An Analog-Digital Simulator for the Design and Improvement of Man-Machine Systems*

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UNDER sponsorship of the Aero Medical Laboratory, Wright Air Development Center, the National Bureau of Standards is designing a simulator facility for research on man-machine systems. The facility is specifically intended to enable experimentation with man-machine control systems such as those for air-traffic control, ground control of interceptors, and command systems in general. The facility is to be equipped for the dynamic representation and simulation of control systems which have human operators as elements of the closed loop. The present work has included the construction of a prototype of the essential elements of a complete simulation facility. This paper presents some design considerations peculiar to this class of simulator, describes the present prototype, and indicates refinements which might profitably be incorporated in the final facility.

The prototype facility incorporates the basic capabilities required for the final simulation facility. The construction of the prototype was intended to serve three important purposes. The first was to deal with technical and economic problems which could be neither properly anticipated nor adequately resolved simply by means of a "paper study." The second was to achieve a better basis on which to specify the facility and estimate the costs of implementation, operation, maintenance, and expansion thereof. The third was to test the utility of the specified facility through application of the prototype to the resolution of one or more of the important issues being faced in current development of systems. The desired capabilities have been provided by combining analog and digital techniques in a manner intended to minimize the requirements for equipment. The equipment includes general-purpose computers, both analog and digital, which may be used independently for the more conventional kinds of simulation and for data reduction.

Simulators have become recognized as an essential tool for research on and development of automatic systems; and the present effort is directed toward extending the application of this tool for research and development of semi-automatic systems. A simulator which permits dynamic as well as operational analysis of a system enables prediction and optimization of the performance of that system in a laboratory. The alternative to simulation is to build the proposed system and carry out extensive testing and modification programs. In the case of complex man-machine systems, the latter procedure is generally prohibitively expensive and time-consuming, and the results are often inconclusive due to the inability to control important experimental conditions in the field. However, the problem of predicting human performance in man-machine systems confronts laboratory simulation as well as system design and field testing. Aside from human factors, the chief difficulty has been to obtain detailed and accurate mathematical statements of the system functions to be performed by the human operators. Simulation forces an objective and quantitative examination, in the laboratory, of the information flow between the man and the machine; it also requires that the human operator be placed in the closed loop if maximum confidence is to be placed in experimental results. This complication, together with the general complexity of the systems of interest, gives rise to a number of requirements which are peculiar to the design of a facility for the simulation of semi-automatic systems.

There are a number of distinctive requirements which characterize a simulator for research on man-machine systems and make it different from one designed for the study of automatic systems. The simulator must be capable of operating in real time, since human operators are to be included as parts of closed loops in the model of the system. Inclusion of the human operator also introduces requirements for coupling the operator to the simulator in such a manner that his performance will be comparable to that in the system being simulated. It is thus necessary to provide appropriate means for presenting information to the human operator and for the acceptance of his responses. Since the configurations of both displays and controls will be as variable as the operations to be studied, the general-purpose computers must be equipped for convenient connection to a variety of special-purpose equipment which more or less duplicates the operator's work space. Human variability precludes exact repeatability of measurements and requires extensive use of statistical methods in analyzing experimental results. Furthermore, special provisions must be made for the automatic handling and reduction of the large amount of data which are produced by statistical procedures. It is also desirable to incorporate equipment for effective qualitative monitoring of experiments so that exploratory or pilot runs may be employed to limit the amount of data which must be quantitatively analyzed. Since practical considerations limit

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the amount and capacity of simulation equipment, it is often necessary to partition a complex system and simulate only a portion thereof. Such partitioning must be accomplished so as to permit a valid integration of partial results. Since the human operator is extremely nonlinear, superposition does not apply. Hence, care must be taken, when partitioning the system, so that features of the human environment, not directly a part of the control loop under study but possibly affecting that loop significantly, are included in the simulation. Man-machine systems of any appreciable complexity usually include one or more sampled-data control loops; therefore, the facility must include the capability for simulating sampled-data systems. Finally, these requirements must be met while keeping the cost and complexity of the equipment at a minimum.

