Anti-Aircraft Fire Control and the Development of Integrated Systems at Sperry, 19251940

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The dawn of the electrical age brought new types of control systems. Able to transmit data between distributed components and effect action at a distance, these systems employed feedback devices as well as human beings to close control loops at every level. By the time theories of feedback and stability began to become practical for engineers in the 1930s, a tradition of remote and automatic control engineering had developed that built distributed control systems with centralized information processors [1]. These two strands of technology, control theory and control systems, came together to produce the large-scale integrated systems typical of World War II and after.

Elmer Ambrose Sperry (1860-1930) and the company he founded, the Sperry Gyroscope Company, led the engineering of control systems between 1910 and 1940. Sperry and his engineers built distributed data transmission systems that laid the foundations of today's command and control systems. Sperry's fire control systems included more than governors or stabilizers; they consisted of distributed sensors, data transmitters, central processors, and outputs that drove machinery.

This article tells the story of Sperry's involvement in anti-aircraft fire control between the world wars and shows how an industrial firm conceived of control systems before the common use of control theory. In the 1930s the task of fire control became progressively more automated, as Sperry engineers gradually replaced human operators with automatic devices. Feedback, human interface, and system integration posed challenging problems for fire control engineers during this period. By the end of the decade these problems would become critical as the country struggled to build up its technology to meet the demands of an impending war.

Anti-Aircraft Artillery Fire Control

Before World War I, developments in ship design, guns, and armor drove the need for improved fire control on Navy ships [2]. By 1920, similar forces were at work in the air: wartime experiences and postwar developments in aerial bombing created the need for sophisticated fire control for anti-aircraft artillery. Shooting an airplane out of the sky is essentially a problem of "leading" the target. As aircraft developed rapidly in the twenties, their increased speed and altitude rapidly pushed the task of computing the lead out of the range of human reaction and calculation. Fire control equipment for anti-aircraft guns was a means of technologically aiding human operators to accomplish a task beyond their natural capabilities

During the first world war, anti-aircraft fire control had undergone some preliminary development. Elmer Sperry, as chairman of the Aviation Committee of the Naval Consulting Board, developed two instruments for this problem: a *goniometer*, a range-finder, and a *pretelemeter*, a fire director or calculator. Neither, however, was widely used in the field [3].

When the war ended in 1918 the Army undertook virtually no new development in anti-aircraft fire control for five to seven years. In the mid-1920s, however, the Army began to develop individual components for anti-aircraft equipment including stereoscopic height-finders, searchlights, and sound location equipment. The Sperry Company was involved in the latter two efforts. About this time Maj. Thomas Wilson, at the Frankford Arsenal in Philadelphia, began developing a central computer for fire control data, loosely based on the system of "director firing" that had developed in naval gunnery. Wilson's device resembled earlier fire control calculators, accepting data as input from sensing components, performing calculations to predict the future location of the target, and producing direction information to the guns.

Integration and Data Transmission

Still, the components of an anti-aircraft battery remained independent, tied together only by telephone. As Preston R. Bassett, chief engineer and later president of the Sperry Company, recalled, "no sooner, however, did the components get to the point of functioning satisfactorily within themselves, than the problem of properly transmitting the information from one to the other came to be of prime importance." [4] Tactical and terrain considerations often required that different fire control elements be separated by up to several hundred feet. Observers telephoned their data to an officer, who manually entered it into the central computer, read off the results, and telephoned them to the gun installations. This communication system introduced both a time delay and the opportunity for error. The components needed tighter integration, and such a system required automatic data communications.

In the 1920s, the Sperry Gyroscope Company led the field in data communications. Its experience came from Elmer Sperry's most successful invention, a true-north-seeking gyro for ships. A significant feature of the Sperry Gyrocompass was its ability to transmit heading data from a single central gyro to repeaters located at a number of locations around the ship. The repeaters, essentially follow-up servos, connected to another follow-up, which tracked the motion of the gyro without interference. These data transmitters had attracted the interest of the Navy, which needed a stable heading reference and a system of data communication for its own fire control problems. In 1916, Sperry built a fire control system for the Navy which, although it placed minimal emphasis on automatic computing, was a sophisticated distributed data system. By 1920 Sperry had installed these systems on a number of US. battleships [5].

