SAGE—A Data-Processing System for Air Defense

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The paper is adapted from a presentation at the 1957 Eastern Joint Computer Conference. The authors give details of the Semi-Automatic Ground Environment (SAGE) system and how it developed.

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Editor's Note

The definition of the SAGE system evolved from the Air Defense Systems Engineering Committee (Valley Committee) concept through many modifications as Lincoln Laboratory, the other contractors, and the U.S. Air Force faced fiscal, technical, and operational realities. By 1956, the definition of the design of SAGE was substantially fixed; most of the critical subsystems had been tested in either the Cape Cod System or the Experimental SAGE Sector. Adequate money was available. The prime contractors were able to predict how long it would take to do their jobs. Instead of writing a new paper on the definition of the design of SAGE, we have chosen to reprint a paper written in 1957, the year before the SAGE system became operational. The paper describes SAGE and all its subsystems as it was understood at the time.

By 1957, some of the SAGE direction-center buildings had been built and some of the subsystems had been installed. The System Program Office was functioning effectively, and all the participants had planned their actions according to a master schedule prepared by the Air Defense Engineering Services Project Office. The following paper was presented at the Eastern Joint Computer Conference in December 1957 in Washington. Changes made in the system after that time were generally those required to adjust (cut back) the system to match the available monies and to correct for the overestimates made by the designers. The changes also reflected the declining priority of air defense, the growing awareness of the need for integration, and the mechanisms set up to control the evolution of the system. Nevertheless, the paper is an excellent description of the system that was initially deployed.

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The Requirement of SAGE

The past decade has shown an increase in the air threat to this country to an extent that has outdated manually coordinated traffic-handling techniques and manual data processing. General Earle E. Partridge, Commander-in-Chief, North American Air Defense Command, stated (*U.S. News & World Report*, 6 September 1957) the need for a defense system that is prepared to work instantly and that will blanket the entire United States. Until recently, we have relied on an air-defense processing system whose traffic-handling techniques were almost identical to those used during the Second World War. Fortunately, there has been substantial improvement in our inventory of automated air-defense *components*. These include improved radar systems, automatic fire-control devices, navigational systems, and both missiles and manned aircraft of high performance. But successful air de-

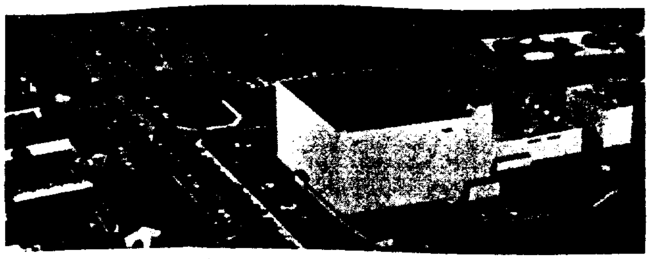

Figure 1. A SAGE direction center building contains power-generation and computing equipment, operational areas for directing sector operation, and office and maintenance facilities. Data are transmitted to this center both automatically and by voice phone. The center communicates with adjacent SAGE centers and transmits guidance data to weapons under its control.

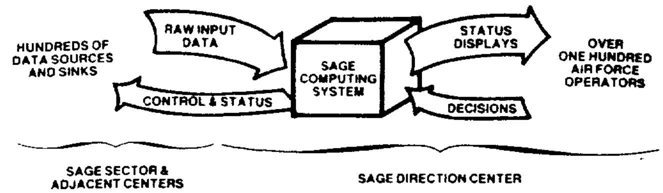

Figure 2. SAGE data processing. The direction center continuously receives input data from hundreds of locations within and without the sector. Some of these data are transmitted digitally over telephone lines and read directly into the computer; some are transmitted by teletype or voice phone and transcribed onto punched cards before input to the computer. In 1 second, over 10,000 bits of data representing hundreds of different types of information can be received at the direction center.

fense requires both good components and intelligent utilization of these components. More important, intelligent commitment of new weapons requires up-to-date knowledge of the complete enemy threat and of the success of weapons already committed.

The air-defense data-processing problem is one of nationwide data-handling capability: facilities for communication, filtering, storage, control, and display. A system is required that can maintain a complete, up-to-date picture of the air and ground situations over wide areas of the country; that can control modern weapons rapidly and accurately; and that can present filtered pictures of the air and weapons situations to the air force personnel who conduct the air battle.

The Semi-Automatic Ground Environment System—SAGE—was developed to satisfy these requirements. SAGE is a large-scale, electronic air-surveillance and weapons-control system and is composed of three groups of facilities: those required to process and transmit surveillance data from data-gathering sources to data-processing centers; data-processing centers where data are evaluated and developed into an air situation and where weapons-guidance orders are generated; and communications facilities to transmit data to weapons, to command levels, to adjacent centers, and to other users such as the Civil Aeronautics Adminstration (CAA) and federal civil defense agencies. SAGE uses very large digital computing systems to process nationwide air-defense data. SAGE is a real-time control system, a real-time communication system, and a real-time management-information system. The basic ideas of this system resulted from the efforts of George E. Valley and Jay W. Forrester, both of MIT.