While the NBS staff has had considerable experience with the simulation of automatic control systems, it possessed but a superficial understanding of the principles and methods of experimental psychology which apply to the simulation of man-machine systems. Therefore, it was necessary to draw heavily upon the experience of groups such as the Psychology Branch of the Aero Medical Laboratory and the Engineering Psychology Branch of the Naval Research Laboratory. The assistance of these groups has been invaluable in converting the requirements of the bioscientists into specifications for simulation equipment. Their contributions are best manifested in the specialized operator work-spaces which have been constructed. Both an interceptor cockpit and an assembly of ground-display equipment incorporate a number of alternative techniques for presenting information to the operators and accepting their responses. The individual features of these work-spaces have been adopted from a number of different systems which are either presently in operation or in the final stages of development, and these features are among those which the psychologists feel to be especially significant. For example, it has been pointed out by the psychologists that the statistical deviations encountered in experimental psychology can be greatly reduced by having each subject serve as his own standard of reference. The accomplishment of this purpose in a system simulator requires the capability for rapidly changing system parameters which include the nature of operators' displays as well as the more conventional boundary conditions and stability parameters.

The foregoing requirements are reasonably well satisfied by the prototype which has been set up at the National Bureau of Standards. The effort to achieve maximum flexibility, economy, and convenience of operation has strongly influenced the functional organization of the simulator, the choices of the techniques employed, and the manner in which they have been integrated. The major pieces of the equipment which comprise the prototype can be functionally divided into five categories as follows: 1) general-purpose electronic computers which operate upon a mathematical model of the system under study; 2) operators' work-spaces which are appropriately fitted for integration of the man with the system being simulated; 3) equipment for centralized control and monitoring of the experiment; 4) equipment for automatic recording of data on the chosen evaluation criteria; 5) devices required for interconnecting the several major components of the prototype.

It was initially decided that both analog and digital computers would be required in order to handle effectively the mathematical models of complex systems. Considerable importance was attached to the apportionment of computing tasks between the analog and digital computers. It was believed that significant economies could be obtained with little loss of flexibility by arbitrarily exploiting the rather complementary advantages of the two types of computers. We have used analog computing equipment for those tasks which we believe can be handled best by analog computers, such as accepting continuous control information, solving complex dynamic equations in real time, and activating conventional display devices. The digital computer has been used for tasks which we believe can best be done by digital computers, such as the control of the experiment, the precise generation of open-loop data, calculations of high precision, handling of variables requiring large dynamic range, storage of data, and statistical analyses of the recorded data. Since the minimum sampling period which can be used in simulation cannot be shorter than the basic cycle of computation of the digital computer, that computer should not be used for calculations which can readily be done elsewhere in the simulator. Hence, all calculations involving the solution of differential equations in real time, such as the solution of the dynamic equations of motion of the airplane, are done on analog equipment. Thus, there is no need for approximating such equations by finite difference methods as would be required if calculated digitally. The requirements upon the speed and size of the digital computer and converter equipments are reduced enormously by confining the solution of differential equations to the analog computer. The price of this economy is the loss of the extreme digital accuracy. However, this loss is believed to be trivial, since there are very few applications which are known to require better than analog accuracy of the dynamic calculations, since the accuracy of solution has but a minor effect upon closed-loop performance.

The ground-controlled interceptor problem has been chosen for the first experiments, since it is an important example of a high-performance sampled-data system which employs human operators as components in a variety of control loops. A relatively comprehensive simulation of this problem has already afforded a fairly severe measure of the capabilities of the prototype. Indications are that the present facility has the capabilities required for the effective study of many other systems of interest, such as air-traffic control, ground-controlled approach and landing, weapon assignment, and certain classes of missile guidance. However, the specificity of the operator's work-

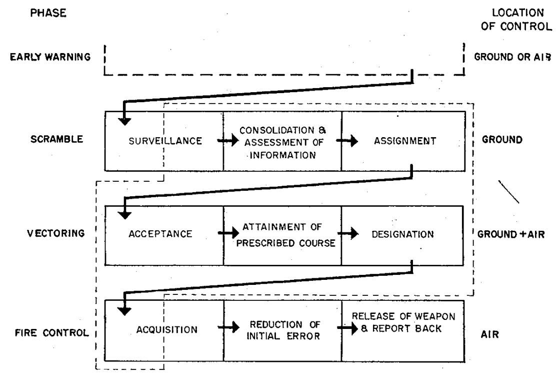

Fig. 1—Ground-controlled intercept system.