Because of the Sperry Company's experience with fire control in the Navy, as well as Elmer Sperry's earlier work with the goniometer and the pretelemeter, the Army approached the company for help with data transmission for anti-aircraft fire control. To Elmer Sperry, it looked like an easy problem: the calculations resembled those in a naval application, but the physical platform, unlike a ship at sea, anchored to the ground. Sperry engineers visited Wilson at the Frankford Arsenal in 1925, and Elmer Sperry followed up with a letter expressing his interest in working on the problem. He stressed his company's experience with naval problems, as well as its recent developments in bombsights, "work from the other end of the proposition." Bombsights had to incorporate numerous parameters of wind, groundspeed, airspeed, and ballistics, so an anti-aircraft gun director was in some ways a reciprocal bombsight [6]. In fact, part of the reason anti-aircraft fire control equipment worked at all was that it assumed attacking bombers had to fly straight and level to line up their bombsights. Elmer Sperry's interests were warmly received, and in 1925 and 1926 the Sperry Company built two data transmission systems for the Army's gun directors.

The original director built at Frankford was designated T- 1, or the "Wilson Director." The Army had purchased a Vickers director manufactured in England, but encouraged Wilson to design one that could be manufactured in this country [7]. Sperry's two data transmission projects were to add automatic communications between the elements of both the Wilson and the Vickers systems (Vickers would eventually incorporate the Sperry system into its product). Wilson died in 1927, and the Sperry Company took over the entire director development from the Frankford Arsenal with a contract to build and deliver a director incorporating the best features of both the Wilson and Vickers systems.

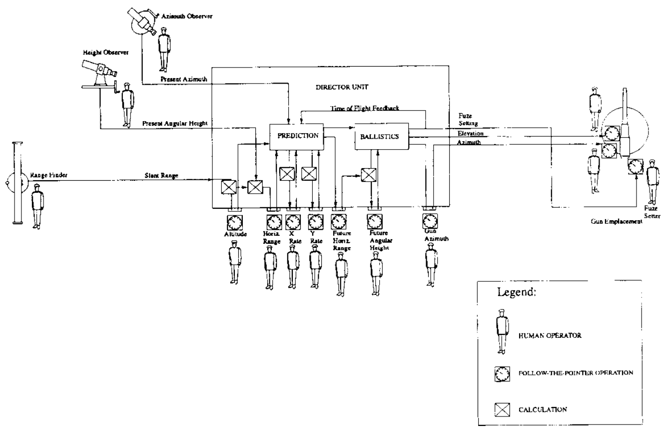

Fig. 1. Simplified system layout and data flow diagram for Sperry T-6 anti-aircraft gun director computer.

From 1927 to 193.5, Sperry undertook a small but intensive development program in anti-aircraft systems. The company financed its engineering internally, selling directors in small quantities to the Army, mostly for evaluation, for only the actual cost of production [8]. Of the nearly 10 models Sperry developed during this period, it never sold more than 12 of any model; the average order was five. The Sperry Company offset some development costs by sales to foreign governments, especially Russia, with the Army's approval [9].

The T-6 Director

Sperry's modified version of Wilson's director was designated T-4 in development. This model incorporated corrections for air density, super-elevation (the need to aim a bit high to compensate for the droop of the trajectory due to gravity), and wind. Assembled and tested at Frankford in the fall of 1928, it had problems with backlash and reliability in its predicting mechanisms. Still, the Army found the T-4 promising and after testing returned it to Sperry for modification [10]. The company changed the design for simpler manufacture, eliminated two operators, and improved reliability. In 1930 Sperry returned with the T-6, which tested successfully. By the end of 1931, the Army had ordered 12 of the units. The T-6 was standardized by the Army (i.e. accepted as operational) as the M-2 director [11].

Since the T-6 was the first anti-aircraft director to be put into production, as well as the first one the Army formally procured, it is instructive to examine its operation in detail. A technical memorandum dated 1930 explained the theory behind the T-6 calculations and how the equations were solved by the system. Although this publication lists no author, it probably was written by Earl W. Chafee, Sperry's director of fire control engineering [12]. The director was a complex mechanical analog computer that connected four three-inch anti-aircraft guns and an altitude finder into an integrated system (see Fig. 1). Just as with Sperry's naval fire control system, the primary means of connection were "data transmitters," similar to those that connected gyrocompasses to repeaters aboard ship.