A large number of organizations have contributed to the development of SAGE since its conception in the Air Force and at MIT's Lincoln Laboratory. The International Business Machines Corporation (IBM) designed, manufactured, and installed the AN/FSQ-7 Combat Direction Central and the AN/FSQ-8 Combat Control Central including the necessary special tools and test equipment. The Western Electric Company, Inc. provided management services and the design and construction of the direction center and combat center buildings. These services were performed with the assistance of the subcontractor, the Bell Telephone Laboratories. The Burroughs Corporation manufac-

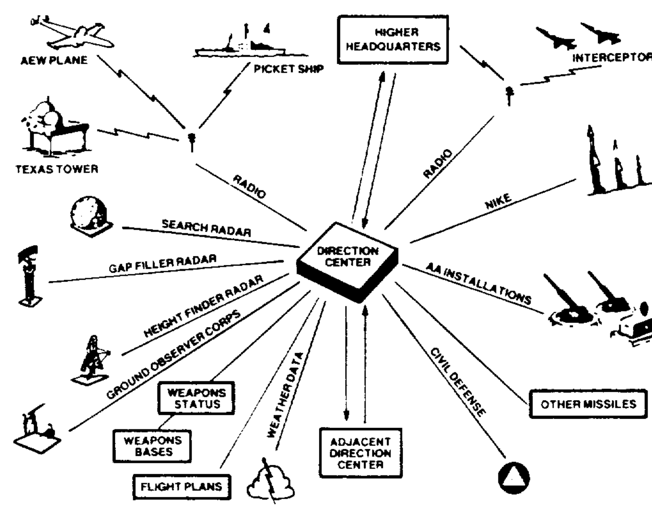

Figure 3. A direction center receives digitally coded data automatically and continuously from search radars and height finders over voice-bandwidth communications circuits. Data on flight plans, weapons status, weather, and aircraft tracks are received, respectively, from the Air Movements Identification Service (AMIS), weapons bases, USAF Weather Service, Ground Observer Corps, and airborne early-warning and picket ships over teletype and voice telephone circuits. Similarly, data from the direction center are transmitted in digitally coded form over voice-bandwidth communications circuits to ground-air data-link systems, to weapons bases, to adjacent direction centers, and to command levels; data to other users are transmitted over automatic teletype circuits.

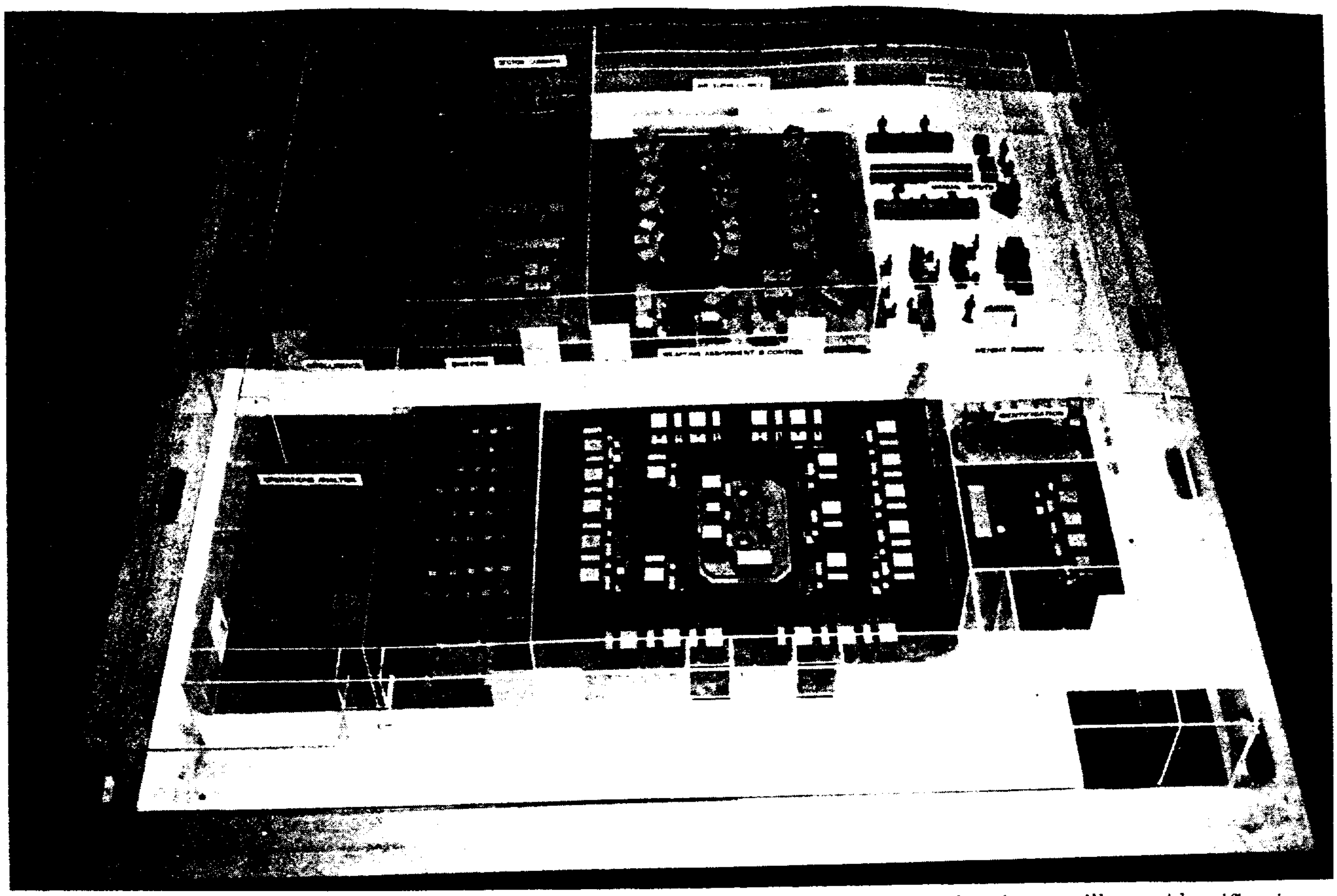

Figure 4. The fourth floor of the direction center contains separate operational rooms for air surveillance, identification, status input, weapons assignments and control, and command functions. Up to 50 operators are required in one room to man the consoles, which are directly connected to the computer.

