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AUTOMATION'S FINEST HOUR: RADAR AND SYSTEM INTEGRATION IN WORLD WAR II

David A. Mindell

> It is nearly as hard for practitioners in the servo art to agree on the definition of a servo as it is for a group of theologians to agree on sin.
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> —Ivan Getting, 1945
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> At first thought it may seem curious that it was a Bell Telephone Laboratories group which came forward with new ideas and techniques to apply to the AA problems. But for two reasons this was natural. First, this group not only had long and highly expert experience with a wide variety of electrical techniques . . . Second, there are surprisingly close and valid analogies between the fire control prediction problem and certain basic problems in communications engineering.
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> —Warren Weaver, 1945[1]

Examining, as this volume does, "the spread of the systems approach," suggests that some coherent approach to systems emerged within engineering before it diffused into other disciplines such as social policy and urban planning. While Thomas Hughes has chronicled a consciousness of systems in electrical power engineering early in the century, the historical literature overall has little to say about systems engineering, and what it meant technically and politically, in the period just before it began colonizing other fields.[2] This chapter examines a particular set of technical and institutional developments during World War II, to show how a new instrument of perception—radar—gave rise to a new approach to engineering systems. Combining servo-controlled gun directors with new radar sets raised problems of a system's response to noise, the dynamics of radar tracking, and jittery echoes. Engineers from Bell Laboratories, in conjunction with their rivals and collaborators at the MIT's Radiation Laboratory, learned to engineer the entire system's behavior from the beginning, rather than just connecting individual, separately designed components.

This new system logic reflected institutional relationships and evolved to suit their shifts. To the Radiation Lab it meant designing the system around its most critical and sensitive component—the radar—and not the director, computer, or gun. By the end of the war, the Radiation Laboratory, in competition with a number of other research labs, assumed control of system design. The Rad Lab ran the war's only successful effort to design a fully automatic radar-controlled fire control system, the Mark 56 Gun Fire Control System. Still, the existing tangle of arrangements between the Rad Lab, Section D-2 (later renamed Division 7) of the National Defense Research Committee (in charge of fire control), and the Navy Bureau of Ordnance did not give the Rad Lab the responsibility it sought. Ivan Getting, director of the Mark 56 project, redefined his organizational role and created the new job of system integrator, a technical, institutional, and epistemological position.

RADAR: AUTOMATING PERCEPTION

During the 1930s, the Army Signal Corps tried to incorporate new "radio ranging" devices into existing mechanical gun directors. In 1937, this work produced the SCR-268 radar (which Western Electric began producing in 1940), designed to supply fire control data to Sperry's M-4 mechanical gun director for directing antiaircraft fire toward attacking bombers.[3] (See figure 1.1.) The SCR-268, although deployed in large numbers, imperfectly matched the M-4, which was designed for use with optical tracking equipment (i.e., telescopes). These early radar sets performed similar to the old sound-ranging equipment they replaced: useful for detecting incoming aircraft and providing an idea where they were, but not as precision inputs to fire control systems. The SCR-268, however, worked much better than acoustic devices, and could direct searchlights to track a target.[4]

The SCR-268's poor accuracy derived in part from its relatively low frequency/long wavelength (1.5 meters). Existing vacuum tubes could not generate higher frequency (shorter-wavelength) signals at high enough powers for aircraft detection. So in 1940, shorter wavelengths, or "microwaves," were part of Vannevar Bush's solution to what he called the "antiaircraft problem," which was then proving critical in the Battle of Britain. When Bush's National Defense Research Committee (NDRC) began operations in 1940, it included microwave research, under Section D-1, the "Microwave Committee."

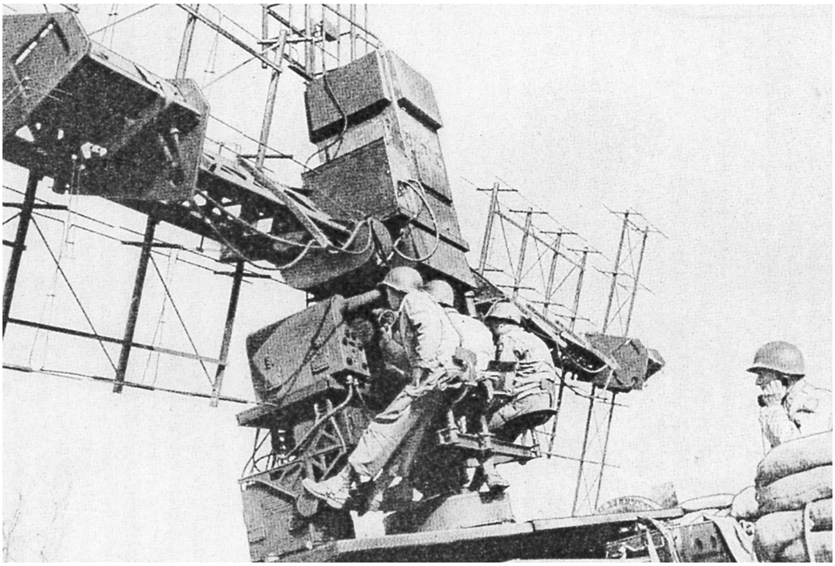


Figure 1.1
Army SCR-268 fire control radar.

It also included a division for "fire control," Section D-2, under the leadership of Warren Weaver, Director of the Natural Sciences Division of the Rockefeller Foundation. During the summer of 1940, Weaver and D-2 toured the field and learned about fire control, and the Microwave Committee did the same for radar. Both groups realized neither the army nor the navy were aware of each other's work. They found very little research on tubes capable of producing waves below one meter, and none for "microwaves," with wavelengths below ten centimeters.[5]

American radar radically changed in September of 1940, when a British technical mission, the famous "Tizard Mission," came to the United States and met with the NDRC. In a remarkable act of technology transfer, the Tizard Mission revealed the "cavity magnetron" to the Microwave Committee.[6] The device could produce microwave pulses with peak powers of ten kilowatts at a wavelength of ten centimeters. Not only did high frequencies produce more accurate echoes, but their small antennas could be carried aboard aircraft. Bush and the NDRC set up a central laboratory for microwave research at MIT, the "Radiation Laboratory," or Rad Lab. It become the NDRC's largest project.

The Rad Lab had three initial projects. Top priority was airborne radar for intercepting bombers, known as Project I. Project II sought automatic fire control. Harvard physicist Kenneth T. Bainbridge joined the Rad Lab and brought a young physicist named Ivan Getting. Getting, the son of Czeckoslovakian diplomats, had grown up in Europe and Washington, D.C. He attended MIT on scholarship and did an undergraduate thesis in physics under Karl Compton in 1934.[7] After completing graduate work in physics as a Rhodes Scholar at Oxford, he returned to the United States as a member of the Harvard Society of Fellows. In November 1940, Getting joined Project II, "to demonstrate automatic tracking of aircraft by microwave radar of accuracy sufficient to provide data input to gunnery computers for effective fire control of ninety-millimeter guns."[8] The intense, blue-eyed Getting was put in charge of the "synchronizer," the master timing device "which tied the system's operation together."[9] The group also included electrical engineers Henry Abajian and George Harris, and physicists Lee Davenport and Leo Sullivan.

