Automation's Finest Hour: Bell Labs and Automatic Control in World War II

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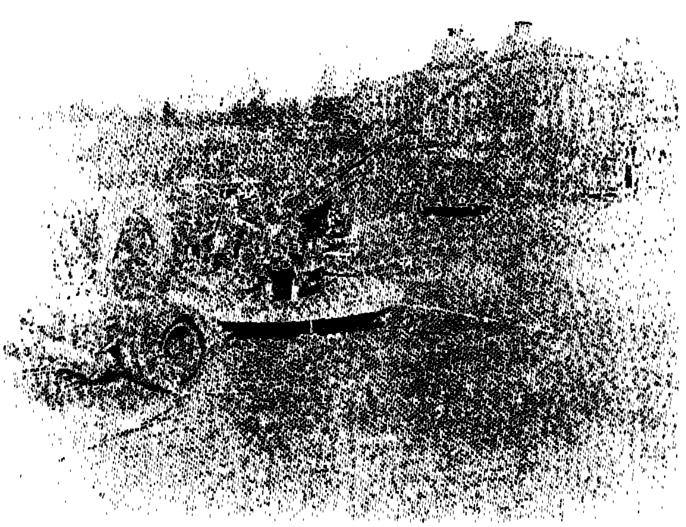


What does a telephone have to do with an anti-aircraft gun? In World War II, the two became intimately connected, as telephone engineering reshaped the technology for shooting down airplanes. In 1945, Warren Weaver, former head of research on control systems at the National Defense Research Committee (NDRC), explained the unlikely role of telephone engineering in solving the "antiaircraft problem."

> *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 [anti-aircraft] 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* [1].

During World War II, engineers at Bell Telephone Laboratories applied their expertise in communications to the control of machinery. They designed and built a gun director that employed electronic circuits and servomechanisms to perform calculations. This device replaced earlier mechanical directors and, when integrated with new microwave radars, proved particularly successful at shooting down the V-1 "buzz bombs"—early cruise missiles. By applying theories of feedback amplifiers to servomechanisms and automatic control systems, Bell Labs engineers merged electronic messaging with technological power.

This article outlines the contributions of Bell Telephone Laboratories to "system engineering" of anti-aircraft guns. Detailing the labs' more significant projects illustrates how techniques originally developed for the telephone system acquired utility and conceptual power when applied to military problems. The products of this research, tempered by war, were then adapted to general problems in electronics, communications, and information systems. Research into control systems, which addressed computing, noise and prediction, and communications theory, shaped today's information society as much as did the digital computer itself.

By 1940, more than a decade of development had defined the basic layout of an "anti-aircraft system." Optical input devices (rangefinders and tracking telescopes) supplied the range, bearing, and elevation of the target. As the war progressed, radar took over these functions, at first just for rangefinding and later for target tracking. A central computer or "gun director" integrated these data with settings for wind, terrain, and predetermined ballistics, which depended on the particular gun and shell. The director predicted the future location of the target based on its speed and direction and calculated as output the azimuth and elevation for aiming the guns, as well as a fuze setting (the time after firing when the shell would explode). These data were transmitted to the guns, which pointed automatically with hydraulic power controls or manually with "follow-the-pointer" indicators. Still, the existing solutions used mechanical calculations, which were inadequate, especially as the advent of radar and advances in aircraft technology stressed system performance to its limit.

Meanwhile, BTL initiated its own gun director project independent of the earlier efforts, starting with the dream of a BTL staff member, D.B. Parkinson. Parkinson, a Ph.D. in physics, was working on a device to record the logarithm of applied voltage on a strip chart. To derive this value, the machine employed a shaped card wound with wire as a logarithmic potentiometer, and "to all intents and purposes, this small potentiometer could be said to control the motion of the pen [of the recorder]."[2]

In the spring of 1940, as Nazi conquest swept over France, Parkinson recalled,

> *I had been working on the level recorder for several weeks when one night I had the most vivid and peculiar dream. I found myself in a gun pit or revetment with an anti-aircraft gun crew. ...There was gun there ... it was firing occasionally, and the impressive thing was that every shot brought down an airplane! After three or four shots one of the men in the crew smiled at me and beckoned me to come closer to the gun. When I drew near he pointed to the exposed end of the left trunnion. Mounted there was the control potentiometer of my level recorder! There was no mistaking it—it was the identical item. ... It didn't take long to make the necessary translation—if the potentiometer could control the high-speed motion of a recording pen with great accuracy, why couldn't a suitably engineered device do the same thing for an anti-aircraft gun?*

About June 1, 1940, Parkinson proposed this idea to his superior, C.A. Lovell. He described three BTL technologies that could contribute to an "electrical predictor for automatic control, calculation, and pointing of a small anti-aircraft gun or machine gun." It required (1) a means of solving equations electrically (potentiometers), (2) a means of deriving rate for prediction (an electrical differentiator), and (3) a means of moving the guns in response to firing solutions (servomechanisms) [3]. With no prior experience in fire control, Parkinson had quickly grasped the essence of the problem.