tured, installed, and provided logistic support for AN/FST-2 coordination data-transmitting sets. The System Development Corporation (until recently a division of the Rand Corporation) assisted Lincoln Laboratory in the preparation of the master computer program and the adaptation of this program to production combat direction centers.

Sectors and Direction Centers

With SAGE, air defense is conducted from about 30 direction centers located throughout the United States (Figure 1). A center is responsible for air surveillance and weapons employment over an area called a sector. Each center contains a digital computing system—the AN/FSQ-7—containing almost 60,000 vacuum tubes. Over 100 air force officers and airmen within the center control the air defense of the sector. Most of these men sit at consoles directly connected to the computer where they receive filtered displays of the computer's storage of system-status data; they direct the computer through manual keyboards at each console. The Boston sector is typical; its direction center is located at Stewart Air Force Base in New York. Its area of responsibility extends from Maine on the north to Connecticut on the south and from New York on the west to a point hundreds of miles off the seacoast on the east.

The computer in the direction center can store over 1 million bits of information representing weapons and surveillance status of the sector at one time (Figure 2). These bits represent thousands of different types of information. For example, the computer generates and stores positions and velocities of all aircraft, or it stores wind velocity at various locations and altitudes. Within the computer, a program of 75,000 instructions controls all automatic operations; input data are processed, aircraft are tracked, weapons are guided, outputs are generated. Each second, the computer can generate over 100,000 bits of digital information for display to air force operator consoles. Each operator receives cathode-ray-tube displays that are tailored to his needs, and he may request additional information or send instructions to the computer by means of keyboard inputs on his console. Each second, the computer can generate thousands of bits of information for automatic digital transmission via telephone or teletype to weapons and missiles, to adjacent centers or higher headquarters, and to other installations within the sector.

Figure 5. Each operator sits at a console that contains display and input facilities tailored to his responsibilities.

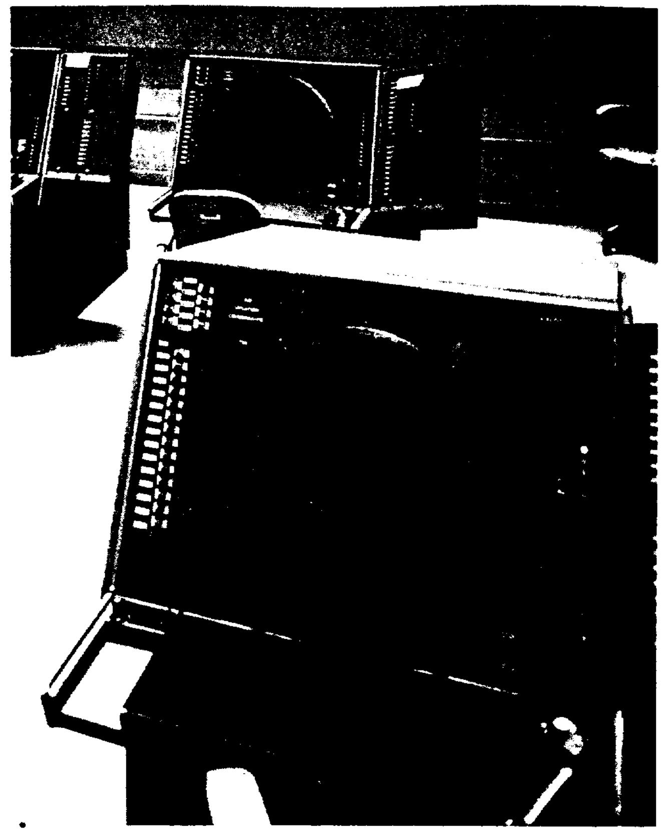

Figure 6. The operators insert data into the computer through keyboard actions.

How fast is this system? Obviously, response times from input to output vary with the task performed. Fastest response is required by automatic control functions (such as weapons guidance) and for man-machine communication (such as displays of requested information). For many of these functions, only several seconds are required from stimulus to response. For others, several minutes may elapse before the effects of new data are reflected throughout the system. We will now consider, in more detail, the three major areas that comprise SAGE data processing. First, the *sector* or *environment* that contains the data sources or sinks coordinated by the direction center. Next, the *man-machine component*—how the operators within the direction center are informed of the air situation and how they affect its progress. Finally, the *computing system* that performs the automatic component of the direction-center function.