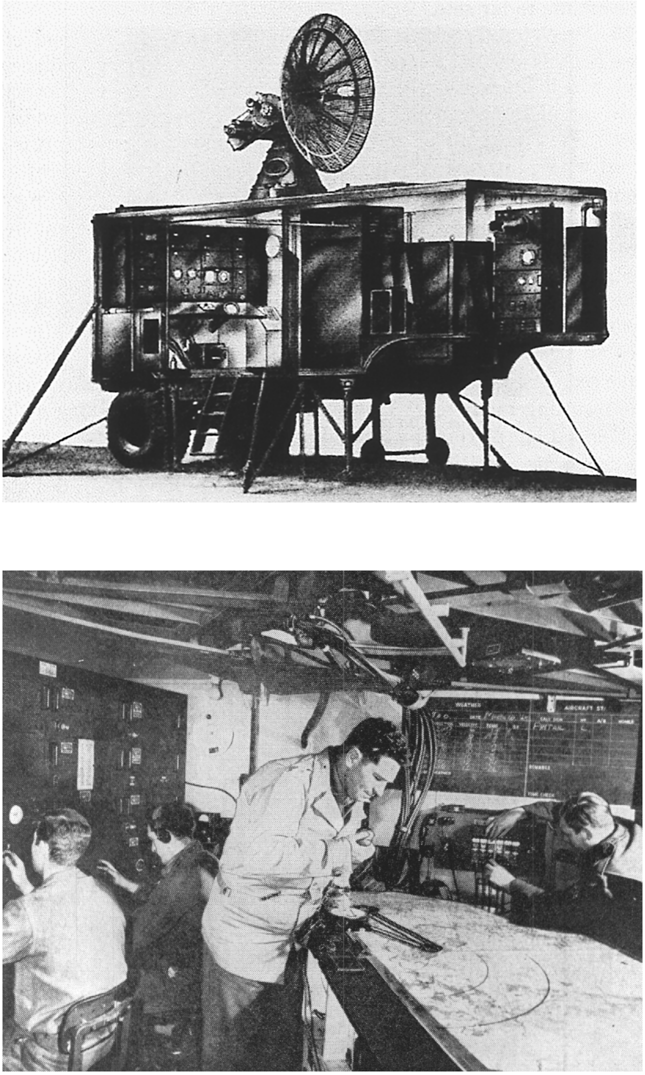
At this time, tracking targets with radar remained a manual activity; it required "pip matching." The operator viewed radar return signals on an oscilloscope screen and used a handwheel-controlled blip to select which radar echo was indeed the target. Then the blip or "pip" and not the actual radar signal went on as the valid range. The operators worked as the "human servomechanisms" did in earlier Sperry directors: they distinguished signals from noise. Bowles and Loomis, aware of MIT's strength in servomechanisms automatic control, suggested Project II mechanize this task for "automatic tracking." If the radar signal itself could drive servos to move the antenna, the radar would follow the target as it moved. Project II set out to automate the work of the radar operator.

To solve this problem, the Rad Lab developed "conical scan," which rotated an off-center beam thirty times per second to make a precise "pencil-beam" for tracking. If the target was "off axis," that is, off the centerline of the beam, a feedback loop moved the antenna to return the target "on axis" to the center. If the target was moving, like an airplane, the antenna would thus track its motion. The Rad Lab obtained a machine-gun mount from General Electric to move the antenna, and G.E. engineer Sidney Godet to adapt the amplidyne servos for tracking. Godet became an informal Rad Lab member and taught the group about G.E.'s experience with servos. They first tested conical scanning at the end of May 1941 on the roof of one of MIT's engineering buildings.[10] By February 1942 the Rad Lab built a prototype, the XT-1; they bought a truck and modified the radar to fit inside.

The truck added more than mobility; it added enclosure. Earlier army radar sets (the SCR-268) mounted displays and operators directly on the rotating antenna platform, much as the Sperry directors had in the 1930s. This arrangement reflected the army's conception of the radar operators: they were soldiers on the battlefield operating a piece of equipment like a radio. To Getting it seemed foolish; the operators' eyes could not adjust to see the cathode-ray displays in bright sunlight; exposed to rain and snow, their hands got too cold to precisely tune the equipment.[11] Getting and his engineers saw the operators as technicians more than soldiers, reading and manipulating representations of the world. The XT-1 truck brought the operators inside a darkened, air-conditioned trailer: a control room, a laboratory.

Enclosure allowed their eyes to adjust to the delicate blips on the CRT; it freed their hands from cold; it isolated their ears from the sounds of battle. Glowing radar screens presented a captivating simulacrum of the world outside. Earlier oscilloscope displays, including the XT-1, showed a single horizontal trace of the radar echo over time. These were soon replaced, on the production version of the machine, with a "plan position indicator" or PPI: a round tube displaying a rotating beam tracing out a virtual map of the area being scanned. Now radar operators and their commanders could perceive and manipulate the field of battle as a map and not as electrical reflections. Radar created an analog of the world, collecting data from a broad area and representing them in compressed form. These systems were among the first in which an operator controlled a machine based on visual input from a cathode-ray tube—an act akin to today's interaction with computers.

After testing, the army reported, "The Radio Set XT-1 is superior to any radio direction finding equipment yet tested by the Coast Artillery or Anti-aircraft Artillery Boards for the purpose of furnishing present position data to an anti-aircraft director."[12] In April 1942 the XT-1 was standardized, or accepted by the army for production, as the SCR-584 radar system; the army ordered more than a thousand units from General Electric, Westinghouse, and Chrysler. (See figures 1.2 and 1.3.) As an "early warning system" it could scan the skies up to 90,000 yards and then track an aircraft to one-twentieth of a degree to a range of 32,000 yards. It provided output signals for azimuth, elevation, and range that could feed into the Sperry M-4 or M-7 directors,



Figures 1.2 and 1.3
SCR-584 Fire control radar with control van. Note tracking operator's console at left in van, and range operator's console at right. [From Louis Ridenour, *Radar System Engineering* (New York: McGraw Hill: 1947), 209.]

or the BTL M-9 director. The SCR-584 became the most successful ground radar of the war, with nearly 1,700 units eventually produced.[13]

The SCR-584 by itself was a remarkable device, "the answer to the antiaircraft artilleryman's prayer."[14] Rad Lab Project II, however, aimed at more than a tracking radar: it sought automatic fire control. Marching toward that goal, however, tread on D-2's terrain. Early on, Warren Weaver recognized the potential for overlap. He wrote to Loomis of his desire for "a reasonably definite understanding of the location of the fence between our two regions of activity . . . a wire fence, through which both sides can look and a fence with convenient and frequent gates." Weaver proposed the relationship between the organizations mirror that of radar to a computer, of perception to integration: "The boundary between the activities between the two sections I would suppose to be fairly well defined by saying that your output (three parameters obtained from microwave equipment) was our input (input to a computer or predictor)."[15] Karl Compton, in charge of Division D, agreed and set up a special committee, known as D-1.5 to represent its liaison between D-1 (radar) and D-2 (fire control). It consisted of Bowles of D-1, Ridenour and Getting of the Rad Lab, and Caldwell and Fry of D-2. This group, in existence for only about a year, conducted a comprehensive survey of all radar development in the United States and Canada.

Where did the Sperry Gyroscope Company fit into this new domain? With a strong background in fire control and new work in radar, the company should have been the obvious choice to build new integrated control systems. The army, however, distrusted the company and requested Sperry only integrate its existing M4 director with the SCR-268 radar, both of which the army already possessed in large numbers.[16] But both the army and the NDRC drew on Sperry corporate knowledge in another way. Sperry's fire control director, Earl Chafee, joined the Ordnance Department and was assigned to survey existing technology and propose "the best all-around fire control system which could be put together out of equipment on which the basic research is now completed." Chafee was to work with D-2 and not only examine individual components, but "the emphasis is to be placed on the over-all aspects of the *system* . . . on the role which radar should play in such a unified system."[17] The so-called Chafee Inquiry did not lead to a new development program but it clarified the systems nature of the problems involved in automating traditional instruments

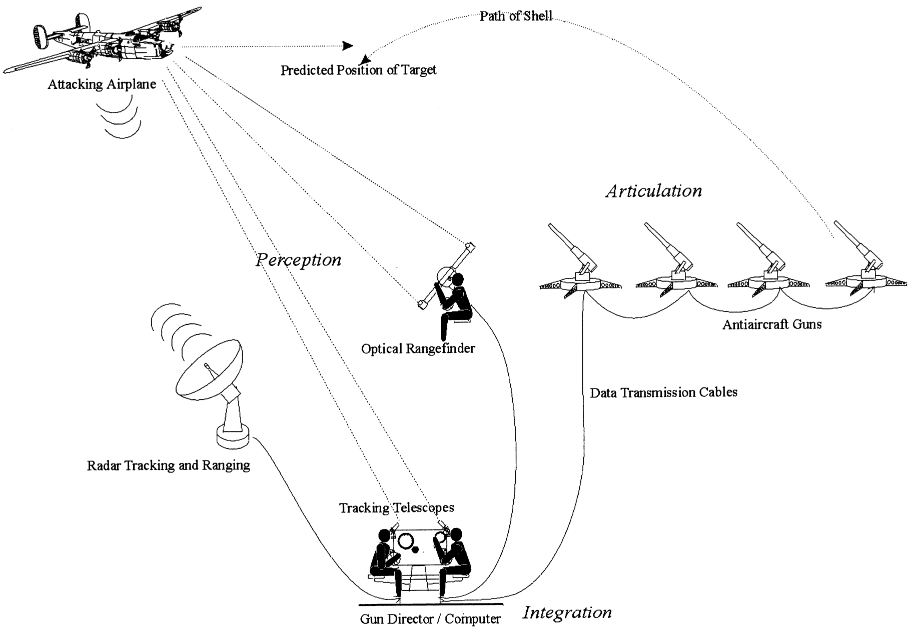


Figure 1.4
The antiaircraft problem. A tracking device (optical or radar) follows the target; the computer calculates its speed and direction, and then extrapolates that velocity into the future to choose an aiming point for the guns. A ballistics calculation turns this information into angles of elevation and azimuth for the guns.