The director takes three primary inputs. Target altitude comes from a stereoscopic range finder. This device has two telescopes separated by a baseline of 12 feet; a single operator adjusts the angle between them to bring the two images into coincidence. Slant range, or the raw target distance, is then corrected to derive its altitude component. Two additional operators, each with a separate telescope, track the target, one for azimuth and one for elevation (these telescopes are physically mounted on the director). Each sighting device has a data transmitter that measures angle or range and sends it to the computer. The computer receives these data and incorporates manual adjustments for wind velocity, wind direction, muzzle velocity, air density, and other factors. The computer calculates three variables: azimuth, elevation, and a setting for the fuze. The latter, manually set before loading, determines the time after firing at which the shell will explode (corresponding to slant range of the predicted position of the target). Shells are not intended to hit the target plane directly but rather to explode near it, scattering fragments to destroy it.

The director performs two major calculations. First, *prediction* models the motion of the target and extrapolates its position to some time in the future, based on an assumption of constant course, speed, and altitude. Prediction corresponds to "leading" the target. Second, the *ballistic* calculation figures how to make the shell arrive at the desired point in space at the future time and explode, solving for the azimuth and elevation of the gun and the setting on the fuze. This calculation corresponds to the traditional artillery man's task of looking up data in a precalculated "firing table" and setting gun parameters accordingly. Ballistic calculation is simpler than prediction, so we will examine it first.

The T-6 director solves the ballistic problem by directly mechanizing the traditional method, employing a "mechanical firing table." Traditional firing tables printed on paper show solutions for a given angular height of the target, for a given horizontal range, and a number of other variables. The T-6 replaces the firing table with a "Sperry ballistic cam." A three-dimensionally machined cone-shaped device, the ballistic cam or "pin follower" solves a pre-determined function. Two independent variables are input by the angular rotation of the cam and the longitudinal position of a pin that rests on top of the cam. As the pin moves up and down the length of the cam, and as the cam rotates, the height of the pin traces a function of two variables: the solution to the ballistics problem (or part of it). The T-6 director incorporates eight ballistic cams, each solving for a different component of the computation including superelevation, time of flight, wind correction, muzzle velocity. air density correction. Ballistic cams represented, in essence, the stored data of the mechanical computer. Later directors could be adapted to different guns simply by replacing the ballistic cams with a new set, machined according to different firing tables [13]. The ballistic cams comprised a central component of Sperry's mechanical computing technology. The difficulty of their manufacture would prove a major limitation on the usefulness of Sperry directors.

The T-6 director performed its other computational function, prediction, in an innovative way as well. Though the target came into the system in polar coordinates (azimuth, elevation, and range), targets usually flew a constant trajectory (it was assumed) in rectangular coordinates-i.e. straight and level. Thus, it was simpler to extrapolate to the future in rectangular coordinates than in the polar system. So the Sperry director projected the movement of the target onto a horizontal plane, derived the velocity from changes in position, added a fixed time multiplied by the velocity to determine a future position, and then converted the solution back into polar coordinates. This method became known as the "plan prediction method" because of the representation of the data on a flat "plan" as viewed from above; it was commonly used through World War II. In the plan prediction method, "the actual movement of the target is mechanically reproduced on a small scale within the Computer and the desired angles or speeds can be measured directly from the movements of these elements." [14]

Together, the ballistic and prediction calculations form a feedback loop. Operators enter an estimated "time of flight" for the shell when they first begin tracking. The predictor uses this estimate to perform its initial calculation, which feeds into the ballistic stage. The output of the ballistics calculation then feeds back an updated time-of-flight estimate, which the predictor uses to refine the initial estimate. Thus "a cumulative cycle of correction and recorrection brings the predicted future position of the target up to the point indicated by the actual future time of flight." [15]

A square box about four feet on each side (see Fig. 2), the T-6 director was mounted on a pedestal on which it could rotate. Three crew would sit on seats and one or two would stand on a step mounted to the machine, revolving with the unit as the azimuth tracker followed the target. The remainder of the crew stood on a fixed platform; they would have had to shuffle around as the unit rotated. This was probably not a problem, as the rotation angles were small for any given engagement. The director's pedestal mounted on a trailer, on which data transmission cables and the range finder could be packed for transportation.