Going from a bright idea to a full-scale development program, however, required selling it to the labs' leadership, and then to the military services. Lovell liked Parkinson's idea, and proposed it to his boss, Mervin J. Kelley, then Director of Research at BTL. Kelley, in turn, presented the proposal to BTL founder Frank Jewett, now at the National Academy of Sciences and a member of the NDRC, who got in touch with the Army Signal Corps, the logical contact for the telephone company [4]. The BTL group not only proposed their own work, but also learned about the army's existing antiaircraft technology, which had been in development since the 1920s.

Later in June, Parkinson, Lovell, Kelley, and a number of other BTL engineers met with the Signal Corps at Fort Monmouth, N.J., which at that time was working on microwave detection, or early radar. The Bell engineers inspected a Sperry M4 director and other fire control equipment, and received manuals and books on antiaircraft guns and fire control [5]. [See this column, April 1995, for a discussion of the Sperry anti-aircraft development projects] They also presented their ideas to the Navy, which declined interest in the project because it already had sophisticated fire control, and a cadre of officers and contractors trained in the technology [6]. The army was interested, however, and in a letter of September 5, 1940, Col. Roger Colton, Chief Signal Officer, strongly endorsed the BTL gun director idea.

During this initial period of exploration, Parkinson and Lovell gathered a group of BTL engineers to do some preliminary analysis. They produced a study titled "Electrical Mathematics," which examined electrical or electromechanical means of performing the mathematical functions required for fire control equations: addition, subtraction, multiplication, division, integration, differentiation, and looking up tabulated data. Lovell's notebooks indicate he had picked up a general knowledge of the Sperry antiaircraft directors from his visit to Fort Monmouth a few weeks before. He understood Sperry's "plan prediction method," which transformed the observed data from polar to Cartesian coordinates, represented the target's flight in a mechanical analog, and extrapolated from that analog to predict future target position (the so-called "plan prediction") before converting back to polar.

The Sperry systems incorporated servos within their calculating units, but only to transmit information between successive stages. Lovell's idea, in contrast, had a servo perform actual calculation by putting a mathematical element directly in the feedback loop. The servo then "solved" an equation, merely by its tendency to reduce the error to zero. Lovell described how "servomechanisms may be used directly in making transformation from one coordinate system to another without the necessity for setting up scale models having to be considered." While Bell engineers and NDRC staff commonly referred to this technique as "electronic," it was really "electromechanical" (a fact they acknowledged)—the servo motor turned the special potentiometer, whose output voltage was a function of the angular position.

During the summer of 1940, Parkinson worked on similar problems. He learned that a gun director requires a means of calculating the firing solution from the ballistics of the gun, i.e., a firing table. While his original idea included a wire-wound potentiometer for solving equations, he had intended it only to for mathematical functions, such as sines and cosines (Fig. 1). Now he realized that the potentiometers could also provide tabular data [7]. Like Lovell, Parkinson displayed growing understanding of fire control technology and computing. Where Sperry

