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THE SCANNING AND MEASURING PROJECTOR

John H. Munson
(Ph. D. Thesis, Part I)

December 6, 1963

THE SCANNING AND MEASURING PROJECTOR

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ABSTRACT

The Scanning and Measuring Projector (SMP) is a semiautomatic device for making rapid and accurate measurements on bubble chamber or other photographs. The SMP, its human operator, and a general-purpose digital computer work together in an integrated system. The operator scans the film and specifies the approximate path of the points to be measured, and the points are accurately digitized by a novel apparatus that sweeps the specified portion of the image across a fixed lattice of reference marks. This paper describes the SMP digitizing mechanism and process, and the configuration of the over-all system. Also discussed are the pattern-recognition and time-sharing aspects of the associated computer program, and its error-correcting capabilities. The paper outlines the history and performance of the SMP, and plans for extending the scope of the SMP system.

I. INTRODUCTION

The Scanning and Measuring Projector (SMP) is a device for making rapid and accurate measurements on bubble chamber photographs or other photographic records. (The SMP is an invention of Dr. Luis W. Alvarez of the Lawrence Radiation Laboratory, University of California, Berkeley. Patent rights are assigned to the Atomic Energy Commission. U. S. Patent applied for, by the AEC.) The SMP employs a unique method of digitization, in which points in the image are located relative to a lattice of accurately positioned reference marks. The method is analogous to the use, by surveyors, of bench marks as accurate local reference points. The coordinates of a point on the SMP (a bubble image) are found by specifying a "bench mark" (whose coordinates are accurately known) and incremental coordinates relative to the bench mark. Thus on the SMP, a combination of two measurements of lower relative precision replaces a single high-precision measurement usually made with a costly high-precision element.

One feature of the design of the SMP is that the photographic records to be measured may be visually scanned by the operator at the same time. Another feature is the specification, by the operator, of only the approximate location of the points to be measured, which leaves the precise digitization of the points to the SMP apparatus. The operator and the SMP thus supplement each other in obtaining the measurement of points on those parts of the image selected by the operator.

Along the scale of automatic measuring devices, therefore, the SMP occupies a position between the currently prominent digitized projection microscopes of the Franckenstein class and the proposed fully automatic systems (PEPR, FSD, ILLIAC III),^{1, 2} which would eliminate the human operator.

The SMP, as it has been developed at the Lawrence Radiation Laboratory, operates on-line to a general-purpose digital computer.^{3d} The computer is incorporated directly into the system with the SMP and its operator (or, in fact, several SMP's and their operators). The computer is immediately able to process, examine, and certify data

generated by the SMP. Immediate feedback of results to the SMP operator enhances the operating efficiency and reliability of the SMP.

This paper describes the SMP as it presently exists and is used for the measurement of tracks in bubble chamber photographs.^{3f} The SMP, however, should be applicable to a variety of problems involving the measurement of points on photographic records. Conversion of the SMP-based system to other tasks primarily involves conversion of the computer program, with a minimum of changes in hardware. An application of the SMP to measuring spark chamber photographs is under development, and further applications await investigation.

II. THE DIGITIZING MECHANISM

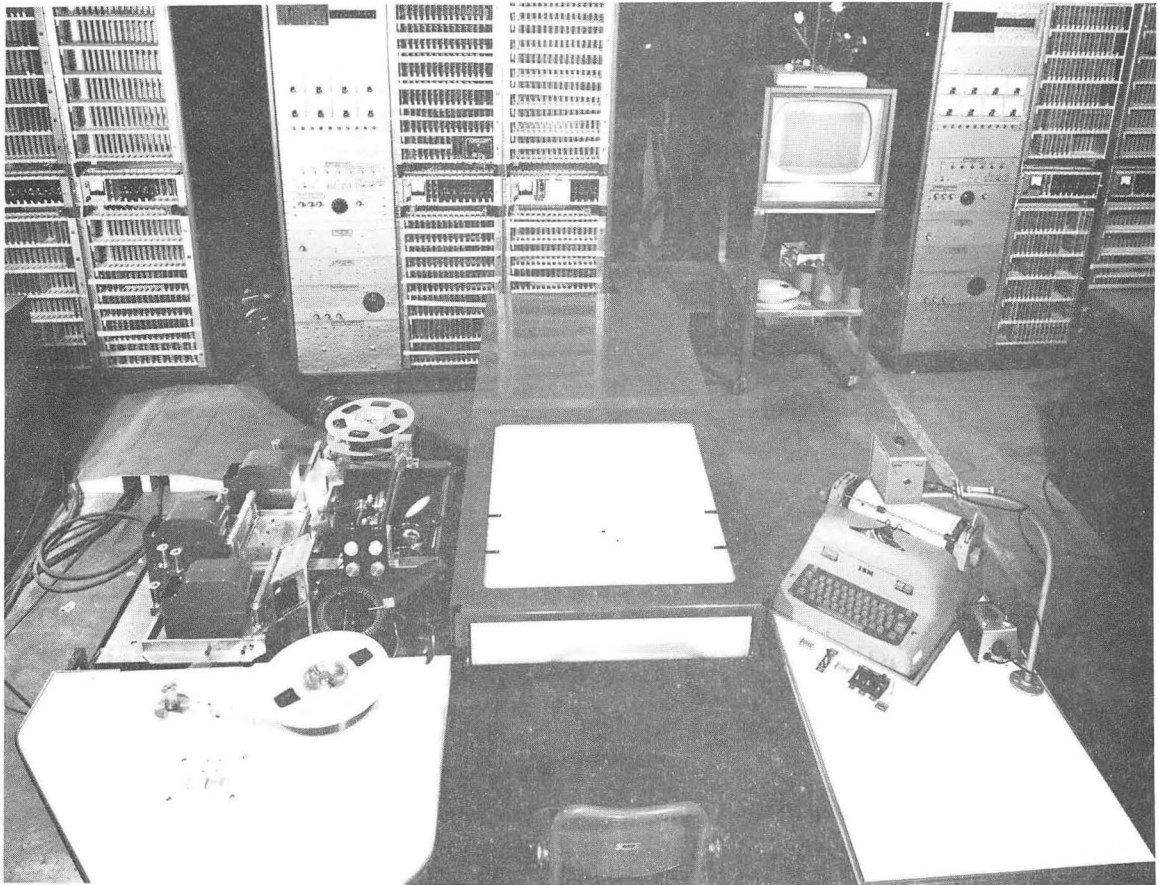
The SMP table is a desk-sized structure at which the operator sits, flanked by a projector on the left and a typewriter on the right, both within convenient reach (Fig. 1).^{4c, 4e} The image of the film frame to be scanned or measured is sent from the projector to an overhead mirror and thence is focused onto the top surface of the SMP table. On this flat white surface the operator can visually scan the image. The operator uses the projector controls to position the film, and uses the typewriter to converse with the digital computer throughout the measuring sequence. The SMP table, projector, typewriter, and associated electronics comprise the complete SMP.

Enclosed within the SMP table, below the white scanning surface, is a lighttight volume containing the SMP digitizing apparatus. The digitizing apparatus has four parts (Fig. 2), which are described below. Historically they are called the window shades, the periscope, the benchmark plate, and the light collector.