We have seen that the T-6 computer took only three inputs, elevation, azimuth, and altitude (range), and yet it required *nine operators*. These nine did not include the operation of the range finder, which was considered a separate instrument, or the men tending the guns themselves, but only those operating the director itself. What did these nine men do?

Human Servomechanisms

To the designers of the director, the operators functioned as "manual servomechanisms." One specification for the machine required "minimum dependence on 'human element."' The Sperry Company explained, "All operations must be made as mechanical and foolproof as possible; training requirements must visualize the conditions existent under rapid mobilization; . .." The lessons of World War I ring in this statement; even at the height of isolationism, with the country sliding into depression, design engineers understood the difficulty of raising large numbers of trained personnel in a national emergency. The designers not only thought the system should account for minimal training and high personnel turnover, they also considered the ability of operators to perform their duties under the stress of battle. Thus, nearly all the work for the crew was in a "follow-the-pointer" mode: each man concentrated on an instrument with two indicating dials, one the actual and one the desired value for a particular parameter. With a hand crank, he adjusted the parameter to match the two dials.

Still, it seems curious that the T-6 director required so many men to perform this follow-the-pointer input. When the external rangefinder transmitted its data to the computer, it appeared on a dial and an operator had to follow the pointer to actually input the data into the computing mechanism. The machine did not explicitly calculate velocities. Rather, two operators (one for X and one for Y) adjusted variable-speed drives until their rate dials matched that of a constant-speed motor (the adjustment on the drive then equaled velocity). When the prediction computa-

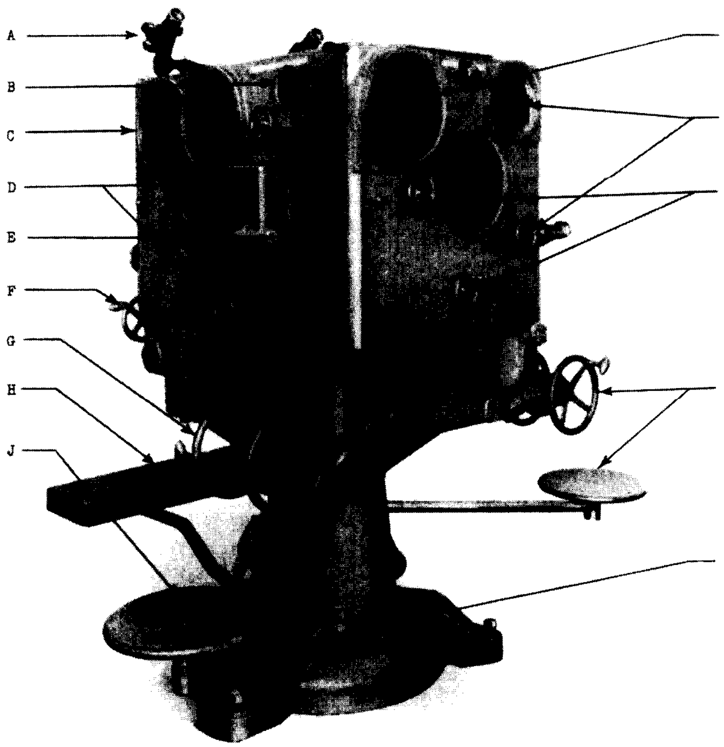

Fig. 2. The Sperry T-6 director: A. Spotting scope. B. North-south rate dial and handwheel. C. Future horizontal range dial. D. Super-elevation dial and handwheel. E. Azimuth tracking telescope. F. Future horizontal range handwheel. G. Traversing handwheel (azimuth tracking). H. Fire control officer's platform. J. Azimuth tracking operator's seat. K. Time of flight dial and handwheel. L. Present altitude dial and handwheel. M. Present horizontal range dial and handwheel. N. Elevation tracking handwheel and operator's seat. 0. Orienting clamp. (Courtesy Hagley Museum and Library)

tion was complete, an operator had to feed the result into the ballistic calculation mechanism. Finally, when the entire calculation cycle was completed, another operator had to follow the pointer to transmit azimuth to the gun crew, who in turn had to match the train and elevation of the gun to the pointer indications.