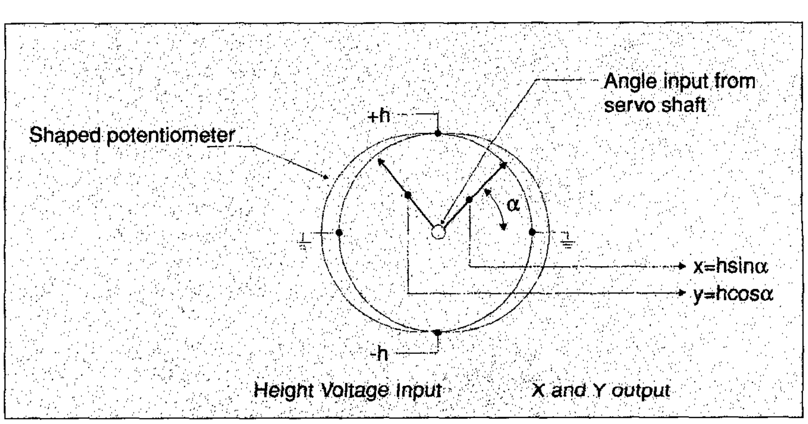
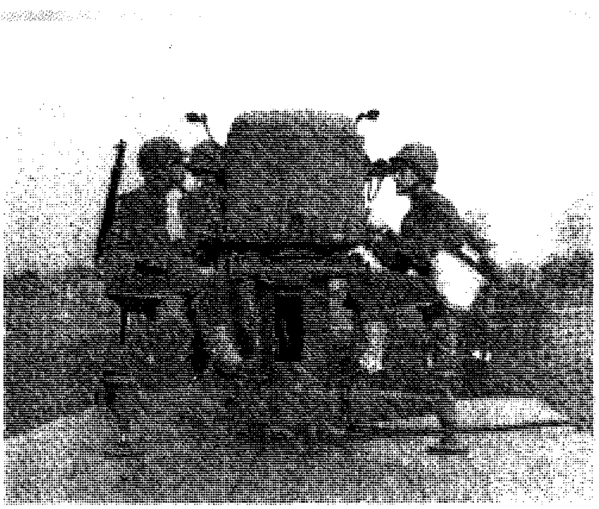


Fig. 1. Coordinate conversion with a sinusoidal potentiometer driven by a servo shaft (from "Final Report: D-2 Project #2c, Study of Errors in T-10 Gun Director").

directors employed three-dimensional mechanical cams to store the firing table, Parkinson suggested a "space potentiometer," which would provide solutions as a function of two variables rather than the single variable embodied in his "logarithmic potentiometer."



The tracker of the M-9 electrical gun director in action. As one soldier orients the telescopes in elevation, the other orients them in azimuth by turning the entire tracker head. Photographs courtesy of AT&T Archives.

Most important from a historical perspective, Lovell noted that modeling mathematics with servomechanisms had far-reaching implications:

> *A digression from the principal subject is made to comment that the use of servo mechanisms to solve simultaneous systems of equations is feasible and, in a large number of cases, practicable. This fact may lead to the application of this type of mechanism to the solution of many types of problems dissociated from the one in question* [8].

He recognized that the computing elements were analogous to the mechanical elements used in earlier computers:

> *... the availability of accurate differentiators and servo-mechanisms make possible the solution of differential equations, and BTL had been using such circuits for that purpose for another project. I want to point out that machines of the same character as the differential analyzer of Bush and Caldwell can be made to operate electrically by the use of the means at our disposal, and that a machine can be built to solve systems of simultaneous differential equations, in particular multi-mesh network equations* [9].

In his notebook, Lovell sketched an equivalent for the MIT differential analyzer made entirely out of servomechanical computing devices. From the beginning, Bell Labs researchers saw that their innovative work on fire control problems had general importance for electronics and computation.

NDRC Section D-2 Funds the BTL Director

Until this point the BTL gun director work remained an internally funded project. But that same summer of 1940, President Roosevelt and Vannevar Bush created the National Defense Research Committee to fund scientific research into military problems. Warren Weaver of the Rockefeller Foundation became head of the NDRC's fire control section, named Section D-2. Weaver assembled a committee and traveled around the East Coast learning about fire control. In October, at the Coastal Artillery Board at Fort Monroe, VA, they were told of BTL's electronic director. Weaver and D-2 then visited Bell Labs and met with Kelley, Lovell, Parkinson, and other Bell engineers. The BTL team explained their idea and showed schematics of their circuits. The NDRC representatives also saw BTL's machine for winding potentiometer cards of any shape, and a completed "sinusoidal" potentiometer [10].

BTL's work appealed to Weaver and his committee. An electronic machine would provide a necessary alternative to Sperry's directors, whose shortcomings in performance and production became clearer every day. Bell engineers argued that electronic computing provided greater accuracy and speed at lower cost than corresponding mechanical techniques—the traditional arguments for electronic over mechanical computing. But in 1940, these were not the arguments that appealed to the NDRC. Rather, they saw that an electronic fire control computer would be easy to reconfigure to change the algorithm (the components could be rewired). In contrast, a mechanical computer's algorithm was tightly bound to its physical structure and was difficult to change. More important, Sperry's resources, as well as those of many precision mechanical manufacturers, were already stretching thin. In contrast, Western Electric's vast manufacturing capacity remained underutilized for war production, and thus could produce the electronic director. Moreover, workers possessing no specialized skills could build electrical devices with existing components, as opposed to the complex machining procedure required for the Sperry ballistic cams. Finally, the idea came from engineers from a successful laboratory with a good reputation and an organization familiar to the NDRC. After all, Bell Labs' founder and former president, Frank Jewett, was a founding member of the NDRC.

