SCR-584 Radar and The Mark 56 Naval Gun Fire Control System

Ivan A. Getting

How to become a pioneer is relatively simple. One has to be at the right place at the right time. Of course, IEEE makes the problem a little more difficult. You have to have been at the right place and at the right lime more than 20 years ago. The story that I am about to unfold starts in 1940 over a third of a century ago; and it all started for me when I joined the Radiation Laboratory at M.I.T. in November of 1940.

The concept of setting up the Radiation Laboratory to work in the field of microwave radar resulted from a meeting on October 18, 1940 when the British mission on radar, commonly referred to as the Tizard Mission, met with the Microwave Committee of the National Defense Research Committee of the U.S. Earlier that year Vannevar Bush had persuaded President Roosevelt to establish NDRC as an independent federal agency for the application of science by civilians to military needs. You will recall that Dunkirk was over, the dictators of Nazism and Fascism had defeated France and had overrun the Benelux countries as well as the Scandinavian countries. England was fighting for its life facing alone on the west the Juggernaut. The battle for Britain was at its height and western democracy was on trial. Officially, the U.S. was at peace and Pearl Harbor was more than a year off.

As we now know, it had been the plan of Hitler to break the will of the British people by heavy aerial bombardment and then to invade. Later Churchill eulogized the fighter pilots of the Royal Air Force who blunted the Nazi bomber attacks. Speaking on be half of the grateful Englishmen, he said. "Never have so many owed so much to so few." What had made the defense of England possible was the successful development and exploitation of long-wave radar. The British coastal radar net detected and tracked German bombers from nearly takeoff to their arrival over Britain. With this information fighters were scrambled as needed so that a relatively small number of fighters could efficiently intercept a large number of attacks. Some fighters were alsoequipped with radar, operating at frequencies of meter wavelength.

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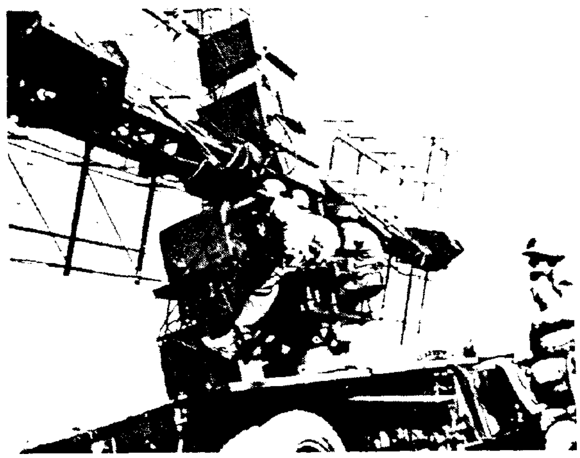

Fig. 1. U.S. Army SCR-268 Radar

The scientific leaders of Great Britain recognized that any further advance in the efficiency of aircraft intercept required the use of much higher frequencies, frequencies corresponding to wavelengths of approximately 10 centimeters. Under this stimulus early in 1940, Randall and Boot, working in Oliphant's Lab in Birmingham, England developed the internal cavity magnetron. Oliphant and his associates were physicists and were completely uninhibited by the then current state-of-the-art in the design and construction of oscillator tubes. They placed the resonant circuit inside of the vacuum envelope, instead of outside. They used oxide-coated cathodes at high plate voltages when everyone knew that this would ruin the cathode. Nevertheless, under pulsed conditions these combinations resulted in a demonstration of a laboratory model of an efficient high-power (10 kw) pulsed oscillator operating at the 10-centimeter wavelength region. Thus it was that when Sir Henry Tizard, Sir John Cockcroft and Taffy Bowen came to the United States in October to meet with the Microwave Committee headed up by Alfred Loomis, they brought with them a model of this remarkable new invention, the internal cavity magnetron.

Fig. 2. First Security Passes at the M.I.T. Radiation Laboratory, November 20, 1940

Radar was also under development on this side of the Atlantic, in fact, independently in two major efforts: the one at the Naval Research Laboratory in Washington and the other by the Army Signal Corps at Fort Monmouth and at Fort Hancock in New Jersey. At the time the Tizard Committee arrived in the United States, the Army and the Navy had in production both long-range search sets and fire control sets for their heavy antiaircraft artillery (Fig. 1). By Pearl Harbor hundreds of these sets were in operational use in the fleet and by the Army in various parts of the world including Pearl Harbor. The SCR-268 of the Signal Corps operating at 1.5 meters, and the Navy FD sets at 60 cm had extended the radar art to the technically possible limits of the time; both used lobe switching and manual tracking with pip matching to optimize angular accuracy. Both sets had more than adequate range performance but both suffered from excessive beam width—the physical limitations of the transmitted frequency. The beam patterns were wide, in the order of 20 degrees, and side lobes were quite high. Thus, angular resolution was poor and interference of large ground or surface reflecting objects often made accurate tracking impossible . The interference of ground reflections in the so-called Lloyd's mirror effect also prevented elevation tracking at angles below approximately 10 degrees.

The Microwave Committee was headed up by Alfred Loomis of Tuxedo Park. The secretary of the Committee was Professor E.L. Bowles of M.I.T. The Committee itself was designated D-1 and reported to Carl Compton, head of Section D of the NDRC. It is significant that Alfred Loomis had himself been working for several years in the field of microwaves, in the region of 10 centimeters. He and his associates, including Barrow and Stratton of M.I.T., had applied low-power cw microwaves to the problems of blind landing, that is, glide path localization. The committee had recently surveyed all the work in microwave oscillators including the pioneering work of the Varian brothers in klystrons and they had been briefed also by the Army and Navy of all their radar plans. It was clear to this group that improvements in radar could be made if the frequency could be pushed from the meter wavelengths to the centimeter wavelengths; but the group as a whole was frustrated by the results of their survey. The industry position in general appeared to be that even if an oscillator could be made, the problems of converting industry into the new technology of microwave frequency components were beyond its capability to handle. It would just take too long to go from concepts to component development, to systems design, to production design and to manufacture. It was in this environment that Sir John Cockcroft pulled out of a box the laboratory model of the cavity magnetron. To Loomis and his academic friends this oscillator gave a purpose. This combination of circumstances in effect gave the Microwave Committee through its operating mechanism, the Radiation Laboratory at M I.T., a unique charter as well as a pledge of support in this new field from both the services and from industry as well.

The October 18th meeting at Tuxedo Park was important also because it laid the foundations for the Radiation Laboratory to be established at M.I.T. and of defining the direction of systems applications which the Laboratory should take. The Tizard Committee was asked to name the three most urgent systems applications based upon British experience in the war in Europe. The highest priority was ascribed to an airborne intercept radar for use by fighters and operating in the 10-centimeter region. This became Project I at the Radiation Laboratory and received the principal early support. The second priority as described by the British was gun laying—and this subsequently became Project II at the Radiation Laboratory. The third highest priority was long-range radio navigation to provide navigation beyond a few hundred miles range of the British systems such as Oboe, then in use for bombing in continental Europe. This third priority became Project III at the Radiation Laboratory and is more commonly known as Loran. As you know, Loran operates at about 2 megacycles and this project was practically independent of the microwave effort at the Radiation Laboratory.

As it happened, Sir John Cockcroft dropped in at Harvard to visit with his old friend, Professor K.T. Bainbridge, who had studied at the Cavendish Laboratories at Cambridge, England, and whose laboratory was next to mine. Thus it was that I was drawn into the fold, although without being told at that time the full implications. The Radiation Laboratory was established in November of 1940 (Fig. 2). As far as I know, I was amongst the first to arrive and walked into some empty rooms at M.I.T. carrying my 10-kilovolt power supply and my 3-inch RCA oscilloscope, the first experimental equipment available to the Radiation Laboratory. My first assignment was to work with K.T. Bainbridge and J.C. Street on modulators. By the end of December, in a matter of some six weeks, the Laboratory was going, sections organized and black boxes began appearing. The Microwave Committee had independently ordered various black boxes from industrial contractors representing the state-of-the-art at that time. The Bell Telephone Laboratories were full speed at work, copying the British magnetron and providing scaled off samples to the Radiation Laboratory.

Project II was activated in the January 1941 period. Louis N. Ridenour[1] had just arrived at the Laboratory and was put

[1]Ridenour was head of Project II from February 1941 to April 1942 at which time he was transferred to the Airborne Division—one of the subdivisions which had been in Project II.

