Section 21

MILITARY ELECTRONICS

Organized with the assistance of the IRE Professional Group on Military Electronics

The Early History of Radar*

R. M. PAGE†, FELLOW, IRE

Summary—**Five basic ideas are identified, the combination of which consitutes radar. A clear distinction is then made between this combination of ideas, the contemporary technology from which it grew, and the contemporary scientific knowledge on which it was based. The mainstream of the development of radar is traced in a sequence of related events from 1922 to 1941. The technical problems encountered and the solutions employed in the first radar development are outlined in some detail. Two sidestreams of radar development are identified. The relationships among the three streams are discussed.**

TECHNOLOGICAL innovation grows out of contemporary technology, which in turn rests on the research and scientific discoveries of an earlier day. Only when clear distinction is made between innovation, contemporary technology, and contemporary scientific knowledge can lines of interdependence be meaningfully drawn.

The combination of five basic ideas constitutes the innovation which is radar. They are 1) that electromagnetic radiation at high radio frequency be used to detect and locate remote reflecting objects, 2) that the radiation be sent out in pulses of a few microseconds duration, separated by "silent" intervals very many times the pulse duration, 3) that pulses returned from reflecting objects be detected and displayed by receiving equipment located at the point of transmission, 4) that distance be determined by measuring in terms of an independent time standard the time of flight of pulses to "target" and back, and 5) that direction be determined by use of highly directive radio antennas.

We first identify the scientific knowledge underlying these ideas. Faraday and Maxwell had established the theoretical possibility of the electromagnetic field. Hughs had demonstrated its existence at radio frequency. Hertz had demonstrated that radio waves behaved as light waves, obeying the known laws of propagation and reflection. Appleton and Barnet had demonstrated that radio waves could be used in interferometer fashion to determine apparent height of the ionosphere. Their method used phase velocity to measure the difference in length of two propagation paths. Swann and Frayne had suggested and Breit, Tuve, and Taylor had demonstrated that radio waves could be used to measure ionosphere height by observing the relative flight time of pulses of radio transmission. Their method used group velocity to measure the difference in length of two propagation paths. Various experimenters in radio, including Breit and Tuve of the Carnegie Institution, working with ionosphere measurements, engineers of the British Post Office working with short wave radio, and engineers of the Bell Telephone Laboratories working with television, had observed that aircraft flying near their receivers or transmitters created noticeable disturbances in the radio propagation field. This was regarded merely as interference with their experiments, and otherwise ignored. These constitute the elements of scientific knowledge basic to the idea of radar. Since radar was not in any way an objec-

* Received by the IRE, August 8, 1961.
† U. S. Naval Research Laboratory, Washington, D. C.

tive in the discovery of these facts, since no problem was recognized for which radar was the proposed solution, and since radar was only one of many technological innovations dependent on these same scientific discoveries, it is not proper to ascribe to any of the named discoverers any responsibility for the origin of radar by virtue of their discoveries.

Our next step is to identify the contemporary technology out of which radar grew. A catalogue of the state of the art in radio engineering in the 1930's would be both tedious and superfluous. Certain elements have a degree of specificity to radar, however, and require special mention. The cathode-ray tube, devised by the German scientist Braun in 1897 and used on an experimental basis in the early 1920's, became generally available as a laboratory tool in the early 1930's. In 1900 Nikola Tesla suggested the use of electromagnetic waves to determine relative position, speed, and course of a moving object. In 1903 Huelsmeyer applied for a patent in Germany on an anti-collision device for ships, based on directive transmission and reception of continuous waves at very short radio wavelength. Transmitter and receiver were shown on the same ship, but separated as widely as possible. In June 1922 Marconi again suggested the use of radio as an anti-collision device. In 1923 Loewy filed a patent application in the U. S. Patent Office for a radio object detector employing the Fizeau principle. The transmission consisted of chopped CW, with approximately equal intervals on and off. A target would be detected when its reflection coincided with the intervals between transmission. While Loewy's disclosure appears at first to anticipate radar, it fails to meet the requirements for radar, since range indication is ambiguous, and the presence of one target would jam the system for all other targets. Thus it gave no operational advantage over Huelsmeyer, except the possibility of locating transmitter and receiver close together. In 1925 Breit and Tuve proposed a radio pulse method, which they credited originally to Swann and Frayne of the University of Minnesota, for probing the ionosphere. In cooperation with Taylor, Young, and Gebhard of the Naval Research Laboratory the method was used for the first time in that same year. Although this has been said to demonstrate the basic principles of radar, it fails to meet the radar criteria on several counts. The pulses were much too long, being about half a millisecond. This would blank out the first 50 miles of range. The ratio of pulse spacing to pulse duration was too low, being only four or five, therefore subject to saturation by a very few targets. The receiving equipment was not at the point of transmission, so time of flight of radio pulses to target and back could not be measured in terms of an independent time standard. Only the difference in length of two propagation paths was measured, and direction was not indicated. These deficiencies from the radar viewpoint were imposed by the state of the art in 1925. They detracted nothing from the excellence of the method or the apparatus for probing the ionosphere. In 1930 patent applications were filed by Wolf and Hart for a radio pulse altimeter. The disclosures were based on the technology of the ionosphere probe, and were therefore subject to some of the same limitations. No development of radar apparatus resulted from these disclosures. In November, 1933, Hershberger (U. S. Signal Corps) proposed a method essentially similar to that of Loewy and then did some work on microwave generators in a vain attempt to obtain the power required for useful echoes. In 1936 the French liner Normandie was equipped with a microwave anti-collision device similar to that of Huelsmeyer.