A. The Window Shades

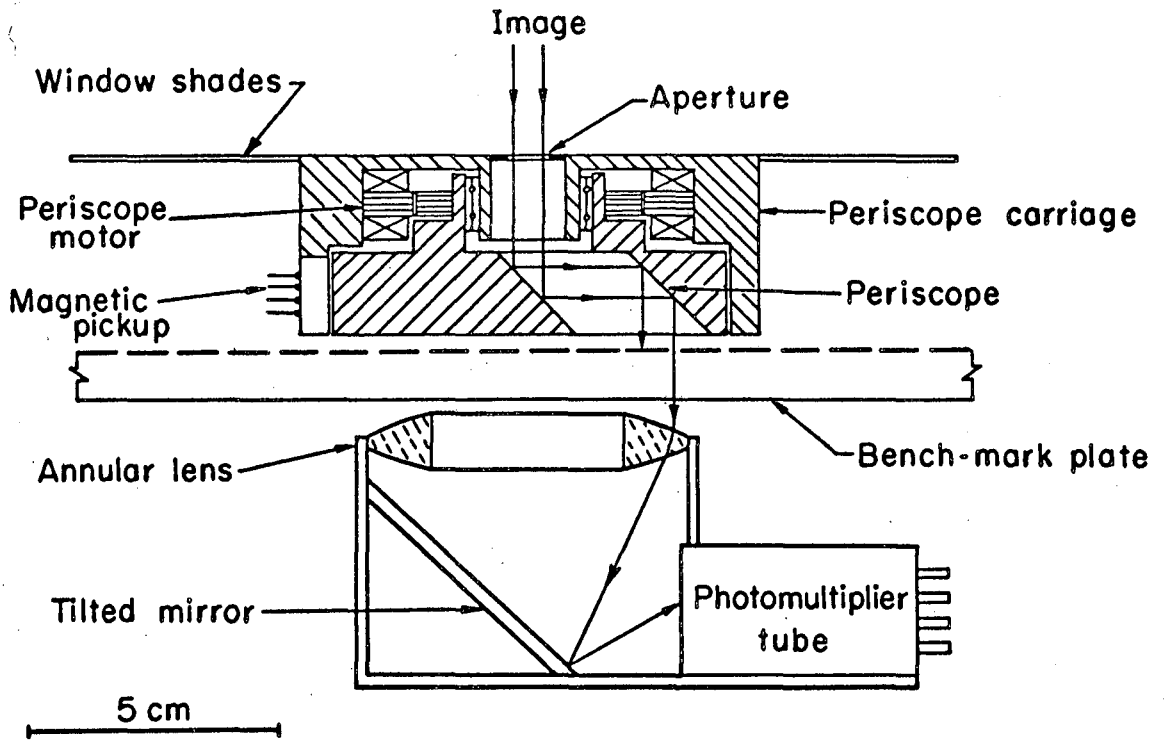
The window shades form the horizontal scanning surface of the SMP table, as well as the top of the lighttight enclosure. The shades are of sheet Mylar, aluminized for opacity and painted white on top. The larger shade is mounted on rollers so that it is free to move in one dimension, away from and toward the operator. The larger shade covers the entire scanning surface, 55 cm by 70 cm, except for a gap 10 cm wide extending across the shade from the operator's left to his right (Fig. 3). Mounted in this gap is a second smaller window shade. This "transverse" shade is free to roll in the left-right direction, and is also carried with the motion of the larger shade. Mounted in a gap in the smaller shade is a 10-cm by 10-cm carriage. The top of this carriage is white and flush with the two window shades, and is broken only by a small dark aperture, whose diameter is approximately 0.6 cm.

The effect of these mountings is that the carriage may be positioned anywhere in the scanning plane, by rolling the two window shades. The



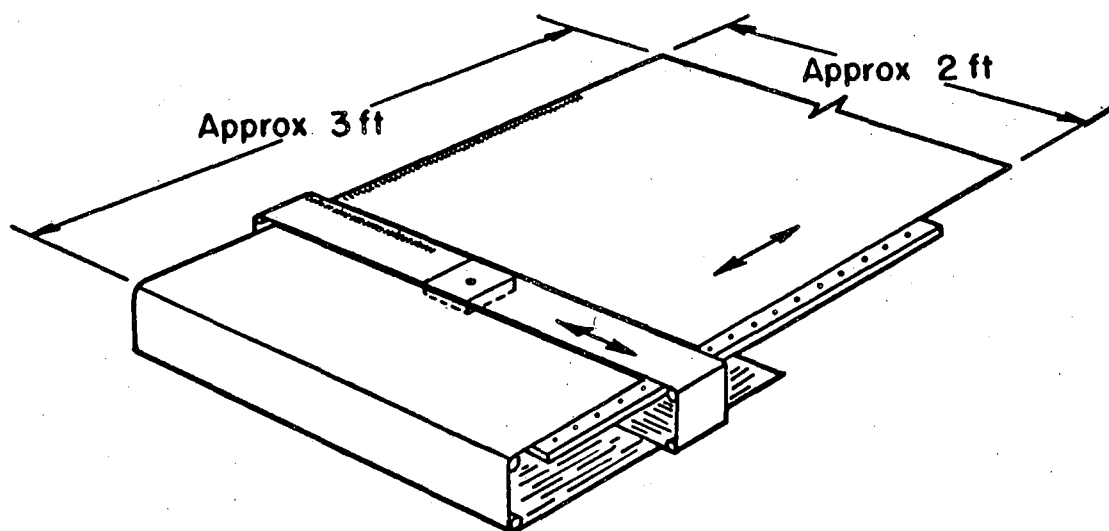
ZN-4071

Fig. 1. Overall view of the SMP showing the SMP table, projector, typewriter, and electronics racks. The electronics racks for two other SMP's, and the CRT display for the IBM 709, are also visible. The right-hand rack of the three shown for one SMP is nearly empty, and has since been removed from the design.



MU-33028

Fig. 2. Cross-sectional view of the digitizing apparatus.



MU-33027

Fig. 3. Drawing of the two window shades, viewed as if from over the operator's right shoulder. Arrows indicate the direction of travel of the shades. The slots used for producing the coarse coordinates, the bench-mark plate, and the location of the periscope carriage are also shown.

aperture in the carriage becomes, in effect, a movable hole in an opaque viewing surface. In measuring, the operator moves this aperture along the line, curve, or track of bubbles to be measured. Only that portion of the image striking the aperture passes into the lighttight volume below.

The two window shades are kept under tension to resist deformation due to gravity and touching by the operator on the scanning surface. Along one edge of each shade is punched a row of small rectangular slots (dimensions: $1/16$ cm. by $1/2$ cm). Two small light bulbs are mounted above the row of slots, and two photodiodes below. As the slots move with the shade, the signals from the photodiodes indicate the motion of the shade, including the direction. The photodiode pulses for each shade are counted in a reversible scaler in the electronics rack. The scalars for the two shades always contain the current values X_C and Y_C (in centimeters) of the position of the aperture in the carriage, as it moves with the shades. X_C and Y_C are coarse measurements; they have a least count of $1/32$ cm and an accuracy of approximately $1/8$ cm. A special punched slot and photodiode are used to reset the scaler for each window shade to a fixed number, each time the shade passes the approximate center of its travel.

B. The Periscope

The aperture in the carriage is the entrance to a periscope mounted in a rotating drum within the carriage (Fig. 2). At any instant the portion of the image falling into the aperture is displaced laterally by a vector \underline{R} as it traverses the periscope and exits downward. The displacement is a perfect translation; that is, any point \underline{P} in the aperture is displaced to $(\underline{P} + \underline{R})$.

The periscope drum is the rotor of a synchronous motor, which spins with constant angular velocity ω . (Speeds of 1200 and 1800 rpm have been used.) As the drum spins, the displacement vector $\underline{R}(t)$ traces out a circle. The fixed magnitude R of \underline{R} is the lateral "length" of the periscope (presently 2.4 cm), and the angle θ changes linearly with time. Thus \underline{R} has components

$$X_D = R \cos\theta = R \cos\omega t \text{ and}$$

$$Y_D = R \sin\theta = R \sin\omega t.$$

On the outer rim of the periscope drum are magnetic recordings giving X_D and Y_D directly in centimeters. Pulses from the heads reading these two recordings are sent to two reversible scalers, which keep a running count of X_D and Y_D . The least count of the X_D and Y_D recordings is $1/128$ cm. Special "quadrant pulses" from two more magnetic recordings on the drum are used to reset the X_D and Y_D scalers each revolution, as an initializing procedure and as a guard against possible cumulative errors in the scalers.

C. The Bench-Mark Plate

The bench-mark plate is the next element of the digitizing apparatus to be considered. It is a fixed horizontal plate extending over the entire measuring area. The periscope carriage moves just above the bench-mark plate. The disk of the image passing through the aperture, and displaced by the periscope, strikes the bench-mark plate as it leaves the periscope.

The plate is opaque and has small clear holes placed accurately on the vertices of a lattice 1 cm square. These holes are the accurate reference points for SMP measurements, and are called "bench marks" after the reference points used in surveying. The diameter of the clear holes (0.5 mm) approximately matches the projected image of a single bubble.

In practice, the bench-mark plate is in the form of photographic emulsion on a glass plate, and the pattern of clear bench marks on an opaque background is reproduced by contact printing from a master. Thus, this accurate element can be reproduced at relatively low unit cost. The master bench-mark plate consists of a Lucite sheet, into which conical holes for the bench marks have been milled to a positional tolerance of better than 25 microns.