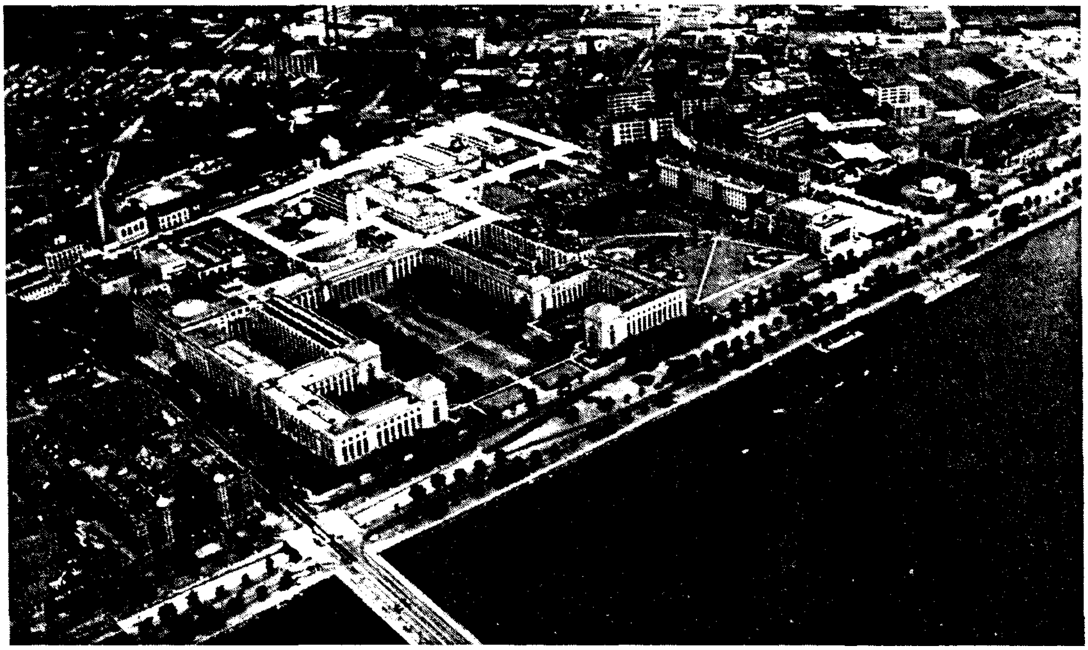

Fig. 3. M.I.T. and the Radiation Laboratory

in charge. Other members of the group in addition to myself were AI Grass and John Meade. Our task was to develop and demonstrate automatic radar tracking for application to gunnery . Block diagrams were made, jobs were assigned and everybody went to work in a great spirit of adventure. To provide a test bed, a 50 calibre gun turret was on order from General Electric. Contracts were placed for power supplies to Raytheon, the component divisions of the Laboratory were tasked and special equipment was designed and built by the individuals of the group. Thus, Al Grass went to work on the accurate range circuits and the newly invented J-scope indicators. My task was the test system and the development of the so-called synchronizer which tied the system's operation together.

But, from where did the idea of automatic tracking come? Who invented the conical scan? How was the decision made? These were not the questions asked at the time. We were just working on the project. So, my comments of today are, in retrospect, an attempt to reconstruct the environment that led to Project II in the form that it developed.

Many of the people who were involved in the October 1940 decisions are no longer alive. The documentary records are fragmentary and those who are still alive, such as Alfred Loomis, Ed Bowles and Taffy Bowen, necessarily plead that a third of a century has passed since those eventful days and that some of the details have necessarily been lost in the fragility of man's memory. Certainly, it is clear that the British mission, in suggesting gun laying, did not intend that the American effort should involve the concept of automatic tracking. In fact, it is quite clear that the British were opposed to this approach. Their experience, as that of the U.S. Navy and the U.S. Army, with longer wavelengths clearly indicated the need of an operator in the loop—the information was just not good enough for automatic, unattended tracking. Perhaps the idea of going to automatic tracking can be traced to some early work done at M.I.T. (Fig. 3) under the direction of Professor Barrow. Three of his students, F.C. Lewis, W.W. Mitcher and D.S. Pencil in 1939 demonstrated automatic, azimuthal tracking using two receiver horns on a moveable platform with 15 degrees between the centers of the horns. The transmitter was a very low-powered 10-cm; the receiving horns were sequentially interrupted mechanically, the two received signals were compared, and the motor drive automatically nulled the difference. This equipment was used to track students walking in the great court at M.I.T. The idea was abandoned at that time, but concurrently Barrow and William Hall and others were measuring overlapping beams at microwave frequencies, to do glide path localization. Professor E.L. Bowles at M.I.T., who became the first Secretary of the Microwave Committee, was well aware of these experiments going on in the Electrical Engineering Department at M.I.T. and one of his associates. Professor Woodruff, was teaching and working in the area of automatic controls. In fact, in the '39-'40 period the M.I.T. Electrical Engineering Department was unique as a center of study of servomechanisms. Sam Caldwell, an associate of Vannevar Bush in the design and construction of the differential analyzer, and Gordon Brown and his groups added to the overall strength of the Department. It is my surmise that this background probably prompted the combination of E.L. Bowles and Alfred Loomis to suggest automatic tracking with the rationale that the American effort in gun laying should differ from the more conventional British stimulated microwave effort in Canada. Certainly, the seeds had been planted and the soil was now ready.

Additional stimulus was provided through the findings of Professor Woodruff who, in December of 1940, made a tour of industry to look into the matter of applications of automatic controls under the auspices of the Microwave Committee. During this tour Professor Woodruff visited the Aeromarine Division of the General Electric; Company at Schenectady where

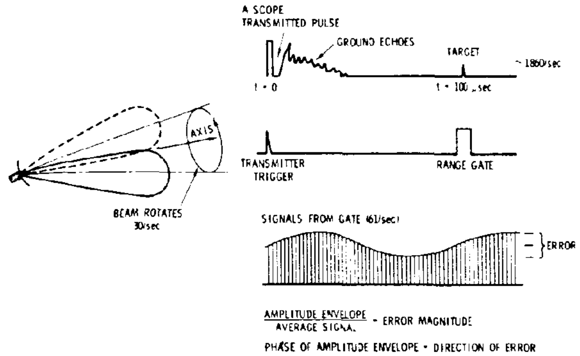

Fig. 4. Concept of Conical Scan

he met with Dick Porter, who was in charge of the development of a 50-calibre remote gun turret for use in the B-29. Woodruff was impressed by what he saw and recommended to the Microwave Committee that an order be placed for a duplicate 50-calibre turret for possible use in the radar program. This turret was subsequently ordered by Project II. Dick Porter assigned Sid Godet to the task of implementing this contract. Sid Godet, for all practical purposes, became a member of the Project II team.

As mentioned previously, Project II was established at the Radiation Laboratory in January of 1941. Each project group of the laboratory transferred an individual to the new group. The first task was to build a bread-board 10-cm system to verify the concept of conical scan and the use of a narrow range gate to separate the return signal of the target to be tracked from those of unwanted targets (Fig. 4). The beam is tilted off-axis and rotated, say 30 rev/sec. If the target is on the axis, the return signals are nominally constant. If the target is off-axis, the signal amplitude is modulated at the conical scan rate—the fractional amplitude is a measure of off-axis error magnitude and the phase of the envelope gives the direction. In automatic tracking, the envelope is demodulated with respect to a sine wave generator mounted on the conical scan drive, the outputs being the error signals for the azimuth and elevation drives on the antenna mount.

It took Dick Porter and his associates at General Electric 90 days to deliver the gun turret together with the servo amplidyne drive and the demodulator amplifier. In the meantime, back at the ranch, we had assembled all the support microwave units and range circuits including the narrow gate required to isolate the signal to be tracked. A camera with a telephoto lens was mounted on the antenna. This permitted determination of the accuracy of the tracking. For a target plane, Dave Griggs,[2] then a geologist at Harvard, flew his Luscombe. The data reduced from the camera showed accurate tracking with a probable error of the order of 1/20 degree. However, the tracking was characterized by a certain amount of jerkiness or jitter—resulting in part from the fact that the preponderant reflections from the aircraft shift from one part of the plane to another. This jitter is important because fire control requires the prediction of the movement of the target during the time of flight of the bullet and such prediction requires accurate angular rate measurements. Clearly, the data was not adequate for such prediction without further treatment.