The SAGE Sector

The direction center communicates with over 100 adjacent installations (Figure 3). Air-surveillance data are received from several types of radars. Long-range search and gap-filler radars located throughout the sector provide multiple coverage of the air volume within the sector; picket ships, airborne early warning (AEW), and Texas Towers extend this coverage well beyond the coastline; height finders supply altitude data. Within the direction center, these data are converted by the computer to a single positional frame of reference and are used to generate an up-to-date picture of the air situation. Other inputs to the direction center include missile, weapons, and airbase status; weather data; and flight plans of expected friendly air activity. Such data, which are received from many installations within and without the sector, are automatically processed by the computer and used by direction-center operational personnel to assist identification of aircraft, employment of weapons, or selection of tactics.

The direction-center computer communicates automatically and continuously with adjacent direction centers and command-level headquarters in order to ensure that air defense is coordinated smoothly between sectors and conducted intelligently over larger areas than a single sector. For example, an aircraft flies out of a sector; surveillance data from the center are automatically transmitted to the proper adjacent center in order to guarantee continuous tracking and

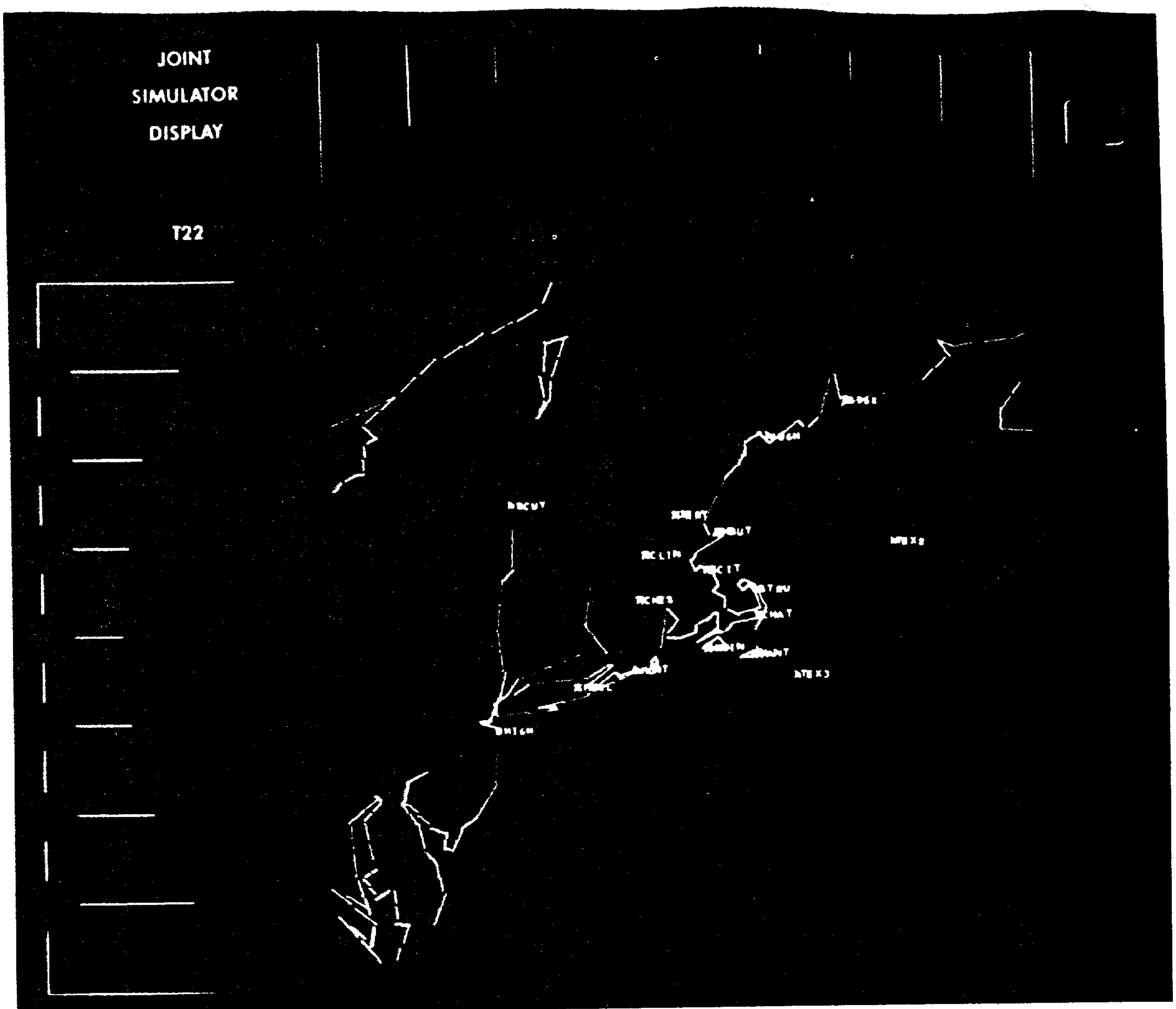

Figure 7. Situation display (on Charactron tube developed by Hughes Products Co.) of New England coastline and adjacent installations.

interception. In this way, adjacent centers are continuously warning, informing, and acknowledging. The final function of the direction center is to continuously transmit status, command, or guidance data to airborne interceptors and missiles or to related ground installations.