Fig. 3 shows the crew arrayed around the T-6 director, in an arrangement that today seems almost comical. Strange as these operations seem, they reveal Sperry engineers' conception of what the human role in the operation of an automated system ought to be. The numerous follow-the-pointer operations were clearly preferable to data transmission by telephone; in that sense the system was automated. Operators literally supplied the feedback that made the system work, although Sperry's idea of feedback was rather different from the one prevalent today:

"In many cases where results are obtained by individual elements in the cycle of computation it is necessary to feed these results back *into the mechanism or to transmit them."*

The Sperry document acknowledges the possibility of doing these operations automatically, but does not find it the preferable option:

"When mechanical methods are employed, it is necessary to use some form of 'servo-motor,' and electrical servo-motors are used to a limited degree for 'feeding back' data into the computer.

It has been found in many cases to be much easier to rely on a group of operators who fulfill no other function than to act as servo-motors... This operation can be mechanically performed by the operator under rigorous active service conditions." [16]

Human operators were the means of connecting "individual elements" into an integrated system. In one sense the men were impedance amplifiers, and hence quite similar to servomechanisms in other mechanical calculators of the time, especially Vannevar Bush's differential analyzer [17].

The term "manual servomechanism" itself is an oxymoron: by the conventional definition, all servomechanisms are automatic. The very use of the term acknowledges the existence of an automatic technology that will eventually replace the manual method. With the T-6, this process was already underway. Though the director required nine operators, it had already eliminated two from the previous generation T-4. Servos replaced the operator who fed back superelevation data and the one who transmitted the fuze setting. Furthermore, in this early machine one man corresponded to one variable, and the machine's requirement for operators corresponded directly to the data flow of its computation. Thus the crew that operated the T-6 director was an exact reflection of the algorithm inside it.

Why, then, were only two of the variables automated? Where the Sperry literature proudly trumpets human follow-the-pointer operations, it barely acknowledges the automatic servos, and even then provides the option of manual follow-ups "if the electrical gear is not used." This partial, almost hesitating automation indicates there was more to the human servo-motors than Sperry wanted to acknowledge. As much as the company touted "their duties are purely mechanical and little skill or judgment is required on the part of the operators," men were still required to exercise some judgment, even if unconsciously. The data were noisy, and even an unskilled human eye could eliminate complications due to erroneous or corrupted data. Noisy data did more than corrupt firing solutions. The mechanisms themselves were rather delicate and erroneous input data, especially if it indicated conditions that were not physically possible, could lock up or damage the mechanisms [18]. The operators performed as integrators in both senses of the term: they integrated different elements into a system, and they integrated mathematically, acting as low-pass filters to reduce noise.

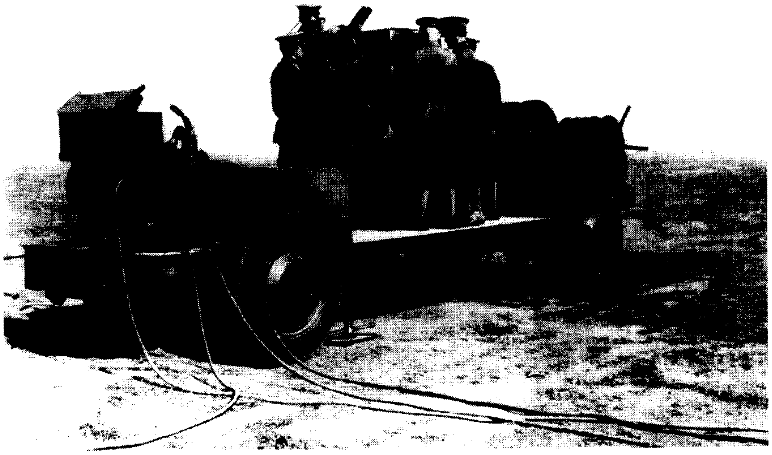

Fig. 3. The Sperry T-6 Director mounted on a trailer with operators. Note power supply at left and cables to other system elements. (Courtesy Hagley Museum and Library)