[2] Later joined Rad Lab

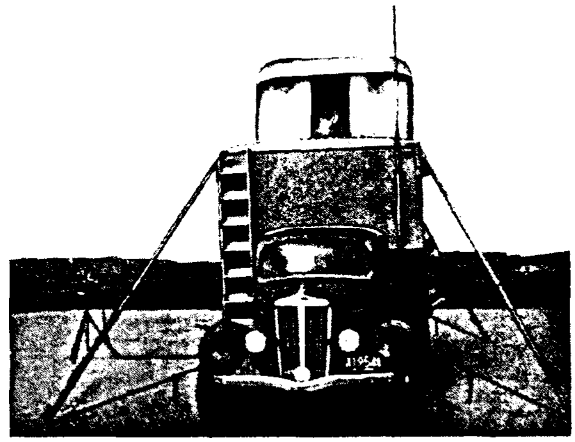

Fig. 5. XT-1 Experimental Auto-Tracking Radar

Fig. 6. Lee Davenport, I.A. Getting and Arthur Warner on Production SCR-584

Even as the roof model was being demonstrated, a truck version was being built—which was dubbed XT-1 (Fig. 5) and which became the laboratory prototype of the SCR-584. I must specifically mention two other individuals who were critical in the development of the XT-1 and the production follow-on, the SCR-584 (Fig. 6). About a month after Project II was initiated, Lee Davenport joined the group. Lee had interrupted his doctoral program at the University of Pittsburgh. His good judgment and his fine sense of humor contributed immeasurably to the success of the program. He provided a continuity in the program from its beginning to its end. Arthur Warner joined the group in November of 1941 just in time to participate in the field tests of the XT-1. A professor from the University of California, he was also a reserve colonel called into active duty, but assigned to the laboratory. Towards the latter part of the war, he was assigned to the staff of General Eisenhower.

I must now distract you by introducing another element into the picture. Just as the Army divided responsibility of the fire control problem between the Signal Corps for the radars and

Fig. 7. The M-9 Gun Director

Fig. 8. Early Airborne PPI (Plan Position Indicator) Nantucket Island

the Ordnance Corps for the computers, so had NDRC in that Section D-1 under Alfred Loomis had the responsibility for radar development and Section D-2 under Warren Weaver had the responsibility for computers.

A major contribution of Section D-2 was the early initiation of a new fire control program at the Bell Telephone Laboratories as suggested by Mervin Kelly, then the President of the Bell Telephone Laboratories. This electrical computer designated T-10 and in production as the M-9 (Fig. 7) was developed under the leadership of Lovell and Parkinson of the Bell Telephone Laboratories Previous AA computers, using optical tracking, assumed that the airplane flew at constant altitude. Since it was based on the use of radar, the T-10 treated range, azimuth and elevation with equal weight; but further, the Bell Telephone Laboratories were able to build into the system concepts of smoothing based on their long experience with feedback and filter theory. Thus, the Bell Labs people, working directly with the XT-1 group at the Radiation Laboratory, were able to optimize the overall system including the noise spectrum of the radar tracking.

While the Bell Telephone Laboratories people were applying their theories to the T-10 computer, a parallel program was underway at the Radiation Laboratory. This resulted in fundamental work of enduring value on the optimum design of servomechanisms where the output performance of the system is optimized to meet required conditions and where the input data is characterized by a noise spectrum superimposed on the error signals. This work headed up by Ralph Phillips, Witold Hurewicz and N. B. Nichols has been published in the Radiation Laboratory series, the volume entitled "Servo Mechanisms."

Now, back to the chronology. The truck version, called XT-1, arrived at Fort Hancock, New Jersey, for tests and demonstrations by the Signal Corps just before December 7, the day of Pearl Harbor. Pandemonium broke loose at Fort Hancock where hundreds of SCR-268 radars appeared from behind bushes for deployment along the east coast to protect us against hypothetical raids which never did occur; but it was certainly no time to burden the Signal Corps with deliberate technical demonstration tests. Advantage was taken of this delay to return to the Radiation Laboratory, increase the power of the transmitter to a megawatt, increase the dish diameter from four feet to six feet, put in a new generation of RF hardware and incorporate the Plan Position Indicator, PPI, which had been developed by another Radiation Laboratory group for use in equiment designed for use in submarine search (Fig. 8). These points are all significant. This increase in power and in the size of the dish extended the performance of the equipment way beyond the specified 20,000 yards, and provided the margin of performance which proved itself in the field. The continuous improvement by the component groups under Lee Hayworth and Jerald Zacharias were providing new generations of components every few months. It must be recalled that microwave waveguides and coaxial lines were in their early infancy and that high-power pulsed circuits and wide-band circuitry, in general, constituted a wholly new technology. It was the combination of continued improvement in the basic components and their rapid incorporation into the XT-1, and subsequently on a continuing basis into the production SCR-584, that made the equipment so reliable in the field.

The early concept of the XT-1 provided for target acquisition either from a remote optical site or from target designation from some search radar such as the SCR-268. The incorporation of the PPI into the SCR-584 made it possible for the unit to acquire its own target and to reduce the dependence of the SCR-584 on external data sources. This again did much to increase the usefulness of the equipment in the field. The XT-1 thus appeared at Fort Monroe, the home of the Coast Artillery Board,

[3] Leo Sullivan was the Radiation Laboratory field representative.

to actually fly an airplane remotely from the SCR-584 cab.

JAN 1941	**PROJECT II, GUNLAYING, STARTED**
MAY 1941	**FIRST DEMONSTRATION OF AUTO-TRACKING (on M.I.T. roof)**
JUN 1941	**XT-1, MOBILE VERSION BEGUN**
FEB 1942	**XT-1 TEST AT FT MONROE**
APR 1942	**LIVE FIRINGS WITH T-10 DIRECTOR AND 90-mm GUNS. DECISION TO PROCEED ON SCR-584**
SEP 1942	**PRODUCTION ORDER 200/mo.**
MAY 1943	**PRODUCTION DELIVERY BEGINS**
FEB 1944	**FIRST BLOOD—184th AAA IN ENGLAND**
MAR 1944	**SCR-584 IN COMBAT AT ANZIO, ITALY**
JUN 1944	**D-DAY: 39 SCR-584 IN NORMANDY**
JUN-JUL '44	**LONDON V-1 RAIDS BLUNTED**
OCT 1944	**OVER 300 JAPANESE AIRCRAFT DOWNED IN LEYTE**
DEC 1944	**FINAL DEFEAT OF GERMAN AIR FORCE. 394 AIRCRAFT DOWNED AND 112 PROBABLES**

Fig. 9. SCR-584 Chronology

in February, 1942. In a few weeks the test of this equipment showed angular probable errors of tracking adequate for blind fire control and the Board recommended the adoption of the SCR-584 as a standard fire control radar. Fortunately, by April of '42 the Bell Telephone Laboratories' T-10 (designated in production as the M-9) electrical computer arrived at Fort Monroe making possible the test of the two units simultaneously. Among other advantages the T-10 input data of range, azimuth and elevation were directly measured in the XT-1 by having the range, elevation and azimuth potentiometers mounted directly as an integral part of the antenna mount, thus eliminating operators who are often characterized by fatigue and battle nerves. Within weeks a completely live demonstration of the XT-1 with the T-10 controlling 90-millimeter guns was demonstrated, drones being shot down in as little as eight rounds.

As I look back I marvel at the speed of events. In current practice, it takes years to study a new weapon system. It takes a year or two for DoD to make up its mind. This is followed by a two- to three-year development program and, if a fly-before-you-buy concept is in vogue, it can easily take anywhere from seven to ten years from the conception of an idea to the introduction of the equipment into the services. In contrast, the XT-1 went from nothing to a demonstration in approximately one year (Fig. 9). The decision to procure was made by the Department of Defense in a matter of weeks and the first prototype was delivered within the next 11 months. In summary, it took two years from conception to IOC and a production rate of ten systems a day.

How was this possible? In the first place, credit must be given to the enlightened leadership provided by Col. W.S. Bowen, President of the Coast Artillery Board and to Col. J. E. McGraw, his Deputy for Antiaircraft. Credit is also due to Gen. Roger Colton of the Signal Corps and to Col. Rex Corput, then Commander of the Radar Programs at Camp Evans in New Jersey, for their wholehearted support under difficult wartime procurement conditions. The Signal Corps gave the Radiation Laboratory group a blank check for the technical management of the production program and the Signal Corps procurement types had a difficult time patching up the contractual trail often on an after-the-fact basis.