of perception with microwave radar, problems Bell Labs and the Radiation Lab already faced.[18]

Bell Labs (BTL) was building an electrical computer, or gun director, under the NDRC's fire control section, D-2. The device would track and predict target positions for antiaircraft guns. (See figure 1.4.) It used the same algorithms as the mechanical Sperry directors, but implemented them with electromechanical servo-driven computing mechanisms and feedback amplifiers. Tracking input came from optical telescopes, but BTL built in provisions for radar inputs. The project got under way as soon as the NDRC began letting contracts in 1940, and the first prototype was delivered to the army a few days after Pearl Harbor. The army immediately ordered several hundred of the units, designated T-10 in development, for production, and "standardized" the machine (i.e., accepted it as operational) as the M-9 gun director. (See figures 1.5 and 1.6.)

Figure 1.5
M-9 gun director, tracking head with operators. One follows the target in elevation, the other in azimuth. The unit and the operators rotate with azimuth tracking. (AT&T Archives)

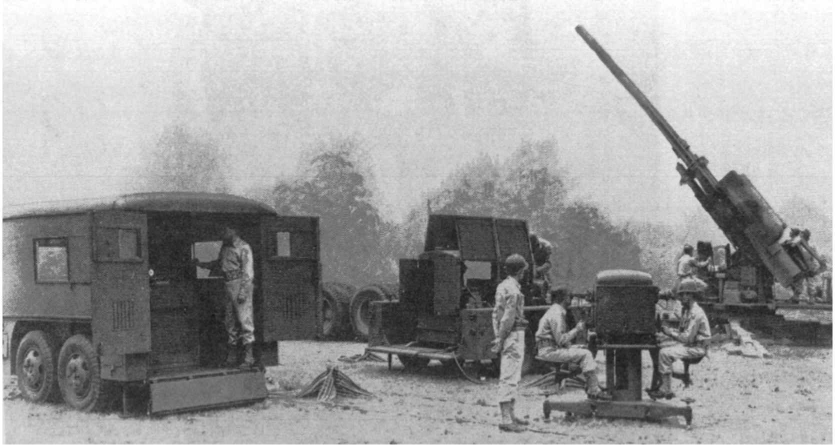


Figure 1.6
M-9 antiaircraft director with power supply, computer, tracking head, and servo-driven 90mm gun. With the SCR-584 radar, this machine fought the V-1. (AT&T Archives)

Ivan Getting learned of the Bell Labs director project during the D-1.5 survey; he began working with BTL to connect his XT-1 tracking radar to the M-9. Weaver's "wire fence" worked fairly well in this case. The T-10 and XT-1 designs proceeded together, and throughout BTL stayed in touch with the MIT group. Ridenour and Getting of the Rad Lab and Stibitz and Lovell of BTL visited back and forth, exchanging information and discussing interfaces between the machines. Getting was particularly interested in "time constants," measures of how quickly the T-10 could respond to inputs. When designing his antenna and tracking unit, he had to know how fast the T-10 could keep up with incoming data—its frequency response.[19] The T-10 final report touted the value of coordinated work: "Close liaison should be maintained between director designers and designers of radars and other tracking equipment. The specifications on each unit should be written with full consideration of the features and capabilities of the other."[20] During this project, the idea emerged that a system might be more than the sum of its parts; the added element was noise.

What difficulties did the Rad Lab and BTL face in trying to connect their instruments? Noise posed the biggest problem. Servos worked fine as calculators when input data was smooth and ideal. Errors in tracking, however, "would produce prediction errors of dominating proportions"; differentiating the prediction signal tended to emphasize high-frequency noise.[21] Radar signals had several sources of noise, making the problem especially bad. For example, as a radar beam reflected off an airplane, it would shift from one part of the plane to another (analogous to the airplane "twinkling" in the sun). A data smoother could eliminate short, high-frequency perturbations from the input data, but with trade-offs. Smoothers introduced time lag, so the smoothed data was no longer current when sent into the predictor.

How could one determine the optimal smoothing versus time lag for a network? Could one reduce the time lag for a given network? How did the smoother distinguish proper tracking data from erroneous inputs? What effect did the time lag of a smoother have on the dynamics of a feedback loop? Would smoothing avoid or induce instability? These questions resembled those telephone engineers had been asking for at least a decade. The work of BTL engineers Harry Nyquist and Hendrik Bode showed the answers depended on the frequency response of the system's components. Warren Weaver put it best when he observed that building radar-controlled systems raised "certain basic problems in communications engineering … if one applies the term *signal* to the variables which describe the actual true motion of the target; and the term *noise* to the inevitable tracking errors, then the purpose of a smoothing circuit (just as in communications engineering) is to minimize the noise and at the same time distort the signal as little as possible."[22] At BTL and the Rad Lab, just as at MIT's Servo Lab, building control systems meant rethinking the nature of electronic information. Using radar to close a feedback loop required paying attention to connections as well as to components. With radar, control engineering became a practice of transmission, of signals, of communications.

Neither the Bell Labs director nor the Rad Lab's radar had been designed from the first with such a practice of "systems engineering." Rather, the two groups tried to connect two separate machines, neither having formal responsibility for coordination. Still, the cooperation paid off. In the fall of 1942, the army held a competitive test of radar-controlled "blind firing."[23] The XT-1 was matched against two other radars, all connected to a T-10 director and Sperry power drives on a 90mm gun. The XT-1 performed best and competing programs were canceled. Although problems remained, particularly extraneous electrical noise in the cables, the system demonstrated that a radar-controlled director could track a target, figure a firing solution, and aim the guns (although it still required human input for target selection, pip matching, and a number of other tasks). By late 1943, the M-9/SCR-584 combination entered service in the European theater as an automatic antiaircraft fire control system.

The T-10/XT-1 program gave Getting new ideas for engineering systems. Technical success brought him new responsibility and the opportunity to articulate his vision: the Radiation Lab reorganized into a number of divisions for components, support, research, and "systems." Ivan Getting took charge of Division 8, responsible for all army ground radar and naval fire control. Nathaniel Nichols headed a special subsection for servos that included a theoretical section headed by Ralph Phillips and had on staff Walter Pitts and economist Paul Samuelson. While this group seemed to violate Weaver's cordial fence between division between D-1 and D-2, Getting believed system design orbited around radar; under his direction the Rad Lab would become the center of gravity for integrated systems.

THE DIFFICULT STEPCHILD: RADAR AND FIRE CONTROL IN THE NAVY

The source of that gravity, however, would not be the army but the world's fire control expert, the navy's Bureau of Ordnance (BuOrd). Between the world wars, BuOrd had been the world's leader in fire control systems, at first for heavy guns and then for antiaircraft, and had developed a closely knit, secret set of contractors, including the Ford Instrument Company, the Arma Engineering Company, and General Electric.[24] But by 1943, the M-9/SCR-584 combination gave the army the most automated fire control system in the war, leapfrogging the navy with help from the NDRC. BuOrd, for its part, had done little work with D-2, Division 7, or the Radiation Lab. Still, the navy was pushing radar because automated perception radically altered naval fire control. Naval control systems, especially for heavier guns, changed more slowly than equivalent army technology, because they depended on modifying ships instead of just sending systems into the field on trucks. This momentum, combined with the conservatism of BuOrd and its contractors and their failure to take immediate advantage of the NDRC, meant that the bureau came to Division 7 and the Rad Lab for help designing a new automated system. Before examining Getting's handling of this project, however, and hence his definition of system engineering, we must understand BuOrd's difficult cultivation of fire control radar.