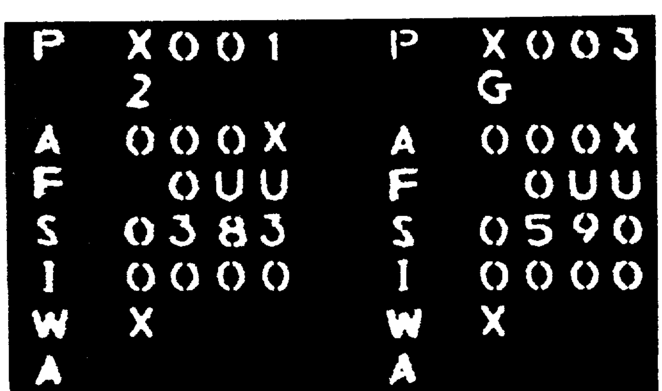

Figure 8. Typotron digital display (developed by San Diego Division of Stromberg-Carlson; formerly Convair Division of General Dynamics).

Three types of data transmission are used for both inputs and outputs. First, data sources or sinks that require high transmission rates communicate directly with the SAGE computer by means of digitally coded data transmitted at 1300 pulses per second over voice-bandwidth telephone lines and radio channels. Typical applications of this type of channel are inputs from search radars and intercommunication between adjacent centers. Teletype provides a second channel that is slower but equally automatic. Input flight plans are transmitted from Air Movement Identification Services. Finally, voice telephone communications are used in cases where high automaticity is either unnecessary, too expensive, or not feasible. If such information must be entered into the computer, either punched cards or operator keyboard inputs are used.

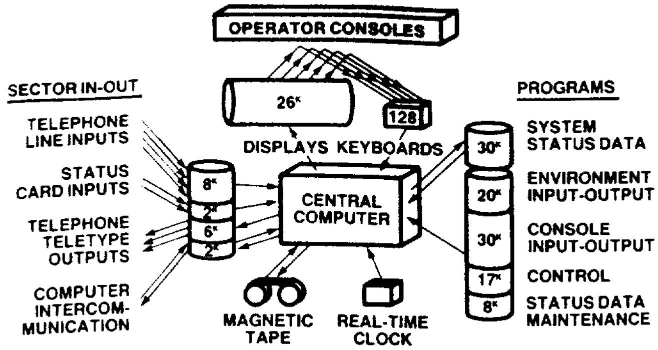

Figure 9. Each of two identical computers includes the central computer that performs all calculations, the 75,000-instruction air-defense program, and the millions of bits of system-status data. Both of the latter are stored on auxiliary magnetic drums.

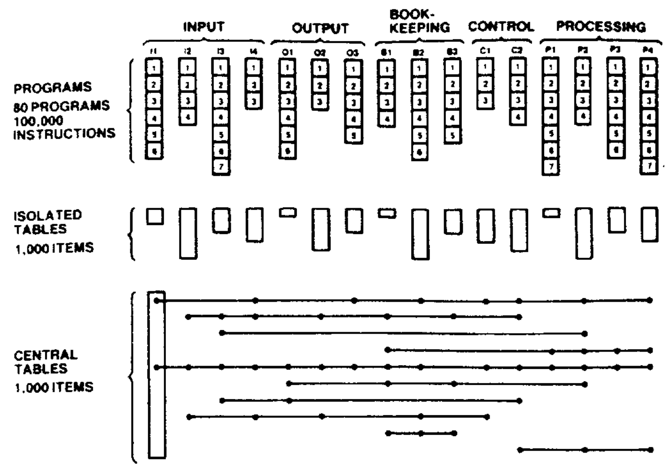

Figure 11. Static program organization.

All data sources and sinks in the sector operate asynchronously. Inputs from each source arrive at the direction center with very different average and peak rates. Each source is processed by the computer with a priority and sampling rate consistent with the role of the particular data in the overall air-defense function. Likewise, the computer generates output messages with a frequency and timing that will ensure adequate transmission of guidance and status data and yet will make maximum use of finite phone-line and teletype capacity. *One of the major functions of the SAGE computer is coordination and scheduling in real time of sector inputs and outputs with the manual and automatic functions performed in the direction center.*

The Man in the System

Although SAGE has made many of the data-processing functions in a direction center automatic, many tasks remain that are better performed by the man. Operators can relay computer outputs by phone or radio to adjacent installations and weapons; they can recognize certain patterns more rapidly and meaningfully than any of our present computers and take appropriate action. Most important, operators are required for tactical judgments such as aircraft identification or weapons deployment and commitment. If a major advantage of the FSQ-7 computer is its ability to maintain and store a complete picture of the sector situation, an equally important advantage is that the *same* computer can rapidly summarize and filter these data for individual presentation to the more than 100 air force personnel who both assist and direct air-defense operations.

The fourth floor of the center contains operational areas from which air force personnel supervise the computer and the sector. Each of the major air-defense functions—radar inputs, air surveillance, identification, weapons control, operations analysis, training, simulation, and sector command (Figure 4)—is supervised from a separate room.

Each operator sits at a console that contains display and input facilities tailored to his responsibilities (Figure 5). The operators insert data into the computer by pushing keyboard buttons (Figure 6). Each console is

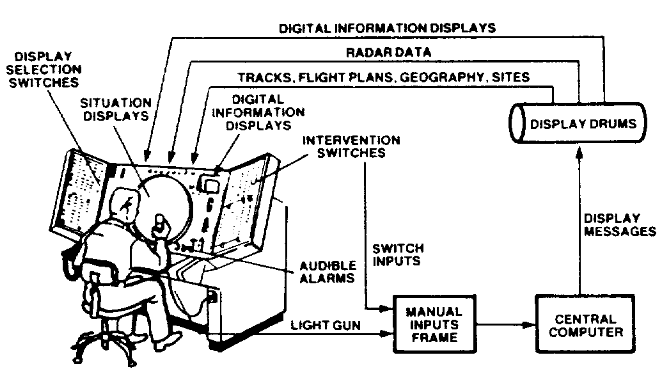

Figure 10. Major means of communication between automatic equipment and operating personnel.