D. The Light Collector

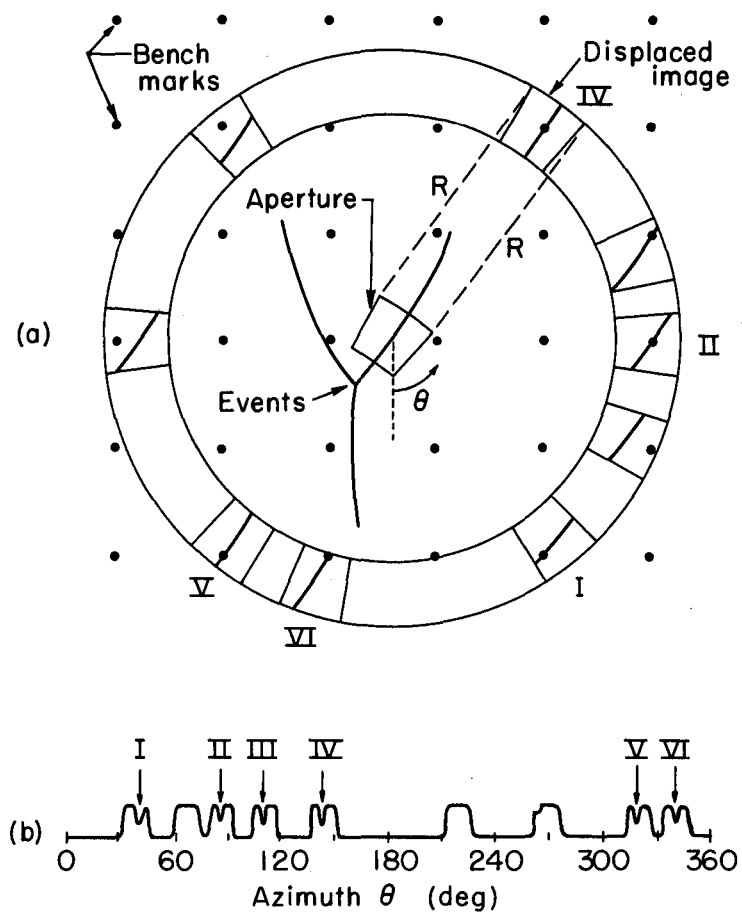
Below the bench-mark plate is the light collector, consisting of an annular lens and a photomultiplier tube. The light collector is mounted with a pulley arrangement so that it always travels directly underneath the periscope carriage, with the annular lens positioned to receive the image that has been displaced in a ring by the periscope. No matter what the orientation θ of the periscope, any light of the displaced image passing through a bench mark will be collected by the annular lens for the photomultiplier tube. (A tilted mirror is placed below the lens so that the photomultiplier tube may be mounted on a horizontal axis, taking up less vertical space.)

III. THE DIGITIZING PROCESS

The events leading to the digitization of points may now be traced. As the image falls onto the scanning surface, a disk of the image, centered approximately at (X_C, Y_C) , falls into the aperture and enters the periscope. In the spinning periscope, the image disk is translated so that it is centered approximately at $(X_C + X_D(t), Y_C + Y_D(t))$. As the periscope executes one revolution, the displaced-image disk sweeps out a circular path over the bench-mark plate (Fig. 4) and passes in turn over a number of bench marks (approximately nine). The output signal from the photomultiplier thus consists of approximately nine plateaus during the revolution, each of approximately two msec duration and each generated as light passes through a bench mark and reaches the photomultiplier. (The image field is light; the bubbles are dark. In practice, the "0.6-cm diameter" aperture is not circular, but is stopped down by a mask rotating with the periscope. The mask makes the displaced-image disk a sector of an annulus. This configuration causes all plateaus to have the same time duration.)

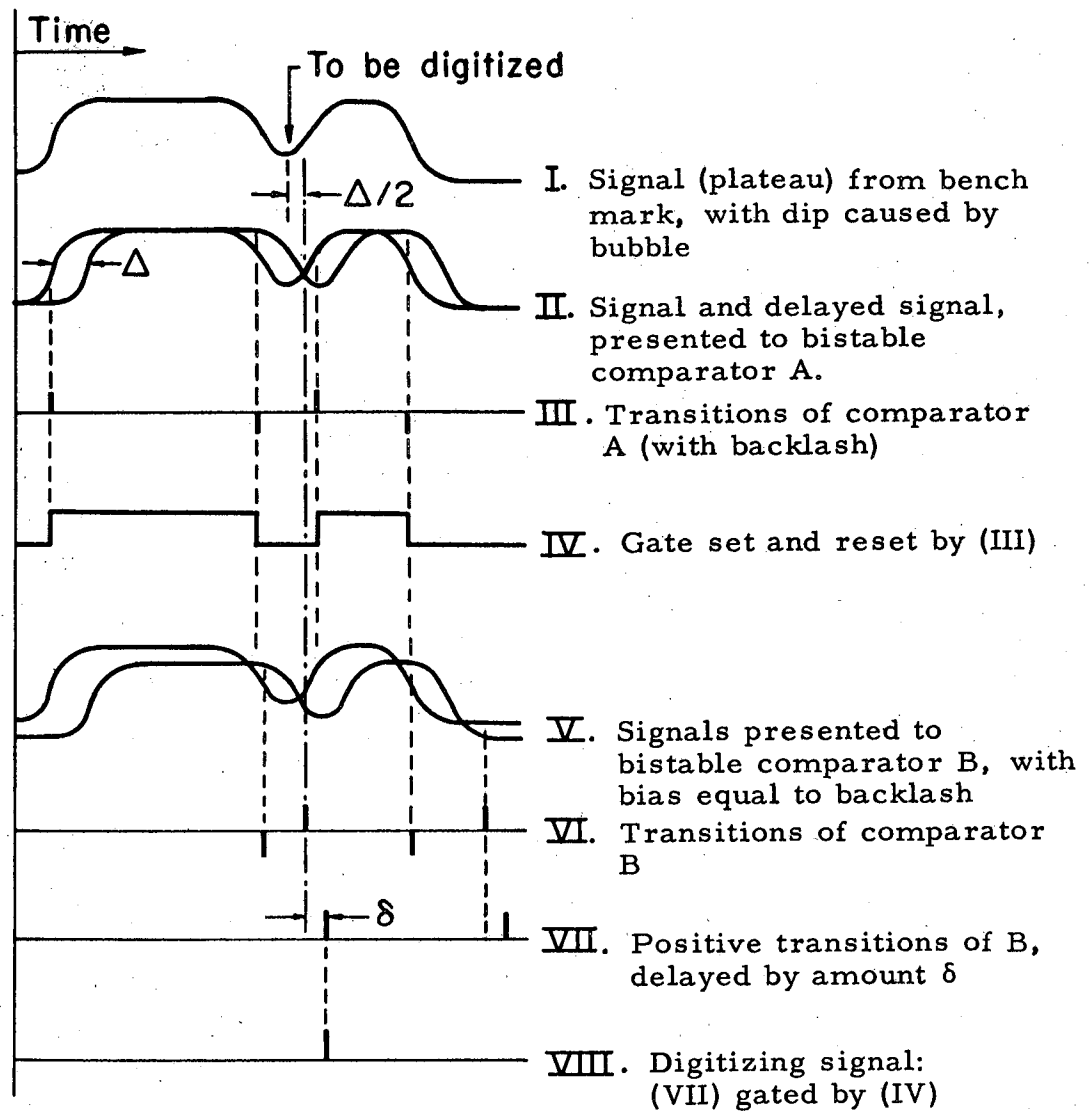
Now let there be the dark image of a bubble in the image disk. Furthermore, let this bubble image lie exactly at periscope radius R from one of the bench marks. Then, as the displaced image sweeps over this bench mark, the bubble image "eclipses" the bench mark at one instant, causing a dip in the photomultiplier output. The electronic circuit viewing the photomultiplier output is designed to find the center of each such dip in light level. At the center of the dip (the "height" of the eclipse), the circuit generates a "digitizing signal," which indicates that a dark image point is crossing a bench mark and is to be digitized (Fig. 5).

At the beginning of the periscope revolution the coordinates X_C and Y_C are sent from the SMP to the digital computer. When a digitizing signal occurs, the coordinates X_D and Y_D are sent to the computer. The computer then forms $(X_C + X_D)$ and $(Y_C + Y_D)$. These numbers are the approximate coordinates of the center of the displaced-image disk, near the bench mark through which the digitization occurred.



MU-33031

Fig. 4. Motion of the displaced image and the digitization of six points on a track, during one revolution of the periscope. (a) Motion of segment of image across the bench-mark plate; (b) photomultiplier output.



MU-33029

Fig. 5. Operation of the circuit that produces the signal for digitization of points. The circuit may be seen to effect a discrimination against dark spots (on the film) that are much smaller or much larger than a bubble image. Digitizing signal occurs $(\delta + \Delta/2)$ after actual center of eclipse, and recording on periscope drum is set back by this amount to compensate.

Since the bench marks are spaced exactly at the intersections of a 1-cm-square grid, they may be taken as lying at integral centimeter values in X and Y . The bench mark eclipsed by the point to be digitized may be exactly specified, therefore, by rounding $(X_C + X_D)$ and $(Y_C + Y_D)$ to the nearest integers. In practice, an equivalent process is used: X_C and Y_C are permanently set 0.5 cm too high, and the computer performs a truncation rather than a rounding, forming $[X_C + X_D]$ and $[Y_C + Y_D]$ as the coordinates of the bench mark causing the digitization. (The numbers being truncated here are always positive. For positive X , $[X]$ indicates the greatest integer less than or equal to X .)

At the instant of digitization, the vector $\underline{R} = (X_D, Y_D)$ is known to have exactly displaced the digitized point so that it eclipsed the bench mark just found. So the exact coordinates of the undisplaced-image point are

$$X = [X_C + X_D] - X_D \text{ and}$$

$$Y = [Y_C + Y_D] - Y_D.$$

This calculation of X and Y for each point is easily carried out in the digital computer.