Despite the navy's early work with the technology, in the words of an official BuOrd history, radar was "a stepchild slow to win affection." Typically it augmented existing fire control equipment not designed for electronic inputs. During the war, BuOrd's tough love spawned twenty-seven different fire control radar designs, only ten entered production, seven actually saw action, and only three (Marks 3, 4, and 8) became widely available.[25] They had problems with reliability, maintenance, short ranges, and target discrimination. Only intense human mediation—similar to the old "human servomechanisms"—could produce high-quality electronic inputs for rangekeepers (the mechanical computers that calculated solutions for naval guns). Operators needed to "pip match" to eliminate noise, and to manually follow the target with the antenna, much as with traditional optical rangefinders and telescopes. They routinely switched between optical and radar tracking, and the combination threatened to overload their attention. Optical tracking remained necessary, because tracking radars frequently jittered between closely spaced targets; they had particular trouble locking onto airplanes attacking low across the water—a weakness Japanese pilots exploited for tactical advantage. Radar underscored the navy's problems with antiaircraft fire control in general; it worked fairly well against high, straight-flying targets, but broke down when confronting fast, maneuverable, close-in attacks. Still the navy dreamed about fully automatic "blind firing," which could accurately shoot at night or through overcast (the anthropomorphic "blind firing" echoes the early use of radar for "blind landing" of airplanes).

Since 1941, BuOrd had attempted several projects to adapt existing control systems for blind firing, including several at the Rad Lab, all of which were terminated. Radar still played the frustrating stepchild. BuOrd and its established clique of secretive contractors simply could not produce a director and a radar at the same time. Blind firing remained an elusive goal.

IVAN GETTING AND COORDINATED DESIGN

Ivan Getting believed he could bring the stepchild into the family and make blind firing a reality. He redefined the system: no longer a set of separate components connected together, but a single, dynamic entity. Signals, dynamics, time constants, and feedback needed to be specified first—this *was* the system. The physical equipment and mechanical components merely solidified these relations. Beyond the technical relations, Getting's vision entailed a new role for his laboratory. BuOrd's earlier attempts at blind firing had failed, he argued, because they lacked a central, coordinating technical body that could oversee the integration of the system:

> 1. There was no attempt made to integrate the radar and the computer into a functioning whole.
> 2. The gross engineering was done by the Bureau of Ordnance, whereas the detailed engineering was done by the company [i.e., contractor], who was not informed of the problem as a whole.[26]

The fire control clique still saw the computer and the radar as comprising the "functioning whole." But to Getting they were subsidiary to a more abstract notion of the system. Similarly BuOrd, with its highly specified and compartmentalized contracting, still believed it could break the fire control problem into component parts, technically and contractually ("gross engineering" versus "detailed engineering").

Getting wanted to redefine the boundaries between components and between organizations in "a totally integrated effort starting from basic principles."[27]

Getting found willing allies in the NDRC and BuOrd. The NDRC reorganized in the end of 1942, and Section D-2 for fire control became Division 7, now headed by Harold Hazen, MIT's Department Head in Electrical Engineering who had made fundamental contributions to servomechanism theory in the early 1930s. Warren Weaver, though he remained an adviser to Division 7, left to head the newly created NDRC Applied Mathematics Panel. Section D-1, for radar, now became Division 14. Hazen, head of the new Division 7, recognized the value of coordinating radar and fire control design (he had grappled with similar systems problems ten years before with the Differential Analyzer). Among Division 7's priorities, Hazen announced, would be "the overall design of fire control systems and the optimum use of radar on navy directors."[28] To smooth relations with the Rad Lab, he invited Getting to join. Soon thereafter, Division 7 began discussing a blind firing director for the navy's 5-inch 38-caliber guns with Emerson Murphy, head of fire control research at BuOrd.[29] Getting proposed "a joint project under Division 14 and Division 7 . . . [for] compact blind firing director for heavy machine guns, 3-inch guns, and 5-inch guns for the U.S. Navy." Murphy, attending a Division 7 meeting, endorsed the idea. BuOrd chief William Blandy concurred, designating the project Gun Fire Control System Mark 56.[30]

Now Getting could start from scratch, defining the machine and defining his position. The NDRC would go one step beyond its usual role of designing equipment, building prototypes, and preparing drawings for production. It would now oversee the selection and preparation of manufacturers, and oversee a production run. This arrangement would allow the NDRC complete technical control of all phases of the project. But which part of the NDRC? A radar-driven fire control device fell within two domains: Division 14 (the Radiation Lab) and Division 7. Division 7 members argued the Radiation Laboratory didn't have sufficient experience with fire control, and that the project should use M-9 director technology developed for the army (BTL was then building for BuOrd the naval equivalent of its electrical director, an electronic rangekeeper).[31] Getting's idea for the new system, however, had radar at its core.

To connect radar and fire control, Hazen created a special section of Division 7, dubbed 7.6, "Navy Fire Control with Radar." Ivan Getting would head Section 7.6 as a member of both Division 7 and the Radiation Lab's systems division. He described the new section as "an attempt by Dr. H. L. Hazen to bring together the necessary elements which had been more or less artificially separated by organization, personality, and history."[32] Getting questioned the traditional lines between subunits: the NDRC's divisions dated from a time, just a few years before, when fire control and radar comprised separate technologies. For earlier projects, such as the M-9/SCR-584 combination, the arrangement worked well, given a high degree of communication between Bell Labs and the Radiation Lab. From that experience, however, Getting learned the value of coordination at the design stages and all the way through production—and the value of controlling that coordination. Section 7.6 absorbed a few other Division 7 projects relating to navy fire control and undertook a number of small contracts, but the Mark 56 formed its major work. Getting called the project, "the first fully integrated radar fire control system that was not restricted by history or by prejudices."[33]

Yet Getting took advantage of history. For the new section, and for the Mark 56, Getting tapped members of BuOrd's fire control clique. He included vice presidents from Ford Instrument and Arma, Al Ruiz of General Electric, MIT's Charles Stark Draper, and Robert M. Page, who had done the early radar work at the Naval Research Lab.[34] The committee did not actually meet until January of 1944, by which time the Mark 56 project was well under way. Section 7.6's primary function then became "supplying a forum where communications between the principals, including the Bureau of Ordnance, could be provided openly."[35] By this date, most 7.6 members were already overloaded with other work. Those from industry were further constrained: they had other contracts with BuOrd and could not discuss status or technical details. Nor did they wish to share such information in a forum in which their commercial competitors participated. The world of naval fire control, with its multilayered secrecy and its seeming archaism, frustrated Getting, used to the heady and open world of the early days of microwave radar.[36]

Despite Getting's vision, nothing inherent in "coordinated design" dictated it should be a radar group to capture and hold the terrain. He and Division 7 confronted not only BuOrd's fire control establishment, but also other centers of technical expertise. “Blind firing” became the high prestige project for BuOrd, and several groups vied for the technical spotlight. Others argued that Draper’s “gyro culture” was best positioned for system engineering, or Bell Labs, where research shared a corporate umbrella with Western Electric’s manufacturing (and “System Engineering” had been an established department since the 1920s). Getting bitterly opposed bringing Western Electric in even as a manufacturer; he disparaged his earlier work with the telephone company—“In fact the Radiation Laboratory and Bell Telephone Laboratories are not complementary but rather the same type of laboratories,” he wrote to Karl Compton—and threatened to resign from the Mark 56 project if production contracts were given to Western Electric.[37] The contracts, instead, went to General Electric, the established navy fire control supplier with whom Getting had worked so successfully on the SCR-584.