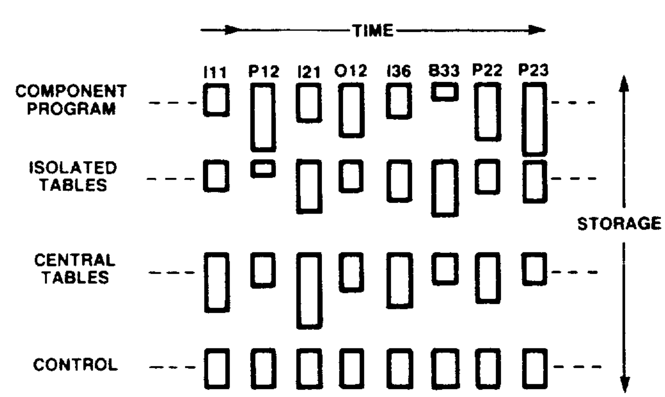

Figure 12. Dynamic program operation.

Figure 13. Digital data transmitted automatically to the direction center via telephone lines can be selected for insertion into the computer at an input patch panel.

provided with an input capacity to the computer of 25 to 100 bits of information at one time. The total keyboard input capacity for all consoles is over 4000 bits, which are sampled by the computer every several seconds.

A 19-inch Charactron cathode-ray tube displays geographically oriented data covering the whole or part of the sector (Figure 7). On this *air-situation display scope*, the operator can view different categories of tracks or radar data, geographic boundaries, predicted interception points, or special displays generated by the computer to assist his decision.

Every 2½ seconds, the computer generates about 200 different types of displays, requiring up to 20,000 characters, 18,000 points, and 5000 lines. Some of these are always present on an operator's situation display. Others he may select. Some he may request the computer to prepare especially for his viewing. Finally, the computer can force very high-priority displays for his attention.

The operator's console can also contain a 4-inch Typotron digital-display tube that is used to present status data such as weather conditions at several airbases or attention data that, for example, show the operator why the computer rejected his action (Figure 8). Sixty-three different characters are available in the Typotron. The FSQ-7 display system can display these characters at the rate of 10,000 characters every few seconds to all the digital display scopes.

SAGE Computing System

The SAGE FSQ-7 computer occupies the entire second floor of the direction center. About 70 frames containing almost 60,000 vacuum tubes are required to handle all input-output data, to perform air-defense calculations, and to store system-status data. In order to ensure round-the-clock operation, two identical computers are required. These are located on opposite sides of the floor with unduplicated input-output equipment and maintenance consoles situated in between.

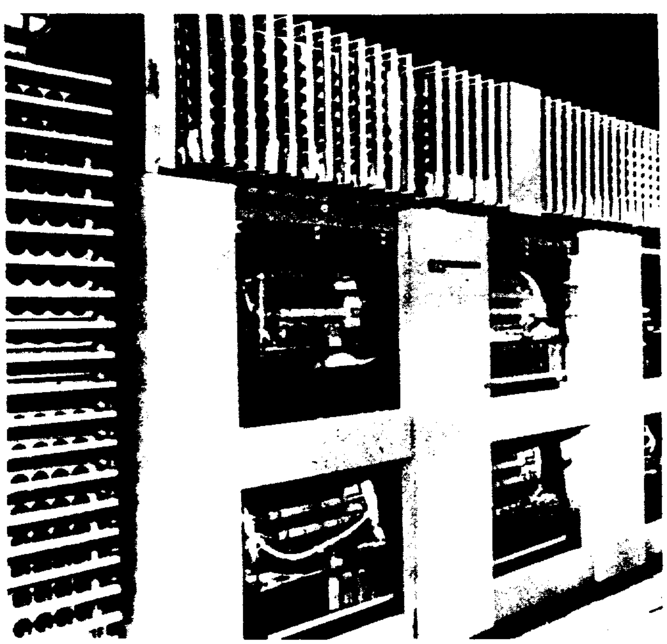

Figure 14. Magnetic drums are used for buffer storage of I/O data and storage of system-status data and computer programs. Twelve physical drums (six shown) have the capacity for almost 150,000 32-bit words. Half of this capacity is required for storage of the real-time program.