As the periscope makes a complete revolution, several digitizing signals may occur, one for each bench mark crossed by the image and eclipsed by a dark point. For each digitizing signal, a drum coordinate pair, X_D and Y_D , is read out to the computer. Each of the drum coordinate pairs is combined with the X_C and Y_C for the entire revolution to form point coordinates X and Y as described above. Two image points may even eclipse the same bench mark and cause two distinct digitizing signals during the same 2-msec photomultiplier pedestal. The minimum time interval between two such digitizations is on the order of 1 msec, corresponding to a "peak instantaneous data rate" of 1 kc on the SMP.

The selection of the correct bench mark by truncation to integers depends on the circumstance that the uncertainty in position of the

digitized point is less than the 1-cm spacing between adjacent bench marks. This uncertainty is the sum of the width of the aperture (0.6 cm) and the error in X_C (or Y_C), which must therefore be kept less than 0.4 cm. It is possible for the operator to move the carriage so fast that the X_C and Y_C established at the beginning of a periscope revolution become invalid during the 30 to 50 msec of the revolution. Sensing the change in coordinates, however, the SMP reads out to the computer a new X_C and Y_C , which are used for the remainder of the revolution.

The digitization of a point does not depend on the precise location of the periscope carriage; as long as the point falls into the aperture, the displacement vector R carries it in the same circle on the benchmark plate. Thus, the operator need only guide the carriage accurately enough to keep the object to be measured somewhere within the aperture. By the same token, however, if the operator moved the carriage slowly, or stopped, the same points would be repeatedly digitized as long as they fell into the aperture, uselessly overloading the computer. To avoid this repetition, the transmission of coordinates to the computer is gated to occur for only one periscope revolution, each time the aperture is moved by 0.5 cm in X or in Y. Thus a "snapshot" is taken each time the aperture moves by approximately its own diameter.

To be digitizable, a dark point in the image must be able to eclipse some bench mark; that is, it must lie at distance R from some bench mark, to within a fraction of a bench-mark diameter. In other words, the loci of possible digitizations in the image plane are circles of radius R centered on every bench mark. The "uniformity" with which these circles cover the image plane is a critical factor in choosing the exact periscope radius R (Appendix A).

A point not lying on any of the circles cannot be digitized by the SMP. Thus, the SMP is not directly able to measure any arbitrarily chosen point. (Indirect and special methods of single-point measurement are discussed in Sec. VII.) If a dense bubble chamber track is thought of as being composed of adjacent bubbles of 0.04-cm image diameter, then approximately one bubble in three can be digitized. In other words, the SMP digitizes some six to ten points per centimeter on a dark track, on the average.

The SMP does produce useful bubble-density information. As is seen above, the SMP digitizes a statistical sampling of the bubbles on a track. If the density of bubbles varies, so does the density of digitizations. The observed density must be corrected for track dip angle and chamber and film-developing conditions, as well as for factors peculiar to the SMP: the average density of digitizing loci, the frequency of recording-periscope revolutions, multiple digitizations of single points, and any peculiarities of the motion of the aperture (such as straying off the track!). All these problems are considered solvable, in view of the analytic capabilities of the computer and the statistical nature of the bubble-density information itself. Preliminary tests have indicated that the digitized information is indeed quite valid,^{4d} and initial steps have been taken to use a simple count of digitizations per centimeter. Slowness in utilizing bubble-density information, in fact, has been due to the lack of provision for it in subsequent analysis programs, due in turn to the previous unavailability of such information.

IV. LEAST COUNT AND ACCURACY

The bit lengths of the various SMP coordinates (in cm) are given in Table I.

Table I. Bit lengths of SMP coordinates.

Coordinates	Integral bits	Fractional bits	Total bits
X_C and Y_C	6	5	11
X_D and Y_D	3	7	10
X and Y	6	7	13

The least count of the SMP- 2^{-7} cm on the SMP table—corresponds to 5 microns on the film. (The magnification is 15X.) This least count applies to the individual digitizations, not to the SMP output points.

We take the "accuracy" of the SMP to mean the magnitude of the spatial differences between points output by the SMP program, and the corresponding points in the nearest "true" transformation from the film plane, which involves only translation, rotation, and magnification. All such "true" transformations are acceptable, since the fiducial marks measured provide the four parameters necessary to specify the transformation.^{5a} In adopting this definition of accuracy, the computer processing is considered to be an integral part of the SMP measurement. Such an assumption is plausible in view of the fact that the computer must extensively process the SMP digitizations to produce data in the conventional form output by digitized microscopes.

Two special considerations apply to the discussion of accuracy on the SMP. First, the optical distortions may be neglected as sources of inaccuracy if they are corrected in the computer. The form of distortions in the projection system and smooth "global" distortions in the lattice of bench marks may be found directly by making SMP measurements of an accurately ruled grid placed in the projector. The computer then applies the appropriate corrections to the digitized information;

in the present program, for example, a polynomial correction is applied for cubic radial distortion and for "keystoning."

The second consideration pertaining to accuracy is that all the nonglobal sources of inaccuracy either are sources of statistical error or enter into the measurement as if they were sources of statistical error. There are two sources of true statistical error: the least-count quantization and the jitter in the electronic signal marking the instant of digitization. The remaining sources of inaccuracy in the digitizations are misalignments causing increments in the periscope radius and azimuth, and inaccuracies in the positioning of the individual bench marks. These are systematic errors. However, it is to be noted that nearby points on a track are digitized through many different bench marks and at all angles of periscope orientation. Since 10 digitizations on the track are averaged together to give one output point, the contributions of the aforementioned errors will tend to average out over the 10 points. Measurements of tightly stretched shadow wires (simulating straight tracks) typically show an rms scatter off the track of approximately 5 microns on the film (one SMP least count) for individual digitizations. The rms scatter off the track of the averaged output points is then reduced by a factor of approximately $\sqrt{10}$, to approximately 2 microns on the film. By comparison, the least count on the digitized projection microscopes used by the Alvarez group is 2.5 microns. Periodic maintenance tests consisting of straight-line measurements on the projection microscopes typically yield rms point scatters of approximately 2 microns. (The minimum theoretically attainable rms scatter of single measurements of a uniformly distributed variable, measured with a quantization of least count L , can easily be shown to be $L/\sqrt{12}$.)

Direct comparison of SMP and projection-microscope measurements has also been made at the geometric reconstruction and kinematic-analysis levels. A quantity calculated by the reconstruction program, indicating the scatter of measured points from the curve fitted in space, was examined. The distribution of this quantity is not noticeably different between the SMP's and the projection microscopes. A sample of

elastic scatterings was measured on both machines, and the values of χ^2 obtained in the kinematic fit of both measurements were graphed on a scatter plot of χ^2 (SMP) against χ^2 (projection microscope). The plot was symmetric, indicating the same distribution of χ^2 values from both machines.

V. AUXILIARY HARDWARE

A. The Projector and Film Transport

The detailed description of the projector and film transport for the SMP depends on the format of the photographic records being analyzed, and thus will vary among installations. The projectors designed at the Radiation Laboratory to handle film from the 72-inch bubble chamber are described here.

The optical system must have a long light path, so that the rays passing through the SMP digitizing apparatus will have small divergence and so that the image will be well focused both on the scanning surface and on the bench-mark plate. This long light path (approximately 10 feet, minimum) necessitates bending of the light path in rooms with typical ceiling heights. It is also desirable to give the operator direct access to the film transport. For these reasons, the projector is mounted at the side of the SMP table, and the image is projected to a ceiling mirror, thence down onto the scanning surface. The ceiling mirror is a rigid, yet lightweight, construction of two glass plates separated by cylindrical glass columns. The plates are fused to the columns, then the outer surface of one plate is ground optically flat and silvered.

The projector is a single-film, three-view projector for un-sprocketed 46 mm film. The three objective lenses have a focal length of 300 mm and are usually operated at $f/8$ or $f/11$. The chamber image is projected at $15\times$ magnification from the film (approximately life size). Thus, the length of the 72-inch bubble chamber image is about twice the extent of the scanning surface. All three views are vacuum-clamped onto a single platen carriage, which moves in one dimension to bring any region of the chamber image into view. The platen carriage is clamped by an electromagnet. Any combination of the three stereo views may be turned on at once, and the views superimposed by moving two of the three objective lenses. The operator may use this superposition as an aid to stereo visualization. The views are turned on and off by mechanical shutters, or, in a newer design, by turning up and down the voltages on the 500-watt incandescent projection lamps.

The operator has fast film forward and rewind controls, with an automatic approximate frame finder. The film may conveniently be positioned by unclamping it and manipulating the feed reel at the operator's left hand, and finally by adjusting the platen carriage.

The three projection axes are placed as close together as is possible, to minimize the divergence of light paths in the digitizing apparatus. In the present design, two of the paths are folded close to the third with mirrors.

B. The Typewriter

The SMP typewriter is located at the operator's right, within convenient reach. The operator uses the typewriter to converse with the digital computer, as they progress together through the measuring sequence. The typewriter paper constitutes a permanent record of the entire measuring sequence (Fig. 6). Automatic color shift of the typewriter ribbon separates those messages typed by the computer from those typed by the operator.