The Army concurred, and suggested the NDRC fund the BTL project, "during the development stage, when flexibility of contract is important."[11] NDRC Section D-2 let a contract to BTL to design and build an electronic gun director, to begin Nov. 6, 1940 [12]. [See this column, August 1995, for a survey of the NDRC's other control system projects.] Under the contract, BTL would design the machine, designated T-10, for use with the Army's new 90mm gun, which had hydraulic power controls for remote aiming. An optical rangefinder would provide altitude input, but the machine would include provision for radar inputs. It would also keep the "constant altitude assumption" of previous directors, which predicted the future position of the target by assuming straight and level flight at constant speed.

During the next few months, BTL continued gathering information and resources on control systems and antiaircraft directors. Lovell visited the army's training schools for antiaircraft gunners and the arsenals responsible for technology development. He requested samples of telescopes, data transmitters, receivers, and other equipment [13]. The Frankford Arsenal sent him blueprints for the tracking mechanisms in the Sperry M4 director, and drawings of other directors [14]. Ed Poitras of the NDRC sent Parkinson and Lovell copies of Gordon Brown's servomechanisms paper, "Behavior and Design of Servomechanisms." This paper, which the NDRC published in secret, explained to BTL engineers the MIT transient analysis approach to servomechanisms, which Harold Hazen, Brown, and others had developed during the 1930s, and which still remained distinct from feedback amplifier design [15]. In less than six months, Bell Labs had transformed an individual's dream into one of the country's leading control systems projects.

Enter the T-10 Director

During 1941, Lovell, Parkinson, and their engineers designed and built the T-10 director. Fig. 2 shows the block diagram for the T-10 computer. The basic algorithm and data flow closely resemble that of the mechanical Sperry directors built during the late 1930s. Warren Weaver, in a foreword to the final report on the T-10 project, explained the similarity as a conservative approach to the new electrical technology. "It seemed sensible to construct a predictor which would be a rather close electrical counterpart of the [Sperry] mechanical predictor which was the army's then standard for heavy AA. In this way one would get the most direct and easily interpretable comparison between the mechanical and electrical ways of going at the problem."[16]

The T-10 consisted of four servos, each with a selsyn transmitter for sending firing data to the gun, 30 DC amplifiers, five power supplies, and a host of voltage regulators, adjustment panels, and controls. The entire unit weighed 1600 pounds. The human trackers operated telescopes on a small, separate unit called the "tracking head," which electrically transmitted its data to the "computer" (see photo). The system was "ballistically complete": it included all known factors into the ballistic calculation, and "approaches the ideal of completely automatic operation. The only manual processes involved in its operation were the tracking functions for deriving suitable input data."[17]

The director takes three inputs: azimuth (α), elevation (ε), and range (r). It produces three outputs for the guns, azimuth (α_p), elevation (ε_p), and the fuze setting/time of flight (ΔT). Box I converts the slant-range input to a voltage, and Box II combines slant-range with elevation to derive its height component. Box III combines the target height with azimuth to derive the target position in rectangular coordinates (x, y, and v for vertical height). Box IV performs the actual prediction, deriving the target velocities (i.e., differentiating the position components with respect to time), multiplying the velocities by the time of flight (ΔT), and adding them to the original positions. As in the Sperry system, the time-of-flight parameter closes a feedback loop around the prediction calculation—the time of flight depends on the predicted position and the predicted position depends on the time of flight. The output of Box IV, then, is the predicted position of the target, x_p, y_p, and v_p. Blocks V, VI, and VII then convert this set of three voltages representing rectangular voltages back to polar coordinates, represented now by angular shaft positions. Servomotors perform both the conversion calculation (multiplying by a sine or cosine) and the electrical-to-mechanical conversion.