Beginning in 1943 the Rad Lab undertook the Mark 56 program. (See figure 1.7.) Its conical-scan, X-band (3cm wavelength) radar could search broadly for targets, and then automatically track them, even at low angles. A “line of sight gyro” in the Mark 56 established a reference as the line between gun and target. Radar operations took place below decks; two sailors in the director itself could acquire and track targets optically. For the computers, the Rad Lab did not defer to prior experience, over Division 7 objections. Instead, Czech exile and fire control expert Tony Svoboda in the Rad Lab designed a wholly new type of mechanical computer, using innovative four-bar linkages. The MIT Servo Lab modified their Vickers servo to drive the director, but the devices were never used. In August 1943 Division 7 let a contract with General Electric’s Aero and Marine Division in Schenectady for the gyro assembly. General Electric contracted to do production design on the radar based on a Rad Lab prototype. The Librascope Corporation of California (chosen over a competing proposal from Ford Instrument) produced the ballistic computer. The device was first tested on a specially constructed rolling platform at Fort Heath north of Boston in the spring of 1944. The first full-up test, including guns, took place the following December.[38]

The project’s radical character adversely affected its timing. BuOrd, tuned for wartime production and deployment, allocated its priorities solely by anticipated delivery date. The long-term Mark 56 fell low on the list and its schedule suffered. Still, Getting saw his “ultimate” system as a crash program to get blind firing to the fleet as

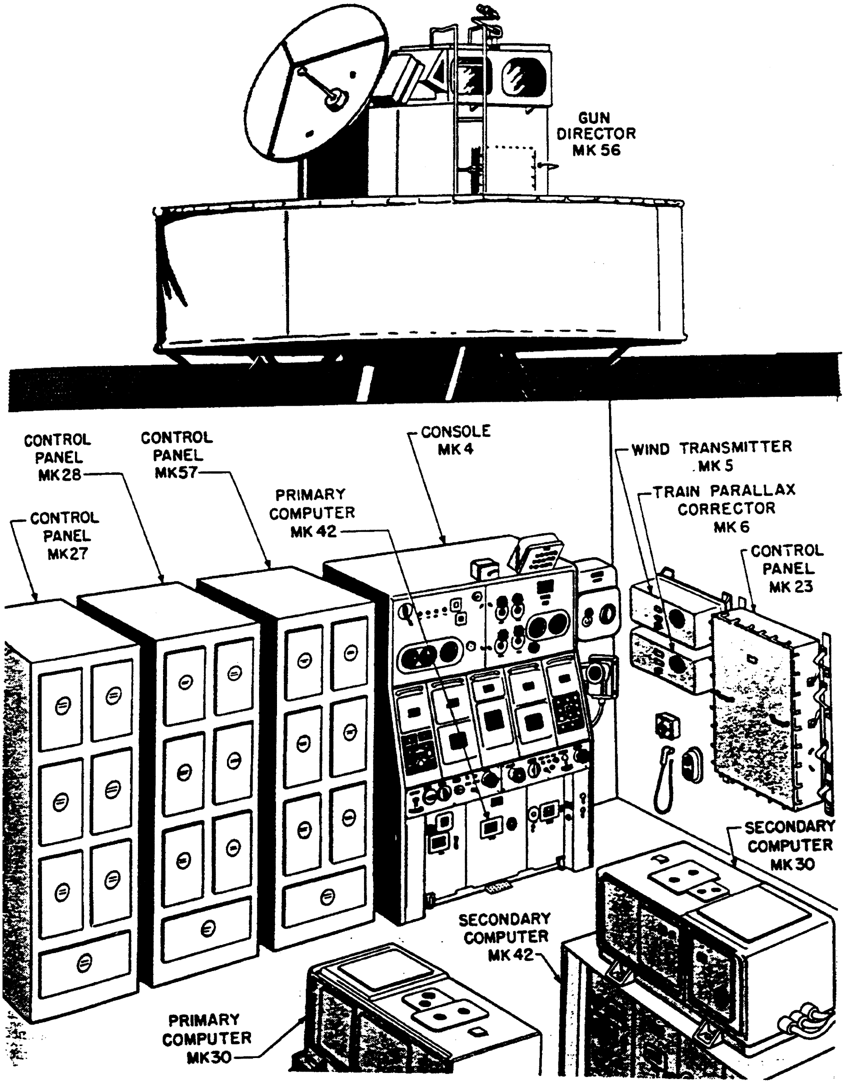


Figure 1.7
Layout of Mark 56 Gun Fire Control System. Two operators track optically from the deck positions, and two more work at the console in the control room below deck. [From *Naval Ordnance and Gunnery: Volume 2, Fire Control* (U.S. Navy, Bureau of Personnel, NavPers 10798, 1955, 319.]

soon as possible. He was greatly helped by Admiral King, Chief of Naval Operations, who was impressed by the Mark 56 and pushed BuOrd to let production contracts. But King voiced the fleet's frustration with previous automatic tracking radars and demanded the new system include optical as well as radar tracking—a further source of delay. When the war ended, Division 7 had five prototypes on order from General Electric, two of which neared completion. When the NDRC closed down in 1945, it transferred the contract to BuOrd in October 1945, which ordered 100 systems. Further problems, delays, and changes by the Bureau delayed Mark 56 production models from reaching the fleet until 1947. The device did, however, proliferate widely in the fleet and remained in service through the 1970s (never firing a shot in anger).

Throughout the Mark 56 project, Getting continued to redefine the work of building control systems. It entailed two parallel moves: transforming the Rad Lab from a radar group to a system integrator, and transforming the human operator into a dynamic component. For the first, Getting elaborated the Rad Lab's earlier position between the government and its contractors as a coordinating technical body. Earlier in the war, the urgency of the antiaircraft situation tended to smooth over political problems, and the NDRC's novelty provided a certain temporary authority. Furthermore, a new field like radar had no established expertise to resist the scientists' designs, so Getting had "complete technical control." Late in the war, however, as things became more established, routine, and industrial, they also became more complicated. Getting was used to dealing with the army, a low-tech service still awed by electronics; now he took on the Bureau of Ordnance, among the most technically sophisticated—and entrenched—groups in the services. Getting wanted to control not only engineering but production; otherwise the role of the Rad Lab would evaporate as the Mark 56 design neared completion. Toward this goal, Getting continued to cross established boundaries. He had joined Division 7, he had merged it with the Rad Lab (7.6), now he reached into the belly of the beast and sought to place a liaison within BuOrd. Warren Weaver, by now experienced at compromise with the services, thought the plans too ambitious, "discussed in over-pretentious terms," and suggested "the way to work with the BuOrd is, so to speak, to work with the BuOrd."[39] Still, in March 1945, Radiation Lab Director Loomis ordered that Getting be assigned to the Bureau of Ordnance, "to devote your time and efforts to technical problems on fire control and their application to radar."[40]

Getting now acquired the long-sought authority to delineate the role of the Radiation Lab. He formalized the Rad Lab's job of system integrator, which had previously been merely informal. Now the Rad Lab would

1. Make all technical information available to GE and the navy
2. Check and criticize designs at all stages of development
3. Send skilled representatives to participate in conferences
4. Report to the BuOrd on the progress of the project
5. Participate in testing of prototypes
6. Test preproduction models
7. Assist in establishing test and alignment procedures for manufacturing and acceptance tests
8. Assist in training programs

Engineering, production, testing, alignment, training: these activities comprised Getting's systems vision as much as time constants and signal spectra. To carry out these functions, the lab would have the following privileges:

1. To receive copies of correspondence between the navy and contractors
2. To receive copies of drawings and specifications prepared by contractors
3. To be notified when significant tests are carried out so representatives of the laboratory may participate
4. To be notified of technical conferences and conferences where technical decisions are to be made so that representatives of the laboratory may be present
5. To be given the opportunity to examine and criticize production designs or models before final design specifications are frozen
6. To have access to the establishments of the contractor and subcontractor by appointment, to confer with engineers, or to inspect equipment
7. To receive one of the first production models for test and study if directed by the navy[41]

Correspondence, drawings, specifications, tests, conferences, inspections: these embodied the relations between institutions. Getting needed to control them as much as the signal flows between components.

These remarkable lists reflect the experience Getting had acquired in a few years of doing research and managing contracts for the NDRC.

Each point seems to correspond to a particular episode where he lacked necessary authority: being excluded from meetings, not receiving correspondence, not having access to factory facilities. Getting redefined control engineering as an organizational as well as a technical task, and he vehemently argued BuOrd by itself was not up to it. Rather, Getting argued, the Radiation Laboratory had the best overall view of automatic control.

Where Getting appropriated authority from contractors, designers, and manufacturers, he also appropriated the work of human operators. Unlike system integrators who organized and collated different types of data, Getting's operators functioned purely mechanically, like "human servomechanisms." In 1945, while fighting for his project's priority, Getting wrote to Admiral Furer, the navy's Coordinator of Research and Development, connecting his ideas for designing new integrated systems with the principle of "automatic operation." Getting argued wartime experience had demonstrated the value of automation:

1. Human judgment introduced wrong guesses.
2. Human operators succumbed to battle fever.
3. The human mind reacts slowly compared to modern servo equipment.
4. The intellectual processes were incapable of utilizing most efficiently all the observable data.[42]

Radar burdened rather than relieved the operator by radically increasing the amount of information he had to sort through. Radar brought such complexity to military control that it strained human attention to hold the system together. Getting's automation would rein in that human involvement—a strategy that resonated with plans for demobilization, when men left the services but the machines remained.