Later Sperry Directors

When Elmer Sperry died in 1930, his engineers were at work on a newer generation director, the T-8. This machine was intended to be lighter and more portable than earlier models, as well as less expensive and "procurable in quantities in case of emergency." [19] The company still emphasized the need for unskilled men to operate the system in wartime, and their role as system integrators. The operators were "mechanical links in the apparatus, thereby making it possible to avoid mechanical complication which would be involved by the use of electrical or mechanical servo motors." Still, army field experience with the T-6 had shown that servo-motors were a viable way to reduce the number of operators and improve reliability, so the requirements for the T-8 specified that wherever possible "electrical follow-up motors shall be used to reduce the number of operators to a minimum." [20] Thus the T-8 continued the process of automating fire control, and reduced the number of operators to four. Two men followed the target with telescopes, and only two were required for follow-the-pointer functions (for the two rate follow-ups). The other follow-the-pointers had been replaced by follow-up servos fitted with magnetic brakes to eliminate hunting (the inclusion of these brakes suggests that the hesitating use of servos in earlier models may have been due to concerns about their stability). Several experimental versions of the T-8 were built, and it was standardized by the Army as the M3 in 1934.

Throughout the remainder of the '30s, Sperry and the army fine-tuned the director system as embodied in the M3. Succeeding M3 models automated further, replacing the follow-the-pointers for target velocity with a velocity follow-up which employed a ball-and-disc integrator [21]. The M4 series, standardized in 1939, was similar to the M3 but abandoned the constant altitude assumption and added an altitude predictor for gliding targets. The M7, standardized in 194 1, was essentially similar to the M4 but added full power control to the guns for automatic pointing in elevation and azimuth [22]. These later systems had eliminated errors to the point where the greatest uncertainty was the varying time it took different crews to manually set the fuze and load the shell into the gun. Automatic setters and loaders did not improve the situation because of reliability problems. The M7 model also added provision for entering azimuth observation from radio locator equipment, prefiguring the addition of radar for target observations. At the start of World War II, the M7 was the primary anti-aircraft director available to the army.

Following 15 years of work at Sperry, the M7 was a highly developed and integrated system, optimized for reliability and ease of operation and maintenance. As a mechanical computer, it was an elegant, if intricate, device, weighing 850 pounds and including about 11,000 parts. The design of the M7 capitalized on the strength of the Sperry Company: manufacturing of precision mechanisms, especially ballistic cams. By the time the U.S. entered the second world war, however, these capabilities were a scarce resource, especially for high volumes. Production of the M7 by Sperry and Ford Motor Company as subcontractor was a "real choke" and could not keep up with production of the 90mm guns, well into 1942 [23]. The army had also adopted an English system, known as the "Kerrison Director" or M5, which was less accurate than the M7 but easier to manufacture. Sperry redesigned the M5 for high-volume production in 1940, but passed on manufacturing responsibility to the Singer Sewing Machine and Delco companies in 1941 [24]. By 1943, an electronic computing director developed at Bell Labs would supersede the M7, and the M7 ceased production (the Western Electric/Bell Labs gun director will be the subject of another article in this series).

Conclusion: Human Beings as System Integrators

The Sperry directors we have examined here were transitional, experimental systems. Exactly for that reason, however, they allow us to peer inside the process of automation, to examine the displacement of human operators by servomechanisms while the process was still underway. Skilled as the Sperry Company was at data transmission, it only gradually became comfortable with the automatic communication of data between subsystems. Sperry could brag (perhaps protesting too much) about the low skill levels required of the operators of the machine, but in 1930 it was unwilling to remove them completely from the process. Men were the glue that held integrated systems together.

As products, the Sperry Company's anti-aircraft gun directors were only partially successful. A decade and a half of development produced machines that could not negotiate the fine line between performance and production imposed by national emergency. Still, we should judge a technological development program not only by the machines it produces but also by the knowledge it creates, and by how that knowledge contributes to future advances. Sperry's anti-aircraft directors of the 1930s were early examples of distributed control systems, technology that would assume critical importance in the following decades with the development of radar and digital computers.

When building the more complex systems of later years, engineers at Bell Labs, MIT, and elsewhere would incorporate and build on the Sperry Company's experience, grappling with the engineering difficulties of feedback, control, and the augmentation of human capabilities by technological systems.

Notes and References

(All documents referred to in Elmer Sperry Papers and Sperry Company Papers are located in the archival collection of the Hagley Museum and Library, Wilmington, DE.)