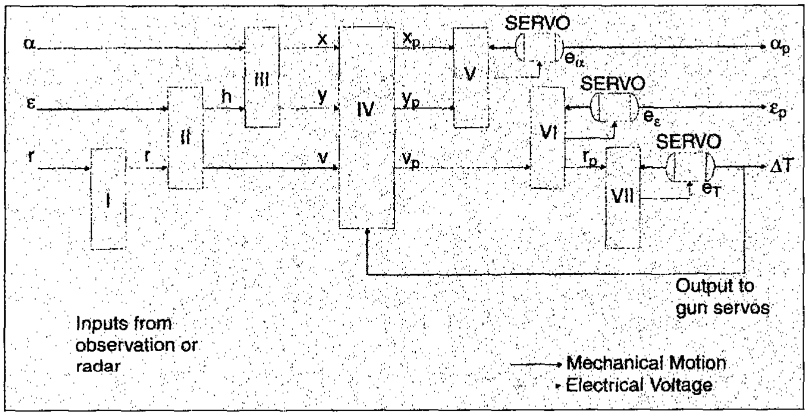


Fig. 2. Simplified block diagram of T-10 director "computor structure" (from "Final Report: D-2 Project #2c, Study of Errors in T-10 Gun Director").

The T-10's "electro-mechanical" mathematical units represented a conscious compromise because, as the designers noted, "[while] a completely electrical solution might be obtained by the use of variable electrical elements ... the problem of controlling these elements accurately is difficult." Rather, by including mechanical elements (i.e., potentiometers) in the calculating mechanisms, they can be driven by servomechanisms, and "servo performance is readily studied by the highly developed method of feedback analysis. That a servo is a feedback system becomes apparent from a comparison of its action and that of the feedback summing amplifier."[18]

BTL engineers used feedback theory not only for the individual components but also to understand the system overall. They envisioned T-10 director as a feedback system at every level, from the electrical amplifiers, to the servos which performed calculation, to the algorithm itself. A section in the T-10 final report, "The Computer as a Servo," explains that the prediction loop itself works just like a servo. Were it not for the many corrections and firing data within that loop, the report added, the entire prediction could be performed by a single servomechanism. The smaller servos "merely introduce local feedback and, provided they are fast and stable, do not affect the operation of the major prediction loop. For those familiar with servo operation the understanding of the prediction process will be clarified by considering the computer as a servo."[19] Overall, "the system has a structural resemblance to a feedback amplifier with multiple loop feedback, and may be analyzed by the usual feedback methods."[20]

Throughout, BTL engineers conceived and described the problem in the language of communications. As one engineer put it, "A servo, in general, involves a carrier, and a means for modulating that carrier according to some function," using terms from radio and telephony [21]. In a similar vein, Sidney Darlingon suggested a circuit for an electronic differentiator, to determine the rate of change of a signal, so necessary for the prediction computation in fire control systems. This device did not include a servo, but rather a standard electrical amplifier with a capacitor in its feedback loop. Bell engineers constructed the circuit and made it work, and gradually developed other methods for using feedback amplifiers for mathematical purposes [22]. In fact, the 1947 paper by Ragazzini, Randall, and Russell which coined the term "operational amplifier" acknowledges the authors drew inspiration from "the circuits employed in the Western Electric M-IX antiaircraft gun director [the operational version of the T-10]."[23] By applying their experience in telephone engineering to control systems problems, then, BTL engineers made fundamental contributions to modern electronics.

Making it Work—Delivery and Testing of the T-10

Designing this electrical computer was no easy task, but making it actually work proved even more difficult. Numerous problems delayed the first T-10 prototype, which was supposed to ship to the Anti-Aircraft Artillery Board at Fort Monroe on Sept. 1, 1941. The project faced many difficulties, but none as challenging as the specially shaped potentiometers that provided functions and range table data. The wire that wrapped the potentiometers needed to have uniform resistance down its entire length, and to maintain consistency despite temperature changes [24]. Winding the wire smoothly on the odd shapes demanded new and specialized equipment. The NDRC, while frustrated at the missed delivery date, recognized the novelty of the machine, and that its success was by no means assured [25]. Finally, the unit was ready and shipped to Fort Monroe for testing, the day before Pearl Harbor [26]. Using testing machines constructed specifically for comparing gun directors, the T-10 performed about as well as, or perhaps a bit worse than, the Sperry directors.