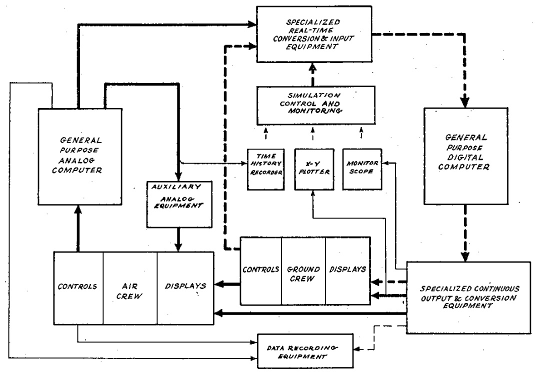

Fig. 2—Man-machine systems research simulator.

spaces limits the number of immediate applications of the present facility, and the ease of adaptation to other applications is closely related to the complexity required of the displays and controls to be added.

For our current experiments, we are simulating a class of systems which encompass a five hundred-mile-square air space populated by a number of target, interceptor, and civilian aircraft which are under the surveillance of search radars. In these systems, coordinate data from the radars are placed in an electronic store either automatically or by means of manual tracking. An operator then correlates these with aircraft identity and other descriptive data. Means are provided to enable him to evaluate the air situation and assign target-interceptor pairs. The assigned interceptor might be manually vectored by voice or data link, manually tracked and automatically vectored, or placed under fully automatic control of a ground computer. Ground-control instructions are presented to the pilot of a high-speed interceptor who controls his aircraft so as to arrive at the correct position and heading for attack upon the selected target. The ground-controlled interceptor system is shown diagrammatically in Fig. 1. The parts of the system that can be simulated on the experimental facility are outlined by the dotted lines in the figure. Following the arrows in the diagram, this includes surveillance, consolidation and assessment of information, assignment of interceptors to specific targets, the acceptance of the assignment by the interceptor, the interceptor pilot's attainment of the prescribed course, the designation of the target to the interceptor pilot and the acquisition of the target by the pilot.

The experimental setup is shown in block diagram form in Fig. 2. Dotted lines represent the flow of digital information and solid lines the flow of analog information. The system includes a general-purpose electronic analog computer, a general-purpose digital computer (SEAC), a ground crew with associated displays and controls, an air crew with its displays and controls, and specialized equipment for computer inputs and outputs, for control of experiments, and for recording of data.

First, let us consider the digital loop on the right side of the diagram. This includes the items connected by heavy dotted lines—the general-purpose digital computer, the specialized continuous output and conversion equipment, the ground crew with associated input displays and output controls, and the real-time conversion and input equipment. This loop carries all information going to and from the ground crew, with the exception of voice communication and analog vectoring information to the cockpit. Data on raid size and on the position, identity, size, speed, altitude, and combat status of all aircraft are stored in the digital-computer memory, one 44-bit word containing the complete set for each aircraft. The displays of the ground crew comprise two large cathode-ray oscillographs on which the aircraft-position pips are presented on a continuous synthetic PPI display, and an electronic status board on which the description of any aircraft may be displayed. The ground crew's control equipment includes a joy stick by means of which a small circle may be placed around any selected pip, a light pencil which may be placed upon any desired pip on the scope, a descriptor key set, and means for selecting the desired mode of operation. The ground crew's control console is shown in Figs. 3 and 4. In Fig. 3, the status board is seen between the scopes, the key set at the lower left, the joy stick at the lower right, and the selector switches in the center foreground. In Fig. 4, the light pencil is being held up to the master scope. Provision is made so that on the second scope, any desired part of the entire area displayed on the first or master scope can be magnified up to 32 times. The part magnified is selected by using the joy stick to move a circle of adjustable area about the master display. Information stored in the digital computer concerning the status of any aircraft can be presented on the status board by using the light pencil, the joy stick, or the flight number designator switches. The data thus displayed can be modified as required by means of the keyset, and the modified data can then be introduced into the digital computer by use of a master key. The keyset can be alternatively used to brighten the pips which represent aircraft falling within the designated ranges of altitude, speed, size or identity.

Let us now consider the analog loop at the left of the diagram of Fig. 2. This loop includes the general-purpose analog computer, auxiliary analog equipment, and the air

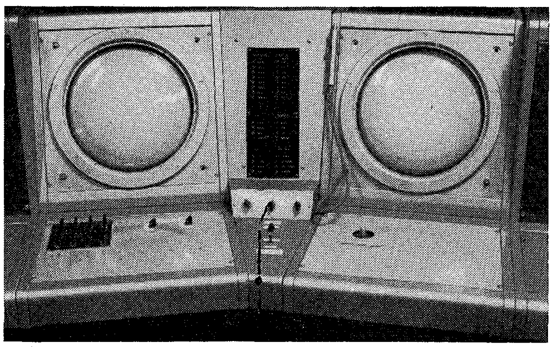

Fig. 3—Ground-control console.