The technology of the microwave art was continuously advancing and it was necessary to feed this information to General Electric and Westinghouse. The U.S. total mobilization included training engineers who had no previous experience in these new areas of technology. Thus, at General Electric the radio frequency component engineers and draftsmen had been transferred from the air conditioning divisions—after all, they were used to guiding air in ducts so perhaps they should convert to guiding electromagnetic energy in waveguides. Similarly, the Chrysler engineers, under Gus Syrovy, designing the antenna mounts were from the transmission and rear-end Dodge division; and while they were experienced at designing transmissions and rear ends, they had no experience with the requirements of accurate servomechanisms. Finally, the advancing war kept injecting new requirements on equipment such as the need of loading into holds of Victory Ships, the integration of IFF, the weatherization of the units to withstand jungle parasites, the need of off-shore loading and total immersion in salt water, etc. The fact that the Radiation Laboratory had complete technical control permitted rapid decision-making and optimization of the system even though three major contractors were involved—General Electric, Westinghouse and Chrysler. Nearly 2,000 sets were ordered and the production rate went up to 200 units per month. Simultaneously, training schools were established at Camp Davis in North Carolina; and thousands of maintenance crews were put through school.

In reviewing the actual production design and the production of the SCR-584, one cannot help but pay tribute to American industry. The General Electric Company, the Westinghouse Electric and Manufacturing Company, and the Chrysler Corporation spent only 11 months in the transition from the XT-1 pre-prototype to the initiation of production; and production was complete within approximately eight months, during which time 1,600 units were produced. During the 11 months of engineering, duplicate sources of all components had to be established; major special tooling ordered, constructed and delivered; complete detailed specifications, quality control and test procedures instituted. Units out of the production line were shipped from the factories directly to all parts of the world for immediate operational use. An early production unit was shipped to England for tests by the British at ADRDE, the Air Defense Research and Development Establishment of the British Army, then directed by Sir John Cockcroft. The unit arrived in Scotland the day after a major Luftwaffe bombing attack on the harbor. The unit was off-loaded from the ship onto a barge and rolled up on the beach with nearly complete immersion in the salt water. A British armed convoy drove all night from Scotland to Malvern, England, Lee Davenport was in Scotland when the SCR-584 arrived and accompanied the convoy to Great Malvern. I happened to be in England at that time as the senior member of the second Compton mission and greeted Lee at the breakfast table. After breakfast we removed what seemed like miles of sealing tape, removed two hundred cases of spare parts, removed some 1,000 bags of silica gel which seemed to be hanging from every attachable point within the trailer, drained about five gallons of petrol from some nearby trucks (since we did not have official British Government authorization for petrol), got everything into position and started up the three-phase 15-kilowatt generator. By 11:00 a.m. we were ready for tests. The only fault was that the TR frequency adjusting screw had fallen out and had to be put back into place.

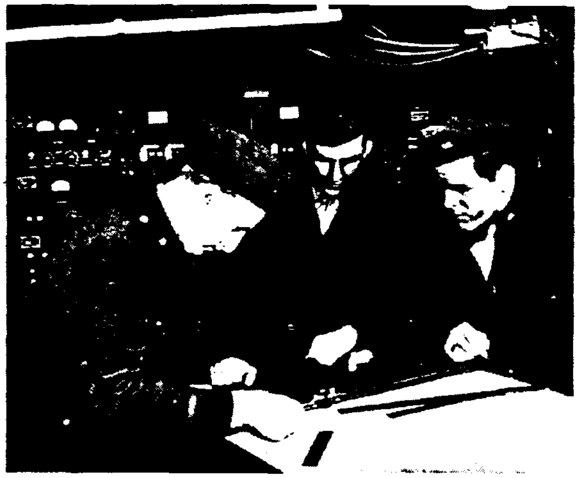

Fig. 10. Automatic Plotting Board; Close Support Bombing; H.J. Hall, R.L. McCreary and CD. Huff

Sitting down to our lunch of boiled potatoes and cabbage with our English friends, we smugly announced that we were operational. This came as a shock to our British colleagues who stared at us in stunned silence. There did not exist in England at that time the industrial base which could be mobilized, nor did the British social and economic system make possible the availability of a large reservoir of engineers. In England, production radar closely resembled the laboratory models with the result that production was slow and the end products lacked reliability and maintainability, thus setting a much lower limit to the overall national capability in transferring scientific results into field use.

Within a year of the decision to go ahead, production units were in the hands of troops.[3] Blood was first drawn on 4 February 1944 when Battery A of the 184th AAA Gun Battalion shot down a German plane at Lippets Hill, London. That same month the equipment saw action when on 24 February, 1944 two SCR-584's and four 90-millimeter guns were unloaded at night at Anzio, Italy. The invasion of Italy had started. The beachhead had been established at Anzio, but development of the beachhead had been made impossible by the nightly raids of Nazi airplanes. The next night seven of 12 attacking planes were shot down. That month at Anzio 63 German planes were destroyed; 20% of German attackers were being destroyed. In one raid, the score was five out of five. The bombing stopped, and the beachhead was developed into a full-fledged invasion.

A few months later on 6 June 1944, 39 SCR-584's with their accompanying 90-millimeter batteries were landed on the beach of Normandy providing, from D-Day on, protection against German airborne attacks.

That same month, Hitler unleashed his terror weapon against London. There were now some 300 SCR-584's in operational use in England, approximately half with the British and half with U.S. Forces. By this time, Col. Art Warner was with General Eisenhower, and a joint U.S.-British program was established for intercepting the V-1 's. The V-1 blitz against London lasted 80 days. The effectivity of the SCR-584, working with the Bell Laboratories M-9 computer and with the NDRC Section T developed proximity fuses, increased to where 95% of the attacking V-1's were destroyed in the air. On the last day of the blitz, of 104 buzz bombs detected over the channel only four reached London. Some 1,629 V-1's were destroyed by AA fire, mostly directed by SCR-584.

A similiar situation developed later in Antwerp. After the Normandy landing, Antwerp became the prinicipal logistic base. Antwerp, with its tremendous harbor, was the backbone of the supply of all the forces in Europe. The V-l's had been directed against Antwerp beginning October 26th. The SCR-584 was rushed in. Within 30 to 40 days, 90% of the V-l's directed against Antwerp were being destroyed.

The German Air Force fighter-bombers continued to attack Allied Forces until the end of 1944 by which time this portion of the GAF had essentially been destroyed by Allied Air Forces and Allied Antiaircraft fire. On December 23, 1944, theGAF fighters mounted over 1,000 sorties, half in support of the battle area. By 28 December, the number of sorties dropped to 150. In a last desperate effort, 800 planes attacked on January 1, 1945—all in a three-hour period. AA batteries claimed 394 kills plus 112 probables.

While these activities were continuing in the field, much work continued back at the Laboratories. There were two trends; (1) to improve the SCR-584 against possible enemy jamming; and (2) to further applications of the highly accurate three-dimensional tracking. In the first category, an X-band version of the SCR-584 was developed in the laboratory and demonstrated. This included the nutating antenna which was later used in the more sophisticated spiral scan antenna of the Navy Mark 56 fire control system. The second innovation was the introduction of the so-called N^2, a narrower adjustable gate superimposed on the narrow gate, which permitted discrimination between chaff thrown from an airplane and the airplane itself. Thus, if the leading edge of the pulse were tracked, the reflection from the chaff, which took some time to expand as it was dropped out of the airplane, was eliminated. A third innovation was the introduction of the sector scan and programmed search. This made it possible to assign SCR-584's to a smaller angular sector and increased the probability of early acquisition. Some 215 units were built in the lab and sent to England. This particular kit turned out to be very useful in the buzz bomb attacks.

Many new applications for use of the SCR-584 began to develop. It was pointed out that the data available in the SCR-584 made possible continuous plotting of the position of an airplane. A lash-up plotting board was put together in the SCR-584 cab. This lash-up board, driven by the synchros on the antenna mount, was called an R-theta board, because of the polar coordinates inuse. If a beacon were put in the airplane, such beacons could be tracked for distances in excess of 50 miles. It was thus demonstrated that an XT-1 located at the Boston Airport could vector an airplane over the Worcester Railroad Station (some 50 miles distant) with sufficient accuracy to drop a simulated bomb on the railroad tracks using a bag of flour as a simulated bomb. It took little extra work to put coding on the beacon and on the SCR-584 transmitter, to add a control link into the autopilot of a B-17 or a B-24, and to actually fly an airplane remotely from the SCR-584 cab.