The SMP typewriter is an electric typewriter, equipped with encoders and decoders for transforming characters to six-bit codes, and vice versa. In an installation containing an IBM 7000 series computer, the typewriter is connected to the 10 input and 10 output sense lines of the computer's direct data channel.^{4a} Six lines each way are used for character transmission, and four lines for specifying the SMP number. As the operator strikes a character key, the corresponding code is impressed on the input sense lines, and an interrupt signal is sent to the computer, interrupting the program in progress. It is the responsibility of the special program section reached by this interrupt to accept the character on the sense lines and process it in a few milliseconds. After approximately 10 msec, the code on the sense lines is removed by the typewriter multiplexer, and may be replaced by another character from another SMP typewriter.

If the computer is sending a typewriter message to the operator, a single computer instruction presents a character code on the 10 output

```

BEGIN15✓
OP. NO. 26✓
MO. 11✓/DAY 27✓/YR. 63✓
EXP. NO. 08✓
R, F, B, 6748, 445, 01✓ (roll, frame, beam track, of
the last measured event)
MEASURE ROLL 6748, FRAME 469, B.T. 01, P.E.T. 094, ZONE 0524
MEAS? R✓ (reject this event)
COMMENT 110✓/RESTART PT. , I✓ (vertex is obscured) ("T" means
read tape to get next event)
MEASURE ROLL 6748, FRAME 489, B.T. 01, P.E.T. 062, ZONE 0404
MEAS? R✓ (reject)
COMMENT 105✓/RESTART PT. , I✓ (outside region for measuring)

MEASURE ROLL 6748, FRAME 491, B.T. 01, P.E.T. 032, ZONE 0318
MEAS? Y✓

VR, T/VR 2, 3, 2✓,, (vertices and tracks from
each vertex)

F, π,,, (fiducial)
VRT, π,
T1, π,
T2, π,
T3, π,,,
VR2, π,
T1, π,
T2, π, (T2 failed filter program and
ERR D, π,,, was remeasured)

F, π,,,
VRT, π,
T1, π,
T2, π,
T3, π, (T3 failed filter program and
ERR F, π,,, was remeasured)
VR2, π,
T1, π,
T2, π,,,

F, π,,,
VRT, π,
T1, π,
T2, π,
T3, π,,,
VR2, π,
T1, π,
T2, π,
FIN Y✓,RESTART PT. , I✓ (event complete; get next one)

```

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Fig. 6. A page of typewriter output, showing the actual production measurement of a two-prong-plus-V event. The operator's typing has been underlined. Explanatory notes in parentheses have been added. The $\sqrt{\quad}$ symbol indicates the end of the operator's message, and the π symbol means that he has completed a measurement. Excess commas indicate computer-controlled functions, such as automatic changing of views. Note the detection and correction of two mistakes in measuring tracks.

sense lines. The character is immediately passed to a buffer in the SMP, allowing the computer to proceed to other operations. Upon receiving the character in the buffer, the typewriter initiates a stroke cycle to print the character. At the completion of the stroke, the typewriter interrupts the computer so that the special program may send the next character. Codes for nonexistent characters on the typewriter are used for special functions to be controlled by the computer, such as turning on and off views in the projector, and allowing and inhibiting the ability of the SMP table to transmit coordinate data.

The typewriter electronics includes the buffer for characters coming from the computer, and the control circuitry required between the typewriter and the computer or multiplexer. The typewriter electronics is contained in a few rows of printed circuit boards mounted below the typewriter.

C. The Electronics Racks

Two floor-standing racks contain the bulk of the electronics for the SMP. The majority of the logical electronics consists of four reversible scalars for holding the coordinates X_C , Y_C , X_D , and Y_D . The coarse (C) scalars hold 12 bits each, whereas the drum (D) scalars hold 10 bits each, including sign. Associated with each scalar is a register of equal bit length used for transferring the data to the computer.

Additional logical electronics consists of gating and control circuitry, including a multiplexer to interleave coarse and drum coordinate transmission. For transmission to the computer, in an installation with an IBM 7000 series computer, a partial coordinate pair, either X_C and Y_C or X_D and Y_D , are placed together in a single 36-bit data word. The word also contains an indicator bit telling whether it is a coarse word or a drum word, and bits specifying the SMP number.

One of the two floor-standing electronics racks contains the various power supplies: for the periscope-drum motor, the typewriter, the projector, and the film-transport relay chassis. This rack also contains turn-on circuitry, indicator lights, meters, overload relays, and power-supply controls.

The high-voltage supply for the photomultiplier, and the circuitry that produces the digitizing signals, are mounted in the electronics racks. Connections to the moving periscope and photomultiplier carriages are made through flexible cables in the SMP table. With the exception of the photomultiplier tube, all of the SMP electronics is solid state.

D. The Combining, or Multiplexer, Unit

In most existing and proposed SMP installations, several SMP's are connected to a computer that has only one data channel for input of coordinate data. This situation holds at the Radiation Laboratory, where the computers involved are of the IBM 7000 series. (Some medium-scale digital computers appear to have facilities for attaching each SMP to a separate data channel.)^{3d}

A combining, or multiplexer, unit is used to interleave the data generated by a number of SMP's and to present the data to the data channel as if from a single source.^{4f} The present design of the combining unit will handle four SMP's, and the combining units may be cascaded to handle a greater number.

The combining unit contains two independent multiplexers, one to service the coordinate data, and one for the typewriter characters going to the computer. Each multiplexer is essentially an asynchronous ring circuit that circulates among the SMP's until it encounters a demand for data transmission. The multiplexer then remains switched to the requesting SMP until the data transmission is accomplished. Typewriter characters output from the computer do not pass through a multiplexer but are immediately gated to a buffer register in the proper SMP.

The combining unit, along with line drivers for the cables to the computer, is housed in a separate electronics rack.

VI. THE SMP COMPUTER PROGRAM

A. The Program in General

The SMP computer program operates on two separate levels. On the processing level, the program does all the processing and checking of the data from a measured nuclear event for an individual SMP, assembling the data to pass on to subsequent programs. The program also performs a function on the executive level, making the processing phase of the program available to all the SMP's connected to the computer, on an independent time-sharing basis.

In the processing phase of the program, called the "inner program," the computer deals at any one time with data from a single SMP. The input coordinate information is transformed into X-Y coordinate pairs, and the desired measurement information is then abstracted or "filtered" from the set of X-Y coordinates. This filtered information is assembled, as it is generated over a period of minutes, into a record to be output on magnetic tape for subsequent programs. To this record is added indicative information supplied by the SMP operator via the typewriter. These processing operations are discussed further in Secs. VI-B and IX of this report.

On the executive level, the computer deals with all the SMP's in a time-sharing fashion. The executive phase of the program acts as a superstructure for the inner program, providing access to the same inner program to every SMP, as requested individually. The resulting structure is not that of a typical time-sharing system, in which control is passed among several independent programs. Rather, in the SMP system, all the operators share the same processing program, which is continuously in the computer memory, and which may service all of the SMP's in a fraction of a millisecond.

In the paper describing this novel executive structure,^{5g} the author called it a multiprocessing program, but recent usage favors calling it a multiprogramming structure. To achieve the multiprogramming structure, the inner program is segmented into natural subunits, such as the transmission of a single typewriter character or the

filtering of a single track. Each class of subunits is assigned a priority level, with the shortest and most often-repeated operations having the highest priority. As the SMP operators generate requests for processing operations, the requests are dealt with by a priority-handling section of the executive phase. Thus, the executive phase acts as a traffic controller, ensuring that the processing requests of the various SMP's are handled in an efficient manner and without interference. The individual operators may in effect consider themselves as having sole access to the computer. An operator does not even feel the presence of other SMP's and operators in the system, except for occasional short delays caused by other processing requests of higher priority.

The present complete SMP program, including the filter programs, occupies the IBM 709 computer for approximately 30 seconds in processing a single event. This figure is for a typical event, and of course depends on the event topology. For a typical event, approximately 20 seconds are taken by the filter programs to filter five tracks, two vertices, and a fiducial, each in three views. The bulk of the remaining time is used in "unpacking" the data coordinates and calculating X and Y for each point. The figure of 30 seconds does not include waiting times for the typewriter, the measurements, and the operator's reactions. During all such times the multiprogramming structure frees the computer to do other work.

The IBM 709 is a vacuum-tube computer, with a 25- μ sec add time. Even at this speed, slow by present standards, the present program could process a million events a year. To permit efficient utilization of faster computers, SMP programs that time-share the computer with other tasks will clearly be called for. Development of one such time-sharing program is described in Sec. IX. In an IBM 7000 series computer, the present program requires approximately 10,000 (decimal) words of storage plus 1,200 words per SMP in the system.