But even before the unit shipped, while BTL still conducted its own tests, the Army announced an order for 200 of the directors, without waiting for the NDRC's approval or for any field testing by the Army [27]. This move caused concern at the NDRC; Duncan Stewart, who oversaw the BTL project, worried about performance. He found the test data inconclusive, and "little to choose between any of these [Sperry or BTL directors] on the basis of results."[28] George Stibitz, himself a researcher at Bell Labs and now a member of Section D-2 as well, echoed Stewart's reservations. He warned that "the mechanical inaccuracies in T-10 are completely swamped by poor use of data." In Stibitz's view, the Army was overly impressed with BTL's new machine, and rushing it into production would waste money, "I cannot emphasize too strongly my own feeling that, since at least $2.5 million will be spent on the first few directors, every effort should be made to improve this part [the data handling] of the predictor, and this effort should be made as promptly as possible."[29] Both Stewart and Stibitz built automatic testing machines for quantifying the performance of the T-10 and other new directors.

The Army's Anti-Aircraft Artillery Board reported that tests showed the T-10 to be about equal in performance to the mechanical directors. D-2 agreed, arguing the device should not go into full production but rather a pilot production lot be run for field trials. For the Army, however, advantages of production and procurement outweighed deficiencies in performance. They told Weaver, "If a good supply of instruments [the T-10] were available which were not even as good as the Sperry M-4, [Army] Ordnance would still feel compelled to purchase this supply."[30] In these tense weeks after Pearl Harbor, the Army needed decisive action on new technologies. In mid-February 1942 the T-10 was standardized by the Army as the M-9 Director.

Section D-2 was uncomfortable with the Army's decision to uncritically adopt the T-10 [31]. Weaver thus extended BTL's contract to allow for improvements in smoothing and error reduction of the T-10 before production. This work, in the spring of 1942, achieved most of its intended results, bringing director's performance to a level that satisfied D-2, including the addition of an averaging circuit for data smoothing. In 1942, the M-9 went into production with Western Electric as prime contractor, subcontracting out the tracking unit and a few other components to the Ford Instrument Company [32]. During the war, Western Electric produced more than 1500 M-9 directors and its derivatives, M-10, M-12, M-13, as well as the M-8 and M-14 which included ballistics for British guns [33].

Fundamental Director Studies

The T-10 was a essentially a rush project to design an electrical director and get it into production as quickly as possible. Hence, it introduced no innovations in computation; it only implemented existing algorithms with new electronic techniques. But the original Sperry algorithm had a number of basic problems. Its "Plan Prediction Method" derived the target's rate (i.e., its velocity) directly from its position, by differentiating. The observed position data unavoidably contained roughness, due either to the jerky nature of human tracking or to electrical noise in a radar signal. Thus the instantaneous rate derived from this signal fluctuated wildly. Smoothing could average out these errors over some time period, but only by introducing time delays which caused errors in prediction (i.e., the predictor operated on stale data). Also, the DC amplifiers tended to "drift," or fall out of adjustment over time. Furthermore, each of the T-10's conversions—from polar, to Cartesian, and then back to polar coordinates—introduced distortion and loss of accuracy. To accommodate these conversions, then, each stage required comparatively higher performance to maintain the overall accuracy of the system.

To overcome these problems, only three months into the T-10 project, BTL and the NDRC initiated a new project to study algorithms and electrical computing, "Fundamental Director Studies." In February 1941, BTL undertook the design of another director, the T-15, as a competing project to the T-10, headed by Walter McNair. Henrik Bode, as part of McNair's team, applied his previous experience with feedback amplifiers to design the smoothing networks for the T-15. Instead of the Plan Prediction Method, the T-15 employed a "memory point method" and worked entirely in polar coordinates. The director stored an initial data point for the target in a mechanical "memory." For any future time, it derived target velocity by subtracting the initial from the current position, and the dividing the difference by time. This calculation required no differentiation and even smoothed out perturbations. Because this method, which came to be called "one plus," used the difference between the current position and the predicted position, it operated on relatively small magnitudes, which required less accurate computing mechanisms. Second, because the T-15's computation required no differentiation, it could use AC circuits, inherently drift-free and more accurate than DC amplifiers. While the T-15 proved more accurate by about a factor of two than the T-10, and settled on a solution twice as quickly, it never went into production.