[3] Leo Sullivan was the Radiation Laboratory field representative.

Fig. 11. Tactical SCR-584-Near Geilenkirchen

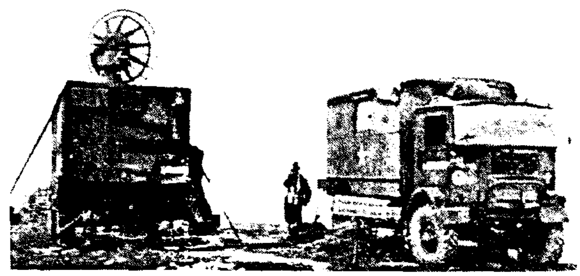

Fig. 12. SCR-584 and Recording Van Set up at V-2 Site Holland

While these experiments were going on, the U.S. Air Force in Great Britain had modified some B-17's and B-24's into what was called the Weary Willy Program. One airplane, completely stripped of normal equipment, took off loaded with 28,000 pounds of TNT. When in level flight and heading in the proper direction, the pilots bailed out. This was Willy Orphan. The Willy Mother plane was another B-24 equipped with a radio command link. A television camera and transmitter in the Orphan was supposed to provide information by which the co-pilot in the B-24 Mother ship could remotely fly the unmanned orphan airplane so as to crash into the German submarine pens along the coast of Western Europe. Unfortunately, in an early flight, one of the Orphan planes exploded over England before the pilots had jumped. One of them was the oldest son of Joseph Patrick Kennedy—by family lore destined to become president. Following this accident, General Arnold solicited the help of NDRC and the system described above was incorporated. Some 200 remote beacons were modified for this use. In the meantime, automatic servocontrol plotting boards were ordered from the Bell Telephone Laboratories (Fig. 10) where the concept of automatic plotting boards was developed in support of their M-9 computer to give a pictorial presentation of the combat situation to the antiaircraft battery commander. With the range, azimuth and elevation potentiometers already in the SCR-584, the adaptation was "neat." I mention these specific things because this application was the forerunner of all the automatic output plotting devices which are so prevalent today.

The same technique was also provided for the control of tactical aircraft. Some 50 automatic tracking boards were procured from the Bell Telephone Laboratories and sent to the Radiation Laboratory branches in London and in Paris and introduced into the Eighth and Ninth Tactical Air Forces. In the previous normal procedure, fighter bombers were dispatched to bomb specific targets un the German side of the FEBA. It was difficult to identify these targets. A number of runs had to be made. Time of flying over enemy territory was excessive and many planes were lost to ground fire; and, often the wrong targets were bombed. By using the automatic plotting board with the SCR-584, fighter-bombers could be vectored directly to their target on a course which avoided known enemy antiaircraft installations. The fighters could then be vectored to return through entry points over our own antiaircraft fire. This application was so successful that it was used even in times of good visibility (Fig. 11). Thus, inJuly 1944, during the Battle of the Bulge, General El wood Quesada, commanding the Ninth Tactical Air Force, said of the battle in an official report:

"Radar's work during the period of the German breakthrough was outstanding. The Bulge contained no well-defined topographic features, the whole thing could be flown around in less than ten minutes. Roads were chockablock with movement. From the air we couldn't distinguish our vehicles from theirs. It is our hope to track by radar each flight directed into the Bulge. The number of American lives saved by our ability to stop attacks on our own columns and installations cannot be measured."

During a good portion of the Battle of the Bulge the weather was so bad that the entire Tactical Air Force was grounded, except for a few P-47' s which flew through the fog and at night dropping bombs on the Cologne Aachen Road loaded bumper to bumper with German trucks bringing supplies to their troops. The P-47's were simply directed on the automatic tracking boards to follow the road and drop bombs at intervals. Even one cratering of the road was enough to block the traffic for hours.

Field innovations put the SCR-584 to uses for which it was not intended—nor readily adaptable. Thus, some SCR-584's were buried by being bulldozed so that the entire semi-trailer was below ground level. At night the elevator was raised and the antenna placed in its normal operating condition. In this position it could scan across a battlefield and by Doppler flutter distinguish between a moving vehicle or man and fixed targets such as buildings. The position of the target was determined by superimposing the narrow gate on the fluttering signal and artillery fire was immediately directed. This technique was used at night by the XV Corps during the Battle of the Bulge to keep man-packed supplies from reaching the German front lines. Gen. Ott assigned 150-mm howitzers to provide support fire.

Another application of the remote automatic control through the SCR-584 was its application to the American version of the buzz bomb. Bob Lovett, the Assistant Secretary of the Army for Air, had been in London during the buzz bomb krieg. He was so impressed that on returning to the United States he put into production an American copy of the buzz bomb at the rate of 100 per day. The first production unit was shipped to the Radiation Laboratory where a coded, modified, Rosebud beacon was installed. The overall system was operational when VE-Day arrived; but the system would have provided a devastating capability had it gone operational.

Another application of the SCR-584 was found when in January 1943 the XT-1A tracked a 90-millimeter shell to 10,000 yards at Camp Davis. The unit was then shipped to Aberdeen where ballistic tables were generated. The normal procedure for generating ballistic tables was to fire shells from a gun at a given elevation and at a measured muzzle velocity. The impact of the shell was then measured. Using the best known drag theory, the trajectories were calculated on a differential analyzer, a copy of the one which Vannevar Bush and Sam Caldwell had built at M.I.T. These ballistic tables were then converted into three-dimensional cams for use in the M-4 computer and specially shaped potentiometers in the M-9 computer. When the XT-1A was used to measure the actual flight of the projectile, it was found that the assumed drag theory had resulted in errors in the time-of-flight to operational altitudes of the order of a second. These corrections were incorporated in the ballistic potentiometers of the M-9.

A related development came in experience with the field Army forces in Italy. Something like 85% of all the casualties to troops in World War II were the result of mortar fire. Mortars are quiet when they're fired. They are fired on a high trajectory; and, from behind a hill or obstruction. The recipient is not aware of the firing until the mortar shell itself has exploded; but, just as with the 90-millimeter shell, it was found possible to scan a portion of the sky using the sector scan device at a high elevation angle and pick up and lock on an individual mortar shell. At the same time the automatic plotting board would draw a line on the map showing the horizontal projection of the trajectory. Clearly, the enemy mortar had to lie somewhere on that line. To find the exact point, a vertical automatic plotting board was added on which the trajectory of the mortar appeared as a partial parabola. With simple drafting-type aids, it was possible to extrapolate this parabola to the ground and locate the exact point from which the mortar shell had been fired. Operationally, these procedures were not very significant because it was impossible to move such large equipment in sufficient numbers to cover any reasonable fraction of all the mortar firings.

The technique however was also employed when Col. A. H. Warner moved some SCR-584 units into Holland during the V-2 ballistic missile blitz-krieg (Fig. 12). One SCR-584 at Steenbergen detected 88 V-2's and tracked 81%. While the ranges were substantially higher than with mortar shells, the targets themselves were much larger and generally broadside to the radar. It was thus possible not only to predict where the V-2's were going to hit, but also to locate the launch pads. Tactical fighter bombers were then to be directed to the launch pads; but progress of the war in Europe forced German withdrawal.

When the war moved to the Pacific, the SCR-584 followed.[4] While it was principally a Navy war, Army AA did play a role in defense of islands. Thus in October 1944, over 300 Japanese planes were destroyed by SCR-584 M-9 90-mm guns (and also some 40-mm guns) in the first few weeks. InDecember 1944, over a two-week period, in Mindoro, 16 SCR-584's plus 64 90-mm guns shot down 21 Japanese planes. In Leyte and Luzon, SCR-584's controlled recce and mapping plans and also controlled artillery fire.