To make his point, Getting invoked the success of the army's automated antiaircraft fire control. The M-9/SCR-584 system he helped design had entered the field, and Getting used the authority he gained by its success to sharply criticize the Navy's lack of automation: "In short the navy is an order of magnitude behind the army in heavy antiaircraft fire control and radar." The solution, of course, was to grant highest priority to Getting's Mark 56, "a wholly integrated operational system." But to what experience did he refer? How did automatic control perform in combat? What had been the experience of the human operators, whose behavior Getting now used to make his claim for automation? The M-9/SCR-584 combination did see service in the war. What were its successes? Where were its limitations?

AUTOMATIC CONTROL'S FINEST HOUR

As Getting promoted and composed his new project, the first automated antiaircraft system, the Radiation Lab's SCR-584 combined with Bell Labs' M-9 gun director, made its way off the production line and onto the battlefield. It was first successful at the beachhead in Anzio, Italy, in March 1944, when two of the radars and sixteen directors systems were deployed on the beach to cover the landing force. Together the SCR-584 and the M-9, combined with Sperry power drives to move the 90mm guns, shot down enemy aircraft that had been harassing the stalled landings.[43]

The M-9 still maintained the "constant altitude assumption" of the prewar Sperry directors. Rushed into production in 1942, it did not incorporate the latest results on predicting curved flight from work at BTL and MIT (being done by Norbert Wiener and others). The M-9 worked best, then, against attackers that flew straight and level—a tactic enemy bombers quickly learned to avoid. In June 1944, however, a new threat emerged from Nazi engineers, which perfectly matched the constant altitude assumption, exactly because it had no human operator. This threat itself relied on an automatic control system to fly, and hence was the perfect target for the automatic antiaircraft gun: the first operational robot bomb, the V-1.

Germany unleashed the "V-1 blitz" against London in mid-1944, and launched almost 7,500 "buzz bombs" against the English capital during the following eighty days. In the words of the British commander of the Antiaircraft Command, "It seemed to us that the obvious answer to the robot target of the flying bomb . . . was a robot defense."[44] Here the M-9/SCR-584 combination, to paraphrase Churchill, saw its finest hour. In anticipation of the V-1 blitz, and in response to a special request by Churchill, Radiation Lab engineers rushed systems out of production, onto ships and accompanied them to England. Members from the original SCR-584 design group (Davenport, Abajian, and Harris) and other Rad Lab staff members traveled along the English coast from battery to battery, aligning equipment, training crews, and tuning the radars—conveying tacit laboratory knowledge to crews in the field.[45]

One other technology completed the system: the proximity fuze, developed by Merle Tuve's Division T before their own foray into fire control. The proximity fuze (known as VT or variable-time fuze) placed a miniature radar in each shell which sensed when it neared the target airplane and set off the explosion.[46] Until then, antiaircraft, with all its feedbacks and controls, remained an open-loop system once the shell left the gun. The proximity fuze closed the loop—making each shell a one-dimensional guided missile, capable of reacting to its environment.

Buzz bombs posed no easy targets. Smaller than a typical airplane, they flew faster than bombers of the day (380 mph), and at low altitudes, averaging about 2,000 feet (indeed fast and low would become the classic radar-evading strategy). And they proved remarkably robust to shellfire, sometimes taking several hits before falling. Still, between 18 June and 17 July 1944, the automated guns shot down 343 V-1's, or 10 percent of the total attack, and 22 percent of those shot down (the others were hit by aircraft, barrage balloons, and ships). During this period the AA batteries were deployed in a ring south of London; and their ability to fire was limited to avoid hitting fighters that also pursued the buzz bombs. The guns could fire only on positive identification of the target and if no fighter were in pursuit, giving aircraft the first chance to shoot down the missiles. In mid-July, the AA batteries moved to the coast, where they could fire without limit over the channel. From 17 July to 31 August, the automated guns accounted for 1,286 V-1 kills, or 34 percent of the attack, 55 percent of those shot down (the improved success rate probably also reflects the effects of the Rad Lab members' assistance).[47] That October, the M-9/SCR-584/VT-Fuze combination defended Antwerp from the V-1 with similar success. In this tense confrontation of robot weapons, the automated battlefield, which even today remains a dream of military technologists, began to take shape.

Despite its success, the system had seams in its automation. Radar's new way of seeing did not immediately replace ocular vision. Throughout the war, automatic and manual perception had an uneasy coexistence—translating between the two proved difficult, error-prone, and fatiguing. A detailed assessment of these issues came not from Ivan Getting but from his rivals and former collaborators at Bell Labs. In July and August of 1944, a group of four army officers and two BTL employees, including Clarence A. Lovell (who headed the T-10/M-9 design team), traveled to Europe to tour antiaircraft batteries and observe their operation against the V-1's. This group's report set out requirements for future antiaircraft systems. Unsurprisingly, the BTL report criticized the Rad Lab radar because the SCR-584 could not search and track simultaneously (BTL's rival SCR-545 could).[48] BTL also reported the system demanded unreasonable concentration from its operators—"there are too many sources of present position data for the computer"—because it allowed radar, optical trackers, and a rangefinder, or a combination. Operators had to judge and juggle these alternate instruments. Manual tracking, for example, was still necessary because of interfering ground echoes (for targets low on the horizon), closely spaced targets that a radar might not be able to distinguish, and the possibility of jamming.[49]

The M-9/SCR-584 was more a combination of two separate units (the BTL director and the Rad Lab radar) than an integrated system. Radar trackers sat inside a trailer while optical trackers and rangefinders (on the director) sat outside. BTL's report proposed adding a means for switching between radar and optical tracking. Ultimately, it argued, any new system should mount optical instruments right at the radar station so operators could "track either optically or by radar without changing their positions or the controls which they employ." BTL's report recommended combining tracking and computing in a single unit, similar to the integrated, blind-firing system Ivan Getting proposed to the navy in 1944.

Getting built that case on the success of the SCR-584/M-9 combination, and on the seeming inability of human operators to keep up with the data flow. Much of the trouble, of course, arose not from the limits of human performance, but from relationships between design organizations divided among perception of inputs, integration of several sources of data, and articulation or output of results. Getting's Mark 56, the "wholly integrated, operational system," proposed to overcome these difficulties by defining a new institutional role, the system integrator, supervising tighter coupling of radar and computer, design and production, operator and machine.

MORE THAN THE SUM OF ITS COMPONENT PARTS: DYNAMIC SYSTEMS AND MILITARY CONTRACTING

Radar's new subtlety accompanied new expertise; the Radiation Lab staked out a role as a system integrator. Organizational relationships solidified as technical systems, at first the partially integrated but combat-tested SCR-584 radar, and then the integrated Mark 56 Gun Fire Control System. The Rad Lab also embodied its claims as knowledge, among its most lasting contributions. After the war, the laboratory, with OSRD funding, published a twenty-seven-volume series on radar to distribute the results of its wartime work. Getting proposed a volume on fire control but series editor Ridenour turned him down because of security restrictions. Still, three of the twenty-seven volumes emerged from the work of Getting and his associates: Louis Ridenour's *Radar System Engineering*, Tony Svoboda's *Computing Mechanisms and Linkages*, and *Theory of Servomechanisms* by physicist Hubert M. James, Rad Lab Division 8 servo engineer Nathaniel B. Nichols, and Division 8 mathematician Ralph S. Phillips.[50] Along with similar volumes from Bell Labs and the Servo Lab, "James, Nichols, and Phillips" became a canonical postwar text of control engineering, introducing a generation of engineers to newly constituted discipline.[51]

For the Rad Lab scientists and engineers, the boundaries of this knowledge derived from the boundaries of radar-driven fire control. The book opens, "The work on servomechanisms in the Radiation Laboratory grew out of its need for automatic-tracking radar systems." Ivan Getting introduces the volume and reviews the basic definitions of servomechanisms and the history of design techniques. Noting the field's lack of stable epistemology, Getting observes, "It is nearly as hard for practitioners in the servo art to agree on the definition of a servo as it is for a group of theologians to agree on sin." Getting and his co-authors certainly acknowledged their predecessors; the twenty-page introduction cites earlier pioneers in servo design and theory: Hazen, Bush, Minorsky, Nyquist, Harris, Brown, Hall, Wiener, and Bode. Still, the book reflects Radiation Lab culture: design examples include the SCR-584 radar, numerous automatic and manual tracking schemes, filters for radar signals, and methods for dealing with noisy echoes. The Rad Lab volume, while stabilizing control systems as a coherent body of knowledge, defined that stability by the systems vision of radar scientists.