[1] Another important element of control technology in this period was process control. For a detailed exploration of control technologies in the 1930s, see Stuart Bennett, *A History of Control Engineering: 1930-1955,* London, 1993, IEE Press, Chapter 1.

[2] John Testuro Sumida, In *Defence of Naval Supremacy: Finance, Technology, and British Naval Policy 1889-1914,* London: Routledge 1989.

[3] Elmer Sperry to T. Wilson, Frankford Arsenal, July 10, 1925. Elmer Sperry Papers, Box 33.

[4] Sperry Company memorandum, probably Preston R. Bassett, "Development of Fire Control for Major Calibre Anti-Aircraft Gun Battery," p. 2. Sperry Gyroscope Company Records, Box 33.

[5] Thomas P. Hughes, *Elmer Sperry: Inventor and Engineer* (Baltimore, 1971), p. 233.

[6] Elmer A. Sperry to T. Wilson, Frankford Arsenal, July 10, 1925. Elmer Sperry Papers, Box 33.

[7] United States Army, Ordnance Department, "History of Anti-Aircraft Director Development," no date, probably prepared in the fall of 1935. Sperry Gyroscope Company Records, Box 4.

[8] Note 4 above.

[9] Note 4 above. See also Sperry Company Form #1607, "Sperry Universal Director: Information to be Furnished by Customer." Sperry Gyroscope Company Records, Box 3. A document clearly intended for foreign governments allowing Sperry to customize their directors to different types of guns.

[10] Note 7 above, pp. 12-14.

[11] Note 7 above, pp. 9-16.

[12] Sperry Gyroscope Company, "Anti-Aircraft Gun Control," Publication No. 20-1640, Brooklyn, New York: Sperry Gyroscope Company Inc., 1930. Sperry Gyroscope Company Papers. This document does not list an author, but its language and explanations are quite similar to those in an article published by Chafee, "A Miss is as Good as a Mile," in *Sperryscope,* the official Sperry Company organ, in April 1932.

[13] Robert Lea, "The Ballistic Cam in Dean Hollister's Lamp," Sperry Company Papers.

[14] Note 12 above, p. 21.

[15] Note 12 above, p. 32.

[16] Note 12 above, pp. 24-25.

[17] Henry M. Paynter, "The Differential Analyzer as an Active Mechanical Instrument," Keynote speech to the 1989 American Control Conference, *IEEE Control Systems Magazine,* December 1989, pp.3-7.

[18] *Anti-Aircraft Defense,* Harrisburg, PA, 1940, reprints the manuals for the Sperry M-2 director and discusses the mechanical problems that can be caused in this generation of Sperry directors by contradictory input data.

[19] Note 12 above, p. 18

[20] "Universal Director and Data Transmission System," Sperry Company Publication no. 14-8051, Aug. 1, 1932, p. 6. Sperry Company Records, Box 2. This document is essentially a specification for the T-8.

[21] For an explanation of the Sperry velocity servo, see Allan G. Bromley, "Analog Computing Devices" in William Aspray, ed., *Computing Before Computers,* Ames, Iowa, 1990, p. 190.

[22] Automating the pointing of the gun was a more difficult problem than data transmission because it involved significant power amplification. The Sperry Company had purchased the rights to the Nieman torque amplifier system from Bethlehem Steel in 1926. During the next several years, Sperry applied power controls to a number of individual guns. None was incorporated into actual systems, due to Army concerns about reliability, and perhaps also to problems of stability. No further work was done on power controls for guns for almost 10 years. It was not until 1939 that Sperry began a contract to develop an electro-hydraulic remote control system for the Army's new 90mm A.A. gun. This work was well underway when reports from the British in combat with Germany indicated that automatic power controls for gun pointing "was not only desirable but was absolutely necessary." Sperry Company Report, "Power Controls," Feb. 7, 1944. Sperry Company Records, Box 40.

[23] Harry C. Thompson and Lida Mayo, *The United States Army in World War II: The Ordnance Department, Volume 2: Procurement and Supply,* Washington, DC, 1960, p. 86.

[24] Sperry Company memo on M-5 and M-6 directors. Sperry Company Records, Box 33. Also see Bromley (note 21 above) pp. 186-191

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