Finally, I should mention that the combination of the SCR-584 with its plotting board and its beacon, which became known as the APW-11, was adopted by SAC immediately after the War as a means for scoring SAC bombers in simulated attacks on cities and other targets. The bombardier went through his normal blind bombing procedure and at the proper moment pressed the button for the "bombs away." During this interval, the SCR-584, now designated as the MPQ-1, tracked the airplane to its point of bomb drop; the bomb drops were then computed to see whether the bomber would have in fact struck its assigned targets under the wind conditions then prevailing. (I should add that all the bombing tables towards the end of the War were revised by using the XT-1A at Aberdeen, actually tracking the airplane and also the bomb during its fall.) This equipment has continued to be used; and, as a matter of fact, the MPQ-1 was used during the Vietnamese War to direct B-52 bombers in their attacks over North Vietnam.

Now let us turn to the Navy. Actually, it is necessary to break this story into two parts: the light antiaircraft guns, principally the 40-millimeter Bofors guns, and the heavy antiaircraft guns (dual purpose) consisting principally of the 5″/38-calibre automatic rifles. The Navy had developed a 1.1-inch rapid-firing gun for use against dive bombers and torpedo planes. Just before Pearl Harbor, the Navy had switched to the 40-millimeter Swedish Bofors gun and this was the principal light AA gun used by the Navy for the duration of the War. A crash program for fire-control directors and predictors had been started by the Navy at the Ford Instrument Company, the Mark 45 and Mark 49, and at the Anna Corporation, the Mark 50, both in Long Island City, the two principal sources of Naval range-keepers or computers. About that time, a young Lt. Commander by the name of Rivero, recently the Chief of Naval Operations and the only admiral in the United States Navy of Puerto Rican extraction, had returned from the Mediterranean where, as official U.S. Navy observer, he had seen the major part of the British fleet sunk by Nazi and Fascist planes. Early in 1941, Lt. Com. Rivero called a meeting at the Ford Instrument Company attended by Ridenour and myself from the Radiation Laboratory. An immediate decision was made to develop a range-only radar to go with these directors; and, under the persuasion of Louis Ridenour, it was agreed that a radar angular error signal would also be provided to assist the optical trackers in the directors. John Meade of Project II was assigned to this project; and, as a matter of historical fact, this was the first microwave radar that went into production. It was designated radar Mark 9. Unfortunately, none of the directors was brought into successful production—all were cancelled. In short, the directors had become too complicated and too expensive to support the 40-millimeter guns whose employment was to proliferate by the thousands throughout the Navy. In part, this cancellation was influenced by the dramatic success of Stark Draper in producing a relatively simple lead-computing-sight designated the Mark 14. Stark Draper, then a professor at M.I.T., had been working with the Sperry Company to develop the simplest possible lead-computing sight. It consisted of a single gyro which was displaced ahead of the line-of-sight so that the sight was pointing at the predicted position and the present position was only a virtual optical line produced by mirrors appropriately positioned from the gyro line through springs. A simple pendulum correction was added for super elevation; and estimated range was used. This sight was several orders of magnitude cheaper than the Mark 49 and Mark 50 and it went into large

4 Accompanied by Henry B. Abajian of the Radiation Laboratory.

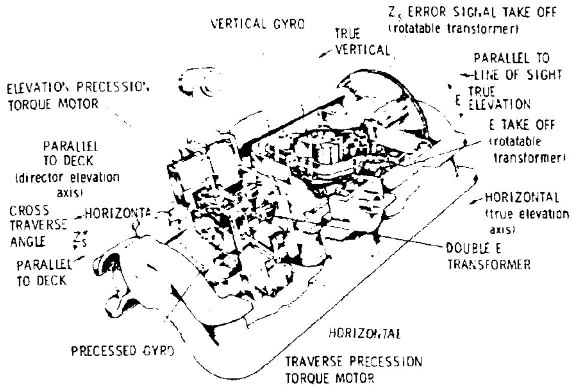

Fig. 13. GFCS Mk56 Geometry

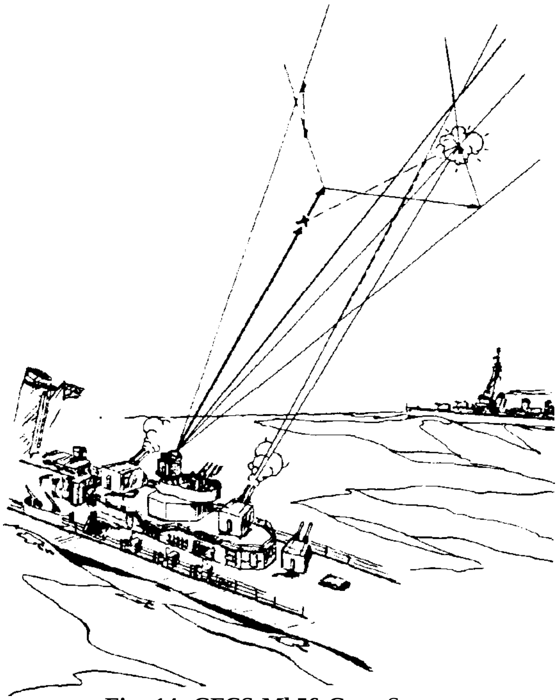

Fig. 14. GFCS Mk56 Gyro System

production paralleling the large production of the 40-millimeter Bofors guns. To a large degree, the success of the defense of the Navy against Japanese airplanes in the Pacific is to be attributed to the combination of the 40-millimeter guns and the Draper sight. Fortunately, for the U. S. Navy most of these attacks were in daylight.

In late 1943 a system was demonstrated for adapting the Draper sight to complete blind firing. This project was a joint program between Section T of OSRD and the Radiation Laboratory at M.I.T. In essence the SCR-584 mount, which was then in large production, was used to track the target airplane and the radar Mark 9 described above, then in the warehouse, was modified to operate with this mount. The radar present position was tied into an angle converter built by the Radiation Laboratory which then positioned two supplemental mirrors in a modified Draper Mark 14 sight—this modification being made by Section T. This second set of mirrors presented to the operator a red circle indicating the position of the radar antenna—quite apart from how the operator moved the Draper sight. Thus, under normal operation in good visibility, the operator would see the airplane on the sight cross-hairs as he was tracking with his lead-computing sight and the airplane was surrounded by a red circle. If the airplane disappeared in a cloud or smoke, the operator merely tracked the red circle. This system was tested at the Naval Annex on Chesapeake Bay. The results indicated that all-weather firing could be performed as accurately as the best visual firing; but the Bureau of Ordnance chose not to implement the system. Thus, the Navy went throughout World War II without any capability for all-weather firing of its 40-millimeter guns.

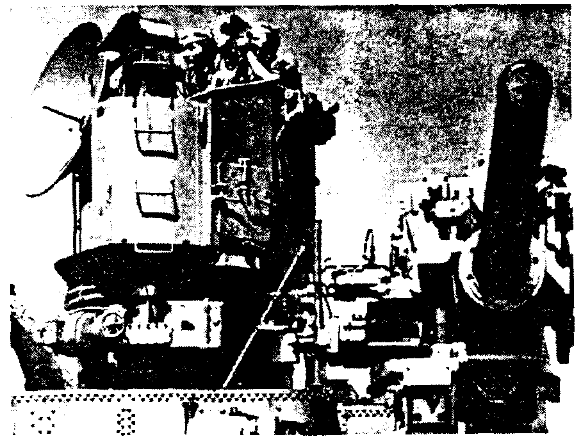

Fig. 15. GFCS Mk56 Director

The story on the 5-inch dual purpose guns was different. By 1940, the Navy was equipping the Mark 37 director with the 60-cm FD radar developed by NRL and built by Western Electric . This radar was certainly an outstanding piece of work and at that time led all other radars in the world in regard to range performance and accuracy. Nevertheless, it had its limitations because of the wide-beam and its inability for accurate tracking at low elevation angles.[5] However, the overall system, including the radar, the director and the range-keeper had other basic limitations. It was the outgrowth of the original range-keeper designed by Hanibal Ford in World War I for main battery control—and actually a brilliant piece of work. Ford had optimized the range-keeper to make maximum use of observables. Before the advent of radar, the gunnery officer got bearing and bearing rates by tracking through a telescope. He could see the enemy ship and estimate its course and speed (in World War I ships were painted in peculiar zigzags to confuse the estimate of course). Speed was relatively easy to estimate either by listening to the revolution rate of the enemy ship's propellers or by observing the bow wave. The range-keeper, therefore, used estimated enemy course and speed and own course and speed to generate an analog model of the battle. Again, the most difficult datum was the range. An estimated range was put into the range-keeper. The range-keeper then generated the bearing position for the Mark 37 director; and the optical tracker in correcting the bearing fed back into the computer a correction in the bear-

5 Towards the end of the War, the Bureau of Ordnance added a microwave radar to the Mark 37 director to assist in the problem of measuring elevation angles at low elevations.