It is now obvious that contemporary technology contained much that was suggestive of radar. However, none of the art described contained all five elements necessary to radar, and no radar development resulted from any of it. It is therefore inappropriate to trace the development of radar to any of these proposals or related developments.

The first incident that led ultimately to radar was the accidental observation by Taylor and Young in September 1922 that a ship interrupted some experimental high-frequency radio communication across the Potomac when it intercepted the propagation path between transmitter and receiver. Taylor and Young had for many years been employed by the Navy, and were keenly aware of the problem of screening Naval forces from penetration by other ships in darkness and fog. Though the observation was unrelated to their experiment, the application was obvious to them, and they immediately proposed that high-frequency radio transmitters and receivers be installed on destroyers to detect the passage of other ships between any two destroyers in radio contact. Obviously this was not radar. It did not even involve reflection of radio waves, and was in no way related to Marconi's suggestion, as has sometimes been inferred. It is identified with radar here only because Taylor and Young later originated the first radar development project, and this incident started them thinking in terms of detection of moving objects by radio.

The second incident was another accidental observation, this time by Hyland, a colleague of Taylor and Young. During experiments on high-frequency radio direction finding in June 1930, he detected a severe disturbance of the propagation field by an airplane flying overhead. Hyland was also an experienced Navy employee, and was sensitive to the potential threat of military aircraft and the need for warning devices against them. The observation again was unrelated to his experiment, but the application was obvious, and he immediately proposed that high-frequency radio be used for aircraft warning.

On Taylor's recommendation a project was established at the Naval Research Laboratory in January 1931 for "Detection of Enemy Vessels and Aircraft by Radio." Work on this project continued for several years. The "beat" method was employed, in which transmitter and receiver were widely separated and shielded from each other, transmission was CW and reception observed the fluctuating signals, called "beats," when an airplane flew through the radio propagation field. Detection ranges of 40 miles were obtained in these experiments.

The required wide separation of transmitter and receiver precluded the use of the beat method on ships and limited its usefulness to the protection of large land areas such as cities and military bases. Since this was exclusively the responsibility of the Army, it was proposed in January, 1932, that the Army take over the development for its use in that function. Subsequently, Navy interest in the problem lagged until Young suggested to Taylor that the pulse method be tried. Young's proposal combined for the first time all five elements essential to radar. Ultimately, Taylor accepted the proposal and assigned to the author, working under Young's supervision, the task of developing pulse radar. The author's work on this task was started on March 14, 1934.[1]

The first step was to develop an indicator to display the outputs of transmitter and receiver. A suitable sweep circuit was built for a commercially produced 5-in cathode-ray oscilloscope. The next step was development of a pulse transmitter. The transmitter frequncy of 60 Mc was chosen because that was the frequency then used in the beat method. Pulse length was slightly under 10 μsec, and pulse spacing, 100 μsec, these being chosen as appropriate experimental values. The keyer was an asymmetric multivibrator. The antenna was a single half-wave horizontal doublet with a single resonant reflector. The pulse power was estimated to be between 100 and 200 w. The first question to be resolved was whether echo pulse energy could be detected during the intervals between transmitted pulses, since synchronous detection, characteristic of the beat method, was known to be more sensitive than asynchronous detection, characteristic of the pulse method. Autocorrelation and crosscorrelation were unheard of in those days, and the trade-off between time and bandwidth disclosed by Hartley,[2] as well as the significance of average energy were not too well understood. The only sure recourse was to try it, and skepticism was great. A broad-band high-gain experimental communications receiver was borrowed and connected to a second antenna similar to the transmitting antenna. Coupling between the two antennas was appreciable, and the transmitted pulse caused the receiver to ring for 30 to 40 μsec. However, when a small airplane flew across the beam at a distance of about a mile, the received signal caused the receiver output following the transmitted pulse to fluctuate violently between zero and saturation. This test was completed in December,