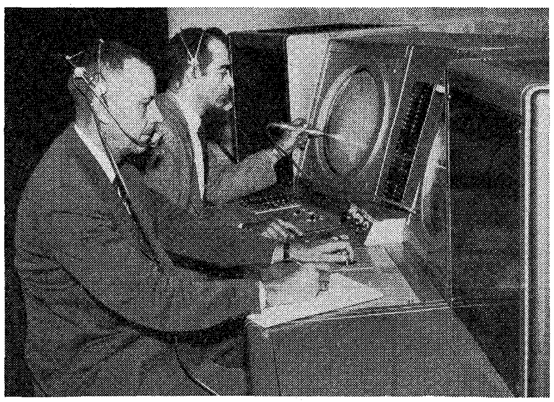

Fig. 4—Ground crew at console.

crew together with its input displays and output controls. The lower left-hand box represents the cockpit of a modern, high-speed, interceptor aircraft, with its instrument panel, joy stick, throttle, and rudder pedals. A view of the interior of the cockpit showing the instrument panel and controls is shown in Fig. 5. Displacement of the controls applies dc input voltages to the analog computer. The dynamical equations of motion of the aircraft are solved in the analog computer in real time. Voltage outputs proportional to such quantities as angle of roll, pitch, and rate of climb are converted by the auxiliary analog equipment to syncho rotations, which are used to drive the flight instruments in the cockpit. Both flight and navigation instruments are shown; the latter are used to present vectoring information from the ground control. Navigation information may be presented on either of the compasses, the ILS indicator, or upon the cathode-ray tube.

Let us now turn to the box in Fig. 2 labeled "simulation control and monitoring." The experiment is specified and modified according to the settings of a series of selector switches and knobs on a control panel. The settings of these switches determine such items as the radar scan period, the tactics, the mathematics of the intercept control computation, the navigation constants, the control lags, the limiting quality of data to be used in the control computation, and the data-smoothing procedures. A view of the experimenters' control panel is shown in Fig. 6.

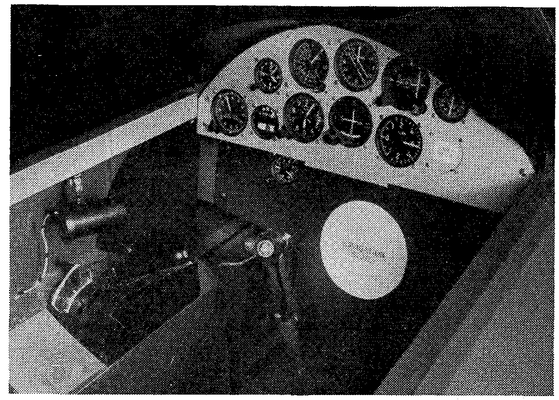

Fig. 5—Interceptor cockpit.

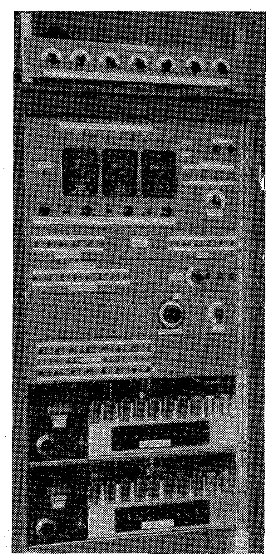

Fig. 6—Experimenters' control panel.

Let us now consider the combined analog-digital loop in which the interceptor is controlled to arrive at the correct position and heading for attack upon the target. The velocity components of the interceptor aircraft obtained from the analog computer are converted to a ground-reference system, integrated over one scan period of the radar to yield incremental position components, and converted to digital form. A specialized equipment called a "format synthesizer" receives the following inputs in digital form: 1) the position increments of the interceptor; 2) the information stored in the positions of the switches and knobs on the experimenter's control panel; and 3) the output information from the ground crew, such as the positions of the joy stick and the switches in the key set. The format synthesizer organizes the data into computer words, and serializes them for direct entry into the digital computer. In the simulation of the ground-aircraft control loop, the digital computer has three jobs to do: 1) update the position of the controlled interceptor once during each sampling period of the system; 2) generate the trajectories of all preprogrammed aircraft; and 3) provide interceptor course data in simulation of the control computer.