Nonetheless, the T-15 did advance the state of the art, both in electrical computing and in analytical understanding of the fire control problem. Although its design used the same assumption of constant target course and altitude as the Sperry and T-10 directors, with the T-15 engineers had begun to consider the possibilities of predicting the position of airplanes taking evasive action, or "curved flight prediction." The NDRC let further contracts to Bell Labs to study this problem, as well as to Norbert Wiener at MIT. In the end, BTL rejected Wiener's statistical approach because of problems of performance and complexity, but Wiener's work proved influential in his later work on cybernetics [see Stuart Bennett's account in this column, "Norbert Wiener and Control of Anti-Aircraft Guns," December 1994 *CS*]. The Bell Labs work culminated in a report by R.C. Blackman, Bode, and Claude Shannon, "Data Smoothing and Prediction in Fire-Control Systems," which, in treating the problem as "a special case of the transmission, manipulation, and utilization of intelligence," specifically applied electronic analogs to the prediction problem, anticipated much of modern signal processing, and influenced Shannon's later work on information theory. Once again, the BTL engineers recognized the broad applicability of their work, noting, "The input data ... are thought of as constituting a series in time similar to weather records, stock market prices, production statistics, and the like."[35] Thus, BTL's electrical computer, although sharing little circuitry or architecture with modern computers, shaped the fundamental conception of an information processing system.

Radar and Fire Control

Prediction, however, was not the only problem that required subtle data manipulation. Integrating radar into the automatic control system proved equally as challenging. Warren Weaver had instructed BTL to design the T-10 to accept microwave input data, and all through the design process in 1941, the BTL group cooperated with the NDRC radar group at MIT [36]. Louis Ridenour, who headed fire control radar work at the Radiation Lab, maintained close contact with Lovell at Bell Labs during the whole design process [37]. Similarly, George Stibitz visited MIT and discussed the interfaces between the T-10 and the Rad Lab's new fire control radar, which was being designed under the leadership of Ivan Getting. To connect the radar to fire control computers, Getting was particularly interested in the time constants of the system elements [38]. When designing his antenna and tracking unit, he had to know how fast the T-10 could keep up with input data. The close contact between BTL and the Rad Lab was critical to making an integrated system work properly, and the T-10 group stressed the value of systems engineering across organizational boundaries. "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."[39]

In April 1942, the Radiation Lab's new fire control radar was standardized by the Army as the SCR-584 and went into production. It could track an aircraft to one-twentieth of a degree out to 32,000 yards and included a PPI or "plan position indicator," which displayed a flat representation of the space it scanned on a cathode ray tube, much as the "plan position method" laid out the trajectory of its target in a flat mechanism. The SCR-584 became the most successful ground radar of the war, with 1700 units eventually delivered [40].

Even with close relations between design groups, however, integrating the radar into a fire control system remained difficult. The first time it was connected, the system nearly shook itself apart because of noise. The electrical or electromechanical servos worked fine as calculators when the input data was perfect. But errors in tracking, if treated as good data, "would produce prediction errors of dominating proportions."[41] This problem arose particularly with radar inputs: 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). Some kind of data smoothing and filtering system was necessary, especially because differentiating the prediction signal would aggravate the noise problem. A data smoother could eliminate short, high-frequency perturbations from the input data, but it carried a tradeoff. The more smoothing, the greater the time lag, so the smoothed data was no longer current when sent into the predictor. How could one determine the optimal smoothing versus 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? These questions all depended on the frequency characteristics of the radar reflection, the tracking mechanism (human or radar), and the calculation mechanism itself.

They were not simple questions, and the problems raised by the T-10 initiated a major program of research in data smoothing that complemented the work on prediction. In the words of MIT engineer A.C. Hall, "The advent of radar required the controls engineer to design equipment to operate well in the presence of signals that he could not even describe in terms then in general use." These problems added impetus to efforts already underway by Hall, Herbert Harris, and others to apply Nyquist's frequency-response methods to automatic control problems [42]. Hence, Warren Weaver's observation, quoted above, that the design of the electrical director raised "certain basic problems in communications engineering," and that "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."[43] The noise problem, as well as the problem of prediction, led to the idea that all elements in an integrated system can be defined in terms of the signals they accept and produce, a key component of modern systems engineering.

Battle of the Robot Weapons

Even by itself, the SCR-584 radar was a remarkable device, "the answer to the antiaircraft artilleryman's prayer."[44] Combined with Bell Lab's electrical director, it had great potential as an automated weapon. But despite automatic radar tracking, prediction, and ballistics calculation, gunfire remained essentially an open loop process; once the shell left the gun, one could only hope for the best. One other technology, however, began to close that loop, by putting a single dimension of control into the shell itself: the proximity fuze, developed by Merle Tuve and his special "Division T" of the NDRC. This device, dubbed the VT (for Variable-Time) fuze, had a microwave detector inside the shell which detonated it near the target. Together these devices began to make fire control a fully closed-loop system.