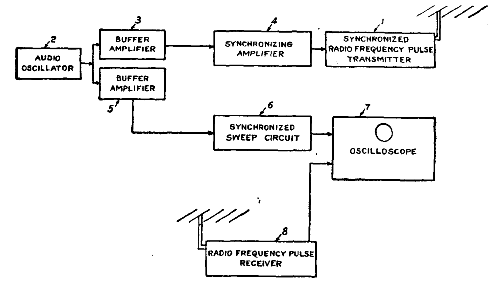

Fig. 1—Block diagram of radars operated in 1936. The block diagram for the radar tested in December, 1934, was similar to this one.

1934. Although synchronous detection prevailed due to the transient ringing of the receiver, the great amplitude of the response left no doubt that an asynchronous detector would also have responded to the reflected pulse. The result was accepted as evidence that echo signals could be detected during the intervals between transmitted pulses, and development of a superior radar receiver was immediately undertaken.

Radar imposed four severe requirements on the receiver which were not encountered in conventional receivers of the time. Close proximity of receiver and transmitter subjected the receiver to paralyzing overload, from which recovery to full sensitivity in the incredibly short time of a few microseconds was mandatory. The first design requirement was to eliminate grid blocking. This was achieved by using a tuned grid circuit with the grid returned to the cathode through the tuning coil. Grid coupling capacitance was then reduced to a minimum by using maximum inductance to capacitance ratio in the tuned circuit, and loading the tuned circuit to the proper Q value with the driving plate resistor.

The second design requirement was to minimize the ring time of tuned circuits from the transmitter-induced high signal level. This was achieved by returning grids to cathodes without bias, thus limiting the level to which the circuits could be driven by the transmitter.

The third requirement was fast response to amplify the short pulse echoes. This meant tailoring the Q values of all tuned circuits so that the composite Q of the receiver would match the pulse length. This was accomplished with the help of the appropriate equation published by Mesny.[3]

The fourth requirement was complete absence of regenerative feed-back in the presence of high gain. A communication receiver of that day was considered stable if it did not oscillate. Equivalent Q, however, is a sensitive function of feed-back, and response characteristics are readily altered by feed-back long before the point of oscillation is reached. This requirement was met by using a superheterodyne receiver, limiting volt-

[1] A. H. Schooley, "Pulse radar history," Proc. IRE (*Correspondence*), vol. 37 p. 405; April, 1949.
[2] R. V. L. Hartley, "Transmission of information," *B.J.T.S.*, vol. 7, p. 535; 1928.
[3] R. Mesny, "Time constants, build-up time and decrements," *l'Onde Elec.*, vol. 13, pp. 237–243; June, 1934.

age gain on any one frequency to one thousand, and changing intermediate frequency as required to accomplish an over-all voltage gain on the order of 10^7. In addition, extreme precautions were taken in shielding, filtering, and common point grounding.

The receiver was intended for a 5-μsec pulse. The over-all response was 90 per cent of steady state in 5 μsec. This characteristic was independent of gain up to the point where thermal noise at the input filled the cathode-ray screen.

A new transmitter of the self-quenching or "squegging" type was built to go with the new receiver. The transmitting antenna was a 4×4-wavelength curtain array with resonant reflector. The receiving antenna was a single half-wave doublet with single resonant reflector. The frequency was 28.6 Mc, with pulse length of 5 μsec and pulse recurrence rate of 3720/sec giving a range scale of 25 statute miles. The system went on the air in April, 1936. The receiver recovery to full sensitivity following the transmitted pulse appeared to be instantaneous. Beautifully sharp echoes from aircraft were observed almost at once, and within a few days they appeared all the way to the 25-mile limit of the indicator.