Readout from the digital computer, SEAC, is concurrent with calculations and proceeds in an uninterrupted series of cycles. Output information is then routed to the various display devices where the selection of the desired information is accomplished. This readout procedure makes possible the display of information when desired without requiring special instructions for the digital computer. The specialized output equipment consists of a "staticizer" which is connected to twelve tanks of the acoustic memory in each of which are circulating eight words, each containing 44 binary bits which represent all of the data on one aircraft. Every ninth word is read out, which causes all words in the tank to be read out in succession at 432-microsecond intervals. At the option of the experimenter, the output cycle may be set to any number of tanks from one to twelve. The shortest output cycle will consist of 8 words repeated about 280 times per second, and the longest output cycle will consist of 96 words repeated approximately 24 times per second. In each word, two blocks of 10 bits each are connected, respectively, to two digital-to-analog converters. The resulting series of analog voltages go to a switching system which distributes them in a predetermined sequence among display equipments, plotting boards, and graphical recording equipment.

When the staticizer is reading out from that part of the memory which stores the position coordinates of aircraft, these voltages are connected to the plan-position indicators which display the location of all aircraft to the ground crew. The remaining 24 bits (those not connected to the digital-to-analog converters) contain the complete description of whatever aircraft is represented by the associated pair of coordinates. These bits are used for the selected gating of the aircraft to be displayed as well as for activating the electronic status board.

A study of the evaluation of the air situation and manual assignment of aircraft as interceptors or targets may be accomplished through use of the master key, while the equipment is alternatively switched between the "interrogation" and "assignment" options of operation. When the simulator is used for ground control of an interceptor which has been assigned for attack on a specific target, the digital computer operates on the position data of these aircraft, provides simulated degradation and smoothing, calculates the information necessary for attaining the prescribed course, and relays this information to the interceptor where it is displayed on the pilot's instrument panel. If manual tracking and automatic control is to be simulated, the ground crew manually tracks the target and the interceptor with the joy stick, and the digital computer uses this data to calculate the information necessary for attaining the course. The pilot receives the information directly from the computer as before.

The advantage of using a digital computer, when the dynamic range of the variable is large, is illustrated here. Assume that the analog voltage which represents the interceptor velocity is converted to a 10-bit code in which the least significant digit is made equal to one yard per second. With an interceptor velocity of 500 yards per second, a displacement of 1,000,000 yards or about 500 miles would be produced in about 33 minutes. To maintain the above resolution and permit this not unreasonable range, at least 20 bits must be provided in the position registers. It would not be possible to integrate over long periods of time to the resolution required here by means of electronic analog computers, because of noise and amplifier drifts.

Considerable attention was devoted to providing for convenient and effective utilization of the facility. One feature that has been emphasized is the ability to modify experimental procedures and vary system parameters rapidly and conveniently at the control panel. The experimenter, who may be either psychologist or engineer, does not have to be greatly concerned with programming difficulties, since changes in the experiment are made by turning knobs or throwing switches on the control panel which modify computer instructions, change system parameters, and control the selection of program subroutines. This avoids the need for frequent reprogramming of the digital computer, with the attendant experimental delays and costly programming staff.

Due to the variability of human performance, a facility intended for research on man-machine systems is likely to produce large quantities of experimental data. The provisions for data handling and data reduction require particular attention in order that an experimental investigation may be properly directed and that conclusions may be reached promptly. The requirements for data reduction may be divided into three categories: 1) that which must be performed concurrently with the experimental run to enable necessary monitoring and control; 2) that which should be accomplished between runs of a single experiment; and 3) that which is performed after the experimental investigation has been completed. It is desired to minimize the requirement for concurrent data reduction since the combining of simulation and data reduction would serve to increase substantially the requirements for size and speed of the computing equipment. Therefore, special provisions have been made for the recording of appropriate measurements as the experiments proceed. These data are recorded on magnetic tape in digital form. Data may thus be re-evaluated as new methods of analysis are developed, and the results may be compared with equivalent analysis of subsequent experiments.