This automatic fire control system first achieved success at the beachhead in February 1944 in Anzio, Italy. Together, the

SCR-584 and the BTL M-9 director shot down enemy aircraft, over a hundred in one month, which had been harassing Allied landings. On D-day, 39 systems landed in Normandy to protect the invasion force against air attack. Despite their automation, however, these systems still maintained the "constant altitude assumption." The M-9, rushed into production in 1942, did not even incorporate the latest results on predicting curved flight from BTL and MIT. The systems worked best, then, against attackers that flew straight and level. German aircrews, of course, learned to maneuver to throw off the simple predictors.

In June 1944, nevertheless, a new threat emerged from Nazi engineers, one that perfectly matched the constant altitude assumption because the new airplane had no human operator. This threat itself relied on an automatic control system to fly, and hence formed the ideal target for the automatic antiaircraft system: the first operational robot bomb, the V-1 "buzz bomb." Although they did fly straight and level, the buzz bombs were no easy targets. Smaller than a typical airplane, they flew at about 380 miles per hour, much faster than bombers of the day, and at low altitudes, averaging about 2000 feet—indeed, "fast and low" would become a radar-evading strategy in later years. And the V-1s proved remarkably resistant to shellfire, sometimes taking several hits before falling.

But in the words of the British head of the Anti-Aircraft Command, "It seemed to us that the obvious answer to the robot target or the flying bomb ... was a robot defense."[45] Against the V-1, to paraphrase Winston Churchill, the automatic anti-aircraft control system saw its finest hour. Hitler unleashed the "V-1 Blitz" against London in mid-1944, and over the next 80 days launched about 7500 against the English capital. In anticipation of the V-1 blitz, and in response to a special request by Churchill, the Radiation lab rushed experts to England who helped set up nearly 100 anti-aircraft batteries. Between June 18 and July 17, 1944, the systems, consisting of the Bell Labs M-9 gun director, the Radiation Lab SCR-584 Radar, the 90mm gun, and the Proximity fuze, shot down 343 V-1s, or 10% of the total and about 20% of those shot down (the others were brought down by aircraft, barrage balloons, and ships) [46]. During this period the AA batteries deployed in a ring south of London, and their ability to fire was limited by the need to avoid hitting Allied fighters that were also attacking the buzz bombs. Thus, aircraft had the first chance at the missiles. That situation changed in mid-July when the AA batteries moved to the coast, where they could fire over the English Channel. From July 17 to Aug. 31, the automated guns accounted for 1286 V-1 kills, or 34% of the attack and more than 50% of those shot down [47]. That October, the M-9/SCR-584/VT-Fuze combination defended Antwerp from the buzz bombs 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.

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Conclusion

Despite this success, or indeed because of it, by the end of the war anti-aircraft control systems were reaching their limits. Electronic circuits calculated ballistics and other factors with an accuracy that exceeded the uncertainty of the system overall. Radar and telescopes could track targets with similar precision. But "straight and level" prediction schemes had fatal flaws, and predictions based on past history could only marginally improve their performance. There was simply no reliable way to hit a distant, rapidly maneuvering target with a ballistic shell. The fire control system, or part of it, needed to move into the projectile, extending the feedback in the proximity fuze to several more dimensions. The stage was set, then, for the guided missile. In fact, Bell Labs built the first postwar anti-aircraft guided missile, Nike, with personnel and technology from its wartime fire control projects [48].

Before World War II, Bell Labs researchers applied their expertise primarily to "The System" and problems in communications. As engineering became more analytical and scientific, those problems assumed increasingly general importance for electrical engineering. The crisis of World War II thrust Bell Labs, like much American science and technology, into defense research. In tackling the design problems of anti-aircraft control systems, Bell Labs engineers found that their experience in communications, especially with feedback amplifiers, prepared them to analyze a broad range of problems with similar techniques. These included electromechanical and electronic computing circuits, prediction machines, and radar signal processing. Together with other research supported by the NDRC, the wartime efforts of Bell Labs in fire control contributed to a new vision of technology, a vision that treated different types of machinery (radar, amplifiers, electric motors, computers) in analytically similar terms—paving the way for information theory, systems engineering, and classical control theory. These efforts produced not only new weapons but also a vision of signals and systems. Through ideas and through people, this vision diffused into engineering culture and solidified as the technical and conceptual foundations of the information age.

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