The spectacular success of the experiment was followed by a greatly intensified effort. A primary objective was to reduce the size of the equipment so it could be used on ships. The 28.6-Mc antenna was about 200 ft square. Reduction in directivity of antenna pattern was not desired. A smaller antenna therefore meant higher frequency. On July 22, 1936, a small radar was put in operation on 200 Mc. In that same month the first radar duplexer was successfully tested, also on 200 Mc, enabling both transmitter and receiver to use the same antenna. These two quick developments made it

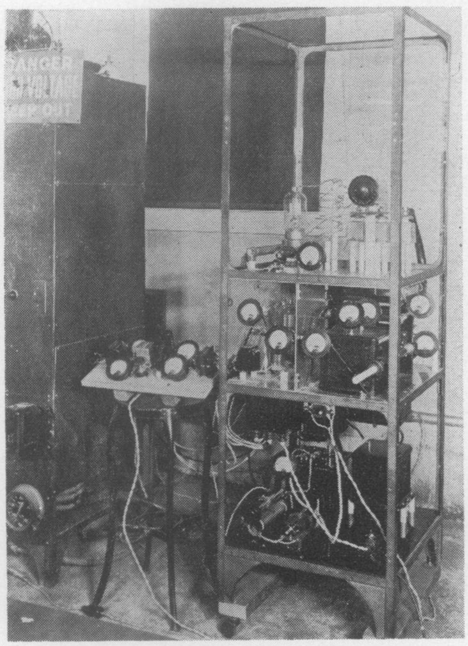

Fig. 2—Original 28-Mc radar transmitter with synchronizing keyer. 17,000 v on exposed wires and condensers on top shelf. April, 1936.

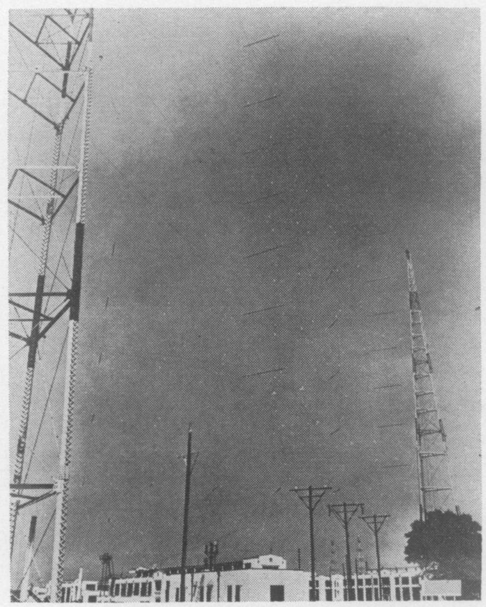

Fig. 3—28-Mc transmitting antenna suspended between 250 ft towers. 1936.

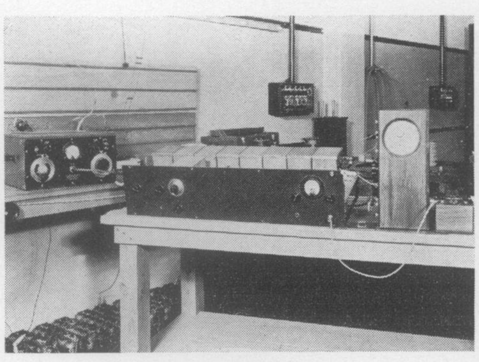

Fig. 4—Original 28-Mc receiver with indicator on test bench showing (left to right) standard signal generator, receiver, indicator, audio output meter. 1936.

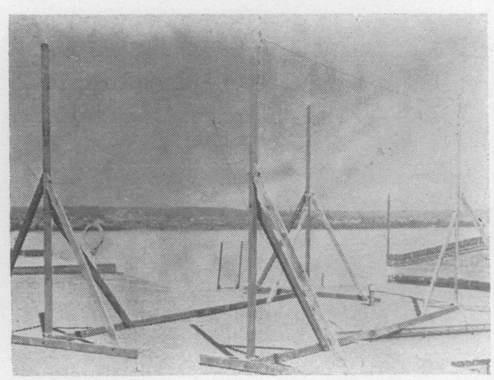

Fig. 5—Original 28-Mc radar receiving antenna; $\lambda/2$ dipole with $\lambda/2$ reflector. April, 1936.

possible to put radar on a ship for tests at sea. The first seagoing radar tests were made in April, 1937, on the USS *Leary*, an old destroyer of the Atlantic Fleet. The success of these tests led to the development of the model XAF, designed for Naval service at sea. Extensive tests on the USS *New York* in 1939 disclosed operational values beyond all dreams. The XAF was made prototype for the model CXAM, which was in service on 19 ships, the only U. S. Naval radar in service on December 7, 1941. It made an excellent wartime record.

