.

On the resulting print-out, select those points measured from bench marks under the wire (i. e., those whose X coordinate is within 1 mm of that of the wire). Mark the points whose Y coordinate is lower than that of their bench mark with a +, those higher than their bench mark with a -. Subtract the average X coordinate of the - points from that of the + points. This difference is twice the azimuthal error, at the periscope radius, between the periscope axis and that of the delta recording on the drum. (The effect of the various delays in the video channel--see Sec. 2.4.3--is, of course, automatically included.) If this difference is positive, the periscope axis should be advanced relative to the drum in the direction of its rotation, or the time of the calibrating one-shot in the video channel reduced. If it is negative, the

periscope should be retarded or the delay increased. An azimuthal error of 100μ corresponds to a change of about $22\mu\text{sec}$ in delay at 1800 rpm. If the change in one-shot time would cause it to become either less than $75\mu\text{sec}$ or more than 200, the detecting head must be removed from the table, and the periscope advanced (or retarded) physically by about the right amount. It will be seen that the one-shot adjustment will correct a physical azimuth error of up to $\pm 0.35\text{ mm}$. The correction should be checked and the delay time once more adjusted until the difference between + and - points is less than 50μ .

Correct conclusion of this routine completes the calibration of all parts of the SMP between the computer and the plane of the measuring table.

4.2.4 Calibration of projector optics

To calibrate the projection system between the plane of the film and the table, a rectangular grid of about 10×8 lines is clamped, in turn, to the platen of each view. This grid is very accurately ruled and periodically checked by means of a measuring microscope. All lines on the grid are measured with PT 109 writing on tape; the T key is struck after each one.

This is repeated for all three views; the computer filters the lines and accurately reconstructs the grid vertices, as distorted in the projection. It then generates and optimizes constants that correct for errors in the distance of each vertex from the optical axis as a function of the cube of the distance, and also for differences in magnification between X and Y. These constants, different for each view of each SMP, are finally inserted into the measuring program, where they are applied as corrections to the

5. IMAGE SPECIFICATIONS FOR PROJECTOR

Since different bubble chambers produce film in different formats, the physical design of an SMP projector may have to be considerably different than that of the Berkeley one. (A general description of the Berkeley projector is given in Sec. V. A of Ref. 1). However, it is possible to specify exactly all those properties of the image, as projected on the SMP table, which enable it to be measured with the full accuracy of the measuring machine.

The image must be at least 50×70 cm to employ the whole measuring area of the Berkeley bench-mark plate. A longer image might well be used to assist in scanning film from chambers that are longer than wide; that part of the image used only for scanning could be of much lower quality and projected at a considerable angle onto a scanning surface extending away from the operator.

The illumination anywhere in the measuring area should be 5 ft-c $\pm$ 20% without film on the platen. For the present bench-mark plate, whose holes are about 450 μ in diameter on a 1-cm-square grid, it has been found best to make the images of the bubbles about the same size as the holes. The resolution of the image must be no worse than 5 lines/mm anywhere in the plane of the bench-mark plate--this must, of course, include any deterioration due to curvature of the focal plane.

Over-all cubic distortions and differences in magnification in X and Y can be compensated for by the present programs so long as they nowhere exceed about 0.8 mm (10 least counts); irregular distortions cannot be corrected, so should not exceed about 15 μ (one fifth least count).

The angle at which light strikes the table must be kept less than 6° in the corners of the measuring area in order to lose no more than 20% of the light entering the periscope aperture due to cut-off by the second mirror.

This work was performed under the auspices of the U. S. Atomic Energy Commission.

ACKNOWLEDGMENTS

The authors wish to acknowledge most gratefully the continued support and encouragement of Dr. Luis Alvarez, who was the inventor of the SMP instrument. Thanks are also due for the work of Richard Blumberg and Charles MacDonald on the projector, and that of Ronald Zane and Matthew Renkas on the electronics.

S. O. Buckingham built the prototype SMP almost single-handed, and we owe much to his persistent and ingenious practical help ever since.

APPENDIX

Effect of Carry Propagation Time in Delta Scalers

The delta scalars contain nine places, counting in binary. The "enter delta" pulse may transfer the scaler contents into the register at any time, including while the count in the scaler is being carried. The probability P of entering a garbled word into the register is equal to the total time spent carrying during a cycle of the scaler (T_c) divided by the time for that cycle to occur (T).

T_c is partly due to a few long carries and partly to many short ones. Consider a 9-bit scaler counting from zero to ($2^9 - 1$), its full count. An exact expression for the total carry time is

$$T_c = t_c \sum_{n=1}^{n=9} (10-n) 2^{(n-1)}$$

$$P = \frac{T_c}{T} = \frac{t_c}{T} \sum_{n=1}^{n=9} (10-n) 2^{(n-1)}$$

so that

where t_c is the propagation time for each stage.

The delta scalars cycle from zero to maximum in one quarter of a drum revolution, so substituting $T = 8.25$ msec and $t_c = 45$ nsec (an average, obtained by measuring carry time over 15 places), we have

$$P = \frac{0.045}{8,250} \times 1,013 = \frac{1}{180} .$$

This indicates that the probability of getting a garbled delta word is substantially less than 1 in 180, since the maximum count of the delta scalars is actually only 308, and not 512 as assumed in obtaining P . It is not worthwhile, therefore, to include lock-out logic which would prevent the scaler from being read while carrying.

FOOTNOTES AND REFERENCES

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