B. The SMP Filter Programs

The SMP's method of digitization dictates the unique characteristics of the data generated. Specific individual points cannot be measured directly; the SMP is more suited to measuring along figures composed of lines and curves. When a specific point, such as an interaction vertex or a fiducial mark, is required, it is currently found as the intersection point of two straight lines or curves. Thus, in the present arrangement, the data are always generated on the SMP as the operator moves the measuring aperture along a curve to be measured. In the following discussion, the object being digitized is taken to be a single smooth curved segment of a particle-track image. Whether the bubbles on the track are distinguishable by eye, or merge to form a continuous line, is immaterial, except that the digitization density will be different.

It is assumed that the information to be abstracted, or "filtered," from a track measurement in one view consists of a series of X-Y coordinates of points accurately located along the track. In all existing and proposed measuring systems, the data pass through this stage. To enter existing analysis programs, the output data are also generally required to simulate the output data of digitized microscopes. The output points must be rather few in number, and in order along the track. Such data are easily derived from the greater number of SMP digitizations on the track, by a process of averaging, which also reduces the scatter of the output points. Thus, the central task in preparing the output data is to select, from the set of point digitizations produced by the SMP, the subset of points actually lying on the track. This pattern-recognition task falls to a portion of the SMP computer program called the track-filter program.^{5h} (There are corresponding specialized filter programs for the fiducial marks and vertex points.)

The set of digitized points has the following characteristics. There is no guarantee that any given track point, or a point in any given small region, will be digitized. On the other hand, a point may be digitized more than once. Points on the track may be digitized out of order by a distance equal to the measuring aperture diameter, although

the gross ordering of the points will follow the aperture down the track. Any "background" of dark points on the path swept out by the aperture will be digitized along with the track points. Other objects in the digitizing path, such as crossing tracks, will be digitized as efficiently as the track itself. Finally, gross defects in the data can be produced by the operator by straying off the track, reversing the direction of measurement, or failing to keep the recording button down continuously. Each of these characteristics represents a handicap to the track-filter program.

In the face of these handicaps, the filter program must select out those points which lie on the track, or return an error comment if it finds itself unable to perform the selection from the data presented. In the existing filter programs, the error comment provides information as to the probable cause of the deficiency in the data, as a guide to the operator in remeasuring the track.^{3e}

The author has considered various approaches to the problem of performing, in a digital computer, this point-selection process so easily done by a human. The problem is truly one of pattern recognition. The processes involved in pattern recognition in the human nervous system are not understood, and even the criteria for evaluating pattern-recognition performance are ill-defined. Yet this problem of selecting out only those digitized points which are on the track is as important for obtaining accurate output as is the accuracy of the digitizing apparatus itself.

Selection methods involving a least-squares fit of a polynomial to the entire track, with casting out of points deviating from the polynomial by more than a certain amount, were considered first. These methods were rejected because of the excessive time required to calculate the sums of products involved in evaluating the coefficients of the least-squares fit. Methods based on the concept of topological connectedness, constructing and extending "islands" of digitized points, were briefly considered, but no promising avenues were found. Programs that considered the data in small batches were tested. These programs tried to progress down the track, projecting a path ahead and finding points on

the track. They were found to be too sensitive to fluctuations in the data. The lack of systematic procedures for investigating and evaluating these approaches, however, does not mean that any of them should be considered demonstrably unproductive in general.

The method ultimately incorporated into the existing SMP filter programs uses histograms of digitizations along coordinates in the image plane. It is based on the concept of a histogram as the "digital equivalent" to the autocorrelation process. As such, the method bears a striking analogy to the servocentering of present-day digitized projection microscopes. In these machines, a slit aligned with the track to be found is swept across the track. The minimum of the light output from the slit corresponds to the peak autocorrelation of bubble image density in the track direction, and gives the location of the track. In the track-filter program, a histogram of digitizations is formed along the coordinate perpendicular to the track. The peak of this histogram signifies the greatest alignment of digitizations in the track direction, again giving the location of the track (Appendix B).

The SMP filter programs were developed by the author during 1961-63, concurrently with the construction of the early SMP's. The filter programs were coded in the FORTRAN programming language, whereas the rest of the SMP computer program was coded in symbolic machine language for the IBM 709 (9AP). The author devised an interface between the two parts of the SMP program, and methods for combining and manipulating them in the computer.^{5c,5d,5f} Programming in FORTRAN simplified the long task of developing the filter programs, and made available valuable diagnostic outputs. After the filter programs had achieved a working status, they were recoded into equivalent machine language. This recoding cut the running time of the programs in half, and reduced the storage requirements by one-fourth, while preserving the convenient structure of the original FORTRAN programs.^{5f}

VII. THE MEASUREMENT OF SINGLE POINTS

Although the SMP cannot measure directly a chosen point in the image, there are various methods by which the location of the point can be derived from measurements of other types.

In the procedure currently used on 72-inch bubble chamber film, a point is found as the intersection of two straight or curved lines. To measure a vertex, or interaction point, the operator actually measures portions of two particle tracks emanating from the vertex. The computer then finds coordinates on the two tracks measured and calculates their point of intersection. The vertex point is thus found, although neither it nor any point very near it may necessarily have been digitized.

It may occur that all tracks emanating from a point to be measured intersect so obliquely that no pair of tracks is satisfactory for the measurement described. At the end point of a stopping track, furthermore, there is no second track. In such cases a device called the shadow wire is used to simulate an extra track. The shadow wire is mounted on a horizontal swinging arm and is positioned by the operator just above the scanning surface. It casts a straight-line shadow whose appearance is that of a densely ionizing track.

A modification of the intersecting-lines method is currently being considered for the measurement of spark chamber photographs. In some spark chamber film, the sparks appear essentially as single points. Only the sparks at the ends of straight-line sections of tracks need be measured. A reticle composed of two crossed shadow wires is positioned over a point to be measured, and the operator triggers a measurement consisting of one periscope revolution. A short test has indicated that in one revolution enough points on the reticle are digitized to enable the computer program to recognize the reticle and find its intersection point, especially if the reticle has a known angular orientation.

Another method of finding single points requires some specialized hardware, but eliminates the necessity of accurately setting a shadow wire or reticle. In this method a shallow prism is used to displace the image by a small amount, perhaps a millimeter. The

prism may be mounted above the measuring aperture. As the prism rotates with a speed of approximately one revolution per second, the image moves with a corresponding small oscillatory motion. During the period of 1 second, the SMP continually sends its digitizations to the computer. The aperture remains stationary.

The effect of this perturbation of the image is to bring every point in the aperture into contact with the SMP's digitizing "raster" at some time during the prism revolution. The point to be found is actually digitized. By examining the complete set of data, a suitable computer program can select the point in question. The feasibility of this technique has been shown in a small test.^{4b} There are no present plans, however, to implement this technique in production measuring.

VIII. SMP HISTORY AND PERFORMANCE

A glance at the chronology of the SMP shows the rapid time scale in which it has progressed from a new invention to a production-measuring machine.

Spring 1960	Computer control of measuring machines suggested. ^{3a}
Fall 1960	Visualization by Dr. Luis Alvarez of the SMP, with an oscillating bench-mark plate. ^{3b}
Late 1960	Introduction of rotating periscope.
1961	Construction of prototype SMP, with light-pipe light collector. ⁶
Fall 1961	Prototype SMP attached to IBM 709 computer.
Late 1961	Computer program for multiple SMP's structured by Dr. James Snyder; coding of programs begun. ^{3c}
Summer 1962	Introduction of present light-collector design; construction of first production-model SMP begun.
December 3, 1962	First SMP-measured event passes KICK analysis program.
April 29 to July 31, 1963	Shakedown experiment (K^- two-prongs). SMP running on day-to-day production basis.
August 1, 1963	SMP's join digitized projection microscopes as mainstays of Alvarez group measuring effort.

The second, third, and fourth SMP's were completed during and immediately after the two-prong experiment. Three SMP's are currently being used by the Alvarez group, and the fourth is at the University of Illinois under the collaborative SMP development arrangement. More SMP's are being constructed. During the shakedown experiment (K^-p elastic scattering at 1.22 Bev/c), 7000 two-prong events were measured and failing events remeasured, and procedures were established for integrating the SMP's into the Alvarez group data-analysis system for subsequent experiments.⁷

To date, the SMP's in the Alvarez group have been used for measuring only, not for scanning. The decision not to scan film concurrently with measuring is an economic one, dictated by the existence of a large number of scanning tables in the group and by the present small number of SMP's. At a given installation, the question of whether the SMP's are used for scanning during measuring, in "off hours," or not at all, depends on the relative availability of SMP's and other scan tables, the hours when the computer is available for measuring, and the frequency of events on the film. Even when the computer is unavailable, the SMP can be used as a scanning table merely by turning the projector on.

In the Alvarez group, up to the present, the SMP's have been made to fit into the data-analysis system exactly in place of the conventional digitized projection microscopes. The input from the scan lists has been identical for the two types of machines, as has the output to the PANAL preanalysis program. A direct comparison of the performance of the two machines is therefore possible. Within the wide variations experienced on both machines, the SMP's performed on a par with the projection microscopes both with respect to speed (six to ten events per hour) and reject rate (25 to 30%) in the first months of SMP production measurements. (The reject rate is the percentage of measured events rejected for all causes by the later analysis programs.)