Their notion of the system as a dynamic entity, however, conflicted with the prewar vision, which saw a system as a "sum of component parts." In the 1930s, for example, Harold Hazen defined the modular blocks of the differential analyzer so he could manipulate and recombine them ad infinitum. In this world, the whole was exactly the sum of its parts. But radar, noise, and feedback complicated that simplicity. Hazen articulated the newer approach in his 1945 preface to Division 7's "Summary Technical Report":

> One must always remember that a fire-control system is more than the sum of component parts. It is an integrated whole with inter-

> related functioning of all its parts and one is safe in considering parts separately only if one always keeps in mind their relation to the whole.[52]

In a dynamic control system, each component affected the others. Computer design, for example, depended on the bandwidth of the radar, its noise spectrum, and the capabilities of the human operator. But in the early 1940s, the political economy of military technology was built on the older model where systems were decomposable. BuOrd divided up problems, assigned pieces to separate contractors, and assembled the pieces into systems. That approach only worked, however, if a system really was the sum of component parts; noise proved it was more, and pushed systems to a higher level of complexity. The NDRC's fire control division, and then the Radiation Lab's Ivan Getting, reconfigured the structure of contracting to suit a dynamic, noisy, error-prone model of a system. To embody their model in working systems, however, they needed a set of engineering techniques to complement institutional relationships. In parallel developments, those techniques began to emerge during the war as well, driven by similar problems of radar noise and feedback loops, gradually defining a general quantity to flow through the new integrated systems: information.

NOTES

1. Ivan Getting, "Introduction," in Hubert M. James, Nathaniel B. Nichols, and Ralph S. Phillips, *Theory of Servomechanisms* (New York: McGraw Hill, 1947), Radiation Laboratory Series #25. Warren Weaver, foreword to "Final Report: D-2 Project #2, Study of Errors in T-10 Gun Director," National Archives RG-227, Office of Scientific Research and Development, Division 7 (hereafter referred to as OSRD7) Office Files of Warren Weaver, 3.

2. Thomas P. Hughes, *Networks of Power* (Baltimore: Johns Hopkins University Press, 1983).

3. Roger B. Colton, "Radar in the United States Army: History and Early Development at the Signal Corps Laboratories, Fort Monmouth, N.J.," *Proc. I.R.E.* (November 1945): 740–753.

4. Henry Guerlac, *Radar in World War II* (New York: Tomash Publishers/American Institute of Physics), 103–110. A similar device developed by the army, the SCR-270, with a wavelength of 2.5 meters, was designed as an early warning and search system. It was deployed in Hawaii in August 1940, and detected the attack on Pearl Harbor at a distance of over 100 miles.

5. Guerlac, *Radar in World War II*, 243–250.

6. David Zimmerman, *Top Secret Exchange: The Tizard Commission and the Scientific War* (London: A. Sutton Publishing/McGill Queen's, 1996).

7. Ivan Getting, *All in a Lifetime: Science in the Defense of Democracy* (New York: Vantage Press, 1989), 37.

8. Getting, *All in a Lifetime*, 107.

9. Ivan Getting, "SCR-584 Radar and the Mark 56 Naval Gun Fire Control System," *IEEE Trans. Aerospace and Electronic Systems*, AES-11 no. 5 (September 1975): 924.

10. Getting, "SCR-584 Radar." For a technical discussion of the 584 servos, see Hubert M. James, Nathaniel B. Nichols, and Ralph S. Phillips, *Theory of Servomechanisms* (New York: McGraw Hill, 1947), Radiation Laboratory Series #25, 212–224, Stuart Bennett, *A History of Control Engineering: 1930–1955* (London: Peter Peregrinus, 1993), 143–146, which includes Godet's servo.

11. Ivan Getting, interview with author, 3 March 1996, Coronado, California. Notes and recording in author's possession. Getting oral history interview by Frederik Nebeker, 11 June 1991. IEEE Center for the History of Electrical Engineering, Radiation Lab Oral Histories, available on the World Wide Web at http://www.ieee.org:80/history_center/oral_histories/oh_rad_lab_menu.html

12. "Report of A.A.B. Test on XT-1 at Fort Monroe, Virginia, February, 1942," Radiation Laboratory Report no. 359. For firsthand accounts of the XT-1/SCR-584 development and its field deployment, see Henry Abajian oral history interview by Frederik Nebeker, 11 June 1991; Lee Davenport oral history interview by John Bryant, 12 June 1991; and Leo Sullivan oral history interview by Frekerik Nebeker, 14 June 1991. IEEE Center for the History of Electrical Engineering, Radiation Lab Oral Histories.

13. For a summary of SCR-584 projects, including a number of modifications, see National Defense Research Committee, *NDRC Division 14 Final Project Report*, MIT Archives, 2-41 to 2-68.

14. The SCR-584 proved no simple device to manufacture. It required 140 tubes and a host of specialized electronics parts, weighed ten tons total, and cost about $100,000. It did not go into full production until mid-1943. For the difficulties of producing the SCR-584 see George Raynor Thompson, Dixie R. Harris, Pauline M. Oakes, and Dulany Terrett, *The United States Army in World War II: The Technical Services, The Signal Corps: The Test (December 1941 to July 1943)* (Washington, D.C.: Office of the Chief of Military History, United States Army, 1957), 265–274; Getting, *All in a Lifetime*, 121–127; Guerlac, *Radar in World War II*, 481–483; Getting, Harris, Abajian, Davenport oral histories. For the operational history of the SCR-584, see George Raynor Thompson and Dixie R. Harris, *The United States Army in World War II: The Technical Services, The Signal Corps: The Outcome (Mid-1943 through 1945)* (Washington, D.C.: Office of the Chief of Military

History, United States Army, 1966), 474–477. Guerlac, *Radar in World War II*, 480–496, 853–862, 882–897, 1018–1025. Field commanders employed the rugged and versatile SCR-584 for numerous uses beyond the one originally envisioned. It could track mortar shells back to their source, so army units could attack mortar positions. It tracked V-2 trajectories, so American bombers could go after their launch facilities. In combination with automatic plotting boards, it enabled air controllers to "talk" fighter planes to their targets—prefiguring the automated air defense systems of the Cold War and the air traffic control systems of today. During testing at the Aberdeen Proving Ground, it tracked shell fired from the army's 90mm guns and revealed a significant error in their firing tables. The firing table had been calculated on a Bush differential analyzer, but its operator had set up its gearing incorrectly. These errors had then been built into all the Sperry M-7 directors, but since the T-10 was still in development, it could be properly corrected. The army used it during the Battle of the Bulge for tracking enemy vehicles as well. It was also used to track remote-controlled planes for automated bombing attacks (like the one in which Joe Kennedy, Jr., was killed). A number were given to the Soviet Union, and for many years Soviet radars incorporated many of the SCR-584's design features. Getting, *All in a Lifetime*, 130–135. Also see Abajian, Davenport, Harris, Getting oral histories.

15. WW (Warren Weaver) diary, 5 December 1940, meeting with Loomis. WW to Loomis, 10 December 1940. WW diary, 13 December 1940. OSRD7 General Project Files, box 70, collected diaries, vol. 1.

16. See TCF (Thornton C. Fry) diary of meeting with Col. Bowen, 3 July 1941, OSRD7 General Project Files, box 70, collected diaries, vol. 2, and Earl W. Chafee, "Memorandum of Conference in Fire Control Department," 24 September 1942. OSRD7, E-83 Office Files of Warren Weaver, box 4, Sperry Gyroscope folder.

17. Emphasis original, WW diary, 12 November 1942. ORSD7 General Project Files, box 72, collected diaries, vol. 5. WW to Lovell, 23 November 1942. WW to Chafee, 1 December 1942. OSRD7 E-82 Office Files of Harold Hazen, box 9, Rad Lab folder; see other correspondence to Weaver from Fry, Hazen, and Caldwell as input for Chafee's report, many of which are more informative on issues of "coordination" between system elements than the report itself.