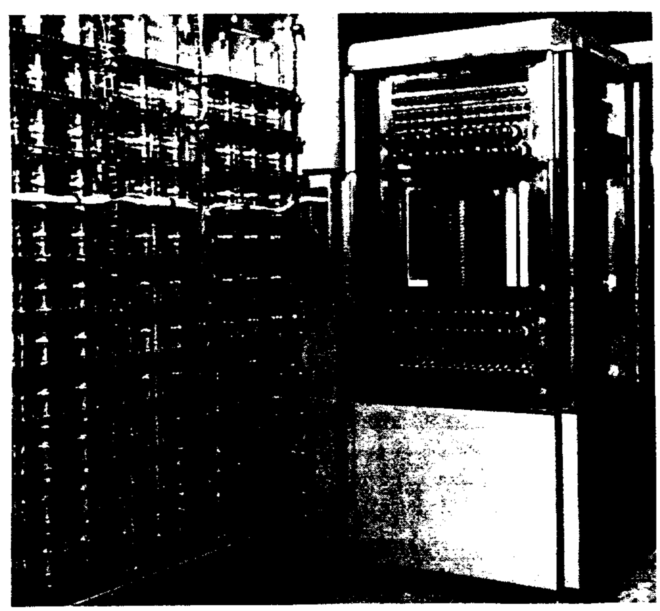

Figure 15. Magnetic core memory. The central computer is a binary, parallel machine with an 8192-word core memory and a speed of roughly 75,000 single-address instructions per second. Numbers representing positional data are stored and processed as vectors with two 16-bit components in order to facilitate processing.

Figure 16. Control console. Separate control consoles (including standard IBM punched-card equipment) and magnetic-tape units are provided for each of the duplexed computers.

Figure 9 shows the logical organization of one of the two identical computers. Since only one of these computers performs the real-time air-defense function at any one time, we can discuss simplex processing before considering the problems of duplex operation.

The computer system consists of the following major components: a central computer, the air-defense computer programs, and the system status data stored on auxiliary magnetic drums. The central computer is buffered from all sector and console in-out equipment by magnetic drums (except for the console keyboard inputs, which use a 4096-bit buffer core memory). Finally, a real-time clock and four magnetic tape units (used for simulated inputs and summary recorded outputs) complete the FSQ-7 system.

The *central computer* is a general-purpose, binary, parallel, single-address machine with 32-bit word length and a magnetic core memory of 8192 words. The memory cycle time is 6 microseconds. Each instruction uses one 32-bit word, and the effective operating rate is about 75,000 instructions per second. Four index registers are available for address modification. One unique feature of the central computer is the storage and manipulation of numerical quantities as two-dimensional vectors with two 16-bit components. In this way, a single sequence of instructions can simultaneously process both components of positional data, effectively doubling computing speed for this type of processing. Twelve magnetic drums, each with a capacity of 12,288 words of 32 bits, are used for storage of system-status data, system-control programs, and buffer in-out data. Under control of the central computer, data can be transferred in variable-length blocks between these drums and core memory. The total drum storage capacity is about 150,000 words of 32 bits.

During an average 1-second period, the central computer transfers from 20 to 50 blocks of data, each containing 50 to 5000 words, between the central computer's core memory and the terminal devices. In order to ensure maximum utilization of the central computer for air-defense processing and control, an in-out break feature is used. With this feature, calculations in the central computer continue during input-output operations; they are only interrupted for the one core-memory cycle required to transfer a word between the core memory and the terminal device. The in-out break has proved very valuable since considerably more than 50 percent of real time is required for input-output searching, waiting, and transferring.

The input-output buffering devices process in-out data independently of the central computer and so free the computer to do more complex air-defense processing. (Separate read-write heads are provided for the buffering equipment and for the central computer.) In their buffering role, these devices can receive or transmit data while the computer is performing some unrelated function.

Consider, for example, the general manner in which input data from voice-bandwidth phone lines are received. The serial 1300-pulse-per-second message is demodulated and stored in a shift register of appro-

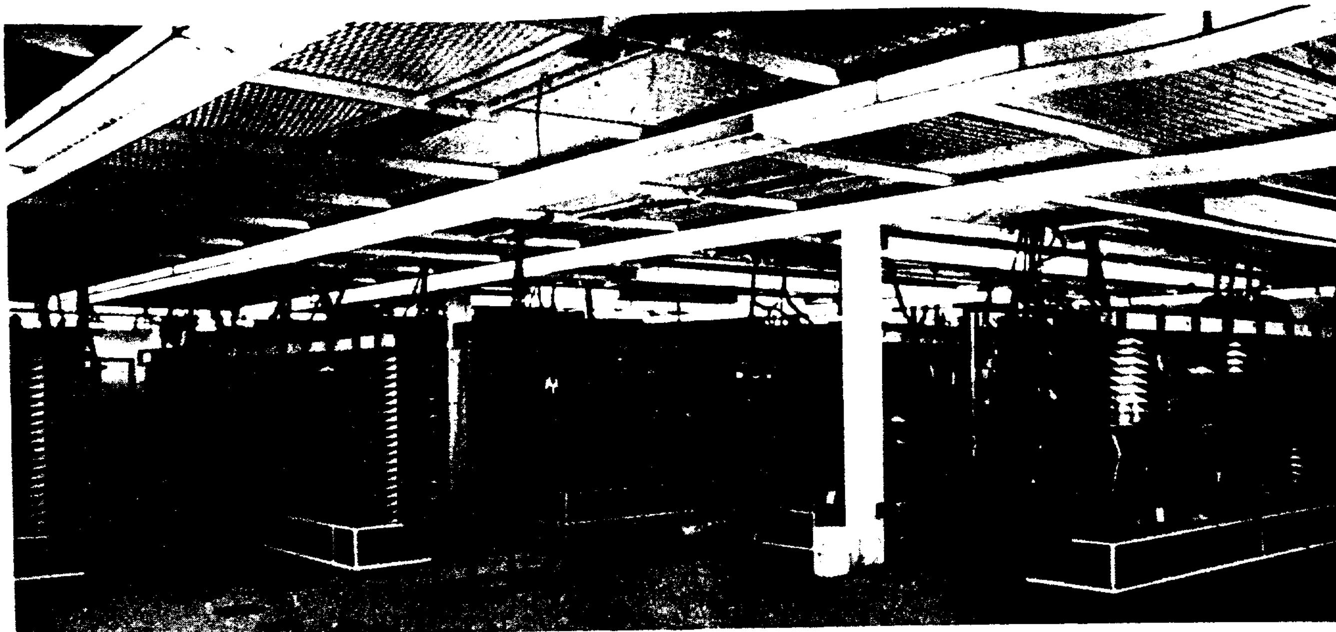

Figure 17. Central computer frames. There are about 70 frames containing nearly 60,000 vacuum tubes in the system.