This is a brief outline of the main stream in the early development of radar, resting on a sequence of related events from 1922 to 1941. Up to the summer of 1935 it was a single stream. At that time two other streams started, both remarkably parallel to the main stream. The one in England, sparked by the proposal of Watson-Watt in February, 1935, and conducted under the aegis of the Royal Air Force, was completely independent of the American developments until 1940, at which time the two countries pooled their resources. In the technological trade, America gained the uniquely-British cavity magnetron, and Britain gained the uniquely-American duplexer. The trade was not as one-sided as may have been inferred in some of the postwar literature. The pooled resources formed the technological capital for the newly-formed National Defense Research Committee in the superb development of microwave radar by the Radiation Laboratory of the Massachusetts Institute of Technology. The other stream, in the U. S. Army Signal Corps, sparked by the dynamic leadership of Colonel Roger B. Colton, was independent in part, but received much stimulation, both competitive and cooperative, from the more advanced work of the U. S. Naval Research Laboratory. It is one of the most remarkable coincidences in history that the three streams of radar development, operating more or less independently, issued in three vital but non-overlapping employments, each requiring basically different designs. At the war's beginning the finest mobile ground-based radar came from the U. S. Army Signal Corps, the finest airborne radar came from the Royal Air Force, and the finest Naval radar came from the U. S. Navy.

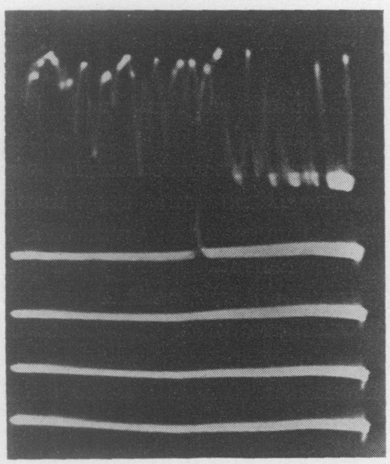

Fig. 6—Echoes of ground clutter (first line, 10 miles) and airplanes (second line, range about 15 miles) with 80-Mc radar installed with duplexer in field house. 5-Line sweep, 10 miles per line—total, 50-mile time base. December, 1936.

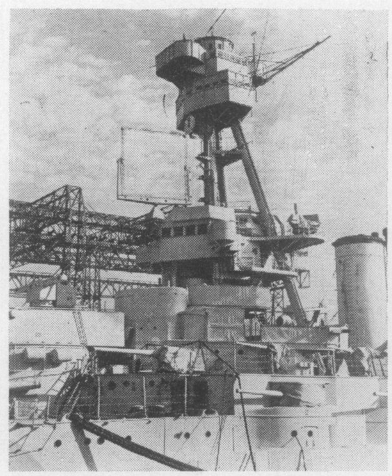

Fig. 7—XAF antenna installed on USS *New York* at the Norfolk Naval Shipyard. December, 1938.

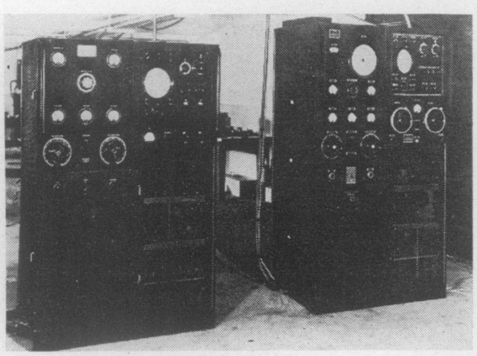

Fig. 8—The XAF radar (left) and the CXAM radar (right). Summer, 1940.

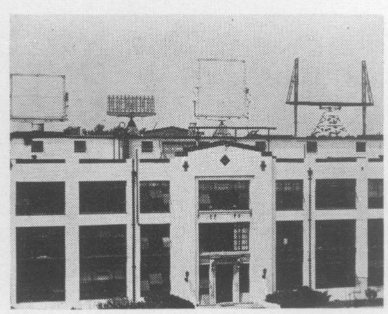

Fig. 9—Penthouse roof, Bldg. 12, showing (right to left), pre-XAF, XAF, 400-mc and CXAM antennas. Pre-XAF is hand driven; all others are motor driven with remote control. Summer, 1940.