18. Earl W. Chafee, "Study of the Requirements for a Satisfactory Antiaircraft Fire Control System," 15 February 1943. Sperry Gyroscope Company Papers, box 33, Hagley Museum and Library. The report can also be found in OSRD7 E-82 Office Files of Harold Hazen, box 9, Rad Lab folder. The Chafee Report includes the most comprehensive history of Sperry's prewar antiaircraft development program in the historical record. A meeting held at Sperry Gyroscope in February 1943 covers similar issues, with input from Rad Lab officials (Ridenour, Griggs), the Ford Instrument Company (Tear, Jahn), and Sperry (Draper, Bassett, Holschuh, Willis, White). John B. Russell diary, OSRD7 General Project Files, box 70, collected diaries, vol. 3.

19. WW to Fletcher, 28 February 1941. Project file 23140, ATT. Ridenour to Lovell, 24 September 1941. Project file 23140, ATT. GRS diary, 21 May 1941.

Ridenour to Lovell, 6 August 1941. Lovell to Ridenour, 23 September 1941. OSRD7 General Project Files, Project #2. Getting, interview with author.

20. "Final Report: D-2 Project #2, Study of Errors in T-10 Gun Director."

21. "Study of Errors in T-10 Gun Director," 72. For a Rad Lab study of jitter in a tracking servo from radar data, see "Data Smoothing," Radiation Laboratory Report, no. 673.

22. Warren Weaver, foreword to "Final Report: D-2 Project #2, Study of Errors in T-10 Gun Director," OSRD7 Office Files of Warren Weaver, 3.

23. The competitors were a similar Bell Labs radar, the SCR-545 (which was produced in limited numbers), and the Canadian GL-III-C, which had been designed in response to Tizard's initial assignment for gunlaying. The SCR-545 was the closest rival to the Radiation Lab set, and included a long-wave search radar along with its microwave tracker. SHC (Samuel H. Caldwell) diary, 26 March 1942, and J. B. Ridenour Diary, 4 April 1942. OSRD7 General Project Files, Project #2.

24. For a detailed account of BuOrd and its "fire control clique," see David A. Mindell, "Datum for Its Own Annihilation: Feedback, Control, and Computing, 1916–1945" (Ph.D. diss., MIT, 1996), chap. 2.

25. Rowland and Boyd, *The U.S. Navy Bureau of Ordnance*, 421, 429.

26. IAG (Ivan A. Getting) to KTC (Karl Taylor Compton), "U.S.N. AA Director Mk. 56," 29 December 1943. OSRD E-39, Office Files of Karl Taylor Compton, box 51, Division 7 folder.

27. Getting, "SCR-584 Radar," 932; interview with author.

28. Division 7 meeting minutes, 3 February 1943. OSRD7 General Project Files box 72, Division 7 meetings folder.

29. HLH (Harold Locke Hazen) diary, 20 and 21 April 1943. OSRD7 General Project Files, office files of Harold Hazen, box 70.

30. Division 7 meeting minutes, 28 April 1943. Guerlac mistakenly recounts these events as the summer of 1942, in *Radar in World War II*, 490, based on a misunderstanding of Getting's letter to Compton of 29 December 1943.

31. Getting, "History of Division 7.6," 7. See Fagan, ed., *History of Engineering and Science in the Bell System*, 158–162. BTL built a prototype of this computer, designated Mark 8, which directly replaced the Ford Instrument Mark I, but it was never put into production.

32. Getting, "History of Division 7.6," 7.

33. Getting, oral history interview.

34. The Complete 7.6 membership was George Agins, vice president, Arma Corporation; R. F. Cooke, vice president, Ford Instrument Company; C. S.

Draper, MIT; A. W. Horton, Bell Telephone Laboratories; R. M. Page, Naval Research Laboratory; E. J. Poitras, Division 7 (Ford Instrument Company); R. B. Roberts, Section T, OSRD; A. L. Ruiz, Division 7 (General Electric).

35. Getting, *All in a Lifetime*, 201.

36. Getting, "History of Division 7.6," 10.

37. IAG to KTC, "U.S.N. AA Director Mk. 56," 29 December 1943. OSRD7, E-39, Office Files of Karl Taylor Compton, box 51, Division 7 folder.

38. For the design history of the Mark 56, see IAG diary, "Conference on Mark 56 Director," 10 June 1943, "Mk 56 Radar Discussions at Bureau of Ordnance," 15 July 1943, "Mk 56," 2 July 1943, "Mk 56," 26 July 1943, OSRD7 General Project Files, box 72, IAG diary folder. Division 7 "Minutes of Rochester Meeting," 5 January 1944, OSRD7 General Project Files, box 72, Division 7 Meetings folder. Getting, *All in a Lifetime*, 177–181. For an operating description of the system, see *Naval Ordnance and Gunnery, Volume 2: Fire Control* (U.S. Navy Bureau of Personnel, NavPers 10798), 318–340. For project history, see *Division 14 Final Report*, 4-55 to 4-63. For Svoboda's relay computers, see "Eloge: Antonin Svoboda, 1907–1980," *Annals of the History of Computing* 2, no. 4 (October 1980): 284–292.

39. WW to IAG, 16 January 1945. OSRD7, office files of Ivan Getting, box 62.

40. Loomis to IAG, 9 March 1945. OSRD7, office files of Ivan Getting, box 62.

41. "Statement of Relationships between the Bureau of Ordnance, U.S. Navy and the National Defense Research Committee, OSRD, on the Development and Production of the Gunfire Control System Mark 56," reprinted in Getting, *All in a Lifetime*, 186.

42. Getting to Furer, 26 April 1945, reprinted in *All in a Lifetime*, 182–185.

43. Leo Sullivan from the Rad Lab accompanied the SCR-584 to Anzio. See Sullivan oral history.

44. General Sir Fredrick Pile, *Ack-Ack, Britain's Defence against Air Attack during the Second World War* (London: Harrap, 1949), 314–315. Also see Pile to George C. Marshall, quoted in Bush to Hazen, 31 August 1944. OSRD7 E-82 Office Files of Harold Hazen, box 9, Rad Lab folder.

45. Getting, Davenport, Abajian oral histories.

46. "Antiaircraft Artillery Fire Control," prepared by the Bell Telephone Laboratories for the Ordnance Department, U.S. Army in fulfillment of Contract W-30-069-Ord-1448, 1 May 1945. ATT, 14. Those manning the batteries were often slow to recognize the value of the fuze. If the VT fuzed shells didn't find a target, they exploded after some fixed time-out period due to a self-destruction mechanism. Because these explosions were likely to be far from the targets, the proximity fuze did not produce large numbers of explosions near the target like time fuzes did. Instead, gunners would see very few explosions near the target and

many explosions far beyond it. “To those used to seeing large numbers of bursts around the target from time fuzed ammunition, this distribution of bursts makes the performance of the battery look very poor,” despite much improved accuracy.

47. Guerlac, *Radar in World War II*, 859. For a personal account of the automatic system versus the V-1, see Abajian interview.

48. “Antiaircraft Artillery Fire Control,” 9.

49. Ibid., 10.

50. Hubert M. James, Nathaniel B. Nichols, and Ralph S. Phillips, *Theory of Servomechanisms* (New York: McGraw Hill, 1947), Radiation Laboratory Series #25. Antonin Svoboda, *Computing Mechanisms and Linkages* (New York: McGraw Hill, 1948), Radiation Laboratory Series #27. Louis B. Ridenour, *Radar System Engineering* (New York: McGraw Hill, 1948), Radiation Laboratory Series #1.

51. Gordon S. Brown and Donald P. Campbell, *Principles of Servomechanisms* (New York: Wiley, 1948). Leroy MacColl, *Fundamental Theory of Servomechanisms* (New York: Van Nostrand, 1945). See Chris Bissel, “Textbooks and Subtexts: A Sideways Look at the Postwar Control Engineering Textbooks, Which Appeared Half a Century Ago,” *IEEE Control Systems* 16, no. 2 (April 1996): 71–78, for an account of the postwar publishing effort, and a comparative discussion of control textbooks. Comparing degrees of importance for these books is, of course, splitting hairs, although Bissel calls the Rad Lab volume “perhaps the most influential of all the American publications of the 1940s.”

52. Harold Hazen, “Fire Control Activities of Division 7, NDRC,” in *Summary Technical Report of Division 7, NDRC*, volume I: *Gunfire Control*, 4. Stuart Bennett has noted the “systems approach” in his comparison of British and American fire control work during the war in *A History of Control Engineering: 1930–1955*, 125.