For data in categories 2) and 3) above, experience has shown that the bottlenecks in the reduction process are due to computer input rates rather than to computation speed, since a large volume of data is produced which requires relatively little manipulation. In most computers, as with SEAC, provisions for reading from auxiliary storage are the fastest of the conventional input means. Among the available storage media, magnetic tape offers the advantage of being separable from the computer for purposes of both preparation and filing. Hence, the auxiliary magnetic-tape storage system of the computer was chosen as the input medium. The basic requirement is that optimum use of the tape be made, consistent with the tape-reading speed of the computer itself. It is also desirable that the data be organized on the tape in appropriate computer language so as to avoid the need for using computer time for data reorganization. Since both simulation input and direct recording must proceed concurrently, a second format synthesizer is used for the direct-recording system. Recorded data takes the form of information blocks which correspond to an 8-word tank, having capacity for 16 variables of 20 bits each. The recording frequency has been made variable from ½ to 32 cycles per second, in binary increments. It is expected that the computer will be programmed to call for one or more tanks of data at a time, but since the exact number cannot be predicted, space for stopping and restarting the tape is allowed between the recording of each tank of data. As a result, the information density is somewhat less than optimum, but still permits reading 20-bit data points into SEAC at the rate of 1200 points per second.

It should be re-emphasized that the configuration which this research tool might take ultimately should not be identified with the organization of the equipment which constitutes the prototype facility at NBS. We have been assembling only the essential elements of a facility in order to provide specific information about the functions and performance characteristics required in a versatile system simulator, to clarify some of the equipment problems relating to a general study of man-machine systems through the use of simulation, to enable a more judicious specification and a better estimate of cost, and to serve as the basis on which the detailed design and procurement of such a facility could proceed. Although we have used the ground-controlled intercept as an example, the facility is equally well adapted to other systems of interest, such as air-traffic control, missile assignment and guidance, and other complex systems involving human beings in the control loop. To simulate other systems, the basic equipment connecting the analog and digital computers would remain the same. The changes required would involve modification of the human operators' input displays and output controls, the patching of the analog computer, and the programming of the digital computer.

As has been indicated, one of the chief purposes for building a prototype simulator was to gain essential experience. Although the assessment of the prototype is not yet complete, some of the more important points thus far noted are discussed below.

The analog computer which is incorporated in the prototype is relatively modest. However, it is adequate since it is believed to be both appropriate and sufficient to limit the dynamic simulation to the flight realm which is pertinent to the control system under examination. While it is always desirable to have plenty of computing units, it is of particular interest to note the kinds of computing elements needed for the present class of simulation and the minimum number of each of such elements:

Operational amplifiers and integrators	50
Multipliers	15
Servoresolvers and nonlinear units	6
Electronic function generators	10
DC voltage to synchro output	12 or more

It might be noted that the number of synchro outputs is governed largely by the display requirements in the operator's work-spaces.

The SEAC has been found to have sufficient operating speed and memory capacity for a rather wide range of simulator applications. However, it must be remembered that this capability was achieved only by very circumspect use of the digital computer in combination with the analog computer. It is believed that a computer with somewhat less capability than SEAC could be profitably employed for system simulation; however, it presently appears that a well-balanced facility would incorporate a digital computer with substantially greater capability than SEAC. It is preferable that the computer employ binary arithmetic; have a word length of about 36 bits; and be equipped for completely concurrent input as well as output.

The concurrent output presently employed in the prototype appears to be very satisfactory in concept. The principle of having each display console set up to take only the desired information from an endless-belt flow of data is in contrast to the principle of externally directing the computer to supply the specified data. The endless-belt approach enables the modular addition of display consoles to an output "bus bar" of uniformly high output efficiency. Implementation of this approach, however, requires that each such console be equipped with its own selection logic and also requires that more bits of coded data be available in each of the output sets. An output set of two 36-bit words would be preferred to the single 44-bit word available from SEAC.

Perhaps the greatest room for improvement exists in the present provisions for real-time input to the digital computer. Before discussing this matter, it should be noted that there appears to be no real need for the digital computer to be able to read from the memory locations where output data is stored, and, conversely, no need for the computer to be able to enter data into the storage reserved for real-time input. These conditions greatly facilitate the provision of means for truly concurrent input and output. The present input equipment enters data through the regular input-shift register of the SEAC and is therefore not concurrent. This circumstance arose because it was expedient to adapt the solution of the direct recording problem to the real-time input problem. The chief shortcomings are that all input rates are slaved to the selected system sampling rate without means for aperiodic or sporadic input, which is very costly of time. It would be preferable to