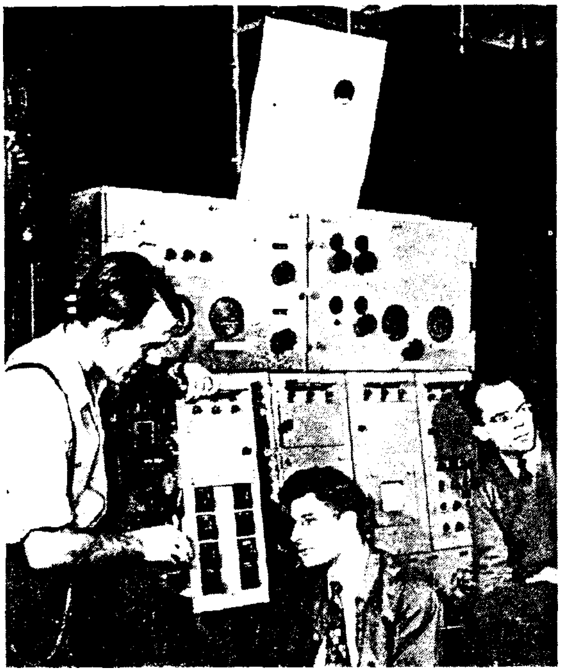

Fig. 16. GFCS Mk56 Console (Rad Lab Model), R.W. Lantz, H.B. Battey and R.V. Harris

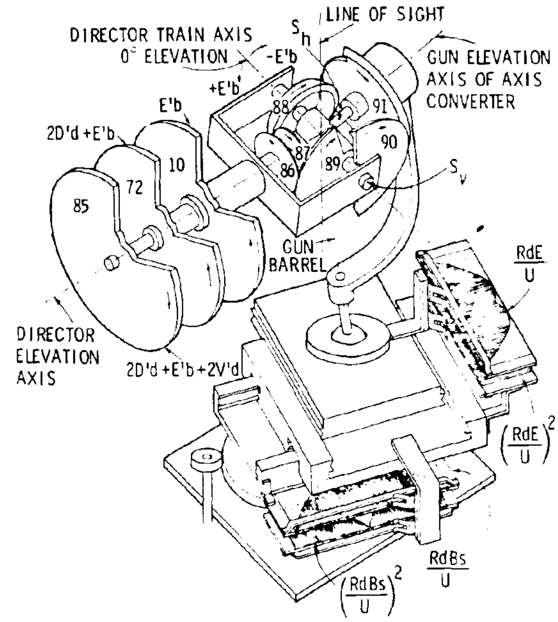

Fig. 17. GFCS Mk56 Axis Converter

ing rate; and the range-keeper would exponentially solve the problem—including range. Finally, by observing the splashes from the first trial shot, range was corrected and the problem was completely solved. There were many advantages to this system: the ship could change its course and speed and the computer kept continuous tabs; the ship could roll and pitch, but the stable vertical (a beautiful unit built by Arma) would keep the optics on the target, and the guns continuously pointing in the right direction for continuous fire in spite of roll and pitch; and, if vision was interrupted by gun-fire smoke, the range-keeper kept the system going with uninterrupted fire.

Between World War I and II this range-keeper had been modified for antiaircraft use by adding the third dimension airplane altitude. But the Mark I computer or range-keeper in use with the Mark 37 director and the FD radars had all the limitations built into the system. For example, the equipment was so large that only one could be installed in a destroyer which usually had three twin gun turrets. So, while the guns could in principle engage three different targets, the overall system was limited to one attacking plane at a time. It was necessary to insert the estimated heading and speed of the aircraft; and, even though the radar could provide bearing, elevation and range, the computer arrived at the solution exponentially. If the airplane changed course, or if the original estimates of course and speed were in gross error, the correct solution was not available until the airplane had released its weapons. Many of these deficiencies of the Mark 1 range-keeper turned up when a dynamic tester developed by Section D-2 of NDRC was made available to the Radiation Laboratory These tests further demonstrated that in the interval between World War I and II, when the modifications had been made to adapt the range-keeper to three-dimensional use, simplifications in the computation of the roll of the ship resulted in substantial errors. These limitations were not fully understood within the Navy; and, in any case, for substantive reasons, the Bureau of Ordnance was loath to make any changes in the combination of the FD radar, the Mark 37 director, Mark 1 computer directing the five-inch guns. These equipments were in large production, all the ships at sea had been equipped, training schools had been established and spare parts and maintenance were available. Ships return only every two years or so for major overhaul and the prospect of making any serious changes in such a complicated and integral system was more than the Bureau of Ordnance was willing to accept.

Early in 1943 it became apparent that progress in applying radar to Navy Antiaircraft gunnery could be accomplished only by a totally integrated effort starting from basic principles. Such a gun fire control system would take advantage of the radar for continuous measurement of range, elevation and azimuth. It should be designed for rapid target acquisition either remotely from search radars, target designation from the Combat Control Center, or locally by means of its own optical search and radar search. The computer had to be optimized for very rapid solution with minimum smoothing consistent with the overall system dispersion, including the guns. Settling time of the computer had to be measured in seconds and, in particular, dive bombing targets and low flying torpedo planes were to be the principal targets. In particular, emphasis was to be placed on ranges from 10,000 yards down, though the system should be able to operate at ranges in excess of that and also serve a secondary function of main battery control against fixed land targets or against rapid surface targets such as torpedo boats.

About 1943 NRDC had been merged into a new structure—the Office of Scientific Research and Development under Vannevar Bush. The old Section D-2 on fire control with Warren Weaver as Chairman had become Division 7 with Harold Hazen as Chairman. (In addition to my role as Division Head of Fire

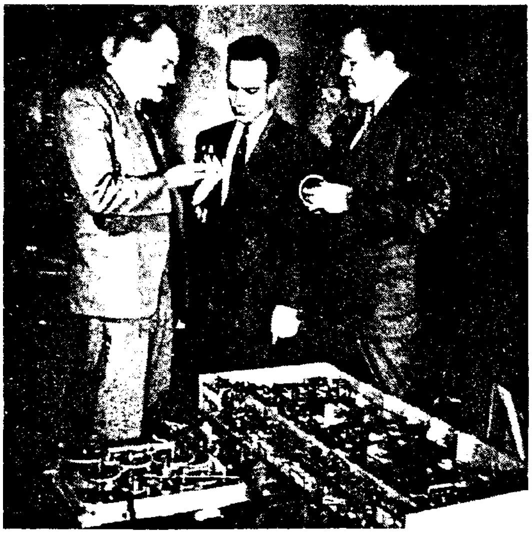

Fig. 18. GFCS Mk56 Ballistic Computer, R.L. Kenngott, C.W. Miller and A. Svoboda

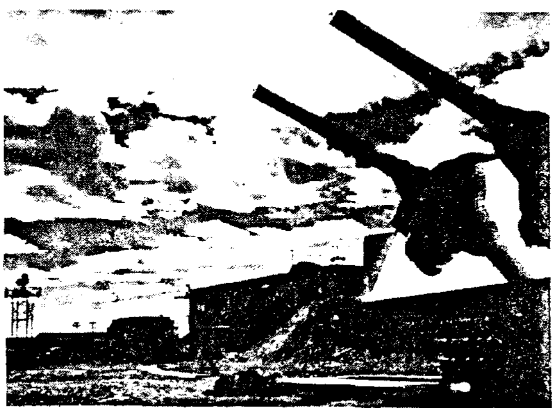

Fig. 19. Ft. Heath Test Station 5"/38 Guns and GFCS Mk56

Fig. 20. GFCS Mk56 Div 7, NDRC—A. Ruiz; Com. R. Burroughs; I.A. Getting and H. Hazen, Div. Chief

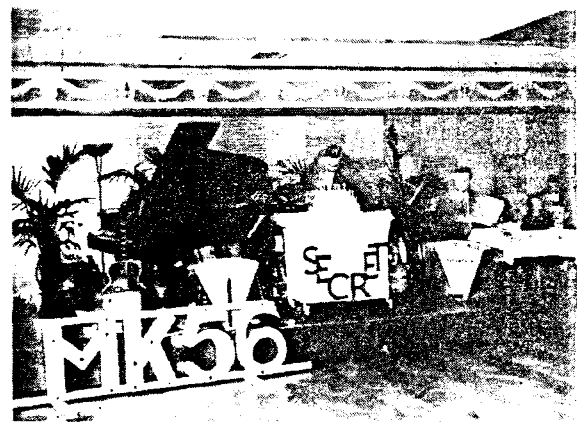

Fig. 21. Dr. L. DuBridge, Director of Radiation Lab at GFCS Mk56 Production Party

Control Radar (Division 8) at the Radiation Laboratory, I was also a member of Harold Hazen's division on fire control.) It was agreed between Hazen, Chief of Division 7, and Lee DuBridge, Director of the Radiation Laboratory, that Division 8 of the Radiation Laboratory would be charged with the direction of such a new integrated naval fire control project. The Bureau of Ordnance indicated its support by requesting the establishment of Project NO-166 in a letter dated May 18, 1943, and designated the new system as the Gun Fire-Control System, Mark 56. The backing of Captain Emerson Murphy and that of Captain D.P. Tucker was very heartening.