priate length. When the complete message has been received, the message is shifted at a higher rate into a second shift register (whose length is a multiple of 32 bits), thus freeing the first register to receive another message. When the first empty register is located on the input buffer drum, parallel writing stores the word in 10 microseconds. A relative timing indicator is also

Figure 18. Air surveillance room. From this location the air force operators direct aircraft detection and tracking and communicate with adjacent direction centers. The operator in the foreground is instructing the computer to assign one of the tracks shown on his 19-inch cathode-ray display (Charactron) to another operator for special monitoring. Situation displays on this tube can be forced by the computer or requested by the operator. The small 4-inch tube (Typotron) is used for display of tabular status data. In addition, the console contains keyboard facilities for inserting data into the computer and telephone facilities to provide appropriate priority communications with other stations within and without the direction center.

stored on the drum with the message since the computer may not process the message for several seconds and since time of receipt at the direction center is often critical. The central computer can read these randomly stored data by requesting a block transfer of occupied slots only. Output messages are processed conversely. In a few milliseconds, the central computer can deposit (on the output buffer drum) a series of messages that will keep several phone lines busy for 10 seconds.

The processing ability of the buffer devices is fully exploited in the display system (Figure 10). In this case, the central computer maintains a coded table on the buffer display drum. This table is interpreted and displayed by special-purpose equipment every 2½ seconds at the appropriate console. The central computer can change any part of the display at any time by rewriting only appropriate words on the drum.

The central computer performs air-defense processing in the following manner (see Figures 11 and 12). The buffer storage tables, the system-status data, and the system computer program are organized in hundreds of blocks—each block consisting of from 25 to 4000 computer words. A short sequence-control program in the central computer's core memory transfers appropriate program or data blocks into core memory, initiates processing, and then returns appropriate table blocks (but never programs) back to the drum. To take advantage of the in-out break feature, operation of each air-defense routine is closely coordinated with operation of the sequence-control program so that programs and data are transferred during data processing.

By time-sharing the central computer, each of the air-defense routines is operated at least once every minute—many are operated every several seconds. One interesting feature is that the frequency of program operation is locked with real time rather than allowed to vary as a function of load; during light load conditions the sequence-control program will often "mark time" until the real-time clock indicates that the next operation should be repeated. Such synchronization with real time simplifies many of the control and input-output functions without causing any degradation in system performance. Figures 13–19 show the SAGE system in operation.

Reliability

One last aspect of the computing system remains to be discussed: reliability. As mentioned earlier, 24-hour-per-day uninterrupted operation of the computing system was a requirement that could not be compromised. The FSQ-7 is a crucial link in the air-defense chain. If the computing system stops, the surveillance and control functions are interrupted, men and machines throughout the sector lose vital communications, and the sector is without air defense.

In order to ensure continuous system operation, any component whose failure would cripple the system has been duplexed whenever possible. As a result, two complete, independent computers are provided—each with separate drums, central computers, input-output buffering devices, and magnetic tapes. Equipment associated with individual input-output channels is generally not duplicated: consoles, phone-line demodulators, shift registers, etc. Loss of one of these pieces of equipment would merely cause loss of some data and minor system degradation, rather than complete shutdown of the direction center.

At any one time, one computer performs the air-defense job—this is the active computer. The standby machine may be operating in one of several modes: it may be down for repair (unscheduled maintenance time); it may be undergoing routine preventive maintenance (marginal checking), or even assisting in the maintenance of other equipment within the sector.

The switchover process interchanges the roles of the computers—the standby machine goes active, the active machine goes to standby. Simplexed devices connected to one machine are automatically transferred to the other, and the air-defense program begins operation in the newly active machine. From an equipment point of view, switchover requires only a few seconds. However, all of the system-status data that were available before switchover must be available to the newly active computer. Otherwise, the entire air-situation picture would need to be regenerated; this would cripple sector operations as effectively as if both computers had stopped. Accordingly, the active machine transmits changes in the air-situation data to the standby machine several times per minute via an intercommunication drum. Computer switchover is hardly noticeable to operating personnel.

Figure 19. Command post (experimental SAGE sector). Operation of the direction center and the sector is supervised in the command post by the sector commander and his staff. A summary of the current air situation in the sector and adjoining areas is projected on a large screen.

Although the requirement for continuous operation is a stringent one, SAGE is less vulnerable than many other digital computer applications to transient errors in the FSQ-7. For most operations, the computer operates iteratively in a feedback loop. In these applications, the system is self-correcting for all but a few improbable errors. Parity-checking circuits in the input and output buffer equipment and in the computer-memory system eliminate some data subject to transient errors.

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