SMP developments currently in progress will have a significant effect on both the measuring speed and the reject rate. One development is the elimination of the separate measurement of vertex points. In bringing the SMP's into operational status, it was decided as a matter of expediency to measure the vertex points separately, from the intersection of two track segments or line segments. The vertex points should instead be found from the intersections of the various tracks emanating from the vertex, after the tracks are measured. Modifications to the SMP program are currently being written to use the measured track information for vertex points and for end points.

These modifications will eliminate the extra vertex measurements presently made, and the rejects and track remeasurements due to misaligned vertex and end points. We expect a reduction in the reject rate by perhaps 5% of the events measured, and an increase in speed by a factor of from 1.5 to 2.

Another development in progress has the potential of eliminating all measurement-dependent rejects, and perhaps ultimately all remeasurement requests in general. This development, the extension of checking and information feedback to all levels of the event analysis, is discussed in Sec. IX.

Another development was given low priority, but would surely repay the effort spent on it. This project is the revamping of the typewriter messages of the measuring sequence for efficiency and speed, and indeed a careful "human engineering" analysis of the measuring sequence and of the whole man-machine system. A few seconds saved per event would soon add up, just as a single program instruction removed from the track-filter program can save as much as a day of computing time on the IBM 709 every year.

IX. SMP SYSTEM CONSIDERATIONS

The incorporation of a general-purpose digital computer into the SMP system establishes an information-processing system whose great power can be exploited in several directions. To begin with, the computer can govern the sequence followed by the operator in measuring an event, and can filter the SMP data into data of more conventional form. These functions of the computer are the ones incorporated into the present program, and are sufficient to allow the SMP's to take the place of digitized projection microscopes in the analysis system.

In striving to bring the SMP's into production-measuring status quickly, however, other services that the computer may perform have not been implemented. The computer may be programmed to occupy itself with other useful tasks whenever there is a lull in the fluctuating SMP work load. Such a "time-sharing" program is a logical extension of the structure whereby the computer shares its work among several SMP's. The computer may also be programmed so that, in conjunction with the human operator it assumes more of the recordkeeping and data-analyzing functions of the overall data-analysis system. These extended services of the computer are presently being developed for use in various SMP installations, and they are described in the remainder of this section.

A. Time-Sharing Structure

The central arithmetical and logical processing units of digital computers currently operate much faster than do many of the input-output units and external systems with which the computers deal. This fact has led to much recent investigation of "time-sharing" systems, in which the external bottleneck is avoided by having the central processor service a number of external systems or input-output units. The multiprogrammed SMP system is an example of such a time-sharing system. However, a present-day large-scale solid-state digital computer is still far faster than is needed to service the SMP's in a typical installation. Even if the computer were perfectly matched

to the peak data load from the SMP's, it would still be idle much of the time, due to the great variations in the measuring rate of the SMP operators. The cost of this idle computer time is too great to be ignored, and so one must consider systems in which the SMP's time-share the computer with other programs as well as with each other.

Three variations of the time-sharing system have been considered. In the first variation, the SMP executive control coexists in the computer memory with a general-purpose monitor system. The monitor system allows general use of the computer by the user community, and typically includes executive routines, machine-language assemblers, and compilers such as FORTRAN or ALGOL. In the existing systems considered, the exhaustive demands the monitor system makes of the computer have made this approach appear infeasible.

The second approach to time sharing uses a smaller computer as a buffer between the SMP's and the large computer. The monitor system in the large computer can be dealt with by intermittently "dumping" it out of the computer memory (onto a magnetic disk storage) and reading in the SMP program. This transfer of programs is quite uneconomical, unless it only happens once per several seconds, or even minutes. Yet each SMP demands attention ten times a second, for example, during the typing of a message. Furthermore, the data produced by the SMP tables must always have access to some storage bank. The buffer computer is used to handle these repetitive small-scale demands of the SMP's and to assemble data in larger blocks for the large computer. Systems of this nature are currently being developed for various installations. A difficulty of such systems is that, as processing of the data moves farther from the SMP, the feedback of information to the operator becomes less immediate.

The third time-sharing system is one in which the SMP program shares the (single) computer with a restricted class of other programs, rather than with a general computing service. The advantage of this approach is that the programs sharing the computer with the SMP program are specifically tailored for compatibility. The programs might be simple ones to perform "clerical" computer tasks, such as

listing of tapes and card-to-tape conversion. The author has pointed out that it should also be possible to accommodate a wide spectrum of programs, such as FORTRAN object programs, under certain ground rules. Provision for such time-sharing is included in the author's outline of SMP program structure.^{5g}

Perhaps most pertinent to this discussion is the fact that the measuring of masses of bubble chamber data implies the analysis of these data by standardized, time-consuming computer programs. These programs are ideal candidates for time sharing, using the very data being produced in the computer by the SMP program. These analysis programs will typically be run on the same computer in any case; the only additional problem of this time-sharing approach is fitting the SMP and analysis programs into the computer simultaneously. This approach to efficient time sharing is intimately connected to the question of immediate information feedback, and is further discussed in Sec. IX. B.

B. Fast Feedback and Automatic Bookkeeping

Measured bubble chamber events that fail in the various later analysis programs constitute a problem of ever-increasing magnitude, as the number of events typically measured in an experiment increases with time. In the Alvarez group, an extensive "library system" of computer programs and hand operations has been developed, primarily to cope with the bookkeeping for failing events that must be remeasured. This library system occupies a significant portion of the programming effort and computer time of the group. If the need for remeasurements could be eliminated, the savings would be great.

The computer in the SMP system can eliminate failing events by recognizing each failure and immediately requesting that the operator remedy the cause of the failure, while the data in question are still in front of the operator. Presently, however, this fast feedback and error correction is applied at only two levels: in governing the sequence of the measurement dialogue, and in filtering measurements. If a message typed by the SMP operator is unallowable, the computer will

not accept it. For example, if the operator is asked the frame number of an event, and he returns alphabetic rather than numerical characters, the computer will signal an error and request the information again. Similarly, if a measurement of a track, vertex, or fiducial mark does not pass standards of acceptability in the filter programs, the computer will immediately ask that the offending measurement be remade, and will not proceed until the measurement is made acceptably. The operator may be required to measure more carefully; or, owing to the nature of the SMP data, a second measurement the operator feels is "identical" may sometimes pass where the first one failed by statistical accident.

It might be thought that the aforementioned error correction would eliminate failing events. However, there are reasons (beyond the imperfections of the present filter programs) why the event may fail in later programs, although the measured elements of it were found satisfactory. For example, an end point may be measured out of correspondence with its track, or different events might even be measured in different views! Even beyond all measurement errors there remain events that fail because the interactions actually recorded on the film are not provided for in the analysis. Such events are in a sense perfectly good physics, but because they fall into unwanted categories in the experiment, they are classed as rejects. This class of events includes interactions by particles contaminating the incident beam, event configurations that simulate other topologies and are misidentified, and, in fact, all interactions not included in the list of hypotheses to be tried in the analysis programs.

Thus, the checking of events and the correction of measurement errors through referral to the SMP operator need to be extended down through the chain of event analysis. A brute-force method would be to "patch" the existing format checking, geometrical reconstruction, and kinematics programs (PANAL, PANG, and KICK in the Alvarez group) onto the SMP program.^{5e} The existing error branches of the programs would be modified to request corrective actions by the operator. But problems of time-sharing and efficient computer utilization arise.

The analysis programs are too bulky and generally too time-consuming to coexist with the SMP program in today's computers.

Accordingly, the following compromise solution is being pursued in the Alvarez group. To the SMP program will be added whatever is needed from PANAL, the complete PANG, and a first-order pseudo-KICK. The pseudo-KICK program will avoid fitting measurements to the equations of constraint and handling error matrices. It will run far faster than the real KICK kinematics program, allowing feedback to the operator in a reasonable time. Furthermore, pseudo-KICK will be under the control of a general hypothesis-generating routine. The latter will generate, within a set specified by the experimenter, all physical hypotheses compatible with the event topology and the applicable conservation laws of physics.⁵ⁱ The measured event will be tested against the hypotheses generated. If a hypothesis is found that the event fits (according to established criteria), the event is assured of passing the real KICK program, to a high level of probability. An event reaching this point has a virtual guarantee that it will never have to be remeasured.

What of events that fail some test in the programs before passing pseudo-KICK? The event, the SMP, and the operator are immediately available to participate in corrective action. The action taken will depend on the sophistication of the computer program. Failures in the event measurement should be detected rather easily, and the operator given detailed instructions, such as "Remeasure track 2 in view 3," or "Look for another origin of the neutral particle." There will be a residuum of events that defy correction by the SMP operator. These events will perhaps be output as a separate group and will probably require individual investigation. The important point is that the rejected events will be far fewer than the present remeasurements, and that they will be identified from the outset.