Fire control aboard ship is substantially more complicated than that on land because of the motion of the ship (Fig. 13); and it is necessary to establish an inertial frame of reference. For the Gun Fire-Control System Mark 56, and to provide for the integration with radar, the inertial frame of reference was selected as the line-of-sight between the ship and the target airplane. This was accomplished by a line-of-sight gyro (Fig. 14). If the target airplane were not to move, this gyro would automatically keep the radar and the director pointing at the airplane regardless of the motion of the ship. The entire director was slaved to this gyro. Of course, the plane does move thus making it necessary to precess the gyro continuously, so that its axis followed the moving line-of-sight. This was accomplished by precision torque motors whose currents were designed to be proportional to the angular rates of the line-of-sight. There was also a second gyro which measured true vertical. This gyro served two basic purposes: one it stabilized rotation around the line-of-sight to permit optimum data smoothing and also permitted the calculation of super elevation, being the added angle in gun elevation to account for the influence of gravity on the bullet during the time of flight.

In this system the error signal from the conical scanning radar is fed directly into the elevation and traverse torque motors, while the gyro itself automatically takes out the motion of the ship.

The gyro system of the Gun Fire-Control System Mark 56 is mounted in the director (Fig. 15). In addition, the director contains the transmitter and receiver of the Mark 35 radar; and the director has two operators. One of them controls a slew sight. His job is to point using wide-angle binoculars to the next target. When the other optical tracker or the radar operator, who is below deck, releases the system from the current engagement, the director automatically slews to the next target. Under conditions of bad visibility, these operators become redundant, and all the control is from the console below decks (Fig. 16). At the console information is received from the Combat Control Center; and, alternatively, the Mark 56 is doing its own search pattern by means of a spiral scan mechanism in which the antenna is nutated in a spiral scan with a field of approximately 15 degrees. If a target is seen by the radar, it automatically locks and converts from spiral scan to conical scan for tighter tracking. In a matter of approximately three seconds, the guns can start to fire.

Unlike the range-keeper used by the Navy or the M-4 and M-9 directors of the Army, the Mark 56 system did not explicitly solve the total geometrical problem. In effect, it used the two angles and range plus the first derivatives, to solve the lead angles in traverse (azimuth) and elevation. These lead angles were then added to the line of position and converted to gun coordinates by a modification of a three-dimensional analog angle solver (Fig. 17) adapted from the work of John Moore at General Electric for use in the B-29 gun computer. Ballistics computations, adaptable to various types of guns, was done by a linkage computer (Fig. 18) designed by Tony Svoboda.

Industry was brought in from the beginning and participated in the production design in parallel with the work at the Radiation Laboratory. The radar was built by GE at Syracuse and contained all the goodies that had resulted from experience with the SCR-584. It operated at X-band with 1/10th of a microsecond pulse and vertical polarization, all contributing to reducing the effect of sea clutter and permitting tracking at elevation angles approaching a degree. (There was a special operating mode for low angle operations against torpedo planes in which it was assumed that the target was flying at 100 feet. This special mode provided for the stable vertical gyro to take over control from the elevation error signal of the radar.) The director itself was manufactured by the General Electric Company in Bureau of Ordnance plants at Pittsfield, Mass. Other parts of the system were made by Librascope, by the Ford Instrument Company, and by the Arma Corporation.

Two prototypes were built, the first was installed at the Division 8 field station at Fort Heath in the Boston Harbor (Fig. 19). The Navy furnished a twin 5-inch 38 turret. The director was mounted on a rolling platform and a complete systems checkout was made, except for actual firing. The second system was installed in a destroyer at the Boston Navy Yard.

Interest within the Navy was great and many visitors came to Fort Heath to see this system in operation. Amongst them was Com. Robert Burroughs from the Office of the Chief of Naval Operations (Fig. 20). Commander Burroughs, a reserve Naval officer and a physicist, was particularly intrigued by the substantially greater promise which the Mark 56 system provided. However, as the moment of decision arrived, the Bureau of Ordnance hesitated, and quite properly, because of the magnitude of the job facing the Navy should they decide to add this system to the hundreds of combat ships at sea. Commander Burroughs' enthusiasm prevailed; and Admiral King, Chief of Naval Operations, commanded the Bureau in a written memorandum to procure immediately an initial buy of 50 Mark 56 systems. This raised a statutory question, since the Bureau of Ordnance was an independent agency. But the issue was never closed; because, that same day, before Admiral King's memo could travel from one office to the other, the Chief of the Bureau of Ordnance independently ordered an initial buy of 50 Mark 56 systems.

Somewhere along the line there was a Radiation Laboratory celebration (Fig. 21). Here is Lee DuBridge, Director of the Radiation Laboratory, helping. Throughout the history of the Lab, Lee had strongly supported the SCR-584 and the Mark 56—both programs reflected the results of the total efforts of the Radiation Laboratory in advancing the microwave art. When the services were dismayed by the magnitude of improving blind-firing, Lee DuBridge continued support by keeping "gun laying" at a high level of priority within the Laboratory.

The War came to an end before any of the production systems of the Mark 56 got into ships; but the continued buys of the Mark 56 system represented the largest investment made by the Bureau of Ordnance up to that time; and today, a third of a century later, more than half of all the fire-control systems in the Navy are still the Gun Fire-Control System Mark 56. It is impossible to test fully this equipment in peacetime; but, I am sure, had the Navy been exposed to the intensive attacks which it experienced near the end of World War II, the system would have demonstrated its designed capabilities.

In this talk I have described to you the pioneering effort of marrying precision radar to antiaircraft fire control computers. As you saw, the effort opened many areas of new applications. The effort involved many people; and there were a number of collateral programs which time did not permit to mention. The subject matter was one fitting for your concept of the pioneer award in that the events took place more than 20 years ago and in that the experiences were new to those who were involved. Precision radar today is commonplace; but in 1940 it seemed like a miracle.

REFERENCES

1. A.F. Kowe, "*ONE STORY OF RADAR,*" Cambridge, London, 1948.
2. Henry Gerlac, "*THE RADIO BACKGROUND OF RADAR,*" J. Franklin Inst.. Vol. 250, No. 4., p. 286, Oct. 1950.
3. Carl F.J. Overhage, Editor, "*THE AGE OF ELECTRONICS,*" McGraw-Hill Book Co.. 1962. Chapter IV Radar (by I.A. Getting)
4. Vannevar Bush, "*PIECES OF THE ACTION,*" William Morrow & Co., 1970
5. James Phinney Baxter, 3rd, "*SCIENTISTS AGAINST TIME,*" Atlantic Monthly Press, Little, Brown & Co., 1946
6. Joseph C. Boyce, Ed., "*NEW WEAPONS FOR AIR WARFARE,*" Atlantic Monthly Press. Little, Brown & Co.. 1947
7. Harold A. Zahl, "*RADAR SPELLED BACKWARDS,*" Vantage Press, 1972
8. Wesley W. Stout, "*THE GREAT DETECTIVE.*" Chrysler Corp., 1946
9. M.I.T.. "*FIVE YEARS AT THE RADIATION LABORATORY,*" Cambridge, Mass., 1946
10. Henry E.Guerlac, "*RADAR IN WORLD WAR II OSRD,*" Distributed by Office of the Publication Board, Department of Commerce
11. Radiation Laboratory Staff Members, 1940-1945, M.I.T., June 1946.