In addition to being extended down the chain of analysis programs, the SMP program can be extended ahead to include the film-scanning operation. The combined scanning-and-measuring operation fundamental to the SMP (even embodied in its name!) would eliminate a

number of processing and hand-over operations now performed. Scanning information on each event presently passes through scan lists, keypunch cards, magnetic tape, computer, more magnetic tape, and measurement-control cards, before reaching the measurement-output tape. In the SMP system, all of these steps can be replaced by a single operation in which the operator scans and measures the event and adds descriptive information via the typewriter. The computer processes the information and produces all required magnetic tape outputs. (The economic reasons why this scanning-and-measuring operation is not yet in use are mentioned in Sec. VIII.)

As the SMP program is expanded to include the scanning of film and the analysis programs, it will assume more of the clerical and bookkeeping operations of the analysis system. Those operations presently involved in the hand-over of data from one person or program to the next will be eliminated. The automatic performance of many bookkeeping operations and the elimination of others, together with the reduction of the remeasurement problem, will enable the SMP to replace in large measure the complex library systems that now exist.

ACKNOWLEDGMENTS

It is a tremendous pleasure for the author to acknowledge the contributions of many fine people to the SMP development program. It can only be said of their work that it was excellent without exception.

Thanks and admiration go to Dr. Luis Alvarez for his continued leadership and guidance as well as for the invention of the SMP. The author feels special bonds of friendship to Dr. Ronald Ross, Dr. William Humphrey, and Dr. Robert Hulsizer, each of whom contributed careful overseeing and much pure hard work, in ensuring that the SMP "made the grade" from the physicist's point of view. Dr. James Snyder's comprehensive design of the SMP computer program must be considered as vital a part of the total instrument as the hardware itself.

Mr. Pete Schwemin and Mr. Peter Davey have contributed the hundreds of little designs, and many of the large ones, that have given true form to the SMP. At the same time, they, with their competent co-workers, have speedily brought the form to reality. It has been a pleasure for the author to share the able companionship of Mr. Ben Abington and Mr. Ralph Jones in the writing of the SMP program.

Others too numerous to mention from the Alvarez group, the support groups at the Radiation Laboratory, and the University of Illinois have contributed their special talents to the SMP, with uniformly gratifying results.

A special word of thanks goes to the International Business Machines Corporation, for its partial grant of the IBM 709 computer to the Radiation Laboratory for the development of the SMP and other advanced data-analysis systems.

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APPENDICES

A. The Bench-Mark Covering Problem

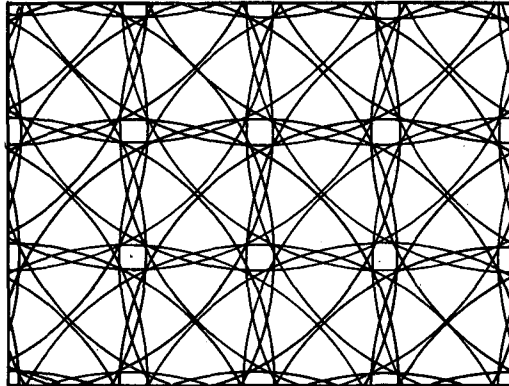
As described in the text, the circles of radius R about each bench mark are the loci of digitization of points in the SMP image plane. The pattern of circles corresponds to the raster on a flying-spot device, which determines where information can be gathered. It is important that the "raster" of circles on the SMP cover the image plane as uniformly as is possible.

If we assume a square grid of bench marks, the SMP raster pattern is a function of only one variable, namely:

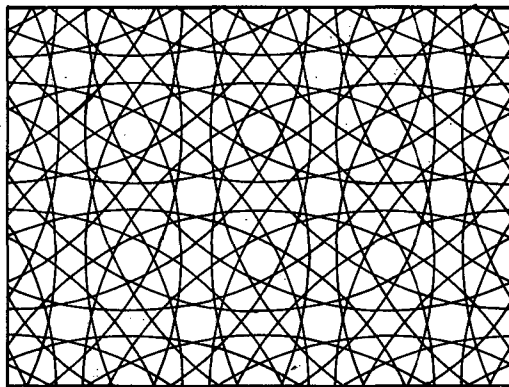
$$\frac{\text{Radius of circles}}{\text{Distance between bench marks}} = \frac{R \text{ cm.}}{1 \text{ cm}} = R.$$

The patterns for different values of R are shown in Fig. 7. The most obvious indications of poor values of R are the dense clusters of circles and large blank regions, or gaps, as in the pattern for R = 2.10.

After a short study of the problem by Dr. William Humphrey and the author, Dr. Humphrey wrote a computer program to investigate the uniformity of bench-mark covering.^{4g} This program examines the rasters for different values of R, and searches for large gaps in which line segments may fall without intersecting the raster pattern. By using this program, values of R giving maximum uniformity of covering were found to be 2.40, 3.48, and 4.39 (cm). The value of R = 2.40 cm was then incorporated into the SMP periscopes. Although arbitrarily large values of R are theoretically possible, and would lead to a greater density of covering of the image plane, problems of periscopedrum design and diverging light path in the periscope limit the acceptable size of R. The value R = 2.40 cm produces a pattern of circles with an average of nine digitizing intersections per cm with a randomly oriented straight line.



R = 2.10



R = 2.40

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Fig. 7. Bench mark patterns for R = 2.10 and R = 2.40.

B. The SMP Track-Filter Program

In the existing SMP track-filter program, an approximate fit to the track is made with a parabola.^{5h} Each coordinate pair (X, Y) is transformed to new coordinates, which are the distance along the parabola (Z) and perpendicular to it (ZZ). The transformation to new coordinates eliminates the problem of dealing with tracks of arbitrary orientations.^{5b} At the same time, the parabola is "straightened out" in the new coordinates, so that the track lies nearly along the Z axis. Thus, a histogram in ZZ corresponds to a servo-centering slit aligned nearly along the track.

The points (Z, ZZ) are next ordered with respect to Z, since Z represents the distance along the track. Each point receives a "tally" telling how well it corresponds in the ZZ coordinate with its 10 nearest neighbors in Z. The tally is a form of the histogram described in the text, and is analogous to the strength of the signal received from the servo-centering slit as it passes over the point in question. The higher the tally, the greater the indication that the point is part of a curve in the Z direction.

The filter program then progresses along the track, starting either at a previously measured vertex or at the point with the highest tally. In a region of the track ahead, the program examines each point with a criterion involving both the tally for the point, and how well the point lines up with the projected extension of the track. The point best satisfying this criterion is selected as a stepping-stone point, and the program looks beyond it to the next region. When such stepping-stone points have been found up and down the length of the track, they are all considered to be points actually on the track.

The program then constructs a narrow band from each stepping-stone point to the next, and all digitized points lying in these bands are taken as being on the track. The selected points are averaged in groups of 10, to increase the accuracy and to produce the lesser number of output points. The points are averaged in the (Z, ZZ) coordinates, in which the track is nearly straight. Thus, there is no "sagitta error"

in finding the centroid, as there would be in finding the centroid of the coordinates (X, Y). The (Z, ZZ) coordinates of the averaged points are then transformed back to (X, Y) for output.

In various stages of the calculations described above, tests are made to see whether the data exhibit certain standards expected of measurements. If the data fail one of these tests, the track-filter program returns to the SMP program (and thence to the operator) an error comment indicating the nature of the deficiency in the data.

Three factors guided the author in the development of the present track, vertex, and fiducial filter programs. First was the requirement that the programs perform reliably, as evidenced by direct examination and the results of production measuring. Second was the ever-present consideration of program speed. Floating-point operations, typically slow, were eliminated from the SMP program entirely. Only six multiplications per coordinate pair were allowed, this being the bare minimum necessary to transform from (X, Y) to (Z, ZZ). The rest of the operations on individual points are faster operations in the computer: addition, subtraction, and logic.

The author's third guide was a feeling that the filter program, in its pattern-recognition aspects, could profit from analogy with the former system for measuring bubble chamber film--the projection microscope and man. The similarity of the tally procedure with the servo slit of the projection microscope has been described. Our knowledge of man's neural system is so limited that our understanding of his pattern-recognition processes is at best incomplete and intuitive. One of the intuitive hypotheses guiding the author is a doctrine with its roots in Gestalt psychology: that the perception of patterns depends strongly on the characteristics of the pattern as a whole; in other words, on the interrelation, rather than the individualization, of the pattern's elementary parts.

Thus, in the filter programs, a consistent effort was made to defer absolute decisions until the widest range of data was incorporated into the decisions. The small decisions were kept as "fuzzy" as possible until they were blended into the final decision, where a sharp line

must be drawn. This approach appears in the track filter program in the decision not to segregate the data points into groups, in the tally concept (a numerical ranking rather than a yes-or-no decision whether a point is on the track), in the blending of the tally with the distance from the projected track line, and in the deferral of the final selection of track points to one step even past the criterion step.

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